Numerical and Experimental Study of Laminar Mixed Convection in A Horizontal Semicircular Duct

by

Quanmin Lei

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NUMERICAL AND EXPERIMENTAL STUDY OF LAMINAR MIXED CONVECTION IN A HORIZONTAL SEMICIRCULAR DUCT

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QUANMIN LEI

A thesis submitted to the Faculty of Graduate Studies of
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Abstract

This research provided a package of analytical, numerical, and experimental results. By first investigating fully developed laminar flow with zero buoyancy force, velocity and temperature profiles for circular sector ducts (CSD) were expressed in series form and converted to pressure drop and heat transfer data. Then, three-dimensional Navier-Stokes equations were numerically solved in the hydrodynamic entrance region of CSD's. Next was to perform numerically a heat transfer analysis for pure forced convection of thermally developing flow in CSD's. Following these prerequisite studies, numerical predictions were carried out using the modified SIMPLER algorithm for fully-developed laminar mixed convection in a horizontal semicircular duct (SCD). As the last and main target in this research, mixed convection flow and heat transfer were experimentally investigated in the thermal entrance region of the horizontal SCD with uniform heat input axially.

The analytical study included a novel expression of Nusselt number and produced a complete set of practical design data. The hydrodynamic analysis revealed that a smaller apex angle corresponds to a shorter hydrodynamic entrance length. It was similarly found that, for the thermal condition of axial uniform heat flux with uniform peripheral wall temperature, decreasing apex angle enhances local Nusselt numbers and shortens thermal entrance sections. Regarding the mixed convection flow, dual solutions were predicted for the SCD for modified Grashof numbers (Gr^+) up to 2×10^8 with Prandtl values of 0.7, 3, 5, and 20. The buoyancy-induced secondary flow was found to have two counter-rotating vortices which could bifurcate

into a multiple-cell flow structure. For high heating rates, the experimental data showed large circumferential variations in wall temperatures, a factor of over two for friction factor increase, and a factor of about five for heat transfer enhancement. In addition, the onset of thermal instability was observed to advance with increasing Grashof number and with decreasing Reynolds number.

It was concluded that increasing Gr^+ augments flow resistance and, more significantly, greatly enhances heat transfer. The influence of Pr was shown to be insignificant when the Nusselt ratios were plotted against the modified Rayleigh number Ra^+. However, the friction ratios were better correlated to Gr^+ or Gr^+/Pr^n, where n was determined to be 1.8 for $3 \leq Pr \leq 5$. In general, good correlations were obtained for the experimental data, whereas all key features of the mixed convection flow that were disclosed by both measurement and prediction were found to be consistent.

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Nomenclature

A	= cross-sectional area of circular sector duct, ϕR_0^2
A_{fl}	= cross-sectional fluid area
A_{iw}	= inside heated wall area
A_s	= cross-sectional solid area
B	= geometry parameter, $2(\phi + 1)/\phi$
C	= dimensionless pressure drop constant, $(d\bar{P}/dX)R_0^2/(\bar{W}\mu)$
C_1	= geometry parameter; for the $H1$ and $H2$ conditions, $C_1 = 2(\phi + 1)/\phi$; for the $H1_{ad}$ and $H2_{ad}$ conditions, $C_1 = 2$
c_p	= specific heat at constant pressure
$d\bar{P}/dX$	= axial pressure gradient
D_h	= hydraulic diameter, $2\phi R_0/(1 + \phi)$
D_i, D_0	= inside and outside diameters of the duct
f	= Fanning friction factor, $D_h(-d\bar{P}/dX)/(2\rho\bar{W}^2)$
g	= gravity
Gr	= modified Grashof number, $Gr = \beta g \rho^2 D_h^4 Q_f/\mu^2 k A_{iw}$
Gr^+	= modified Grashof number, $Gr^+ = \beta g q' R_0^3/(\nu^2 k)$
$\bar{h}$	= peripherally averaged heat transfer coefficient
$H1$	= uniform axial heat flux with uniform peripheral temperature for all surfaces
$H1_{ad}$	= uniform axial heat flux and uniform peripheral temperature for the curved surface; adiabatic flat surfaces

$H2$	= uniform axial and peripheral heat flux
$H2_{ad}$	= uniform axial heat flux with uniform peripheral heat flux on the curved surface; adiabatic flat surfaces
k	= thermal conductivity of fluid
K	= local incremental pressure drop number, equation (4.11)
$K(\infty)$	= incremental pressure drop number for fully developed flow when $X = \infty$, dimensionless
L	= total heated length
L_H	= hydrodynamic entrance length, L_{H1f}, L_{H1w}, L_{H5f}, L_{H5w}, defined in the text
L_H^0	= hydrodynamic entrance length, L_{H1f}^0, L_{H1w}^0, L_{H5f}^0, L_{H5w}^0, defined by equations (4.13) and (4.14)
L_T, L_T^0	= thermal entrance length, $L_T = X_T/(D_h Re Pr)$ and $L_T^0 = X_T/(R_0 Re_0 Pr)$
$\dot{m}$	= mass flow rate
n, N	= normal coordinate, $n = N/R_0$
Nu, Nu_0	= peripherally averaged Nusselt number, $Nu = \bar{h}D_h/k$ and $Nu_0 = \bar{h}R_0/k$
$\overline{Nu_{x,t}}$, $\overline{Nu_{x,h}}$	= local, but peripherally averaged, Nusselt numbers defined by equation (6.4)
$\overline{Nu_{x,th}}$	= $(\overline{Nu_{x,t}} + \overline{Nu_{x,h}})/2$
P	= total thermodynamic pressure
P', p', p^+	= pressure driving the cross-sectional flow, $p' = P'D_h^2/(\rho\nu^2)$ and $p^+ = P'R_0^2/(\rho\nu^2)$
$\bar{P}$, $\bar{p}$	= axial pressure averaged at a cross-section, $\bar{p} = \bar{P}/(\rho\bar{W}^2)$
$\Delta\bar{p}$	= $\bar{p}_0 - \bar{p}$, the pressure drop
ΔP	= pressure drop across the heated section
Pr	= Prandtl number, $\mu c_p/k$

q' = duct heat transfer rate per unit length

q'' = constant heat flux

$q''_{r\theta}$ = peripherally local heat flux, $q''_{r\theta} = (\pi + 2)(\partial T^+/\partial n)_{wall}$

Q_f = heat gain by the fluid

Q_e = electric power input

$R_0,\ r'_0$ = radius of the duct, $r'_0 = R_0/D_h$

$R,\ r,\ r'$ = radial coordinate, $r = R/R_0$ and $r' = R/D_h$

r^* = radial distance, normalized by R_0, where the axial velocity has its maximum value

Ra = modified Rayleigh number, $Ra = GrPr$

Ra^+ = modified Rayleigh number, $Ra^+ = Gr^+Pr$

Ra' = modified Rayleigh number based on duct inside diameter D_i, $Ra' = Ra(D_i/D_h)^4$

$Re,\ Re_0$ = Reynolds number, $Re = \rho\bar{W}D_h/\mu$ and $Re_0 = \rho\bar{W}R_0/\mu$

$t,\ \bar{t}_w,\ t_{\bar{c}}$ = temperature; $\bar{t}_w$ = average peripheral wall temperature; $t_{\bar{c}}$ = average wall temperature over the curved surface of the duct

T = the boundary condition of constant wall temperature both peripherally and axially

T_i = dimensionless temperature; for the $H1$ and $H1_{ad}$ conditions, $i = 1$ and $T_1 = (t - t_{\bar{c}})/(q''R_0/k)$; for the $H2$ and $H2_{ad}$ conditions, $i = 2$ and $T_2 = (t - \bar{t}_w)/(q''R_0/k)$

T^* = dimensionless temperature, $T^* = (t - t_m)/(q''R_0/k)$

T^+ = dimensionless temperature, $T^+ = (t_w - t)/(q'/k)$

$U,\ u,\ u^+$ = radial velocity, $u = UD_h/\nu$ and $u^+ = UR_0/\nu$

$V,\ v,\ v^+$ = angular velocity, $v = VD_h/\nu$ and $v^+ = VR_0/\nu$

$W,\ w,\ \bar{W}$ = axial velocity, $w = W/\bar{W}$, $\bar{W}$ = mean axial velocity

w_{max} = dimensionless maximum axial velocity at $r = r^*$ and $\theta = \phi$

$X,\ x^+,\ x^*,\ x'$	= axial coordinate, $x^+ = X/(D_h Re)$, $x^* = X/(D_h Re Pr)$, and $x' = X/(R_0 Re_0 Pr)$

Greek Letters

β	= thermal expansion coefficient
δ_f	= fluid mean conduction path length
θ	= angular coordinate
μ	= dynamic viscosity
ν	= kinematic viscosity
ρ	= density
σ	= standard deviation
ϕ	= half the apex angle of a circular sector duct

Subscripts

0	= at the entrance or based on R_0
$\bar{c}$	= average over the curved surface
fd	= fully developed conditions
$H1,\ H2$	= for the $H1$ or $H2$ boundary condition
$H1_{ad},\ H2_{ad}$	= for the $H1_{ad}$ or $H2_{ad}$ boundary condition
i	= 1 for the $H1$ or $H1_{ad}$ condition; 2 for the $H2$ or $H2_{ad}$ condition
j	= indicator for thermocouple positions a, b, and c at each station
lm	= axial length mean
m	= bulk mean; fluid properties evaluated at the average of upstream bulk temperature and downstream bulk temperature
M	= fluid properties evaluated at the average bulk temperature in the fully developed region
max	= maximum value

mi, mo = bulk mean at inlet and at outlet

T = thermal entrance length or for the T boundary condition

w = at the wall

x = axially local

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Chapter 1

Introduction

THE field of heat transfer has continued to grow swiftly during the past twenty years due to ever-increasing research efforts. With the rapid development of modern technology, the use of heat transfer has spread widely to many other branches of science which in some cases has led to the formation of new subfields. One of these subfields is the study of the interacting effects of free and forced convection. Due to its practical importance, this kind of mixed convection has recently received increasing attention.

1.1 Mixed Convection

It has been realized that buoyancy forces can cause a heat transfer result to differ significantly from its pure forced convection value. The importance of buoyancy effects depends on whether the flow is laminar or turbulent, internal or external, on whether the duct is horizontal or vertical, smooth or finned, and on duct geometry as well as duct-cross-section orientation. For turbulent flows, since turbulent diffusion tends to attenuate thermal gradients and hence reduce buoyancy effects, more interest has been given to mixed convection heat transfer in laminar flow. For a vertical duct flow, the gravitational vector ($\vec{g}$) is parallel to the flow direction and thus buoyancy forces act to assist or retard the flow. On the other hand, for a horizontal duct flow, which is considered in the present research, $\vec{g}$ is perpendicular to the flow and the thermogravitational forces are known to generate counter-rotating transverse vortices. This so-called "secondary flow" which is superimposed on the streamwise main flow can lead to substantial circumferential temperature variations and heat transfer increases. For the heating case (i.e., hot wall), due to the downward movement of the core fluid that contains high axial momentum, the axial velocity profile can be also distorted such that significant increases in flow resistance result.

Furthermore, the buoyancy-induced secondary flow can aid the flow development and subsequently shorten the thermal entrance length. It is also possible that large buoyancy effects will result in an early transition from laminar to turbulent flow. Concerning the response to thermal boundary conditions, buoyancy effects persist throughout the whole length of a uniformly heated duct where the wall-minus-fluid temperature difference (Δt) increases from zero at the beginning of the heating to a constant value in a far downstream region. In contrast, for ducts with constant wall temperature Δt, will diminish and eventually vanish in the far downstream region. Therefore, free convection effects exist only in the thermal entrance region of isothermal ducts.

1.2 Circular Sector Ducts and Motivation

In this study, considerable effort was spent on pure forced convection flow and heat transfer in circular sector ducts (CSD) even though the investigation on mixed convection was focused solely on a horizontal semicircular duct (SCD) which belongs to the family of the CSD. The CSD was found to be of special interest after a computer literature survey was conducted at the beginning of the research. Specifically, the important facts may be stated as follows:

1. In food, chemical, and nuclear engineering applications, heat transfer analyses are often encountered for laminar flow through multipassage tubes which consist of CSD's. Also, the CSD (e.g., SCD) can be used to design new com-

pact heat exchangers which provide higher heat transfer coefficients than the smooth tube ones. However, very limited data are available for CSD's.

2. The CSD represents the limiting cases of circular tubes having equi-spaced, radial full fins. Thus, reliable results of measurements and predictions for CSD's can provide a complete analysis for internally finned tubes.

3. The semicircular duct is of particular practical interest. For instance, the flat wall of the duct can be attached on a nuclear reactor surface from which substantial heat might be released. In addition, the results for the SCD serve as a lower bound for circular tubes containing a twisted tape-insert.

It is these considerations that motivated the present research.

1.3 Objectives

The research involved two components; viz., an analytical and numerical study of laminar flow and heat transfer in CSD's without buoyancy effects, and (more importantly) a numerical and experimental investigation on combined laminar free-forced convection in a horizontal SCD. The main objectives were as follows:

A. To find analytical expressions of velocity and temperature distributions for laminar, hydrodynamically and thermally developed flow of zero buoyancy force in CSD's using four different thermal boundary conditions. A complete set of results for friction factors and Nusselt numbers for the entire apex angle range of the CSD were to be provided.

B. To solve numerically three-dimensional momentum equations in the hydrodynamic entrance region of CSD's.

C. To study numerically forced convection heat transfer in the thermal entrance region of CSD's using two thermal boundary conditions in order to furnish base-line references for the mixed convection study.

D. To analyze numerically the flow and heat transfer of mixed convection for fully developed laminar flow in a horizontal SCD. Computations were to be performed for Grashof numbers up to 2×10^8 and Prandtl numbers of 0.7, 3, 5, and 20.

E. To investigate experimentally the flow and heat transfer of laminar mixed convection in the thermal entrance region (and fully developed region) of a horizontal SCD with uniform heat input axially.

1.4 Layout of the Dissertation

This dissertation is composed of seven chapters. An extensive review of the literature is supplied in Chap. 2. The results of objective A are presented and discussed in Chap. 3. Chapter 4 then deals with objectives B and C, i.e., the hydrodynamic and thermal entrance regions. The governing equations for laminar mixed convection and the numerical analysis for objective D are outlined in Chap. 5. The experimental results (objective E) are presented in Chap. 6 where comparisons between measurement and prediction are made wherever possible. Finally, conclusions and recommendations are given in Chap. 7. Since the experimental study deals with developing mixed convection flows which possess the most complicated phenomena in principle, Chap. 6 is deliberately placed to follow the representation of all numerical results. Regarding the raw experimental data, Appendix E lists the outputs that were calculated by the computer program given in Appendix D.

Chapter 2

Review of Literature

THROUGHOUT the literature, information on the fluid flow and heat transfer of combined laminar free-forced convection is widely scattered. Thus, this review is intended to gather the information together to form a clear picture of the background for the present research.

2.1 Scope of the Review

This review is limited to laminar flow although certain referenced papers have involved transitional and turbulent flows. Due to the scarcity of material on circular sector ducts or other similar noncircular ducts, this survey was expanded to include smooth circular tubes and rectangular ducts. However, not much attention was given to internally finned tubes although they are of practical interest. Regarding duct orientation, vertical and inclined ducts were included but the search was mainly focused on horizontal ducts. Whereas mixed convection was emphasized, analytical studies on forced convection flow and heat transfer were also briefly reviewed. The methods of problem solving, rather than details of the results, in each selected paper were particularly discussed. In addition, recent numerical techniques received special attention. To highlight the previous studies, the review is organized in terms of analytical methods, computational analyses, and experimental investigations.

2.2 Analytical Methods

To determine the characteristics of internal fluid flow and heat transfer with and without buoyancy effects, a considerable amount of research effort was directed toward analytical solutions. Even though they are often subjected to certain limitations, demands for these solutions are still increasing. This is primarily because of three reasons: (1) they spark our theoretical interest and promote our insight into physical fundamentals; (2) they precisely represent the limiting cases of real situations and provide useful design data; (3) they also serve as a reliable source for verifying complex numerical solutions when the predicted value converges to its limit. In the past three decades, a number of analytical methods have been successfully developed for obtaining the fields of velocity and temperature, calculating pressure drops and heat transfer coefficients, and determining effects of solution parameters and other quantities of interest.

2.2.1 Exact Solution

From the analogous torsion solution, Eckert *et al.* [1] were the first to derive a series expression for the velocity profile of circular sector ducts in fully developed laminar flow. For the thermal boundary condition of axial uniform heat input with uniform peripheral wall temperature ($H1$), their analytical solution of temperature was obtained by a transformation of the semicircular plate-deflection problem discussed in [2]. For the thermal boundary condition of uniform heat input both axially and peripherally ($H2$), they expressed the temperature solution in the form of a series with arbitrary constants. For both cases, they computed average Nusselt numbers for circular sector ducts for apex angles up to $60°$. Sparrow and Haji-Sheikh [3] extended the work of [1] and plotted the pressure drop data and the Nusselt numbers for apex angles up to $180°$.

Hu and Chang [4] used a partial eigenfunction expansion method to construct a generalized Green's function for the energy equation of finned tubes in fully developed laminar flow. For the $H2$ condition only, their full-fin tubes (which represent several circular sector ducts) gave calculated Nusselt numbers which differed by up to 10% from the results in [1]. To analyze fully developed laminar flow in finned tubes, Soliman and Feingold [5] divided the cross-stream flow domain into two regions. Their solution for the axial velocity distribution within each region was written in the form of an infinite series involving arbitrary constants. They also derived the expressions of the velocity and the product (fRe) of friction factor and Reynolds number for full-fin tubes in terms of the number of fins. Using the method of separation of variables, Soliman [6] analyzed fully developed laminar heat transfer in annular sector ducts. With the aid of numerical integration, he computed Nusselt numbers for both the $H1$ and $H2$ conditions with a wide range of the radius ratio and the duct apex angle.

Regarding thermal boundary conditions, Sparrow and Patankar [7] demonstrated that the following four types of conditions that are compatible with the existence of a thermally developed regime were tightly interrelated. They are: (a) uniform wall temperature; (b) uniform wall heat flux; (c) exponential variation of the wall heat flux; and (d) convective heat transfer from the external surface of the duct to a fluid environment with heat transfer coefficient and temperature both of which are uniform. Through analytical analyses, they concluded that cases (a) and (b) serve as low and high bounds, respectively, on case (c) while case (d) is a specialization of case (c). They also noted that various subclasses of thermal boundary conditions can be formulated if circumferential variations are considered.

2.2.2 Linearized Approximation

The method of linearized axial momentum equation in ducts for determining the incremental pressure drop resulting from the entrance effects is one of the noteworthy analytical techniques. Lundgren *et al.* [8] developed this method and calculated the pressure drops in various duct flows without actually solving for the entrance-region velocity development. Following this theory, McComas [9] generated a procedure for determination of the hydrodynamic entrance length of ducts of arbitrary cross section by knowing only fully developed velocity profiles. A more general analytical approach was made by Fleming and Sparrow [10] to determine the developing velocity field and pressure drop for laminar flow in the entrance region of ducts. Using this linearization method, Soliman *et al.* [11] predicted the velocity distribution and pressure drop in the entrance region of circular sector ducts for apex angles up to 90°.

2.2.3 Perturbation Method

Attention has been long drawn to the perturbation method ([12] is a good source for this method) for investigating problems of buoyancy effects on forced convection. Starting with the forced convection solution as a first approximation, the next approximation can then be found as a buoyancy-driven secondary flow and a secondary temperature distribution due to the modified field of flow. This merely gives a perturbation of the forced convection solution. Morton [13] was the first to use the perturbation method for studying laminar convection in uniformly heated horizontal pipes at low Rayleigh numbers (Ra). Under fully developed conditions, he employed a Stokes stream function and eliminated the pressure between two cross-stream momentum equations. The governing equations were thus written by the dimensionless stream function, axial velocity, and temperature, which were approximated as power series in Ra. Substituting these power series into the corresponding governing equations and equating coefficients of powers of Ra made it possible to have a particular order approximation for these three variables. Morton [13] found that the Nusselt number was a function of the Prandtl number (Pr) and the product of the Rayleigh and Reynolds numbers ($Ra\,Re$).

The influence of tube orientation on combined free-forced laminar convection was theoretically examined by Iqbal and Stachiewicz [14]. Their perturbation series solution was approximated up to second order. Since, to insure convergence of the series, the $Ra\,Re$ value must be small, they made a detailed check of temperature and Nusselt number equations. The upper limits of $Ra\,Re$ were found to be lower than 3000 for the validation of their solutions. Using primitive variables (pressure, temperature, and three velocities), Yao [15] obtained an asymptotic solution of laminar free-forced convection flow near the entrance of an isothermally heated pipe by perturbing the solution of the developing flow in an unheated pipe.

2.2.4 Integral Method

For mixed convection flows, it is often worthwhile to look for approximate methods of solution, such as integral methods. Based on a flow visualization, Mori and Futagami [16] developed an integral solution for theoretically studying the buoyancy-induced secondary flow in uniformly heated horizontal tubes. In their solution procedure, velocity and temperature fields in a core region were assumed to be affected mainly by the secondary flow and effects of viscosity and thermal conductivity were disregarded. On the other hand, in a thin layer along the tube wall, velocity and temperature fields were affected by viscosity and thermal conductivity, and boundary-layer approximations were applied in the analysis. Treating each velocity and temperature as the function of boundary-layer coordinate and its thickness, they integrated equations of momentum and energy for the case of the momentum thickness larger than the thermal thickness and for the case of the reversed condition (Pr effect).

Similar to the method described in [16], Hong and Bergles [17] investigated combined free-forced convection in fully developed laminar flow of horizontal tubes with temperature-dependent viscosity and large Pr. In considering viscosity as temperature-dependent only in the governing equations, they introduced the coefficient γ of viscosity variation due to temperature change Δt ($\gamma = -(d\mu/dt)/\mu$, which is a term analogous to the coefficient of thermal expansion, β). For both the $H1$ and $H2$ conditions, the Nusselt (Nu) results in [17] were presented in the form of $Nu = C_1(\gamma\Delta t)Ra^{1/4}$, where C_1 is a function of a nondimensional viscosity parameter $\gamma\Delta t$ and the thermal boundary conditions. Of course, $\gamma\Delta t = 0$ represents the constant viscosity solution. They reported that, while the proportionality constant C_1 increases as $\gamma\Delta t$ increases, the heat transfer predictions for large $\gamma\Delta t$ were over 50 percent above the constant viscosity predictions.

2.2.5 Other Techniques

Another useful analytical technique, the similarity solution method, was used by several investigators (e.g., in [18,19,20,21]) to approximate laminar mixed convection flows. For the mixed convection laminar flow of a large Pr fluid, Hieber and Sreenivasan [19] divided an isothermal horizontal pipe into a succession of regions: a "near region", an "intermediate region", a "break-up region", and a "far-region". In each region, buoyancy forces were assumed to play a different role.

As a last notable analytical technique, the Gram-Schmidt method has been useful to construct orthonormal functions in fluid flow and heat transfer analyses. For example, Sparrow and Haji-Sheikh [22] used this method to develop a computation-oriented method of analysis for determining series-form solutions for fully developed laminar flow and heat transfer in ducts of arbitrary shape with arbitrary thermal boundary conditions.

2.3 Computational Analyses

As a new field, computational heat transfer and fluid flow has made significant impact on research, design, and education over the past twenty years. One of the most prominent features of computational analysis is cost-effectiveness; namely, providing a convenient way of obtaining detailed solutions for complex physical situations. A large number of computational techniques have been proposed, tested, and applied to combined free-forced convection flow and heat transfer. For purposes of the present research, the following review starts with an outline of numerical methods and proceeds to the recognition of convection-diffusion formulations and flow-equation solution algorithms which are two core ingredients of a nonlinear, iterative, computational technique. Then, applications mainly in laminar mixed convection analyses are selectively reviewed.

2.3.1 Outline of Numerical Methods

Convectional numerical methods that are often applied in heat transfer can be consulted in the book of Shih [23]. Of these, the numerical methods that are of interest to the present research are the finite difference method and the finite element method. A great many subclasses of numerical methods can be grouped if the techniques of equation formulation with solution procedures are considered. A recent review that includes some finite element methods in fluid flow and heat transfer has been given by Patankar [24]. Another method whose applications are rarely found in internal mixed convection flows but widely found in porous media flows is the boundary integral equation method [25]. Also, boundary element methods are widely used in solid mechanics [26].

Whereas the finite difference method earns the most popularity in fluid flow and heat transfer analyses, its first subclass may be clarified by the types of variables present in the Navier-Stokes equations. These are called: primitive variables method, vorticity-stream function method, and vorticity-velocity method. Generally, the vorticity-stream function and vorticity-velocity methods share the difficulties of appropriate implementation of boundary conditions for the vorticity. The primitive variables method, on the other hand, is associated with problems of determining the pressure. The most successful primitive variables method in numerical heat transfer and fluid flow was developed by Patankar and Spalding [27] and by

Patankar [28]. An essential feature of this method is a general, numerical, marching procedure for the calculation of transport processes in three-dimensional *parabolic* flows. The so-called "parabolic flows" are characterized by the presence of one dominant coordinate in which there exist no regions of reverse flow in this direction. This is often accomplished by neglecting axial diffusion terms (second derivative with respect to the axial coordinate) from the *elliptic* differential equations. Should reverse-flow regions exist, Gosman *et al.* [29] provide a good source of using vorticity-stream function methods to handle two-dimensional elliptic flows. A recent review on finite difference methods for natural and mixed convection in enclosures has been given by de Vahl Davis [30] who has stressed vorticity-stream function methods.

For laminar mixed convection problems, most investigators have employed the primitive variables methods, e.g., a vectorized finite difference marching technique [31,32] that was specifically developed for a vector-processing supercomputer of the Cyber 205 and a finite difference procedure [33] for laminar, axisymmetric developing flow in circular tubes with temperature-dependent viscosity. But, the use of vorticity-stream function methods can be found through [34] to [40] and the use of vorticity-velocity methods in [41,42]. Ku and Hatziavramidis [43] used Chebyshev expansion methods for solving the steady two-dimensional Navier-Stokes equations in both the vorticity-stream function and vorticity-velocity formulation.

2.3.2 Convection-Diffusion Formulation

The treatment of convection-diffusion formulation is always a key issue in computational heat transfer when considering accuracy, convergence, stability, and computing time. An improper convection-diffusion formulation may result in excessive numerical errors known as false diffusion which is a multidimensional phenomenon. Especially for large Peclet numbers (Pe) for which real diffusion is relatively small, the matter of false diffusion attains importance. This is one reason why many discretization schemes tend to become unstable and fail to converge at high flow rates.

In a convection-diffusion situation, the *central-difference* scheme that is the natural outcome of a Taylor-series formulation is recognized to give unrealistic results at high Pe. To seek better formulations, Patankar [28] first introduced the well-known *upwind* scheme. This scheme leaves the diffusion term unchanged but the convection term is conditionally calculated by checking the flow direction. Thus, the solutions will always be physically realistic, which is the most important advantage of the *upwind* scheme. However, it generates spurious overshoot and undershoot for diffusion at large Pe values. To remedy the defects, Raithby and Torrance [44] proposed and employed the *exponential* scheme. Despite its desirable behavior, it is not widely used because exponentials are expensive to compute. Spalding [45] developed the *hybrid* scheme whose essence is the three-line approximation to the exact convection-diffusion variation. Another approximation given by the *power-law* scheme was described and recommended by Patankar [28]. While in many situations the last two schemes serve equally well, the *power-law* expression (a closed form was given in [28]) provides a better representation of the exponential behavior.

Recently, a number of new formulations have been proposed. Some of them are based on the *quadratic upstream* (QUICK) scheme of Leonard [46]. Runchal [47] has described a scheme, call CONDIF, which retains the essential nature of the *central difference* scheme but eliminates the over- and under-shoots. Lillington [48] has proposed a scheme that accounts for the magnitude of the source term in addition to the direction of the velocity vector. Other proposed schemes have been discussed and compared in [24].

2.3.3 Algorithm for Discretized-Equation Solutions

Once convection-diffusion terms are properly formulated, successful predictions then lie in the use of an efficient algorithm for obtaining the solutions of the discretization equations. Since finite difference primitive variables methods are of interest here, velocity-pressure coupling techniques that largely affect the performance of solution methods are first reviewed.

Velocity-Pressure Coupling. For internal parabolic boundary-layer flows, longitudinal and lateral pressures are often deliberately decoupled. While the longitudinal pressure gradients are determined by ensuring the *global* conservation of mass, the lateral pressures are obtained by solving the Poisson equation which is derived from the *local* continuity equation. Thus, the pressure serves as a crucial bolt for the coupling between momentum and continuity equations. After proposing a useful procedure to calculate the streamwise pressure gradient, Raithby and Schneider [49] examined several existing methods of handling this coupling. The first method of Patankar and Spalding [27] uses the pressure correction (obtained by solving the Poisson equation) to correct the velocities while also correcting its best estimate pressure with a relaxation parameter. The second Patankar-Spalding method uses under-relaxation of velocities from the momentum equations but assigns the relaxation parameter to 1 for the pressure correction. Several other methods, including a proposed new method, and results of their application to a test problem were discussed and compared in [49].

Solution Procedures. Due to the highly coupled, nonlinear, multidimensional features of the governing equations, iteration methods are employed for the solutions. A number of currently used methods of flow calculation originated from the SIMPLE procedure of Patankar and Spalding. The SIMPLE, which stands for *S*emi-*I*mplicit *M*ethod for *P*ressure-*L*inked *E*quations, has the shortcomings of slow convergence, approximate pressure field, and the need for heavy under-relaxation. A more efficient variant of SIMPLE, called SIMPLER, which stands for SIMPLE *R*evised [28], solves an extra equation of pressure but requires fewer iterations for convergence hence reducing the overall computing time. This method has been widely used for computing mixed convection flow and heat transfer. However, it does not satisfies all situations. When studying mixed convection in a vertical tube with radial internal fins, Prakash and Patankar [50] found that their successivesubstitution technique tended to diverge at high Rayleigh numbers. For a remedy, they developed a simultaneous solution of two coupled variables and accelerated convergence by using a block-correction procedure, which uses the concepts of "additive correction" generalized by Settari and Aziz [51].

Other modifications of SIMPLE have been made by Connell and Stow [52], Latimer and Pollard [53], and Issa [54]. Van Doormaal and Raithby [55] have described the SIMPLEC procedure, which employs consistent under-relaxations for momentum and pressure corrections. Spalding [56] has developed the SIMPLEST procedure, which treats convection explicitly and diffusion implicitly in the momentum equations. Vanka [57] has recently shown that the use of a multigrid method with a coupled solution at a point can lead to a very efficient technique. All these efforts certainly enhance the capability of computational heat transfer and fluid flow. But careful evaluations of different methods are still required for future research.

2.3.4 Applications in Developed Mixed Convection

Problems on fully developed mixed convection are usually numerically dealt with differently from a more general analysis for the developing flow. Thus, it is necessary first to focus attention on fully developed mixed convection studies.

2.3.4.1 Special Computing Features

With the rapid development of computer hardware, a number of investigators have started to use specially developed computers to speed up computations. Fung *et al.* [58] have employed an Array Processor FPS–164 attached to an Amdahl 5860 main frame to study flow pattern phenomena in mixed convection. Using a Cray-1 supercomputer, Braaten and Patankar [59] have vectorized the SIMPLE algorithm for analyzing laminar mixed convection in shrouded arrays of rectangular blocks, e.g., like closely-spaced electronic circuit boards. The time-dependent forms of the vorticity-stream function formulations using the quadratic upstream differencing method have been applied by Kotake and Hattori [60] to steady combined convection in horizontal annuli. To permit a smooth variation in the geometrical shape from a full circle to a semicircle, Nandakumar *et al.* [61] have used a cylindrical bipolar coordinate for their laminar mixed convection analyses in horizontal ducts. Nakamura *et al.* [62] have employed a triangular coordinates system to analyze mixed convection in arbitrary triangular ducts. Using the conjugate gradient method [63], they have also numerically solved a similar problem for rectangular ducts.

2.3.4.2 Secondary Flow Patterns

Nandakumar *et al.* [61] were the first to numerically investigate fully developed laminar mixed convection flow in a horizontal semicircular duct using the $H1$ condition. For the flat wall of the duct at the bottom, they predicted two symmetric counterrotating vortices for their defined Grashof number (Gr) less than about 1.3×10^5 at the Pr value of 5. The two-vortex secondary flow pattern persisted as Gr gradually increased further until the Gr value reached about 1.4×10^6. At this Gr level, they found that the two vortices bifurcated into four vortices, together with a jump in the curves of friction factor and Nusselt number ratios. If this four-vortex solution was treated as initial guessed values for a higher Gr, a four-vortex solution was obtained only. Similarly, but for a lower Gr, the four-vortex solution also resulted. Gradually reducing Gr continued to give the four-vortex results until $Gr <\sim 1.3 \times 10^5$ for which previous two-vortex solution was again obtained. They pointed out that this hysteresis behaviour and the flow bifurcation phenomenon in mixed convection were akin to the phenomenon in Couette flow between rotating cylinders (the Taylor problem) and had features similar to those of laminar flow in helical tubes (the Dean problem) as studied by Nandakumar and Masliyah [64]. They also reported that for $Pr = 0.7$, the upper critical Grashof number could not be reached due to the numerical instability when $Gr >\sim 2.4 \times 10^6$. For their rectangular ducts and circular tubes, similar results were presented in the same paper [61].

As an extension to the above work, Law *et al.* [65] examined the effect of nonuniform heating on laminar mixed convection in the same semicircular duct that was heated from the bottom flat wall but with the curved surface insulated. In this case, calculations for $Pr = 5$ revealed the bifurcation phenomenon but those for $Pr = 0.7$ did not. More recently, Fung *et al.* [58] found even-cellular modes from a numerical study on the mixed convection in rectangular ducts. They concluded that the appearance of cellular flows via buoyancy instability is gradual and that there is no precise value of Gr at which such development occurs abruptly. The secondary flow bifurcation phenomenon was also numerically reported by Chou and Hwang [38], Acharya and Patankar [66], and Patankar *et al.* [67].

2.3.4.3 Heat Transfer Enhancement

The results of Nandakumar *et al.* [61] showed that the buoyancy-driven secondary flow significantly enhances heat transfer in the semicircular duct. If the corresponding forced convection Nusselt number is referenced, the Nusselt ratios are shown to increase with increasing Gr as well as Pr. By comparison, the four-vortex Nusselt ratio for the case of the heating below only [65], for $Pr = 5$ and $Gr \approx 5 \times 10^5$, is about 1.7 times higher than the corresponding value for the uniform heating case [61]. According to Patankar *et al.* [67], at high heating rates, the heat transfer enhancement for the case of heat added along the bottom half of a tube (other half insulated) is even about 8 times higher than the value for the case of heat added along the top half of the tube (other half insulated). These indicate that the bottom heating induces the vigorous secondary flow while the top heating brings about temperature stratification and induces the much weaker secondary flow. For rectangular ducts, the Nusselt ratios predicted by Chou and Hwang [38] show a jump due to the onset of a second pair of eddies when plotted against $Ra\,Re$.

For triangular ducts, heat transfer results in [62] include the effects of an inclination angle and a rotational angle of the duct.

2.3.4.4 Friction Factor Results

While enhancing heat transfer, the buoyancy driven secondary flow also presses down axial velocity profiles and consequently increases overall friction factors. Predictions in [61] for the semicircular duct show, with increasing Gr and decreasing Pr, marked increases in the friction factor relative to its forced convection value. But the increases are often substantially smaller (e.g., about 5 times smaller in [67] for a high Gr and $Pr = 5$) than those attained by the Nusselt number. For the described case of the bottom heating tube, the friction ratios in [67] rise up sharply with Gr for $Pr = 0.7$ but remain fairly constant for all Gr for the top heating case at high Pr, e.g., $Pr \geq 5$. This is consistent with numerical results for an equilateral triangular duct in [62] where the influence of the friction ratio against Pr is plotted. Again, the friction ratios in [36] for rectangular ducts also display a jump at $Ra\, Re$ at which the two-eddy secondary flow breaks up into a four-eddy flow structure.

2.3.5 Applications in Developing Mixed Convection

In recent years, interest has been rising in studying buoyancy effects on laminar heat transfer in the thermal entrance region of ducts. Computations have no longer been limited to the large-Prandtl-number approximation which neglects inertia force terms in momentum equations, as first (in 1972) used by Cheng *et al.* [68]. Many investigators have numerically solved the fully parabolic and even elliptic transport equations for a number of mixed convection problems. However, no numerical efforts have been made so far for developing mixed convection in a semicircular duct.

2.3.5.1 Special Computational Techniques

In recent numerical studies, Mahaney *et al.* [31,32] solved the dimensional governing equations using the SIMPLER procedure. To obtain the solution of algebraic equation systems, they employed the vectorized Jacobi iterative technique which proved most efficient for all but the pressure equations. With the introduction of a new parameter, Choudhury and Patankar [69] formulated the three-dimensional governing equations of an inclined tube in a compact form in which the inclination angle does not explicitly appear. Using the high Peclet number assumption (parabolic flow), Chou and Hwang [41] numerically solved vorticity-velocity governing equations. Coutier and Greif [70,71] used a code, called TOROID, and solved the elliptic equations with three-dimensional grids without marching. Similarly, but using the SOR (successive over-relaxation) method, calculations in [72] involved the three-dimensional time-dependent forms of conservation equations. However, these three-dimensional solvers were costly so that only very coarse grids in the axial direction were used.

2.3.5.2 Longitudinal Distribution of Nusselt Numbers

Uniform Wall Heat Flux. From a numerical study by Incropera and Schutt [73], a typical longitudinal Nusselt number (Nu) distribution would have the following pattern. The sharp decline in the immediate neighborhood of the entrance indicates the development of the thermal boundary layer. With the establishment of thermal gradients, onset of free convection or thermal instability is marked by an ascension in Nu relative to its pure forced convection limit. Then, the Nu value continues to drop until it reaches a minimum. As the heating proceeds, the buoyancy-induced secondary flow grows and the Nu value attains a maximum. Because the secondary flow acts to diminish its own driving potential, another decline in Nu occurs. According to Mahaney *et al.* [31,32], these longitudinal Nu oscillations also happened in their computations which were carried out by a vector-processing supercomputer. But, under certain conditions, the oscillations are damped and yield a fully developed Nusselt number that substantially exceeds the value for pure forced convection. In the predictions of [41], the first minimum and maximum in the Nu distribution are apparent, followed by some degree of oscillations especially for low Pr fluids.

Uniform Wall Temperature. Unlike the case of uniform wall heat flux, buoyancy effects exist only in the thermal entrance region of isothermal ducts. Beyond onset of thermal instability, a Nu curve may rise above its forced convection curve, depending on the significance of buoyancy forces. There always exists a region where free convection effects are most pronounced. In a far downstream region, Nu approaches its forced convection value due to the diminution of the wall-minus-fluid temperature difference. Such axial Nu distributions are predicted in [69,74,75,76].

2.3.5.3 Onset of Thermal Instability

Since onset of the thermal instability is of practical interest in design, it is usually defined based on a given percentage at which the local Nusselt number first exceeds that of pure forced convection. Correlation equations for the onset point based on the 2% deviation are given in [42,76] for rectangular ducts, and in [75] for isothermal tubes. Another criterion, based on the location of minimum local Nusselt number, is also considered in [42]. All these studies show that increasing buoyancy effects advances onset of the thermal instability or the secondary flow.

2.3.5.4 Effects of Reynolds, Grashof, and Prandtl Numbers

Concerning the parameters influencing the Graetz problem, in most numerical work, the Reynolds number dependence of the entry-region mixed convection flow is often accommodated through the Graetz number (Gz). Hence, the role of the

Reynolds number is to "stretch" the flow in the duct [73]. When the large Pr assumption is disregarded, numerical calculations are usually carried out by treating Gr or Ra and Pr as independent parameters (e.g., see [69]). Since Gr is a measure of ratio of buoyancy force to viscous force, the effects of Gr or Ra are evident through [31,68,69]. However, due to the effects of fluid properties, the Pr influence on developing mixed convection flow and heat transfer is not as clear as other parameters. Some examinations on the Pr dependence are given in [41,69,73].

2.4 Experimental Investigations

For horizontal laminar duct flows, widely scattered experimental data have been long attributed to buoyancy effects [77,78]. Measurements of mixed convection heat transfer have been predominately conducted for circular smooth tubes and rectangular channels. However, no similar work to the present experimental study has been reported so far.

2.4.1 Flow Visualization

Mori and Futagami [16] first introduced smoke of NH_4Cl into an air flow in an inner tube at the inlet of the heat transfer section and photographed the pattern of smoke. They observed that the buoyancy-assisted secondary flow generated a pair of vortices which are symmetrical about a vertical meridian plane. A Mach-Zehnder interferometer was employed by Yousef and Tarasuk [79] who provided a nice interferogram showing isotherms of laminar air flow in an isothermal tube. The isotherms exhibiting a marked depression indicated that the buoyancy forces led to an increase in heat transfer coefficients near the tube bottom but a decrease near the tube top. Other flow visualizations were done by Hwang and Liu [80] for air flow in a parallel-plate channel using smoke, Gilpin *et al.* [81] for water over a heated flat plate using an electrochemical technique, Wang *et al.* [82] for an open-channel water flow using a hydrogen bubble and shadowgraph method, and Knox and Incropera [83] for a rectangular duct water flow using two different types of dye and lighting. Water flow was also visualized by Osborne and Incropera [84,85] through the side walls of horizontal parallel plates using both dye-injection and shadowgraph techniques.

2.4.2 Measurements of Velocity and Fluid Temperature

Axial Velocity. Axial air velocities at the cross sections of a uniform heated tube were measured by Mori *et al.* [86] using a traversing device containing cylindrical yaw probes. The measured velocities at the symmetric plane of the tube exhibited an increasing degree of downward asymmetry with intensifying secondary flow. A traversing device carrying a hot-wire probe was also employed by Kamotani and Ostrach [87] to measure axial velocities in a parallel-plate channel air flow. By examining signals of a hot-film anemometer probe placed in a water pipe flow, El-Hawary [88] used velocity fluctuations to detect the stability of the flow that was subjected to significant buoyancy effects.

Fluid Temperature. Cross-sectional distributions of air temperatures at various axial stations were measured by Mori *et al.* [86] and they showed that buoyancy influenced the thermal profiles significantly. Signals of a thermocouple probe placed in the water pipe flow were also studied in [88] for analyzing stability and establishing flow maps. Wang *et al.* [82] obtained vertical temperature distributions in an open-channel water flow by using thermocouple probes, a traversing support, a data logger, and an x-y recorder. Similar techniques of temperature detection were reported in [84,85].

2.4.3 Measurements of Heat Transfer

Obtaining heat transfer data is the major purpose of most experimental investigations on laminar mixed convection. For isothermal conditions, heat transfer measurements were performed in [79,89] for air pipe flows, in [70,90] for water pipe flows, and in [62,91] for high Pr fluid flows in rectangular and triangular ducts. For horizontal smooth tubes with uniform heat input axially, heat transfer data were collected in [86,92] for air, in [88,93] for water, and in [94,95] for ethylene glycol. Mixed convection heat transfer for water flow in inclined rectangular ducts was also measured in [96] where the entire ducts were electrically heated. It should be noted that, in recent years, F. P. Incropera and his colleagues have experimentally investigated mixed convection heat transfer for rectangular ducts, parallel plates, and open channels under various heating conditions [82,83,84,85,97]. Their work has not only contributed useful experimental data, but also revealed some interesting characteristics of buoyancy effects on forced convection flow and heat transfer.

2.4.4 Measurements of Pressure Drop

Experimental pressure drop data that are subjected to significant buoyancy effects are scarce. Shannon and Depew [94] used a manometer to measure pressure drop across the heated section of a tube. Fourteen data points were obtained for Gr up to 2800, and for Pr ranging from 26 to 500. Similar pressure drop measurements were achieved by El-Hawary [88] for a laminar water pipe flow. Limited data points showed an increasing trend in the friction factor as buoyancy forces became large. The overall pressure drop was also measured by Morcos and Bergles [95] for tubes using water and ethylene glycol as working fluids. Since an inclined manometer was used, they were unable to measure the very low pressure drops due to heating for water. For ethylene glycol, they reported that the diabatic friction factors were as much as 50% higher than the corresponding isothermal values.

2.4.5 Empirical Correlations

Based on experimental data, a number of correlations for mixed convection heat transfer have been proposed and applied in order to generalize the nature of the flow and expand the range of the existing data. Kakac *et al.* [98] have recently compiled these correlating equations with detailed descriptions of ranges of applicability.

2.5 Remarks

First, from the above review of analytical methods, closed-form or exact solutions were confined to only fully developed laminar flow and heat transfer because of their mathematical existence. A numerical integration is generally required to transfer the exact fields of velocity and temperature to direct design data such incremental pressure drop numbers and Nusselt numbers. It is interesting to note that, for some boundary conditions (e.g., for $H1$), a closed-form Nusselt expression may be obtained without any numerical integration, for example, like the work of Lei and Trupp [99]. In analyses including buoyancy effects, the outlined analytical methods are all approximate to some degree. Due to this reason, they have become unpopular in recent years and most attention is now on the more sophisticated numerical techniques. However, it is the author's point of view that more research efforts should be made to modify the existing analytical methods and/or to develop new analytical methods.

Secondly, the above survey for computational efforts has focused on finite difference primitive variables methods. The existing algorithms for the solutions of discretized governing equations are far from perfect. Handling the velocity-pressure coupling seems to still challenge numerical researchers. For example, Mahaney *et al.* [32] recently reported that several hundred sweeps over the domain of their particular problem were typically required to obtain a converged pressure solution. The author experienced a similar problem during this research. The way to solve the pressure equation definitely needs more exploration. In addition, concerning problems of hydrodynamically developing laminar flow and thermally developing forced convection in circular sector ducts, no similar studies to the present work have been reported so far.

Thirdly, there are very limited experimental data on laminar mixed convection flow and heat transfer in the thermal entrance region of horizontal noncircular (other than rectangular) ducts. Moreover, a number of investigators have numerically reported the phenomenon of the secondary flow bifurcation. Will this phenomenon be confirmed experimentally? If positive, a solid theory should be developed to explain the processes of the flow bifurcation.

Chapter 3

Laminar Fully Developed Flow and Heat Transfer Without Buoyancy

THE scope of this chapter is limited to laminar, hydrodynamically and thermally developed flow of a constant properties fluid. Circular sector ducts are considered as shown in Fig. 3.1 which also defines the cylindrical coordinates (r, θ) system. Buoyancy forces are neglected so that the existing solutions are expected to serve as lower limits for problems with free convection effects. Though being far from the finish-line of the research, this mathematical approach is aimed to further understand the fundamentals embedded in the research and to provide some new useful results.

3.1 Governing Equations with Boundary Conditions

Using quantities defined in the Nomenclature and taking advantage of symmetric flow about the line of $\theta = \phi$, the nondimensional axial momentum equation and boundary conditions are

$$\frac{1}{r}\frac{\partial}{\partial r}\left(r\frac{\partial w}{\partial r}\right) + \frac{1}{r^2}\frac{\partial w}{\partial \theta^2} = C \tag{3.1}$$

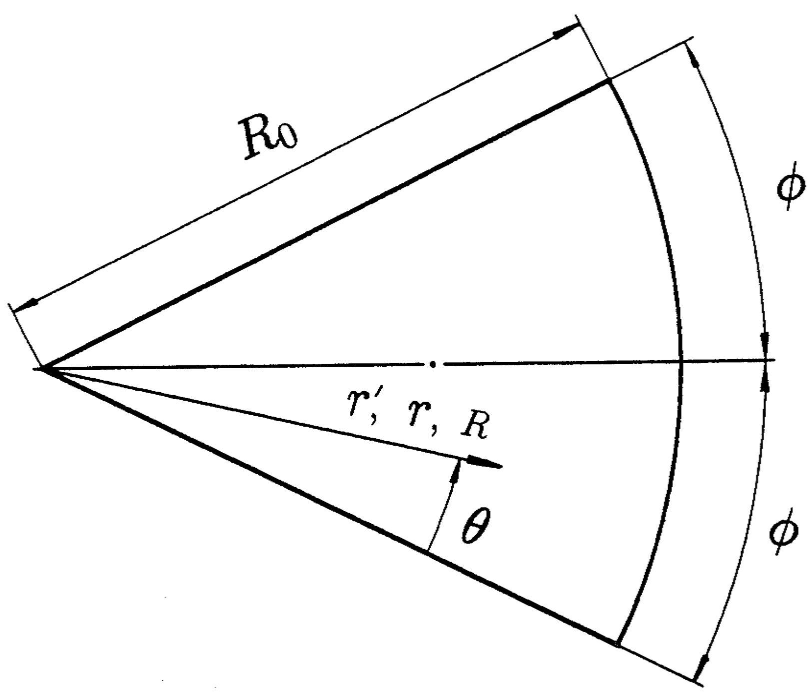


Figure 3.1: The Cross Section of the Circular Sector Duct

$$w(r,0) = w(1,\theta) = 0, \quad \text{and,} \quad \frac{\partial w}{\partial \theta}(r,\phi) = 0 \tag{3.2}$$

With negligible axial conduction and viscous dissipation within the fluid, the nondimensional energy equation can be expressed by

$$\frac{1}{r}\frac{\partial}{\partial r}\left(r\frac{\partial T_i}{\partial r}\right) + \frac{1}{r^2}\frac{\partial T_i}{\partial \theta^2} = C_1 w(r,\theta) \tag{3.3}$$

where T_i and C_1, as defined in the Nomenclature, are a dimensionless temperature ($i = 1,2$) and a geometry parameter, respectively. Uniform axial heat flux is considered such as would occur with nuclear or electric resistance heating. Four peripheral conditions used in this analysis are as follows:

1. Uniform peripheral temperature for all surfaces, denoted by $H1$.

2. Uniform peripheral temperature for the curved surface but with the flat section adiabatic, denoted by $H1_{ad}$.

3. Uniform peripheral heat flux for all surfaces, denoted by $H2$.

4. Uniform peripheral heat flux for the curved surface but with the flat section adiabatic, denoted by $H2_{ad}$.

The mathematical expressions for the above four conditions are readily derived (see [99,100]). Concerning practical situations, the $H1$ condition generally simulates well a duct having a high peripheral thermal conductivity (e.g., copper) while the $H2$ condition may suit a duct having a low peripheral thermal conductivity (e.g., glass). The $H1_{ad}$ and $H2_{ad}$ conditions might serve as a lower bound for circular tubes having internal full tapered fins of poor thermal conductivity and/or defective thermal bonding between tube and fins.

3.2 Maximum Velocity and Pressure Drop

A well-behaved solution of equation (3.1) with equation (3.2) was developed by the finite Fourier transform method as follows:

$$w(r,\theta) = \frac{2C}{\phi}\sum_{n=1}^{\infty}\frac{r^2 - r^{\lambda_n}}{\lambda_n(4-{\lambda_n}^2)}sin(\lambda_n\theta) \quad \text{with} \quad \lambda_n = \frac{(2n-1)\pi}{2\phi} \tag{3.4}$$

$$C = \frac{-\phi^2}{\sum_{n=1}^{\infty}\left(\lambda_n(\lambda_n+2)\right)^{-2}} \tag{3.5}$$

The product of Fanning friction factor and Reynolds number for fully developed conditions, $(fRe)_{fd}$ [1], with each defined in the Nomenclature, can thus be expressed in closed form as

$$fRe = \frac{\pi^2}{8(\phi+1)^2}\frac{1}{\sum_{n=1}^{\infty}\left(4\pi n^2 + (8\phi - 4\pi)n + \pi - 4\phi\right)^{-2}} \tag{3.6}$$

In a special case $\phi = \pi/2$, equation (3.6) yields

$$fRe = \frac{8\pi^4}{(\pi^2-8)(\pi+2)^2} = 15.7668$$

Equation (3.6) is well-behaved for all ϕ, unlike equation (390) in the book by Shah and London [101] which requires special efforts to obtain the limiting values as $\phi \longrightarrow \pi/4$ or $\phi \longrightarrow 3\pi/4$.

Now, the first interest is given to the maximum velocity, w_{max}, and its location, r^*. For developing flow (Chap. 4), this information is very useful in determining hydrodynamic entrance length based on the velocity at r^* attaining a particular percentage of the fully developed value. Due to symmetry, the maximum velocity occurs on the symmetry line defined by $\theta = \phi$. Hence by setting the first derivative of $w(r, \theta = \phi)$ to zero, a unique nonzero root at $r = r^*$ for each given ϕ can be found. Substituting r^* with ϕ into equation (3.4) thus gives w_{max}.

The total pressure drop between the duct inlet and a far downstream station X is also of interest. In engineering applications dealing with ducts that are not too

[1] In this chapter, the subscript fd, indicating fully developed conditions, is unnecessary and hence is omitted hereafter.

short, this pressure drop can be approximated by

$$\frac{P_0 - P(X)}{\rho \bar{W}^2/2} = f\frac{X}{D_h} + K(\infty) \tag{3.7}$$

where the incremental pressure drop number $K(\infty)$ can be computed via the method of Lundgren *et al.* [8] as

$$K(\infty) = \frac{2}{A}\int (w^3 - w^2)dA \tag{3.8}$$

The computed results for r^*, w_{max}, fRe, and $K(\infty)$ are listed in Table 3.1 and shown in Figs. 3.2 and 3.3. As shown in Table 3.1, with increasing ϕ, the location of the maximum velocity moves from near the curved surface towards the apex. This behaviour is illustrated in Fig. 3.2. It is noted that w_{max} occurs at the radius center (i.e.,$r^* = 0.5$) for ϕ about 80°. Figure 3.3 shows that the normalized maximum velocity, w_{max}, increases sharply as 2ϕ becomes smaller than about 60°. This is probably because $\bar{W}$ is progressively reduced (relative to W_{max}) by increasing corner effects associated with reducing ϕ at small apex angles. Also note that as $\phi \to 0$, w_{max} approaches the correct limiting value of 3.00 [101].

For fRe, as given by equation (3.6), as $\phi \to 0, fRe \to 12.000$ which is one-half the corresponding value for the parallel plate channel. In general, the fRe values presented in Table 3.1 are in excellent agreement with those tabulated in [101] for $0 \leq \phi \leq \pi/2$. The fRe values for the extended range, $\pi/2 \leq \phi \leq \pi$, are also believed to be of high accuracy. For $\phi = \pi$, the present fRe value agreed well (as did r^*, w_{max} also) with values calculated from the equations of Soliman and Feingold [5] for one internally full finned tube.

For $K(\infty)$, the numerical integration in equation (3.8) was performed by employing the trapezoidal rule. Different fine grid sizes were used so as to make the fifth digit after the decimal of each $K(\infty)$ independent of grid size. For example, for $\phi = \pi$, a fine (r, ϕ) grid of 70×214 was used. The present computed values of $K(\infty)$ are listed in Table 3.1 together with the available values from Shah and

Table 3.1: Fully Developed Flow Characteristics of Circular Sector Ducts

2ϕ (Deg)	r^*	w_{max}	fRe	$K(\infty)$ Present	$K(\infty)$ Ref. [101]
0	-	3.00000	12.0000	2.9710	2.971
2	0.95734	2.80928	12.1074	2.8189	-
8	0.88730	2.56777	12.4096	2.4957	2.480
10	0.87003	2.51826	12.5042	2.4110	-
15	0.83350	2.42489	12.7284	2.2375	2.235
20	0.80342	2.35858	12.9364	2.1048	-
25	0.77767	2.30883	13.1298	2:0008	-
30	0.75510	2.27013	13.3099	1.9177	1.855
36	0.73121	2.23384	13.5103	1.8385	-
40	0.71682	2.21417	13.6351	1.7952	-
45	0.70026	2.19344	13.7822	1.7494	1.657
50	0.68504	2.17612	13.9200	1.7109	-
55	0.67096	2.16149	14.0495	1.6784	-
60	0.65787	2.14902	14.1711	1.6508	1.580
65	0.64563	2.13831	14.2857	1.6271	-
70	0.63415	2.12905	14.3936	1.6067	-
72	0.62975	2.12570	14.4351	1.5993	-
75	0.62334	2.12101	14.4955	1.5890	-
80	0.61313	2.11397	14.5917	1.5736	1.530
90	0.59427	2.10234	14.7688	1.5484	-
100	0.57720	2.09323	14.9277	1.5288	1.504
110	0.56162	2.08597	15.0709	1.5134	-
120	0.54731	2.08013	15.2004	1.5012	1.488
130	0.53409	2.07538	15.3177	1.4914	-
140	0.52183	2.07148	15.4245	1.4834	-
150	0.51039	2.06824	15.5218	1.4769	-
160	0.49970	2.06553	15.6107	1.4715	1.468
170	0.48967	2.06324	15.6921	1.4670	-
180	0.48022	2.06130	15.7668	1.4632	1.463
190	0.47131	2.05964	15.8356	1.4600	-
200	0.46287	2.05820	15.8989	1.4573	-
210	0.45488	2.05696	15.9573	1.4549	-
220	0.44729	2.05587	16.0114	1.4528	-
230	0.44006	2.05491	16.0614	1.4510	-
240	0.43317	2.05406	16.1078	1.4494	-
260	0.42030	2.05263	16.1908	1.4466	-
270	0.41428	2.05201	16.2281	1.4454	-
290	0.40296	2.05094	16.2951	1.4432	-
300	0.39764	2.05047	16.3253	1.4423	-
320	0.38758	2.04963	16.3799	1.4404	-
340	0.37824	2.04889	16.4276	1.4388	-
360	0.36952	2.04823	16.4696	1.4372	-

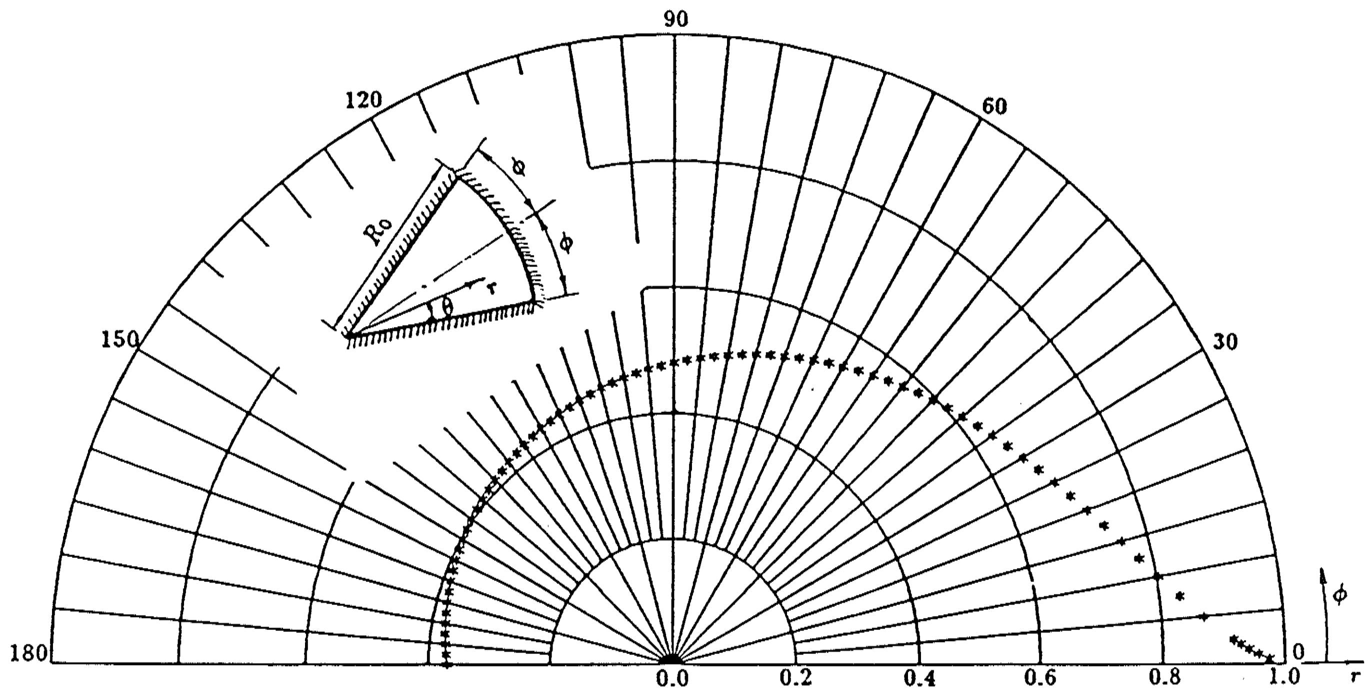


Figure 3.2: Location of w_{max} for Circular Sector Ducts

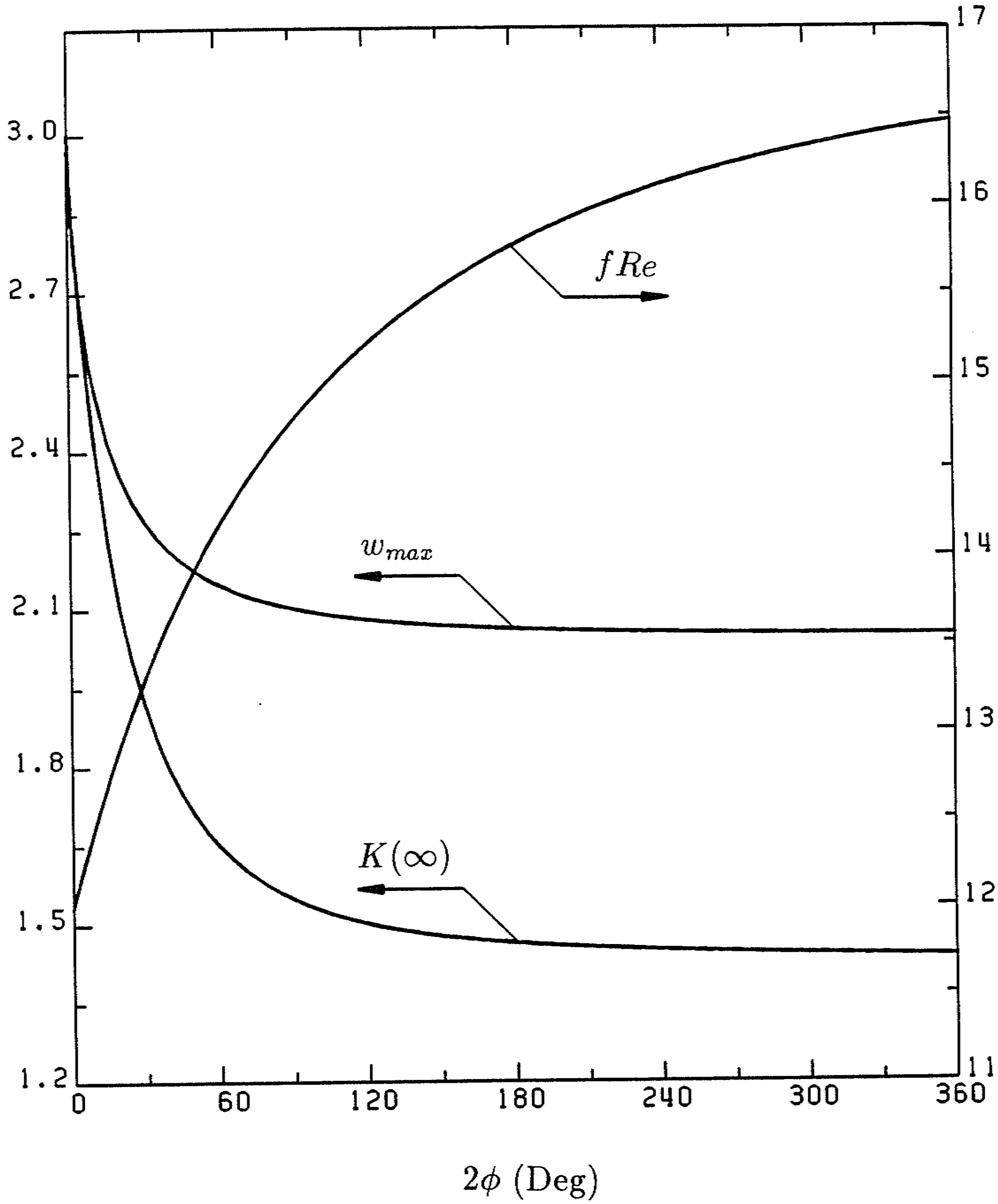


Figure 3.3: w_{max}, $K(\infty)$, and fRe vs. the Apex Angle of Circular Sector Ducts

London [101]. Comparison shows that the present results are slightly higher than the existing values (maximum difference of about 5%), although the agreement is excellent for $\phi = \pi$. In the limit as $\phi \to 0, K(\infty) \to 2.971$. Figure 3.3 shows that $K(\infty)$ has a trend versus ϕ that is similar to w_{max}.

3.3 Heat Transfer Results

The solutions of equation (3.3) associated with the foregoing four boundary conditions can be also obtained by using the finite Fourier transform technique which results in

For the $H1$ condition:

$$T_1(r,\theta) = -C\frac{\phi+1}{\phi^2}\sum_{i=1}^{\infty}\mathcal{H}(\chi_i,r)sin(\chi_i\theta) \quad \text{with} \quad \chi_i = \frac{(2i-1)\pi}{2\phi} \tag{3.9}$$

For the $H1_{ad}$ condition:

$$T_1(r,\theta) = \frac{C}{4\phi^2}\sum_{n=1}^{\infty}\mathcal{G}(\lambda_n,r) + \frac{8C}{\phi^2}\sum_{m=1}^{\infty}\mathcal{S}(\beta_m,\lambda_n,r)cos(\beta_m\theta) \quad \text{with} \quad \beta_m = \frac{m\pi}{\phi} \tag{3.10}$$

For the $H2$ condition:

$$\begin{aligned} T_2(r,\theta) &= A_2 + \left(\frac{\theta^2}{2\phi} - \theta - \frac{1}{\phi} + \frac{\phi}{3}\right)r + \frac{C(\phi+1)}{4\phi^3}\mathcal{E}(\lambda_n,r) \\ &+\frac{2}{\phi}\sum_{m=1}^{\infty}\frac{r-\beta_m r^{\beta_m}}{\beta_m^2(\beta_m^2-1)}cos(\beta_m\theta) + \frac{8C(\phi+1)}{\phi^3}\sum_{m=1}^{\infty}\sum_{n=1}^{\infty}\mathcal{Q}(\beta_m,\lambda_n,r) \end{aligned} \tag{3.11}$$

For the $H2_{ad}$ condition:

$$T_2(r,\theta) = A_{2ad} + \frac{C}{4\phi^2}\mathcal{E}(\lambda_n,r) + \frac{8C}{\phi^2}\sum_{m=1}^{\infty}\sum_{n=1}^{\infty}\mathcal{Q}(\beta_m,\lambda_n,r)cos(\beta_m\theta) \tag{3.12}$$

where $\mathcal{H}(\chi_i,r), \mathcal{G}(\lambda_n,r), \mathcal{S}(\beta_m,\lambda_n,r), \mathcal{E}(\lambda_n,r), \mathcal{Q}(\beta_m,\lambda_n,r)$, and constants A_2 and A_{2ad} are given in Appendix A.

The average heat transfer coefficients for the $H1$ and $H2$ conditions are defined in a customary manner by $q'' = \bar{h}(t_{\bar{w}} - t_m)$ and $Nu_i = \bar{h}D_h/k = -2\phi/(\phi+1)/T_{m,i}$, where the dimensionless bulk temperature $T_{m,i}$ is evaluated by

$$T_{m,i} = \frac{2}{\phi}\int_0^1\int_0^{\phi} wT_i \; rdrd\theta \tag{3.13}$$

However, for the $H1_{ad}$ and $H2_{ad}$ conditions, since the input is imposed on only the curved surface, the average heat transfer coefficient may be defined by $2\phi R_0 q'' = \bar{h}(2\phi R_0 + 2R_0)(t_{\bar{w}} - t_m)$. Hence,

$$Nu_{H1_{ad}} = 2\Big(\frac{\phi}{1+\phi}\Big)^2 \frac{1}{\bar{T}_{w,1} - T_{m,1}} \quad \text{and} \quad Nu_{H2_{ad}} = -2\Big(\frac{\phi}{1+\phi}\Big)^2 \frac{1}{T_{m,2}} \tag{3.14}$$

As discussed later, these definitions, based on overall wall temperature, are improper for small apex angles. Thus, the following Nusselt numbers, based on difference between average wall temperature only over the curved surface and the bulk mean temperature, $(t_{\bar{c}} - t_m)$, are defined by

$$Nu^*_{H1_{ad}} = -2\Big(\frac{\phi}{1+\phi}\Big)^2 \frac{1}{T_{m,1}} \quad \text{and} \quad Nu^*_{H2_{ad}} = 2\Big(\frac{\phi}{1+\phi}\Big)^2 \frac{1}{T_{\bar{c},2} - T_{m,2}} \tag{3.15}$$

where the dimensionless average temperature over the curved surface, $T_{\bar{c},2}$, is also given in Appendix A.

It should be noted that the finite Fourier transform method used in this analysis provides a unique advantage of computing Nu_{H1}. Unlike the solution of Eckert *et al.* [1], equation (3.9) with equation (3.4) offers a very easy way to obtain $T_{m,1}$ through an orthogonality feature. As a result, Nu_{H1} can be written in closed form, without any numerical integration, as

$$Nu_{H1} = \frac{2\phi^4}{(1+\phi)^2 C^2}\left(\sum_{i=1}^{\infty} \frac{\chi_i^2 + 7\chi_i + 11}{(\chi_i+2)^3(\chi_i+6)(\chi_i(\chi_i+4)(\chi_i+1))^2}\right)^{-1} \tag{3.16}$$

In the limit as $\phi \to 0$, this novel expression yields the well-known results of 105/51, or 2.0588.

The computed results for $Nu_{H1_{ad}}$, $Nu^*_{H1_{ad}}$, Nu_{H1}, $Nu_{H2_{ad}}$, $Nu^*_{H2_{ad}}$, and Nu_{H2} are listed in Table 3.2. To minimize truncation error, all calculations involving a series form were continued until the absolute value of the last term of the series was smaller than 10^{-10}. Computation tests showed that reducing this control factor to 10^{-15} produced no significant improvement of accuracy. The numerical integration of equation (3.13) for $T_{m,1}$ and $T_{m,2}$ was performed by employing the trapezoidal

Table 3.2: Heat Transfer Characteristics of Circular Sector Ducts

2ϕ (Deg)	$Nu_{H1_{ad}}$	$Nu^{*}_{H1_{ad}}$	Nu_{H1} Present	Nu_{H1} Ref. [101]	$Nu_{H2_{ad}}$	$Nu^{*}_{H2_{ad}}$	Nu_{H2} Present	Nu_{H2} Ref. [101]
0	-	0.000	2.0588	2.059	-	0.000	0.000	-
2	-	0.004	2.1469	-	-	0.004	0.003	-
8	-	0.052	2.3841	2.384	-	0.052	0.051	-
10	-	0.075	2.4554	-	-	0.075	0.082	0.081
15	-	0.142	2.6189	2.619	-	0.142	0.198	0.195
18	-	0.186	2.7077	-	-	0.186	0.295	-
20	-	0.217	2.7633	-	-	0.217	0.371	0.362
24	-	0.279	2.8670	-	-	0.279	0.549	-
30	-	0.376	3.0052	3.005	-	0.376	0.870	0.838
36	-	0.472	3.1257	-	-	0.472	1.228	1.174
40	-	0.536	3.1976	-	4.835	0.536	1.471	1.400
45	-	0.615	3.2792	3.27	4.051	0.614	1.763	1.667
50	-	0.691	3.3527	-	3.656	0.690	2.027	-
60	-	0.839	3.4792	3.479	3.280	0.837	2.448	-
65	-	0.910	3.5338	-	3.184	0.907	2.604	-
72	-	1.005	3.6023	-	3.100	1.001	2.771	2.608
80	-	1.108	3.6707	3.671	3.040	1.103	2.895	-
90	-	1.230	3.7440	-	3.000	1.222	2.987	-
100	3.128	1.343	3.8064	3.806	2.980	1.333	3.030	-
110	3.134	1.450	3.8600	-	2.973	1.437	3.045	-
120	3.146	1.549	3.9062	3.906	2.970	1.533	3.042	2.898
130	3.161	1.642	3.9466	-	2.971	1.622	3.028	-
140	3.179	1.729	3.9819	-	2.975	1.705	3.010	-
150	3.198	1.811	4.0132	-	2.979	1.783	2.988	-
160	3.217	1.887	4.0409	4.04	2.983	1.854	2.964	-
170	3.236	1.959	4.0657	-	2.988	1.922	2.942	-
180	3.256	2.027	4.0880	4.089	2.994	1.985	2.920	2.923
190	3.275	2.091	4.1081	-	2.999	2.044	2.899	-
200	3.294	2.152	4.1263	-	3.004	2.099	2.879	-
210	3.313	2.209	4.1429	-	3.009	2.151	2.860	-
220	3.332	2.264	4.1581	-	3.016	2.201	2.843	-
240	3.367	2.365	4.1848	-	3.025	2.290	2.811	-
260	3.399	2.456	4.2076	-	3.032	2.370	2.782	-
270	3.414	2.498	4.2178	-	3.034	2.406	2.769	-
290	3.444	2.578	4.2362	-	3.041	2.473	2.746	-
300	3.458	2.615	4.2445	-	3.044	2.504	2.735	-
320	3.486	2.685	4.2597	-	3.051	2.563	2.718	-
340	3.512	2.749	4.2732	-	3.056	2.616	2.702	-
360	3.536	2.809	4.2852	-	3.060	2.664	2.687	-

rule and Simpson's rule, respectively. Different fine grid sizes were used so as to make the fifth digit after the decimal of each $T_{m,i}$ independent of grid size. For example, for $\phi = \pi$, a fine (r, ϕ) grid of 50×151 was used.

3.3.1 The $H1$ and $H1_{ad}$ Conditions

From Table 3.2, for the semicircular duct ($\phi = \pi/2$), the present $Nu_{H1_{ad}}$ value of 3.256 agrees well with the numerical values of 3.170 from [101,37] and 3.160 from [102] after they are converted to a similar basis. But although the differences are within 3%, in order to confirm the accuracy of the present result, equation (3.3) for the $H1_{ad}$ boundary condition was also solved by a finite difference method using a band storage linear equation solver. The numerical value of 3.255 was obtained for $Nu_{H1_{ad}}$ with the $(r, \pi/2)$ grid of 30×44. It is believed that similar high accuracy was obtained for the other ducts.

Figure 3.4 graphically shows the results for $Nu_{H1_{ad}}$, $Nu^*_{H1_{ad}}$, and Nu_{H1} and includes the average wall and bulk mean temperatures for the $H1_{ad}$ condition. In this case, the surface temperature for the curved surface is constant (at t_c or $T_{c,1} = 0$) whereas for the flat surfaces, the temperature is maximum at $r = 1$ and decreases monotonically with decreasing r to reach a minimum at $r = 0$. The overall average wall temperature ($\bar{t}_w$) is consequently less than t_c hence $\bar{T}_{w,1}$ is negative. Figure 3.4 illustrates how $\bar{T}_{w,1}$ varies with ϕ. As ϕ decreases (from large ϕ), the size of the heated curved surface decreases hence $\bar{T}_{w,1}$ decreases. In the meantime, $T_{m,1}$, which is also shown in Fig. 3.4, varies with the opposite trend with ϕ. Consequently $\bar{T}_{w,1} < T_{m,1}$ for $2\phi <\sim 30°$. This, in turn, causes a discontinuity in $Nu_{H1_{ad}}$ whereby $Nu_{H1_{ad}} \rightarrow \infty$ as $\bar{T}_{w,1} \rightarrow T_{m,1}$, followed by negative $Nu_{H1_{ad}}$ numbers. The behaviors of $\bar{T}_{w,1}$ and $T_{m,1}$ at small ϕ are therefore such that the computation of $Nu_{H1_{ad}}$ leads to improper results. Otherwise, as shown in Fig. 3.4, $Nu_{H1_{ad}}$ is fairly constant for $2\phi >\sim 100°$, rising only slightly with increasing ϕ. In Table 3.2, the unrealistic values of $Nu_{H1_{ad}}$ are not presented for $2\phi < 100°$. On the other hand, $Nu^*_{H1_{ad}}$

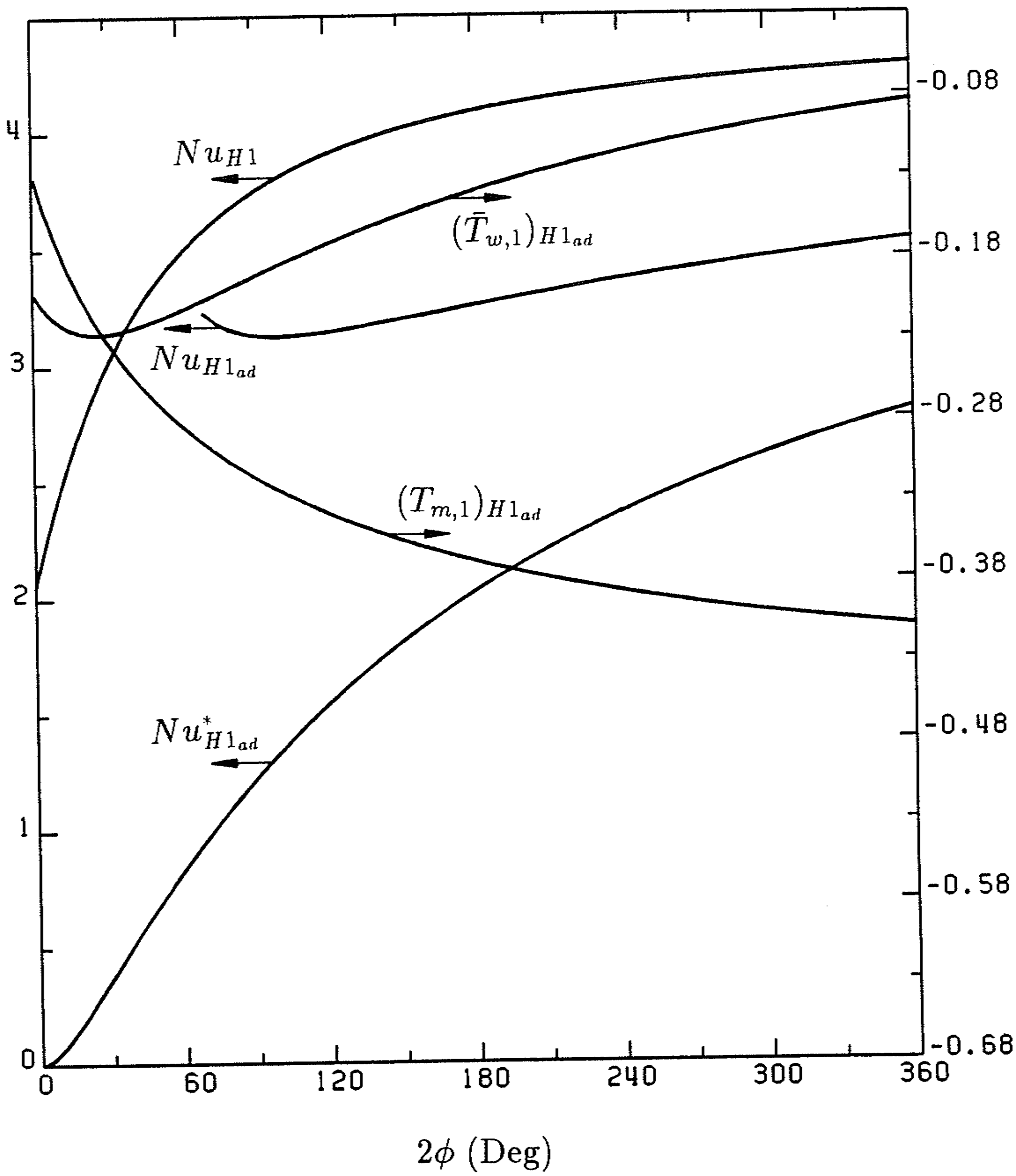


Figure 3.4: Fully Developed Heat Transfer Results for the $H1$ and $H1_{ad}$ Conditions

defined by equation (3.15) is well behaved for all apex angles and varies smoothly with ϕ (see Fig. 3.4). As $\phi \to 0$, $Nu^*_{H1_{ad}} \to 0$ due to the vanishing heat input. At $\phi = \pi$, which represents a tube with one internal full-fin (non-conducting), $Nu^*_{H1_{ad}}$ becomes 2.809.

As shown in Table 3.2, values for Nu_{H1} calculated from the series expression of equation (3.16) are in excellent agreement with those in Shah and London [101] for $0 \leq \phi \leq \pi/2$. The Nu_{H1} values for the extended range, $\pi/2 < \phi \leq \pi$, are also believed to be of high accuracy. For $\phi = \pi$, which represents a tube with one internal full-fin (perfectly conducting), the present Nu_{H1} is 4.2852.

The Nu_{H1} and $Nu^*_{H1_{ad}}$ values listed in Table 3.2 may be compared directly (for a given ϕ) since they are defined on the same surface area and temperature difference bases. Naturally, values for Nu_{H1} are always higher than those for $Nu^*_{H1_{ad}}$ because of the larger heat input area of the $H1$ condition (Fig. 3.4). In engineering applications such as internal full-fin tubes, the two thermal conditions considered in this analysis may represent the limiting cases between which a real situation resides. Accordingly, where applicable, the data in Table 3.2 will bracket the probable thermal performance.

3.3.2 The $H2$ and $H2_{ad}$ Conditions

Since there are no similar data for the $H2_{ad}$ condition in the literature, the accuracy of the present results was confirmed by solving equation (3.3) through the finite difference method. Numerical values for $Nu_{H2_{ad}}$ and $Nu^*_{H2_{ad}}$ were thus obtained and compared with those from the present series solution. The agreement shown in Fig. 3.5 is within 0.4% for the six different apex angles. Regarding Nu_{H2}, as shown in Table 3.2, values for Nu_{H2} calculated from the series expression of equation (3.11) differ from those in [101] (also ref. [4]) for $0 \leq \phi \leq \pi/2$, by up to 6%. The present values also differ by up to 10% from the graph readings in [1] for $\phi \leq \pi/6$. Such differences may be due to earlier truncation of the series

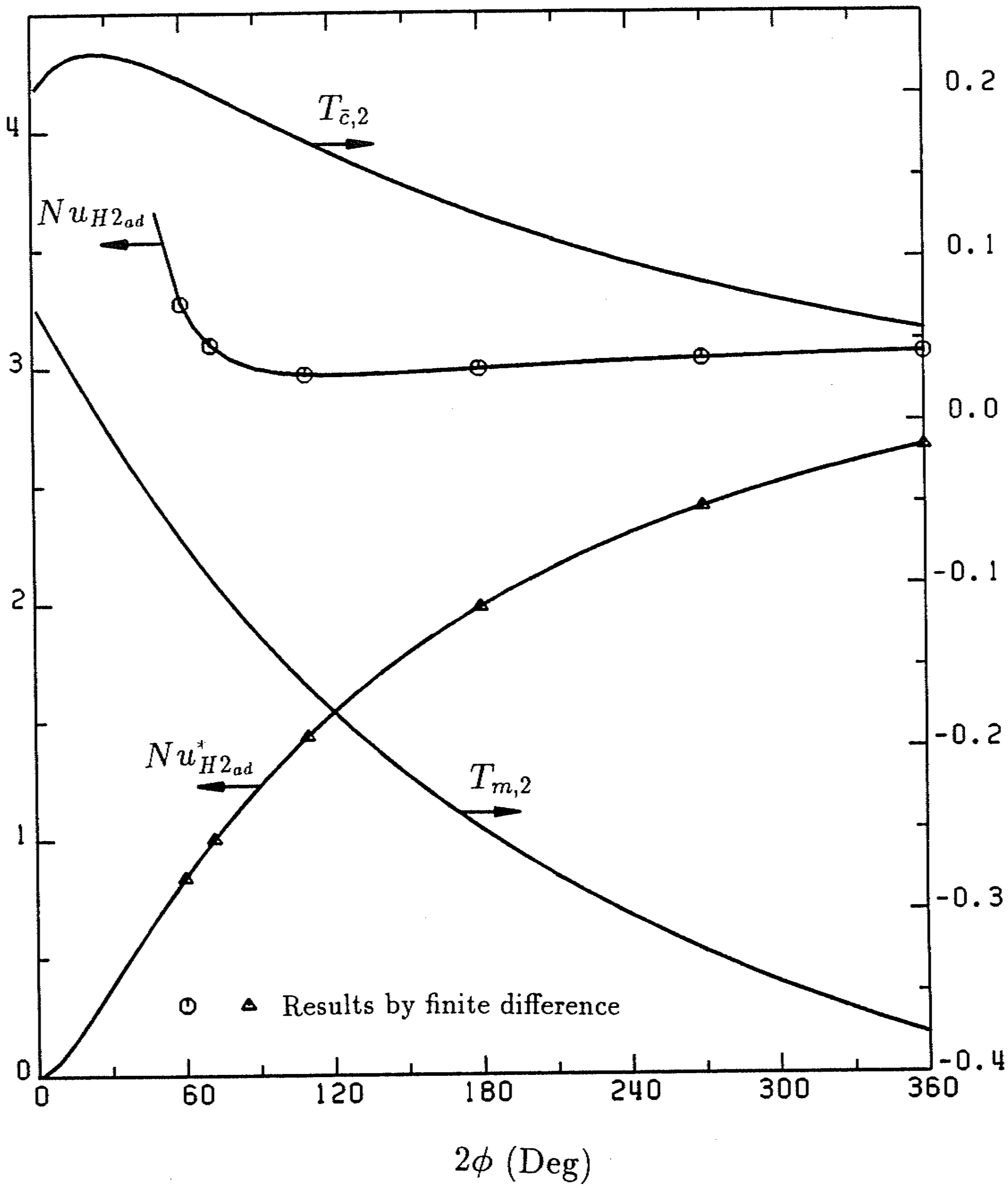


Figure 3.5: Temperatures and Nusselt Numbers for the $H2_{ad}$ Condition

calculations and/or the inaccurate performance of integral equations in their early work. Again, to confirm the present results, values for Nu_{H2} for each of the 10 apex angles corresponding to those reported in [101] plus 2 extra angles were generated by the finite difference method. Agreements (see Fig. 3.6) were all within 0.5% in favour of the series solution presented in equation (3.11). Accordingly, it is believed that similar accuracy was obtained for Nu_{H2} for the extended range, $\pi/2 < \phi \leq \pi$.

For the $H2_{ad}$ condition, the maximum wall temperature occurs at the curved corners and decreases monotonically with decreasing r to reach a minimum at $r = 0$. Thus, as expected, $T_{\bar{c},2}$ is positive for all apex angles (2ϕ) and it varies as shown in Fig. 3.5. On the other hand, for $2\phi >\sim 28°$, the average wall temperature ($\bar{t}_w$) is higher than the bulk mean temperature (t_m) hence $T_{m,2}$ is negative. As ϕ increases, the heat transfer area becomes larger, and so does the difference between $\bar{t}_w$ and t_m hence $T_{m,2}$ varies as shown in Fig. 3.5. As the result of these patterns, for $2\phi >\sim 28°$, $Nu_{H2_{ad}}$ shows only a slight increase with ϕ. However, for $2\phi <\sim 28°$, with decreasing ϕ, the decreasing size of the heated curved surface causes $\bar{t}_w \leq t_m$ hence $T_{m,2} \geq 0$. This, in turn, causes a discontinuity in $Nu_{H2_{ad}}$, namely, $Nu_{H2_{ad}} \rightarrow \infty$ as $T_{m,2} \rightarrow 0$, followed by negative Nusselt numbers. Similar to the case of the $H1_{ad}$ condition, the behavior of $T_{m,2}$ at small ϕ therefore gives rise to the inappropriate computation for $Nu_{H2_{ad}}$. In Table 3.2, the unrealistic values of $Nu_{H2_{ad}}$ are not presented for $2\phi < 40°$. However, $Nu^*_{H2_{ad}}$ defined by equation (3.15) is well behaved for all apex angles and increases smoothly with increasing ϕ (see Fig. 3.5).

Unlike the $H2_{ad}$ case, the $T_{m,2}$ variation with apex angle for the $H2$ condition is no longer monotonical. For small ϕ, large absolute values of $T_{m,2}$ are observed because of the significant corner effects. As ϕ increases, the $T_{m,2}$ absolute values first decrease to reach a minimum and then increase. This behavior of $T_{m,2}$ gives an unusual pattern for the Nu_{H2} variation. Figure 3.6 shows that Nu_{H2} sharply

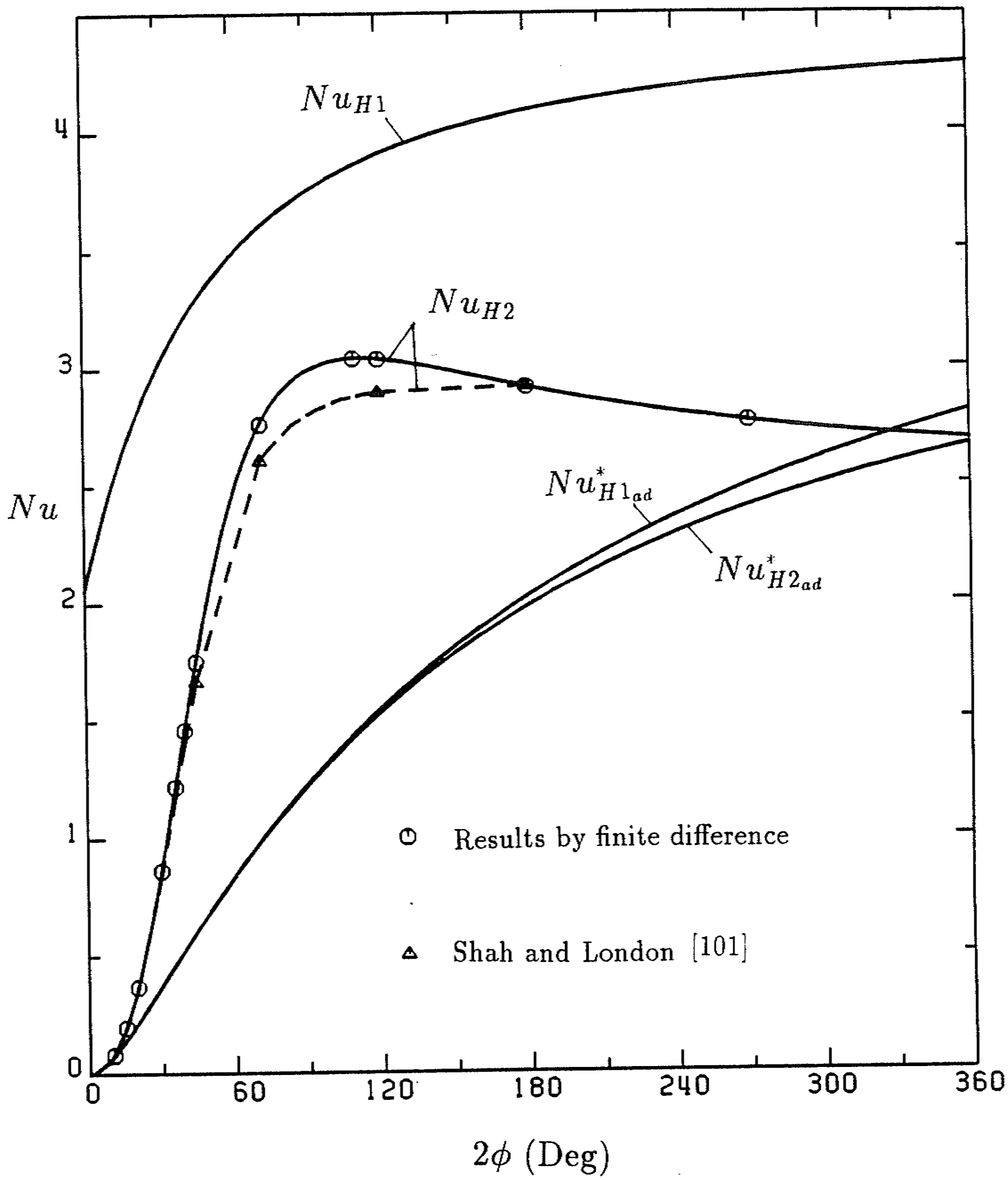


Figure 3.6: Fully Developed Nusselt Numbers for Circular Sector Ducts

increases from zero to a maximum of 3.046 at $2\phi \approx 112°$ and then gradually decreases with increasing ϕ. Note that the 10 values of Nu_{H2} from [101] fail to show this pattern. In fact, their data suggest an increasing trend of Nu_{H2} for $2\phi > \pi$ which of course is misleading.

For comparison purposes, Fig. 3.6 also shows plots of Nu_{H1} and $Nu^*_{H1_{ad}}$ as well as $Nu^*_{H2_{ad}}$. As expected (e.g., as discussed in [101]), values for Nu_{H2} are lower than for Nu_{H1} for all apex angles. For a typical actual duct (e.g., a steel tube), the thermal performance would be expected to lie between these two limiting solutions. Next, referring to the cases of $H1_{ad}$ and $H2_{ad}$, it turns out, for a given duct and the same fixed temperature difference, that the duct heat transfer rate per unit length (q') is proportional to Nusselt number. Hence the two q' values for the two boundary conditions may be compared by comparing the curves for $Nu^*_{H1_{ad}}$ and $Nu^*_{H2_{ad}}$. The correspondence is valid since in each case the duct-average convective heat transfer coefficient is proportional to Nusselt number, the heat transfer surface areas are identical and the temperature difference definitions are essentially the same. For the latter, in the $H1_{ad}$ case the temperature difference is the difference between the bulk mean temperature and the average (but constant) curved wall temperature, whereas in the $H2_{ad}$ case it is also the difference between the bulk mean temperature and the average curved wall temperature but now the curved wall temperature varies somewhat especially near the corners. By comparing the two Nu^* curves in Fig. 3.6, it can be seen that there is no marked difference between $Nu^*_{H1_{ad}}$ and $Nu^*_{H2_{ad}}$ for small apex angles. Furthermore, although $Nu^*_{H1_{ad}}$ starts to exceed $Nu^*_{H2_{ad}}$ at $2\phi \approx 120°$, the differences thereafter remain within about 6%. It follows for a given duct that the fully developed Nusselt numbers (hence also the q' values for the same temperature differences) are almost identical. In other words, it is not necessary to distinguish between the thermal boundary conditions of $H1_{ad}$ and $H2_{ad}$ or, in fact, for any boundary condition on the curved surface that is in between these two. Finally, Fig. 3.6 shows that Nu_{H2} and $Nu^*_{H2_{ad}}$ are almost equal at $\phi = \pi$. But this has no particular significance since these two Nusselt numbers are based on different temperature definitions.

3.4 Remarks

This chapter contributes a complete set of analytical results for fully developed laminar flow and heat transfer in circular sector ducts. New information on the maximum velocity and its location is valuable for determining the hydrodynamic entrance length. A novel closed-form of Nu_{H1} has been found. Results for $Nu^{*}_{H1_{ad}}$ and $Nu^{*}_{H2_{ad}}$ are both novel and of practical use. In addition, highly accurate results for fRe, Nu_{H1}, and Nu_{H2} are provided for the full apex angle range. Some of these results will be used in the following chapters.

Chapter 4

Numerical Analyses of Developing Laminar Flow and Heat Transfer Without Buoyancy

THE previous chapter has mathematically delineated the flow and heat transfer of circular sector ducts in a far downstream region. However, in many engineering applications such as a compact heat exchanger design, knowledge of local pressure drops, velocity profiles, and temperature gradients in the entrance region is also essential. Again, excluding buoyancy forces, the investigation described in this chapter is motivated to understand the laminar developing flow in circular sector ducts and to provide base-line references for mixed convection problems that are targeted in the research. Two main sections are provided in this chapter. The first considers the flow in the hydrodynamic entrance region. The second presents heat transfer results for developing temperature fields with fully developed hydrodynamics.

4.1 Hydrodynamically Developing Flow

This analysis is applicable to steady, laminar flow of incompressible, Newtonian fluids in straight circular sector ducts. Figure 3.1 shows the duct cross section and the cylindrical coordinates (r', θ). The three-dimensional internal flow is assumed to be little influenced by the downstream flow conditions and to have negligible axial diffusion of momentum. Like most boundary layer problems, such a flow is governed by the parabolized Navier-Stokes equations in which the longitudinal and lateral pressure gradients are deliberately decoupled. For the problem being investigated, the decoupling of the pressure can be written as $p(r', \theta, x^+) = p'(r', \theta) + \bar{p}(x^+)$, where $\bar{p}$ is the average pressure over the duct cross section, and p' is the small pressure variation driving the cross stream secondary flow. The main flow is driven by the pressure gradients, $d\bar{p}/dx^+$, which can be determined by the overall mass conservation. As a result, the problem can be solved by employing the marching-type procedure of Patankar and Spalding [27,28], as described in greater detail later.

4.1.1 Governing Equations and Hydrodynamic Parameters

Neglecting the axial diffusion terms $\partial^2/\partial x^{+2}$ and using the defined Nomenclature, the governing Navier-Stokes equations in cylindrical coordinates can be written in the following nondimensional form:

Continuity

$$\frac{1}{r'}\frac{\partial}{\partial r'}(r'u) + \frac{1}{r'}\frac{\partial v}{\partial \theta} + \frac{\partial w}{\partial x^+} = 0 \tag{4.1}$$

Radial momentum

$$\begin{aligned}\frac{1}{r'}\frac{\partial}{\partial r'}(r'uu) + \frac{1}{r'}\frac{\partial}{\partial \theta}(vu) + \frac{\partial}{\partial x^+}(wu) &= \frac{1}{r'}\frac{\partial}{\partial r'}(2r'\frac{\partial u}{\partial r'}) + \frac{1}{r'}\frac{\partial}{\partial \theta}(\frac{1}{r'}\frac{\partial u}{\partial \theta}) \\ &-\frac{\partial p'}{\partial r'} + \frac{1}{r'}\frac{\partial}{\partial \theta}(\frac{\partial v}{\partial r'}) - \frac{3}{r'^2}\frac{\partial v}{\partial \theta} - \frac{2u}{r'^2} + \frac{v^2}{r'}\end{aligned} \tag{4.2}$$

Angular momentum

$$\begin{aligned}\frac{1}{r'}\frac{\partial}{\partial r'}(r'uv) + \frac{1}{r'}\frac{\partial}{\partial \theta}(vv) + \frac{\partial}{\partial x^+}(wv) &= \frac{1}{r'}\frac{\partial}{\partial r'}(r'\frac{\partial v}{\partial r'}) + \frac{1}{r'}\frac{\partial}{\partial \theta}(\frac{2}{r'}\frac{\partial v}{\partial \theta}) \\ &-\frac{1}{r'}\frac{\partial p'}{\partial \theta} + \frac{1}{r'}\frac{\partial}{\partial r'}(\frac{\partial u}{\partial \theta}) + \frac{3}{r'^2}\frac{\partial u}{\partial \theta} - \frac{v}{r'^2} - \frac{uv}{r'}\end{aligned} \tag{4.3}$$

Axial momentum

$$\frac{1}{r'}\frac{\partial}{\partial r'}(r'uw) + \frac{1}{r'}\frac{\partial}{\partial \theta}(vw) + \frac{\partial}{\partial x^+}(ww) =$$

$$\frac{1}{r'}\frac{\partial}{\partial r'}(r'\frac{\partial w}{\partial r'}) + \frac{1}{r'}\frac{\partial}{\partial \theta}(\frac{1}{r'}\frac{\partial w}{\partial \theta}) - \frac{d\bar{p}}{dx^+} \tag{4.4}$$

To specify the problem completely, equations (4.1) to (4.4) are supplemented by the following boundary conditions:

At $x^+ = 0$ for all r' and θ

$$u = v = p' = 0, \quad \bar{p} = \bar{p}_0 = \text{any constant, and } w = 1 \tag{4.5}$$

At $x^+ > 0$

$$\begin{aligned} u = v = w = 0 \quad &\text{at } r' = r_0', \quad 0 \le \theta \le \phi \\ &\text{at } \theta = 0, \quad 0 \le r' < r_0' \end{aligned} \tag{4.6}$$

$$\frac{\partial u}{\partial \theta} = \frac{\partial w}{\partial \theta} = v = 0 \quad \text{at the symmetry line } \theta = \phi, \ 0 < r' < r_0' \tag{4.7}$$

To solve for u, v, w, p' and $\bar{p}$, equation (4.5) at the inlet of the duct is first used. Then the marching solution procedure is carried out along the axial direction. For the cross stream flow the gradients of p' in equations (4.2) and (4.3) can be determined from the local continuity equation (e.g., using equation (4.1)) while $d\bar{p}/dx^+$ is the outcome of the overall continuity equation which can be expressed by the global mass conservation as

$$\int_0^{\phi}\int_0^{r_0'} w r' dr' d\theta = \frac{\phi {r_0'}^2}{2} \tag{4.8}$$

As the solution step is progressed, the flow is gradually developing. In a far downstream region, u, v, p' and $\partial w/\partial x^+$ become zero while $d\bar{p}/dx^+$ approaches an asymptotical constant value. Consequently, in such a fully developed region, equations (4.1) to (4.3) vanish and equation (4.4) reduces to

$$\frac{1}{r'}\frac{\partial}{\partial r'}(r'\frac{\partial w}{\partial r'}) + \frac{1}{r'}\frac{\partial}{\partial \theta}(\frac{1}{r'}\frac{\partial w}{\partial \theta}) = (\frac{d\bar{p}}{dx^+})_{fd} \tag{4.9}$$

where the fully developed pressure gradient $(d\bar{p}/dx^+)_{fd}$ can still be obtained from equation (4.8). An alternative to obtaining $(d\bar{p}/dx^+)_{fd}$ is to solve equation (4.9) directly via series solution, e.g., as done in Chap. 3.

In engineering applications, the *local friction factor* , f, is an important hydrodynamic parameter. Using the local pressure gradient $d\bar{P}/dX$ and hydraulic diameter D_h, the product of local friction factor and Reynolds number can be expressed in dimensionless form as

$$fRe = -\frac{1}{2}\frac{d\bar{p}}{dx^+} \tag{4.10}$$

Another important parameter is the total pressure drop $\Delta\bar{P}(X)$, where $\Delta\bar{P}(X) = \bar{P}_0 - \bar{P}(X)$, which is the pressure difference between the inlet and a particular cross section. This pressure drop can be expressed as

$$\frac{\Delta\bar{P}(X)}{\rho\bar{W}^2/2} = \frac{(\Delta\bar{P}(X))_{fd}}{\rho\bar{W}^2/2} + K(X) \tag{4.11}$$

The first term on the right represents the fully developed pressure drop and $K(X)$ is the incremental pressure drop number considering entrance region effects. In dimensionless form, $K(x^+)$ is given by

$$K(x^+) = 4x^+\left(\frac{\bar{p}_0 - \bar{p}(x^+)}{2x^+} - (fRe)_{fd}\right) \tag{4.12}$$

With increasing axial distance from the entrance, this extra pressure drop number increases, while the product fRe decreases. Both parameters eventually reach their limiting values $K(\infty)$ and $(fRe)_{fd}$, respectively, and remain constant in the fully developed region.

To detect where the flow enters the fully developed region, the axial distance from the entrance, called the hydrodynamic entrance length L_H, is usually estimated by either of two definition methods. One is to compare a local axial maximum velocity to the corresponding fully developed magnitude. Another is to examine the local friction factor referenced to the corresponding fully developed value. The latter is frequently used for a noncircular duct where the maximum velocity and its location are not specifically available. However, the previous work in Chap. 3 on the flow characteristics of circular sector ducts made it possible to define L_H in both ways. It was expected for each geometry that the L_H result defined one way would be different from its value defined the other way. But it was not known whether or not the differences would be significant. It appears that there are no reports on the investigation of these two kinds of definitions for a noncircular duct. Therefore, in this analysis, it was decided to employ the following four definitions [1] of the hydrodynamic entrance length for each circular sector duct:

L_{H5w}, L_{H1w} = the values of x^+ at which the axial maximum velocities first reach 95% and 99% of the fully developed maximum velocities, respectively.

L_{H5f}, L_{H1f} = the values of x^+ at which the local friction factors first drop to within 1.05 and 1.01 times the fully developed friction factors, respectively.

It is noted that L_H contains D_h which is dependent on the duct apex angle ϕ. As shown later, the use of L_H tends to mask the effect of ϕ on entrance lengths. To better isolate the ϕ effect, the hydrodynamic entrance length may also be defined on the basis of duct radius R_0, as

$$L_H^0 = \frac{X}{R_0 Re_0} \tag{4.13}$$

where $Re_0 = \rho R_0 \bar{W}/\mu$. The relationship between L_H and L_H^0 is given by

$$L_H^0 = L_H \left(\frac{2\phi}{\phi+1}\right)^2 \tag{4.14}$$

4.1.2 Computational Procedure and Accuracy Verification

Fully implicit discretization equations of (4.1) to (4.4) were formulated using the control volume integration finite difference method. The SIMPLER algorithm of Patankar [28] was used to solve these finite difference equations. A uniform staggered grid on the cross stream plane was employed. Figure 4.1 illustrates a typical grid map (for u, v, w, p', and $\bar{p}$ only for this analysis) with half sizes near the boundaries. The solution for u, v, w, p', and $\bar{p}$ was progressed along

[1] *This allowed the question of differences to be explored as a secondary issue.*

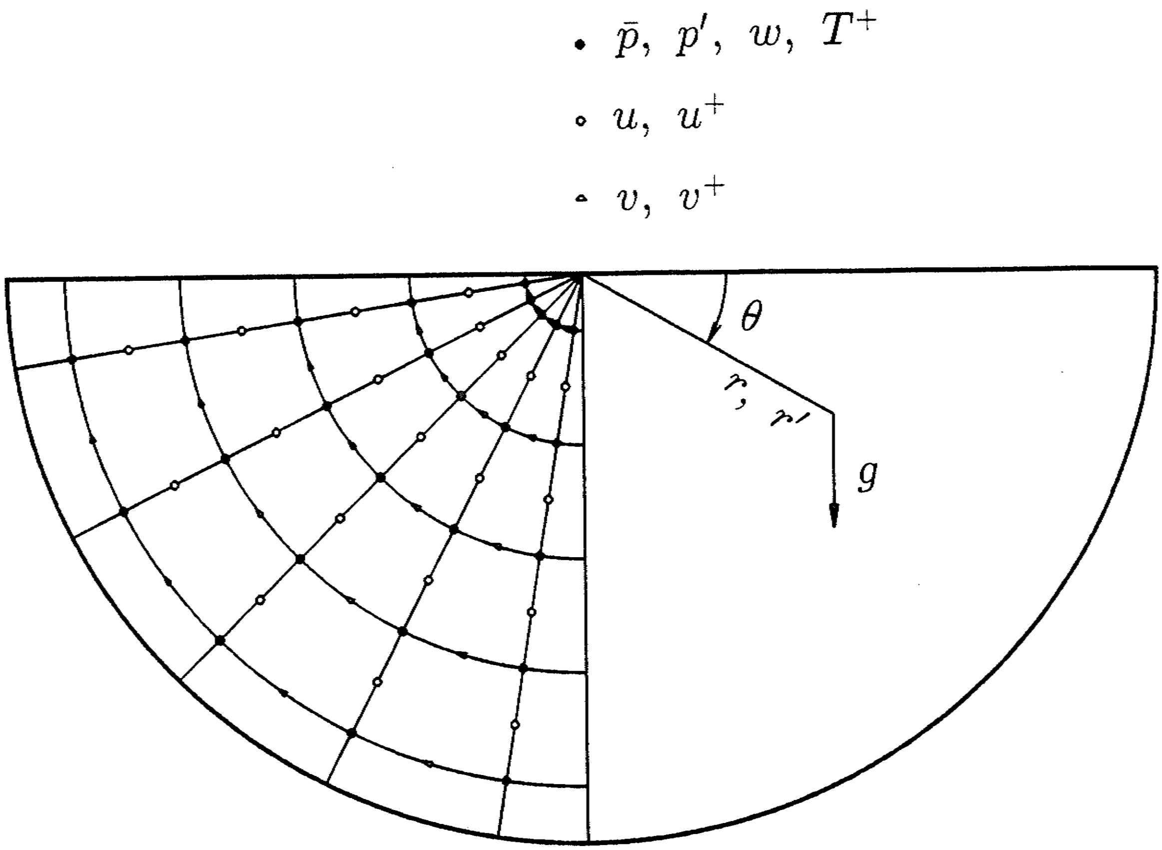


Figure 4.1: A Typical Staggered Grid Map with Cylindrical Coordinates

x^+. At any axial station, the pressure distribution p' was first estimated using equation (4.1). Then, equations (4.2) and (4.3) were solved *simultaneously* for u and v. Next was to compute w, while ensuring the satisfaction of the overall mass conservation. Concerning the coefficients of each discretization equation, they were continually updated using the most recent values of u, v, w, and p'. A line-by-line iterative technique was employed for solving u, v, and w while the p' distribution was *noniteratively* obtained using a band storage linear equation solver.

As reviewed in Chap. 2, it was realized that obtaining converged solutions for p' plays a crucial role in the success of the use of the SIMPLER algorithm. Directly solving p' equation gave an exact p' distribution for the present iteration. This currently-best-p' solution, rather than a not-yet-converged one through iterative method, was used to correct the current velocities. Therefore, it was felt that errors in current velocities might be minimized and that the overall convergence could be accelerated. To confirm this modification of the algorithm, a number of computation experiments were conducted. For example, for a given test, all three momentum equations for u, v, and w, and the pressure correction equation for p' were first solved using the line-by-line iterative method. Then the experiment was conducted once more. This time every condition remained unchanged except for obtaining the p' distribution through the direct solver. Comparison was then made between the results from both the experiments including the number of iterations. It was found that, for the mesh size used in this study, the direct solver for p' not only provided more accurate overall results but also speeded up the convergence hence reducing the computing time. Before marching to the next station along x^+, the following criteria were checked:

1. All absolute differences between the current iterative values and the previous iterative results were not greater than 10^{-5} at all nodal points.
2. The "mass source" term (checking the local continuity) in each control volume

was smaller than 10^{-4} in magnitude.

3. The absolute value of the $d\bar{p}/dx^+$ correction (checking the overall mass balance) was smaller than 10^{-6}.

The cross-sectional mesh size that was employed for each duct geometry was decided on the basis of results obtained using different meshes in solving equation (4.9) numerically for the fully developed velocity distribution and the axial pressure gradient. Table 4.1 lists the mesh sizes used in this investigation, together with the numerical fully developed results plus certain results from the series solution in Chap. 3 or [103]. The chosen meshes were taken to be fine enough when a w_{max} value was obtained that was within 0.5% of the exact solution value. At this stage, as indicated in Table 4.1, $(fRe)_{fd}$ values were consistently a bit low (averaging 1.6% low), but always within 3% of the exact values. Later, with the axial step size pattern fixed, some numerical tests were conducted to check the adequacy of the cross-sectional mesh size for entrance region calculations. For example, tests for an apex angle of 180° (where eventually a $(r' \times \theta)$ mesh of (25×30) was used) showed that increasing the mesh size $(r' \times \theta)$ from (15×28) to (20×38) made the local fRe values noticeably different only near the entrance. Regarding the axial step size, the marching step size Δx^+ for the study was also determined by numerical experimentation. Following a series of trials, the following pattern was adopted for each circular sector duct. The first step size was taken as $\Delta x^+ = 10^{-6}$. Then Δx^+ was increased by 10% for each consecutive station until Δx^+ reached 7×10^{-4} which was then kept constant thereafter. For each case, marching was continued until both w_{max} and fRe were within 1% of the $(w_{max})_{fd}$ and $(fRe)_{fd}$ values respectively as generated by the numerical [2] fully developed solution. Typically, the required

[2] *The numerical solution, rather than the exact solution, was used in case of grid bias. In this connection, tests for $2\phi = 20°$ and 360° were carried out in which the solutions were deliberately marched well beyond the 1% level, and each test positively confirmed that the velocity distribution and the axial pressure gradient for the three-dimensional solution were definitely converging to the two-dimensional fully developed solution for the same cross-sectional grid.*

Table 4.1: Mesh Size and Fully Developed Results

2ϕ (Deg)	$r' \times \theta$	$(fRe)_{fd}$		$(w_{max})_{fd}$		r^* [103]
		Numerical	Exact [103]	Numerical	Exact [103]	
20	25×25	12.582	12.936	2.3490	2.3586	2.7033
45	30×15	13.389	13.782	2.2005	2.1934	1.2417
90	25×20	14.529	14.769	2.1070	2.1023	0.6755
130	25×25	15.153	15.318	2.0782	2.0754	0.5024
180	25×30	15.646	15.767	2.0628	2.0613	0.3930
270	25×32	16.093	16.228	2.0545	2.0520	0.2951
360	30×34	16.277	16.470	2.0567	2.0482	0.2436

number of axial steps ranged from about 200 for large apex angle to about 300 for small apex angle.

Information on the hydrodynamic entrance region is provided next for 7 circular sector ducts. It should be noted that, for the largest apex angle ($2\phi = 360°$), the results are applicable to a circular tube with one internal full fin.

4.1.3 Fully Developed Results

For each circular sector duct, preliminary computations were required to obtain $(w_{max})_{fd}$ and $(fRe)_{fd}$ for fully developed flow as governed by equation (4.9). These numerical values were then used as input to estimate the hydrodynamic entrance length. Values for $(w_{max})_{fd}$ and $(fRe)_{fd}$ as obtained numerically as well as analytically from [103] are listed in Table 4.1. Since knowing r^* where the w_{max} occurs at the symmetry plane is necessary, values for r^* are also included in Table 4.1. For $(w_{max})_{fd}$ and $(fRe)_{fd}$, the good agreement between the present numerical results and the exact results [103] has already been discussed.

4.1.4 Local Values of fRe and K

Variations of fRe and K in the entrance region for 7 circular sector ducts are listed in Table 4.2. For convenience, the dimensionless axial length x^+ is normalized by the corresponding entrance length L_{H1w} as previously defined (values for L_{H1w} will be tabulated later). It is noted that Table 4.2, along with Table 4.1, gives the main hydrodynamic quantities of interest. If the fully developed incremental pressure drop number $K(\infty)$ (also given in Table 4.2; see discussion later) is known, the total pressure drop up to any axial distance can be calculated from equation (4.12).

Results for fRe and K in the entrance region for $2\phi = 20°$ and $360°$ are graphically illustrated in Fig. 4.2. The results for the other 5 angles are not shown in the same figure in order to avoid crowding. But if plotted, each would fall between the present two curves. Values of fRe in Fig. 4.2 show the expected trend of a monotonic decrease with x^+, approaching to the limiting values of $(fRe)_{fd}$ in the fully developed region. On the other hand, K values monotonically increase with x^+ towards the asymptotical constant values of $K(\infty)$ in the very far downstream region.

The present results for fRe and K are compared in Fig. 4.3 with the results of others. For the K values of Prakash and Liu [104] for $2\phi = 45°$, eight graph values were taken from their figure 3(a) in [104] for the circular sector duct. Figure 4.3 shows that, for $2\phi = 45°$, these 8 points closely and consistently follow the present variation of K with a maximum difference of about 5%. It is also interesting to compare the present results to the published data of Soliman *et al.* [11] who used the linearized axial momentum technique [105]. As can be seen from Fig. 4.3, except for immediately near the inlet, the agreement is within about 5% over the last 90% of the entrance section for apex angles of 45° and 90°. This good agreement attests to the sound capability of the linearization method of Sparrow *et al.* [105,10].

Table 4.2: Variation of fRe and K in the Entrance Region of Circular Sector Ducts

$\frac{x^+}{L_{H1w}}$	$2\phi=20°$		$2\phi=45°$		$2\phi=90°$		$2\phi=130°$		$2\phi=180°$		$2\phi=270°$		$2\phi=360°$	
	fRe	K	fRe	K	fRe	K	fRe	K	fRe	K	fRe	K	fRe	K
0.001	148.68	0.131	139.38	0.059	139.18	0.047	142.76	0.046	145.60	0.049	149.16	0.051	188.12	0.067
0.003	75.45	0.238	100.96	0.138	111.52	0.115	120.41	0.117	129.57	0.130	140.00	0.145	138.52	0.187
0.005	58.38	0.303	85.69	0.200	97.03	0.170	108.21	0.177	115.72	0.201	114.88	0.225	86.07	0.254
0.007	50.40	0.353	75.46	0.252	88.85	0.219	98.48	0.231	98.91	0.261	86.77	0.283	72.47	0.301
0.010	43.73	0.416	65.53	0.317	78.44	0.284	83.17	0.300	74.87	0.329	65.76	0.344	61.42	0.358
0.020	33.29	0.567	47.09	0.477	52.79	0.438	49.65	0.443	46.67	0.460	45.20	0.475	43.74	0.490
0.030	28.87	0.678	37.81	0.586	40.55	0.533	40.24	0.530	38.83	0.547	37.59	0.562	36.43	0.579
0.040	26.23	0.768	32.43	0.667	35.17	0.604	35.47	0.597	34.37	0.615	33.39	0.630	32.46	0.647
0.050	24.40	0.845	29.26	0.733	31.93	0.663	32.32	0.653	31.43	0.670	30.62	0.685	29.81	0.703
0.070	21.93	0.973	25.57	0.838	27.91	0.756	28.31	0.743	27.66	0.759	27.07	0.774	26.47	0.791
0.100	19.53	1.121	22.44	0.958	24.45	0.862	24.89	0.844	24.45	0.859	24.04	0.872	23.58	0.889
0.150	17.18	1.294	19.60	1.102	21.35	0.989	21.80	0.965	21.54	0.976	21.31	0.985	21.01	1.000
0.200	15.88	1.414	17.99	1.206	19.57	1.080	20.03	1.051	19.90	1.058	19.80	1.063	19.60	1.076
0.250	15.07	1.502	16.94	1.284	18.40	1.149	18.88	1.116	18.85	1.118	18.85	1.120	18.73	1.131
0.300	14.52	1.570	16.20	1.345	17.58	1.203	18.08	1.166	18.12	1.165	18.20	1.163	18.15	1.173
0.350	14.12	1.623	15.65	1.394	16.98	1.246	17.49	1.206	17.60	1.201	17.75	1.197	17.74	1.205
0.400	13.83	1.666	15.23	1.434	16.52	1.281	17.04	1.238	17.21	1.230	17.41	1.223	17.44	1.230
0.450	13.60	1.701	14.90	1.467	16.16	1.309	16.70	1.265	16.91	1.254	17.16	1.244	17.21	1.250
0.500	13.42	1.730	14.64	1.494	15.87	1.333	16.42	1.286	16.68	1.273	16.96	1.262	17.04	1.266
0.600	13.16	1.773	14.25	1.534	15.45	1.368	16.03	1.318	16.35	1.301	16.68	1.288	16.79	1.291
0.700	12.99	1.803	13.99	1.562	15.17	1.392	15.76	1.341	16.13	1.320	16.50	1.305	16.64	1.307
0.800	12.87	1.825	13.81	1.582	14.98	1.409	15.58	1.357	15.99	1.334	16.38	1.318	16.53	1.319
0.900	12.79	1.840	13.68	1.596	14.84	1.421	15.46	1.368	15.88	1.343	16.30	1.327	16.46	1.328
1.000	12.73	1.851	13.60	1.606	14.75	1.429	15.37	1.376	15.81	1.350	16.24	1.333	16.41	1.333
∞		1.880		1.625		1.445		1.390		1.360		1.341		1.340

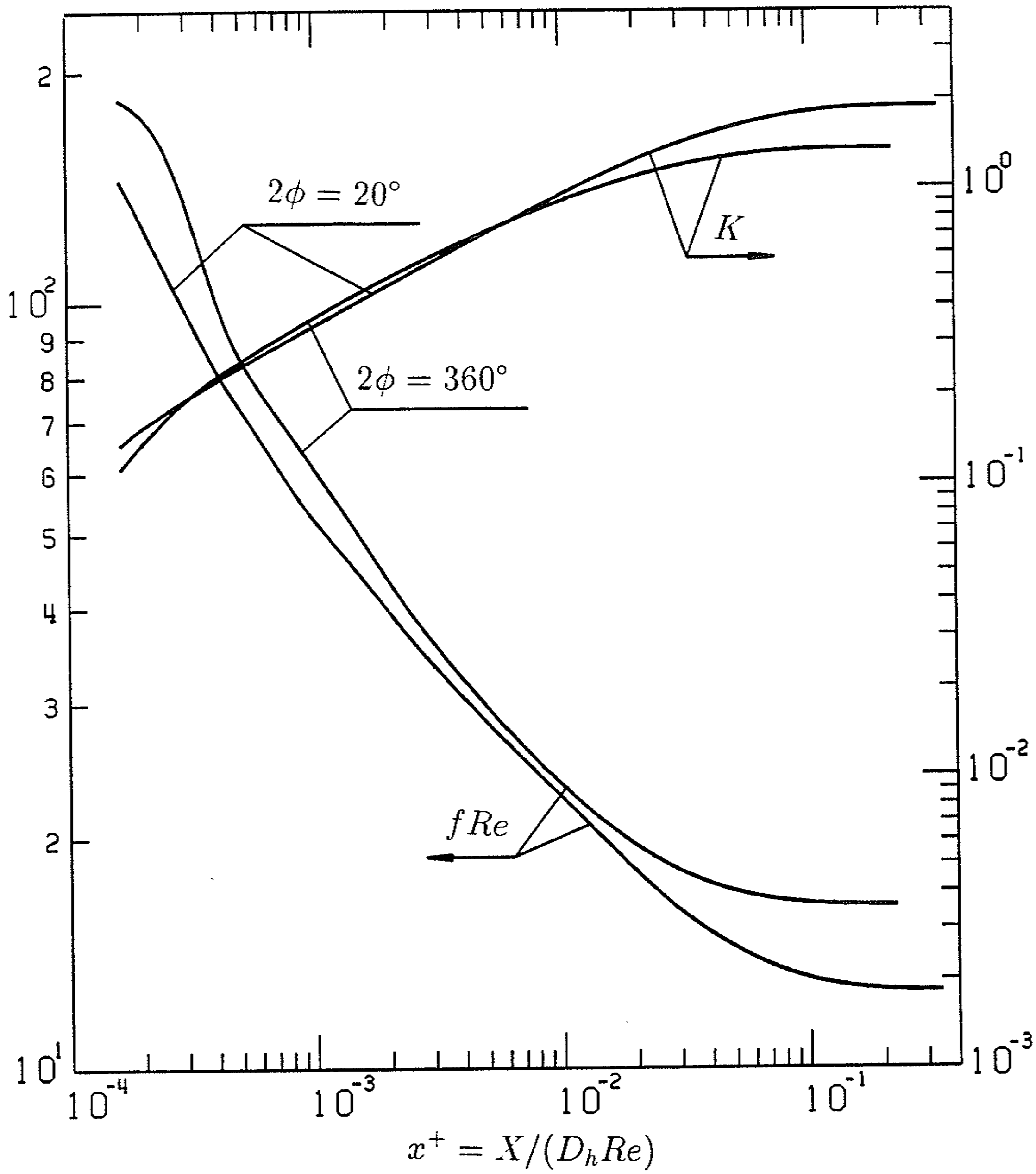


Figure 4.2: fRe and K vs. x^+ for Circular Sector Ducts

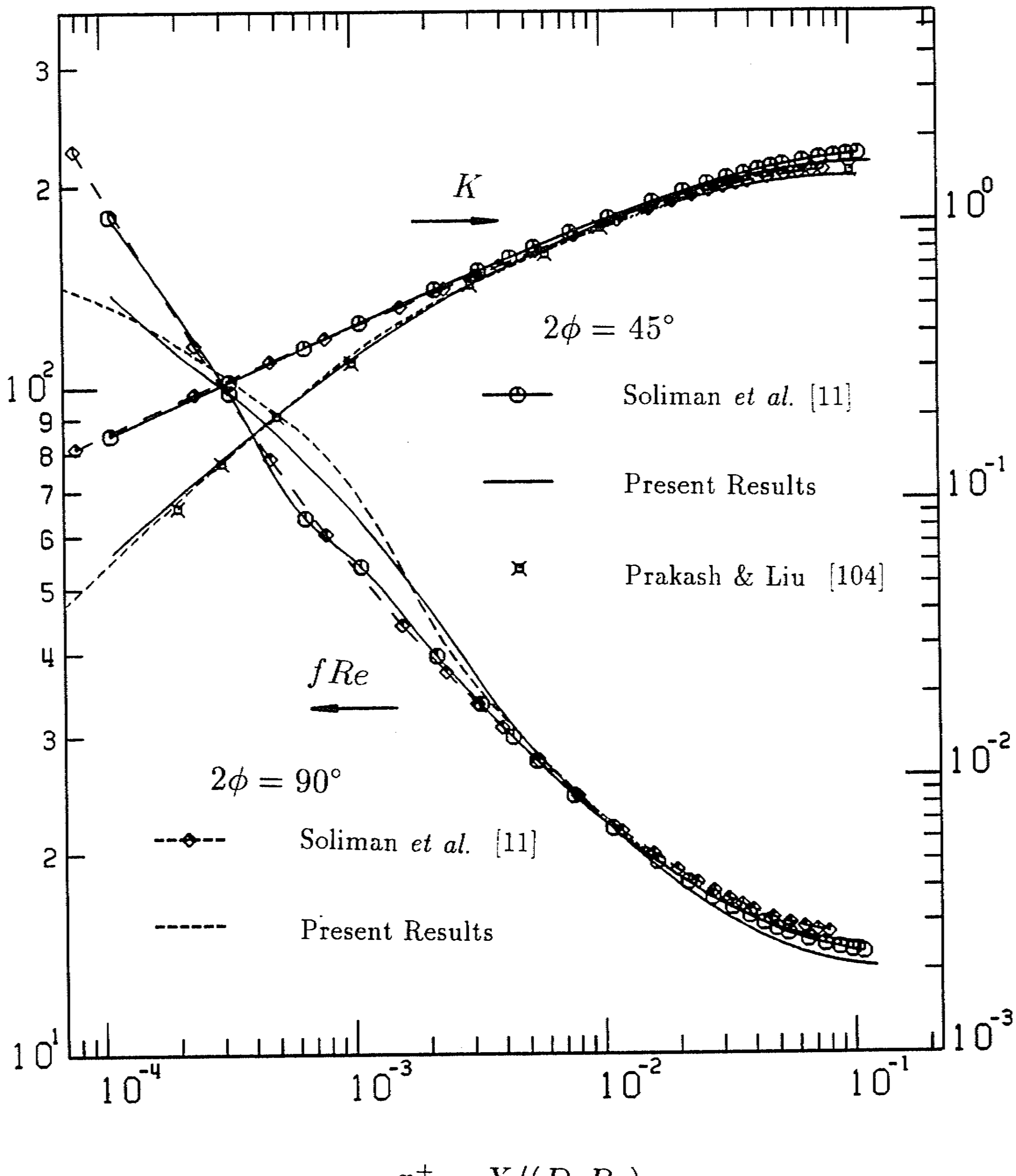


Figure 4.3: Comparison of fRe and K with Other Published Results

4.1.5 Limiting Incremental Pressure Drop Number $K(\infty)$

The variation of K with x^+ in Fig. 4.2 suggests the existence of a limiting incremental pressure drop number $K(\infty)$ which represents the total incremental pressure drop due to the entrance effects. The values of $K(\infty)$ are often estimated by graphically extrapolating the values of K, e.g., as done by Prakash and Liu [104]. In the present investigation, the exponential behavior of K near the end of the entrance region is assumed to take the form:

$$K(x^+) = K(\infty)(1 - e^{-cx^+}) \tag{4.15}$$

In order to obtain $K(\infty)$, K values from the last 21 stations were used to solve this equation numerically for the mean values of $K(\infty)$ and the constant c. Unlike the graphical extrapolation, this curve fitting technique is believed to provide more accurate and consistent values of $K(\infty)$. The present $K(\infty)$ values determined via equation (4.15) for the 7 duct apex angles are listed at the bottom of Table 4.2 for the corresponding infinite length of x^+/L_{H1w}. They are also graphically illustrated in Fig. 4.4, together with the results of others. The three $K(\infty)$ values from [104] are shown to agree well with the present results. For $2\phi = 45°$, the present $K(\infty)$ value of 1.625 is only slightly higher than 1.58 from [104]. Other interesting comparisons can be made with the numerical results [11,101,103] obtained from the linearization method. Figure 4.4 shows that the present results follow a parallel trend to the $K(\infty)$ pattern [103] as also shown in Fig. 3.3 where the fully developed series solution for w_{fd} was used to produce the $K(\infty)$ values for the entire apex angle range. Overall, although linearization methods tend to overestimate $K(\infty)$, all values for $K(\infty)$ through the linearization method were found to be within 12% of the present results.

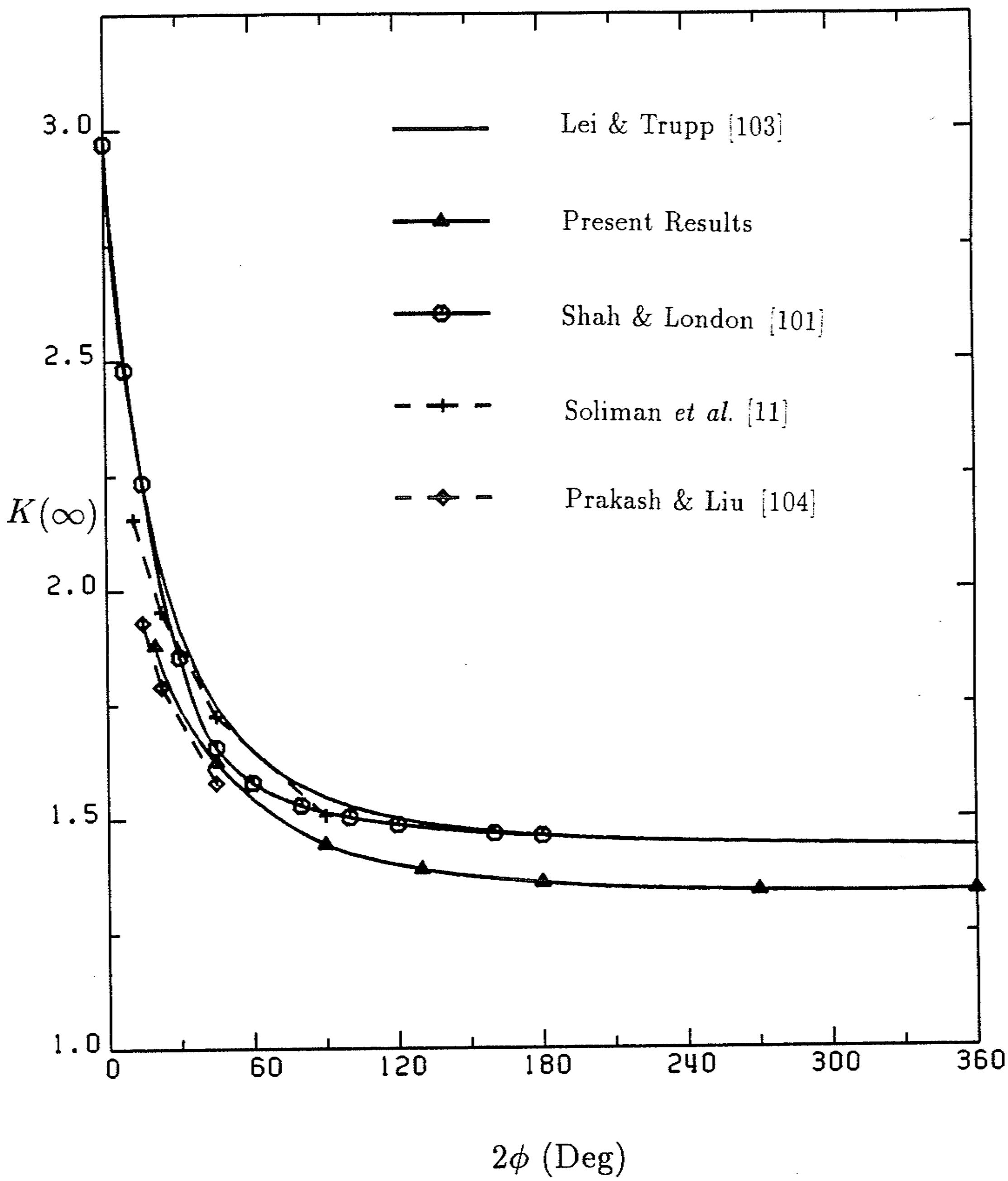


Figure 4.4: Incremental Pressure Drop Number $K(\infty)$ for Fully Developed Flow of Circular Sector Ducts

Table 4.3: Results of Hydrodynamic Entrance Lengths

2ϕ	20°	45°	90°	130°	180°	270°	360°
L_{H1f}	0.1654	0.1122	0.0898	0.0863	0.0863	0.0891	0.0919
L_{H1w}	0.1564	0.0989	0.0800	0.0779	0.0842	0.0912	0.0982
L_{H5f}	0.0905	0.0667	0.0543	0.0499	0.0485	0.0478	0.0478
L_{H5w}	0.0821	0.0541	0.0443	0.0422	0.0429	0.0457	0.0492
L^0_{H1f}	0.0146	0.0357	0.0695	0.0975	0.1289	0.1757	0.2115
L^0_{H1w}	0.0138	0.0315	0.0619	0.0880	0.1257	0.1798	0.2260
L^0_{H5f}	0.0080	0.0212	0.0420	0.0564	0.0724	0.0942	0.1100
L^0_{H5w}	0.0073	0.0172	0.0343	0.0477	0.0641	0.0901	0.1132

4.1.6 Estimate of Hydrodynamic Entrance Lengths

Results for the hydrodynamic entrance length L_H and L_H^0 as defined earlier are listed in Table 4.3 and graphically illustrated in Fig. 4.5 and Fig. 4.6. For comparison purposes, Fig. 4.5 shows three values for L_{H5f} from Prakash and Liu [104]. The agreement with the present results is very good. For example, for $2\phi = 45°$, the present L_{H5f} value of 0.0667 almost coincides with the value 0.0659 reported in [104]. Soliman *et al.* [11] also reported L_H values of 0.108 and 0.0786 for $2\phi = 45°$ and 90°, respectively. Their values were taken at the distance x^+ where **all** axial velocities were within 1% of the corresponding fully developed value. Using the same definition, this study gives the corresponding L_H values of 0.1189 and 0.1079, which are 9% and 27% higher, respectively. These discrepancies are probably due to poorer estimates of L_H by the linearization technique.

From Fig. 4.5, one tends to get the impression that a circular sector duct with smaller ϕ needs a longer length for the flow to be fully developed. This misleading impression arises because L_H is normalized by the product of $D_h Re$ which is depen-

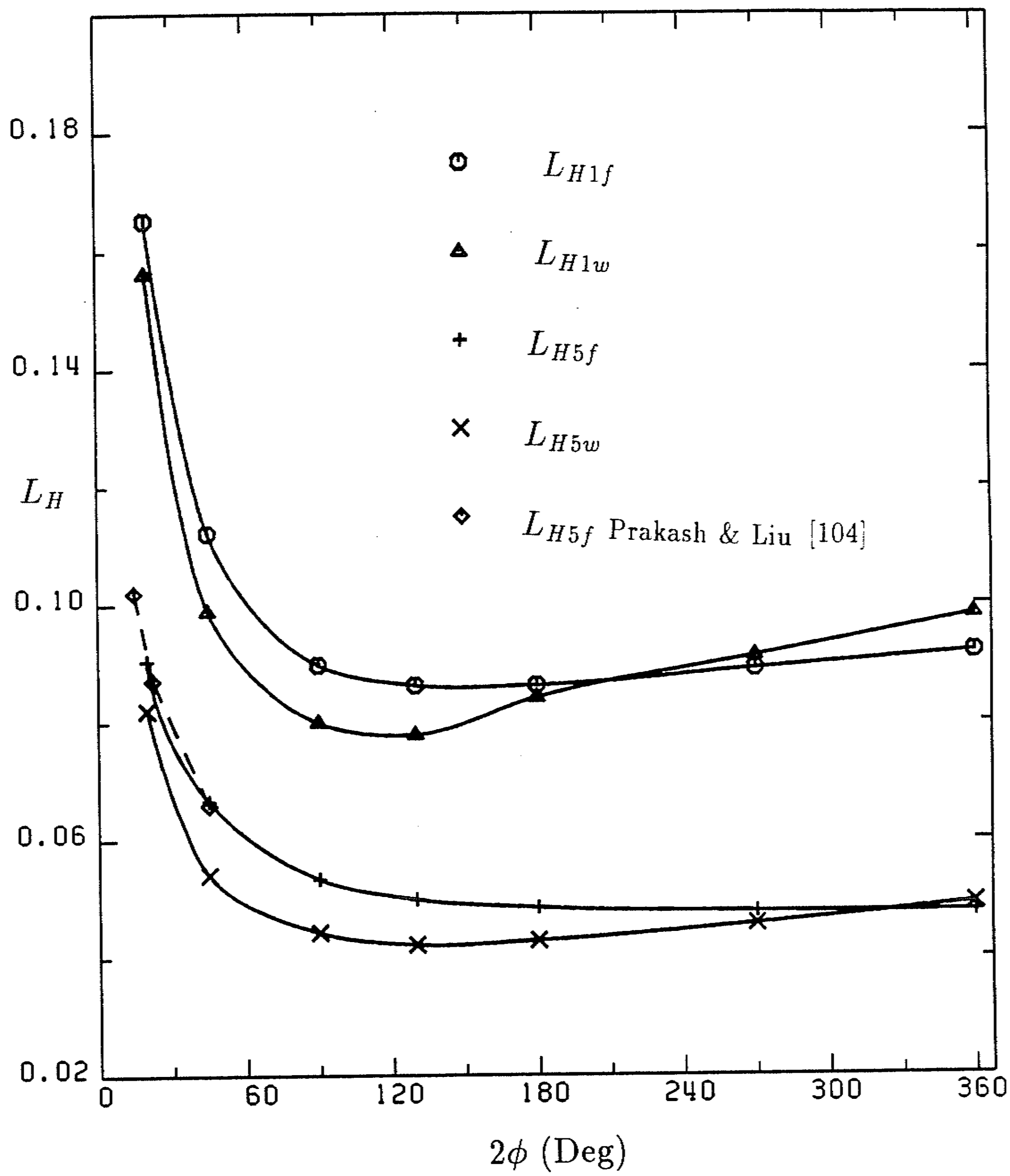


Figure 4.5: Hydrodynamic Entrance Lengths ($L_H = X/(D_h Re)$) for Circular Sector Ducts

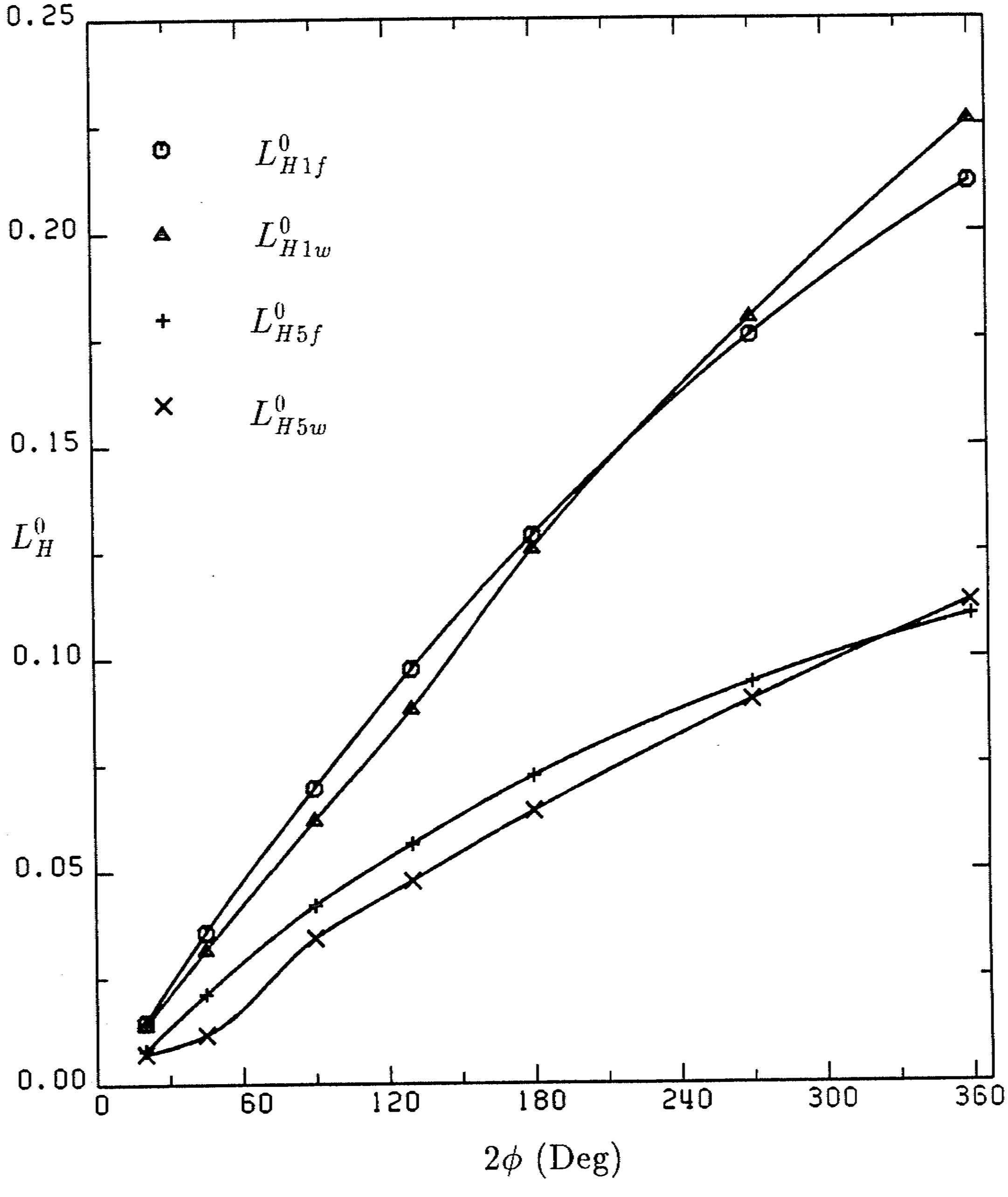


Figure 4.6: Hydrodynamic Entrance Lengths ($L^0_H = X/(R_0 Re_0)$) for Circular Sector Ducts

dent on ϕ. In fact, as shown in Fig. 4.6, for the same duct radius, decreasing the apex angle does indeed shorten the physical hydrodynamic entrance length. This is because decreasing ϕ increases the duct corner effects which aid the development of the flow. As a result, as ϕ increases up to π, which represents a circular tube with one internal full-fin, one reaches the longest hydrodynamic entrance length among circular sector ducts. For example, from Table 4.3, $L^0_{H1w} = 0.2260$ for $2\phi = 360°$. Note that this length is still shorter than the value of 0.2313 (converted to the same base as L^0_{H1w}) reported in [101] for circular tubes, and of course this is as expected.

Regarding the L^0_H outcomes (Fig. 4.6), for $2\phi \geq 270°$, the differences between L^0_{H1w} and L^0_{H1f} and between L^0_{H5w} and L^0_{H5f} are relatively small (within about 7%). But, for $2\phi < 270°$, these differences are more marked and reach up to 21%. For each geometry, the entrance lengths of L^0_{H1w} and L^0_{H1f} are significantly longer than L^0_{H5w} and L^0_{H5f}, especially for large circular sector ducts. For example, for $2\phi = 360°$, the L^0_{H1w} value is about double L^0_{H5w} (Table 4.3). Furthermore, the L^0_{H5w} entrance lengths average about 53% of the L^0_{H1w} values while the entrance lengths for L^0_{H5f} average about 56% of the results for L^0_{H1f}. These illustrate that the flow develops much more gradually near the fully developed region than in the preceding region.

It should be pointed out that Fig. 4.6 shows that L^0_H is almost linearly dependent of ϕ. For a quick estimate, it may be useful, for example, to express L^0_{H1w} as

$$L^0_{H1w} = 0.0020 + 0.07245\phi \qquad (0 < \phi \leq \pi) \tag{4.16}$$

where ϕ is in radian. Equation (4.16) predicts all present data for L^0_{H1w} within 8%.

4.1.7 Axial Velocity Profiles

A sample of the axial velocity distributions at the symmetry plane for $2\phi = 180°$ is plotted in Fig. 4.7. As illustrated, the velocity profile near the entrance is fairly uniform. Then it gradually develops to form a parabolic shape with the apex at

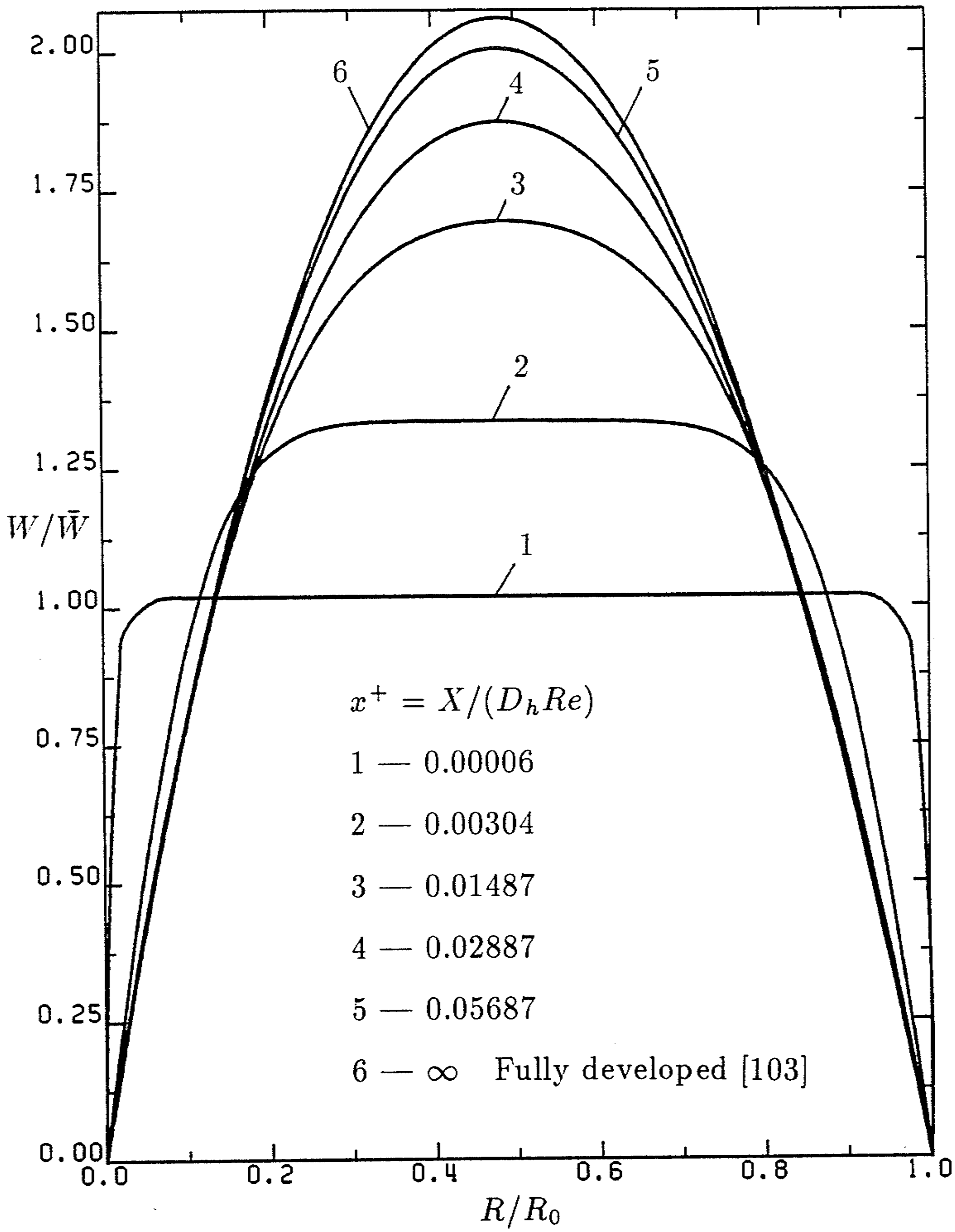


Figure 4.7: Development of the Axial Velocity at Symmetry Plane for $2\phi = 180°$

$R/R_0 = 0.480$ [103] as it approaches the fully developed profile. The plot also shows that as the flow develops, the slope of $\partial w/\partial(R/R_0)$ at the walls is reduced towards the limiting corresponding slope for $\left(\partial w/\partial(R/R_0)\right)_{fd}$. Finally, it is noted that the developing velocity profiles in Fig. 4.7 do indeed progressively approach well the fully developed profile [103] which is also shown in the figure.

4.2 Thermally Developing Flow

This section analyzes forced convection heat transfer in the thermal entrance region of straight circular sector ducts [106]. Primarily, the present investigation was motivated by the experimental study of buoyancy effects on forced convection in a horizontal semicircular duct [107]. Since one practical heating means is heating by electric resistance wires (like the experimental setup described in Chap. 6), this analysis considers the boundary condition of uniform heat input axially. The peripheral conditions being employed are uniform wall temperature and uniform wall heat flux, denoted by $H1$ and $H2$, respectively.

4.2.1 Mathematical Formulation

Figure 3.1 shows the duct cross section under consideration. The analysis is restricted to the steady, laminar flow of incompressible Newtonian fluids with constant properties. The fluid axial heat conduction is treated to be negligible. For circular tubes at least, this idealization is valid [101], except for the immediate neighborhood of the duct inlet providing $(RePr) > 50$. Like most laminar flow analyses, this study also neglects viscous dissipation within the fluid. Using dimensionless variables and parameters defined in the Nomenclature, while the momentum equation and its boundary conditions are given by equations (3.1) and (3.2), the governing energy equation can be written as follows:

$$\frac{\partial^2 T^*}{\partial r^2} + \frac{1}{r}\frac{\partial T^*}{\partial r} + \frac{1}{r^2}\frac{\partial^2 T^*}{\partial \theta^2} = w\left(\frac{\partial T^*}{\partial x'} + B\right) \tag{4.17}$$

where the geometry parameter B is given by $2(\phi + 1)/\phi$. Due to symmetry, solutions are necessary for only half the duct geometry. Thus the energy equation is supplemented by the following boundary conditions.

At $x' = 0$

$$T^* = 0 \qquad \text{for all } r \text{ and } \theta \tag{4.18}$$

At $x' > 0$

for the $H1$ condition:

$$T^* = T_w^* \quad \text{at } r = 1, \quad 0 \leq \theta \leq \phi$$

$$\text{at } \theta = 0, \quad 0 \leq r < 1 \tag{4.19}$$

$$\frac{\partial T^*}{\partial \theta} = 0 \quad \text{at } \theta = \phi, \quad 0 < r < 1 \tag{4.20}$$

for the $H2$ condition:

$$\frac{\partial T^*}{\partial r} = 1 \quad \text{at } r = 1, \quad 0 \leq \theta \leq \phi \tag{4.21}$$

$$\frac{\partial T^*}{\partial \theta} = -r \quad \text{at } \theta = 0, \quad 0 \leq r < 1 \tag{4.22}$$

$$\frac{\partial T^*}{\partial \theta} = 0 \quad \text{at } \theta = \phi, \quad 0 < r < 1 \tag{4.23}$$

Note that, since $T_w^* = (t_w - t_m)/(q'' R_0/k)$, T_w^* is the function of x', namely, $T_w^*(x')$. But, the $T_w^*(x')$ value at each cross section is not known in advance for both the cases. To solve for T^*, a solution method is first to use the initial condition at the duct inlet. Then the solution procedure is progressed along the axial direction. At each axial station, wall temperatures must be initially guessed while equation (4.17) together with its boundary conditions is solved for the T^* distribution. Wall temperatures are then corrected by determining the dimensionless bulk mean temperature. After several iterations, the correct velocity and local temperature fields must ensure that

$$T_m^* = \frac{2}{\phi} \int_0^{\phi} \int_0^{1} T^* w r \, dr \, d\theta = 0 \tag{4.24}$$

As the solution step is marched, the temperature profile gradually develops. In a far downstream region, $\partial T^* / \partial x'$ approaches zero and the temperature field becomes independent of the axial coordinate. Consequently, in such a fully developed region, equation (4.17) reduces to

$$\frac{\partial^2 T^*}{\partial r^2} + \frac{1}{r}\frac{\partial T^*}{\partial r} + \frac{1}{r^2}\frac{\partial^2 T^*}{\partial \theta^2} = Bw \tag{4.25}$$

Complete series solutions for this equation with both the $H1$ and $H2$ boundary conditions were presented and discussed in Sec. 3.3. These accurate fully developed Nusselt numbers were used in this study in connection with grid size selection as discussed later. The cross-sectional-average heat transfer coefficient, $\bar{h}$, is defined in a customary manner as $q'' = \bar{h}(\bar{t}_w - t_m)$. Using the dimensionless peripheral average wall temperature $\bar{T}_w^*$ and the hydraulic diameter D_h, the local Nusselt number is given by

$$Nu_x = \frac{\bar{h}_x D_h}{k} = \Big(\frac{2\phi}{\phi + 1}\Big)\frac{1}{\bar{T}_w^*(x')} \tag{4.26}$$

where $\bar{T}_w^*(x') = T_w^*(x')$ for the $H1$ condition, but for the $H2$ condition, $\bar{T}_w^*(x')$ can be evaluated by

$$\bar{T}_w^*(x') = \frac{1}{\phi + 1}\Big(\int_0^1 T^*(r, 0, x')dr + \int_0^\phi T^*(1, \theta, x')d\theta\Big) \tag{4.27}$$

Since D_h is a function of the duct apex angle, to better isolate the ϕ effect and to facilitate comparison to a circular tube, the Nusselt number may be defined, on the basis of duct radius R_0, as

$$Nu_{0x} = \frac{\bar{h}_x R_0}{k} = \frac{1}{\bar{T}_w^*(x')} \tag{4.28}$$

Information on thermal entrance length is also of practical importance. Thus, in this analysis, values of thermal entrance lengths were taken as the dimensionless distances ($x' = X/(R_0 Re_0 Pr)$) where the local Nusselt numbers first drop to within 1.05 and 1.01 times the fully developed Nusselt numbers, denoted by L_{T5}^0

and L^0_{T1}, respectively. Similarly, the conventional thermal entrance length, L_T, was correspondingly defined with the axial distance normalized by $(D_h RePr)$. The relationship between L_T and L^0_T for circular sector ducts is given by

$$L_T = \left(\frac{\phi + 1}{2\phi}\right)^2 L^0_T \tag{4.29}$$

4.2.2 Computational Details and Accuracy Assurance

The finite difference equation of (4.17) was formulated using the control volume integration method. For the fully developed velocity field, exact values were computed from the series expression of equation (3.4). At a given axial station, equation (4.17) with the $H1$ or $H2$ condition was numerically solved by a band storage linear equation solver. Since wall temperatures were not known in advance, iterations were needed for obtaining the correct T^* distribution. Thus, a number of corrections (2 to 5 for most stations) were made on the wall temperature for the $H1$ condition and on an arbitrary nodal temperature for the $H2$ condition, while ensuring the bulk mean temperature less than 10^{-6} in magnitude. For each case, the solution procedure was marched along x' until the local Nusselt number was at least within 0.1% of the corresponding fully developed value as numerically generated from equation (4.25).

Decisions on the adequacy of the cross-sectional mesh size adopted for each duct geometry were mainly guided by comparing a numerical value of $(Nu)_{fd}$ to the exact value obtained from the series solution in Chap. 3 or in [99,100]. Table 4.4 gives these comparisons and the mesh sizes used in this investigation. For both the cases, the chosen mesh sizes were taken to be fine enough to make a grid value of $(Nu)_{fd}$ within 0.5% of the exact solution value. Regarding the axial step size, the marching step size $\Delta x'$ for the study was also determined by numerical experimentation. For example, for $2\phi = 180°$, with the cross-sectional mesh size (22×25) fixed and the first step size $\Delta x' = 10^{-6}$, two numerical tests were conducted near the entrance. One let Δx

Table 4.4: Mesh Size and Fully Developed Heat Transfer Results

2ϕ (Deg)	$r \times \theta$	$(Nu_{H1})_{fd}$		$(Nu_{H2})_{fd}$	
		Present	Exact [99]	Present	Exact [100]
20	22×15	2.7683	2.7633	0.3692	0.3710
45	22×17	3.2820	3.2792	1.7592	1.7630
90	22×20	3.7460	3.7440	2.9871	2.9870
130	22×22	3.9485	3.9466	3.0282	3.0280
180	22×25	4.0897	4.0880	2.9210	2.9200
270	30×35 22×30	4.2113	4.2178	2.7704	2.7690
360	50×40 22×32	4.2653	4.2852	2.6876	2.6870

be increased by 5% and another by 25% for each consecutive station. Local Nusselt numbers from these two tests showed no noticeable difference. This insensitiveness to the axial step size is mainly attributed to the use of the accurate direct solver for simultaneous linear equations at each cross section. For all cases, it was finally decided to use the following pattern. The first step size was taken as $\Delta x' = 10^{-6}$. Then $\Delta x'$ was increased by 20% for each subsequent step size. Upon reached 8×10^{-4}, $\Delta x'$ remained unchanged for the rest of the entrance section. Using these three-dimensional meshes, specific tests were run which positively confirmed that the three-dimensional temperature profile for each case was indeed converging to the two-dimensional fully developed temperature profile for the same cross-sectional grid.

4.2.3 Fully Developed Nusselt Numbers

Nusselt numbers for hydrodynamically and thermally fully developed flow were generated by solving equation (4.25) numerically. These results, together with values determined from series solutions [99,100], are given in Table 4.4. For both the $H1$ and $H2$ conditions, all present Nusselt numbers fell within 0.5% of the exact solution values with an average difference of about 0.1%. This excellent agreement can be seen (for Nu_0 only) in Fig. 4.8 which shows variations of fully developed Nusselt numbers with duct apex angle. Both Nusselt numbers ($(Nu)_{fd}$ based on D_h and $(Nu_0)_{fd}$ based on R_0) have been plotted, but as can be seen, $(Nu)_{fd}$ tends to mask the ϕ effect. For instance, $(Nu_{H1})_{fd}$ decreases with decreasing ϕ which is accompanied by increasing corner effects. In fact, for the $H1$ condition, this increase of corner effects should enhance the duct capability of thermal energy transfer. The reason for this is as follows; since $\bar{h}_{H1} = -k\overline{(\partial t/\partial N)}/(t_w - t_m)$, where t_w is constant, introducing the fluid mean effective conduction path length δ_f (as in [101]) yields $\bar{h}_{H1} = k(t_w - t_m)/\delta_f/(t_w - t_m) = k/\delta_f$. Accordingly, a circular sector duct with smaller ϕ should have a shorter overall δ_f value, and this means a higher average heat transfer coefficient. Concerning the $H2$ condition, a parallel analysis suggests that wall temperatures at corners are higher than temperatures for surfaces away from the corners. Hence since $\bar{h}_{H2}$ involves the evaluation of average wall temperature, the ϕ effect on $\bar{h}_{H2}$ should not be as marked as on $\bar{h}_{H1}$. On the other hand, as is shown in Fig. 4.8, Nu_0 follows the expected trends of heat transfer coefficients versus apex angle for both cases. Note that a maximum for $(Nu_{0,H2})_{fd}$ occurs at $2\phi \approx 60°$. This particular circular sector duct has an $(Nu_{0,H2})_{fd}$ value which falls between the Nusselt values for equilateral triangular ducts with two rounded corners and no rounded corners [101].

4.2.4 Local Heat Transfer

Results for $Nu_{x,H1}$ and $Nu_{x,H2}$ in the thermal entrance region for the seven circular sector ducts are presented in Table 4.5. For convenience, the dimensionless axial distance x' is normalized by the corresponding thermal entrance length L^0_{T1} as previously defined (values for L^0_{T1} will be tabulated later). It should be noted

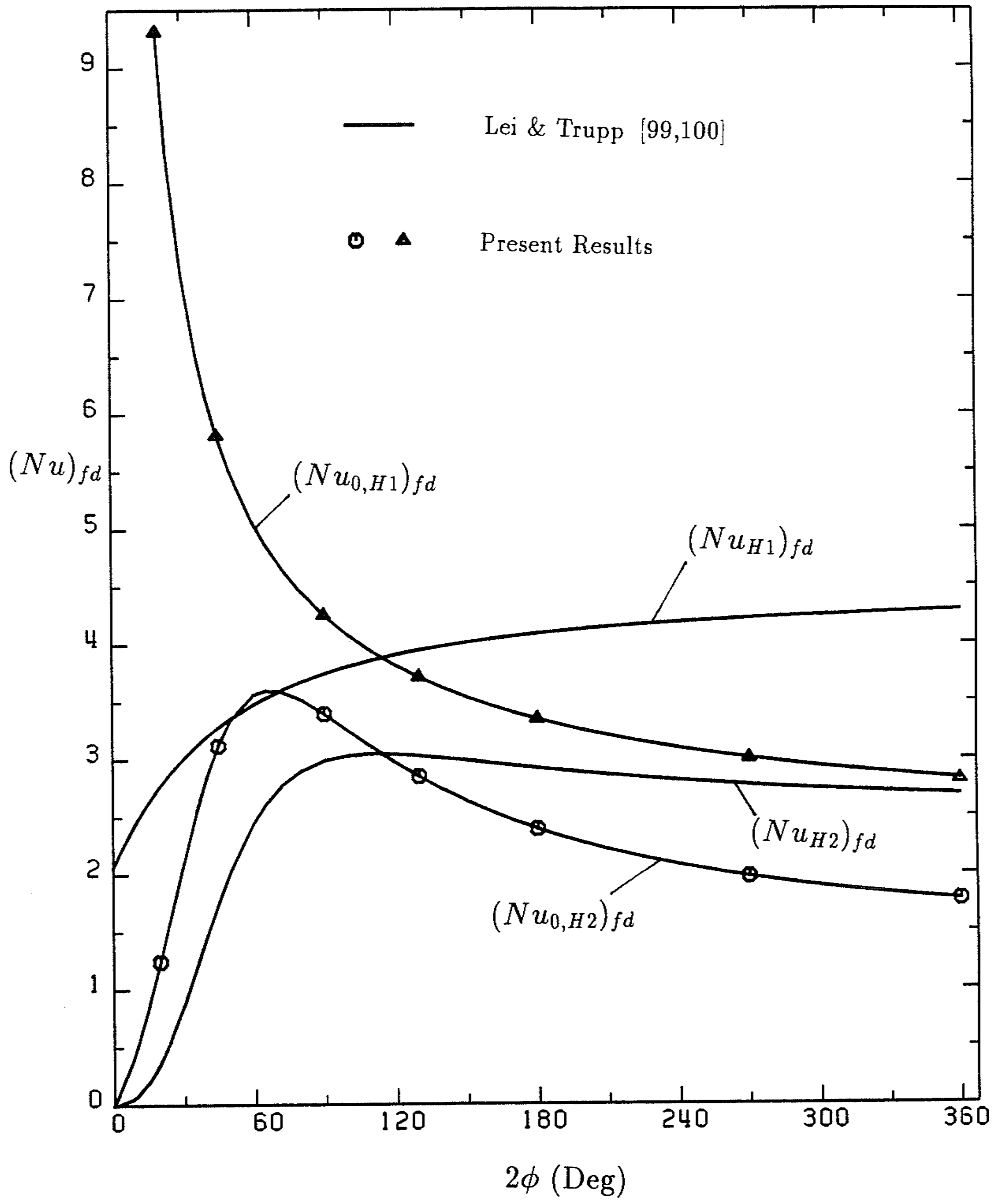


Figure 4.8: Fully Developed Nusselt Numbers for Circular Sector Ducts

Table 4.5: Variation of Nu_x in the Entrance Region of Circular Sector Ducts

$\frac{x'}{L^0_{T1}}$	$2\phi=20°$		$2\phi=45°$		$2\phi=90°$		$2\phi=130°$		$2\phi=180°$		$2\phi=270°$		$2\phi=360°$	
	$H1$	$H2$	$H1$	$H2$	$H1$	$H2$	$H1$	$H2$	$H1$	$H2$	$H1$	$H2$	$H1$	$H2$
0.0001	37.852	9.268	40.809	28.988	44.494	49.603	46.674	51.663	48.602	51.923	58.871	49.247	60.794	45.641
0.0005	22.653	4.812	27.270	17.214	31.850	32.231	34.084	32.330	35.454	30.605	36.330	26.664	34.856	23.739
0.0010	17.880	3.583	22.203	13.308	26.497	25.198	28.141	24.606	28.907	22.881	28.161	19.850	27.429	17.870
0.0030	12.349	2.236	15.888	8.706	18.756	16.392	19.409	15.655	19.545	14.585	19.004	12.930	18.758	11.795
0.0050	10.461	1.796	13.542	7.124	15.682	13.363	16.138	12.791	16.216	12.024	15.909	10.715	15.747	9.807
0.0070	9.386	1.559	12.133	6.243	13.915	11.732	14.302	11.264	14.379	10.626	14.185	9.506	14.061	8.697
0.0100	8.385	1.343	10.763	5.441	12.251	10.242	12.609	9.882	12.700	9.344	12.579	8.382	12.487	7.663
0.0200	6.733	1.013	8.472	4.210	9.629	7.949	9.946	7.731	10.046	7.320	10.011	6.577	9.960	6.043
0.0300	5.916	0.864	7.379	3.641	8.405	6.891	8.700	6.721	8.802	6.368	8.774	5.738	8.739	5.292
0.0400	5.404	0.775	6.709	3.306	7.651	6.246	7.922	6.096	8.024	5.781	8.011	5.227	7.984	4.835
0.0500	5.040	0.713	6.233	3.069	7.129	5.800	7.384	5.662	7.480	5.377	7.474	4.873	7.456	4.520
0.0700	4.547	0.633	5.614	2.754	6.418	5.189	6.648	5.085	6.746	4.839	6.759	4.405	6.752	4.105
0.1000	4.099	0.563	5.050	2.475	5.764	4.639	5.981	4.565	6.081	4.356	6.115	3.986	6.121	3.737
0.1500	3.680	0.499	4.509	2.223	5.143	4.120	5.350	4.080	5.457	3.906	5.511	3.599	5.529	3.402
0.2000	3.436	0.463	4.189	2.084	4.778	3.818	4.981	3.799	5.093	3.646	5.162	3.377	5.189	3.212
0.2500	3.281	0.441	3.975	1.998	4.537	3.619	4.737	3.616	4.854	3.475	4.934	3.233	4.968	3.090
0.3000	3.169	0.425	3.824	1.940	4.365	3.479	4.565	3.487	4.686	3.356	4.775	3.133	4.814	3.006
0.4000	3.024	0.405	3.627	1.871	4.141	3.297	4.341	3.321	4.470	3.200	4.572	3.004	4.618	2.898
0.5000	2.937	0.393	3.508	1.834	4.005	3.190	4.207	3.222	4.342	3.107	4.452	2.927	4.502	2.832
0.6000	2.883	0.385	3.433	1.812	3.920	3.122	4.123	3.160	4.261	3.047	4.376	2.879	4.428	2.789
0.7000	2.848	0.380	3.384	1.798	3.863	3.079	4.067	3.118	4.208	3.007	4.326	2.846	4.380	2.760
0.8000	2.824	0.377	3.352	1.789	3.826	3.050	4.030	3.091	4.172	2.981	4.293	2.824	4.347	2.740
0.9000	2.807	0.375	3.330	1.782	3.801	3.030	4.005	3.072	4.148	2.963	4.270	2.809	4.323	2.725
1.0000	2.796	0.373	3.315	1.777	3.783	3.017	3.988	3.058	4.131	2.950	4.253	2.798	4.308	2.715
1.2000	2.782	0.371	3.298	1.770	3.764	3.002	3.968	3.043	4.110	2.935	4.234	2.785	4.288	2.702
1.5000	2.774	0.370	3.287	1.765	3.752	2.992	3.955	3.033	4.097	2.926	4.220	2.776	4.275	2.693

that Table 4.5 can be also used to estimate the flow length average Nusselt number which is often required in a heat exchanger design.

4.2.4.1 Local Nusselt Numbers for the $H1$ Condition

Figure 4.9 shows the variations of the local $H1$ Nusselt numbers for the seven circular sector ducts. As indicated before, the hydraulic diameter D_h is intentionally removed from the plot to better disclose the apex angle effect. For each circular sector duct, $Nu_{0x,H1}$ exhibits the expected trend of a monotonic decrease with x', approaching the limiting value of $(Nu_{0,H1})_{fd}$ in the fully developed region. Except for very near the duct inlet ($x' < 8 \times 10^{-5}$), local values for $Nu_{0x,H1}$ demonstrate the same ϕ variation as the $(Nu_{0,H1})_{fd}$ values, namely, increased with decreasing apex angle.

The present $Nu_{0x,H1}$ values are compared in Fig. 4.10 to the results of others. Nusselt numbers and dimensionless axial lengths presented in the plot for each duct are on the basis of the same characteristic length R_0. As illustrated, all noncircular ducts including the one internal full-fin tube ($2\phi = 360°$) possess higher Nusselt numbers than a circular tube, except for the proximate neighborhood of the duct inlet. For a semicircular tube ($2\phi = 180°$), the present $Nu_{0x,H1}$ values compare well in Fig. 4.10 with the results of Hong and Bergles [102]. Differences between the local Nusselt numbers averaged 2.7%, but were always within 7%. Figure 4.10 also shows comparison to two noncircular ducts whose Nusselt numbers fall between the curves of circular sector ducts with $2\phi = 45°$ and $90°$. These two ducts are the equilateral triangular duct (comparable with the circular sector duct of $2\phi = 60°$) and the right-angled isosceles triangular duct (comparable with the circular sector duct of $2\phi = 90°$). Using the same basis of R_0 (see Fig. 4.10 for the legend), the $Nu_{0x,H1}$ values for these two ducts appear to have correct trends with x' as well as with ϕ. For instance, higher values of $Nu_{0x,H1}$ for the right-angled isosceles triangular duct are definitely expected when compared to the values for the circular sector

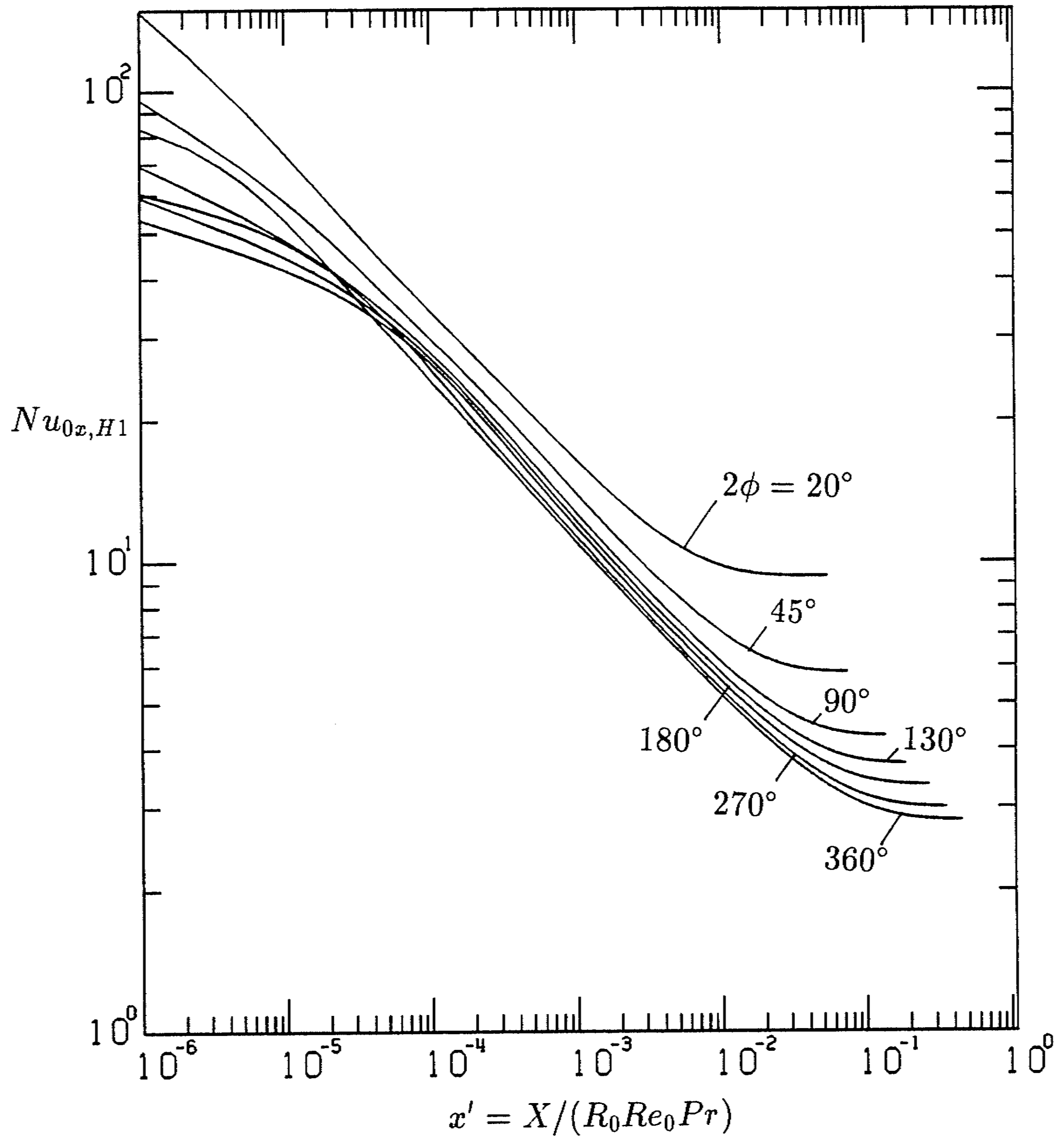


Figure 4.9: Local Nusselt Numbers for the $H1$ Condition

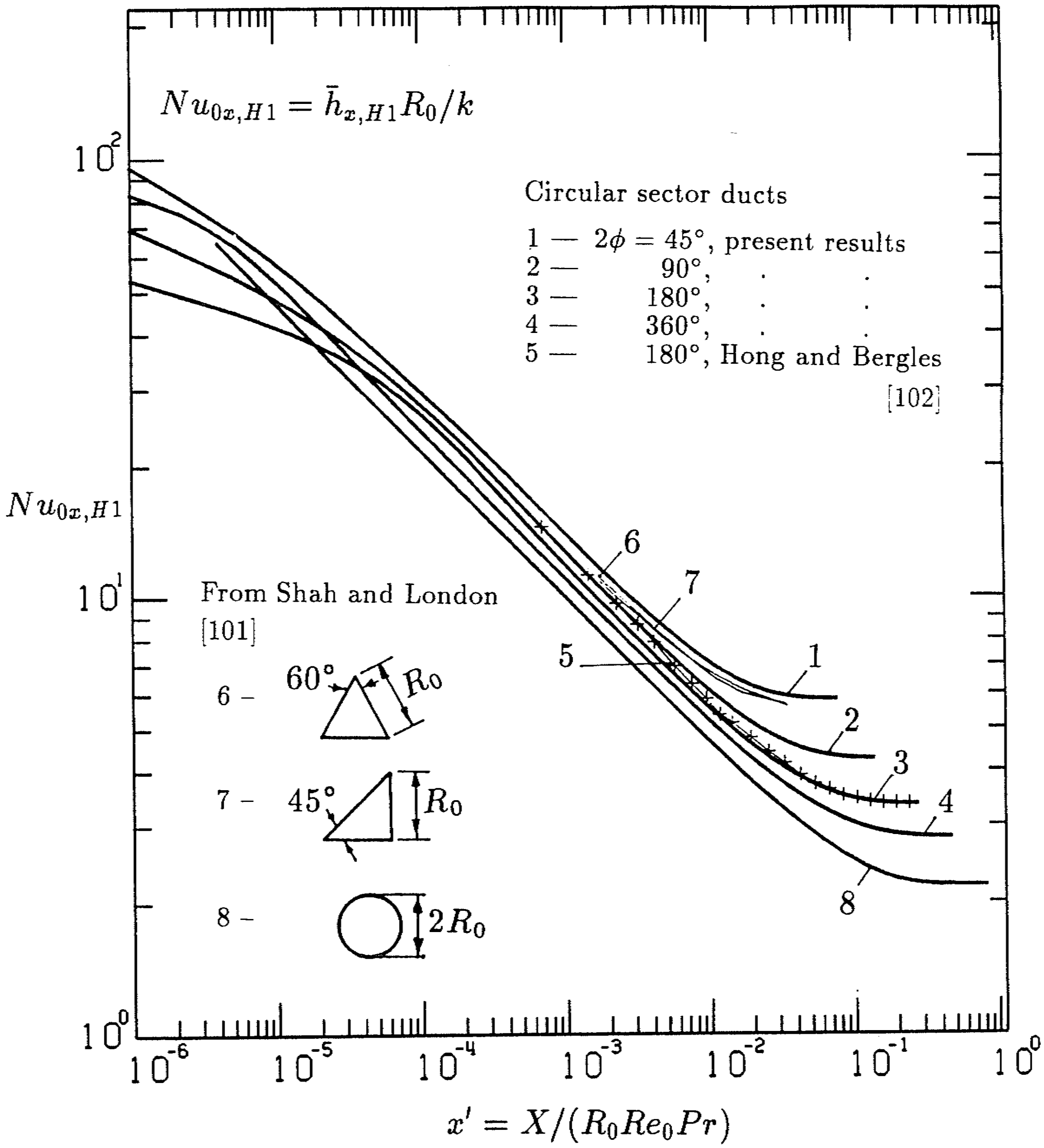


Figure 4.10: Comparison of $Nu_{0x,H1}$ with Other Published Results

duct of $2\phi = 90°$. As demonstrated before, this is because the fluid mean effective conduction path length for the right-angled isosceles triangular duct is relatively shorter.

4.2.4.2 Local Nusselt Numbers for the $H2$ Condition

Variations of $Nu_{0x,H2}$ for the thermally developing flow for the seven circular sector ducts plus a square duct are graphically shown in Fig. 4.11. Like $Nu_{0x,H1}$, for each duct, $Nu_{0x,H2}$ monotonically drops as x' increases. In the far down-stream region, each curve approaches its correct fully developed value of $(Nu_{0,H2})_{fd}$. It should also be pointed out that, near the entrance, Fig. 4.11 appears to show flatter slopes for $Nu_{0x,H2}$ than for farther down-stream. This misleading appearance is due to the logarithmic scale plotting. The actual slopes of Nu_{0x} versus axial distance for all cases of this study were always steepest near the entrance.

Concerning the ϕ effect, for $x' >\sim 6\times10^{-2}$, local values of $Nu_{0x,H2}$ for all circular sector ducts in Fig. 4.11 follow the same pattern as $(Nu_{0,H2})_{fd}$ versus ϕ, as displayed in Fig. 4.8, i.e., increasing apex angle up to 60° gives rise to an increase in $Nu_{0x,H2}$ which then decreases with further increases in ϕ. For the middle region of the flow development, the ϕ effect on $Nu_{0x,H2}$ is very small for $2\phi > 45°$. Figure 4.11 also provides one comparison to the $Nu_{0x,H2}$ results of Chandrupatla and Sastri [108] who studied non-Newtonian fluids in a square duct. Their Newtonian results of $Nu_{0x,H2}$ appear between the curves of the circular sector ducts for $2\phi = 90°$ and 130°. This would also be the case if their Newtonian results of $Nu_{0x,H1}$ were plotted in Fig. 4.10 (not plotted because of crowding).

4.2.4.3 Effect of Thermal Boundary Conditions on Nu_{0x}

The differences between Nusselt numbers for the different thermal boundary conditions are considered next for each geometry. All results obtained in this investigation indicated that, except for the region very near the duct inlet, $Nu_{0x,H1}$

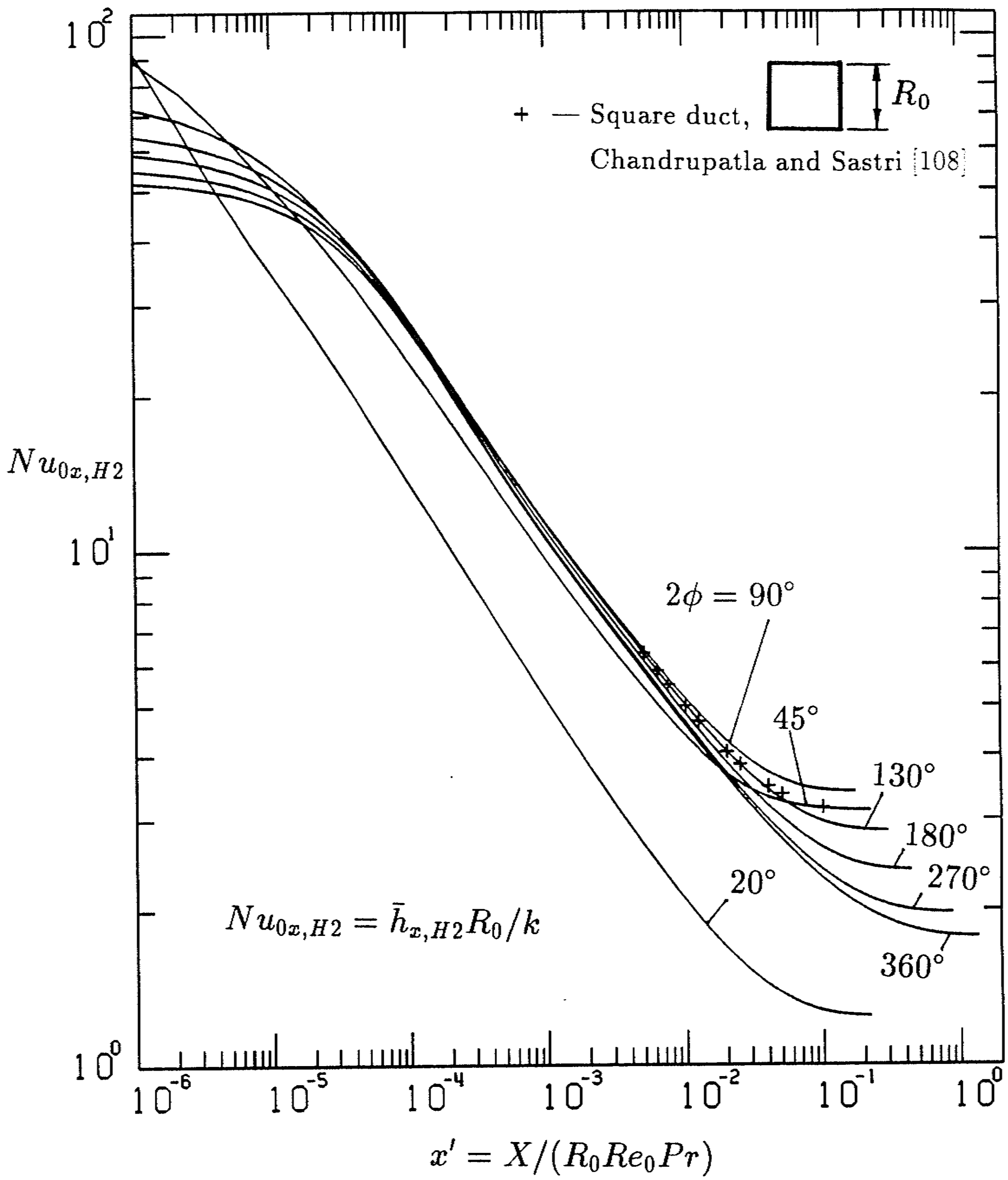


Figure 4.11: Local Nusselt Numbers for the $H2$ Condition

was always higher than $Nu_{0x,H2}$. This expected outcome is graphically shown in Fig. 4.12 using the semicircular tube as a typical example. It can be seen that , near the duct inlet, $Nu_{0x,H1}$ starts to exceed $Nu_{0x,H2}$. As the flow continues to develop, the difference between them increases and reaches up to about 40% (i.e., $(Nu_{0,H1})_{fd}/(Nu_{0,H2})_{fd} \approx 1.4$) in the fully developed region. Figure 4.12 also shows the developing Nusselt numbers for constant wall temperature in both the axial and peripheral directions (T) which were calculated from the correlation equation of the axial length mean Nusselt number (after converted to $Nu_{0x,T}$) reported by Manglik and Bergles [109]. As illustrated, the $Nu_{0x,T}$ values fall between the curves of $Nu_{0x,H1}$ and $Nu_{0x,H2}$ as the flow approaches the fully developed region. It may be pointed out that the T condition produces a lower boundary for Nu_{H1} but not for Nu_{H2}. This is because both the T condition and the $H1$ condition have peripheral uniform wall temperatures therefore they belong to a same family. In fact, as demonstrated by Sparrow and Patankar [7], the T and $H1$ conditions are respectively lower and higher limits for any other *axial* thermal condition provided that *peripheral* uniform wall temperatures are preserved.

4.2.5 Estimate of Thermal Entrance Lengths

Table 4.6 lists results of the thermal entrance lengths for the $H1$ and $H2$ conditions. For the semicircular tube ($2\phi = 180°$), the present values of 0.05395 and 0.09747 for $L_{T5,H1}$ and $L_{T1,H1}$ compare reasonably well with 0.0525 and 0.0893 respectively which were obtained by interpolating the thermal entrance results of Hong and Bergles [102] using a $(Nu_{H1})_{fd}$ value of 4.108 [102]. The differences are 3% for $L_{T5,H1}$ and 8% for $L_{T1,H1}$. For each geometry and boundary condition, Table 4.6 shows significantly higher values for L_{T1} than for L_{T5}. In fact, the $L_{T5,H1}$ entrance lengths average 56% of the $L_{T1,H1}$ values while results for $L_{T5,H2}$ average 54% of the $L_{T1,H2}$ values. These indicate (as expected) that the flow develops very gradually near the fully developed region. Furthermore, each $L_{T,H2}$ value listed in Table 4.6

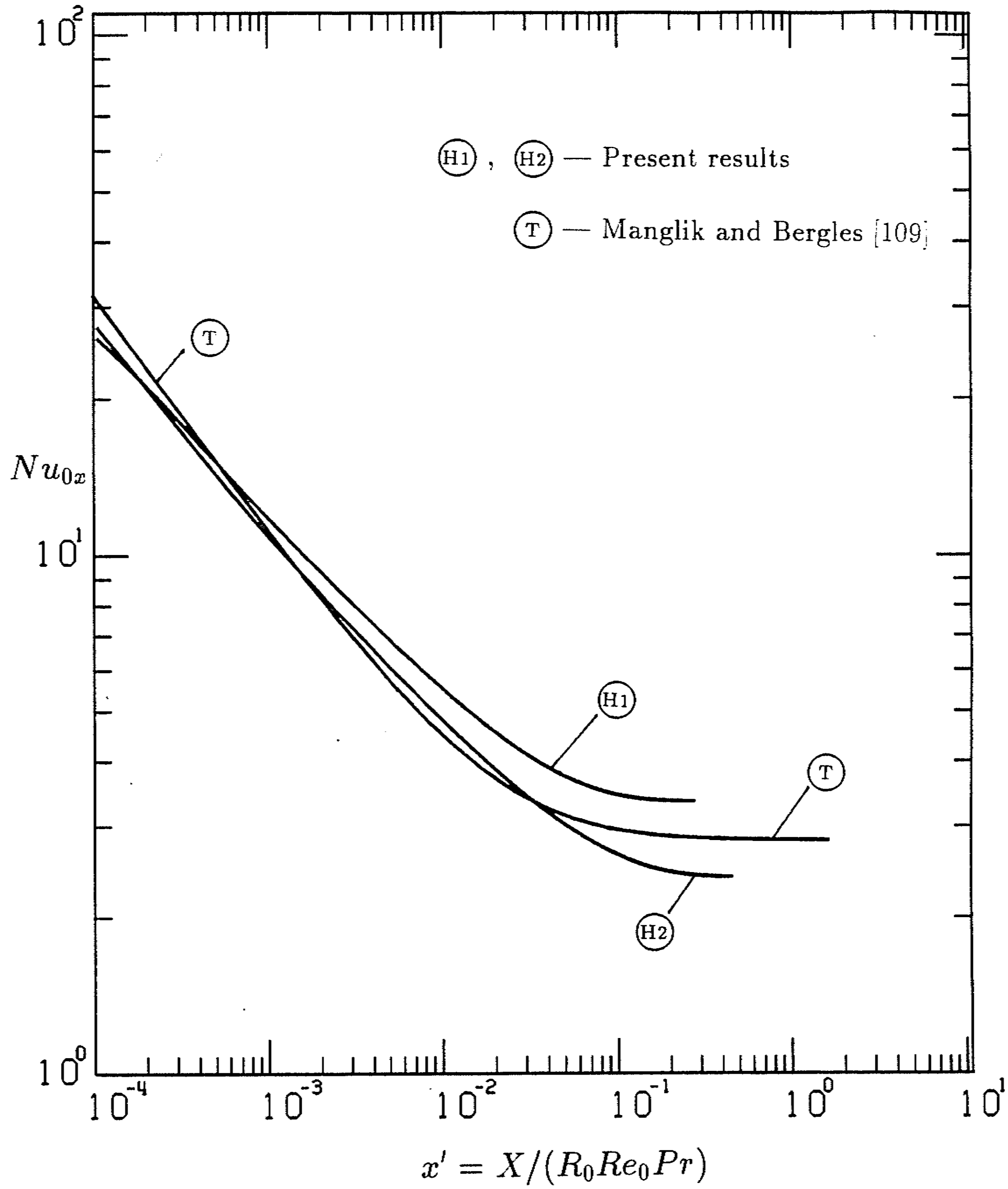


Figure 4.12: Local Nusselt Numbers for a Semicircular Duct with Different Boundary Conditions

Table 4.6: Results of Thermal Entrance Lengths

2ϕ	20°	45°	90°	130°	180°	270°	360°
$L^0_{T5,H1}$	0.01004	0.02345	0.04501	0.06203	0.08057	0.10657	0.12583
$L^0_{T1,H1}$	0.01822	0.04044	0.07749	0.10919	0.14556	0.19935	0.23870
$L^0_{T5,H2}$	0.07607	0.04524	0.05393	0.09367	0.14896	0.26030	0.39179
$L^0_{T1,H2}$	0.13466	0.09878	0.09377	0.16624	0.26542	0.48814	0.75257
$L_{T5,H1}$	0.11372	0.07373	0.05814	0.05489	0.05395	0.05406	0.05467
$L_{T1,H1}$	0.20631	0.12716	0.10011	0.09663	0.09747	0.10112	0.10371
$L_{T5,H2}$	0.86124	0.14225	0.06967	0.08290	0.09975	0.13203	0.17023
$L_{T1,H2}$	1.52464	0.31060	0.12114	0.14712	0.17773	0.24760	0.32698

is higher than its counterpart $L_{T,H1}$. On an average, the thermal entrance length for the $H2$ condition is 2.8 times longer than the section for the $H1$ condition. This indicates that the $H1$ condition when imposed on a circular sector duct is a much stronger thermal boundary condition (compared to $H2$) such that the temperature field requires a much shorter axial length for its full development. The thermal entrance results of Chandrupatla and Sastri [108] for a square duct also show that the $H2$ condition results in longer thermal entrance lengths than the $H1$ condition for Newtonian as well as non-Newtonian fluids.

Variations of thermal entrance lengths with duct apex angle are shown in Fig. 4.13 for the $H1$ condition. For L_T, for large ϕ, thermal entrance lengths appear almost constant, however for $2\phi <\sim 100°$, L_T (which is normalized by D_h) increases with decreasing ϕ. But, in fact, physical variations of thermal entrance lengths are better viewed in terms of L^0_T (normalized by R_0) which show a monotonically increasing trend with ϕ. For small ϕ, duct corner effects assist early temperature development so that the trend is expected. Note that increasing apex angle up to

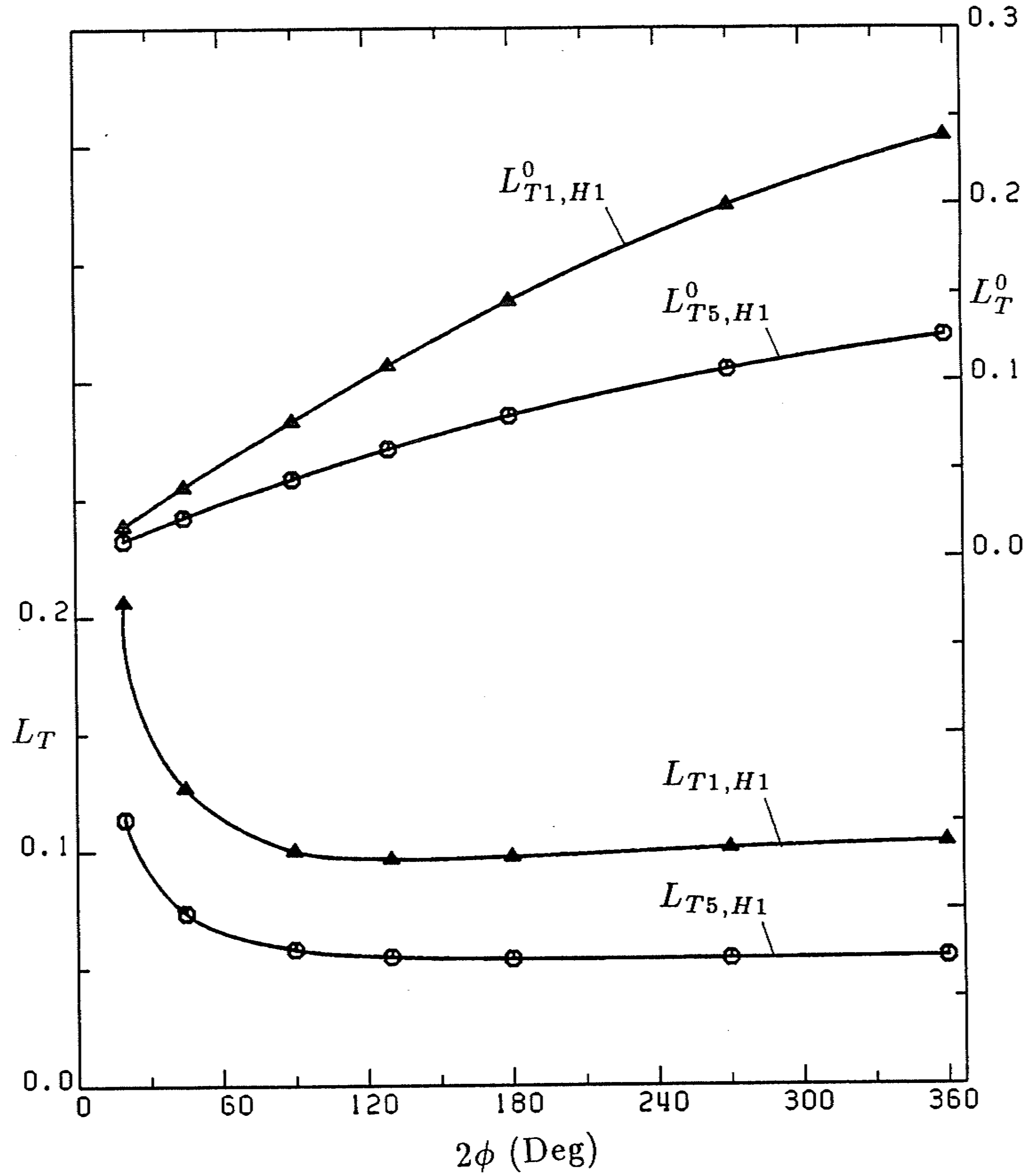


Figure 4.13: Thermal Entrance Lengths for the $H1$ Condition

360° (which forms a circular tube with one internal full fin) results in the largest thermal entrance length for each base, e.g., $L^0_{T5,H1} = 0.12583$. This value is still shorter than 0.17221 for a circular tube [101] which has no "corner effects" at all.

Figure 4.14 plots variations of the thermal entrance length with duct apex angle for the $H2$ condition. Again, L^0_T, rather than L_T, provides a better picture of the ϕ effect. Beyond $2\phi >\sim 45°$, corner effects diminish as the L^0_T values increase gradually with ϕ. It is noted that minima occur at $2\phi \approx 45°$ for $L^0_{T5,H2}$ and at $2\phi \approx 90°$ for $L^0_{T1,H2}$. Such behavior may be attributed to the $(Nu_{0,H2})_{fd}$ versus ϕ pattern which has a maximum value at $2\phi \approx 60°$, as shown in Fig. 4.8.

4.3 Remarks

In Sec. 4.1, successful predictions were obtained for steady, laminar, fluid flow in the hydrodynamic entrance region of circular sector ducts by numerically solving the three-dimensional momentum equations. The presented data covered the entire duct apex angle range and were shown to agree well with the limited published results. Four definitions were deliberately employed to determine the hydrodynamic entrance lengths. The apex angle effects on the pressure drop and the hydrodynamic entrance length were also carefully examined.

Section 4.2 presented numerical solutions of forced convection heat transfer for thermally developing laminar flow in circular sector ducts using the $H1$ and $H2$ conditions. It was observed that the apex angle influences heat transfer quantities differently for these two boundary conditions. Compared to $H2$, the $H1$ condition is thermally stronger hence resulting in higher heat transfer coefficients and shorter thermal entrance lengths. However, in the absence of buoyancy effects, real situations would generally lie between these two, e.g., for a duct with an electric resistance wiring heating. On the other hand, for the experimental investigation of combined laminar convection in a horizontal semicircular duct, the present analytical results will serve as lower boundaries for the data that will be presented in Chap. 6.

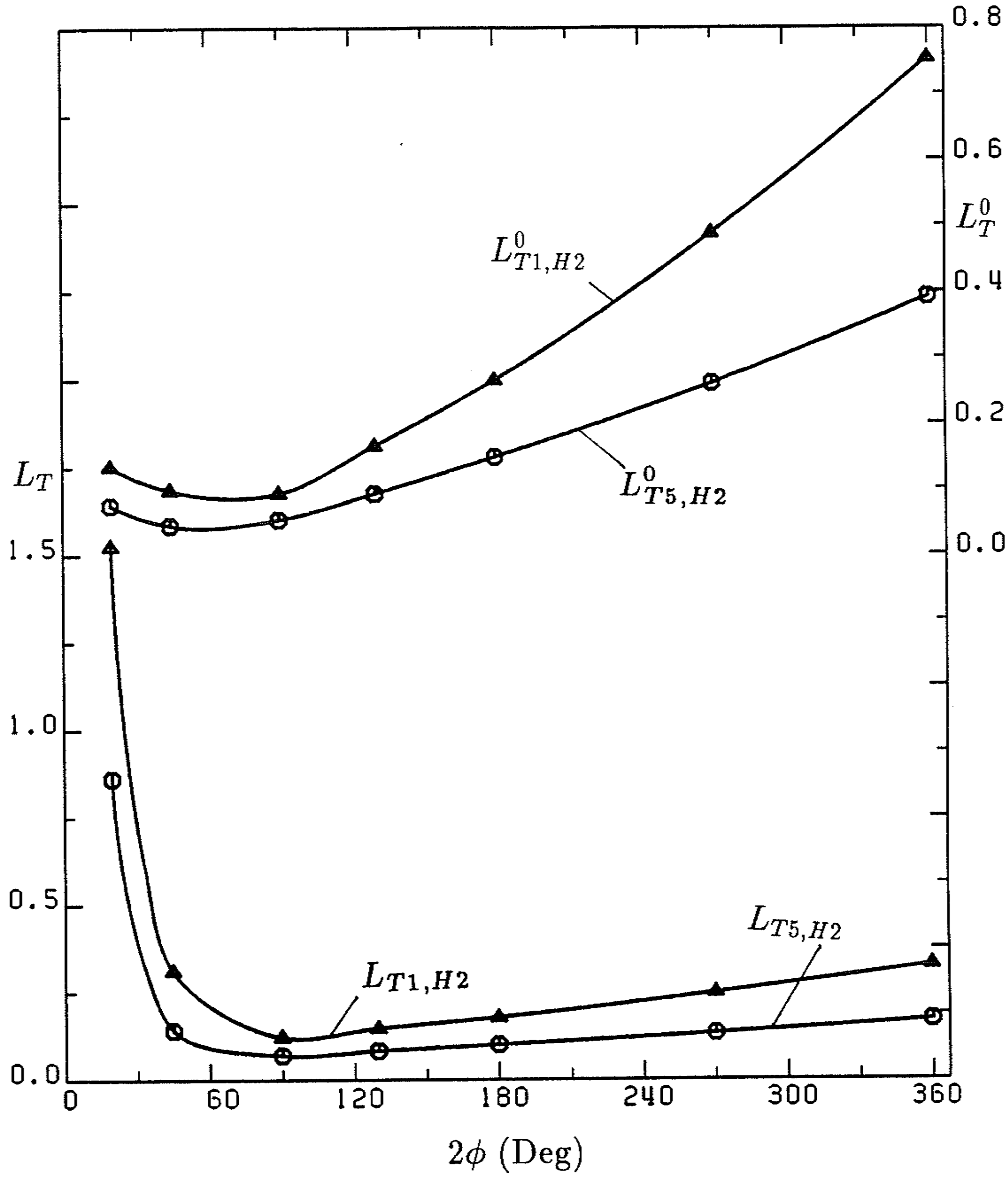


Figure 4.14: Thermal Entrance Lengths for the $H2$ Condition

Chapter 5

Predictions of Mixed Convection in a Horizontal Semicircular Duct

COMBINED free-forced convection flow and heat transfer in a horizontal semicircular duct are numerically analyzed in this chapter. The only new parameter that the present chapter will embrace is the thermogravitational force. The inclusion of this body force term makes it possible to simulate real flows in a much closer manner especially when they are subjected to significant temperature gradients. Unfortunately, the price for such a forward step results in highly coupled momentum and energy equations which therefore complicate computations.

The semicircular duct is considered for only one orientation, viz., the flat wall facing up. This orientation is the same as that used in the experimental set-up (as described in the next chapter). The cross section of the duct, together with the cylindrical coordinates (r, θ) and the staggered grid used in this analysis, is shown in Fig. 4.1. The analysis is confined to the thermal boundary condition of axially uniform heat input [1] with uniform peripheral wall temperature ($H1$). The symmetric steady flow is taken to be fully developed both hydrodynamically and thermally. Other assumptions are identified as follows:

1. laminar flow of a Newtonian fluid;

[1] *Only the case of heating of the fluid (i.e., hot wall) was considered.*

2. negligible viscous dissipation within the fluid;
3. constant properties except for the density contribution to the buoyant forces;
4. negligible axial diffusion of momentum and heat;
5. decoupled longitudinal and cross stream pressure gradients.

5.1 Mathematical Representation

With the above assumptions, the dimensional Navier-Stokes equation can be written in vector notation:

$$\vec{V} \bullet \nabla \vec{V} - \nu \nabla^2 \vec{V} = \frac{1}{\rho}\Big(-\nabla P + \rho \vec{g}\Big) \tag{5.1}$$

where $\vec{V}$ is the velocity vector, ∇ is the operator for the cylindrical coordinate system, P is the thermodynamic pressure, and $\vec{g}$ is the gravitational force vector.

The analysis employs the Boussinesq approximation to account for the density variation which contributes solely to the body force term. If the density ρ is a function of temperature t only, e.g., $\rho = \mathcal{F}(t)$, ρ can then be expanded in Taylor series form around a reference temperature (e.g., the wall temperature t_w), as

$$\rho = \mathcal{F}(t_w) + \frac{\partial \rho}{\partial t}(t - t_w) + \frac{1}{2!}\frac{\partial^2 \rho}{\partial t^2}(t - t_w)^2 + \frac{1}{3!}\frac{\partial^3 \rho}{\partial t^3}(t - t_w)^3 + \cdots \tag{5.2}$$

Taking the first degree approximation and introducing the thermal expansion coefficient at constant pressure ($\beta = -(1/\rho_w)(\partial \rho / \partial t)$) renders

$$\rho = \rho_w - \rho_w \beta (t - t_w) \tag{5.3}$$

Substituting equation (5.3) into the $\rho \vec{g}$ term only and then deleting the subscript $_w$ for ρ (constant property assumption), equation (5.1) thus becomes

$$\vec{V} \bullet \nabla \vec{V} - \nu \nabla^2 \vec{V} = -\frac{\nabla P}{\rho} + \vec{g} - \vec{g}\beta(t - t_w) \tag{5.4}$$

where the last term in the right-hand side is the buoyant force. Referring to Fig. 4.1, the $\vec{g}$ vector can be expressed by

$$\vec{g} = \{g_R,\ g_\theta,\ g_X\} = \{g\,sin\theta,\ g\,cos\theta,\ 0\} \tag{5.5}$$

It is worthwhile to note that, for a more general case such as for a horizontal circular sector duct whose seating position varies with a rotation angle α, the $\vec{g}$ vector may be defined by $\vec{g} = \{g\,sin(\theta-\alpha),\ g\,cos(\theta-\alpha),\ 0\}$. Similarly, for an inclined duct, this vector can be correspondingly modified.

Now, using equation (5.5), the radial component of the right-hand side of equation (5.4) can be written as

$$-\frac{1}{\rho}\frac{\partial}{\partial R}(P - \rho g R\,sin\theta) - g\beta(t - t_w)sin\theta$$

where $\rho g R\,sin\theta$ represents a static pressure referenced to the flat wall of the duct. Similarly, the tangential component is

$$-\frac{1}{\rho}\frac{\partial}{R\partial\theta}(P - \rho g R\,sin\theta) - g\beta(t - t_w)cos\theta$$

The pressure decoupling is implemented by setting $P(R,\theta,X) = P'(R,\theta) + \bar{P}(X)$, where $P'(R,\theta) = P - \rho g R\,sin\theta$. Thus, the fully developed condition simply gives

$$\frac{\partial U}{\partial X} = \frac{\partial V}{\partial X} = \frac{\partial W}{\partial X} = 0, \quad \frac{\partial P}{\partial X} = \frac{d\bar{P}}{dX} \tag{5.6}$$

$$\frac{\partial t}{\partial X} = \frac{\partial t_m}{\partial X} = \frac{\partial t_w}{\partial X} = \frac{2q'}{\rho c_p \bar{W} \pi R_0^2} \tag{5.7}$$

in which the constant q' is the rate of heat transfer to the fluid per unit axial length. As the last step, dimensionless variables and parameters are introduced as follows:

$$r = \frac{R}{R_0} \qquad u^+ = \frac{UR_0}{\nu} \qquad v^+ = \frac{VR_0}{\nu} \qquad w = \frac{W}{\bar{W}}$$

$$T^+ = \frac{t_w - t}{q'/k} \qquad p^+ = \frac{P'R_0^2}{\rho\nu^2} \qquad Re = \frac{\rho\bar{W}D_h}{\mu} \qquad f = \frac{(-d\bar{P}/dX)D_h}{2\rho\bar{W}^2}$$

and, the modified Grashof number Gr^+ and the Prandtl number Pr are defined by

$$Gr^+ = \frac{\beta g q' R_0^3}{\nu^2 k} \qquad Pr = \frac{\mu c_p}{k}$$

Using these variables, the equations for mass conservation, momentum conservation, and energy conservation can be written in the following nondimensional form

Continuity

$$\frac{1}{r}\frac{\partial}{\partial r}(ru^+) + \frac{1}{r}\frac{\partial v^+}{\partial \theta} = 0 \tag{5.8}$$

Radial momentum

$$\begin{aligned}\frac{1}{r}\frac{\partial}{\partial r}(ru^+u^+) + \frac{1}{r}\frac{\partial}{\partial \theta}(v^+u^+) &= \frac{1}{r}\frac{\partial}{\partial r}(2r\frac{\partial u^+}{\partial r}) + \frac{1}{r}\frac{\partial}{\partial \theta}(\frac{1}{r}\frac{\partial u^+}{\partial \theta}) \\ -\frac{\partial p^+}{\partial r} + \frac{1}{r}\frac{\partial}{\partial \theta}(\frac{\partial v^+}{\partial r}) &- \frac{3}{r^2}\frac{\partial v^+}{\partial \theta} - \frac{2u^+}{r^2} + \frac{v^{+2}}{r} + Gr^+T^+ sin\theta\end{aligned} \tag{5.9}$$

Angular momentum

$$\begin{aligned}\frac{1}{r}\frac{\partial}{\partial r}(ru^+v^+) + \frac{1}{r}\frac{\partial}{\partial \theta}(v^+v^+) &= \frac{1}{r}\frac{\partial}{\partial r}(r\frac{\partial v^+}{\partial r}) + \frac{1}{r}\frac{\partial}{\partial \theta}(\frac{2}{r}\frac{\partial v^+}{\partial \theta}) \\ -\frac{1}{r}\frac{\partial p^+}{\partial \theta} + \frac{1}{r}\frac{\partial}{\partial r}(\frac{\partial u^+}{\partial \theta}) &+ \frac{3}{r^2}\frac{\partial u^+}{\partial \theta} - \frac{v^+}{r^2} - \frac{u^+v^+}{r} + Gr^+T^+ cos\theta\end{aligned} \tag{5.10}$$

Axial momentum

$$\frac{1}{r}\frac{\partial}{\partial r}(ru^+w) + \frac{1}{r}\frac{\partial}{\partial \theta}(v^+w) = \frac{1}{r}\frac{\partial}{\partial r}(r\frac{\partial w}{\partial r}) + \frac{1}{r}\frac{\partial}{\partial \theta}(\frac{1}{r}\frac{\partial w}{\partial \theta}) + \frac{(\pi+2)^2}{2\pi^2} fRe \tag{5.11}$$

Energy

$$\frac{1}{r}\frac{\partial}{\partial r}(ru^+T^+) + \frac{1}{r}\frac{\partial}{\partial \theta}(v^+T^+) = \frac{1}{Pr}\Big(\frac{1}{r}\frac{\partial}{\partial r}(r\frac{\partial T^+}{\partial r}) + \frac{1}{r}\frac{\partial}{\partial \theta}(\frac{1}{r}\frac{\partial T^+}{\partial \theta})\Big) + \frac{2}{\pi Pr}w \tag{5.12}$$

This results in a highly coupled system involving the five variables u^+, v^+, w, p^+, and T^+ and two control parameters Gr^+ and Pr. No boundary conditions for p^+ are needed because of the use of the staggered grid. Other explicit boundary conditions are

$$u^+ = v^+ = w = T^+ = 0 \qquad \text{at walls} \tag{5.13}$$

and

$$\frac{\partial u^+}{\partial \theta} = \frac{\partial w}{\partial \theta} = \frac{\partial T^+}{\partial \theta} = v^+ = 0 \text{ at the symmetry line } \theta = \pi/2,\ 0 < r < 1 \quad (5.14)$$

In addition, the axial pressure gradient or fRe must be corrected by conservation of mass, the dimensionless form of which is

$$\int_0^{\frac{\pi}{2}} \int_0^1 w \ r dr d\theta = \frac{\pi}{4} \quad (5.15)$$

The average Nusselt number, based on hydraulic diameter D_h, is given by

$$Nu = \frac{\bar{h} D_h}{k} = \frac{2\pi}{(\pi+2)^2} \frac{1}{T_m^+} \quad (5.16)$$

where T_m^+ is the bulk mean fluid temperature defined as

$$T_m^+ = \frac{4}{\pi} \int_0^{\frac{\pi}{2}} \int_0^1 w \ T^+ \ r dr d\theta \quad (5.17)$$

5.2 Computing Technique and Solution Accuracy

A uniform staggered grid of Fig. 4.1 on the cross stream plane was utilized to discretize the governing partial differential equations. Fully implicit formulations were performed by using the control volume integration finite difference method. Coefficients relating to the convection-diffusion terms in the discretization equations were incorporated by the power-law scheme. To slow down the changes in the values of the dependent variable from iteration to iteration, an underrelaxation factor ($0.1 \leq URF \leq 1$) was inserted in each momentum discretization equation.

The SIMPLER algorithm of Patankar [28] was then used to solve these coupled, nonlinear, and discretized equations. Starting with the guessed velocity and temperature fields, the cross stream pressure distribution for p^+ was first estimated through the continuity equation. Then, the equations for u^+ and v^+ were solved simultaneously. The next step was to compute w, while ensuring the satisfaction of the overall mass conservation of equation (5.15). After the local continuity or the mass source was checked, if unsatisfied, the solution of the pressure correction equation was obtained to correct the cross stream velocities. Next, the T^+ distribution was obtained and the following criteria were examined:

1. All absolute differences between the current iterative values and the previous iterative results were not greater than 10^{-5} at all nodal points.
2. The "mass source" term (checking the local continuity) in each control volume was smaller than 10^{-5} in magnitude.
3. The absolute value of the fRe correction (checking the overall mass balance) was also smaller than 10^{-5}.

In each run, for the given values of Gr^+ and Pr, iterations were continued until all these convergence criteria were satisfied. During the iterations, the most recent values of the dependent variables were used to update continually the coefficients of each discretization equation. All algebraic equations for u^+, v^+, w, and T^+ were solved by a line-by-line iterative technique through the tridiagonal-matrix algorithm (TDMA). However, the distributions of p^+ and the p^+ correction were noniteratively obtained using a band storage linear equation solver. Similar to the descriptions in Sec. 4.1.2, this modification of the algorithm was also numerically verified for the present problem.

Decisions on the cross-sectional mesh sizes were mainly guided by solving the axial momentum and energy equations for $Gr^+ = 0$. Table 5.1 presents three mesh sizes and the corresponding numerical results of $(fRe)_{fd,0}$ and $(Nu_{H1,fd})_0$, where the subscript $_0$ indicates the value for the zero Gr^+ number. As shown in the table, with increasing the grid (r, θ) lines from 18×20 to 30×40, the relative difference between the numerical result and the exact value reduces from 1.3% to 0.5% for $(fRe)_{fd,0}$ and from 0.2% to 0.1% for $(Nu_{H1,fd})_0$. As a compromise between accuracy and computing time, the grid of 20×25 was selected since it appears to be adequate for

Table 5.1: Mesh Size and Results for $Gr^+ = 0$

$r \times \theta$	$(fRe)_{fd,0}$		$(Nu_{H1,fd})_0$	
	Numerical	Exact [103]	Numerical	Exact [99]
18 ×20	15.5558	15.7668	4.0967	4.0880
20 ×25	15.5992	15.7668	4.0956	4.0880
30 ×40	15.6922	15.7668	4.0922	4.0880

the problem under consideration. With this grid, Fig. 5.2a shows close agreement between the exact results and the corresponding numerical values of w and T^+ at the symmetry plane $\theta = \phi$ for $Gr^+ = 0$. Near the boundaries, the differences are relatively large but always within 2% for w and within 4% for T^+. In addition, by examining all nodal values at the cross section, absolute differences between the numerical result and the exact value average 0.7% for w and 1.6% for T^+.

It is appropriate to remark here that, like other schemes, the power-law scheme may numerically generate a fictitious or false diffusion coefficient for multidimensional problems. This is of special concern when the flow is oblique to the grid lines and a nonzero gradient of the dependent variable in the direction normal to the flow is presented. de Vahl Davis [30] has demonstrated that the use of finer grids can reduce such a possible parasitic effect in numerical analyses. In view of this, the 30×40 grid might be a more suitable (but less affordable) choice for this problem. However, the study of the velocity fields obtained from preliminary tests suggested that the secondary flows are most pronounced near the curved wall of the semicircular duct and they generally align with the tangential curved grid lines (e.g., see Fig. 5.8a). This indicates that the false diffusion in the present numerical analysis is significantly reduced by orienting the θ-grid lines to be parallel with the curved wall. Furthermore, since the real diffusion is significant in this problem, the false diffusion was estimated (using the equation in [30]) to be small in comparison with the real diffusion.

In addition, confidence in the use of the 20×25 grid was provided by comparing the values numerically generated with this grid to the published results of Nandakumar *et al.* [61] (they used the (r, θ) grid of 21×21) for a mixed convection problem but for the flat section of the semicircular duct at the bottom. For $Pr = 5$ and $Gr^+ = 10^4$, 6×10^4, and 10^5, the present Nu/Nu_0 values of 1.156, 1.508, and 1.642 correspondingly agreed well with the figure-read values of 1.14, 1.49, and 1.63 in [61]. It must be pointed out that this comparison is valid only at low Gr^+ since duct orientation should has little effect on Nu values when the secondary flow is weak.

To further confirm the present numerical accuracy, the above solution procedurces [2], still with the 20×25 grid, were used to directly produce the results of Nandakumar *et al.* [61]. For $Pr = 5$ and $Gr^+ = 10^4$, 10^5, and 10^6, the present Nu/Nu_0 values of 1.156, 1.640, and 2.477 correspondingly agreed well (within 5%) with the figure-read values of 1.14, 1.63, and 2.35 in [61]. Better agreement for the corresponding fRe/fRe_0 values was found to be within 1%.

5.3 Numerical Results

Two control parameters embedded in equations (5.8) to (5.12) are the modified Grashof number Gr^+ and the Prandtl Pr. Since one of the main goals of this study was to provide numerical data which might be compared to the experimental results for water flow, the Pr values of 5 and 3 were of primary concern. However, results for $Pr = 0.7$ and $Pr = 20$ will also be presented. Regarding Gr^+, the converged solutions for each Pr were continuously achieved till Gr^+ up to 2×10^8 which is about the upper value reached in the experiment.

[2] *The computer program in Appendix B contains a geometry parameter, i.e., the duct seating angle. The present solutions correspond to the angle of 0°. When the angle is 180°, the flat section of the semicircular duct is at the bottom.*

5.3.1 Typical Dual Solutions

Typical influence of Gr^+ on the fully developed friction factor ratios and Nusselt number ratios is illustrated in Fig. 5.1. The forced convection values of $(Nu_{H1,fd})_0$ and $(fRe)_{fd,0}$ are given in Table 5.1 for the (r, θ) grid of 20×25. As the dual solutions (e.g., two values of $(fRe)_{fd}$ or $Nu_{H1,fd}$ for a given Gr^+) are displayed, it is interesting to release the details of the computing procedures. Initially, the distributions of temperature and axial velocity for $Gr^+ = 0$ were used as input to find the solutions for a nonzero Gr^+ , say 10^3. To accelerate convergence, it was now advantageous to obtain the starting values of u^+, v^+, w, T^+, and fRe for the next higher Gr^+ (e.g., $Gr^+ = 5 \times 10^3$) by extrapolating the converged solutions for the preceding two lower values of Gr^+ . This was especially necessary for $Gr^+ > 10^6$. Also, as shown in Fig. 5.1 for $Gr^+ > 10^6$, the Nu and fRe ratios increased sharply with Gr^+ , whereas the computing time required to secure convergence was similarly found to increase markedly with Gr^+ .

Unlike the results reported by Nandakumar *et al.* [61], the upper critical point for the two- to four-vortex transition was never found throughout this study. For a given low Gr^+ , the solution procedures described earlier were able to secure a converged solution with a two-vortex flow pattern. Starting with this two-vortex solution for the next higher Gr^+ (e.g., $Gr^+ = 10^7$), a four-vortex flow pattern was obtained with a slight underrelaxation (say, $URF = 0.8$ for u^+ and v^+). But, by using a heavier underrelaxation (say, $URF = 0.4$ for u^+ and v^+), the same two-vortex flow pattern could be preserved at the higher Gr^+ . Furthermore, an increase in Gr^+ could result in either a two-vortex or four-vortex solution, depending on the initial conditions. If the starting values were taken from a two-vortex solution, a new converged solution with two vortices was obtained. On the other hand, the input of a four-vortex solution converged to a solution for next Gr^+ with four vortices. In this way, gradual increase in Gr^+ up to 2×10^8 or higher did produce

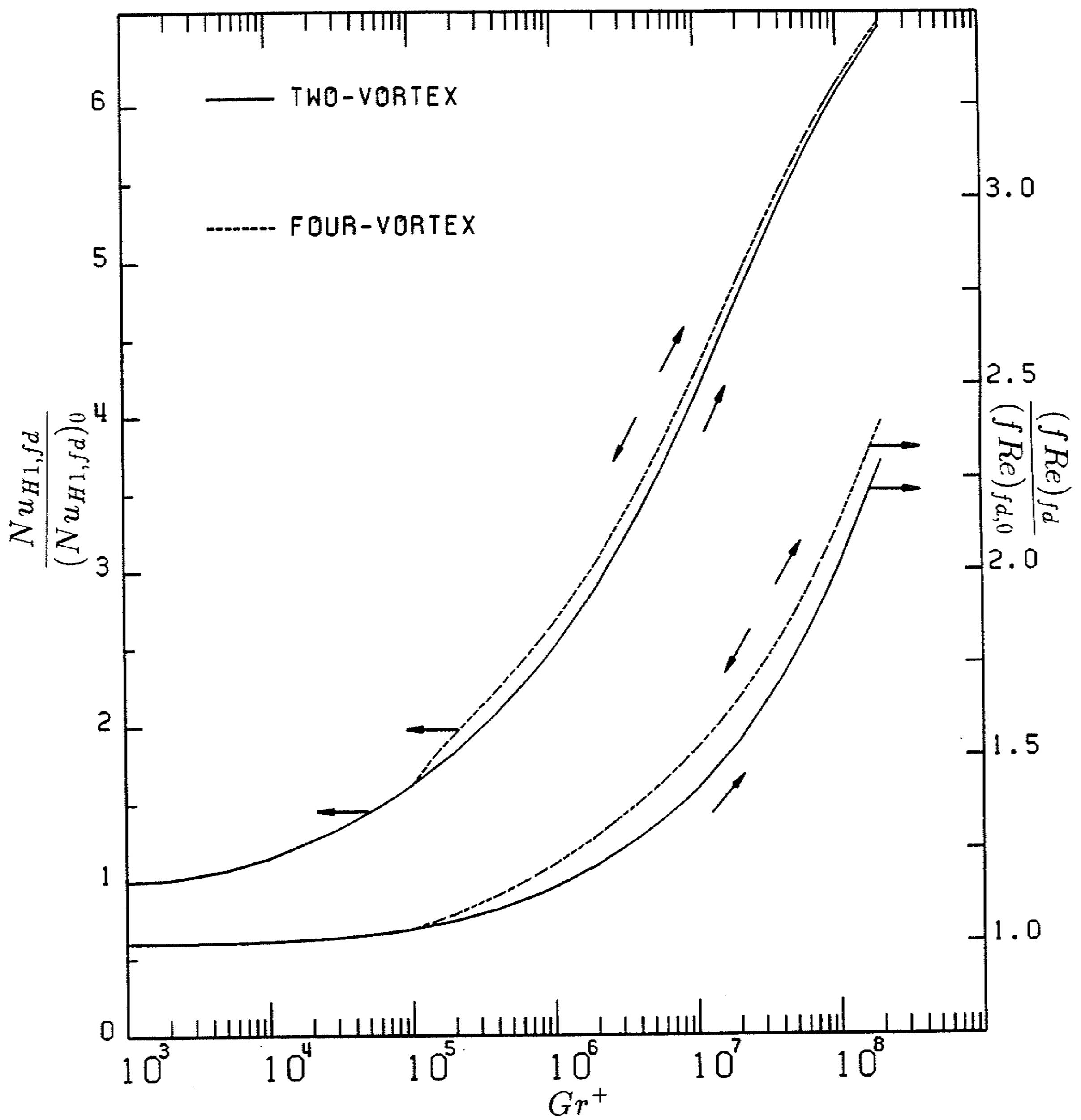


Figure 5.1: Typical Effects of Gr^+ on Friction Factor and Heat Transfer ($Pr = 5$)

the dual converged solutions. Even though the differences between the two-vortex result and the four-vortex result decreased with increasing Gr^+ (Fig. 5.1), the upper critical point (where the two vortices bifurcate and are replaced for higher Gr^+ by four vortices) did not appear to exist. However, decreasing Gr^+ from a four-vortex solution did encounter the lower critical point of bifurcation. For example, for $Pr =$ 5, if calculations were begun with a converged four-vortex solution for lower Gr^+ , a four-vortex solution resulted for lower Gr^+ and this persisted until $Gr^+ \approx 1.25 \times 10^5$. At about this Gr^+ , the transition to the two-vortex result was observed.

The dual solution pattern of Fig. 5.1 is consistent with a recent numerical report by Maughan and Incropera [110] who studied laminar mixed convection with longitudinal fins in a horizontal parallel plate channel. Their multiple solutions were found by prescribing different initial conditions. For instance, for their defined Rayleigh number $Ra = 10^4$, initializing calculations at $Ra = 0$ resulted in a three-vortex solution. However, treating the last converged two-vortex solution as an initial condition, gradually increasing Ra to 10^4 generated a solution with an unchanged two-vortex flow pattern. The first routine indicated that the secondary flow, while set to zero at the beginning, was allowed to vary *substantially.* On the other hand, the latter suggested that the prescribed *nonzero* velocity fields let the new cross stream vortices be formed *gradually.* Clearly, these routines are similar to the underrelaxation techniques which were applied in the present study. Therefore, the consistent outcomes are indeed expected.

A question that may arise now is how the dual solutions occur. For the case of the semicircular duct, the two-vortex flow corresponds to a downward cross stream velocity at the lowest generatrix of the duct (see Fig. 5.6a). As the Gr^+ number *incrementally* becomes high enough, say 10^7, the flow undergoes considerable changes from the initial condition to the same one but plus a large increment. The increment in heat flux not only destabilizes the initial thermal boundary layer, but also magnifies the cross stream velocities near the duct bottom. When the secondary flow grows in size, its inital vortex pattern is also reformed in response to the significant thermal instability which originates from the lowest generatrix. During such changes, before a steady state is physically reached [3], the directions of the cross stream velocities near the duct bottom may be subjected to an alternation due to the thermal instability. For instance, the velocity at the lowest generatrix may be downward or upward. The downward velocity causes the warmer fluid to rise nearly along the curved wall and the two-vortex flow results (Fig. 5.8a). The upward velocity, on the other hand, changes by continuity the directions of the velocities in its neighborhood. Consequently, the warmer fluid near the bottom ascends approximately along the symmetric plane of the duct (see Fig. 5.9a) and the transition to the four-vortex form takes place. Based on these observations, reducing the increment of the cross stream velocities or numerically using the underrelaxation technique (as done in the present study) or approaching gradually the converged solution (as done in [110]) should all suppress the alternation of the velocity vector and hence the initial flow pattern (i.e., a two- or four-vortex flow pattern) can be preserved. Otherwise, the direction of the velocity vector at the lowest generatrix and the path of the rising warmer fluid will alter and, therefore, the secondary flow pattern transition (i.e., from two- to four-vortex form) is anticipated.

The dual solution pattern of Fig. 5.1 is also similar to the heat transport measurement of Walden *et al.* [111] who observed multiple cellular patterns for pure free convection in a rectangular container. However, the profuse multiplicity or anomalous mode behaviour in mixed free-forced convection has not yet been verified experimentally.

[3] *The present solution for the governing equations was assumed to be* steady. *In reality, when subjected to significant buoyancy effects, it is possible that the flow exhibits a steady-periodic behavior rather than an entirely time-invariant one. A numerical and/or experimental examination of this matter is beyond the scope of the present work. However, laboratory observations by the present author did reveal some degree of fluctuation on data readings.*

5.3.2 Effect of the Grashof Number at a Constant Pr

The influence of the modified Grashof number Gr^+ on the fully developed results is explored next. To exclude the Pr effect, results only for $Pr = 3$ will be discussed, however trends were the same for varying Gr^+ at other fixed Pr.

5.3.2.1 Secondary Flow, Axial Velocity, and Temperature for Varying Gr^+

To assess buoyancy effects on a mixed convection flow, it is useful first to consider the limiting case of pure forced convection. At $Gr^+ = 0$, there exist no cross stream velocities of u^+ and v^+ due to the absence of buoyant force. Numerical solutions of temperature T^+ and the axial velocity w can be thus directly validated by comparison to the exact results as was done in Fig. 5.2a and discussed earlier in Sec. 5.2. Contours of these numerical results for T^+ and w that are shown in Fig. 5.2b are seen to be fairly smooth and uniform, indicating no cross-stream flow. The maximum T^+ value of 0.099 and the maximum w value of 2.061 are approximately located by the labels of "T^+" and "w" where they can be respectively interpreted as the coldest spot and the highest axial momentum in the duct. In this case, the expected same location indicates the absence of free convection effect.

With the presence of buoyancy, the warmer and lighter fluid near the duct bottom, which is unstable and beneath the cooler and heavier core fluid, provides a source of vorticity for the cross-stream flow. Fig. 5.3a depicts, for $Gr^+ = 10^4$, these cross-stream velocity vectors (which are the resultants of u^+ and v^+). The scale above the vector plot (e.g., 2.80 in Fig. 5.3a) gives both the scale and the maximum resultant. As can be seen, the secondary flow, which is superimposed on the main flow, is symmetric and contains a pair of counter-rotating vortices. This results in the warmup of the core fluid as shown in Fig. 5.3b for reduction in T^+ (compared to Fig. 5.2b). Contours of Fig. 5.3b are apparently shifted down, particularly for

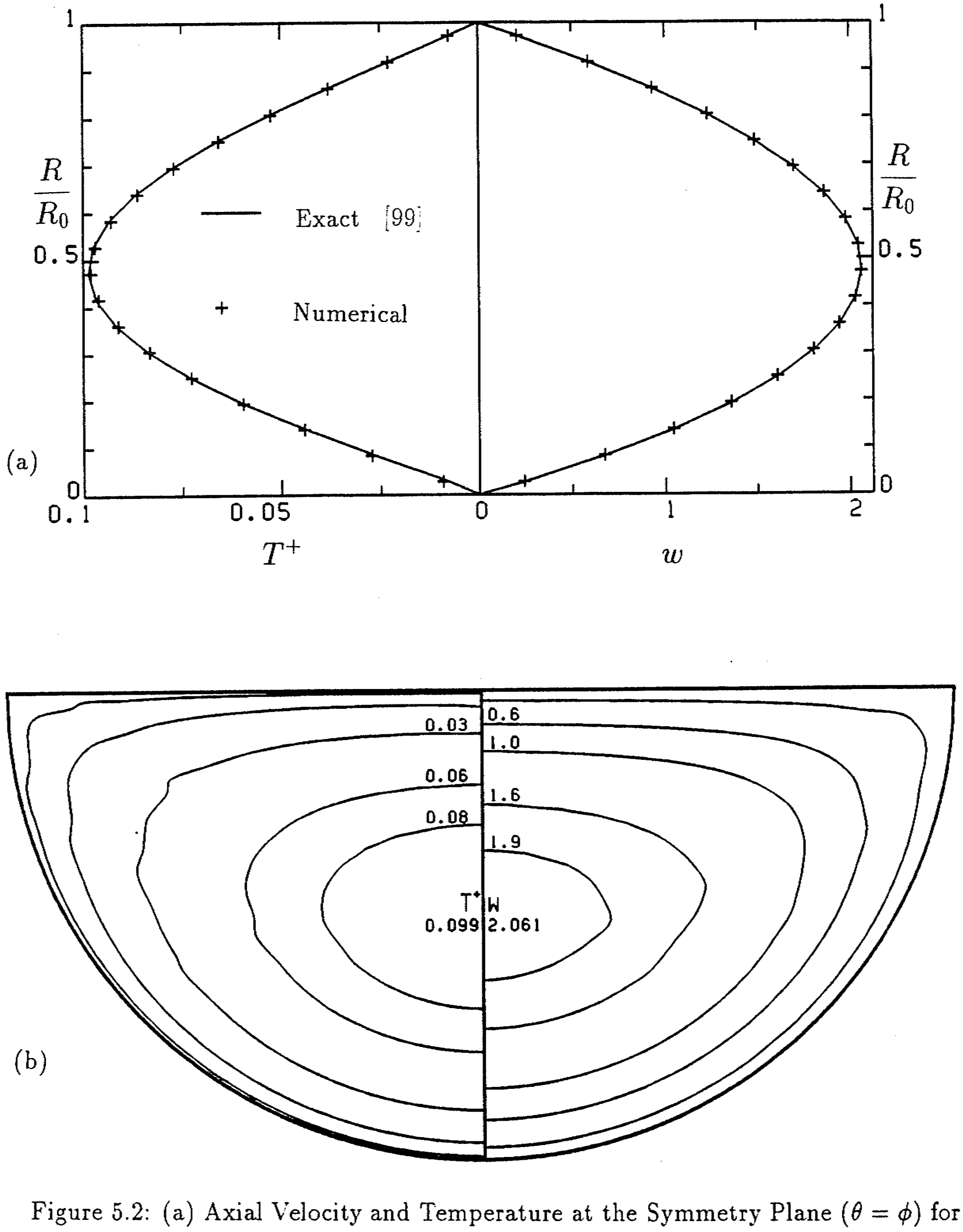


Figure 5.2: (a) Axial Velocity and Temperature at the Symmetry Plane ($\theta = \phi$) for $Gr^+ = 0$ (b) Contours of Temperature and Axial Velocity for $Gr^+ = 0$

T^+ due to the direct influence of free convection heat transfer. The lowering of the isotherms suggests the thinning of the bottom thermal boundary layer and the thickening of the top thermal boundary layer, thereby enhancing and reducing heat transfer, respectively. Also, buoyancy effects cause the positions of the coldest spot ("T^+") and of the maximum axial momentum ("w") to move down vertically from the place for $Gr^+ = 0$.

As Gr^+ increases, the strengthened two vortices and the further depressed contours can be observed from Fig. 5.4 for $Gr^+ = 10^5$. Compared to the ones of Fig. 5.3a, the centres of vortices in Fig. 5.4a have moved closer to the curved wall. This is in agreement with the air flow visualization done by Mori and Futagami [16] who reported a pair of symmetrical vortices in a circular tube. Also, note that the top isotherms display an increasing degree of stratification with increasing Gr^+, revealing that heat transfer coefficients along the top wall are fairly constant. By contrast, the isotherms near the curved wall reflect a gradient variation with θ, thus producing suitable conditions for a secondary instability.

The four-vortex flow pattern for $Gr^+ = 2 \times 10^5$ is illustrated in Fig. 5.5a where two extra smaller vortices appear just beside the symmetry plane. As discussed before, the upward velocity at the lowest generatrix is an indicator of four vortices. The heated unstable fluid in this region encourages the flow to bifurcate into a multiple eddy structure. This time there are four eye-like pupils within which the fluid has low cross-sectional momentum. The two upper pupils can be seen to move further toward the curved wall near which the velocities of the rising warmer fluid are relatively large. As shown in Fig. 5.5b, the two lower vortices obviously carry the coldest fluid down and away from the central plane. A similar effect on the fluid with the highest axial momentum is also evident. Contours of T^+ and w (especially isotherms) are shown to be dense at $\theta \approx 75°$ near the curved wall, implying in this region a significant increase in thermal gradients and in wall-fluid shear stresses. However, the contours adjacent to the lowest generatrix rise up and become sparse.

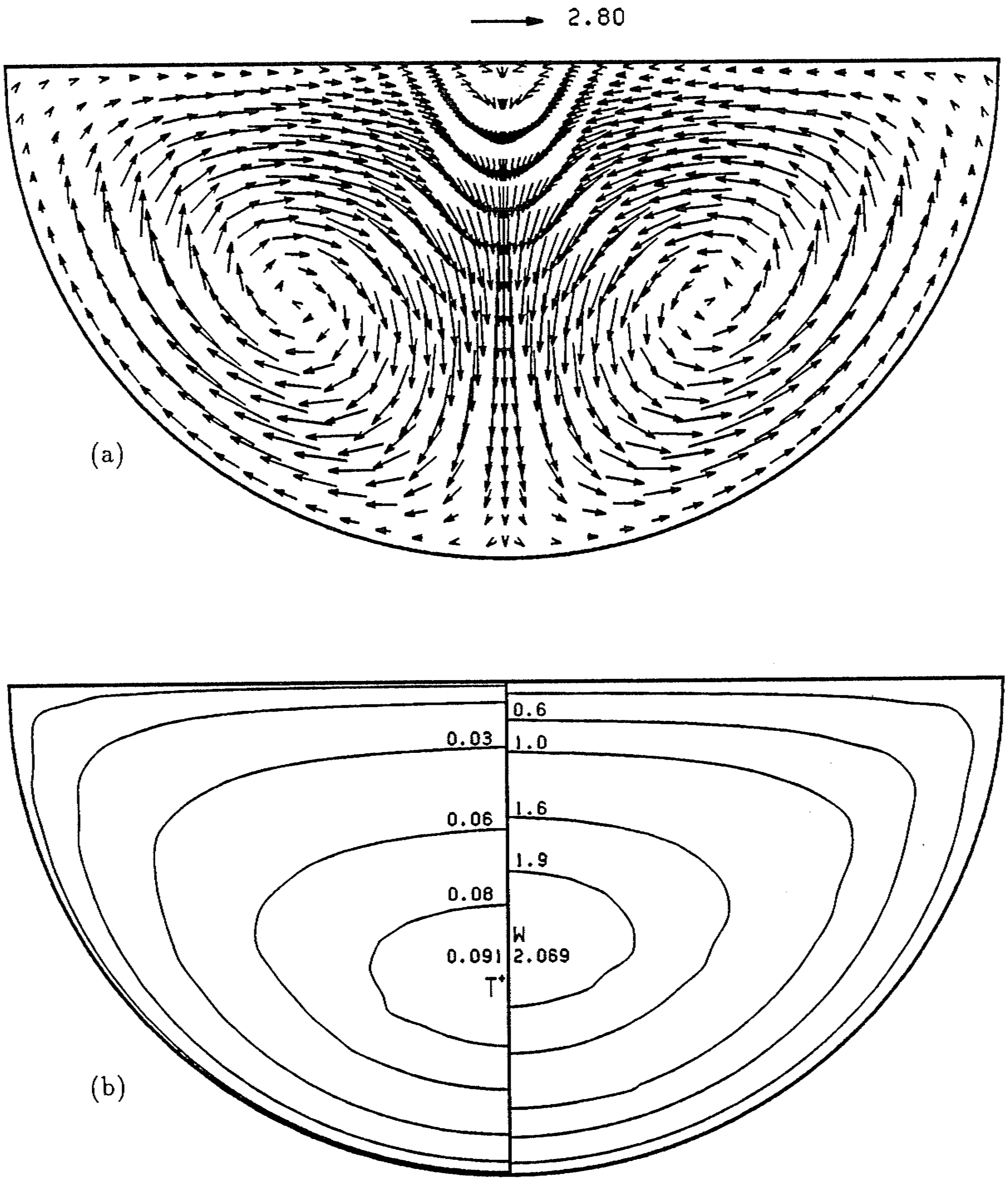


Figure 5.3: Two-Vortex Results for $Gr^{+} = 10^{4}$ and $Pr = 3$. (a) The Secondary Flow (b) Contours of Temperature and Axial Velocity

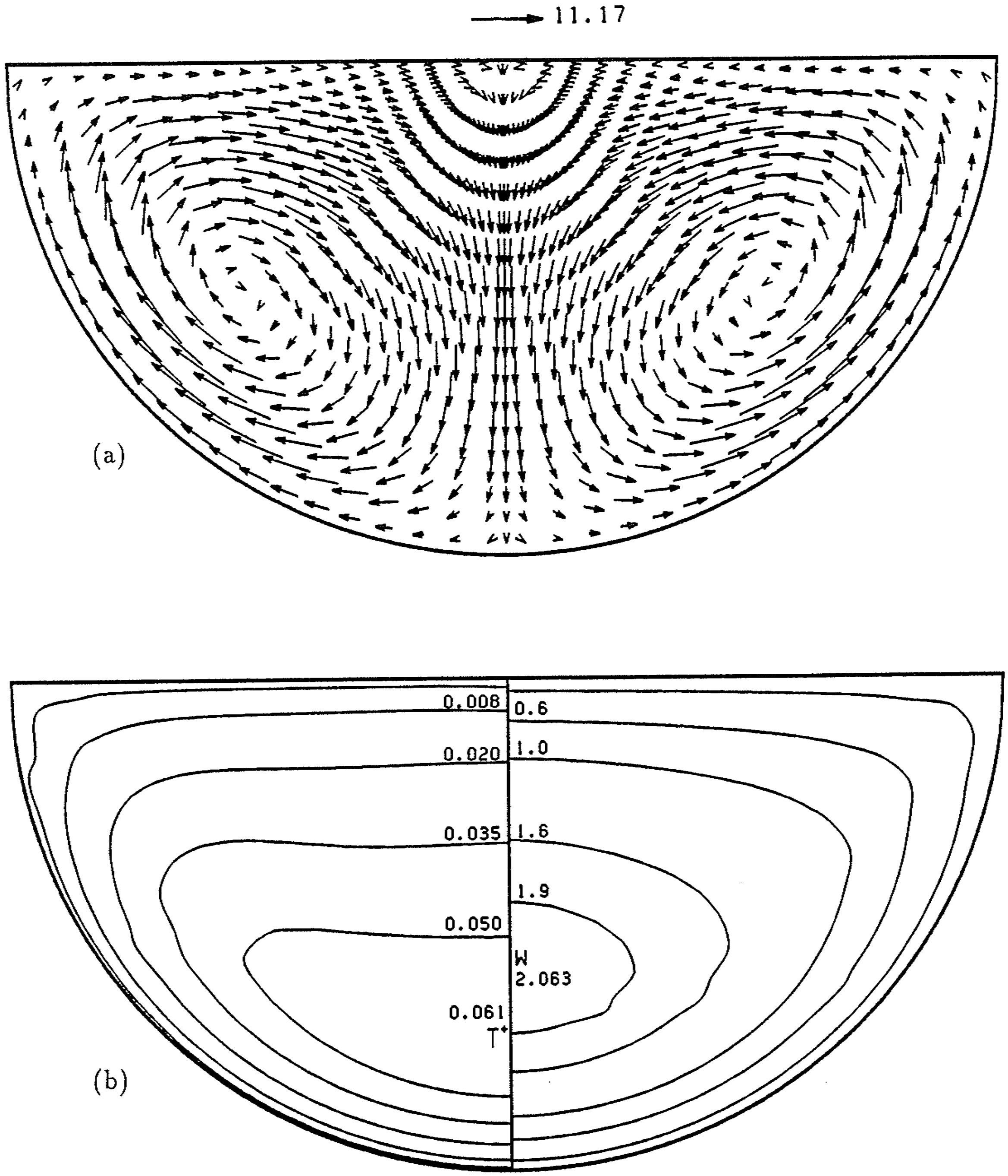


Figure 5.4: Two-Vortex Results for $Gr^+ = 10^5$ and $Pr = 3$. (a) The Secondary Flow (b) Contours of Temperature and Axial Velocity

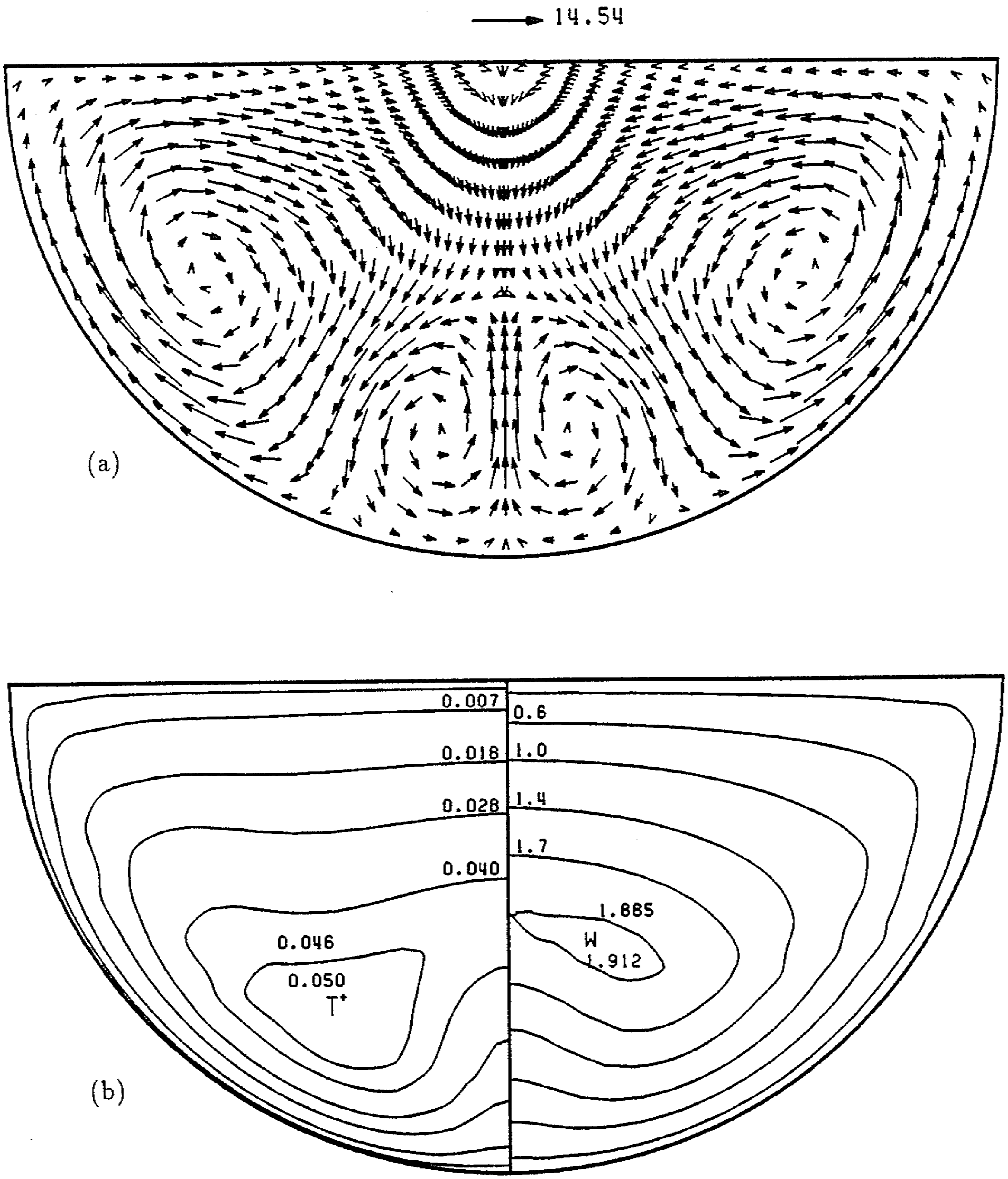
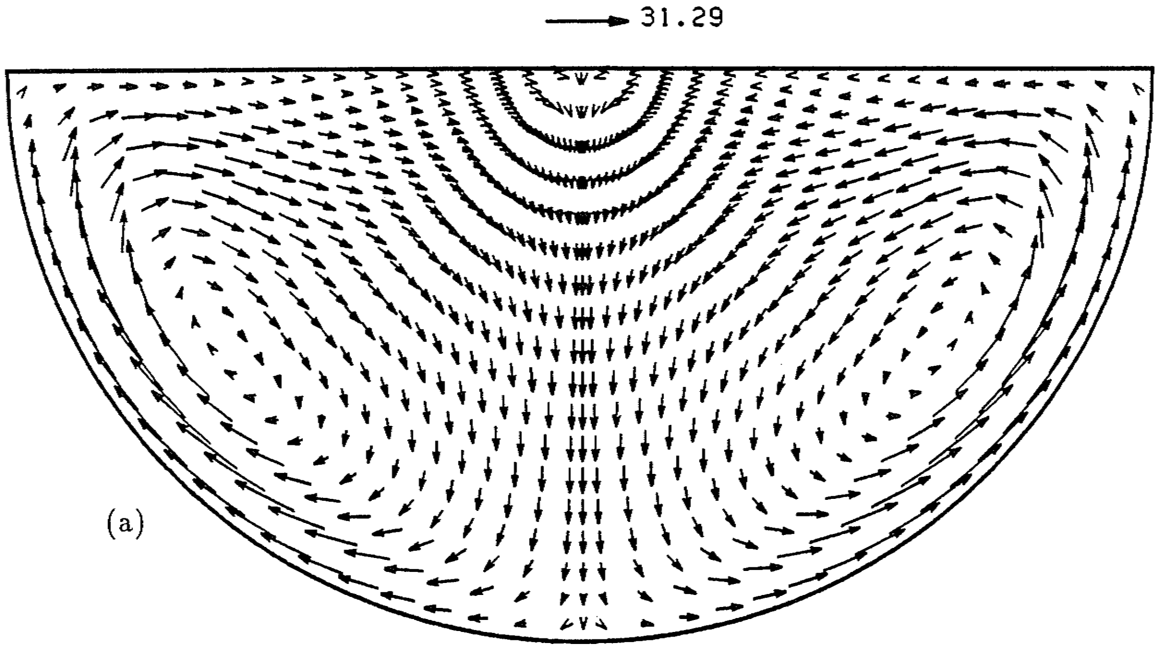


Figure 5.5: Four-Vortex Results for $Gr^+ = 2 \times 10^5$ and $Pr = 3$. (a) The Secondary Flow (b) Contours of Temperature and Axial Velocity

Results for the two-vortex and four-vortex flow structures at $Gr^+ = 10^6$ are plotted in Figs. 5.6 and 5.7. Firstly, contrasted with the velocities shown in Fig. 5.4a, the two-vortex flow in Fig. 5.6a is significantly magnified, with the maximum cross-stream velocities (from 11.17 to 31.29) occurring approximately on the same position ($r \approx 0.92$ and $\theta \approx 41°$). The two counter-rotating eddies continue to depress the contours of Fig. 5.6b, including lowering the positions of "T^+" and "w". Secondly, contrasted with the result of Fig. 5.5a, the maximum cross-stream velocity (33.71) in Fig. 5.7a occurs at the symmetry plane and the sizes of the two lower vortices are clearly enlarged. This indicates that for $Gr^+ = 10^6$ the increased buoyancy force is most pronounced near the duct bottom. Contours in Fig. 5.7b become more distorted compared to the ones of Fig. 5.5b. The coldest spot and the highest axial momentum continue to move down. Next, comparing these two different flow structures but with the same Grashof number in Figs. 5.6 and 5.7, several trends are apparent. The two-vortex flow only depresses its contours (Fig. 5.6b) while the four-vortex flow drives the coldest spot and the highest axial momentum down as well as away from the central plane, hence breaking up some contours (Fig. 5.7b) into a multiple closed map in each symmetric region. A climb on the bottom isotherms is also seen from Fig. 5.7b to match with the rising warmer fluid along the symmetry plane (Fig. 5.7a). This extra path for the rising warmer fluid provides a more powerful mechanism for heat transfer, e.g., resulting in a marked reduction in T^+ (see Figs. 5.6b and 5.7b). Similarly, a reduction in w also reveals an augmentation for flow resistance.

For a further increase of Gr^+, say 10^7, the two-vortex and four-vortex results shown in Figs. 5.8 and 5.9 comparatively keep the same trends as those previously disclosed. Some further observations are as follows. Since the cores of two upper eddies always tend to move toward the curved wall as Gr^+ increases, the phenomenon appears analogous to the effect of centrifugal force. This results in substantially large



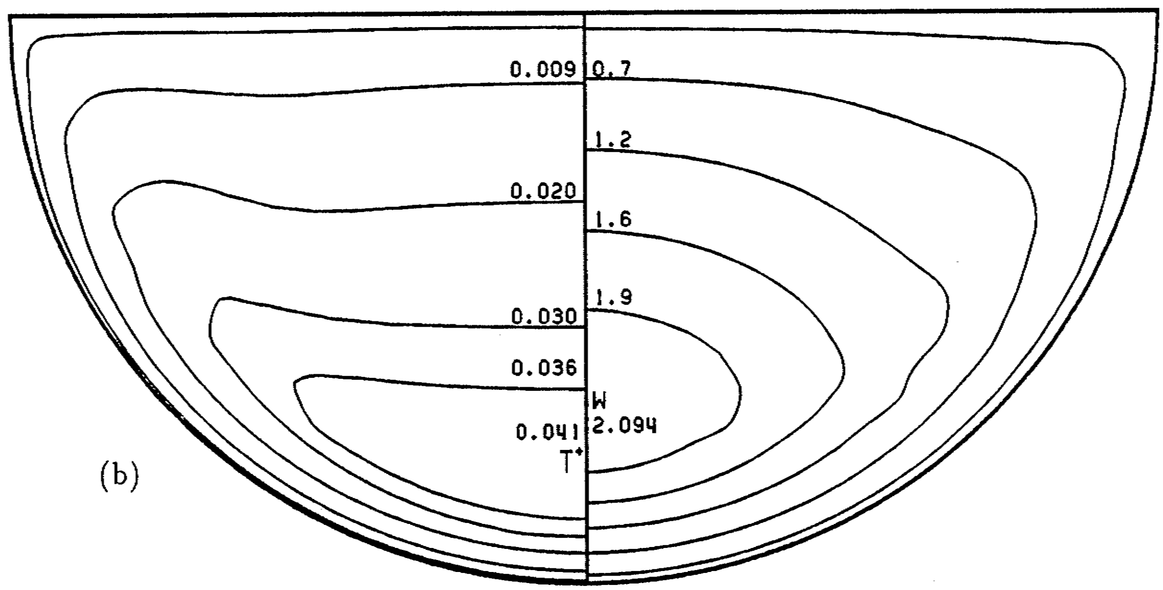


Figure 5.6: Two-Vortex Results for $Gr^+ = 10^6$ and $Pr = 3$. (a) The Secondary Flow (b) Contours of Temperature and Axial Velocity

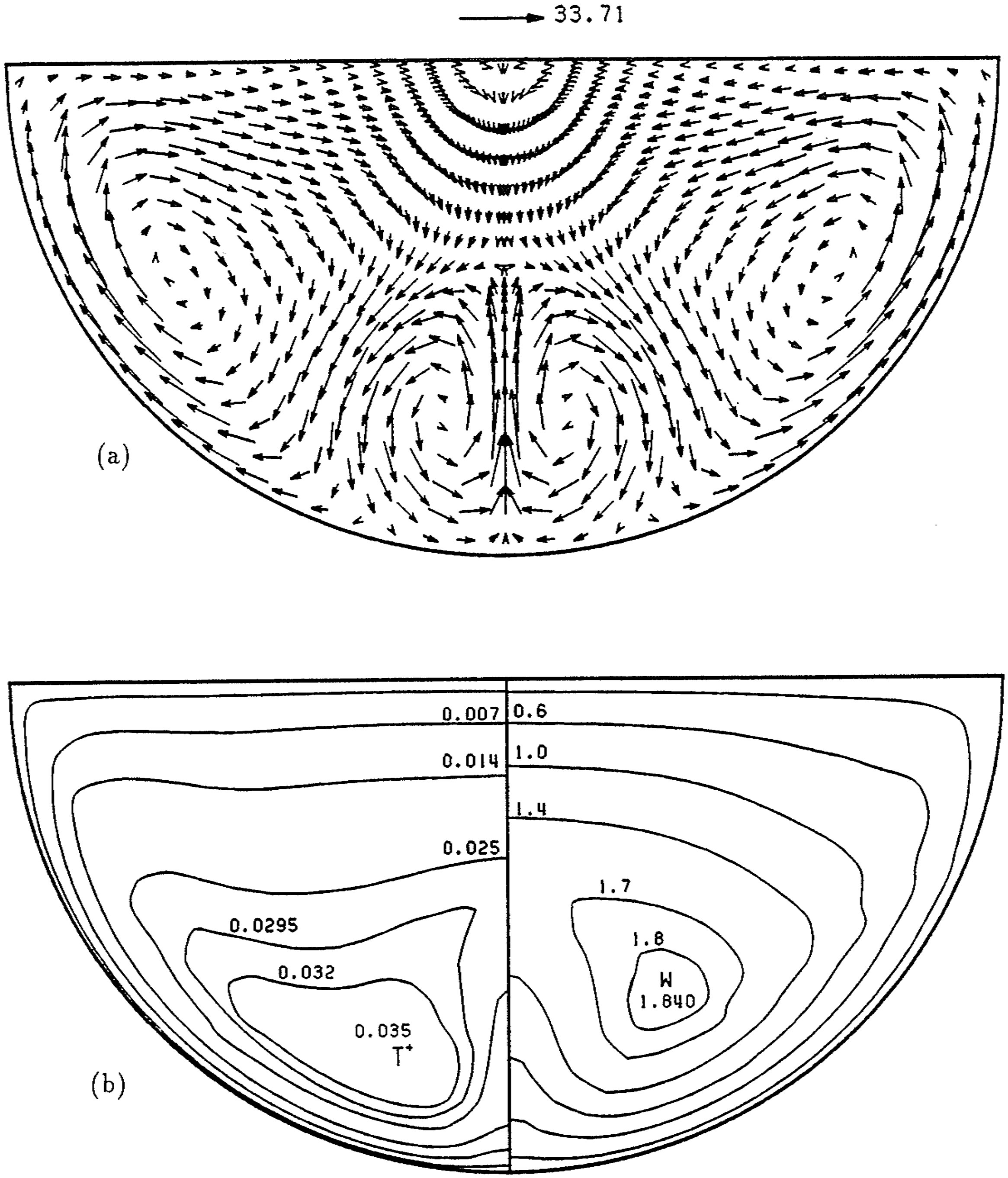


Figure 5.7: Four-Vortex Results for $Gr^+ = 10^6$ and $Pr = 3$. (a) The Secondary Flow (b) Contours of Temperature and Axial Velocity

secondary flow just neighboring the curved wall and relatively small and uniform velocities in the central region of the duct (Fig. 5.8a). Also, the sizes of the two lower eddies in Fig. 5.9a are seen to become smaller than the ones in Fig. 5.7a, indicating, with increasing Gr^+ ($> 10^7$), a decreasing difference between the four-vortex result and the two-vortex result (e.g., referring to Fig. 5.1).

The foregoing observations are more evident in Figs. 5.10 and 5.11 for $Gr^+ = 2 \times 10^8$. For both cases, the most vigorous secondary flow ascends primarily along the curved wall. The resulting contours are severely distorted and this accounts for significant increases in heat transfer coefficients and friction factors. As can be seen in Fig. 5.11a, the two lower vortices are further shrunk thus playing a less important role in the overall Nu and fRe results. Regarding the secondary flow maximum velocity (the scale vector), its magnitude is seen to also increase with increasing Gr^+. For $Gr^+ = 2 \times 10^8$, it reaches about 307 (from about 90 for $Gr^+ = 10^7$). But this magnitude remains approximately the same (e.g., 305.58 in Fig. 5.10a and 307.33 in Fig. 5.11a) for the same Gr^+ but different flow patterns. A last interesting observation can be made from either Fig. 5.10a or Fig. 5.11a where there appear a pair of tiny recirculating eddies close to the centre of the top wall. Examining the contours in this region renders a weak effect on other quantities. It is not clear in this research whether these eddies will grow and significantly affect the corresponding results as Gr^+ further increases.

5.3.2.2 Peripheral Variation of Friction Factor with Gr^+

Information on two local friction factors (at the top and bottom of the symmetry plane) is contained in Fig. 5.12. As illustrated in the upper plot for the two-vortex result, the axial velocity profiles, as expected, exhibit an increasing degree of distortion with increasing Gr^+. The axial velocity gradients normal to the duct bottom increase with increasing Gr^+. However, the gradients normal to the top wall for both flow patterns show a decreasing trend except for $Gr^+ = 2 \times 10^8$ at which the

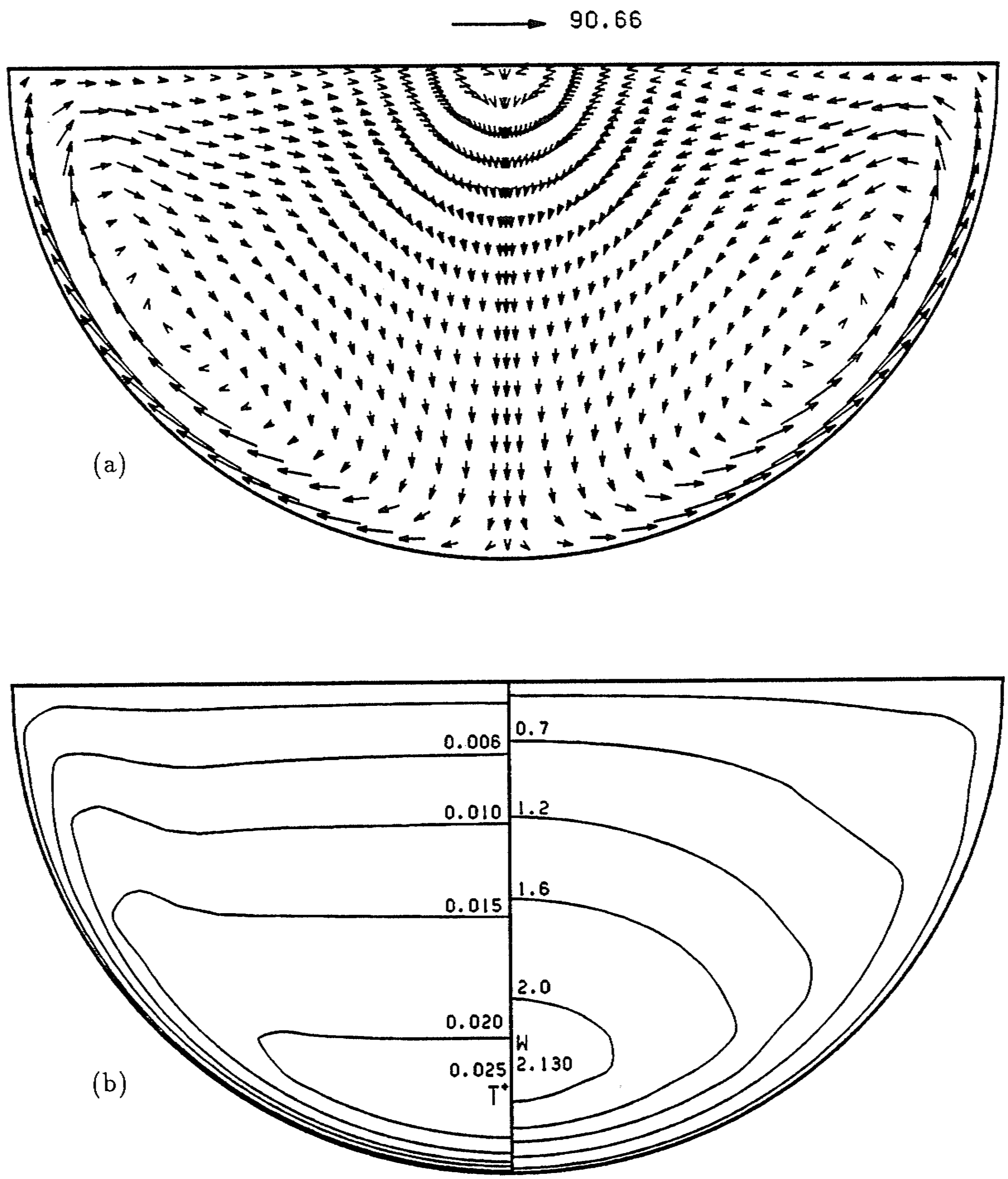
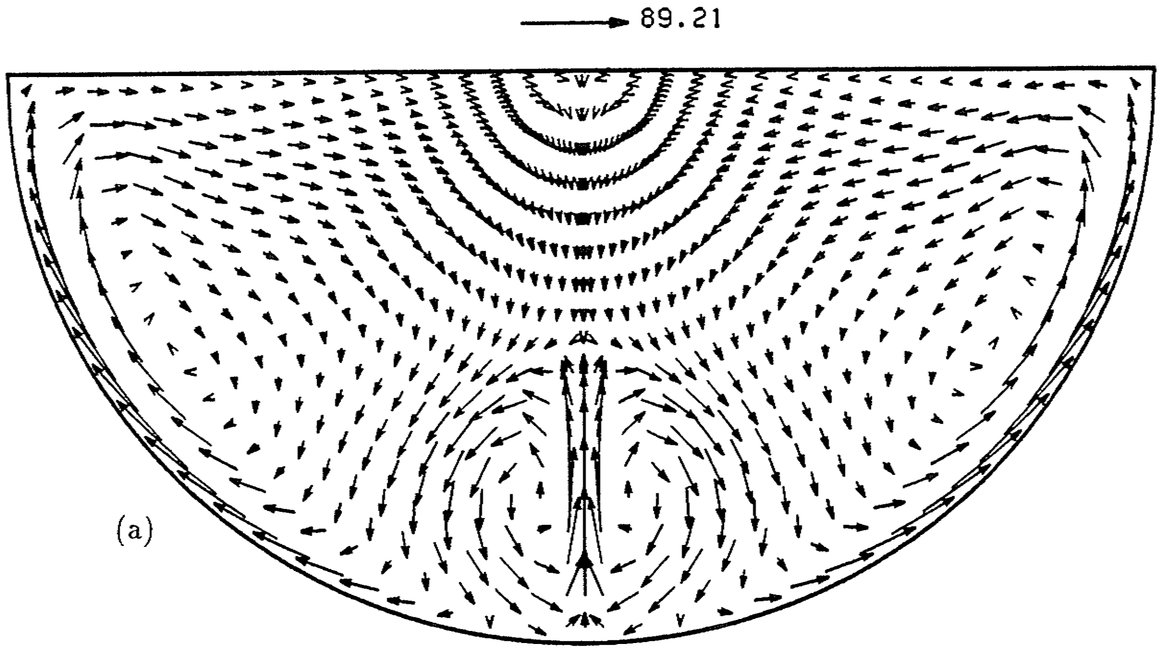


Figure 5.8: Two-Vortex Results for $Gr^+ = 10^7$ and $Pr = 3$. (a) The Secondary Flow (b) Contours of Temperature and Axial Velocity



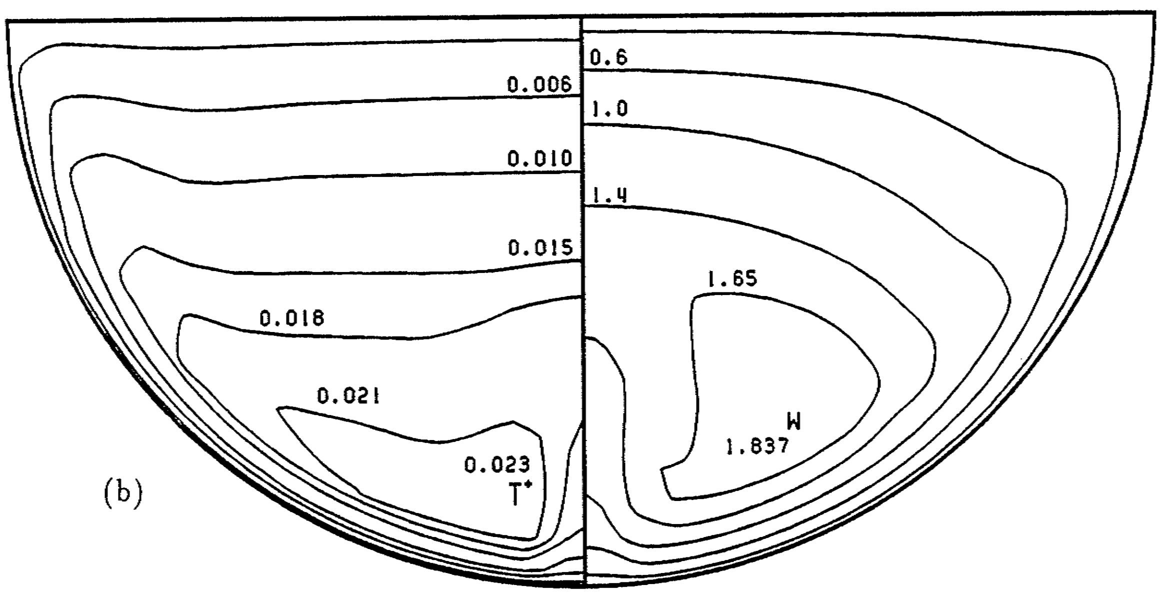


Figure 5.9: Four-Vortex Results for $Gr^+ = 10^7$ and $Pr = 3$. (a) The Secondary Flow (b) Contours of Temperature and Axial Velocity

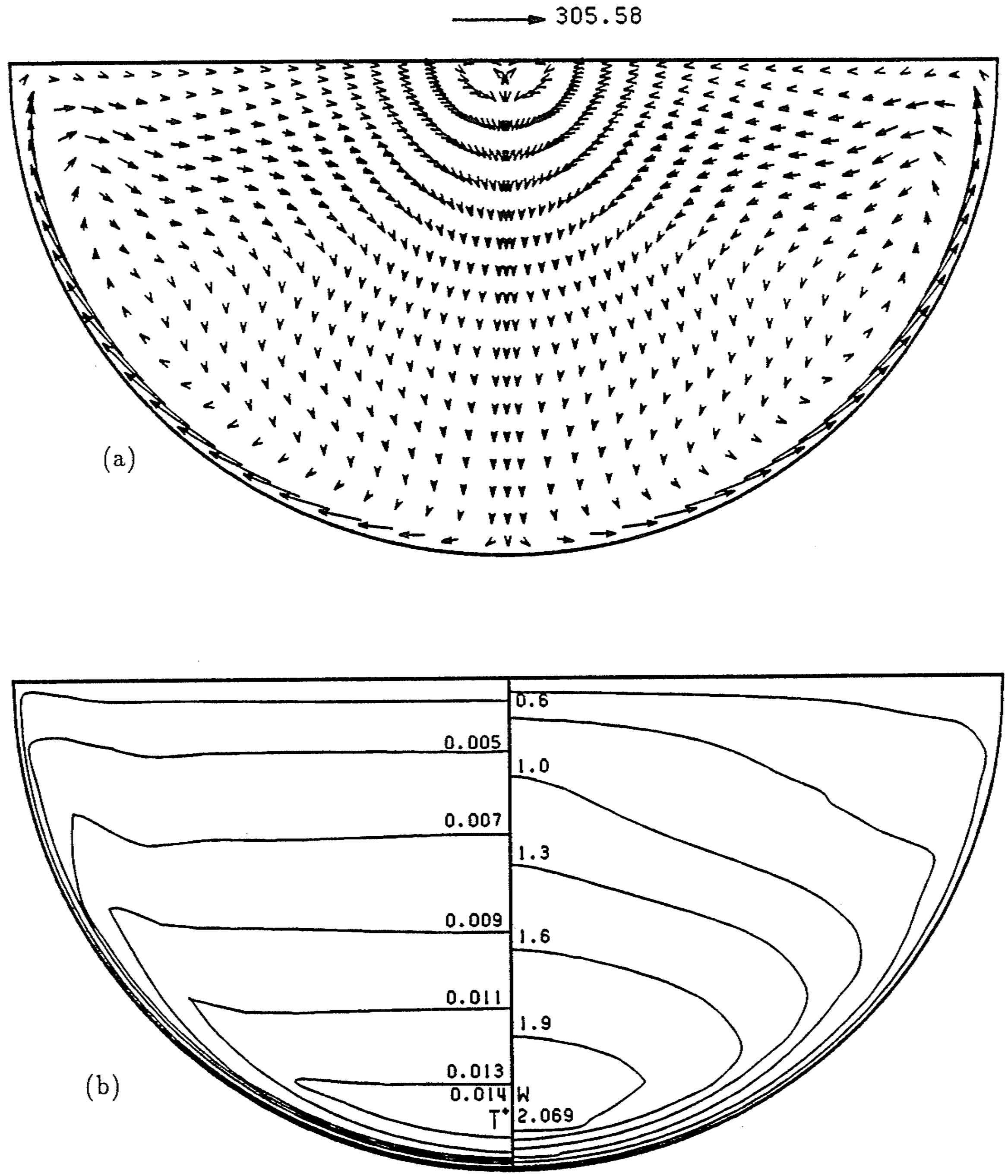


Figure 5.10: Two-Vortex Results for $Gr^+ = 2 \times 10^8$ and $Pr = 3$. (a) The Secondary Flow (b) Contours of Temperature and Axial Velocity

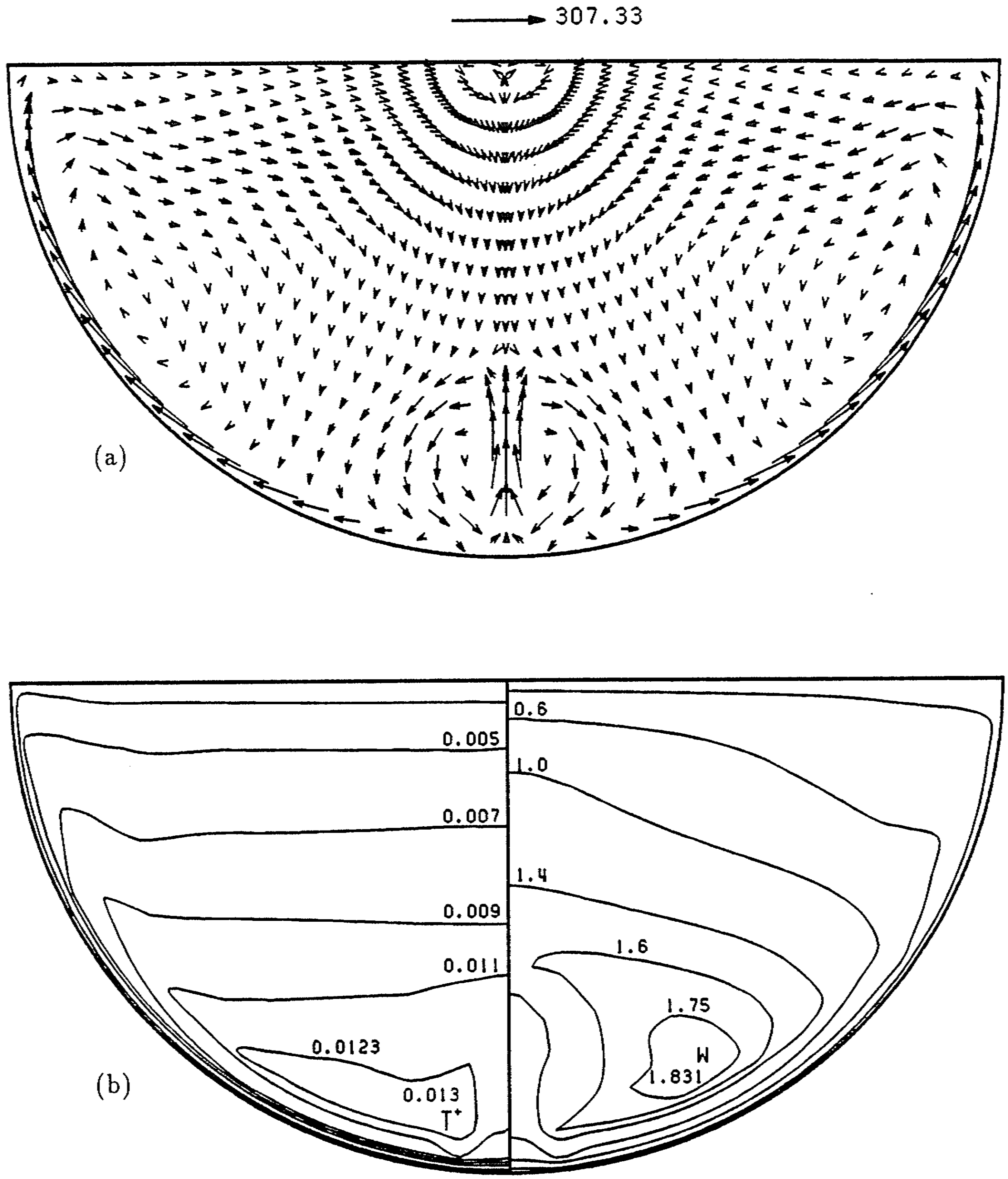


Figure 5.11: Four-Vortex Results for $Gr^+ = 2 \times 10^8$ and $Pr = 3$. (a) The Secondary Flow (b) Contours of Temperature and Axial Velocity

occurrence of two top small eddies (as noted above) causes some high momentum fluid to rise up. For the four-vortex result (Fig. 5.12b), the two lower vortices act to reduce continually the central high momentum as they are strengthened. Consequently, this augments the average friction factor although the secondary flow curtails the shear stresses adjacent to the duct bottom.

Local values for $(fRe)_{fd}$, including the ones at the top "**A**", at the duct corner "**B**", and at the bottom "**C**", are shown in Fig. 5.13. To determine the normal gradient $\partial w/\partial n$ at a wall, a third degree approximation [4] was numerically employed. For both the two- and four-vortex cases, variations of $(fRe)_{fd}$ along the top wall (**A**$\rightarrow$**B**) are nearly identical, indicating that the two lower vortices have little influence on the top friction factors. For Gr^+ ranging from 2×10^5 to 10^7, the $(fRe)_{fd}$ values are independent of Gr^+ and decrease slightly with increasing r and then rapidly approach zero at the duct corner **B**. Due to the depressed axial velocity contours, they are also lower than those for $Gr^+ = 0$. However, higher $(fRe)_{fd}$ values for $Gr^+ = 2 \times 10^8$ are attributed to the very vigorous secondary flow. On the other hand, the $(fRe)_{fd}$ values increase markedly along the curved wall (**B**$\rightarrow$**C**). For example, as shown in Fig. 5.13a for $Gr^+ = 2 \times 10^8$, the $(fRe)_{fd}$ value at the duct bottom (**C**) is about 5 times as high as the value at the centre of the top wall (**A**). In the four-vortex case, friction factors drop sharply near the duct bottom where rising and sparse contours have previously been noticed. Also note that the

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[4] *It is useful to present here the general form of this third-degree approximation derived from the Taylor series expansion of $y = \mathcal{F}(x)$ at a wall, say (x_0, y_0), where x is the coordinate normal to the wall. Let, $Y_i = y_i - y_0$ and $X_i = x_i - x_0$, where $i = 1, 2, 3$ and x_i is a nodal point with its dependent value of y_i. Thus,*

$$\left(\frac{dy}{dx}\right)_{x=x_0} = \frac{((X_3 - X_2)X_2^4X_3^2)Y_1 - ((X_3 - X_1)X_1^2X_2^2X_3^2)Y_2 + ((X_2 - X_1)X_1^2X_2^4)Y_3}{X_1^3X_2^3X_3^2 - X_1^3X_2^4X_3 + X_1^2X_2^5X_3 - X_1X_2^5X_3^2 + X_1X_2^4X_3^3 - X_1^2X_2^3X_3^3}$$

If $X_1 = X_2/3 = X_3/5$, it reduces to

$$\left(\frac{dy}{dx}\right)_{x=x_0} = (\frac{15}{8}Y_1 - \frac{5}{12}Y_2 + \frac{3}{40}Y_3)/X_1$$

which gives an exact gradient value for any third degree polynomial using an arbitrary X_1.

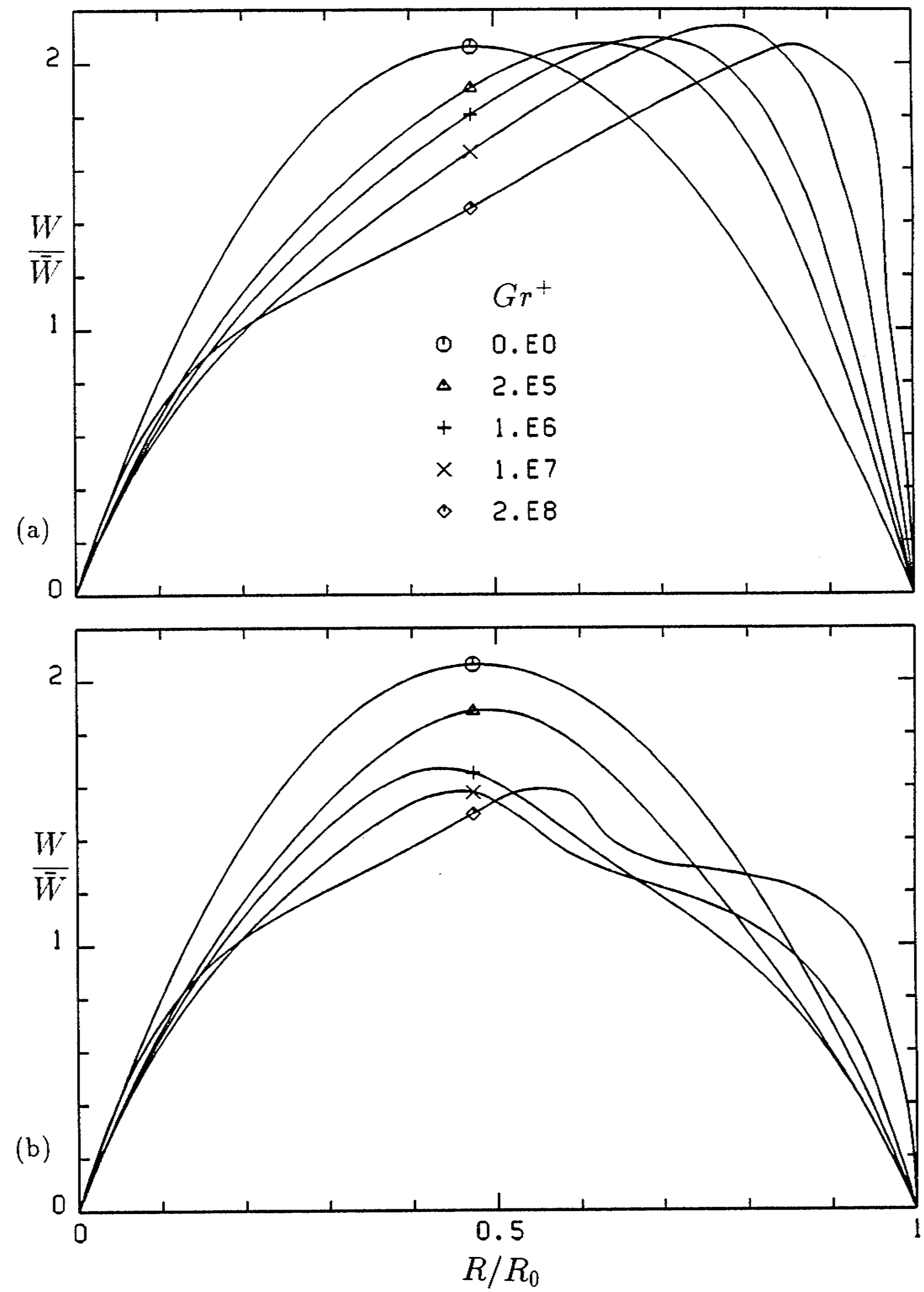


Figure 5.12: Axial Velocity Variations at the Symmetry Plane ($\theta = \phi$) for Varying Gr^+ ($Pr = 3$) (a) Two-Vortex (b) Four-Vortex

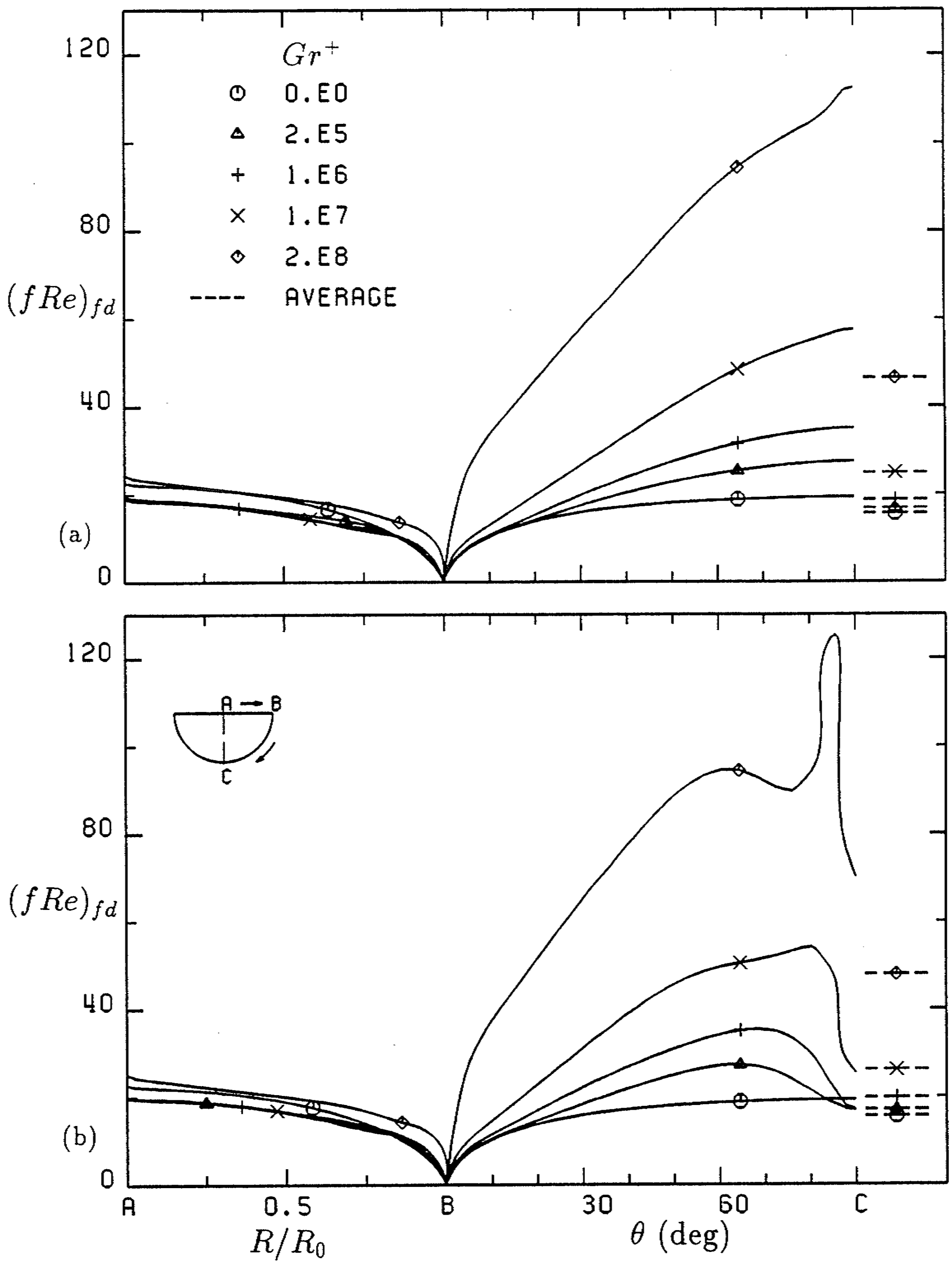


Figure 5.13: Peripheral Variations of $(fRe)_{fd}$ for Varying Gr^+ $(Pr = 3)$ (a) Two-Vortex (b) Four-Vortex

peripherally-averaged values (that were obtained by performing the line integral of $(8\pi/(2+\pi)^2)(\int_A^B(\partial w/\partial n)_{wall}dr + \int_B^C(\partial w/\partial n)_{wall}d\theta))$ are illustrated in Fig. 5.13. Since the $(fRe)_{fd}$ value in equation (5.11) is obtained by ensuring the conservation of mass, the value that is attained by averaging the peripherally local shear stresses can serve as a check point. Accordingly, differences between an average value in Fig. 5.13b and the corresponding result from equation (5.11) are found to range from -0.5% for $Gr^+ = 0$ to 10% for $Gr^+ = 2 \times 10^8$, hence further confirming the appropriateness of the present solution procedures.

5.3.2.3 Peripheral Variation of Heat Flux with Gr^+

The influence of Gr^+ on temperature gradients which are normal to the top and bottom of the symmetry plane can be seen from Fig. 5.14. Similar trends as discussed for Fig. 5.12 are evident. Peripheral variations of the local heat flux $q''_{r\theta}$ are demonstrated in Fig. 5.15 where the normal gradient $\partial T^+/\partial n$ at a wall is also determined by the third degree approximation. By definition, peripherally averaging $q''_{r\theta}$ should yield 1. Thus, examining all numerical average results of $q''_{r\theta}$ gives the values ranging from 0.98 for $Gr^+ = 0$ to 1.14 for $Gr^+ = 2 \times 10^8$.

Comparing the two plots in Fig. 5.15, the flow patterns show a weak effect on the top flux distributions (**A**$\rightarrow$**B**). Except for the proximity of the duct corner **B**, the $q''_{r\theta}$ values tend to become more uniform along the top wall as Gr^+ increases. This tendency agrees with the stratified isotherms near the top wall, as noted earlier. Decreasing the top wall heat flux with increasing Gr^+ is definitely consistent with the previous observations on the thickening of the top thermal boundary layer. Concerning the heat fluxes along the curved wall (**B**$\rightarrow$**C**), the increasing $q''_{r\theta}$ values with θ and Gr^+ (Fig. 5.15a) are due to the corresponding variation of buoyancy forces. Similar to the situation on local friction factors, the flow patterns greatly affect the heat flux distributions along the curved wall. For instance, for the four-vortex flow, higher $q''_{r\theta}$ values along the curved wall and appreciable decays near the

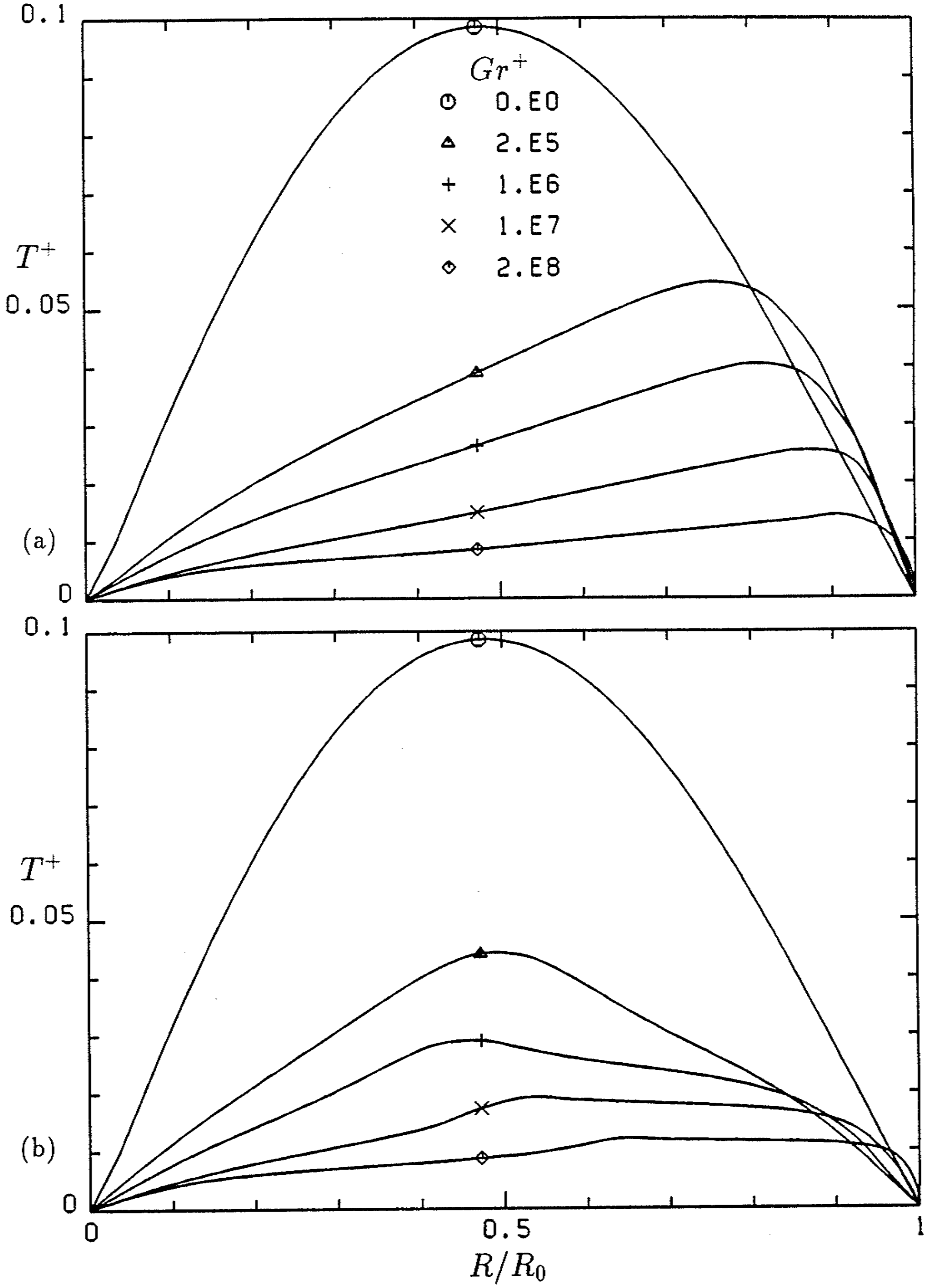


Figure 5.14: Temperature Variations at the Symmetry Plane ($\theta = \phi$) for Varying Gr^+ ($Pr = 3$) (a) Two-Vortex (b) Four-Vortex

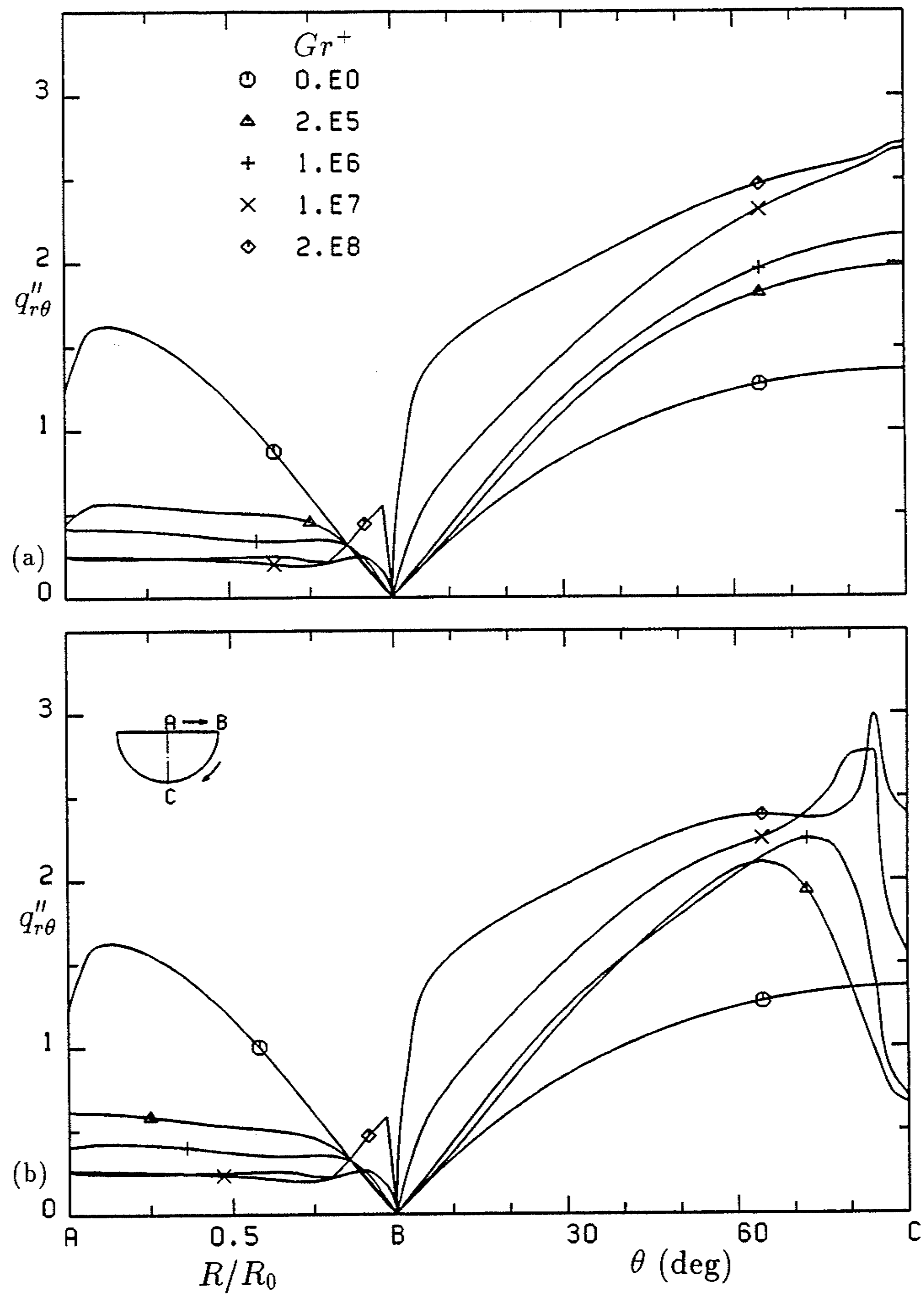


Figure 5.15: Peripherally Local Heat Flux ($q''_{r\theta} = (\pi + 2)(\partial T^+/\partial n)_{wall}$) for Varying Gr^+ ($Pr = 3$) (a) Two-Vortex (b) Four-Vortex

duct bottom do reflect the influence of the multiple vortex flow structure. Finally, it is interesting to note that, for $Gr^+ = 2 \times 10^8$ in Fig. 5.15a, a severe depression of isotherms by the cross-stream vortices can cause the bottom heat flux to be over 10 times as high as the top value.

5.3.3 Effect of the Prandtl Number at a Constant Gr^+

Since the present predictions involved four Prandtl numbers (0.7, 3, 5, and 20), an investigation was made of the effect of this parameter on fully developed mixed convection. Parallel to the study of Grashof number, the discussion begins with typical flow patterns and the associated contours for $Gr^+ = 10^7$, however trends are the same for varying Pr at other fixed Gr^+.

5.3.3.1 Secondary Flow, Axial Velocity, and Temperature for Varying Pr

First attention may be focused on flow patterns for $Pr = 0.7$. In Fig. 5.16a, the two vortices are obviously much stronger than the ones for $Pr = 3$ in Fig. 5.8a at the same heating rate. This amplification of the secondary flow with decreasing Pr can be explained by the following reasoning. Since $Pr = \mu c_p/k$, a decrease in μ and/or an increase in k will reduce the Pr value. For a constant Gr^+, decreasing μ means weakening viscosity forces hence allowing relatively large buoyancy forces. The resulting large cross-stream velocities are then expected. On the other hand, increasing k simply leads to large values for T^+ since $T^+ = k(t_w - t)/q'$. When Gr^+ remains constant, the source terms of $Gr^+T^+sin\theta$ and $Gr^+T^+cos\theta$ in the two cross-stream momentum equations (5.9) and (5.10) become large. This indicates an overall increase in the driving force of the secondary flow under the above conditions.

In Fig. 5.16b, the depressed contours show some rising corners where the vigorous secondary flow climbs, changes directions sharply, and then pushes its adjacent fluid down (Fig. 5.16a). This in turn gives rise to a marked increase of friction near

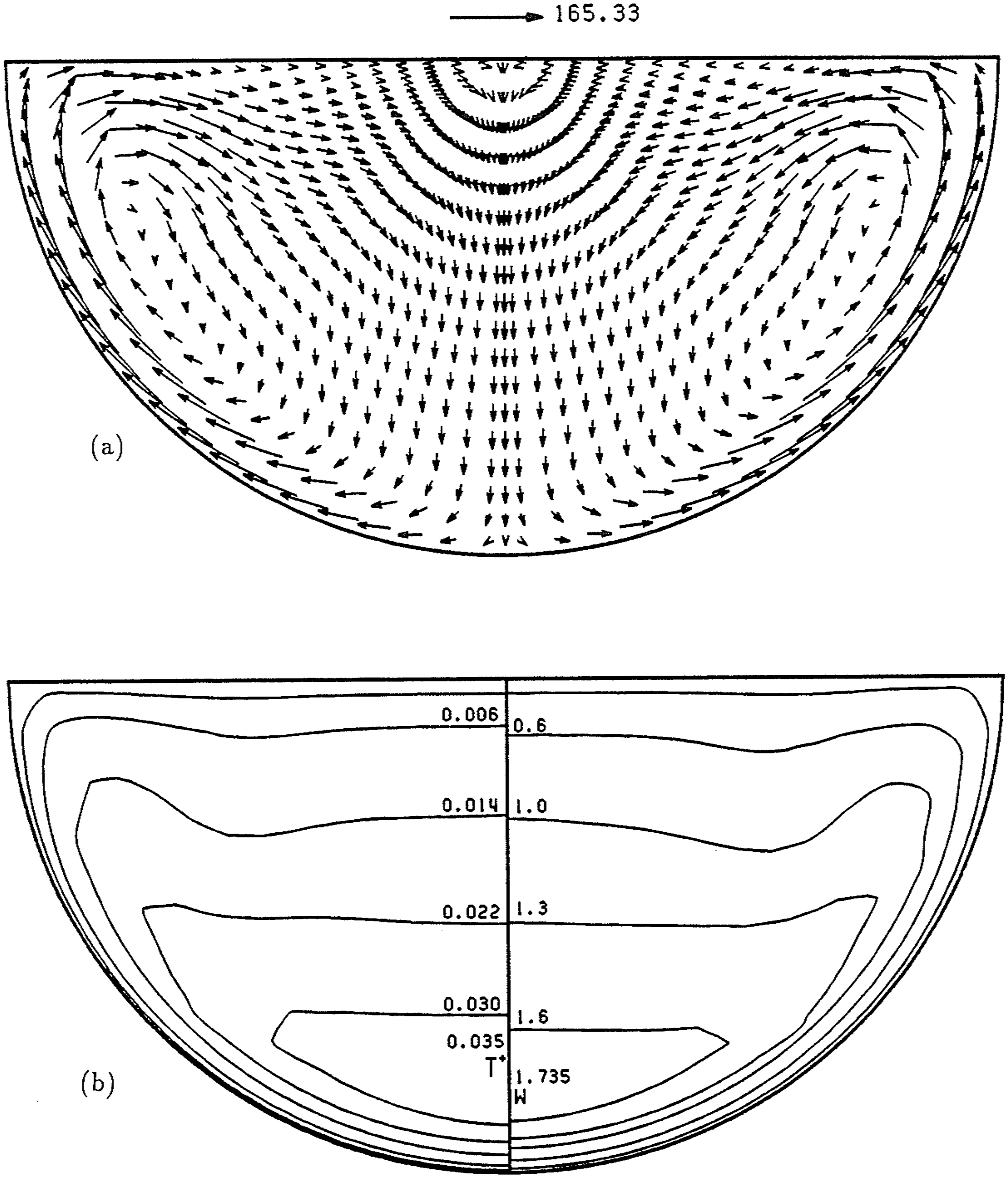


Figure 5.16: Two-Vortex Results for $Gr^+ = 10^7$ and $Pr = 0.7$. (a) The Secondary Flow (b) Contours of Temperature and Axial Velocity

the duct corners. Furthermore, buoyancy effects appreciably retard the main flow (e.g., reducing the w values) and press its highest momentum even lower than the coldest spot (Fig. 5.16b). Consequently, friction factors have an increasing trend as Pr decreases. However, despite more powerful secondary flows, a smaller Pr (relatively larger k) does not contribute to higher temperature gradients at a wall for a constant heat input. For instance, Fig. 5.16b shows that the coldest spot ($T^+ = 0.035$) for $Pr = 0.7$ is even colder than the one ($T^+ = 0.025$) for $Pr = 3$ (Fig. 5.8b) at the same Gr^+, thereby suggesting a declining trend in heat transfer enhancement as Pr decreases.

Compared Fig. 5.17 to Fig. 5.16, the four-vortex flow mechanism for $Pr = 0.7$ is also a stronger one for heat transfer enhancement and friction augmentation. Otherwise, increases in Pr attenuate the secondary flow, which can be further seen from Figs. 5.18 and 5.19 for $Pr = 5$, and from Figs. 5.20 and 5.21 for $Pr = 20$. For example, the magnitude of the secondary flow maximum velocity decreases from about 165 for $Pr = 0.7$ to about 36 for $Pr = 20$. But it varies little for the same Pr but different flow patterns. For both flow patterns, contours for w are seen to become sparse near the duct bottom, where isotherms become condensed, as Pr increases. Of course, these provide further evidences for the foregoing discussions and explanations.

5.3.3.2 Peripheral Variation of Friction Factor with Pr

To illustrate friction factor variations at the top and bottom of the duct, axial velocity profiles at the symmetry plane are shown in Fig. 5.22 for $Gr^+ = 10^7$. With the decrease of Pr, the plots reflect the similar trends as Fig. 5.12 does for increasing Gr^+. The peripheral $(fRe)_{fd}$ variations that are shown in Fig. 5.23 also take some resembling characteristics disclosed by Fig. 5.13. An extra point that should be noted is that the $(fRe)_{fd}$ values along the top wall (**A**$\rightarrow$**B**) are fairly independent on Pr except for in the region of $0.5 < r \leq 1$ where a marked peak occurs for

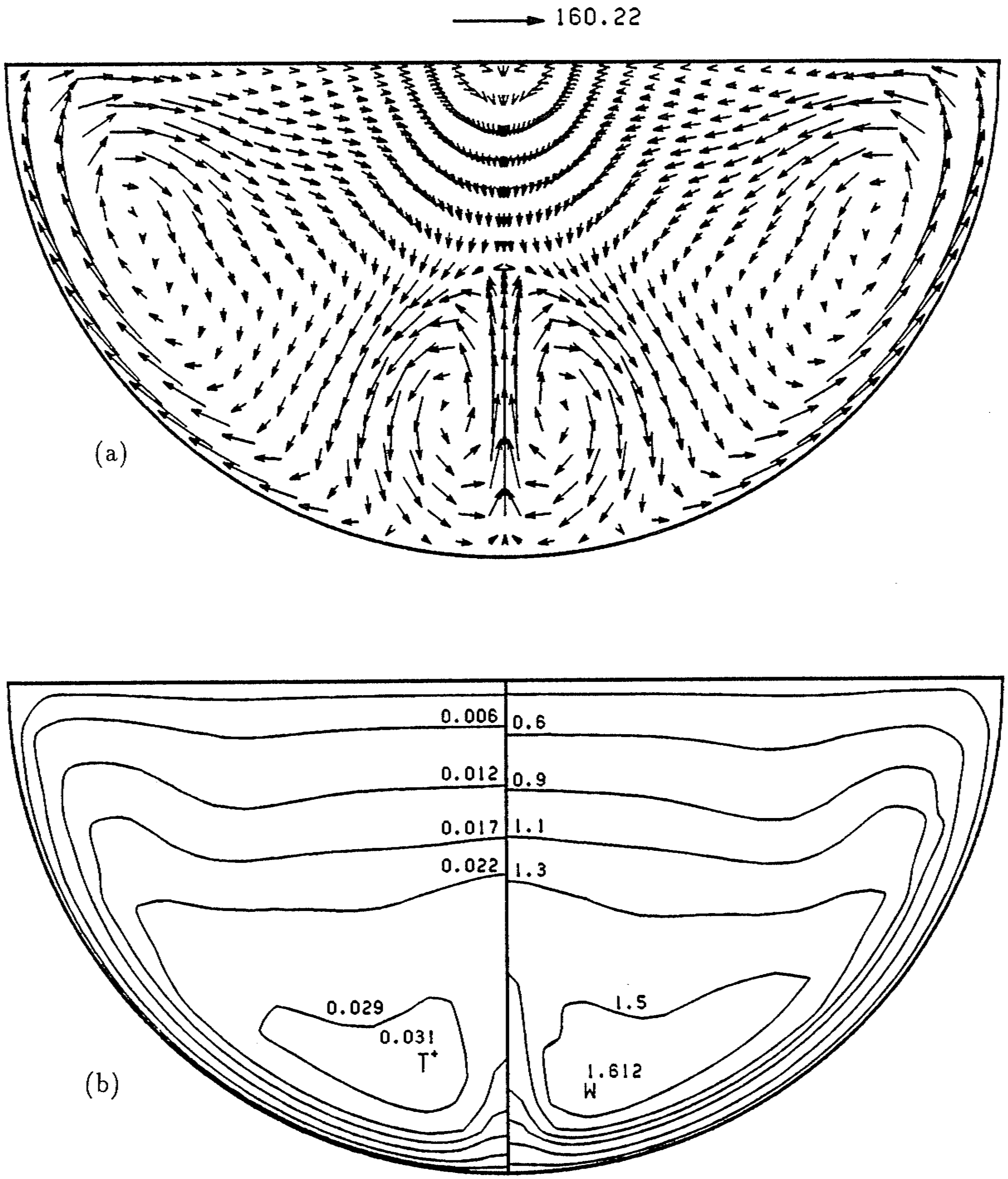
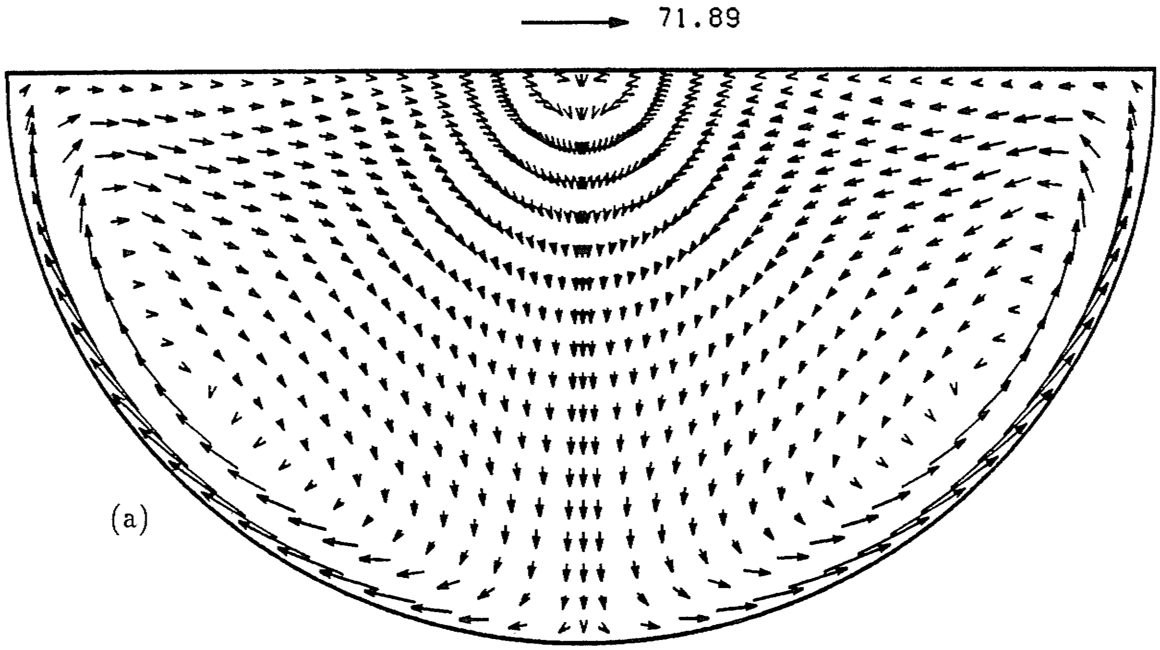


Figure 5.17: Four-Vortex Results for $Gr^+ = 10^7$ and $Pr = 0.7$. (a) The Secondary Flow (b) Contours of Temperature and Axial Velocity



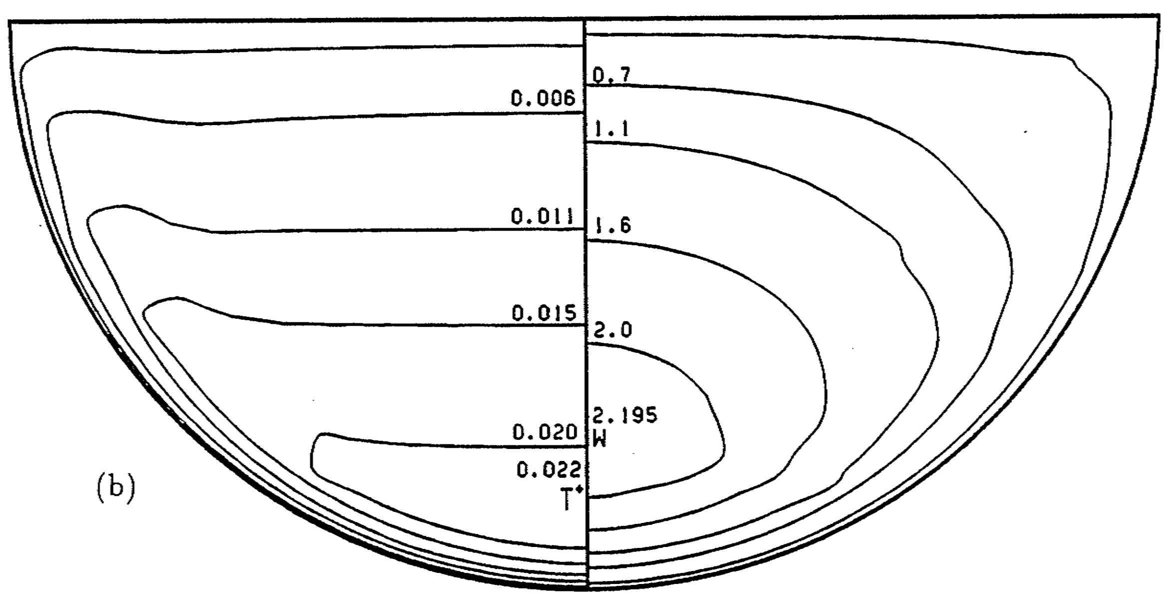
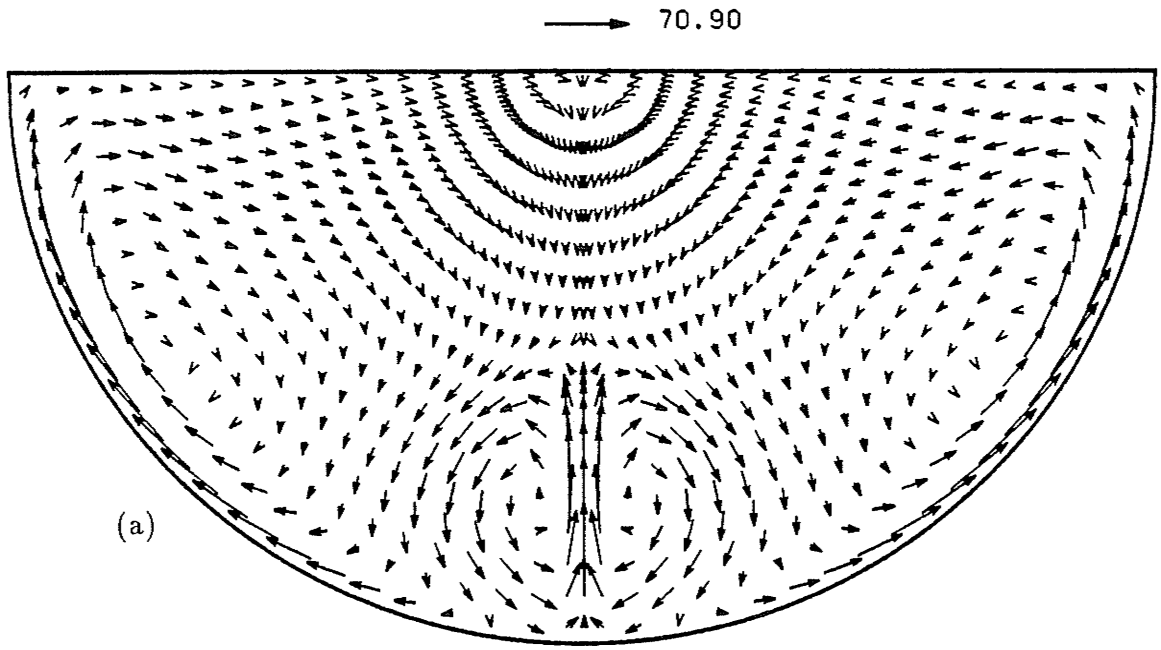


Figure 5.18: Two-Vortex Results for $Gr^+ = 10^7$ and $Pr = 5$. (a) The Secondary Flow (b) Contours of Temperature and Axial Velocity



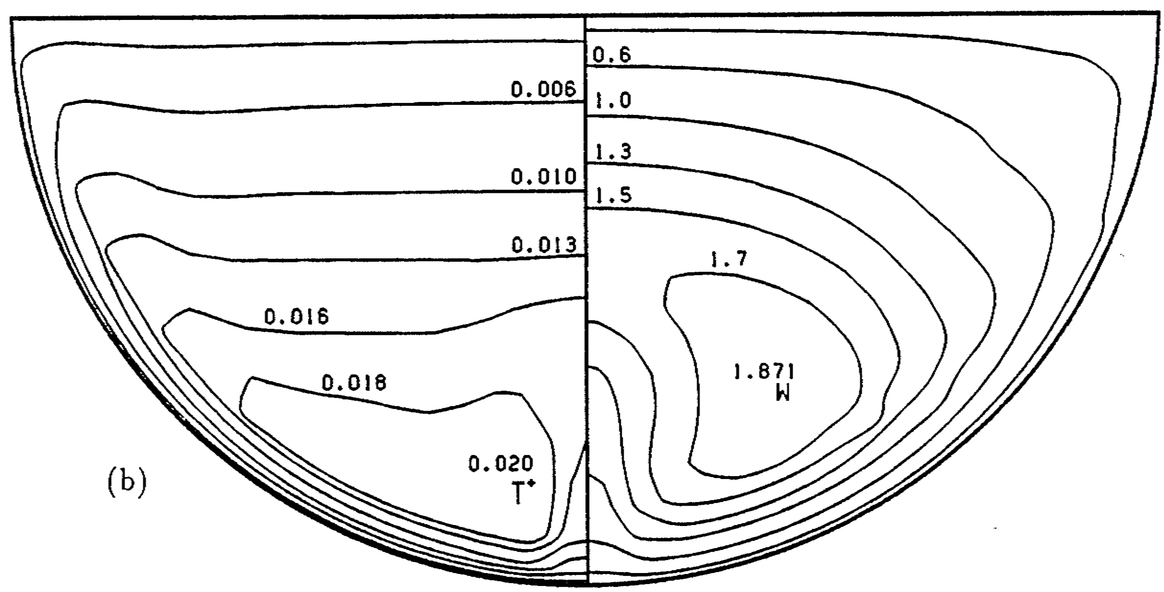
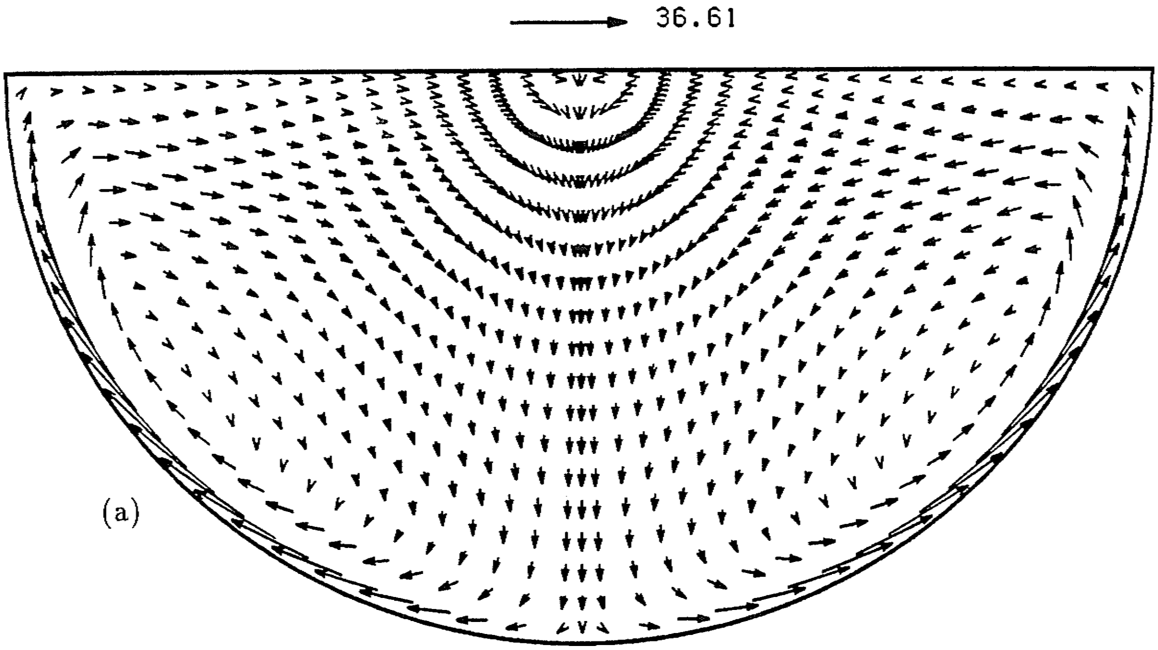


Figure 5.19: Four-Vortex Results for $Gr^+ = 10^7$ and $Pr = 5$. (a) The Secondary Flow (b) Contours of Temperature and Axial Velocity



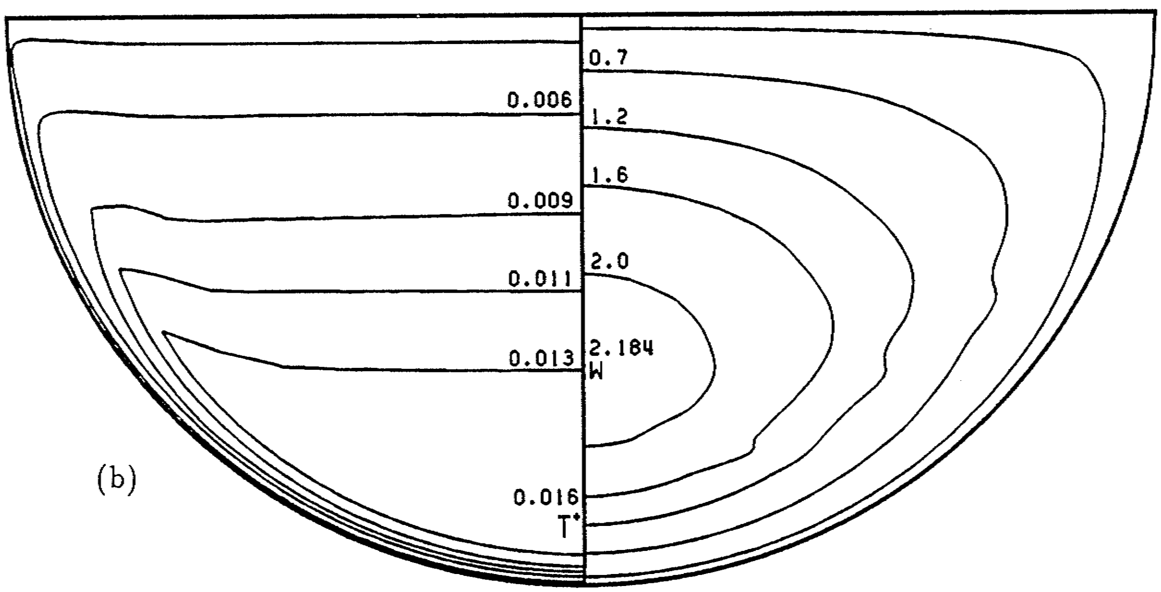


Figure 5.20: Two-Vortex Results for $Gr^{+} = 10^{7}$ and $Pr = 20$. (a) The Secondary Flow (b) Contours of Temperature and Axial Velocity

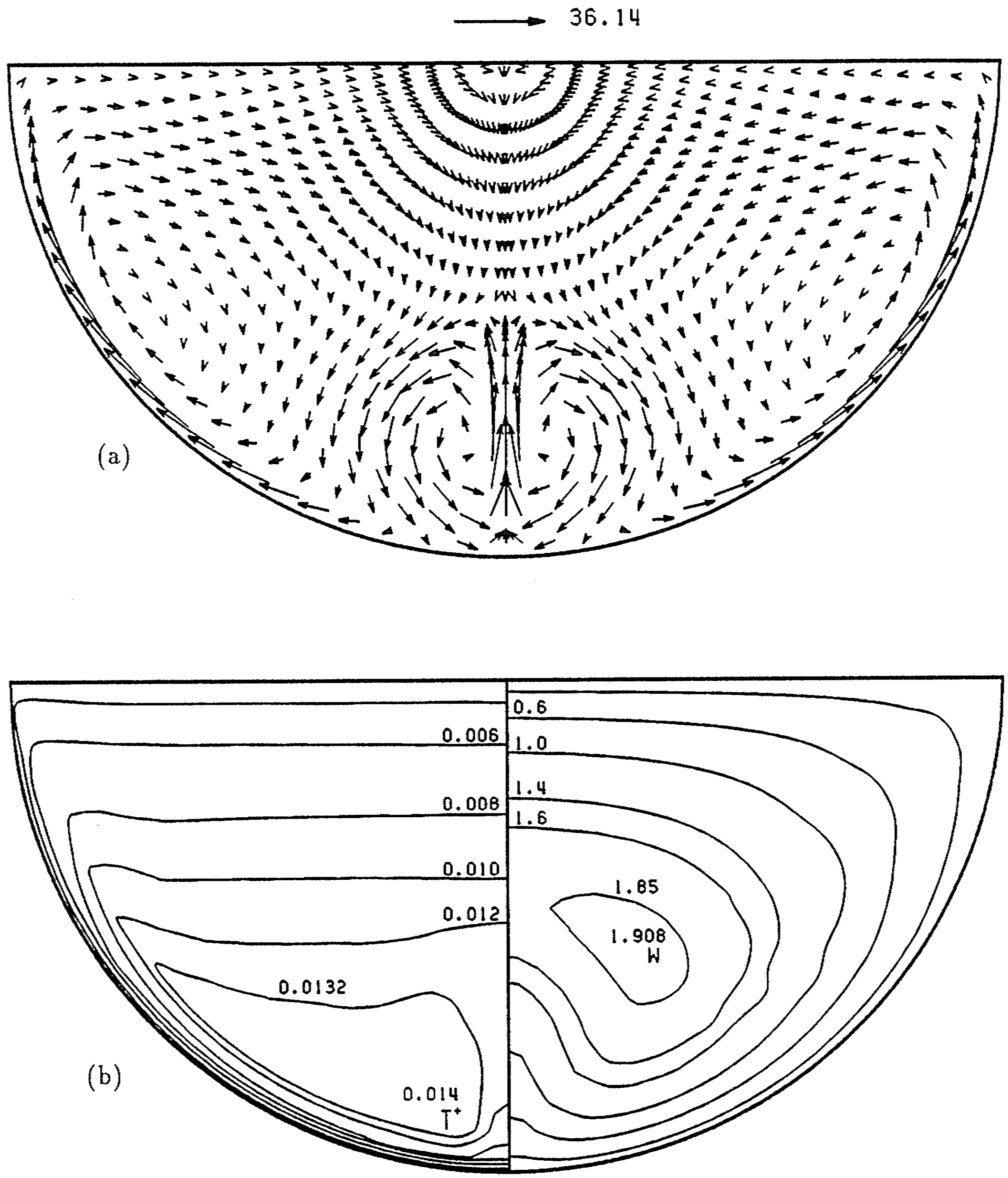


Figure 5.21: Four-Vortex Results for $Gr^{+} = 10^{7}$ and $Pr = 20$. (a) The Secondary Flow (b) Contours of Temperature and Axial Velocity

$Pr = 0.7$. As found earlier, since the buoyancy-induced secondary flow is most forceful for $Pr = 0.7$, relatively large cross-stream velocities near this region (see Figs. 5.16a and 5.17a) are certainly responsible for such a pulse on friction factors.

5.3.3.3 Peripheral Variation of Heat Flux with Pr

The temperature distributions at the symmetry plane, as illustrated in Fig. 5.24 for $Gr^+ = 10^7$, present an decreasing trend in T^+ with increasing Pr. Unlike the case of Fig. 5.14 (constant Pr, varying Gr^+), for a constant heat input, the warmer core fluid for a higher Pr is not primarily attributed to the secondary flow but to a larger average thermal gradient. Again, as shown in Fig. 5.25 for varying Pr, the flow patterns have little influence on the heat fluxes along the top wall ($\mathbf{A}\rightarrow\mathbf{B}$) but affect those along the curved wall greatly ($\mathbf{B}\rightarrow\mathbf{C}$). It is evident that, in spite of the attenuation of the secondary flow, increasing Pr increases the heat fluxes along the curved wall, thereby resulting in higher heat transfer coefficients.

5.3.4 Average Results of Nusselt Numbers and Friction Factors

Average results of Nusselt number ratios $Nu_{H1,fd}/(Nu_{H1,fd})_0$ and friction factor ratios $(fRe)_{fd}/(fRe)_{fd,0}$ (where $(Nu_{H1,fd})_0$ and $(fRe)_{fd,0}$ are as given in Table 5.1) are listed in Tables 5.2 and 5.3, and illustrated in Figs. 5.26 and 5.27, respectively. As predicted earlier, heat transfer enhancement is seen from Fig. 5.26 to be most significant, reaching a factor of about 7, for $Pr = 20$ and $Gr^+ = 2 \times 10^8$ (the highest value for Rayleigh number, $Ra^+ = Gr^+Pr$). Consistently, the higher Pr is, the earlier the response of heat transfer enhancement to buoyancy effects (at low Gr^+) can be observed. For all Pr, the $Nu_{H1,fd}/(Nu_{H1,fd})_0$ values monotonically increase with increasing Gr^+ . The friction factor ratios that are shown in Fig. 5.27 also rise with strengthening the secondary flow. But a marked augmentation for each Pr

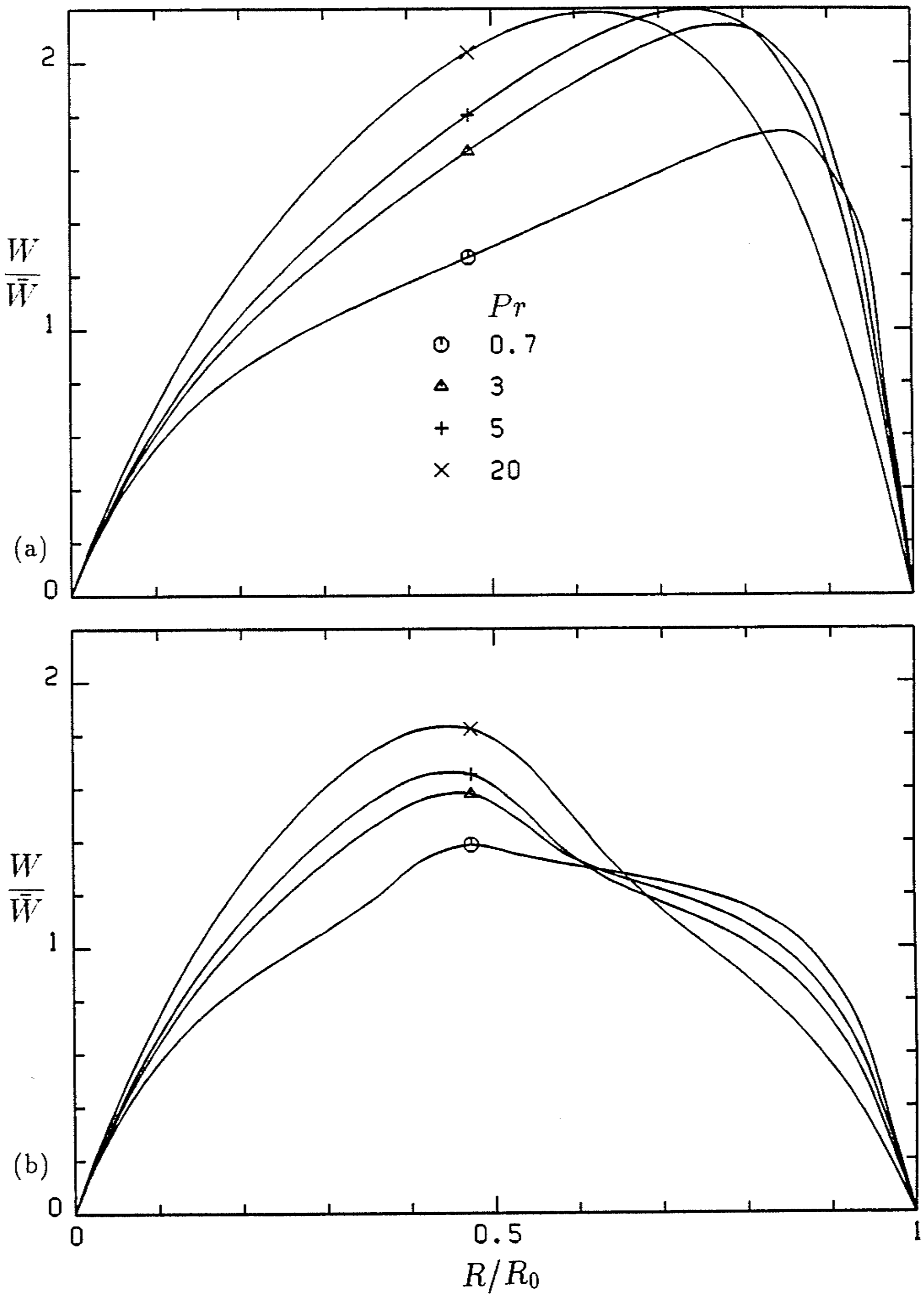


Figure 5.22: Axial Velocity Variations at the Symmetry Plane ($\theta = \phi$) for Varying Pr ($Gr^+ = 10^7$) (a) Two-Vortex (b) Four-Vortex

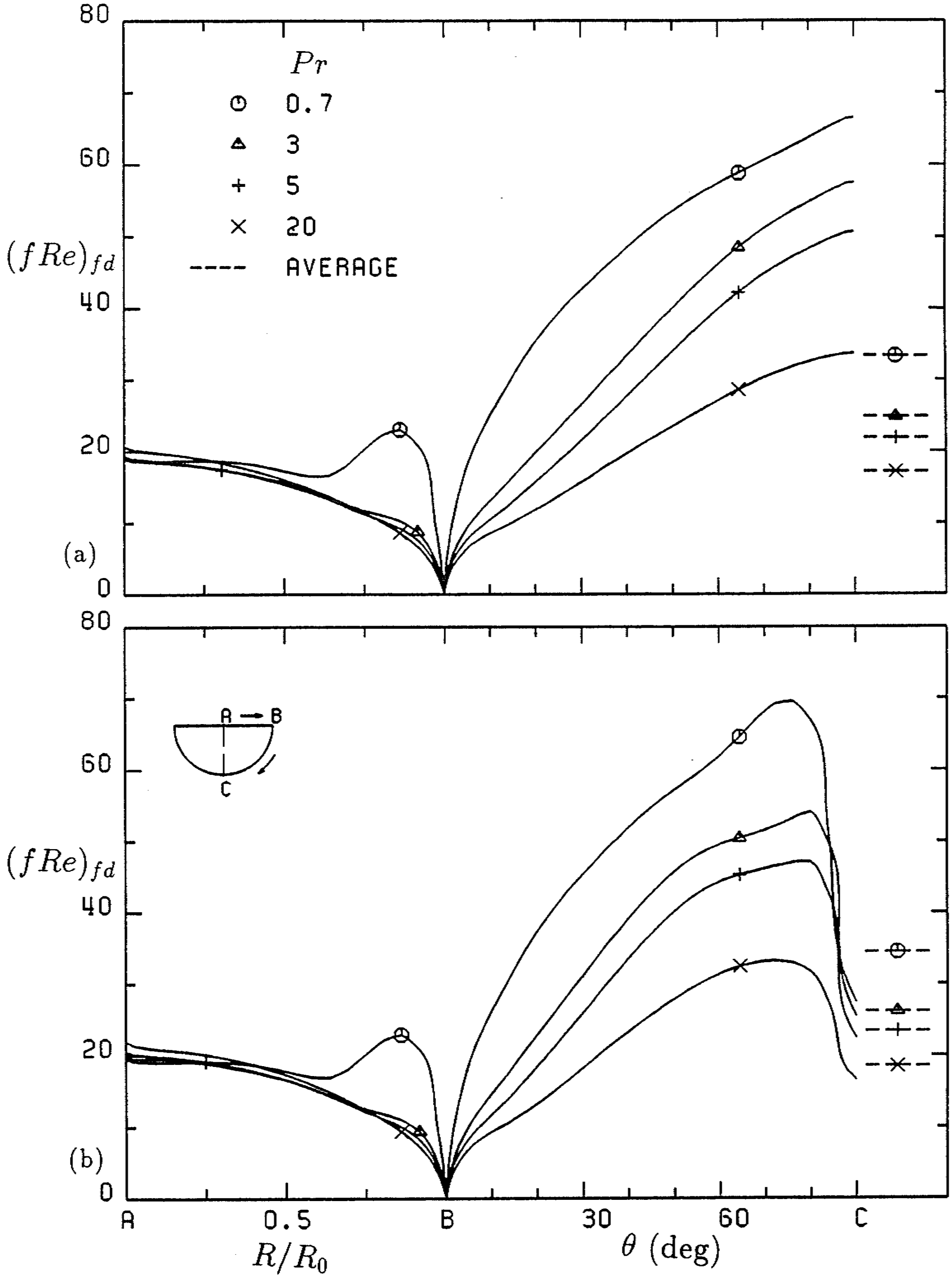


Figure 5.23: Peripheral Variations of $(fRe)_{fd}$ for Varying Pr $(Gr^+ = 10^7)$ (a) Two-Vortex (b) Four-Vortex

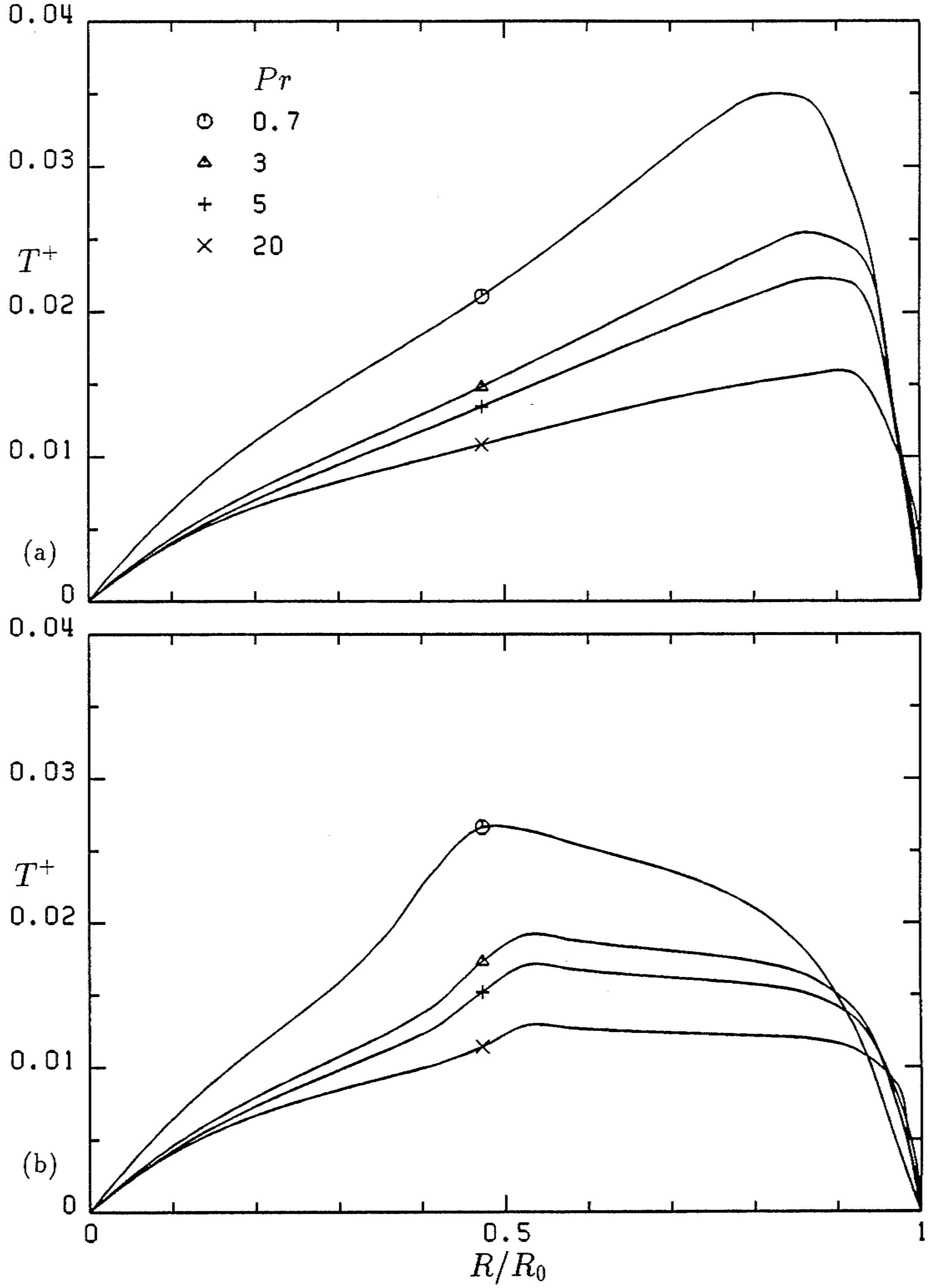


Figure 5.24: Temperature Variations at the Symmetry Plane ($\theta = \phi$) for Varying Pr ($Gr^+ = 10^7$) (a) Two-Vortex (b) Four-Vortex

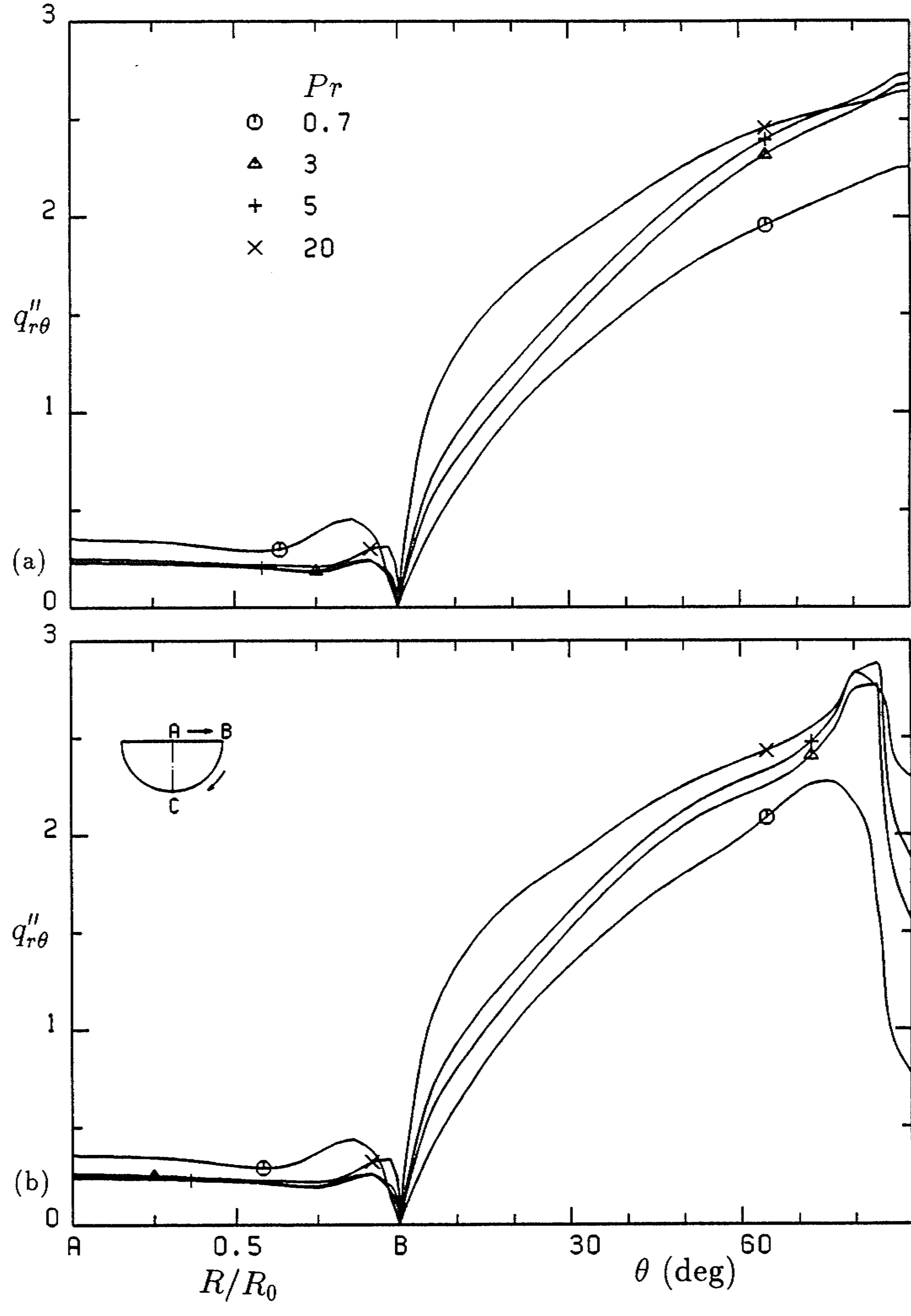


Figure 5.25: Peripherally Local Heat Flux ($q''_{r\theta} = (\pi + 2)(\partial T^+/\partial n)_{wall}$) for Varying Pr ($Gr^+ = 10^7$) (a) Two-Vortex (b) Four-Vortex

does not occur until the Gr^+ value becomes relatively high, e.g., much higher than that at which heat transfer enhances markedly. Unlike heat transfer enhancement, friction augmentation at a given Gr^+ is most pronounced (reaching a factor of about 3.6) for $Pr = 0.7$. This agrees with the previous discussions and with other different predictions in [61,67], namely that decreasing Pr intensifies the secondary flow and hence increases friction factors.

In both Figs. 5.26 and 5.27, the four-vortex results are higher than the two-vortex ones. As can be seen, the effect of the secondary flow patterns becomes less noticeable as Pr decreases, especially for high Gr^+ values. By examining peripherally local heat fluxes and shear stresses (Figs. 5.25 and 5.23), this mainly accounts for the fact that the local four-vortex values near the duct bottom tend to drop more significantly with a lower Pr. Of course, the drop corresponds to the lower counter-rotating vortices (e.g., Fig. 5.21) which carry the high axial momentum fluid away from the duct bottom. Thus, as Pr decreases, this feature of the four-vortex flow structure, on the whole, acts to lessen differences between the two- and four-vortex results. Also, note that the lower critical Gr^+ value at which the secondary flow transits from four to two vortices is seen from Fig. 5.26 to increase with decreasing Pr. The estimated values are 3.5×10^4, 1.25×10^5, 1.5×10^5, and 6.5×10^5 for $Pr = 20$, 5, 3, and 0.7, respectively.

Finally, it is interesting to present the two plots of Fig. 5.28. Using the coordinate of Rayleigh number Ra^+, the Nusselt number ratios appear to be independent of Pr although the curve for $Pr = 0.7$ is slightly higher (Fig. 5.28a). This evidences that the mixed convection heat transfer is well characterized by Ra^+ to which the corresponding data might thus be correlated. Unfortunately, using Ra^+ to re-plot Fig. 5.27 scatters the friction ratio curves. This indicates that friction factor data might be better correlated to Gr^+ rather than Ra^+. Furthermore, by examining any two friction factor curves in Fig. 5.27, it is possible to gather them together using

Table 5.2: Fully Developed Nusselt Number Ratios — $Nu_{H1,fd}/(Nu_{H1,fd})_0$

Gr^+	$Pr = 0.7$		$Pr = 3$		$Pr = 5$		$Pr = 20$	
	2-Vortex	4-Vortex	2-Vortex	4-Vortex	2-Vortex	4-Vortex	2-Vortex	4-Vortex
1×10^4	1.005	NA	1.075	NA	1.148	NA	1.389	NA
3×10^4	1.072	NA	1.233	NA	1.332	NA	1.672	NA
6×10^4	1.162	NA	1.370	NA	1.484	NA	1.910	2.030
1×10^5	1.242	NA	1.486	NA	1.617	NA	2.106	2.252
2×10^5	1.370	NA	1.672	1.739	1.829	1.946	2.415	2.582
4×10^5	1.526	NA	1.894	2.021	2.085	2.232	2.788	2.968
6×10^5	1.633	NA	2.045	–	2.257	2.413	3.042	–
8×10^5	1.715	1.787	2.162	2.306	2.391	2.550	3.240	3.429
1×10^6	1.784	1.866	2.259	2.405	2.503	2.664	3.404	3.595
2×10^6	2.023	–	2.602	–	2.897	3.058	3.976	–
4×10^6	2.310	2.395	3.017	3.155	3.371	3.529	4.605	4.774
6×10^6	2.504	–	3.297	–	3.689	3.842	4.976	–
8×10^6	2.649	2.728	3.514	3.643	3.931	4.079	5.230	5.378
1×10^7	2.783	2.849	3.692	3.818	4.126	4.270	5.418	5.558
2×10^7	3.228	–	4.296	4.405	4.758	4.879	5.933	6.050
4×10^7	3.756	3.788	4.942	5.027	5.377	5.465	6.333	6.425
6×10^7	4.105	–	5.316	5.385	5.708	5.779	6.519	6.578
8×10^7	4.369	4.387	5.571	5.630	5.924	5.986	6.633	6.686
1×10^8	4.582	4.595	5.761	5.813	6.080	6.135	6.712	6.763
2×10^8	5.277	5.279	6.292	6.326	6.500	6.537	6.919	6.962

NA– Not available for four-vortex flow pattern results.

Table 5.3: Fully Developed Friction Factor Ratios — $(fRe)_{fd}/(fRe)_{fd,0}$

Gr^+	$Pr = 0.7$		$Pr = 3$		$Pr = 5$		$Pr = 20$	
	2-Vortex	4-Vortex	2-Vortex	4-Vortex	2-Vortex	4-Vortex	2-Vortex	4-Vortex
1×10^4	1.009	NA	1.005	NA	1.004	NA	1.000	NA
3×10^4	1.051	NA	1.022	NA	1.014	NA	1.002	NA
6×10^4	1.102	NA	1.041	NA	1.025	NA	1.004	1.010
1×10^5	1.147	NA	1.060	NA	1.036	NA	1.007	1.015
2×10^5	1.220	NA	1.095	1.106	1.059	1.077	1.011	1.024
4×10^5	1.312	NA	1.144	1.182	1.090	1.127	1.017	1.038
6×10^5	1.376	NA	1.178	–	1.113	1.162	1.022	–
8×10^5	1.426	1.487	1.206	1.266	1.132	1.189	1.026	1.057
1×10^6	1.468	1.534	1.230	1.295	1.149	1.211	1.029	1.065
2×10^6	1.616	–	1.316	–	1.208	1.287	1.043	–
4×10^6	1.797	1.862	1.421	1.507	1.283	1.377	1.064	1.136
6×10^6	1.922	–	1.493	–	1.334	1.437	1.081	–
8×10^6	2.019	2.075	1.548	1.640	1.375	1.483	1.097	1.190
1×10^7	2.100	2.153	1.594	1.688	1.410	1.521	1.111	1.211
2×10^7	2.384	–	1.757	1.855	1.540	1.657	1.172	1.290
4×10^7	2.715	2.750	1.958	2.057	1.711	1.827	1.267	1.397
6×10^7	2.925	–	2.097	2.195	1.834	1.948	1.339	1.451
8×10^7	3.078	3.102	2.206	2.301	1.932	2.045	1.400	1.514
1×10^8	3.197	3.217	2.295	2.389	2.013	2.126	1.453	1.569
2×10^8	3.559	3.566	2.595	2.678	2.296	2.401	1.648	1.773

NA– Not available for four-vortex flow pattern results.

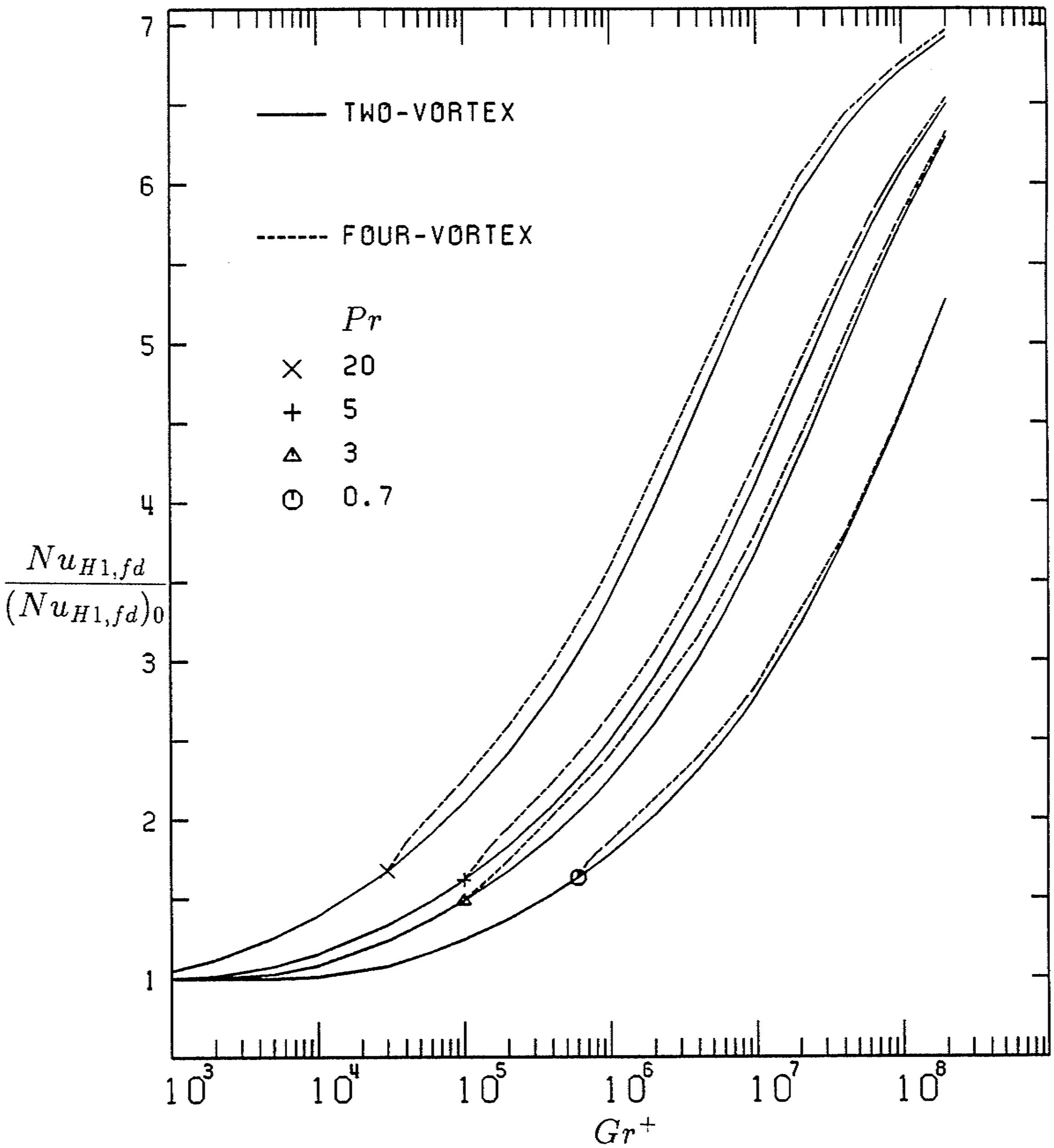


Figure 5.26: Effects of Pr, Gr^+, and Flow Patterns on Heat Transfer Enhancement

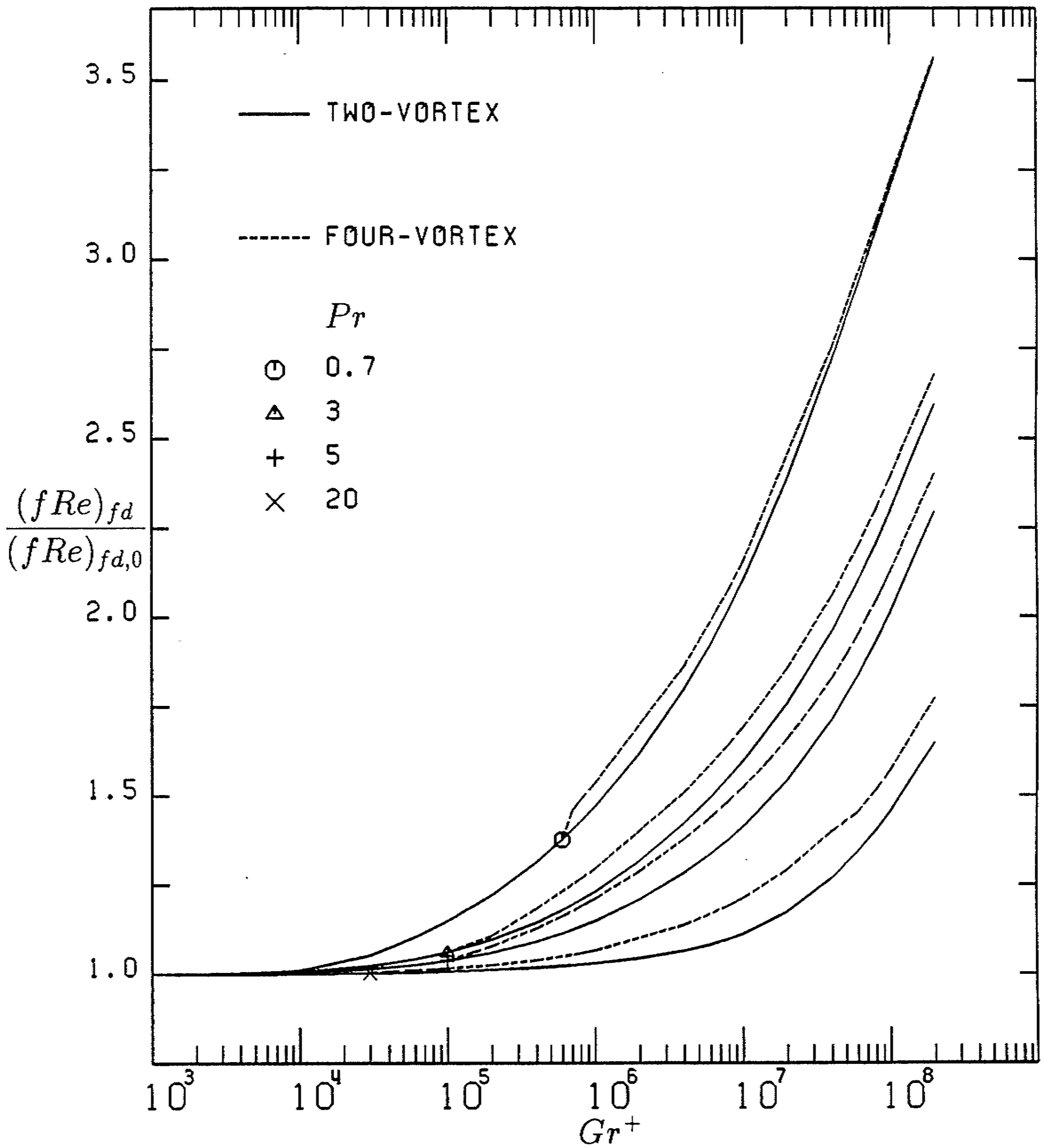


Figure 5.27: Effects of Pr, Gr^+, and Flow Patterns on Friction Factor Ratios

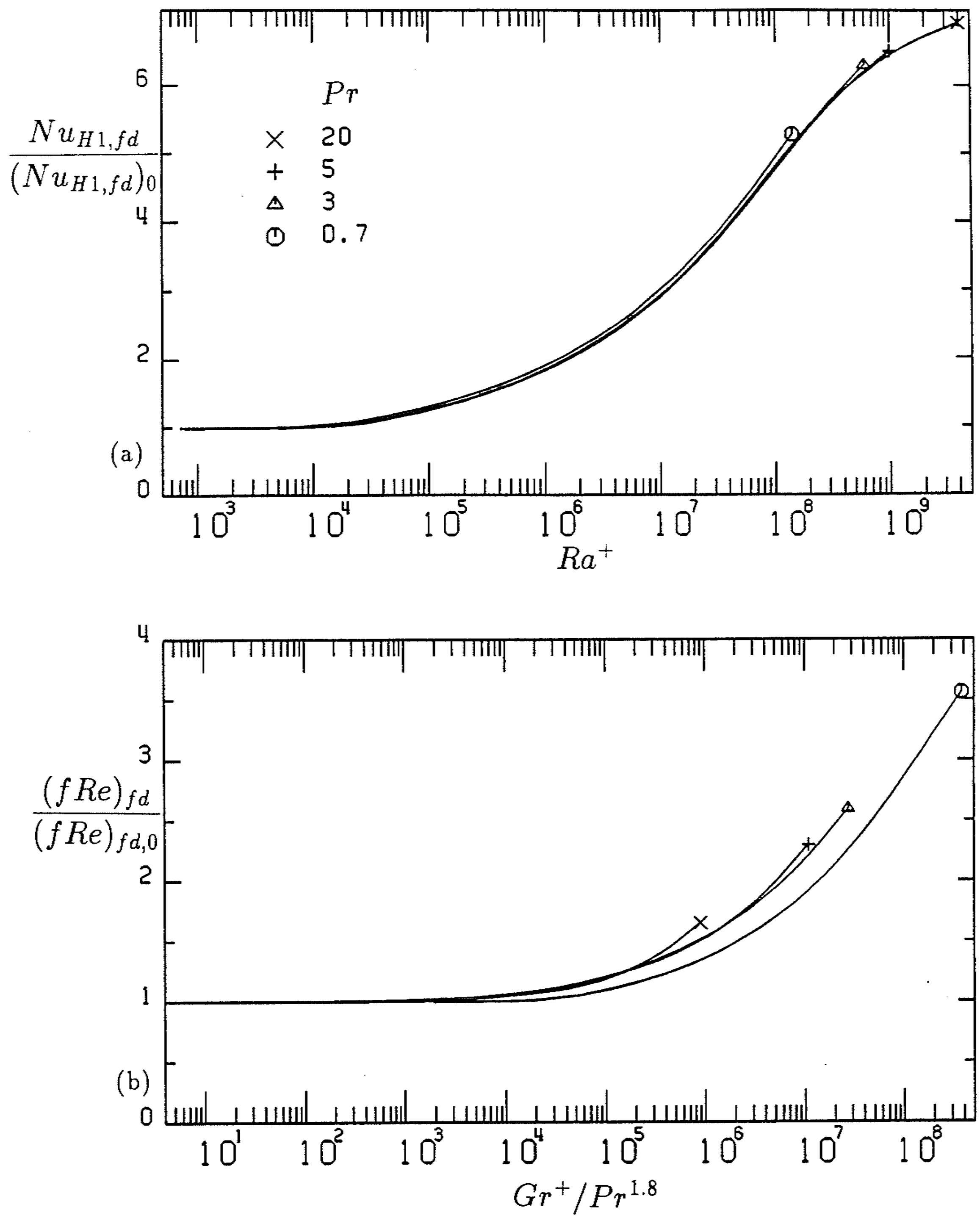


Figure 5.28: Two-Vortex Results for $Pr = 20,\ 5,\ 3,\ 0.7$ (a) Effect of Ra^+ on Heat Transfer Enhancement (b) Effect of $Gr^+/Pr^{1.8}$ on Friction Factor Ratios

a new parameter of Gr^+/Pr^n.[5] An illustration for this is given in Fig. 5.28b where the friction ratio curves are indeed moved closer compared to those in Fig 5.27, especially for the Pr values of 3 and 5.

5.4 Remarks

In summary, this chapter described the numerical solutions for laminar mixed convection flow and heat transfer in a horizontal semicircular duct using the $H1$ condition. Dual solution results were found for a wide range of two parameters, namely, Gr^+ and Pr. Detailed information was provided to investigate the effects of solution parameters and flow patterns on secondary flows, isotherms, axial velocity contours, local friction factors and heat fluxes, as well as average Nusselt number and friction factor ratios. It was found that, while friction factor data are better correlated to Gr^+ or $Gr^+/Pr^{1.8}$, the Rayleigh number Ra^+ is a good measure for mixed convection heat transfer data. Finally, it is noted that the FORTRAN codes for this study are given in Appendix B.

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[5] *In this case, n can be computed by setting $(Gr^+)_i/(Pr^n)_i = (Gr^+)_j/(Pr^n)_j$, where $(Gr^+)_i$ and $(Gr^+)_j$ are Grashof numbers at which the two curves have the same friction factor ratios for $(Pr)_i$ and $(Pr)_j$, respectively. For example, for $Pr = 3$ and 5, letting $4 \times 10^5/3^n = 10^6/5^n$ (see Table 5.3) yields the n value of about 1.8.*

Chapter 6

Measurements of Mixed Convection in a Horizontal Semicircular Duct

THE experiments described in this chapter were originally designed to examine buoyancy effects on laminar water flow and heat transfer in the thermal entrance region of a horizontal semicircular duct. No particular attention was given to the verification of the flow bifurcation phenomenon. Also, it was simply planned to test the duct at various orientations including the orientation of Nandakumar *et al.* [61]. The first arbitrary choice of orientation was the flat surface on top, but due to the large number of tests and the lengthy procedure per test (see Sec. 6.2.3), other orientations had to be left as future experiments. Hence only the results for the orientation with the flat surface on top will be described in this chapter. The duct was subjected to an axially uniform heat input after the flow was hydrodynamically fully developed. Specifically, the main purposes of this study were:

1. to measure the streamwise pressure drops with and without heating;
2. to measure local circumferential temperature variations (as evidence of buoyancy effects) and;
3. to obtain heat transfer data under various flow and heating rates.

Additional objectives were to correlate flow and heat transfer results and to estimate and correlate the onset of the buoyancy flow.

Table 6.1: Dimensions of the Semicircular Duct

Inside diameter, D_i (mm)	49.76	Cross-sectional fluid area, A_{fl} (cm^2)	9.7229
Outside diameter, D_0 (mm)	53.98	Inside heated wall area, A_{iw} (m^2)	0.5997
Hydraulic diameter, D_h (mm)	30.40	Cross-sectional solid area, A_s (cm^2)	3.4311

6.1 Experimental Apparatus

6.1.1 Duct Geometry

Five semicircular ducts, each 2 m long, were carefully manufactured in the Heat Transfer Laboratory at the University of Manitoba. Starting with a type K copper tube (id = 49.8 mm and od = 54.0 mm), several rectangular openings were cut along the tube so as to allow the tube to retain its original shape. With the aid of these openings and an inside rod (od = 24.9 mm), a machined brass plate (3.175 mm thick) was inserted into the tube and cautiously clamped in a desired position. Then, the plate and the tube were joined by performing a tungsten inert-gas welding. After the outside unwanted material was cut and the inside surfaces were thoroughly cleaned, the semicircular duct was put in a steam bath and subjected to a pressure of about 552 kN/m^2 (80 lb/in^2) for over two hours. This test ensured that the built duct was strong enough to suit the experimental conditions and was free of leaks. To examine the correctness of the geometry, inner and outer diameters as well as radii at each duct end were measured to be within $\pm1\%$ of corresponding nominal values. Volume tests by filling water at room temperature to the duct gave a maximum relative error of 2%. Each duct was straight and the duct twist angles were all within 1°. Table 6.1 lists the dimensions and other geometric properties of the semicircular duct.

6.1.2 Test Facility

Experiments were carried out in a test facility of Fig. 6.1. A tank with 227-liters capacity was used to collect the working fluid (distilled water). The water was circulated around the closed loop by a 3/4 horsepower centrifugal pump. A filter was used to prevent any solid impurities from entering the loop. A bypass line controlled by two valves made it possible to adjust the water flow rate and pressure level in the system. The upstream bulk mean temperature was measured as the fluid entered the horizontal section of 3.8 m for the development of hydrodynamics. Following the heated section, a mixing chamber (that has a diameter of 60 mm, a length of 200 mm, and a thermocouple well filled with a high thermally conductive paste, and a 24 gage copper-constantan thermocouple [112]) was installed to generate vortices so that the fluid was properly mixed and a uniform downstream temperature was measured. The water was then cooled in one or two double-pipe, counterflow heat exchangers using city water as a heat sink. [1] Before the test fluid was returning to the accumulating tank, it passed through a flowmeter measurement station where two flowmeters operating on the variable area principle were used to measure the instantaneous fluid flow rate.

6.1.3 Heated Section

The heated section was 4.7 m long, on which wall temperatures were detected at 19 axial stations, each employing three, 24 gage, copper-constantan thermocouples (as shown in Fig. 6.1). An additional 8 thermocouples were mounted on the duct wall just before and after the heating in order to estimate heat conduction losses along the duct ends. The actual axial distribution of thermocouples is reported in the List

[1] *The temperature of the cooled test fluid was also measured and compared to the upstream bulk temperature or the tank temperature. If different, adjustment could be done manually by changing the flow rate of city water using a needle valve. For most specified run tests, it was necessary to let the pre-calculated upstream bulk temperature remain unchanged. Thus, the adjustment was desirable.*

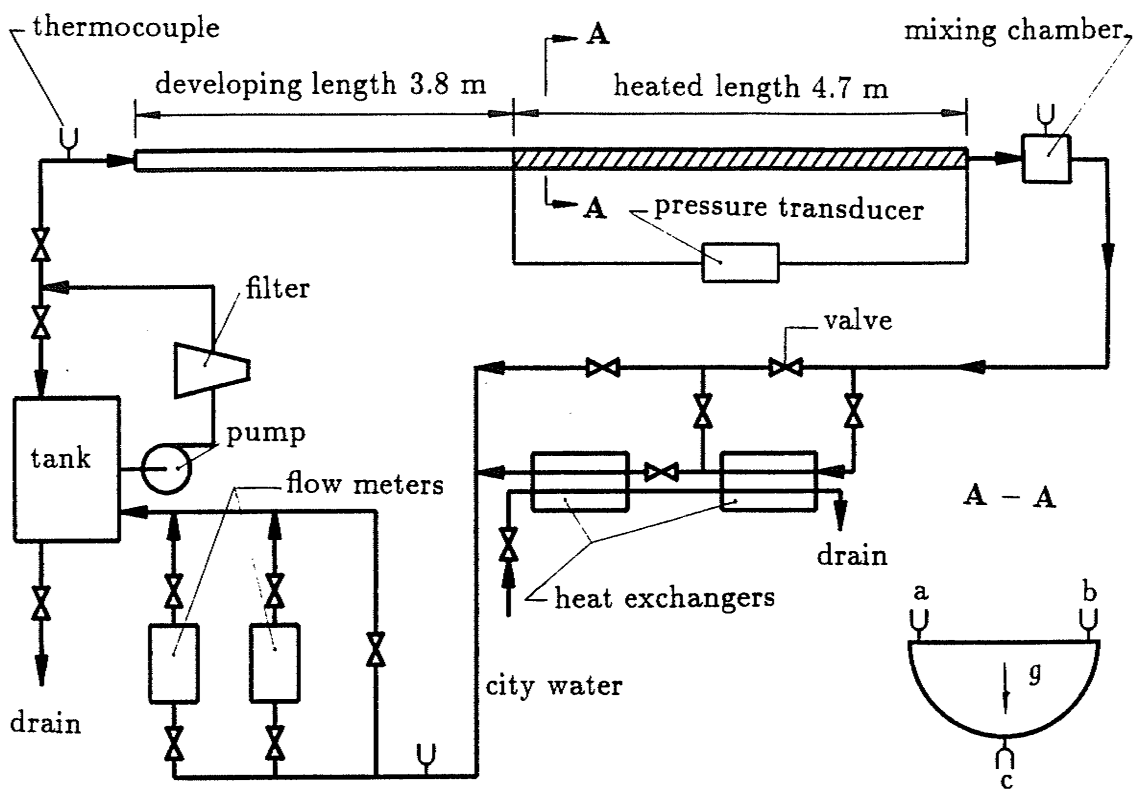

Figure 6.1: Layout of Experimental Facility and the Seating Position of the Semi-circular Duct

of Experimental Data in Appendix E. The axial locations of the measuring stations were such that thermocouples were more sparsely allotted as the distance from the beginning of heating increased. However, more thermocouple stations along the last one-third of the heated section were intentionally set up to watch buoyancy effects on the streamwise main flow. At each thermocouple location a small copper tube or well, 2.5 mm in diameter, was soldered onto the duct wall for the thermocouple attachment.

To construct the heated section, a thin layer of insulating varnish (dielectric strength of 2000 volts per one-thousandth inch) was sprayed on the wall and then a thin dielectric tape was wrapped around the wall. Two parallel lines of electric resistance wires (Hoskin Copel [2]), having a total resistance of 6.61 ohms, were then tightly wound around the duct with an equal space of 5 mm. Uniformity was tested by measuring the wire resistance for each 200-mm axial length (ohms/mm). This resulted in a maximum nonuniformity error of 6% relative to its mean value. The resistance of two wire leads was also measured to have a value of 0.09 ohms. Next, the duct was coated using a high thermal conductivity and high temperature cement to firmly position the wiring and to uniformly distribute heat.

A specially designed bed was used to support the test section and to facilitate the future rotation of the duct. After the duct was connected to the test loop with an exceptional care as to its horizontality, each initially calibrated thermocouple was installed in the thermocouple well and attached to the duct wall. Each well was then filled with a high thermally conductive paste (Omegatherm 201, k = 125 W/mK) and sealed with solid epoxy to keep the paste always in contact with the duct wall. All thermocouple readings were taken by a digital potentiometer in °F or °C (Leads and Northrup, model 938 Numatron). Input power to the heating

[2] *The chosen resistance ribbon was made of copper-nickel resistor alloy, having a thickness of* 0.51 *mm, a width of* 3.18 *mm, and a resistance of* 0.3209 *ohms/m. Its favorable physical properties are low temperature coefficient of resistance and low thermal coefficient of linear expansion (* $\pm 20 \times 10^{-6}$ *ohms/ohm/°C and* 14.9×10^{-6} *cm/cm/°C, respectively, for temperature ranging from* 20 *to* 100°C).

wire was regulated by a power variac connected to a 208 A.C. supply and measured by a digital wattmeter (Electron Industries, model W100). The input voltage and current were displayed in a voltmeter and an ammeter. Their accurate readings were also obtained by a digital multimeter. Pressure drop across the heated section was sensed through a diaphragm differential pressure transducer (Rosemount Inc., model 1151DP; output: 4 – 20 mA DC; range: 0 – 1.5 inches water). The transducer was excited by a D.C. power supply (Lambda Electronics, model LL-905) with an adjustable range of 0 – 120 V and 0 – 0.65 mA. An analog computer, Macsym 2, was used to receive the transducer outputs and to average the pressure readings. All test sections were finally covered by a 50-mm layer of fiberglass insulation to minimize external heat losses. Estimates of the heat conduction losses through the insulation were obtained using a thermo-electric heat flux transducer (Heatprobe, model HA-100, range of 0.3 – 300 W/m^2) attached to the insulation.

6.2 Procedure and Data Reduction

6.2.1 Calibration

All measuring devices such as the flowmeters, the wattmeter, the pressure transducer and thermocouples were calibrated. The pressure transducer was calibrated at room temperature using a water-column manometer, a multimeter, and the analog computer. After the upstream and downstream fluid thermocouples were calibrated, errors in the wall-thermocouples readings were detected through the isothermal maximum flowrate tests. These were achieved by closing the by-pass line and isolating the flowmeters and heat exchangers. Whereas no heat was added in the test section, an isothermal wall-and-fluid condition was established and used to correct the wall-thermocouples readings. To cover all the range expected during testing, 13 calibration runs were done for fluid temperature levels ranging from 18 to 83 °C. Using the 13 readings at each wall thermocouple and the corresponding bulk temperatures, a calibration formula was generated and was used to correct the readings of that particular thermocouple during the heat transfer tests.

6.2.2 Isothermal Pressure-Drop Test

To determine the critical Reynolds number Re_{cr} for laminar-turbulent transition in the semicircular duct, isothermal pressure-drop measurements were begun at a low flow rate of about 5.8 cm^3/s ($Re \approx 200$). For this constant flow rate, readings for the upstream and downstream bulk temperatures and the pressure drop were taken when steady state conditions were reached. The same procedures were repeated for next higher flow rate or an increase in Re until the flow evidently transformed to turbulent flow. All runs were conducted at an inlet fluid temperature nearly equal to the room temperature. Since the test section received no heat, the upstream and downstream bulk temperatures were approximately the same.

6.2.3 Heat Transfer Measurement

For each run with a flow rate and an input power, at least 5 hours of operation were needed to keep the input conditions unchanged before a thermal equilibrium was established. Such steady state conditions were indicated by the constancy of all thermocouples, flowmeters, and pressure-transducer readings. Then, all data of wall and bulk thermocouples, flowmeters, wattmeter, multimeters, and analog computer were recorded. Meanwhile, heat conduction losses through the insulation were measured by attaching the thermal electric heat flux transducer on the insulation at a number of axial locations. Next, the pump was shut off, and so was the input power immediately thereafter. The analog computer continued to record the pressure transducer readings for over 5 minutes. These time-variant data were then used to determine the reference pressure at which the pressure transducer would have given zero output if it had been calibrated under the above conditions, namely, stagnant fluid but with a certain temperature distribution.

6.2.4 Data Reduction

A FORTRAN computer program listed in Appendix D was prepared to reduce the experimental data. The program accommodated a table of thermophysical properties of saturated water [113] for interpolating any property value at a known temperature. To take into account heat conduction dissipation along the longitudinal duct wall at the beginning and the end of heating, a procedure described in [112] was used to correct the upstream bulk temperature t_{mi} and the downstream bulk temperature t_{mo}. Between them, a straight line was fitted to determine local bulk temperature: $t_{x,m} = t_{mi} + (t_{mo} - t_{mi})X/L$, where X/L is the ratio of the distance from the beginning of heating to the total length of the heated section. The rate of heat gain by the test fluid Q_f was then calculated and compared to the electric power input Q_e. Each set of data with an overall energy balance error within $\pm 8\%$ was accepted. The Reynolds number and Darcy friction factor were defined, in terms of mass flow rate $\dot{m}$, pressure drop ΔP across the heated section L, and the actual flow area A_{fl}, as

$$Re = \frac{D_h \dot{m}}{\mu A_{fl}} \quad \text{and} \quad f = \frac{\Delta P D_h \rho A_{fl}^2}{2L\dot{m}^2} \tag{6.1}$$

The modified Grashof number and Rayleigh number were defined by

$$Gr = \frac{\beta g \rho^2 D_h^4 Q_f}{\mu^2 k A_{iw}} \quad \text{and} \quad Ra = GrPr \tag{6.2}$$

where A_{iw} is the inside circumferential heated duct area. [3] The local Nusselt number was also given by

$$Nu_{x,j} = \frac{h_{x,j} D_h}{k} = \frac{Q_f D_h}{A_{iw} k (t_{x,j} - t_{x,m})} \tag{6.3}$$

where j refers to a, b, and c for the wall thermocouple positions as shown in Fig. 6.1. The fluid thermal conductivity k was evaluated at the local bulk mean temperature $t_{x,m}$. The local but peripherally averaged Nusselt numbers could be obtained either

[3] *Note that* $Gr/Gr^+ = (2\pi)^4/(\pi+2)^5 \approx 0.4337$ *for the semicircular duct.*

by averaging the peripheral wall temperatures $t_{x,j}$, or by averaging the peripheral heat transfer coefficients $h_{x,j}$, namely,

$$\overline{Nu_{x,t}} = \frac{Q_f D_h}{A_{iw} k(\overline{t_{x,j}} - t_{x,m})} \quad \text{or} \quad \overline{Nu_{x,h}} = \frac{Q_f D_h}{A_{iw} k(t_{x,j} - t_{x,m})} \tag{6.4}$$

Due to symmetry, a better way to average a peripheral quantity ($t_{x,j}$ or $h_{x,j}$) may be, taking $\overline{t_x}$ as an example, like $\overline{t_x} = ((t_{x,a} + t_{x,c})/2 + (t_{x,b} + t_{x,c})/2)/2$. It is also useful to obtain the mean value of $\overline{Nu_{x,t}}$ and $\overline{Nu_{x,h}}$, denoted by $\overline{Nu_{x,th}}$, where $\overline{Nu_{x,th}} = (\overline{Nu_{x,t}} + \overline{Nu_{x,h}})/2$.

6.2.5 Experimental Uncertainties

Experimental uncertainties were estimated using the method of Holman [114]. For this experiment, friction factors and Reynolds numbers were considered to be accurate to within $\pm 8\%$ and $\pm 4\%$, respectively. Regarding heat transfer, it was noted first that the effects of axial heat conduction through the duct wall might cause the heat flux gained by the fluid to differ from the heat flux imposed on the outer surface of the duct. Such effects were significant in the thermal entrance region but they diminished as the change in the axial gradients of wall temperatures decreased. Assuming uniform peripheral wall temperature and negligible effects of the duct thickness, an analysis was performed (see Appendix C for details) which predicted a maximum difference of 3% between the fluid heat flux and the input flux on the outer surface of the duct. Including this consideration, uncertainties for the Rayleigh number and Nusselt number were estimated to be within $\pm 12\%$ and $\pm 14\%$, respectively.

6.3 Experimental Results

Experiments were performed for both the isothermal and heating cases. For the latter, 92 different condition runs (see Appendix E) were completed for Re_m ranging from 400 to 1600 and for Ra_m ranging from 5.6×10^6 to 4.6×10^8, where the

Table 6.2: Ranges of Operating Conditions for the Heating Case

$\dot{m}$ (g/s)	7.10 – 46.37	Re_m	399 – 1061
W (mm/s)	7.39 – 47.81	Gr_m	$9.1 \times 10^5 - 1.3 \times 10^8$
Q_e (kW)	0.133 – 4.578	Ra_m	$5.6 \times 10^6 - 4.6 \times 10^8$
Q_f/A_{iw} (kW/m^2)	0.213 – 7.164	Pr_m	3.36 – 6.24

subscript $_m$ for Re_m and Ra_m indicates that the corresponding fluid properties were evaluated at the average of the upstream bulk temperature and the downstream bulk temperature. For each combination of Re_m with Ra_m, the downstream bulk temperature was controlled not to exceed 85 °C while all local Reynolds numbers were less than 2100. More details on the ranges of these operating conditions are provided in Table 6.2. The following sections present the experimental results, together with comparisons to the previous predictions and available results of others.

6.3.1 Isothermal and Diabatic Friction Factors

Figure 6.2 shows both the isothermal friction factor and a typical diabatic result. The f values for $Ra_m = 0$, which are subjected to fully developed conditions, monotonically drop with increasing Re in the laminar region. These results are in good agreement with the Darcy friction factor prediction of $15.7668/Re$ ([103,101]), with a maximum deviation of 8%. At the critical Reynolds number (Re_{cr}) of about 2100, a sudden jump in the value of f indicates the laminar-turbulent transition. For a heating case, as shown in Fig. 6.2 for $Ra_m = 1.73 \times 10^8$, significant increases in f can be seen especially at low Re. These are due to buoyancy effects on axial velocity distributions. As Re decreases, the intensity of the buoyancy-induced secondary flow becomes relatively stronger (e.g., having higher values of Gr/Re^2). This causes severer distortions of the axial velocity profile as predicted in Chap. 5, hence resulting in large increases in the f values.

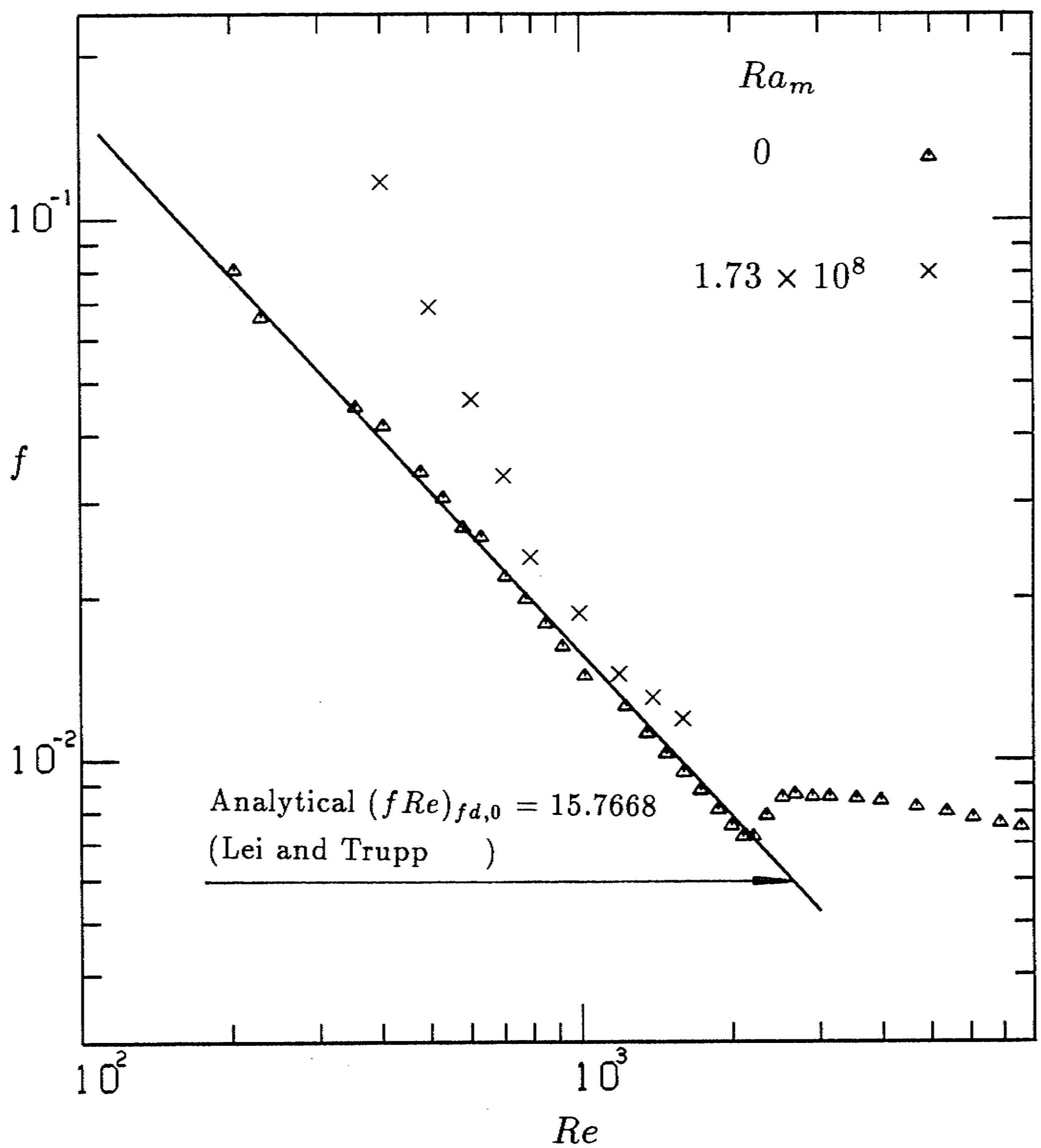

Figure 6.2: f vs.Re Variation

Buoyancy effects on friction factor are further illustrated in Fig. 6.3 which shows the ratio of diabatic friction factor (f_{dia}) to isothermal friction factor (f). The augmentation can be observed to be as much as a factor of two at high Gr_m. As suggested in Chap. 5, the mean Grashof number Gr_m, rather than Ra_m, [4] was used to correlate the experimental data and a least-square-fit expression is given by

$$\frac{(f_{dia}Re)_m}{(fRe)_{fd,0}} = 1 + 5.269 \times 10^{-10}(Gr_m)^{1.138} \qquad (\sigma = 7.5\%,\ \sigma_{max} = 16\%) \tag{6.5}$$

which satisfies the lower limit value of the ratio $(f_{dia}Re)_m/(fRe)_{fd,0}$. Equation (6.5) correlates all data fairly well, having a standard deviation (σ) of 7.5% of the average friction ratio in the range and a 16% maximum deviation (σ_{max}). As indicated by Fig. 5.28, using the parameter of $Gr_m/Pr_m^{1.8}$ results in a slightly better fit:

$$\frac{(f_{dia}Re)_m}{(fRe)_{fd,0}} = 1 + 2.736 \times 10^{-7}\Big(\frac{Gr_m}{Pr_m^{1.8}}\Big)^{0.926} \qquad (\sigma = 7\%,\ \sigma_{max} = 15\%) \tag{6.6}$$

Note that in Fig. 6.3 all the data are divided into two groups partitioned at $Re_m = 1000$. An attempt to isolate the small Re_m effect on the friction ratio revealed the following pattern. For $Gr_m \leq 2\times10^7$, the ratios, although rising slightly with increasing Gr_m, show only a very weak dependence on Re_m. The data points for $Re_m < 1000$ appear somewhat lower than those for $Re_m > 1000$. Besides the experimental uncertainties, this is probably due mainly to fluid properties variations (e.g., high flow rates bring about low fluid temperature variations and tend to wash out the effect of fluid properties, hence nearly giving an expected unit ratio at low Gr_m). On the other hand, for $Gr_m > 2 \times 10^7$, it is apparent that friction factor ratios increase markedly with increasing Gr_m. For a given Gr_m, the ratio is now generally somewhat higher for data with $Re_m < 1000$. This can probably

[4] *If Ra_m is used, the experimental data are correlated by*

$$\frac{(f_{dia}Re)_m}{(fRe)_{fd,0}} = 1 + 1.8121 \times 10^{-4}(Ra_m/10^6)^{1.40} \qquad (\sigma = 8.4\%,\ \sigma_{max} = 17.3\%)$$

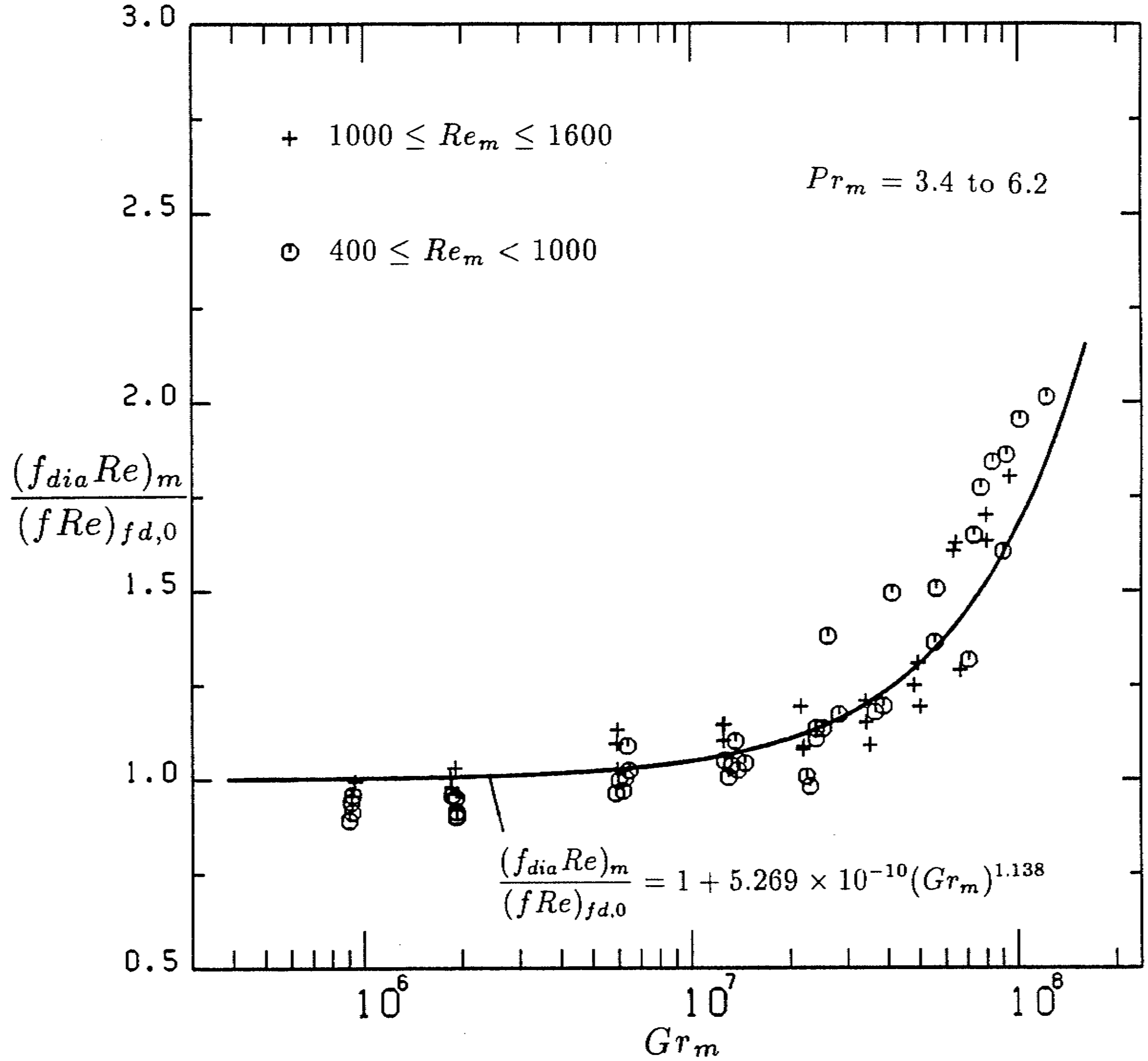

Figure 6.3: Buoyancy Effects on Measured Friction Factor Ratios

be attributed to relative buoyancy effects, e.g., for low Re, a higher Gr/Re^2 value, as discussed earlier. It should be noted that, in the existing literature, no similar experimental data are available. A comparison was made (not illustrated) with the friction ratio of Morcos and Bergles [95] who studied laminar flow in a stainless tube using ethylene glycol as a working fluid. For a given same Gr_m, their friction ratios were significantly higher than the present results. This was consistent with the predictions of Nandakumar *et al.* [61] who found that circular tubes resulted in higher friction ratios than semicircular ducts.

6.3.2 Wall Temperature Distribution

The axial distributions of wall temperatures are shown in Fig. 6.4 for two different heating rates but the approximately same Reynolds number ($Re_m \approx 600$). Since the same trends hold at other Re_m level, these plots serve as a typical example. At each axial station, three temperatures are shown corresponding to the three wall thermocouples (see Fig. 6.1 for the positions). These provide an indication of peripheral variations in wall temperatures. As illustrated, all t_a and t_b values are nearly equal. This indicates that in the present study, a symmetric three-dimensional flow exists about the vertical center plane of the duct. However, all wall temperatures at the duct bottom, t_c, are noticeably lower than t_a or t_b, except for near the entrance where free convection effects are negligible. In this early thermal boundary layer development region, the copper duct distributes heat fairly uniformly on the circumferential walls of the duct. This is particularly evident for the lower heating rates in Fig. 6.4a. Thus, the theoretical thermal boundary condition $H1$ may be utilized here as a good approximation.

As the thermal boundary layer develops, the heated fluid near the bottom becomes lighter and rises up while, by continuity, the cooler and heavier core fluid descends (see the predicted counter-rotating vortices in Chap. 5). As a result, the buoyancy-induced secondary flow gives rise to the variation of circumferential wall

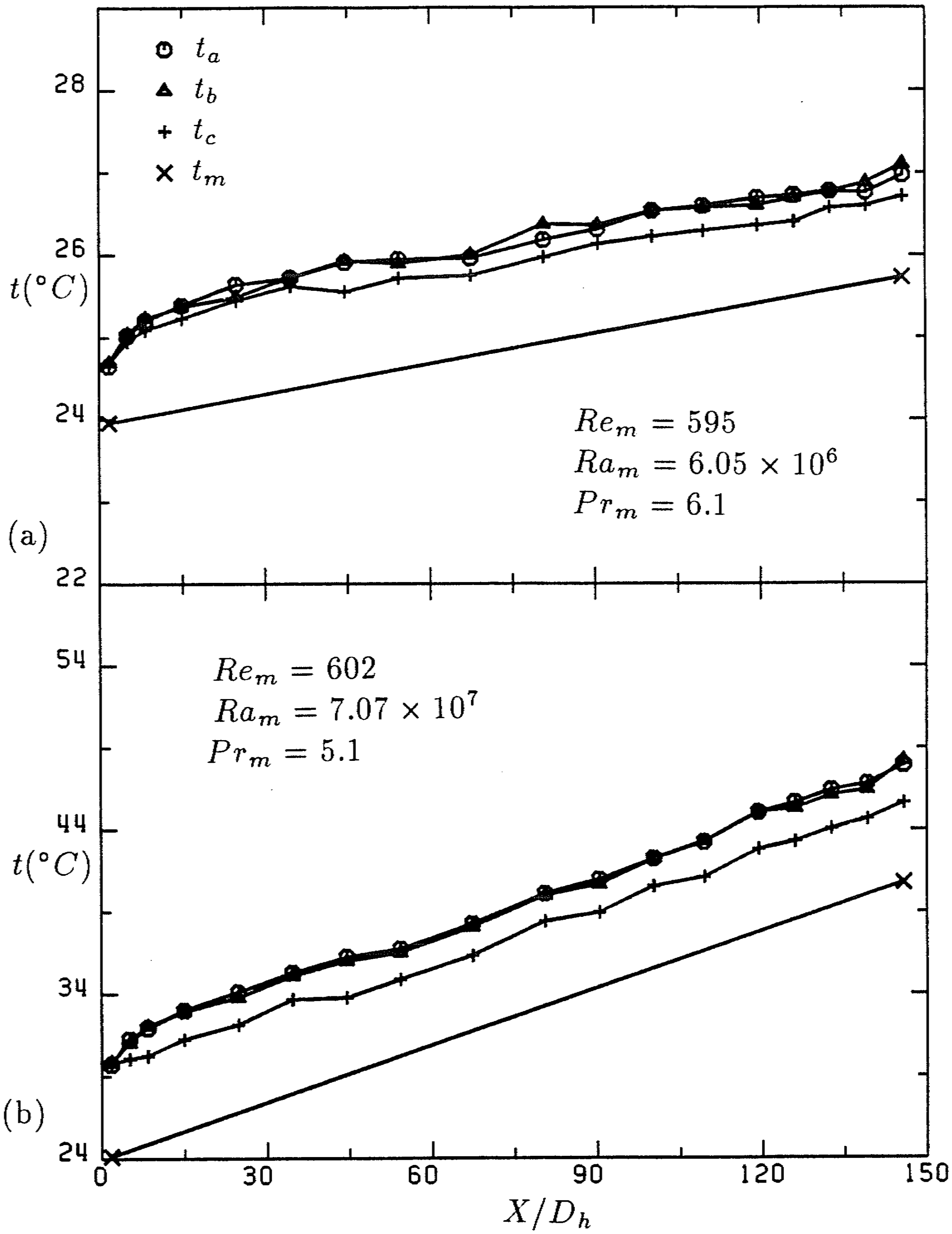

Figure 6.4: Distributions of Measured Axial Temperatures

temperatures. In Fig. 6.4a for $Ra_m = 6.05 \times 10^6$, an average difference between t_a (or t_b) and t_c is about 0.3 ℃ while it is about 2.1 ℃ in Fig. 6.4b for $Ra_m = 7.07 \times 10^7$. The first discernible reduction of t_c relative to t_a (or t_b) indicates the onset of the secondary flow. In Fig. 6.4b, this reduction is observed to occur at a much earlier longitudinal station than in Fig. 6.4a where Ra_m is lower. This indicates earlier onset of the secondary flow with increasing Ra_m. Beyond that, the secondary flow continues to grow and causes t_c to remain relatively lower. It is then followed by slight fluctuations in the rising t_c due to the strengthening and weakening pattern (as discussed next) of thermal instability at the bottom surface. In contrast, the increase of t_a or t_b is more stable because of the thermal stratification of the top boundary layer, as predicted and discussed in Chap. 5. Also, these results are consistent with the flow visualization and temperature measurements of Osborne and Incropera [84] who observed a weak buoyancy influence on their top plate condition for parallel plates with asymmetric heating.

6.3.3 Local Heat Transfer

6.3.3.1 Nusselt Number Distribution

Figure 6.5 illustrates typical Nusselt number distributions with the inverse Graetz number x^* for the same conditions as those in Fig. 6.4a. At each location, Nusselt numbers for positions a and c as well as a cross-sectional-average value are presented. For $x^* < 0.001$, they all nearly fall between the two forced convection limits of Lei and Trupp [99,100] for the $H1$ and $H2$ conditions. The expected decay in Nu_x and its small circumferential variation indicate that the dominant laminar forced convection flow still has negligible free convection effects. As x^* increases beyond about 0.001, temperature gradients at the bottom surface first induce thermal instability, resulting in a lower temperature at the bottom surface (Fig. 6.4a) and hence a higher $Nu_{x,c}$ value. With the development of the secondary flow, $Nu_{x,c}$

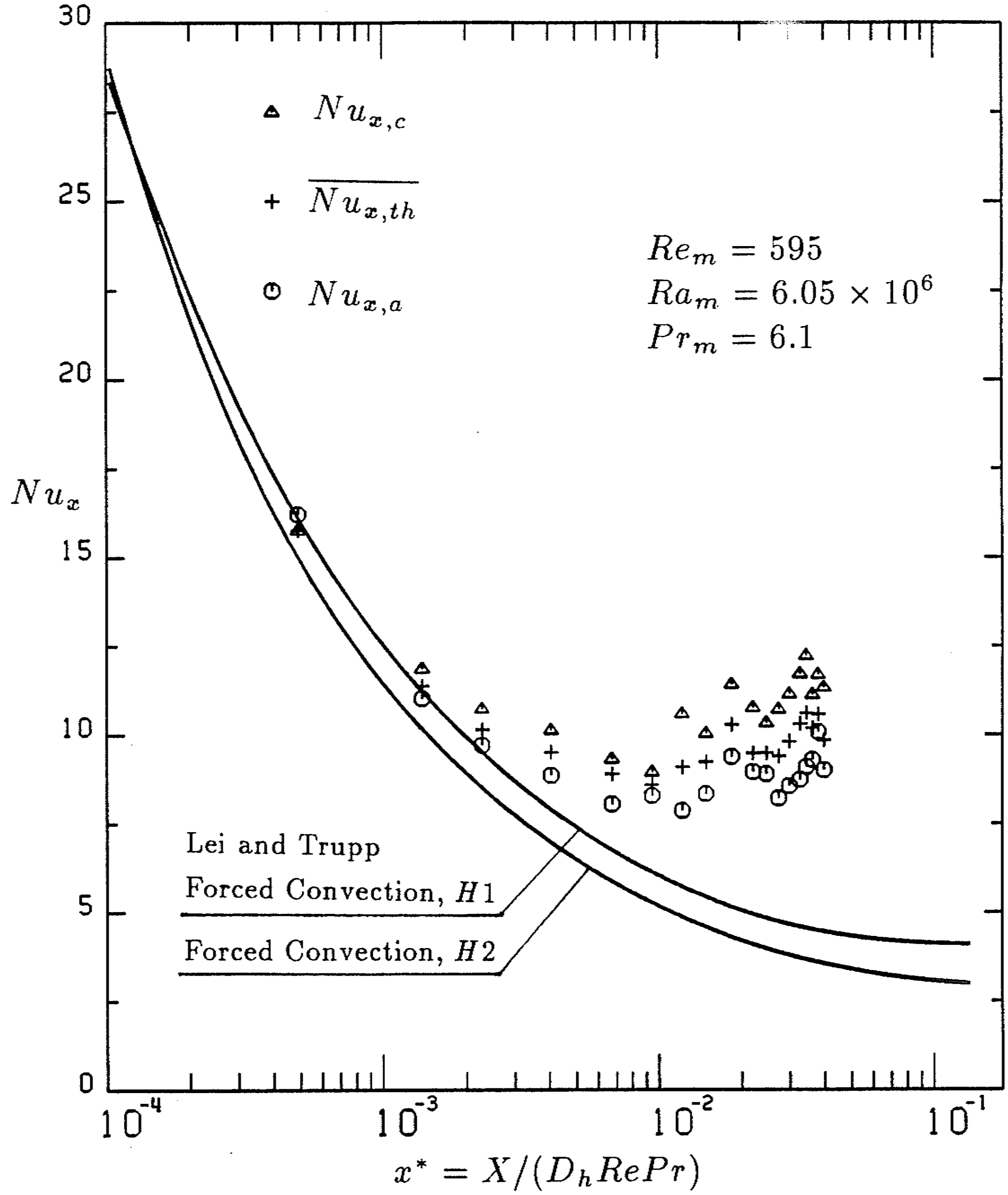

Figure 6.5: Typical Nusselt Number Distributions

progressively exceeds its forced convection limits and the difference between $Nu_{x,a}$ and $Nu_{x,c}$ becomes appreciable. At $x^* \approx 0.01$, a minimum for $\overline{Nu_{x,th}}$ is observed. Subsequently, $\overline{Nu_{x,th}}$ continues to increase due to continuing development of the secondary flow until its first maximum is reached at $x^* \approx 0.018$. The maximum is followed by a decreasing trend in all local Nusselt numbers. This is because the core fluid has been already warmed by the secondary flow and the reduction in the surface temperature by the descending fluid is less pronounced. Accordingly, the cross-sectional fluid circulation becomes weaker and the Nusselt numbers begin to decline. As the heating continues, the decline ends, e.g., at $x^* \approx 0.028$ for the second minimum of $\overline{Nu_{x,th}}$. Beyond the minimum point, the warm fluid rising and the cool fluid descending once more strengthen the secondary flow and cause another increase in the Nusselt number. Further observations suggest that the fully developed conditions for the mixed convection flow have been practically achieved within last 6 stations. Although the continuing oscillations can still be seen in this fully developed region especially for $Nu_{x,c}$, the magnitude between a peak and a valley is now relatively much less. In effect, the development of the secondary flow is first such that it "overshoots" its steady-state strength, but it is forced to return since temperature differences (which drive the buoyancy forces) have been diminished. There is then an "undershoot" in which temperature differences are regained to cause a subsequent correction.

As just described, the foregoing oscillations in Nusselt numbers have been recognized by many investigators. A recent numerical study by Mahaney et al. [32] has been reported that the secondary flow is characterized by a fluctuating intensity along the longitudinal direction, which is consistent with the above observations. Since the secondary flow itself attenuates its size and strength and is intensified by further heating, the oscillating behavior should be detected in both measurements and predictions of horizontal laminar mixed convection flows.

6.3.3.2 Effect of Reynolds Number

Comparisons of the local cross-sectional-average Nusselt number $\overline{Nu_{x,th}}$ for three different Re_m but $Ra_m \approx 1.17 \times 10^7$ are made in Fig. 6.6 using the coordinates of X/D_h and x^*. The effect of Reynolds number on $\overline{Nu_{x,th}}$ in Fig. 6.6a appears weak except for $X/D_h <\sim 25$. At the first station, $X/D_h = 1.8$, axial heat conduction within the fluid appreciably influences $\overline{Nu_{x,th}}$, giving a lower $\overline{Nu_{x,th}}$ value for a smaller Péclet number ($Pe = RePr$) and a higher $\overline{Nu_{x,th}}$ value for a larger Pe. Such characteristics are consistent with those of pure forced convection laminar flow as documented in great detail by Shah and London [101]. In the presence of free convection effects, decreasing Reynolds number can be observed from Fig. 6.6a to shift the onset of the secondary flow upstream (see the start symbol for the onset locations). Maughan and Incropera [97] have demonstrated a similar pattern in mixed convection heat transfer measurements for airflow in a horizontal parallel plate channel. Other experimental results with $Ra_m < 7 \times 10^7$ ([115]) and numerical predications ([73,116]) suggest that mixed convection flows may be scaled with the inverse Graetz number, x^*. The present results are thus shown in Fig. 6.6b where $\overline{Nu_{x,th}}$ vs. x^* is seen to be fairly independent of Re_m. Hence, at low or medium heating rates, Re_m, though stretching the flow, has practically little influence on the local Nusselt number when x^* is used as a scaling parameter.

The influence of Reynolds number on $\overline{Nu_{x,th}}$ is further shown in Fig. 6.7 for a higher Rayleigh number ($Ra_m \approx 2.88 \times 10^8$). At this much higher heating rate, the destabilization of thermal boundary layer occurs further upstream. Reducing Reynolds number not only advances the onset of secondary flow but also decreases $\overline{Nu_{x,th}}$ (Fig. 6.7a), i.e., there appears to be a distinct Re_m dependence. In addition, the present results show considerable scatter when plotted against the inverse Graetz number (Fig. 6.7b) although experimental uncertainties and property variations are considered to contribute partially to this increased scatter. With increasing

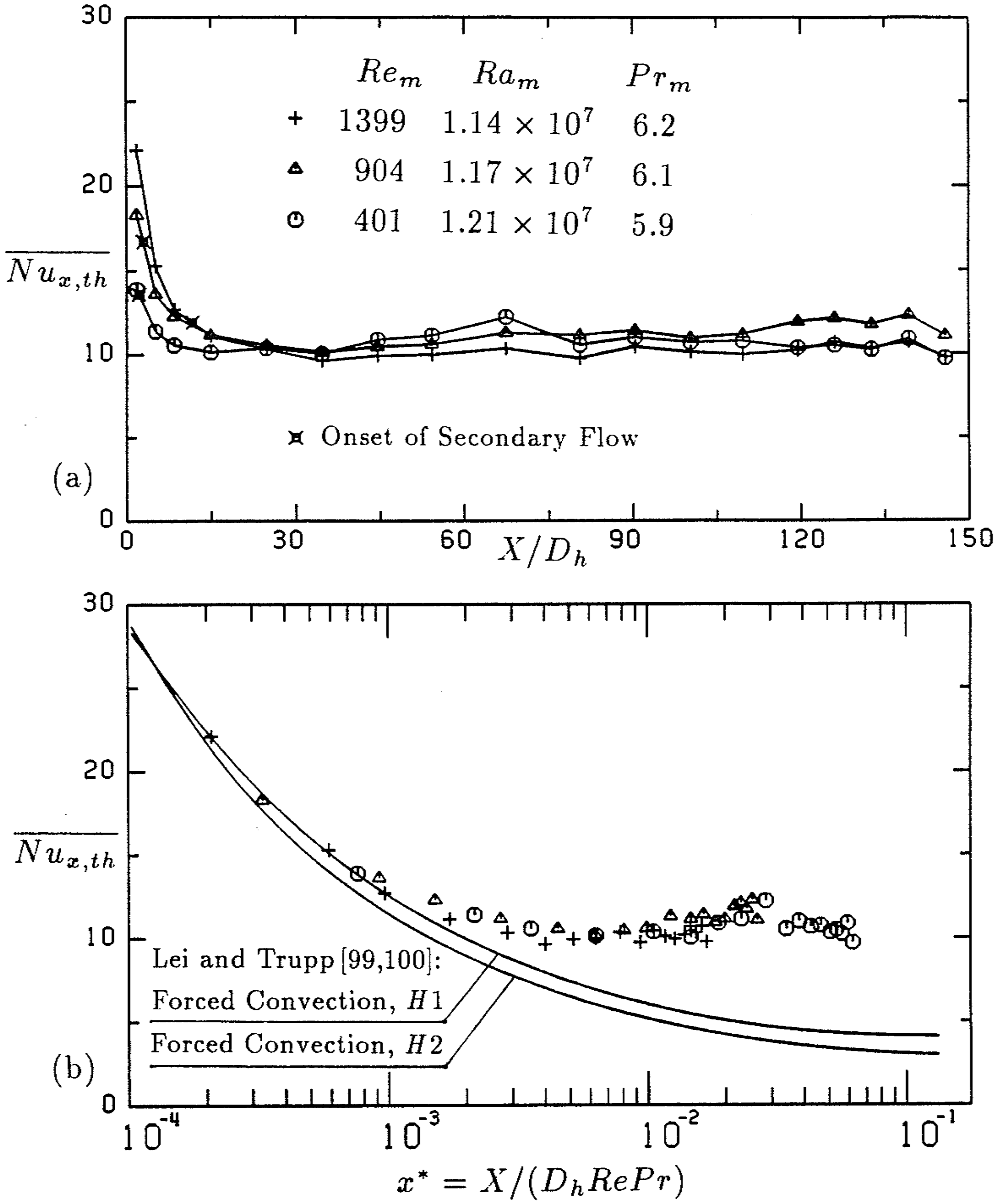

Figure 6.6: Influence of Reynolds Number on Local Nusselt Numbers for $Ra_m \approx 1.17 \times 10^7$

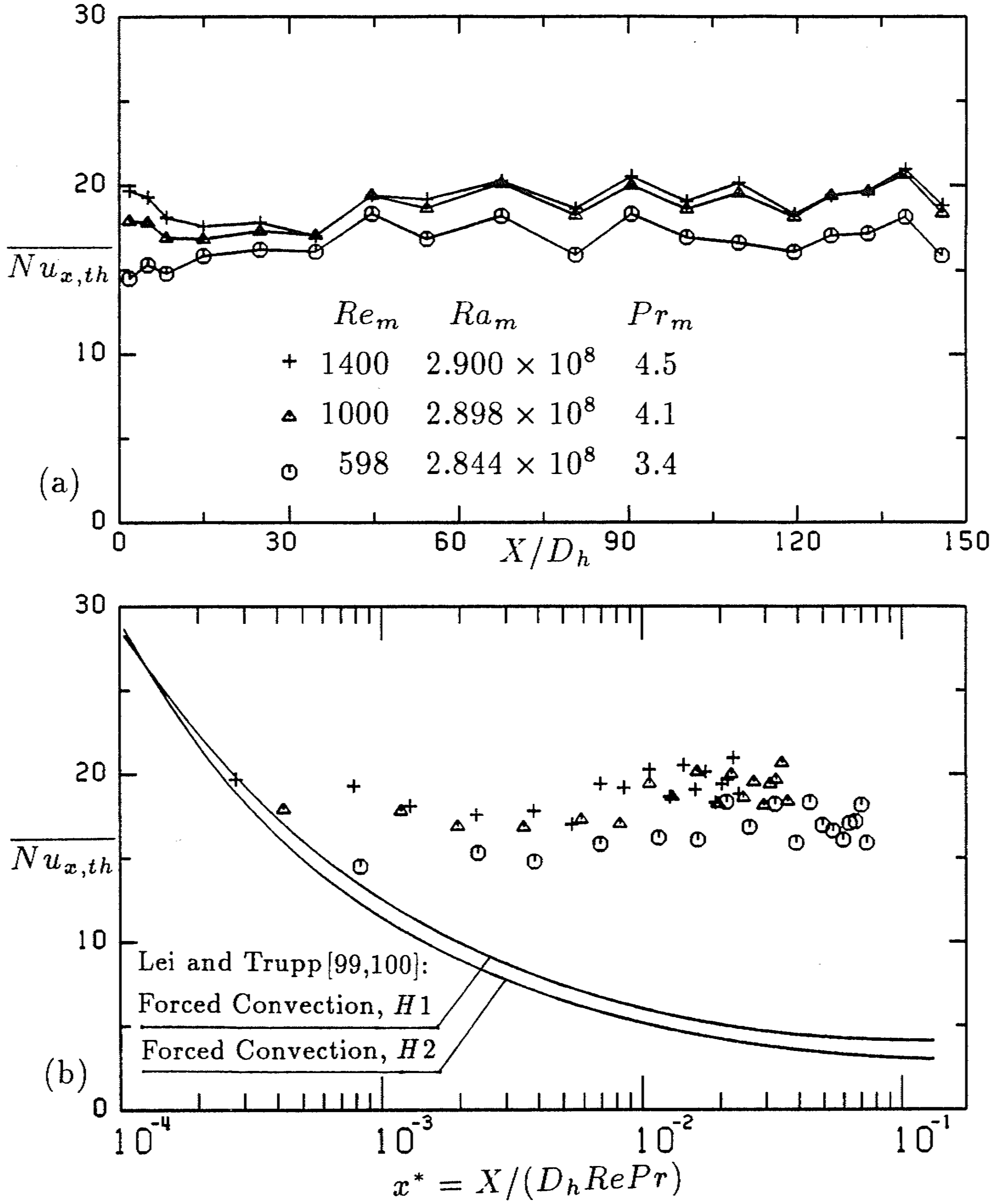

Figure 6.7: Influence of Reynolds Number on Local Nusselt Numbers for $Ra_m \approx 2.88 \times 10^8$

Ra_m, the intensity of the secondary flow increases and hence may promote earlier transition to turbulent free convection. Existing experimental results of other investigators ([83,88,117]) also display substantial fluctuations with Reynolds number, particularly when subjected to high heating rates. Another possible reason for the Re_m dependence at high Ra_m may be accounted for by the type of vortex secondary flow pattern which has been explored in Chap. 5.

6.3.3.3 Effect of Rayleigh Number

A sample illustration of the Rayleigh number influence on $\overline{Nu_{x,th}}$ is provided in Fig. 6.8 for three different Ra_m but approximately the same Re_m. The zero Ra_m curve for the $H1$ condition serves well as a base-line reference for the lowest heating rate in the laminar forced convection region. First, increasing Ra_m can be seen to have a strong effect on heat transfer enhancement. The fully developed results of $\overline{Nu_{fd,th}}$ for these three Ra_m exceed respectively a factor of 2.2, 3.2, and 4.4 over $(Nu_{fd,H1})_0$, and 3.1, 4.5, and 6.2 over $(Nu_{fd,H2})_0$, where $(Nu_{fd,H1})_0$ and $(Nu_{fd,H2})_0$ are the fully developed Nusselt numbers for the laminar forced convection ([99,100]). The enhancement is due to the presence of free convection currents which form a powerful mechanism for the fluid to transport momentum and thermal energy. Secondly, increasing Ra_m is observed to shorten the thermal entrance length [5] and to move the onset of the secondary flow upstream. Thirdly, Fig. 6.8 shows that the frequency and magnitude of oscillations in $\overline{Nu_{x,th}}$ (as discussed before) decrease with reducing Ra_m or weakening of the secondary flow.

[5] *For design purposes, similar to the case of pure forced convection, information may be required on thermal entrance lengths for the mixed convection flow. However, the characteristics of buoyancy-induced secondary flow make it very different to provide this information with reasonably accuracy. From Fig. 6.8, the estimate of the distance required to achieve a relatively flat pattern for* $\overline{Nu_{x,th}}$ *is about 7%, 9%, and 15% of the thermal entrance length for the forced convection flow for* Ra_m *of* 1.76×10^8, 3.47×10^7, *and* 5.69×10^6, *respectively.*

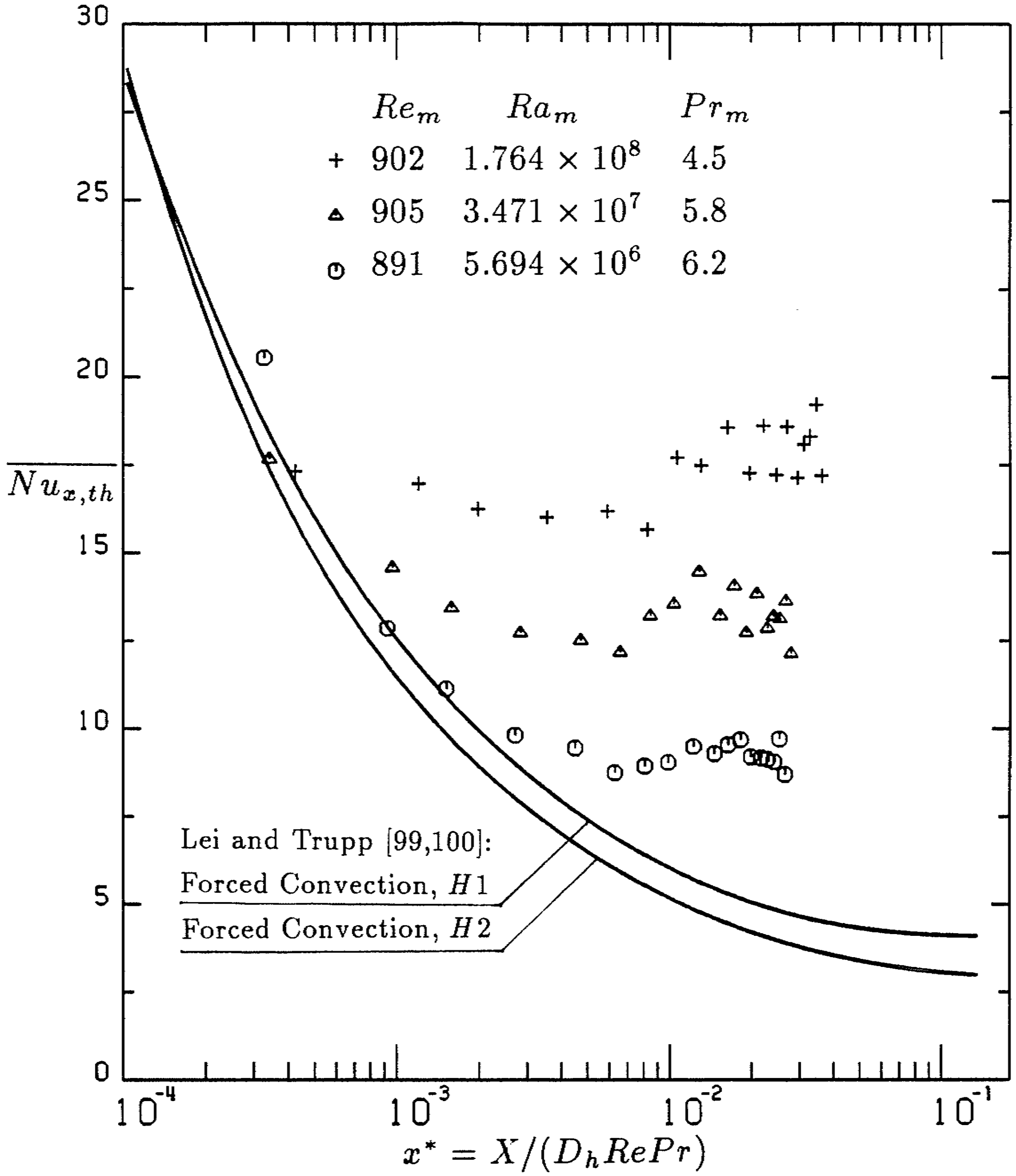

Figure 6.8: Influence of Rayleigh Number on Local Nusselt Numbers

6.3.4 Onset of the Secondary Flow

The axial distance where the local $\overline{Nu_{x,th}}$ value is first to exceed 5% of the forced convection value $(Nu_{x,H1})_0$ was taken to mark the onset of the secondary flow. From previous observations, the onset point was known to advance with reducing Reynolds number and with increasing Rayleigh number. This suggests that the critical value $(X/D_h)_{cr}$ may be correlated with the parameter of $(Gr/Re^2)_{cr}$. Figure 6.9 indeed shows this to be the case. As illustrated, the majority of the data points for $(X/D_h)_{cr}$ are below 5 which correspond to values over 3 for $(Gr/Re^2)_{cr}$. These indicate the early onset of the secondary flow for most test runs in which about 96% of the heated section [6] was subjected to significant free convection effects. Such an expected outcome is due to the use of a relatively large hydraulic diameter ($D_h = 30.4$ mm) and high heat flux levels.

When studying onset of the secondary flow in horizontal rectangular ducts, Ou et al. [76] correlated their Rayleigh number in terms of Graetz number while Gilpin et al. [81] correlated their Grashof number versus Reynolds number. Efforts to produce parallel correlations for the present experimental data were unsuccessful. However, as shown in Fig. 6.9, a least-square-fit gives the following expression

$$\left(\frac{X}{D_h}\right)_{cr} = 1.4 + 9.63\left(\frac{Gr}{Re^2}\right)_{cr}^{-0.86} \qquad (\sigma = 9\%,\ \sigma_{max} = 29\%) \tag{6.7}$$

which deliberately introduces a constant, 1.4, to better fit the majority of the data and correlates 83% of the data within 10%. Theoretically, $(X/D_h)_{cr}$ should approach zero as $(Gr/Re^2)_{cr} \to \infty$ and vice versa. Clearly, equation (6.7) obeys the latter limit but approximates the former limit.

An empirical correlation obtained from Incropera et al. [118] for horizontal rectangular ducts is also illustrated in Fig. 6.9 (using $Pr = 5$ and $Re = 800$). Their onset points of the secondary flow, best fitted by $(Gr)_{cr} = 754(Gz)_{cr}^{4/3}$, were determined from measurements using a 10% enhancement of the Nusselt number.

[6] *Note that the total heated section has a X/D_h value of about 150.*

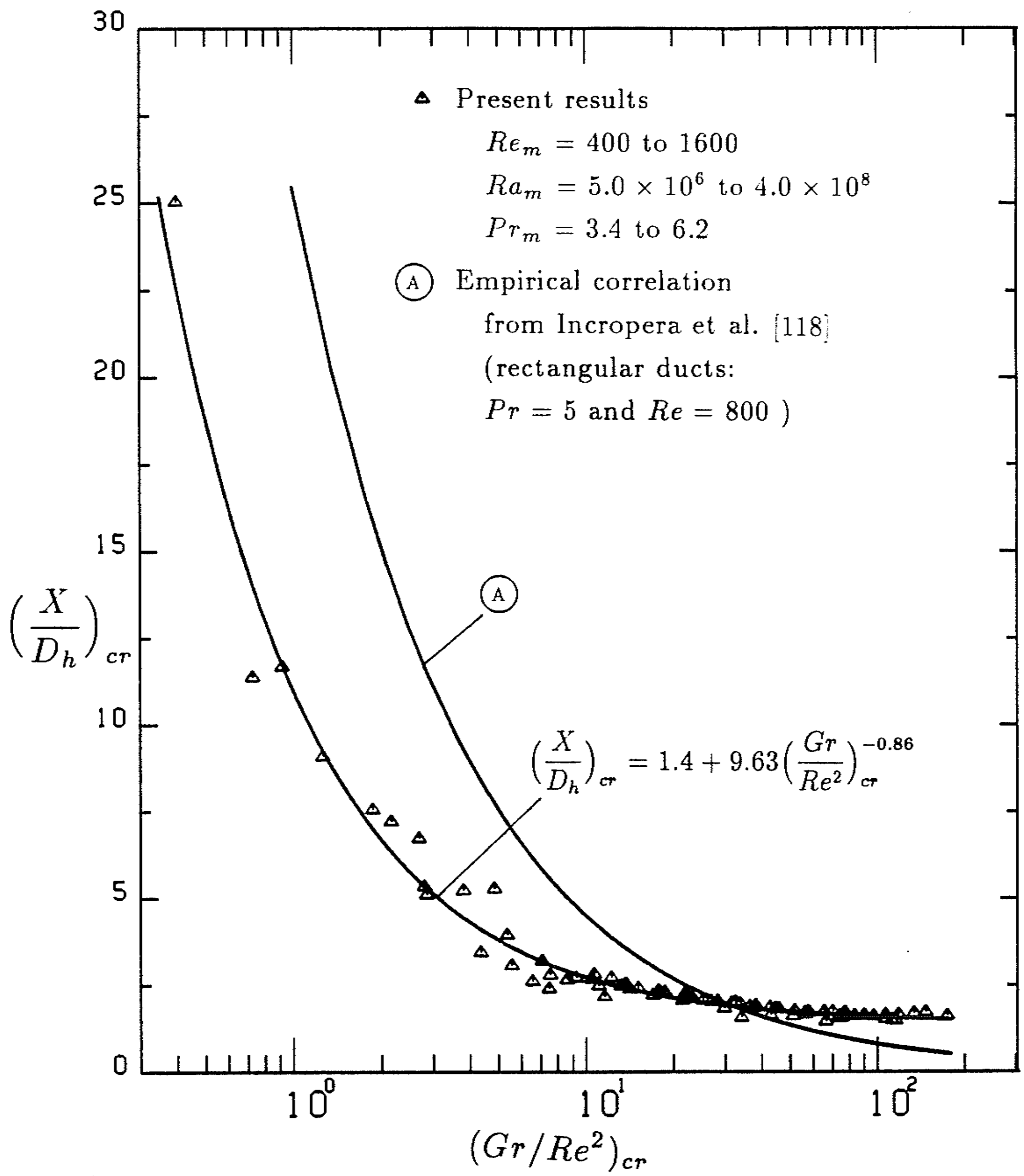

Figure 6.9: $(X/D_h)_{cr}$ vs. $(Gr/Re^2)_{cr}$ for Onset of the Secondary Flow

In spite of the different basis, as shown in Fig. 6.9 for $(Gr/Re^2)_{cr} > 30$, the present results indicate that the thermal boundary layer in the semicircular duct is more stable than that in a rectangular duct heated from below.

6.3.5 Fully Developed Nusselt Number

Even though values of Nu_x (see Figs. 6.5 to 6.8) showed some buoyancy-induced fluctuations and property variations in the flow direction, fully developed conditions were established in most test runs after the eighth wall-temperature-measuring station. To flatten the influences of the above factors, values for the fully developed Nusselt number Nu_{fd} were determined by computing the length-mean average of Nu_x after the twelfth station. Similarly, other quantities (e.g., Re_M, Ra_M, Pr_M, and t_M, etc.) were obtained.

Figure 6.10 demonstrates effects of both Ra_M and Re_M on fully developed heat transfer results. $\overline{Nu_{fd,th}}$ was first normalized by the forced convection $(Nu_{fd,H1})_0$ value (from Table 3.2, $(Nu_{fd,H1})_0 = 4.088$). Then, it was multiplied by a viscosity ratio (as recommended by Kays and Crawford [119]) to take account of property variations in the cross section. As can be seen, increasing Ra_M enhances heat transfer, with a factor up to 4.9 for high heating rates. On the other hand, within the experimental scatter, Re_M has little influence on heat transfer enhancement for $Ra_M <\sim 5 \times 10^7$, which is in agreement with the previous observation made in connection with the thermal entrance region (see Fig. 6.6). But for higher Ra_M, the Nusselt ratios gradually increase with increasing Re_M. This trend, as discussed before, was revealed in Fig. 6.7 from the local Nusselt numbers. Such a Re_M dependence indicates that the experimental data might be correlated by the product of $Re_M Ra_M$ which has a theoretical basis [13] and has been used successfully for circular tubes [98].

First, neglecting any Re_M dependence, the correlating equation can be expressed

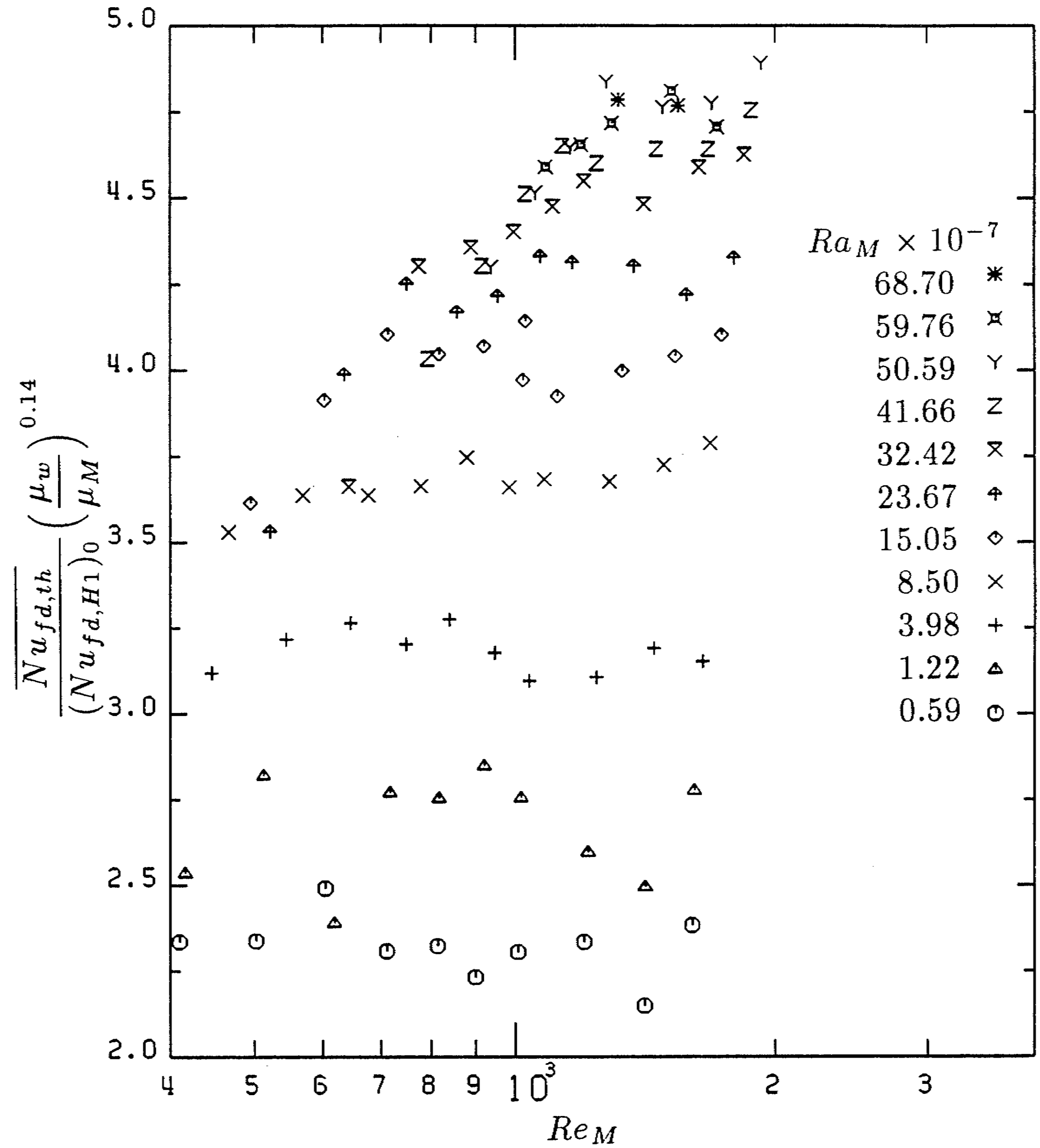

Figure 6.10: Effects of Re_M and Ra_M on Fully Developed Heat Transfer Enhancement

as

$$\frac{\overline{Nu_{fd,th}}}{(Nu_{fd,H1})_0} = 1 + 0.040(Ra_M)^{0.2288} \quad (\sigma = 4.6\%,\ \sigma_{max} = 9.2\%) \tag{6.8}$$

where unity is imposed to satisfy the low limit. By taking into account property variation, an alternative correlation is given by

$$\frac{\overline{Nu_{fd,th}}}{(Nu_{fd,H1})_0}\left(\frac{\mu_w}{\mu_M}\right)^{0.14} = 1 + 0.0446(Ra_M)^{0.2218} \quad (\sigma = 4.0\%,\ \sigma_{max} = 8.8\%) \tag{6.9}$$

As indicated by the values of σ and σ_{max}, equation (6.9) fits the experimental data slightly better than equation (6.8). These two correlations are practically acceptable. Of course, as suggested by Fig. 6.10, still better correlations can be obtained by partitioning the data at $Ra_M = 5 \times 10^7$ into two sets. For $Ra_M < 5 \times 10^7$, the correlation is given by

$$\frac{\overline{Nu_{fd,th}}}{(Nu_{fd,H1})_0}\left(\frac{\mu_w}{\mu_M}\right)^{0.14} = 1 + 0.0267(Ra_M)^{0.2522} \quad (\sigma = 3.4\%,\ \sigma_{max} = 5.8\%) \tag{6.10}$$

This good correlation is illustrated in Fig. 6.11a together with equation (6.9). For $Ra_M > 5 \times 10^7$, the use of the $Re_M Ra_M$ product results in an excellent correlation which is given by:

$$\frac{\overline{Nu_{fd,th}}}{(Nu_{fd,H1})_0}\left(\frac{\mu_w}{\mu_M}\right)^{0.14} = 0.2662(Re_M Ra_M)^{0.1052} \quad (\sigma = 2.3\%,\ \sigma_{max} = 4.7\%) \tag{6.11}$$

Figure 6.11b shows that the use of $Re_M Ra_M$ leads to Nusselt ratios being distributed very uniformly along the fitting curve.

6.3.6 Axial Length-Mean Nusselt Number

For engineering purposes, information is also needed on average Nusselt values in the thermal entrance region. Figure 6.12 provides computed values for the axial length-mean Nusselt number, Nu_{lm}, which is defined by

$$Nu_{lm} = \frac{\int_0^L \overline{Nu_{x,th}}\, dX}{L} \tag{6.12}$$

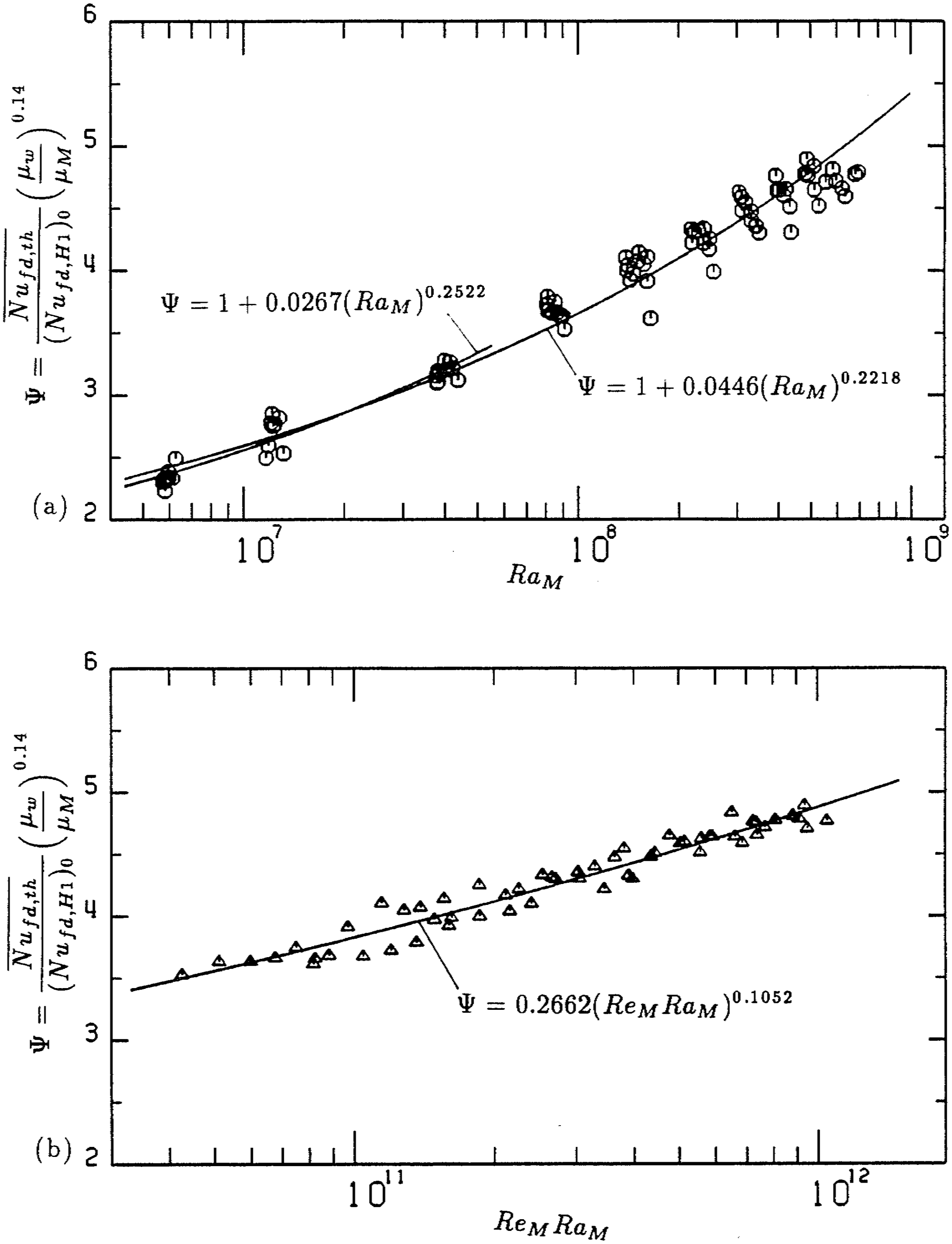

Figure 6.11: Correlations of Fully Developed Nusselt Ratios

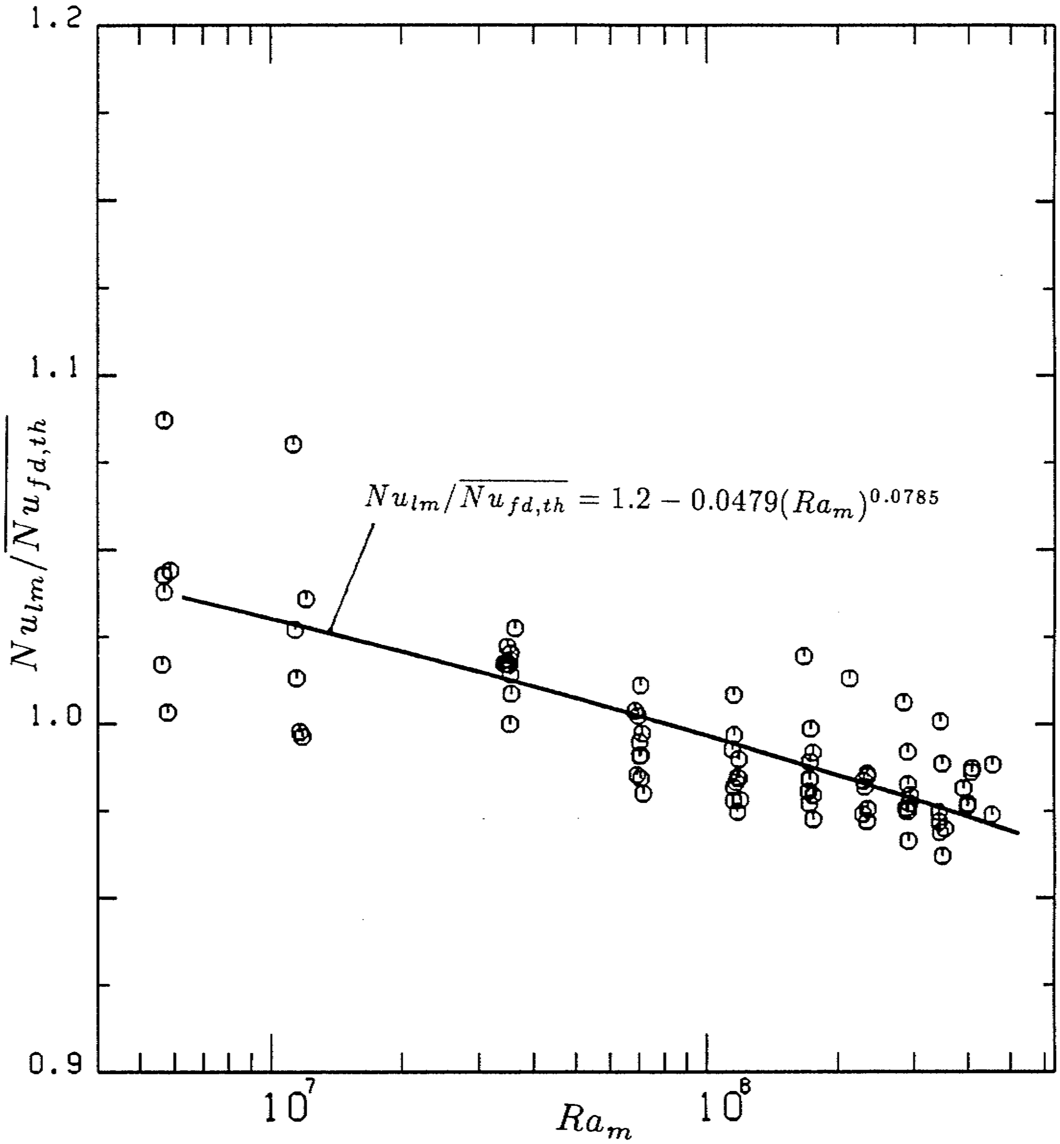

Figure 6.12: Axial Length Mean Nusselt Numbers

As illustrated, the $Nu_{lm}/\overline{Nu_{fd,th}}$ ratios range from 0.96 to 1.09. For $Ra_m < 7 \times 10^7$, most the ratios are over 1. As Ra_m increases, the ratios are seen to decrease and most the ratios become slightly less than 1. This is mainly due to the large values obtained for $\overline{Nu_{fd,th}}$ as buoyancy effects become increasingly significant. Also, note that for pure forced convection cases Nusselt numbers monotonically decrease with increasing the axial length (e.g., see Fig. 4.9). The corresponding ratio of Nu_{lm} to the fully developed Nu value is known to be about 1.2. However, free convection effects generally cause the Nusselt number to vary nonmonotonically with the axial length. For example, referring to Fig. 6.8 for $Ra_m = 3.47 \times 10^7$, the axial Nusselt distribution first exhibits a marked decay for $x^* <\sim 0.007$. The decay is then followed by significant increases in $\overline{Nu_{x,th}}$ as the secondary flow has a chance to be fully developed. Therefore, the shown "valley" region is responsible for the "undershoot" for Nu_{lm}, i.e., causing the $Nu_{lm}/\overline{Nu_{fd,th}}$ to be less than 1.

The data points shown in Fig. 6.12 also display some degree of fluctuation for a given Ra_m. Besides experimental uncertainties, this can be attributed to the Reynolds effect as discussed earlier. In any event, the average ratio for $Nu_{lm}/\overline{Nu_{fd,th}}$ is approximately equal to 1 and the following correlation describes the data:

$$Nu_{lm}/\overline{Nu_{fd,th}} = 1.2 - 0.0479(Ra_m)^{0.0785} \quad (\sigma = 1.4\%,\ \sigma_{max} = 5\%) \qquad (6.13)$$

6.4 Comparison Between Measurement and Prediction

By comparing the measured data with the predicted results, this section is aimed at further understanding of laminar mixed convection in the horizontal semicircular duct. It is necessary first to distinguish between the laboratory flow and the flow described in Chap. 5. The experiments covered the entire processes of the flow development. At the beginning of the heating, the flow with fully developed hydrodynamics started to develop thermally. In the far downstream region, the flow was hydrodynamically and thermally fully developed. However, the simulated flow, subjected to several idealizations that were explicitly stated in Chap. 5, was analyzed only in the fully developed region. In addition, differences between the theoretical thermal boundary condition and the experimental condition should be discussed before some comparisons are made.

6.4.1 Differences Between the $H1$ Condition and the Resistance Wiring Heating Condition

The present predictions utilized the thermal boundary condition of axial uniform heat input with peripheral uniform wall temperature ($H1$). For the experiment, this thermal boundary condition was found (e.g., see Fig. 6.5) to be a good approximation only near the beginning of the heating where buoyancy effects were insignificant. When the buoyancy-induced secondary flow was strong, as predicted in Chap. 5, the warmer fluid continued to ascend primarily along the curved wall until it reached the duct corner. Meanwhile, the cooler core fluid was driven toward the duct bottom. In spite of these flow patterns, the duct wall was numerically forced to remain at a uniform wall temperature. However, the secondary flow in the experimental duct simply deteriorated the uniform wall temperature condition, as seen in Fig. 6.4 and further discussed later. Regardless of the high peripheral thermal conductivity of the copper duct, substantial variations in circumferential wall temperatures were experimentally apparent due to significant secondary flows.

Besides buoyancy effects, the following observation demonstrates that there are difficulties in practically achieving the condition of uniform peripheral wall temperature by heating the semicircular duct with resistance wires. First, consider a piece of the wire with a width δ and a length 2δ. The area of outside duct wall that is directly touched and heated by the wire is thus $2\delta^2$. Then, at a cross section, a fictitious circle with a radius δ may be drawn by taking the centre of the circle on the duct wall. If the centre is on the flat plate, half of this fictitious circle is in the flow. Thus, the ratio of the heated area ($2\delta^2$) to the area ($\pi\delta^2/2$) of the circled cross-stream flow is $4/\pi$. If the centre is on the curved wall, the ratio is approximately the same. If the centre is exactly at the duct corner, less than a quarter of the fictitious circle is in the flow. However, the heated area is still $2\delta^2$ and hence the ratio is over $8/\pi$. This simply suggests that hot spots (high wall temperatures) may occur at the two duct corners. Generally, even though the high thermal conductivity of a noncircular duct (including the use of high thermal conductivity cement for positioning the heating wire, as done in this study) tends to distribute heat uniformly, the $H1$ condition may be hardly practical to achieve by wrapping resistance wires around the noncircular duct wall. In view of this, it is interesting to expect that, for the semicircular duct whose flat wall is at the bottom, the hotter corner fluid should ascend along the curved wall hence resulting in the reduction of wall temperature variations. This indicates that, when buoyancy effects exist, the $H1$ condition should have a better degree of approximation for the semicircular duct with the flat wall at the bottom than for the same duct but with 180° rotation.

6.4.2 Examination of Experimental Flow Patterns

By qualitatively extrapolating the predictions in Chap. 5, it seems probable that, for the same heating rate, the temperature difference ($t_b - t_c$) (which is the measured temperature near the corner t_b (or t_a) minus the measured temperature at the duct bottom t_c) is higher for the two-vortex flow pattern than for the four-vortex flow pattern. Reasons are as follows. The predicted two-vortex flow (e.g., see Fig. 5.6a) drives most the cooler core fluid toward the duct bottom, thereby tending to lower the temperature of the wall of the duct bottom. On the other hand, for the same Grashof number, the predicted four-vortex flow (Fig. 5.7a) moves only about half of the cooler core fluid toward the duct bottom, hence less significant temperature reduction of the wall of the duct bottom. This suggests that the measured wall temperature difference ($t_b - t_c$) be used to examine the experimental flow patterns.

Hence it was decided that $(t_b - t_c)$ at a fixed station be plotted against Ra_m. At low Ra_m, the expectation was for a two-vortex secondary flow with $(t_b - t_c)$ increasing with increasing Ra_m. If the experimental flow bifurcated into a four-vortex flow pattern at a critical Rayleigh number $(Ra_m)_{cr}$ and remained four vortices for further increases in Ra_m, the $(t_b - t_c)$ vs. Ra_m plot was expected to show a drop in its slope near $(Ra_m)_{cr}$.

Figure 6.13 is such a plot which attempts to detect this slope drop caused by the flow bifurcation. Note that $log_{10}(Ra_m)$ is used in order to get linear scales. All $(t_b - t_c)$ values are taken at station 16 for four different Re_m levels. From Fig. 6.13, there appears to be no distinct slope drop. Since the lowest Ra_m value is 5.63×10^6 (or 2.09×10^6 for Gr^+) which is higher than all estimated lower critical values for Gr^+ (Sec. 5.3.4), the slope drop may have occurred at a still lower Ra_m, i.e., a level not covered in the experiments. On the other hand, the slope drop may not detectable. Clearly, the former indicates that the measured data correspond to the four-vortex flow pattern while the latter admits to the possibility of a two-vortex flow pattern for part of the region.

In spite of failure to infer flow patterns, Fig. 6.13 does provide distinct evidence of wall temperature variations. For a given Re_m, the $(t_b - t_c)$ values increase with increasing Ra_m. For $Re_m \approx 1400$, the temperature difference is seen to become over 9 °C for high heating rates. Besides the effect of hot spots at the duct corners (as speculated earlier), wall temperature variations are mainly due to the influence of the secondary flow. Also, from Fig. 6.13, $(t_b - t_c)$ seems to show a Re_m dependence. In fact, this is likely an effect of fluid property variations. For a smaller Re_m, the average (t_m) of downstream bulk temperature and upstream bulk temperature is higher than for a larger Re_m. Thus, at the same heat input, the Ra_m (note, $Ra_m = q'' D_h^4 g(\beta\rho^2/\mu^2 k)_m$) is larger for a higher t_m due to the larger value of $\beta\rho^2/\mu^2 k$. Therefore, the curve for a lower Re_m moves to the right, and vice versa. Examining the experimental data in detail suggests that this is indeed the case. The appearance

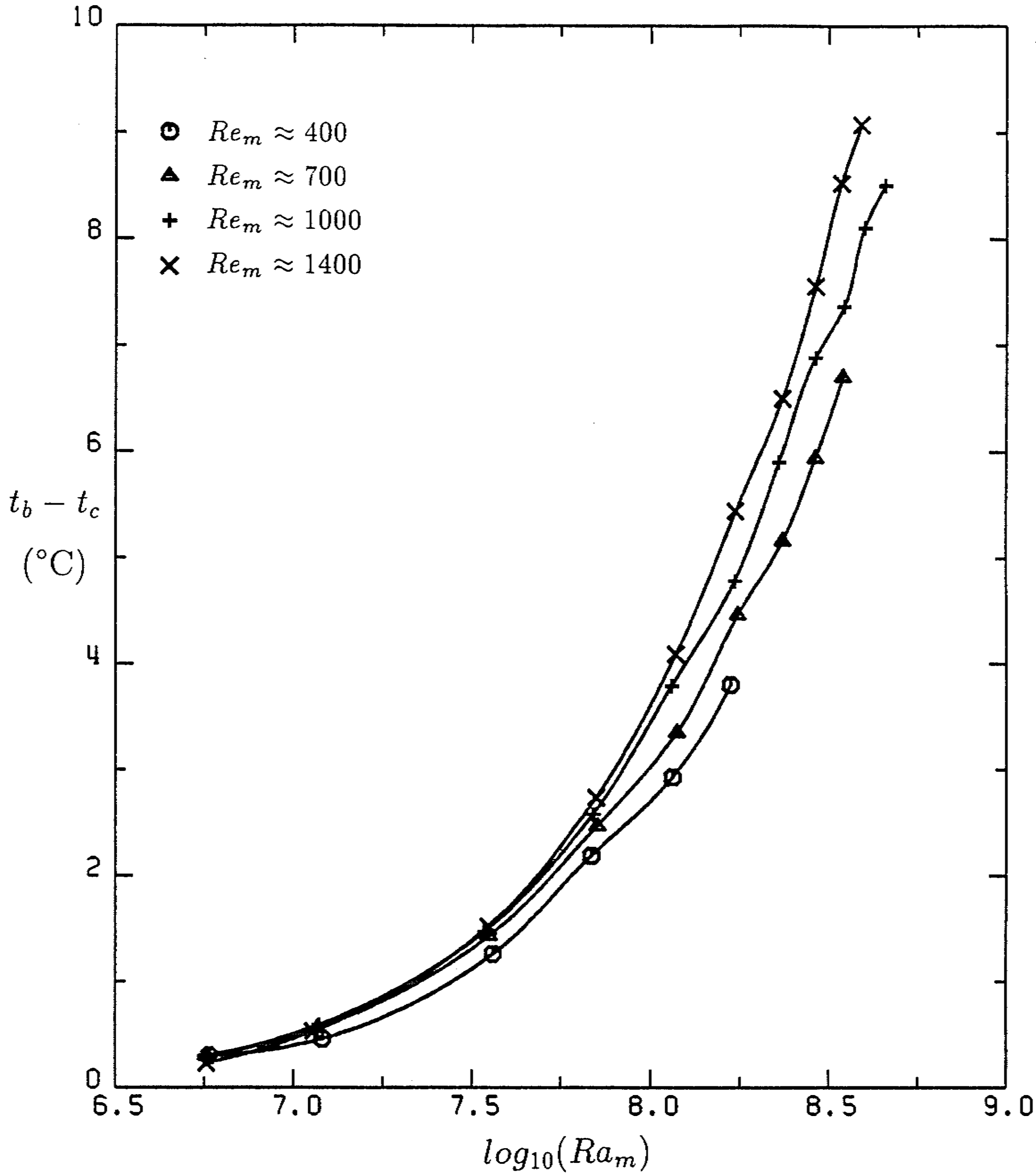

Figure 6.13: Wall Temperature Differences $(t_b - t_c)$ at Station 16

of the Re_m dependence shown in Fig. 6.13 is thus mainly a matter of fluid properties effects.

6.4.3 Comparison of Friction Factors

A comparison is made in Fig. 6.14 between the measured friction factors and the predicted ones. It should be remarked here that two differences be noted. First, the average pressure drop across the entire heated section (including the thermal entrance region) was measured while the friction factor only in the fully developed region was predicted. Secondly, for the measured data (Gr_m was converted to Gr^+), all fluid properties were evaluated at the average (t_m) of the downstream bulk temperature and upstream bulk temperature. But, for the fully developed numerical results, fluid properties were evaluated at a temperature which was much higher than t_m.

Nevertheless, fair agreement can be seen from Fig. 6.14 for both high and low Gr^+ values. For low Gr^+, buoyancy effects are insignificant and thus the thermal entry-region effect is small. Since the laboratory flow is hydrodynamically fully developed before the heating starts, the measured and predicted friction factor ratios are expected to be comparable. For high Gr^+, on the other hand, buoyancy effects are significant and the thermal entry-region effect does exist. However, thermal entrance lengths shorten markedly with increasing Gr^+. Consequently, the measured pressure drops are mainly contributed to by the fully developed region. This trend is apparent from Fig. 6.14 where differences between measurement and prediction reduce as Gr^+ becomes very large.

Figure 6.14 also shows that numerical curves for higher Pr (e.g., $Pr > 5$) tend to move closer to the correlated curve. Furthermore, by partitioning the data at $Pr_m = 5$ into two sets, most lower friction factor ratios correspond to higher Prandtl numbers, which is consistent with the predicted trend of the Pr dependence (see Fig. 5.27). However, the measured ratios are seen to be overall lower than predic-

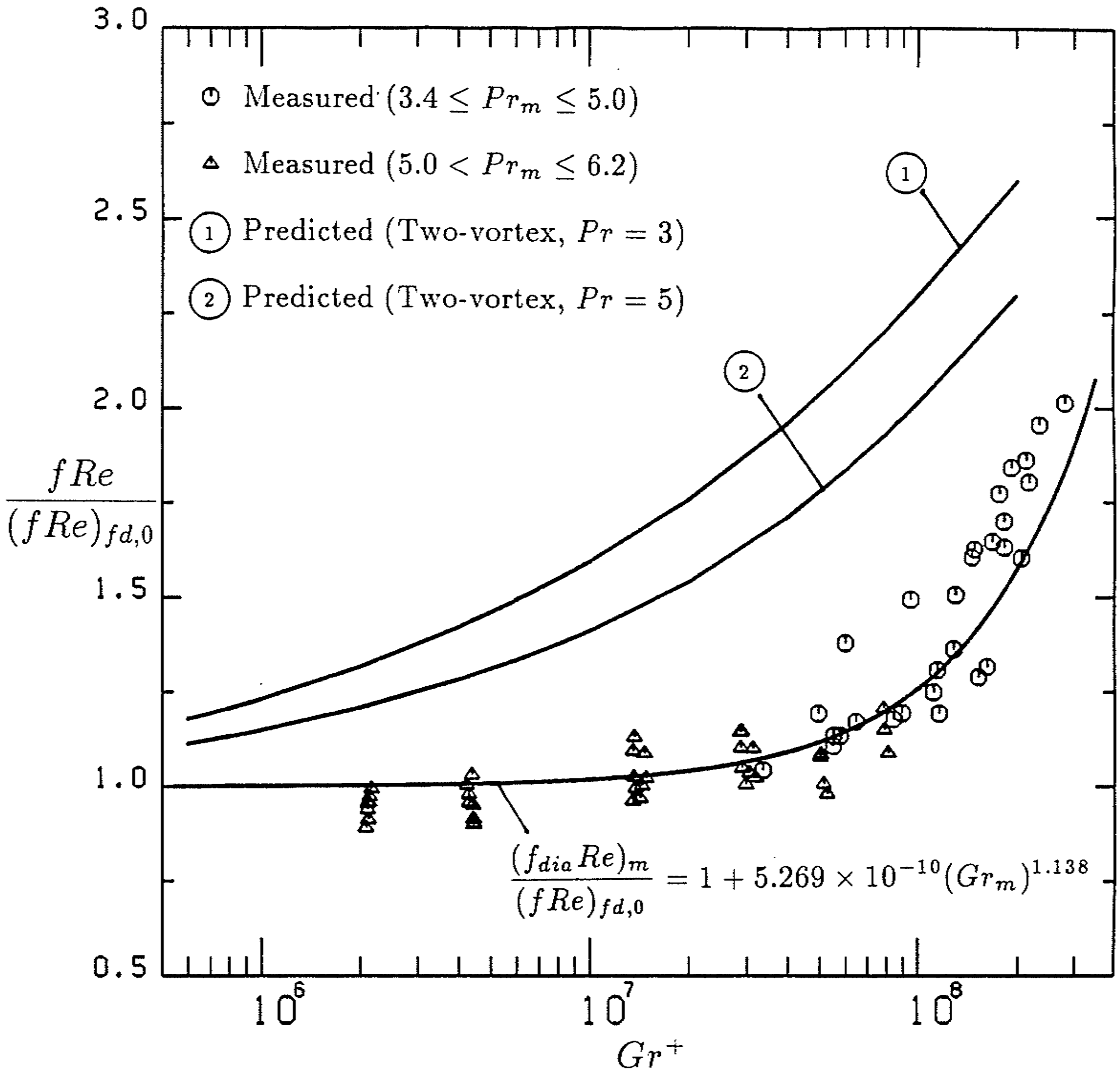

Figure 6.14: Comparison of Friction Factor Ratios Using Gr^+

tions. Besides the differences noted above, the unmatched thermal boundary conditions between measurement and prediction (as discussed earlier) should account for part of the discrepancy. Fluid properties variations may also be partly responsible. In predictions, constant fluid properties (except for density) are assumed while, in measurements, fluid properties are all temperature-dependent especially for μ, β and ρ. For example, an average friction factor predicted in Chap. 5 is based on a constant cross-sectional viscosity that corresponds to the bulk mean temperature. But, in reality, a heating case always decreases the viscosity of the fluid close to the duct wall hence resulting in lower fluid-wall shear stresses. In other words, the numerical friction factors are over-estimated due to the neglect of viscosity variations. In addition, since the real secondary flow tends to attenuate its cross-sectional thermal source, the intensity of the secondary flow under the laboratory conditions is believed to be lower than the predicted intensity, thus leading to further higher predicted results.

Figure 6.15 compares the same friction factor ratios but uses the coordinate of $Gr^+/Pr^{1.8}$. As suggested in Chap. 5, this indeed reduces the Pr effect on the ratios. Better agreement is seen and now even the data points tend to be distributed more uniformly along the fitting curve.

6.4.4 Comparison of Fully Developed Nusselt Numbers

Concerning fully developed heat transfer, Fig. 6.16 shows Nusselt number ratios versus Ra'_M (that is based on the inside diameter of the duct) which facilitates several comparisons. Three comparisons are made in the plot. One is with the numerical two-vortex and four-vortex solutions in Chap. 5 for $Pr = 5$. Numerical results for other Pr values are not plotted because Fig. 5.28a indicates a weak effect of Pr when the Rayleigh number is used. As shown in Fig. 6.16, results obtained from equation (6.8) (converted to Ra'_M) agree well with the predicted values at low Ra'_M. But as Ra'_M increases, the predicted four-vortex values exceed the experimental

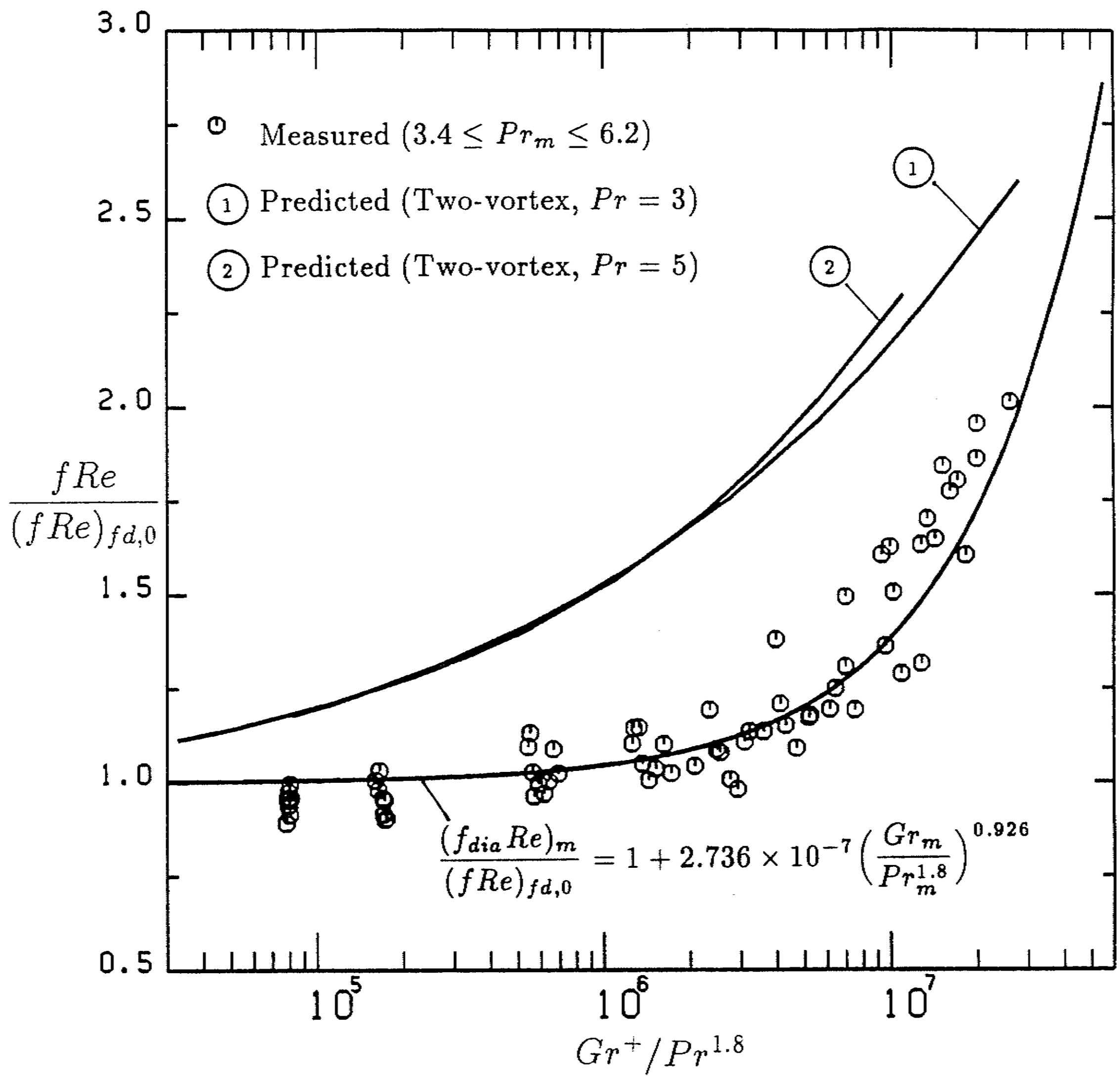

Figure 6.15: Comparison of Friction Factor Ratios Using $Gr^+/Pr^{1.8}$

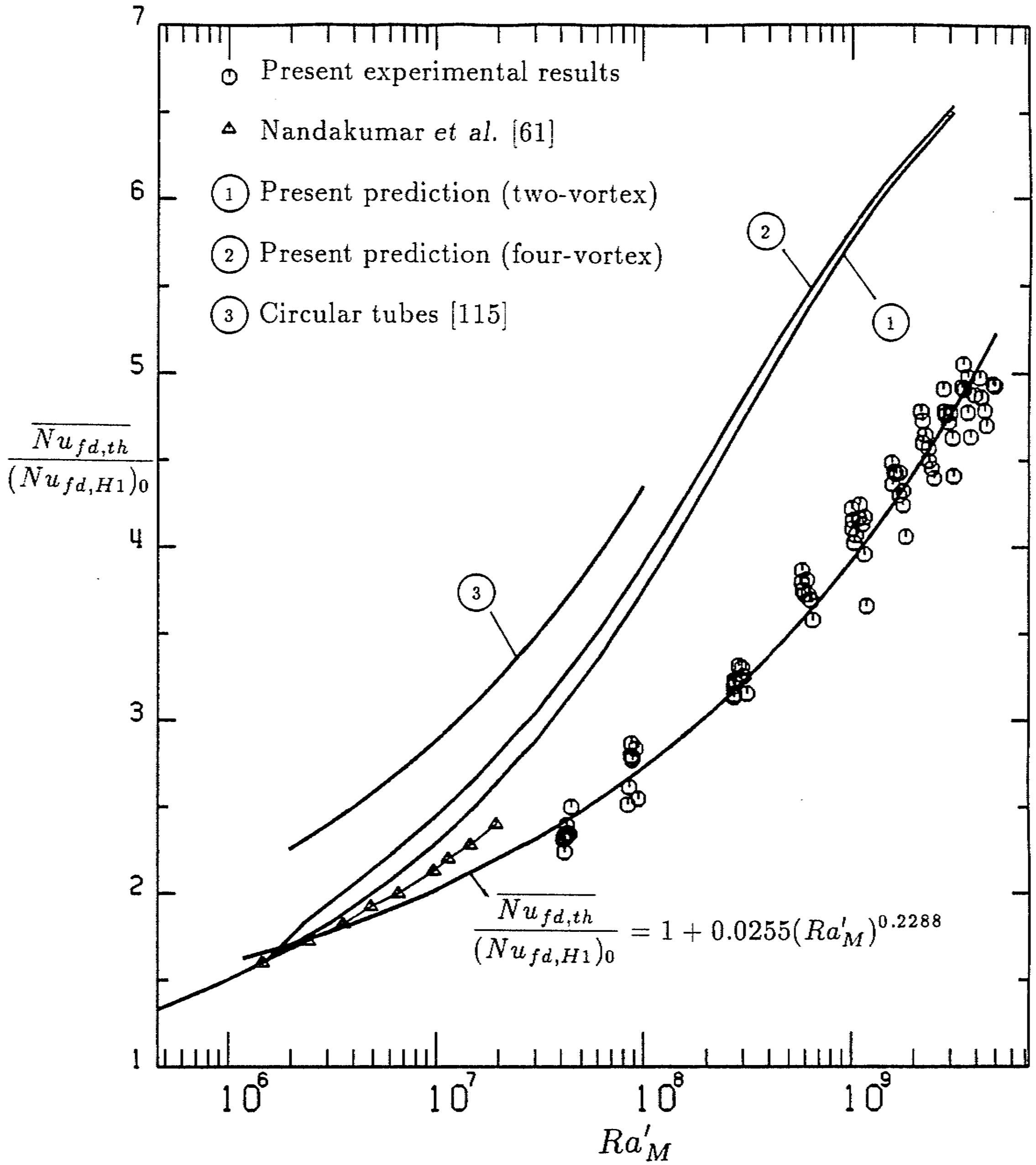

Figure 6.16: Comparison of Fully Developed Nusselt Number Ratios

correlation by up to about 1.4 times higher than the measured data at $Ra'_M \approx 10^9$. Besides the experimental uncertainties, the discrepancy is largely attributed to the difference between the theoretical condition $H1$ and the practical resistance-wiring heating condition as well as fluid properties variations. For high heating rates, large variations in circumferential wall temperatures were observed experimentally. Of course, they are mainly induced by the secondary flow regardless of the high thermal conductivity of the copper duct. However, using the $H1$ condition assumes a uniform peripheral wall temperature and hence cross-sectional temperature differences (e.g., $t_w - t_m$) or driving forces for the secondary flow are artificially much larger than the real situation. This is particularly true if the temperature differences near the duct bottom are concerned. Consequently, over-predictions result.

In view of this, the experiment should be better simulated by the $H2$ condition. Instead of imposing a uniform temperature over all duct surfaces, the $H2$ condition allows the wall temperature to vary with the secondary flow patterns inside the duct as well as with the nonuniform curvatures of the duct surfaces. This, in turn, will reduce the unrealistic high temperature differences ($t_w - t_m$) (e.g., near the duct bottom) and hence yield an overall lower secondary flow intensity. As a result, a closer simulation of the experimental flow should be achieved by using the $H2$ condition.

In Fig. 6.16, another comparison is made with the numerical two-vortex results of Nandakumar *at al.* [61] for a semicircular duct using the $H1$ condition. Note that under their fully developed conditions the duct seating position differs by 180° from the duct position in this investigation. Figure 6.16 shows excellent agreement between these two predictions at low Ra'_M. This outcome suggests a weak effect of duct orientation on heat transfer enhancement at low Ra'_M. Of course, the duct orientation has no influence at all in the limiting case of zero buoyant force ($Ra'_M = 0$). For $Ra'_M > 3 \times 10^6$, the differences between these two numerical results and between each prediction curve and the empirical curve become appreciable. At

$Ra'_M \approx 2 \times 10^7$, the predicted Nusselt ratio in [61] is about 11% lower than the present numerical two-vortex value but is about 17% higher than the correlated value. Although further studies on the duct orientation effects are required, the indicated trend of increasing deviations with increasing Ra'_M indicates that the semicircular duct with the flat surface on top (duct 1) may enhance the secondary flow more than the duct with the flat surface at the bottom (duct 2). This is because the curved surface of duct 1 assists the warmer fluid to rise up while the curved surface of duct 2 resists the ascending flow.

Comparison is also provided in Fig. 6.16 with the empirical correlation of Rustum and Soliman [115] for a uniform heated smooth tube (here, $(Nu_{fd,H1})_0 = 4.36$). At $Ra'_M = 4.9 \times 10^6$, their correlation gives a Nusselt ratio which is about 1.4 times higher than that obtained from equation (6.8). At the same Ra'_M, the predicted Nusselt ratio in [61] for the circular tube is about 1.5 times higher than their semicircular duct. In addition, an earlier climb in the Nusselt ratio for circular tube could be seen from Fig. 6.16 if all these curves were extrapolated back to very low Ra'_M. This indicates that the secondary flow in the semicircular duct begins to enhance heat transfer at a relatively larger Rayleigh number.

6.5 Remarks

Experiments were performed on mixed convection flow and heat transfer in the thermal entrance region of a horizontal semicircular duct with the flat surface at the top. Since only distilled water was used as the working fluid, the influence of Prandtl number on friction factors and Nusselt numbers was unclear from the experimental data. Even though the cross-stream viscosity ratio was employed to correlate the data and the influence of viscosity variation was discussed qualitatively in certain instance, no other special effort was made to reveal the effects of properties variation. During each run, all local Reynolds numbers were controlled not to exceed 2100.

However, thermal instability was not detected so that information on conditions under which the mixed convection flow commences to reach the transition region was not provided from this work.

Otherwise, the measured data showed consistent trends with predictions. The effects of Grashof, Rayleigh, and Reynolds numbers on friction factors, local and fully developed Nusselt numbers, and the onset points of the secondary flow were generally in agreement with numerical analyses and the existing measured data for other different ducts. Differences between the theoretical $H1$ condition and the resistance-wiring heating condition were discussed before detailed comparisons between measurement and prediction were made. Effort was also spent on examining the experimental flow patterns by using the measured wall temperature difference $(t_b - t_c)$ at a particular station.

Chapter 7

Conclusions and Recommendations

THIS research mainly comprises three parts, namely, analytical work, numerical analysis, and experimental investigation. Therefore, concluding remarks, together with recommendations, are given for these three aspects.

7.1 Analytical

The finite Fourier transform method was successfully used to develop exact velocity and temperature expressions for hydrodynamically and thermally developed laminar flow in circular sector ducts. The work contributes a complete set of practical results. The main conclusions can be drawn as follows:

1. New information on the maximum velocity and its location was provided. A series form of fRe was obtained and the values were calculated for the entire apex angle range. More complete and accurate computations were also made for fully developed incremental pressure drop number $K(\infty)$.

2. Four thermal boundary conditions were employed for studying the fully developed Nusselt numbers. A novel closed-form of Nu_{H1} was found. The Nu_{H2} variation within its full apex angle range revealed (for the first time) a maximum value at $\phi \approx 65°$ (Fig. 4.8). For the $H1_{ad}$ and $H2_{ad}$ conditions, the use

of the overall average wall temperature for calculating Nusselt numbers caused a discontinuity in Nu at small ϕ. Hence the use of Nu^* was recommended.

3. Although Nu_{H1} is higher than Nu_{H2}, the differences between $Nu^*_{H1_{ad}}$ and $Nu^*_{H2_{ad}}$ are small (within about 6%) for all ϕ.

Parallel to the above work, further heat transfer analyses are recommended, for example, for the same conditions as the $H1_{ad}$ and the $H2_{ad}$ but with the curved surface (not the flat surfaces) insulated. It is realized that there exist some applications for these kinds of nonuniform heating, e.g., in [65] for laminar mixed convection in a semicircular duct. Therefore, analytical Nusselt numbers for these two conditions of circular sector ducts should be also of practical importance.

7.2 Numerical

Without Buoyancy Effects. In Sec. 4.1, the three-dimensional Navier-Stokes equations were numerically solved for steady, laminar, fluid flow in the hydrodynamic entrance region of circular sector ducts. Regarding this work, the following conclusions can be stated as:

1. The Patankar's SIMPLER algorithm was modified by noniteratively solving the pressure and its correction equations. Computation experiments showed that this modification provided more accurate overall results and accelerated convergence hence reducing the computing time.

2. The calculated presure drop data covered the entire apex angle range and were shown to agree well with the limited published results.

3. For each circular sector duct, hydrodynamic entrance lengths that were obtained using four definitions were found to be very sensitive to the criterion used. The use of the velocity criterion in this work is new for noncircular duct analyses.

4. The apex angle effects were also carefully examined. Results indicated that the use of duct radius, rather than the hydraulic diameter, gave a better picture of the apex angle dependence.

In Sec. 4.2, numerical solutions were presented for laminar, forced convection heat transfer in the thermal entrance region of circular sector ducts using the $H1$ and $H2$ conditions. The concluding remarks on this study are summarized below:

1. Detailed information on local Nusselt numbers and thermal entrance lengths was provided. Comparisons were made with other circular and noncircular ducts. Under the $H1$ condition, the circular sector ducts produce higher heat transfer coefficients than a circular tube.

2. For the $H1$ condition, decreasing apex angle (increasing the duct corner effects) was found to enhance local and fully developed Nusselt numbers and to shorten thermal entrance sections. But, for the $H2$ condition, maximum local and fully developed Nusselt numbers and the shortest thermal entrance length occur at the apex angle value of about 65°.

3. The $H1$ condition is thermally stronger than $H2$ hence resulting in higher heat transfer coefficients and shorter thermal entrance lengths.

Based on the above work and previous literature survey, the author recommends furthering the forced convection heat transfer study for laminar flow in circular sector ducts in the following three aspects. (a) For different boundary conditions, similar analyses can be carried out for isothermal (note, one study done for $2\phi = 180°$) and nonuniform heating conditions. (b) For properties variations, it will be useful (e.g., for studying experimental data) to continue this work by introducing the temperature-dependent viscosity ratio into the governing equations. Also, it will be of practical interest to obtain heat transfer results for non-Newtonian (μ is the function of velocity gradients) fluids such as rubber, greases, paints and biological fluid. (c) For different flow conditions, the simultaneous development of the velocity and temperature profiles should be analyzed. A more complete study may also take into account both axial diffusion of momentum and heat. Obviously, these three can be combined to encourage various research efforts. It may be noted that the last one requires simultaneously solving the elliptic three-dimensional Navier-Stokes and energy equations.

With Buoyancy Effects. Fully developed mixed convection in a horizontal semicircular duct using the $H1$ condition was numerically studied and reported in Chap. 5. Results for pressure drop and heat transfer were obtained for Gr^+ up to 2×10^8 and Pr values of 0.7, 3, 5, and 20. The main conclusions are follows:

1. The modified SIMPLER algorithm (as stated before) and the under-relaxation techniques (for u^+ and v^+) were successfully used to obtain solutions with restricted convergence criteria. The solution was confirmed by comparing velocity and temperature profiles, friction factor, and Nusselt number with the corresponding exact values at zero buoyancy force.

2. While dual solution results were obtained, the phenomenon of cross-stream flow bifurcation was encountered at certain Grashof levels. For the two-vortex flow, the maximum axial momentum and coldest fluid are moved down along the symmetry plane. For the four-vortex flow, on the other hand, they are not only pushed down but also carried away from the symmetry plane.

3. Results showed that increasing Grashof number strengthens the secondary flow, hence pressing down isotherms and axial velocity contours and resulting in increases in the heat transfer coefficient and the flow resistance. In addition, it was observed that significant increases in friction factor ratios do not occur until much higher Grashof numbers are reached compared to the heat transfer enhancement.

4. For a given Gr^+, reducing Prandtl number decreases the Nusselt number ratios but increases the friction factor ratios.

5. From Figs. 5.13, 5.15, 5.23, and 5.25, both the two- and four-vortex secondary flows were observed to modestly decrease shear stresses and heat fluxes along the top flat wall but to markedly increase them along the curved surface. Also, the four-vortex solution exhibited a sharp drop in these two quantities near the duct bottom. From Figs. 5.5a, 5.7a, 5.9a, and 5.11a, further observations on the size of the two lower vortices in the four-vortex flow revealed that it first enlarges and then subsides as the secondary flow is further strengthened. Therefore, the differences between two- and four-vortex results increase and then diminish with increasing the intensity of the secondary flow (see Fig. 5.26).

6. It was found that, when Nusselt number ratios are plotted against the Rayleigh number Ra^+, the Prandtl number effects on the ratios become insignificant, indicating that Ra^+ is a good measure for mixed convection heat transfer data. However, friction factor data are better correlated to Gr^+ or Gr^+/Pr^n, where n was determined to be 1.8 for $3 \leq Pr \leq 5$.

The above work is worthy of extension and should spark further research interest. Accordingly, the author would like to give the following views for guiding future research.

a) In order to provide more sound evidences (i.e., statistic numbers in terms of convergence speed, stability, and accuracy, etc.), special efforts should be made on further confirming the modified SIMPLER algorithm (which was used in this research) so that it will benefit future computations.

b) Detailed studies on the bifurcation phenomenon are necessary. During this research, attempts were made to provide theoretical grounds for the development of the flow bifurcation. But, no numerical experiments have been done for detecting the processes of the vortex pattern transition. It will be very interesting to develop a theory that can account for why and how the bifurcation takes place.

c) It is of practical importance to examine numerically the effect of duct orientation.

d) Concerning comparison with the experimental results, more research efforts are needed to simulate the laminar mixed convection in the semicircular duct using the $H2$ condition.

e) Analyses in the thermal entrance region are particularly necessary. During such analyses, total pressure drop data can be obtained which may then be compared with the measured values. It will be also interesting to see if "undershoots" and "overshoots" in local Nusselt numbers and in the secondary flow intensities will be predicted when the laboratory flow conditions are numerically approximated.

f) The completed and proposed work can be extended to horizontal or even inclined circular sector ducts.

7.3 Experimental

Mixed convection was experimentally investigated for laminar water flow in the thermal entrance region of a horizontal semicircular duct with a uniform heat input axially. The following conclusions and observations are directed to these experimental data.

1. Fully developed isothermal friction factors agreed within 8% with analytical values in the laminar region. The diabatic friction factor ratios increased with increasing buoyancy effects and reached a factor of over two at high

heating rates. Good correlations to Gr_m and $Gr_m/Pr_m^{1.8}$, rather than Ra_m, were provided.

2. At each station, two temperatures measured symmetrically at the top flat wall were approximately equal, indicating a symmetric three-dimensional mixed convection flow. But, wall temperatures at the duct bottom were increasingly lower than the top wall temperatures as the heating rate increased.

3. Experimental data showed that numerical analyses for pure forced convection heat transfer furnished excellent base-line references for mixed convection results. In a region not far from the beginning of heating, the local average Nusselt number first followed and then began to exceed its pure forced convection curves. In the fully developed region, it became up to about five times as high as the pure forced convection value when buoyancy effects were increasingly significant.

4. The onset of thermal instability was found to advance with increasing Rayleigh number and decreasing Reynolds number. Thus, the data for $(X/D_h)_{cr}$ were successfully correlated to the parameter of Gr/Re^2.

5. Local and fully developed Nusselt numbers showed a certain degree of Reynolds number dependence. Hence, very good correlations of Nusselt number ratios were achieved by partitioning the data at $Ra_M = 5 \times 10^7$ into two sets. For $Ra_M < 5\times10^7$, the data were best fit against Ra_M only. For $Ra_M > 5\times10^7$, the Re_M dependent data were excellently correlated using the $Re_M Ra_M$ product.

6. The axial length-mean Nusselt numbers were found to be approximately equal to the fully developed Nusselt numbers. Also, differences between the $H1$ condition and the resistance-wiring heating condition were discussed. A special effort was spent on examining the experimental flow patterns by detecting the measured wall temperature difference $(t_b - t_c)$ with Ra_m.

7. The predicted fully developed Nusselt ratios agreed well with the measured results at low Rayleigh numbers. For high heating rates, the predicted values are up to 40% higher than the measured results.

With a view to improving the experimental procedure, the author puts forward two suggestions. (a) Since the fluid temperature difference between two pressure tap locations was observed to affect the pressure drop readings, it will be helpful to calibrate the pressure transducer for different temperatures at its two inlets. Results for a number of these calibrations should provide better calibration equations. (b) Instead of taking readings manually, a data acquisition system should be established to record temperature readings automatically and simultaneously.

Regarding further experimental investigation, the author gives the following recommendations.

a) More experiments should be performed for different duct orientations.

b) Different working fluids may be used to examine the Prandtl number effect.

c) The above work can be extended to the inclined duct.

d) Flow visualization and/or the measurements of fluid velocity and temperature should be conducted to confirm experimentally the phenomenon of flow bifurcation.

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Appendix A

Series Terms for Mathematical Solutions

This appendix serves as a supplement for Sec. 3.3. The following series terms or functions provide a complete representation of solutions for equation (3.3) associated with the described boundary conditions.

For the $H1$ condition:

$$\mathcal{H}(\chi_i, r) = \frac{(\chi_i - 2)(\chi_i + 6)r^{\chi_i} - 4(\chi_i + 1)r^4 - (\chi_i^2 - 16)r^{\chi_i + 2}}{\chi_i(\chi_i^2 - 4)(\chi_i^2 - 16)(\chi_i + 1)} \tag{A.1}$$

In the limit cases:

$$\mathcal{H}(\chi_i \to 2, r) = \frac{2r^4 - 3r^4 lnr - 2r^2}{72} \tag{A.2}$$

$$H(\chi_i \to 4, r) = \frac{2r^4 - 2r^6 + 5r^4 lnr}{480} \tag{A.3}$$

For the $H1_{ad}$ condition:

$$\mathcal{G}(\lambda_n, r) = \frac{(\lambda_n + 6)(2 - \lambda_n) + (\lambda_n + 2)^2 r^4 - 16r^{\lambda_n + 2}}{\lambda_n^2(\lambda_n + 2)^2(4 - \lambda_n^2)} \tag{A.4}$$

$$\mathcal{S}(\beta_m, \lambda_n, r) = \sum_{n=1}^{\infty} \frac{(\lambda_n + 6)(2 - \lambda_n)r^{\beta_m} + ((\lambda_n + 2)^2 - \beta_m^2)r^4 - (16 - \beta_m^2)r^{\lambda_n + 2}}{(16 - \beta_m^2)((\lambda_n + 2)^2 - \beta_m^2)(\lambda_n^2 - \beta_m^2)(4 - \lambda_n^2)} \tag{A.5}$$

In the limit cases:

$$\mathcal{G}(\lambda_n \to 2, r) = \frac{1 - r^4 + 2r^4 lnr}{32} \tag{A.6}$$

$$\mathcal{S}(\beta_m \to 4, \lambda_n \neq 2, r) = \sum_{n=1}^{\infty} \frac{(\lambda_n + 6)(2 - \lambda_n) r^4 lnr - 8r^4 + 8r^{\lambda_n+2}}{8(\lambda_n^2 - 16)(4 - \lambda_n^2)(2 - \lambda_n)(\lambda_n + 6)} \quad \text{(A.7)}$$

$$\mathcal{S}(\beta_m \to 4, \lambda_n = 2, r) = \frac{r^4 lnr(1 - 4lnr)}{3072} \quad \text{(A.8)}$$

$$\mathcal{S}(\beta_m \neq 4, \lambda_n \to (\beta_m - 2), r) = \frac{2\beta_m r^4 - 2\beta_m r^{\beta_m} - (16 - \beta_m^2) r^{\beta_m} lnr}{8\beta_m^2 (16 - \beta_m^2)(1 - \beta_m)(4 - \beta_m)} \quad \text{(A.9)}$$

$$\mathcal{S}(\beta_m \neq 4, \lambda_n \to 2, r) = \frac{8r^{\beta_m} - 8r^4 + (16 - \beta_m^2) r^4 lnr}{4(16 - \beta_m^2)^2 (4 - \beta_m^2)} \quad \text{(A.10)}$$

For the $H2$ condition:

The arbitrary constant A_2 can be determined by evaluating the average peripheral wall temperature which results in

$$A_2 = \frac{-\phi^2 + 6\phi + 3}{6\phi(\phi + 1)} + \frac{C}{4\phi^2}\mathcal{F}(\lambda_n) + \frac{C}{20\phi^3}\mathcal{P}(\lambda_n) + \frac{1}{\phi(\phi + 1)} \sum_{m=1}^{\infty} \frac{1}{\beta_m^2 (\beta_m + 1)^2} + \frac{8C}{5\phi^3} \sum_{m=1}^{\infty} \sum_{n=1}^{\infty} \mathcal{L}(\beta_m, \lambda_n) \quad \text{(A.11)}$$

where

$$\mathcal{F}(\lambda_n) = \sum_{n=1}^{\infty} \frac{\lambda_n + 6}{(\lambda_n + 2)^3 \lambda_n^2} \quad \text{(A.12)}$$

$$\mathcal{P}(\lambda_n) = \sum_{n=1}^{\infty} \frac{\lambda_n^2 + 9\lambda_n + 34}{(\lambda_n + 3)(\lambda_n + 2)^3 \lambda_n^2} \quad \text{(A.13)}$$

$$\mathcal{L}(\beta_m, \lambda_n) = \frac{(\beta_m - 2)(\beta_m^2 + 7\beta_m + 15) - \lambda_n^2(\beta_m + 5) - \lambda_n(4\beta_m + 25)}{\beta_m(\beta_m + 1)(\lambda_n + 3)(\lambda_n + 2)(\beta_m + 4)((\lambda_n + 2)^2 - \beta_m^2)(\lambda_n^2 - \beta_m^2)} \quad \text{(A.14)}$$

Other functions in equations (3.11) and (3.12) are defined by

$$\mathcal{E}(\lambda_n, r) = \sum_{n=1}^{\infty} \frac{(\lambda_n + 2)^2 r^4 - 16r^{\lambda_n+2}}{\lambda_n^2 (\lambda_n + 2)^2 (4 - \lambda_n^2)} \quad \text{(A.15)}$$

$$\mathcal{Q}(\beta_m, \lambda_n, r) = \frac{(\lambda_n + 2) r^{\beta_m} - \beta_m r^{\lambda_n+2}}{\beta_m((\lambda_n + 2)^2 - \beta_m^2)(\lambda_n^2 - \beta_m^2)(4 - \lambda_n^2)} + \frac{\beta_m r^4 - 4r^{\beta_m}}{\beta_m(16 - \beta_m^2)(\lambda_n^2 - \beta_m^2)(4 - \lambda_n^2)} \quad \text{(A.16)}$$

It is noted that some special apex angles may cause the denominators of equations (A.14), (A.15), and (A.16) to be zero. But, like the above cases, all of their limits do exist.

For the $H2_{ad}$ condition:

Similarly, the arbitrary constant A_{2ad} is given by

$$\begin{aligned} A_{2ad} = &\frac{C}{4\phi(\phi+1)}\mathcal{F}(\lambda_n) + \frac{C}{20\phi^2(\phi+1)}\mathcal{P}(\lambda_n) \\ &+\frac{8C}{5\phi^2(\phi+1)}\sum_{m=1}^{\infty}\sum_{n=1}^{\infty}\mathcal{L}(\beta_m,\lambda_n) \end{aligned} \qquad \text{(A.17)}$$

where $\mathcal{F}(\lambda_n)$, $\mathcal{P}(\lambda_n)$, and $\mathcal{L}(\beta_m,\lambda_n)$ are defined by the same as those for the $H2$ condition. Finally, the dimensionless average temperature over the curved surface, $T_{\bar{c},2}$, may be shown that

$$T_{\bar{c},2} = A_{2ad} - \frac{C}{4\phi^2}\mathcal{F}(\lambda_n) \qquad \text{(A.18)}$$

Appendix B

List of the Computer Program for Mixed Convection Simulations

```
//QLEI JOB ',,,T=220,I=8,L=90,','QLEI',NOTIFY=QLEI
// EXEC FORT7CLG,SIZE=1200K,P=D,PARM='LC(88)'
//FORT.SYSIN DD *
C THE ABOVE //-LINES ARE THE JOB CONTROL CARDS FOR THE MACHINE OF
C AMDAHL 580 AT THE UNIVERSITY OF MANITOBA
C
C=====================================================================
C* THIS PROGRAM PREDICTS CHARACTERISTICS OF LAMINAR MIXED CONVECTION  *
C* FOR FULLY DEVELOPED FLOW OF A HORIZONTAL SEMICIRCULAR DUCT USING   *
C* H1 THERMAL BOUNDARY CONDITION (ALPHA=0 -- FLAT WALL IS UP)         *
C*          NOVEMBER, 1989                                            *
C* KEY FEATURES:                                                      *
C*  1. THE DUCT CAN BE ROTATED BY SETTING NON-ZERO "ALPHA" VALUE      *
C*  2. THE PROGRAM CAN BE EXTENDED TO CIRCULAR SECTOR DUCTS           *
C*  3. ANY PRANDTL AND GRASHOF NUMBERS CAN BE PRESCRIBED ("PR" >0)    *
C*  4. MESH SIZES CAN BE EASILY CHANGED BY "TOTI" AND "TOTJ"          *
C*  5. CONVERGENCE CRITERIA AND UNDERRELAXATION FACTORS ARE AS INPUT  *
C*  6. THE PROGRAM CAN BE EXECUTED IN A PIECE-BY-PIECE FASHION        *
C* NOTES:                                                             *
C*  1. IF ASYMMETRIC, ALL "IF (ALPHA ..." MUST BE ACTIVATED           *
C*  2. IF ASYMMETRIC, ALL DOUBLE INTEGRALS SHOULD BE CHECKED (2 OR 1) *
C=====================================================================
C
      INTEGER TOTI/20/,TOTJ/25/,M,N,MM,NN,I,J,YES,NIT,TNIT
      REAL*8 ALPHA/0.0D0/,R(20),DR,DF,GR/0.40D5/,PR/20.0D0/,
     *   FRE,COEFA,INTEG,COETH,CFRE,
     *   U(20,25),V(20,25),W(20,25),TH(20,25),P(20,25),APAP(20,25)
      REAL*8 DUP(20,25),DVP(20,25),FALSU(20,25),FALSV(20,25),MS(20,25)
      REAL*8 FCRUV/1.D-5/,FCRW/1.D-5/,FCRTH/1.D-5/,CRM/1.D-5/
      REAL*8 CRUV,CRW,CRTH,URFUV/0.80D0/,URFW/1.0D0/,URFTH/1.0D0/
      CHARACTER CARD1*80
C
C=====================================================================
C*                    --- VARIABLE DICTIONARY ---                     *
C* === INTEGER ===                                                    *
C* TOTI   = NO. OF CONSTANT ANGULAR LINES                             *
C* TOTJ   = NO. OF CONSTANT RADIAL LINES                              *
C* M, MM  = TOTI-1, TOTI-2                                            *
C* N, NN  = TOTJ-1, TOTJ-2                                            *
C* I, J   = SUBSCRIPTS FOR ARRAYS                                     *
C* YES    = CONVERGENCE CHECK INDICATOR                               *
C* NIT    = NO. OF ITERATIONS IN THE MAIN PROGRAM (A COUNTER)         *
C* TNIT   = TOTAL NO. OF ITERATIONS DESIRED (WHEN NIT=TNIT, STOP)     *
C* === DOUBLE PRECISION REAL ===                                      *
C* ALPHA  = DUCT ORIENTATION ANGLE (ZERO FOR THE FLAT WALL AT TOP)    *
C* R      = 1-D ARRAY FOR THE RADIAL COORDINATE (0 TO 1, R(TOTI))     *
C* DR, DF = RADIAL & ANGULAR DIFFERENTIAL LENGTHS                     *
C* GR, PR = GRASHOF & PRANDTL NUMBERS                                 *
C* FRE    = PRODUCT OF FRICTION FACTOR & REYNOLDS NO. BASED ON RO     *
C* COEFA  = FUNCTION FOR COEFFICIENTS OF A'S (FOR U,V,W)              *
C* INTEG  = FUNCTION FOR PERFORMING AREA INTEGRATION                  *
C* COETH  = FUNCTION FOR COEFFICIENTS OF ENERGY EQ. (TH)              *
C* CFRE   = CORRECTION OF FRE                                         *
C* U,V,W  = RADIAL, ANGULAR, AXIAL VELOCITIES ARRAY (TOTI,TOTJ)       *
C* TH     = TEMP ARRAY, TH(TOTI,TOTJ)                                 *
C* P      = CROSS-STREAM PRESSURE ARRAY, P(TOTI,TOTJ)                 *
C* APAP   = PRESSURE CORRECTION ARRAY (2-D)                           *
C* DUP    = 2-D ARRAY FOR COEFFICIENTS OF PRESSURE RELATED TO U       *
C* DVP    = 2-D ARRAY FOR COEFFICIENTS OF PRESSURE RELATED TO V       *
C* FALSU  = FALSE VELOCITY OF U (2-D)                                 *
C* FALSV  = FALSE VELOCITY OF V (2-D)                                 *
C* MS     = MASS OF SOURCE (2-D)                                      *
C* FCRUV  = PRESCRIBED CONVERGENCE CRITERION FOR U & V                *
C* FCRW   = PRESCRIBED CONVERGENCE CRITERION FOR W                    *
C* FCRTH  = PRESCRIBED CONVERGENCE CRITERION FOR TH                   *
C* CRM    = PRESCRIBED CONVERGENCE CRITERION FOR MS                   *
C* CRUV   = CONVERGENCE CRITERION FOR U & V                           *
C* CRW    = CONVERGENCE CRITERION FOR W                               *
C* CRTH   = CONVERGENCE CRITERION FOR TH                              *
C* URFUV  = UNDER-RELAXATION FACTOR FOR U & V                         *
C* URFW   = UNDER-RELAXATION FACTOR FOR W                             *
C* URFTH  = UNDER-RELAXATION FACTOR FOT TH                            *
C* === CHARACTER ===                                                  *
C* CARD1  = CHARACTER STRINGS                                         *
C=====================================================================
C
C--GENERATE COORDINATES AND INPUT/OUTPUT DATA
C
      WRITE(6,*) 'URFUV=',URFUV,'URFW=',URFW,'URFTH=',URFTH
      CALL GRID(TOTI,TOTJ,R,ALPHA,DR,DF,GR,PR)
C
C--INITIALIZATION OF VELOCITY AND TEMPERATURE
C
      M=TOTI-1
      N=TOTJ-1
      MM=M-1
      NN=N-1
      DO 10 I=1,TOTI
      DO 10 J=1,TOTJ
         U(I,J)=0.D0
         V(I,J)=0.D0
```

```
         W(I,J)=0.DO
10      TH(I,J)=0.DO
C
C--INPUT U, V, W, AND TH FROM DATASETS AND PRINT OUT
C
        CALL DATAIN(TOTI,TOTJ,M,MM,N,NN,U,V,W,TH,1,FRE)
C
C--THIS IS THE MAIN LOOP
C
        TNIT=200
        NIT=0
C
20      CRUV=FCRUV
        CRW=FCRW
        CRTH=FCRTH
           NIT=NIT+1
           CALL PSEUDO(DUP,DVP,FALSU,FALSV,TOTI,TOTJ,R,DR,DF,U,V,W,
     *                 TH,GR,ALPHA,M,MM,N,NN)
           CALL PRESS(P,DUP,DVP,FALSU,FALSV,TOTI,TOTJ,R,DR,DF,
     *                 M,MM,N,NN)
           CALL UVMTUM(DUP,DVP,APAP,MS,TOTI,TOTJ,R,DR,DF,P,U,V,W,
     *                 TH,GR,ALPHA,YES,M,MM,N,NN,CRUV,CRM,URFUV)
           CALL WMTUM(APAP,TOTI,TOTJ,R,DR,DF,U,V,W,FRE,CFRE,
     *                 M,MM,N,NN,CRW,URFW)
           CALL ENERGY(TOTI,TOTJ,R,DR,DF,U,V,W,TH,PR,M,MM,N,NN,
     *                 CRTH,URFTH)
           IF (NIT .EQ. (NIT/50)*50 .OR. NIT .EQ. TNIT) THEN
              CALL OUTPUT(NIT,TOTI,TOTJ,U,V,W,TH,MS,CRUV,CRW,CRTH,CFRE,
     *                 M,MM,N,NN,YES)
           END IF
           WRITE(25,100) NIT,U(10,18),V(10,18),W(10,18),TH(10,18)
        IF ( ((CRUV*0.90DO .GT. FCRUV) .OR. (CRW*0.90DO .GT. FCRW)
     *     .OR. (YES .EQ. 0) .OR. (CRTH*0.90DO .GT. FCRTH) .OR.
     *     (DABS(CFRE) .GT. 1.D-4)) .AND. (NIT .LT. TNIT)) GOTO 20
C
C--SAVE RESULTS TO DATASETS AND CALCULATE NUSSELT NUMBER
C
        CALL DSAVE(NIT,TNIT,TOTI,TOTJ,M,MM,N,NN,U,V,W,TH,GR,PR,FRE,ALPHA)
        CALL NUSSLT(TOTI,TOTJ,M,N,W,TH,APAP,R,DR,DF)
C
100     FORMAT(T2,I4,1X,4(D14.7,1X))
        STOP
        END
C=====================================================================
C* "GRID" GENERATES THE UNIFORM GRID COORDINATES (HALF NEAR BOUNDARY) *
C* IF "ALPHA" IS NOT = 0 & 180 DEG, SOLUTION IS FOR THE ENTIRE AREA    *
C=====================================================================
        SUBROUTINE GRID(TOTI,TOTJ,R,ALPHA,DR,DF,GR,PR)
        INTEGER TOTI,TOTJ,  I,J
        REAL*8 R(TOTI),ALPHA, DR,DF,FTOT,PI/3.1415926535898D0/,GR,PR
C
        R(TOTI)=1.ODO
        R(1)=0.DO
        IF (ALPHA .LT. 0.01DO .OR. ALPHA .GT. 3.1DO) GOTO 5
           FTOT=PI
           GOTO 7
5       FTOT=PI/2.ODO
7       DR=R(TOTI)/(TOTI-2.DO)
        DF=FTOT/(TOTJ-2.DO)
        R(2)=DR/2.DO
        R(TOTI-1)=R(TOTI)-DR/2.DO
        J=TOTI-2
        DO 10 I=3,J
10         R(I)=R(2)+DR*(I-2.DO)
C
        WRITE(6,50) ALPHA,GR,PR,DR,DF
        DO 40 I=1,TOTI
40      WRITE(6,60) I,R(I)
50      FORMAT('1'/T2,'LAMINAR MIXED CONVECTION FLOW AND HEAT TRANSFER',
       * ' FOR A HORIZONTAL SEMICIRCULAR DUCT WITH ALPHA =',F7.4//
       * T2,'GRASHOF NO. = ',D8.2,2X,'PRANDTL NO. = ',F7.3,2X,'DR = ',
       * F9.7,2X,'DF = ',F9.7//T10,'==== R -- COORDINATES ===='/)
60       FORMAT(T10,I3,2X,F15.12)
        RETURN
        END
C=====================================================================
C* "DATAIN" READS U,V,W,TH FROM DATASETS AND PRINTS THEM OUT         *
C* EACH DATASET CORRESPONDS TO THE FORMAT GIVEN IN SUBROUTINE "DSAVE" *
C=====================================================================
        SUBROUTINE DATAIN(TOTI,TOTJ,M,MM,N,NN,U,V,W,TH,ZEROUV,FRE)
        INTEGER TOTI,TOTJ,M,MM,N,NN,I,J,ZEROUV
        REAL*8 U(TOTI,TOTJ),V(TOTI,TOTJ),W(TOTI,TOTJ),TH(TOTI,TOTJ),FRE
        CHARACTER CARD*80
C
        IF (ZEROUV .EQ. 0) GOTO 30
           READ(10,99) CARD
           WRITE(6,99) CARD
           DO 10 I=2,MM
```

```
         READ(10,*) (U(I,J),J=2,TOTJ)
10       WRITE(6,100)  (U(I,J),J=2,TOTJ)
         READ(11,99) CARD
         WRITE(6,99) CARD
         DO 20 I=2,M
            READ(11,*) (V(I,J),J=2,NN)
20       WRITE(6,100)  (V(I,J),J=2,NN)
30    WRITE(6,*) 'ZEROUV = ',ZEROUV
         READ(12,99) CARD
         WRITE(6,99) CARD
         DO 40 I=2,M
            READ(12,*) (W(I,J),J=2,TOTJ)
40       WRITE(6,200)  (W(I,J),J=2,TOTJ)
         READ(12,*) FRE
         WRITE(6,*) '*-----INPUT FRE=',FRE
         READ(13,99) CARD
         WRITE(6,99) CARD
         DO 50 I=2,M
            READ(13,*) (TH(I,J),J=2,TOTJ)
50       WRITE(6,100)  (TH(I,J),J=2,TOTJ)
99    FORMAT(A80)
100   FORMAT((T2,8(D14.7,1X)))
200   FORMAT((T2,12(F9.7,1X)))
      RETURN
      END
C=================================================================
C* "PSEUDO" CALCULATES FALSE VELOCITY BY SUBSTITUTING NEIGHBOR VALUES *
C=================================================================
      SUBROUTINE PSEUDO(DUP,DVP,FALSU,FALSV,TOTI,TOTJ,R,DR,DF,U,V,W,
     *                 TH,GR,ALPHA,M,MM,N,NN)
      INTEGER TOTI,TOTJ,I,J,M,N,MM,NN
      REAL*8 DUP(TOTI,TOTJ),DVP(TOTI,TOTJ),FALSU(TOTI,TOTJ),
     *     FALSV(TOTI,TOTJ),R(TOTI),DR,DF,U(TOTI,TOTJ),V(TOTI,TOTJ),
     *     W(TOTI,TOTJ),TH(TOTI,TOTJ),GR,ALPHA
      REAL*8 SB,COEFA,AE,AW,AN,AS,XR,ASUM,Y
C
C--CALCULATE THE PSEUDOVELOCITY OF U
      DO 10 I=2,MM
         XR=R(I)+0.5D0*DR
         DO 10 J=2,N
            AE=COEFA(1,1,I,J,TOTI,TOTJ,R,DR,DF,U,V,W)
            AW=COEFA(1,2,I,J,TOTI,TOTJ,R,DR,DF,U,V,W)
            AN=COEFA(1,3,I,J,TOTI,TOTJ,R,DR,DF,U,V,W)
            AS=COEFA(1,4,I,J,TOTI,TOTJ,R,DR,DF,U,V,W)
            ASUM=AE+AW+AN+AS+2.D0*DR*DF/XR
            CALL SOURCE(1,SB,I,J,TOTI,TOTJ,R,DR,DF,U,V,TH,
     *                  GR,ALPHA)
            Y=AE*U(I+1,J)+AW*U(I-1,J)+AN*U(I,J+1)+AS*U(I,J-1)
            FALSU(I,J)=(Y+SB)/ASUM
10       DUP(I,J)=DF*XR/ASUM
C
C--CALCULATE THE PSEUDOVELOCITY OF V
      DO 20 I=2,M
         DO 20 J=2,NN
            AE=COEFA(2,1,I,J,TOTI,TOTJ,R,DR,DF,U,V,W)
            AW=COEFA(2,2,I,J,TOTI,TOTJ,R,DR,DF,U,V,W)
            AN=COEFA(2,3,I,J,TOTI,TOTJ,R,DR,DF,U,V,W)
            AS=COEFA(2,4,I,J,TOTI,TOTJ,R,DR,DF,U,V,W)
            ASUM=AE+AW+AN+AS+DR*DF/R(I)
            CALL SOURCE(2,SB,I,J,TOTI,TOTJ,R,DR,DF,U,V,TH,
     *                  GR,ALPHA)
            Y=AE*V(I+1,J)+AW*V(I-1,J)+AN*V(I,J+1)+AS*V(I,J-1)
            FALSV(I,J)=(Y+SB)/ASUM
20       DVP(I,J)=DR/ASUM
      RETURN
      END
C=================================================================
C* "COEFA" CALCULATES COEFFICIENTS OF A'S FOR U, V & W MOMENTUM EQ.S  *
C* "INDEX1" = 1, 2, 3 FOR U, V, W, RESPECTIVELY                        *
C* "INDEX2" = 1, 2, 3, 4 FOR EAST, W, N, S, RESPECTIVELY (E-RADIAL)    *
C* THE POWER LAW IS USED                                               *
C=================================================================
      DOUBLE PRECISION FUNCTION
     *       COEFA(INDEX1,INDEX2,I,J,TOTI,TOTJ,R,DR,DF,U,V,W)
      INTEGER INDEX1,INDEX2,I,J,TOTI,TOTJ
      REAL*8 R(TOTI),DR,DF,U(TOTI,TOTJ),V(TOTI,TOTJ),W(TOTI,TOTJ)
      REAL*8 AP,XX,YY,FF,DD,XR
      AP(XX,YY)=DMAX1(0.D0,(1.D0-0.1D0*DABS(XX/YY))**5)
C
      GOTO (10,20,30), INDEX1
         WRITE(6,*) 'WRONG INDEX OF EQUATION NUMBER'
         STOP
10    CONTINUE
         GOTO (12,14,16,18), INDEX2
```

```
            WRITE(6,*) 'WRONG INDEX OF U-I'
            STOP
 12      FF=DF*R(I+1)*(U(I,J)+U(I+1,J))/2.D0
            DD=2.D0*R(I+1)/DR*DF
            COEFA=DD*AP(FF,DD)+DMAX1(0.D0,-FF)
            GOTO 40
 14      FF=DF*R(I)*(U(I,J)+U(I-1,J))/2.D0
            DD=2.D0*R(I)/DR*DF
            COEFA=DD*AP(FF,DD)+DMAX1(0.D0,FF)
            GOTO 40
 16      FF=DR*(V(I+1,J)+V(I,J))/2.D0
            DD=DR/(R(I)+0.5D0*DR)/DF
            IF (J .EQ. TOTJ-1) DD=2.D0*DD
            COEFA=DD*AP(FF,DD)+DMAX1(0.D0,-FF)
            GOTO 40
 18      FF=DR*(V(I,J-1)+V(I+1,J-1))/2.D0
            DD=DR/(R(I)+0.5D0*DR)/DF
            IF (J .EQ. 2) DD=2.D0*DD
            COEFA=DD*AP(FF,DD)+DMAX1(0.D0,FF)
            GOTO 40
 20   CONTINUE
         GOTO (22,24,26,28), INDEX2
            WRITE(6,*) 'WRONG INDEX OF V-I'
            STOP
 22      XR=R(I)+0.5D0*DR
            FF=XR*DF*(U(I,J)+U(I,J+1))/2.D0
            DD=XR*DF/DR
            IF (I .EQ. TOTI-1) DD=2.D0*DD
            COEFA=DD*AP(FF,DD)+DMAX1(0.D0,-FF)
            GOTO 40
 24      CONTINUE
            IF (I .GT. 2) GOTO 25
               COEFA=0.D0
               GOTO 40
 25         XR=R(I)-0.5D0*DR
               FF=XR*DF*(U(I-1,J)+U(I-1,J+1))/2.D0
               DD=XR*DF/DR
               COEFA=DD*AP(FF,DD)+DMAX1(0.D0,FF)
            GOTO 40
 26      FF=DR*(V(I,J)+V(I,J+1))/2.D0
            DD=2.D0*DR/R(I)/DF
            COEFA=DD*AP(FF,DD)+DMAX1(0.D0,-FF)
            GOTO 40
 28      FF=DR*(V(I,J)+V(I,J-1))/2.D0
            DD=2.D0*DR/R(I)/DF
            COEFA=DD*AP(FF,DD)+DMAX1(0.D0,FF)
            GOTO 40
 30   CONTINUE
         GOTO (32,34,36,38), INDEX2
            WRITE(6,*) 'WRONG INDEX OF W-I'
            STOP
 32      XR=R(I)+DR/2.D0
            FF=XR*DF*U(I,J)
            DD=XR*DF/DR
            IF (I .EQ. TOTI-1) DD=2.D0*DD
            COEFA=DD*AP(FF,DD)+DMAX1(0.D0,-FF)
            GOTO 40
 34      CONTINUE
            IF (I .GT. 2) GOTO 35
               COEFA=0.D0
               GOTO 40
 35         XR=R(I)-DR/2.D0
               FF=XR*DF*U(I-1,J)
               DD=XR*DF/DR
               COEFA=DD*AP(FF,DD)+DMAX1(0.D0,FF)
            GOTO 40
 36      FF=DR*V(I,J)
            DD=DR/R(I)/DF
            IF (J .EQ. TOTJ-1) DD=2.D0*DD
            COEFA=DD*AP(FF,DD)+DMAX1(0.D0,-FF)
            GOTO 40
 38      FF=DR*V(I,J-1)
            DD=DR/R(I)/DF
            IF (J .EQ. 2) DD=2.D0*DD
            COEFA=DD*AP(FF,DD)+DMAX1(0.D0,FF)
 40   CONTINUE
      RETURN
      END
C=================================================================
C* "SOURCE" COMPUTES THE SOURCE TERMS FOR U-AND-V MOMENTUM EQUATIONS  *
C=================================================================
      SUBROUTINE SOURCE(INDEX,SB,I,J,TOTI,TOTJ,R,DR,DF,U,V,TH,GR,ALPHA)
      INTEGER INDEX,I,J,TOTI,TOTJ
      REAL*8 SB,R(TOTI),DR,DF,U(TOTI,TOTJ),V(TOTI,TOTJ),
     *       TH(TOTI,TOTJ),GR,ALPHA
      REAL*8 RR,S1,S2,XX
```

```
C
      GOTO (10,20), INDEX
         WRITE(6,*) 'WRONG INDEX FOR THE SOURCE TERM'
         STOP
10    RR=R(I)+0.5DO*DR
         XX=DR*DF*RR
         SB=-XX*GR*DSIN((J-1.5DO)*DF-ALPHA)*(TH(I,J)+TH(I+1,J))/2.DO
         SB=SB+V(I+1,J)-V(I,J)-V(I+1,J-1)+V(I,J-1)
         S1=(V(I+1,J)+V(I,J)-V(I+1,J-1)-V(I,J-1))/2.DO
         SB=SB-3.DO*DR/RR*S1
         S2=(V(I+1,J)+V(I,J)+V(I+1,J-1)+V(I,J-1))/4.DO
         SB=SB+DR*DF*S2*S2
         GOTO 30
20    XX=DR*DF*R(I)
         SB=U(I,J+1)-U(I,J)-U(I-1,J+1)+U(I-1,J)
         SB=SB+3.DO*DR/R(I)*(U(I,J+1)+U(I-1,J+1)-U(I,J)-U(I-1,J))/2.DO
         S1=(U(I,J+1)+U(I-1,J+1)+U(I,J)+U(I-1,J))/4.DO
         SB=SB-DR*DF*V(I,J)*S1
         S2=(TH(I,J)+TH(I,J+1))/2.DO
         SB=SB-XX*GR*S2*DCOS((J-1)*DF-ALPHA)
30    CONTINUE
      RETURN
      END
C=================================================================
C* "PRESS" SOLVES PRESSURE EQUATION OR PRESSURE CORRECTION EQUATION   *
C* ------------------- DIRECT SOLVER --------(BAND STORAGE)--------   *
C=================================================================
      SUBROUTINE PRESS(P,DUP,DVP,FALSU,FALSV,TOTI,TOTJ,R,DR,DF,
     *                 M,MM,N,NN)
      INTEGER TOTI,TOTJ,I,J,M,N,MM,NN,NROW,NCOL,DC,IER,K
      REAL*8 DUP(TOTI,TOTJ),DVP(TOTI,TOTJ),FALSU(TOTI,TOTJ),
     *     FALSV(TOTI,TOTJ),R(TOTI),DR,DF,P(TOTI,TOTJ)
      REAL*8 AE,AW,AN,AS,XR,Y,CR,XE,XW
      REAL*8 A(414,37),X(414),XL(7866)
C-- NOTE THAT A, X, XL NEED BE CHANGED WHEN THE MESH SIZE IS CHANGED
C-- A(MM*NN,MM*2+1),X(MM*NN),XL(MM*NN*(MM+1)),K=(J-2)*MM+I-1
C
      NROW=MM*NN
      NCOL=2*MM+1
      DC=(1+NCOL)/2
C
C--INITIALIZATION OF A
      DO 10 I=1,NROW
      DO 10 J=1,NCOL
10    A(I,J)=0.DO
C
C--CALCULATE COEFFICIENTS ALONG J=2
C
        I=2
        J=2
        K=1
        XE=R(I)+0.5DO*DR
        A(K,DC+1)=DF*XE*DUP(I,J)
        A(K,DC+MM)=DR*DVP(I,J)
        A(K,DC)=-(A(K,DC+1)+A(K,DC+MM))
        Y=-DF*XE*FALSU(I,J)-DR*FALSV(I,J)
        X(K)=-Y
        I=M
        K=MM
        XW=R(I)-0.5DO*DR
        A(K,DC-1)=DF*XW*DUP(I-1,J)
        A(K,DC+MM)=DR*DVP(I,J)
        A(K,DC)=-(A(K,DC-1)+A(K,DC+MM))
        Y=DF*XW*FALSU(I-1,J)-DR*FALSV(I,J)
        X(K)=-Y
        DO 30 I=3,MM
           K=I-1
           XE=R(I)+0.5DO*DR
           XW=R(I)-0.5DO*DR
           A(K,DC+1)=DF*XE*DUP(I,J)
           A(K,DC-1)=DF*XW*DUP(I-1,J)
           A(K,DC+MM)=DR*DVP(I,J)
           A(K,DC)=-(A(K,DC+1)+A(K,DC-1)+A(K,DC+MM))
           Y=DF*(XW*FALSU(I-1,J)-XE*FALSU(I,J))-DR*FALSV(I,J)
30         X(K)=-Y
C
C--CALCULATE COEFFICIENTS ALONG J=3 AND J=TOTJ-2
C
        DO 70 J=3,NN
           K=(J-2)*MM+1
           I=2
           XE=R(I)+0.5DO*DR
           A(K,DC+1)=DF*XE*DUP(I,J)
           A(K,DC+MM)=DR*DVP(I,J)
           A(K,DC-MM)=DR*DVP(I,J-1)
           A(K,DC)=-(A(K,DC+1)+A(K,DC+MM)+A(K,DC-MM))
```

```
            Y=-DF*XE*FALSU(I,J)+DR*(FALSV(I,J-1)-FALSV(I,J))
            X(K)=-Y
            I=M
            XW=R(I)-0.5DO*DR
            K=(J-1)*MM
            A(K,DC-1)=DF*XW*DUP(I-1,J)
            A(K,DC+MM)=DR*DVP(I,J)
            A(K,DC-MM)=DR*DVP(I,J-1)
            A(K,DC)=-(A(K,DC-1)+A(K,DC+MM)+A(K,DC-MM))
            Y=DF*XW*FALSU(I-1,J)+DR*(FALSV(I,J-1)-FALSV(I,J))
            X(K)=-Y
            DO 60 I=3,MM
               K=(J-2)*MM+I-1
               XE=R(I)+0.5DO*DR
               XW=R(I)-0.5DO*DR
               A(K,DC+1)=DF*XE*DUP(I,J)
               A(K,DC-1)=DF*XW*DUP(I-1,J)
               A(K,DC+MM)=DR*DVP(I,J)
               A(K,DC-MM)=DR*DVP(I,J-1)
               A(K,DC)=-(A(K,DC+1)+A(K,DC-1)+A(K,DC+MM)+A(K,DC-MM))
               Y=DF*(XW*FALSU(I-1,J)-XE*FALSU(I,J))
     *           +DR*(FALSV(I,J-1)-FALSV(I,J))
60             X(K)=-Y
70       CONTINUE
C
C--CALCULATE COEFFICIENTS ALONG J=TOTJ-1
C
         I=2
         J=N
         XE=R(I)+0.5DO*DR
         K=(NN-1)*MM+1
         A(K,DC+1)=DF*XE*DUP(I,J)
         A(K,DC-MM)=DR*DVP(I,J-1)
         A(K,DC)=-(A(K,DC+1)+A(K,DC-MM))
         Y=-DF*XE*FALSU(I,J)+DR*FALSV(I,J-1)
         X(K)=-Y
         I=M
         XW=R(I)-0.5DO*DR
         K=MM*NN
         A(K,DC-1)=DF*XW*DUP(I-1,J)
         A(K,DC-MM)=DR*DVP(I,J-1)
         A(K,DC)=-(A(K,DC-1)+A(K,DC-MM))
         Y=DF*XW*FALSU(I-1,J)+DR*FALSV(I,J-1)
         X(K)=-Y
         DO 80 I=3,MM
            K=(NN-1)*MM+I-1
            XE=R(I)+0.5DO*DR
            XW=R(I)-0.5DO*DR
            A(K,DC+1)=DF*XE*DUP(I,J)
            A(K,DC-1)=DF*XW*DUP(I-1,J)
            A(K,DC-MM)=DR*DVP(I,J-1)
            A(K,DC)=-(A(K,DC+1)+A(K,DC-1)+A(K,DC-MM))
            Y=DF*(XW*FALSU(I-1,J)-XE*FALSU(I,J))+DR*FALSV(I,J-1)
80       X(K)=-Y
C
C--SPECIFY A VALUE AT ONE POINT, CALL "LEQT1B" & SUBSTITUTE BACK TO P
      K=MM*NN
      A(K,DC)=1.DO
      A(K,DC-1)=0.DO
      A(K,DC-MM)=0.DO
      X(K)=0.DO
      CALL LEQT1B(A,NROW,MM,MM,NROW,X,1,NROW,0,XL,IER)
      DO 95 I=2,M
      DO 95 J=2,N
95    P(I,J)=X((J-2)*MM+I-1)
      RETURN
      END


C=================================================================
C* "UVMTUM" SOLVES THE MOMENTUM EQUATIONS FOR VELOCITIES OF U AND V   *
C=================================================================
      SUBROUTINE UVMTUM(DUP,DVP,APAP,MS,TOTI,TOTJ,R,DR,DF,P,U,V,W,
     *                 TH,GR,ALPHA,YES,M,MM,N,NN,CRUV,CRM,URFUV)
      INTEGER TOTI,TOTJ,I,J,M,N,MM,NN,YES,MORE,NI,SI,SJ,IUV
      REAL*8 DUP(TOTI,TOTJ),DVP(TOTI,TOTJ),APAP(TOTI,TOTJ),
     *     R(TOTI),DR,DF,P(TOTI,TOTJ),U(TOTI,TOTJ),V(TOTI,TOTJ),
     *     W(TOTI,TOTJ),TH(TOTI,TOTJ),MS(TOTI,TOTJ)
      REAL*8 GR,ALPHA,CRUV,CRM,URFUV
      REAL*8 SB,COEFA,AE,AW,AN,AS,XE,XW,ADZ,Y,INTEG
      REAL*8 A(50),B(50),C(50),D(50),T(50)
C
C--SOLVE THE MOMENTUM EQUATION FOR U
C
      IUV=20
```

```
      YES=1
      MORE=1
      NI=0
10    NI=NI+1
         IF (NI .LE. 5) GOTO 12
            CRUV=CRUV*3.0D0
12       CONTINUE
C
      DO 35 J=2,N
         A(1)=1.D0
         B(1)=0.D0
         C(1)=0.D0
         D(1)=0.D0
         A(M)=1.D0
         B(M)=0.D0
         C(M)=0.D0
         D(M)=0.D0
         DO 20 I=2,MM
            XE=R(I)+0.5D0*DR
            B(I)=COEFA(1,1,I,J,TOTI,TOTJ,R,DR,DF,U,V,W)
            C(I)=COEFA(1,2,I,J,TOTI,TOTJ,R,DR,DF,U,V,W)
            AN  =COEFA(1,3,I,J,TOTI,TOTJ,R,DR,DF,U,V,W)
            AS  =COEFA(1,4,I,J,TOTI,TOTJ,R,DR,DF,U,V,W)
            A(I)=(B(I)+C(I)+AN+AS+2.D0*DR*DF/XE)/URFUV
            Y=(1.D0-URFUV)*A(I)*U(I,J)
            CALL SOURCE(1,SB,I,J,TOTI,TOTJ,R,DR,DF,U,V,TH,GR,ALPHA)
            DUP(I,J)=DF*XE/A(I)
20       D(I)=AN*U(I,J+1)+AS*U(I,J-1)+SB+DF*XE*(P(I,J)-P(I+1,J))+Y
         CALL TDMA(1,M,A,B,C,D,T)
         DO 30 I=2,MM
            IF (DABS(U(I,J)-T(I)) .GT. CRUV) YES=0
30       U(I,J)=T(I)
35    CONTINUE
C     IF (ALPHA .GT. 0.01D0 .AND. ALPHA .LT. 3.14D0) GOTO 45
         DO 40 I=2,MM
40       U(I,TOTJ)=1.125D0*U(I,N)-0.125D0*U(I,NN)
C45   CONTINUE
C
C--SOLVE FOR V; F-DIRECTION SWEEP ALONG THE RADIUS
C
      DO 90 J=2,NN
         A(1)=1.D0
         B(1)=0.D0
         C(1)=0.D0
         D(1)=0.D0
         A(TOTI)=1.D0
         B(TOTI)=0.D0
         C(TOTI)=0.D0
         D(TOTI)=0.D0
         DO 70 I=2,M
            B(I)=COEFA(2,1,I,J,TOTI,TOTJ,R,DR,DF,U,V,W)
            C(I)=COEFA(2,2,I,J,TOTI,TOTJ,R,DR,DF,U,V,W)
            AN  =COEFA(2,3,I,J,TOTI,TOTJ,R,DR,DF,U,V,W)
            AS  =COEFA(2,4,I,J,TOTI,TOTJ,R,DR,DF,U,V,W)
            A(I)=(B(I)+C(I)+AN+AS+DR*DF/R(I))/URFUV
            Y=(1.D0-URFUV)*A(I)*V(I,J)
            CALL SOURCE(2,SB,I,J,TOTI,TOTJ,R,DR,DF,U,V,TH,GR,ALPHA)
            DVP(I,J)=DR/A(I)
70       D(I)=AN*V(I,J+1)+AS*V(I,J-1)+SB+DR*(P(I,J)-P(I,J+1))+Y
         CALL TDMA(1,TOTI,A,B,C,D,T)
         DO 80 I=2,M
            IF (DABS(V(I,J)-T(I)) .GT. CRUV) YES=0
80       V(I,J)=T(I)
90    CONTINUE
C
      IF (YES .EQ. 0) GOTO 95
         MORE=0
95    YES=1
      IF (MORE .EQ. 1 .AND. NI .LE. IUV) GOTO 10
C
C--CALCULATE THE MASS SOURCE B
C
      YES=1
      AS=-10000.D0
      DO 240 I=2,M
         XE=R(I)+0.5D0*DR
         XW=R(I)-0.5D0*DR
         DO 230 J=2,N
         Y=DF*(XW*U(I-1,J)-XE*U(I,J))
     *      +DR*(V(I,J-1)-V(I,J))
          IF (I .EQ. M .AND. J .EQ. N) GOTO 225
            IF (DABS(Y) .GT. CRM) YES=0
            IF (DABS(Y) .LT. AS) GOTO 225
            AS=DABS(Y)
            SI=I
            SJ=J
```

```
225         CONTINUE
230         MS(I,J)=Y
240      CONTINUE
C
          WRITE(6,300) NI,CRUV,MORE,AS,SI,SJ,YES
300       FORMAT(T2,'NI(UV)=',I3,', CRUV=',D14.6,', MORE=',I1,
     *    ', MAX MASS SOURCE=',F9.5,' AT I=',I2,' J=',I2,', YES=',I1)
C
C--CORRECT U AND V IF THE MASS SOURCES ARE NOT SMALL ENOUGH
C
         IF (YES .NE. 0) GOTO 400
            CALL PRESS(APAP,DUP,DVP,U,V,TOTI,TOTJ,R,DR,DF,
     *                 M,MM,N,NN)
C
C--CORRECT THE VELOCITY FIELD
C
            DO 320 I=2,MM
            DO 320 J=2,N
320         U(I,J)=U(I,J)+DUP(I,J)*(APAP(I,J)-APAP(I+1,J))
C           IF (ALPHA .GT. 0.01D0 .AND. ALPHA .LT. 3.14D0) GOTO 340
               DO 330 I=2,MM
330             U(I,TOTJ)=1.125D0*U(I,N)-0.125D0*U(I,NN)
C340        CONTINUE
            DO 350 I=2,M
            DO 350 J=2,NN
350         V(I,J)=V(I,J)+DVP(I,J)*(APAP(I,J)-APAP(I,J+1))
400      CONTINUE
         RETURN
         END
C======================================================================
C* "TDMA" SOLVES LINEAR ALGEBRA EQ'S (TRIDIAGONAL-MATRIX ALGORITHM)   *
C======================================================================
         SUBROUTINE TDMA(M,N,A,B,C,D,T)
         INTEGER M,N,I,J
         REAL*8 A(50),B(50),C(50),D(50),T(50),P(50),Q(50)
C
         P(M)=B(M)/A(M)
         Q(M)=D(M)/A(M)
         J=M+1
         DO 10 I=J,N
            P(I)=B(I)/(A(I)-C(I)*P(I-1))
10          Q(I)=(D(I)+C(I)*Q(I-1))/(A(I)-C(I)*P(I-1))
         T(N)=Q(N)
         I=N-1
20          T(I)=P(I)*T(I+1)+Q(I)
            I=I-1
            IF (I .GE. M) GOTO 20
         RETURN
         END
C======================================================================
C* "WMTUM" SOLVES THE MOMENTUM EQUATION FOR W (F-DIRECTION SWEEP)     *
C======================================================================
         SUBROUTINE WMTUM(APAP,TOTI,TOTJ,R,DR,DF,U,V,W,FRE,CFRE,
     *                    M,MM,N,NN,CRW,URFW)
         INTEGER TOTI,TOTJ,I,J,M,N,MM,NN,YES,MORE,NI,IW
         REAL*8 APAP(TOTI,TOTJ),W(TOTI,TOTJ),
     *       R(TOTI),DR,DF,U(TOTI,TOTJ),V(TOTI,TOTJ)
         REAL*8 FRE,CRW,URFW,CFRE
         REAL*8 COEFA,AE,AW,AN,AS,BPW,Y,INTEG
         REAL*8 A(50),B(50),C(50),D(50),T(50)
C
         IW=20
         NI=0
         YES=1
         MORE=1
140      NI=NI+1
            IF (NI .LE. 5) GOTO 145
               CRW=CRW*5.0D0
145         CONTINUE
            DO 160 J=2,N
               A(1)=1.D0
               B(1)=0.D0
               C(1)=0.D0
               D(1)=0.D0
               A(TOTI)=1.D0
               B(TOTI)=0.D0
               C(TOTI)=0.D0
               D(TOTI)=0.D0
               DO 150 I=2,M
                  B(I)=COEFA(3,1,I,J,TOTI,TOTJ,R,DR,DF,U,V,W)
                  C(I)=COEFA(3,2,I,J,TOTI,TOTJ,R,DR,DF,U,V,W)
                  AN  =COEFA(3,3,I,J,TOTI,TOTJ,R,DR,DF,U,V,W)
                  AS  =COEFA(3,4,I,J,TOTI,TOTJ,R,DR,DF,U,V,W)
                  Y=2.0D0*DR*DF*R(I)
                  A(I)=(B(I)+C(I)+AN+AS)/URFW
                  BPW=Y*FRE+(1.0D0-URFW)*A(I)*W(I,J)
                  APAP(I,J)=Y/A(I)
```

```
150          D(I)=AN*W(I,J+1)+AS*W(I,J-1)+BPW
             CALL TDMA(1,TOTI,A,B,C,D,T)
             DO 155 I=2,M
                IF (DABS(W(I,J)-T(I)) .GT. CRW) YES=0
155          W(I,J)=T(I)
160       CONTINUE
          DO 170 I=2,M
170          W(I,TOTJ)=1.125D0*W(I,N)-0.125D0*W(I,NN)
          IF (YES .EQ. 0) GOTO 190
             MORE=0
190       YES=1
C       IF ((MORE .EQ. 1) .AND. (NI .LT. IW)) GOTO 140
C
C--CORRECTION OF W AND FRE BY USING MASS CONSERVATION
C
          AE=1.570796327D0-INTEG(TOTI,TOTJ,W,R,DR,DF)
          CFRE=AE/INTEG(TOTI,TOTJ,APAP,R,DR,DF)
          Y=0.5D0
          IF (DABS(CFRE/FRE) .GT. 0.1D0) Y=0.01D0
          FRE=FRE+CFRE*Y
          DO 200 I=2,M
          DO 200 J=2,N
200       W(I,J)=W(I,J)+APAP(I,J)*CFRE*Y
          DO 210 I=2,M
210       W(I,TOTJ)=1.125D0*W(I,N)-0.125D0*W(I,NN)
       IF ((MORE .EQ. 1) .AND. (NI .LT. IW)) GOTO 140
C
       WRITE(6,400) NI,CRW,MORE,CFRE,FRE
400    FORMAT(T2,'NI(W)=',I3,', CRW=',D14.6,', MORE=',I1,
      * ', CORRECTED FRE=',F12.6,', FRE(RO)=',F12.6)
       RETURN
       END
C=====================================================================
C* "INTEG" PERFORMS SIMPLE AREA INTEGRATION: II=SUMMATION OF XI*AI    *
C=====================================================================
       DOUBLE PRECISION FUNCTION INTEG(TOTI,TOTJ,X,R,DR,DF)
       INTEGER TOTI,TOTJ, I,J,M,N
       REAL*8 X(TOTI,TOTJ),R(TOTI),DR,DF,SUM
C
       M=TOTI-1
       N=TOTJ-1
       INTEG=0.D0
       DO 10 I=2,M
          SUM=0.D0
          DO 20 J=2,N
20        SUM=SUM+X(I,J)
10     INTEG=INTEG+R(I)*SUM
       INTEG=2.D0*DR*DF*INTEG
       RETURN
       END
C=====================================================================
C* "ENERGY" SOLVES THE ENERGY EQUATION FOR TH BY THE "TDMA" (F-SWEEP) *
C=====================================================================
       SUBROUTINE ENERGY(TOTI,TOTJ,R,DR,DF,U,V,W,TH,PR,M,MM,N,NN,
      *                  CRTH,URFTH)
       INTEGER TOTI,TOTJ,M,MM,N,NN,I,J,YES,MORE,NI,ITH
       REAL*8 R(TOTI),DR,DF,U(TOTI,TOTJ),V(TOTI,TOTJ),TH(TOTI,TOTJ),
      *     PR,CRTH,URFTH,W(TOTI,TOTJ)
       REAL*8 COETH,AE,AW,AN,AS,XE,XW,BPTH,Y,INTEG,SUM
       REAL*8 A(50),B(50),C(50),D(50),T(50),PI/3.141592653589D0/
C
       YES=1
       MORE=1
       ITH=20
       NI=0
15     NI=NI+1
          IF (NI .LE. 5) GOTO 16
             CRTH=CRTH*5.0D0
16        CONTINUE
          DO 35 J=2,N
             A(1)=1.D0
             B(1)=0.D0
             C(1)=0.D0
             D(1)=0.D0
             A(TOTI)=1.D0
             B(TOTI)=0.D0
             C(TOTI)=0.D0
             D(TOTI)=0.D0
             DO 20 I=2,M
                B(I)=COETH(1,I,J,TOTI,TOTJ,R,DR,DF,U,V,PR)
                C(I)=COETH(2,I,J,TOTI,TOTJ,R,DR,DF,U,V,PR)
                AN  =COETH(3,I,J,TOTI,TOTJ,R,DR,DF,U,V,PR)
                AS  =COETH(4,I,J,TOTI,TOTJ,R,DR,DF,U,V,PR)
                A(I)=(B(I)+C(I)+AN+AS)/URFTH
                Y=(1.D0-URFTH)*A(I)
                BPTH=Y*TH(I,J)-2.D0*DR*DF*R(I)/(PR*PI)*W(I,J)
20           D(I)=AN*TH(I,J+1)+AS*TH(I,J-1)+BPTH
             CALL TDMA(1,TOTI,A,B,C,D,T)
```

```
            DO 30 I=2,M
               IF (DABS(TH(I,J)-T(I)) .GT. CRTH) YES=0
30          TH(I,J)=T(I)
35       CONTINUE
C--BOUNDARY CONDITION FOR THE SYMMETRIC LINE (DTH/DF=0)
         DO 50 I=2,M
50          TH(I,TOTJ)=1.125DO*TH(I,N)-0.125DO*TH(I,NN)
         IF (YES .EQ. 0) GOTO 67
            MORE=0
67       YES=1
      IF (MORE .EQ. 1 .AND. NI .LE. ITH) GOTO 15
      WRITE(6,100) NI,CRTH,MORE
100   FORMAT(T2,'NI(TH)=',I3,', CRTH=',D14.6,', MORE=',I2)
      RETURN
      END
C===================================================================
C* FUNCTION "COETH" CALCULATES COEFFICIENTS OF A'S FOR TH-EQUATION  *
C===================================================================
      DOUBLE PRECISION FUNCTION
     *                 COETH(INDEX,I,J,TOTI,TOTJ,R,DR,DF,U,V,PR)
      INTEGER INDEX,I,J,TOTI,TOTJ
      REAL*8 R(TOTI),DR,DF,U(TOTI,TOTJ),V(TOTI,TOTJ),PR
      REAL*8 XX,YY,FF,DD,XR,AP
      AP(XX,YY)=DMAX1(0.DO,(1.DO-0.1DO*DABS(XX/YY))**5)
C
      GOTO (10,20,30,40), INDEX
         WRITE(6,*) 'WRONG INDEX OF A-S FOR TH-EQUATION'
         STOP
10    XR=R(I)+DR/2.DO
         FF=XR*DF*U(I,J)
         DD=XR*DF/DR/PR
         IF (I .EQ. TOTI-1) DD=2.DO*DD
         COETH=DD*AP(FF,DD)+DMAX1(0.DO,-FF)
         GOTO 50
20    CONTINUE
         IF (I .GT. 2) GOTO 25
            COETH=0.DO
            GOTO 50
25       XR=R(I)-DR/2.DO
            FF=XR*DF*U(I-1,J)
            DD=XR*DF/DR/PR
            COETH=DD*AP(FF,DD)+DMAX1(0.DO,FF)
            GOTO 50
30    FF=DR*V(I,J)
         DD=DR/(R(I)*DF*PR)
         IF (J .EQ. TOTJ-1) DD=2.DO*DD
         COETH=DD*AP(FF,DD)+DMAX1(0.DO,-FF)
         GOTO 50
40    FF=DR*V(I,J-1)
         DD=DR/(R(I)*DF*PR)
         IF (J .EQ. 2) DD=2.DO*DD
         COETH=DD*AP(FF,DD)+DMAX1(0.DO,FF)
50    CONTINUE
      RETURN
      END
C===================================================================
C* "OUTPUT" PRINTS OUT CURRENT RESULTS                              *
C===================================================================
      SUBROUTINE OUTPUT(NIT,TOTI,TOTJ,U,V,W,TH,MS,CRUV,CRW,CRTH,CFRE,
     *                  M,MM,N,NN,YES)
      INTEGER NIT,TOTI,TOTJ,M,MM,N,NN,YES,I,J
      REAL*8 U(TOTI,TOTJ),V(TOTI,TOTJ),W(TOTI,TOTJ),TH(TOTI,TOTJ),
     *       MS(TOTI,TOTJ),CRUV,CRW,CRTH,CFRE
C
      WRITE(6,*) '================> RESULTS FROM ITERATION ',NIT
      WRITE(6,*) ' ---- U VELOCITY ----'
      DO 10 I=2,MM
10       WRITE(6,100)  (U(I,J),J=2,TOTJ)
      WRITE(6,*) ' ---- V VELOCITY ----'
      DO 20 I=2,M
20       WRITE(6,100)  (V(I,J),J=2,NN)
C     WRITE(6,*) ' ---- MASS SOURCE ----'
C     DO 45 I=2,M
C45      WRITE(6,150) (MS(I,J),J=2,N)
      WRITE(6,*) ' ---- W VELOCITY ----'
      DO 40 I=2,M
40       WRITE(6,200)  (W(I,J),J=2,TOTJ)
      WRITE(6,*) ' ---- TH = (T-TW)/(Q/K) ----'
      DO 50 I=2,M
50       WRITE(6,100)  (TH(I,J),J=2,TOTJ)
      WRITE(6,300) NIT,CRUV,CRW,CRTH,CFRE,YES
100   FORMAT((T2,8(D14.7,1X)))
150   FORMAT((T2,12(F9.6,1X)))
200   FORMAT((T2,12(F9.7,1X)))
300   FORMAT(T2,'===> NIT=',I4,', CRUV=',D13.6,', CRW=',D13.6,', CRTH=',
```

```
     * D13.6,', CFRE=',D14.6,', YES (MASS SOURCE SMALL?)=',I2)
      RETURN
      END
C=====================================================================
C* "DSAVE" STORES THE RESULTS TO DATASETS                             *
C=====================================================================
      SUBROUTINE DSAVE(NIT,TNIT,TOTI,TOTJ,M,MM,N,NN,U,V,W,TH,GR,PR,FRE,
     *                 ALPHA)
      INTEGER NIT,TNIT,TOTI,TOTJ,M,MM,N,NN,I,J
      REAL*8 U(TOTI,TOTJ),V(TOTI,TOTJ),W(TOTI,TOTJ),TH(TOTI,TOTJ),
     *   FRE,GR,PR,ALPHA
C
      WRITE(20,400) NIT,TNIT,GR,PR,ALPHA
      DO 10 I=2,MM
10       WRITE(20,100)  (U(I,J),J=2,TOTJ)
      WRITE(21,410) NIT,TNIT,GR,PR,ALPHA
      DO 20 I=2,M
20       WRITE(21,100)  (V(I,J),J=2,NN)
      WRITE(22,420) NIT,TNIT,GR,PR,ALPHA
      DO 40 I=2,M
40       WRITE(22,200)  (W(I,J),J=2,TOTJ)
      WRITE(22,*) FRE,' <=== FRE(RO)'
      WRITE(23,430) NIT,TNIT,GR,PR,ALPHA
      DO 50 I=2,M
50       WRITE(23,100)  (TH(I,J),J=2,TOTJ)
100   FORMAT((T2,8(D14.7,1X)))
200   FORMAT((T2,12(F9.7,1X)))
400   FORMAT(T2,' ---- U VELOCITY  NIT=',I4,' TNIT=',I4,
     *       ' GR=',D9.3,' PR=',F5.1,' AL=',F4.2)
410   FORMAT(T2,' ---- V VELOCITY  NIT=',I4,' TNIT=',I4,
     *       ' GR=',D9.3,' PR=',F5.1,' AL=',F4.2)
420   FORMAT(T2,' ---- W VELOCITY  NIT=',I4,' TNIT=',I4,
     *       ' GR=',D9.3,' PR=',F5.1,' AL=',F4.2)
430   FORMAT(T2,' ---- TH=(T-TC)/(Q/K)  NIT=',I4,' TNIT=',I4,
     *       ' GR=',D9.3,' PR=',F5.1,' AL=',F4.2)
      RETURN
      END
C=====================================================================
C* "NUSSLT" CALCULATES NUSSELT NUMBER NURO(H1) AND NU(DH,H1)          *
C=====================================================================
      SUBROUTINE NUSSLT(TOTI,TOTJ,M,N,W,TH,APAP,R,DR,DF)
      INTEGER TOTI,TOTJ,M,N,I,J
      REAL*8 W(TOTI,TOTJ),TH(TOTI,TOTJ),R(TOTI),APAP(TOTI,TOTJ),
     *       DR,DF,INTEG,NURO,NUDH,PI/3.1415926535898D0/
      DO 500 I=2,M
      DO 500 J=2,N
500   APAP(I,J)=W(I,J)*TH(I,J)
      NURO=-PI/(2.D0*(PI+2.D0))/INTEG(TOTI,TOTJ,APAP,R,DR,DF)
      NUDH=2.D0*PI/(PI+2.D0)*NURO
      WRITE(6,*)  'NUSSELT NO. (NURO,H1)=',NURO,'NU(DH,H1)=',NUDH
      WRITE(23,*) 'NUSSELT NO. (NURO,H1)=',NURO,'NU(DH,H1)=',NUDH
      RETURN
      END
//GO.FT10F001 DD DSN=QLEI.RU,DISP=SHR
//GO.FT11F001 DD DSN=QLEI.RV,DISP=SHR
//GO.FT12F001 DD DSN=QLEI.RW,DISP=SHR
//GO.FT13F001 DD DSN=QLEI.RT,DISP=SHR
//GO.FT20F001 DD DSN=QLEI.WU,DISP=OLD
//GO.FT21F001 DD DSN=QLEI.WV,DISP=OLD
//GO.FT22F001 DD DSN=QLEI.WW,DISP=OLD
//GO.FT23F001 DD DSN=QLEI.WT,DISP=OLD
//GO.FT25F001 DD DSN=QLEI.SP,DISP=OLD
//GO.SYSIN DD *
```

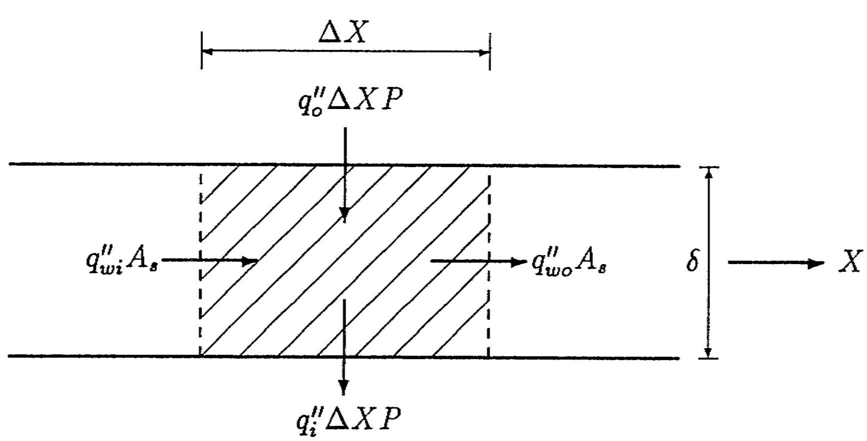
Appendix C

Estimating Effect of Axial Duct Heat Conduction on Inner Heat Flux

The analysis considers a piece of the solid duct (whose cross section is shown below) with an axial length ΔX, a thichness δ, and a perimeter P. If peripheral uniform conditions and no heat losses through the insulation are assumed, an energy balance for the duct results in

$$(q_o'' - q_i'')\Delta X P = A_s(q_{wo}'' - q_{wi}'') \quad \text{(C.1)}$$

where q_o'' and q_i'' are heat fluxes at the outer and inner surfaces of the duct, respectively; q_{wi} and q_{wo}'' are heat fluxes into and from the duct area A_s, respectively.



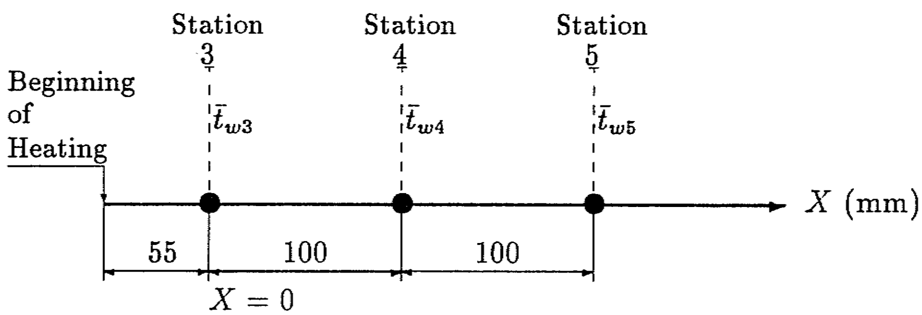
If the temperature distribution at A_s is assumed to be uniform (e.g., represented by a peripherally-averaged wall temperature $\bar{t}_w$), q''_{wi} and q''_{wo} can be related to the axial wall temperature gradient, as

$$q''_{wi} = -k_w(\frac{\partial \bar{t}_w}{\partial X})_i \qquad \text{and} \qquad q''_{wo} = -k_w(\frac{\partial \bar{t}_w}{\partial X})_o \tag{C.2}$$

where k_w is the thermal conductivity of the duct. Thus, the difference of the heat fluxes relative to q''_o can be expressed by

$$\frac{q''_o - q''_i}{q''_o} = \frac{A_s k_w}{\Delta X P q''_o}\Big((\frac{\partial \bar{t}_w}{\partial X})_i - (\frac{\partial \bar{t}_w}{\partial X})_o\Big) \tag{C.3}$$

It is recognized that significant effects of axial heat conduction occur near the beginning of the heating where the change of axial wall temperature gradients is most marked. Therefore, the gradients around station 4 are examined.



Assume that $\bar{t}_w$ can be approximated by

$$\bar{t}_w = AX^2 + BX + C \qquad \text{hence} \qquad \frac{\partial \bar{t}_w}{\partial X} = 2AX + B \tag{C.4}$$

For the shown locations of stations 3, 4, and 5, the constants A and B are given by

$$A = \frac{1}{10^4}(\frac{\bar{t}_{w3}}{2} - \bar{t}_{w4} + \frac{\bar{t}_{w5}}{2}) \qquad \text{and} \qquad B = \frac{1}{200}(4\bar{t}_{w4} - 3\bar{t}_{w3} - \bar{t}_{w5}) \tag{C.5}$$

If $\Delta X = 100$ mm,

$$(\frac{\partial \bar{t}_w}{\partial X})_i = (\frac{\partial \bar{t}_w}{\partial X})_{x=50mm} \qquad \text{and} \qquad (\frac{\partial \bar{t}_w}{\partial X})_o = (\frac{\partial \bar{t}_w}{\partial X})_{x=150mm} \tag{C.6}$$

For the lowest heating rate (experiment 0R20 in Appendix E), $q''_o = 213.28$ W/m^2 and thus

$$\frac{A_s k_w}{\Delta X P q''_o} = \frac{0.34311 \times 10^{-3}(\mathrm{m}^2)110(\mathrm{W/m^\circ C})}{0.1(\mathrm{m})0.1279(\mathrm{m})213.28(\mathrm{W/m}^2)} = 0.013836\ (\mathrm{m/^\circ C})$$

For $\bar{t}_{w3} = 24.57$ °C, $\bar{t}_{w4} = 24.90$ °C, and $\bar{t}_{w5} = 25.02$ °C, $A = -1.05 \times 10^{-5}$ °C/mm^2 and $B = 4.35 \times 10^{-3}$ °C/mm. Then,

$$(\frac{\partial \bar{t}_w}{\partial X})_i = 2(-1.05 \times 10^{-5})50 + 4.35 \times 10^{-3} = 3.3\ (^\circ\mathrm{C/m})$$

$$(\frac{\partial \bar{t}_w}{\partial X})_o = 2(-1.05 \times 10^{-5})150 + 4.35 \times 10^{-3} = 1.2\ (^\circ\mathrm{C/m})$$

Using equation (C.3) thus gives the relative difference of the heat fluxes:

$$\frac{q''_o - q''_i}{q''_o} = 0.013836(3.3 - 1.2) = 0.029 \approx 3\%$$

Similarly, using the data of experiment 0R84 for the highest heating rate, the heat flux ratio is about 0.5%.

In summary, the above one-dimensional analysis has demonstrated that, in this experiment, axial heat conduction through the duct wall influences inner heat fluxes or fluid-wall heat transfer coefficients within ±3%. The effects diminish as the change in axial wall temperature gradients decreases.

Appendix D

List of the Computer Program for Experimental Data Reduction

```
//QLEI JOB ',,,T=15,I=10,L=10,','QLEI',NOTIFY=QLEI
// EXEC WATFIV,SIZE=568K
//GO.FT10F001 DD DSN=QLEI.EXPIN,DISP=SHR
//GO.FT12F001 DD DSN=QLEI.EXPNUDA,DISP=OLD
//GO.FT13F001 DD DSN=QLEI.EXPDS,DISP=OLD
//SYSIN DD *
$JOB  WATFIV   QLEI,NOEXT
C
C*=================================================================
C* THIS READS EXPERIMENTAL DATA, CORRECTS TEMPERATURES, CALCULATES   *
C* ALL LOCAL AND AVERAGE RESULTS. THE OUTPUT IS TABULATED            *
C* -- PRINT FORMAT FOR OUTPUTS = DDA1 OR BDA1 -- MAY 3, 1989         *
C*=================================================================
C
      INTEGER I,J,N
      REAL Z(24),T(24,3),TC(2,24,3),DEN(385),CP(385),VIS(385),KF(385),
     *     PR(385),EXPC(385),TIN,TOUT,MASS,QE,MMH20,TM(24),FP,
     *     TBI,TBO,ER,QF
      REAL REM,GRMP,RAMP,ZP(24),RE(24),GRP(24),RAP(24),NUM(24),NU(24,3),
     *     TBZ(24),PRZ(24),PRM,FF,ITBZ(3),IRE(3),IPRZ(3),IZP(3),IGRP(3),
     *     IRAP(3),INU(3,3),INUM(3),NUMH(24),NUMTH(24)
      CHARACTER TITLE*80
C=================================================================
C*             ------- VARIABLE DICTIONARY -------                   *
C* Z       = AXIAL LENGTH (MM, 1-D)                                  *
C* T       = TEMPERATURES (24 AXIAL STATIONS, 3 PERIPHERAL VALUES)   *
C* TC      = TEMPERATURE CORRECTION CONSTANTS (T=A*X+B) (I,J,K)      *
C*            I=1 FOR A; I=2 FOR B; J FOR STATIONS; K FOR LOCATIONS  *
C* DEN,CP,VIS,KF,PR,EXPC = FLUID PROPERTIES (1-D)                    *
C* TIN, TOUT = INLET & OUTLET FLUID TEMPERATURES (F)                 *
C* MASS    = MASS FLOW RATE (KG/S)                                   *
C* QE      = ELECTRIC POWER INPUT (WATT)                             *
C* MMH20   = PRESSURE IN MM H20                                      *
C* TM      = BULK MEAN TEMP                                          *
C* FP      = FUNCTION FOR FLUID PROPERTIES                           *
C* TBI,TBO= UPSTREAM & DOWNSTREAM BULK MEAN TEMPS                    *
C* ER      = ERROR BALANCE RATIO (%)                                 *
C* QF      = HEAT GAIN BY THE FLUID                                  *
C* REM,GRMP,RAMP = REYNOLDS, GR, RA NUMBERS BASED ON (TBI+TBO)/2, 1-D *
C* RE,GRP,RAP = LOCAL REYNOLDS, GR, RA NUMBERS (1-D)                 *
C* NUM,NUMH,NUMTH = MEAN NUSSELT NUMBERS (SEE DEFINITIONS) (1-D)     *
C* NU      = LOCAL NU (2-D)                                          *
C=================================================================
C
C--INPUT THE LOCATION OF THERMOCOUPLES AND FLUID PROPERTIES
C
      READ(10,*) (Z(I),I=1,12)
      READ(10,*) (Z(I),I=13,22)
      DO 10 I=280,385,5
10    READ(10,*) DEN(I),CP(I),VIS(I),KF(I),PR(I),EXPC(I)
C
C--READ TEMPERATURE CORRECTION EQUATIONS (T=TC(1,I,J)*X+TC(2,I,J))
C
      DO 20 I=1,23
         N=3; IF (I .LE. 2 .OR. I .GE. 22) N=2
         DO 20 J=1,N
20       READ(10,*) TC(1,I,J),TC(2,I,J)
C
      N=1
C--N = NO. OF DATA REDUCTIONS (IF N=M, M SETS OF EXP DATA ARE WANTED)
      DO 100 I=1,N
      CALL DATAIN(Z,T,TC,DEN,CP,VIS,KF,PR,EXPC,TITLE,TIN,
     *                        TOUT,MASS,QE,MMH20,TM)
      CALL TBCORR(TIN,TOUT,TM,MASS,QE,TBI,TBO,ER,QF,CP)
      CALL MAIN(TBI,TBO,TM,T,MASS,QF,MMH20,REM,GRMP,RAMP,Z,ZP,RE,
     *          GRP,RAP,NUM,NU,TBZ,PRZ,PRM,FF,DEN,CP,VIS,KF,PR,EXPC,
     *            ITBZ,IRE,IPRZ,IZP,IGRP,IRAP,INU,INUM,NUMH,NUMTH)
      CALL OUTPUT(TITLE,QE,QF,ER,MMH20,FF,REM,GRMP,RAMP,PRM,TIN,TOUT,
     *             TBI,TBO,MASS,Z,ZP,T,TM,TBZ,RE,PRZ,RAP,NU,NUM,
     *            ITBZ,IRE,IPRZ,IZP,IGRP,IRAP,INU,INUM,NUMH,NUMTH)
100   CONTINUE
      STOP
      END
C=================================================================
C* "DATAIN" READS EXPERIMENTAL DATA, CORRECTED & AVERAGED TEMPS      *
C=================================================================
      SUBROUTINE DATAIN(Z,T,TC,DEN,CP,VIS,KF,PR,EXPC,TITLE,TIN,
     *                   TOUT,MASS,QE,MMH20,TM)
      REAL Z(24),T(24,3),TC(2,24,3),DEN(385),CP(385),VIS(385),KF(385),
     *     PR(385),EXPC(385),TIN,TOUT,MASS,QE,MMH20,TM(24)
      CHARACTER TITLE*80
      INTEGER I,J,K,N,IT,WF/4/
C
      READ 30, TITLE
30    FORMAT(A80)
C
```

```
      DO 40 I=1,23
40    READ, T(I,1),T(I,2),T(I,3)
      READ, TIN,TOUT,MASS,QE,MMH20
      TIN=(TIN-32.0)/1.8; TOUT=(TOUT-32.0)/1.8
C
      DO 50 I=1,23
         N=3; IF (I .LE. 2 .OR. I .GE. 22) N=2
         DO 50 J=1,N
            T(I,J)=(T(I,J)+TC(1,I,J)*T(I,J)+TC(2,I,J)-32)/1.8
50    CONTINUE
C
      T(3,3)=0.5*(T(3,1)+T(3,2))
C
      DO 60 I=1,23
         IF (I .LE. 2 .OR. I .GE. 22) THEN DO
            TM(I)=(T(I,1)+T(I,2))/2.0
         ELSE DO
            TM(I)=(T(I,1)+T(I,2)+(WF-2)*T(I,3))/WF
         END IF
60    CONTINUE
      RETURN
      END
C=====================================================================
C* FUNCTION "FP" COMPUTES THE FLUID PROPERTIES FROM THE STORED        *
C* TABLE BY USING A LINEAR INTERPOLATION                              *
C=====================================================================
      REAL FUNCTION FP(G,TEM)
      REAL G(385),TEM,T
      INTEGER IT,I,XT
C
      T=TEM+273.15; I=T/10; XT=T
      IT=I*10; IF (XT .GE. IT+5) IT=IT+5
      FP=G(IT)+(G(IT+5)-G(IT))*(T-IT)/5.0
      RETURN
      END
C=====================================================================
C* "TBCORR" CORRECTS THE BULK TEMP & DOES AN ENERGY BALANCE           *
C=====================================================================
      SUBROUTINE TBCORR(TIN,TOUT,TM,MASS,QE,TBI,TBO,ER,QF,CP)
      REAL TIN,TOUT,TM(24),MASS,QE,TBI,TBO,ER,QF,DTDZI,DTDZO,
     *     KP/110.0/,AC/343.1127E-6/,TBM,CP(385),FP,X
      INTEGER I,J
C
      X=MASS*FP(CP,TIN)
      DTDZI=((TM(3)-TM(2))+(TM(2)-TM(1))*3.0/5.0)/108.0*1000.0
      DTDZO=-((TM(22)-TM(23))+(TM(21)-TM(22))*22./9.0)/260.*1000.0
      TBI=TIN+KP*DTDZI*AC/X ; X=MASS*FP(CP,TOUT)
      TBO=TOUT+KP*DTDZO*AC/X
      TBM=(TBI+TBO)/2.0; X=MASS*FP(CP,TBM)
      QF=X*(TBO-TBI); ER=(QE-QF)/QE*100.
      RETURN
      END
C=====================================================================
C* "MAIN" COMPUTES ALL LOCAL & AVERAGE VALUES                         *
C=====================================================================
      SUBROUTINE MAIN(TBI,TBO,TM,T,MASS,QF,MMH20,REM,GRMP,RAMP,Z,ZP,RE,
     *           GRP,RAP,NUM,NU,TBZ,PRZ,PRM,FF,DEN,CP,VIS,KF,PR,EXPC,
     *           ITBZ,IRE,IPRZ,IZP,IGRP,IRAP,INU,INUM,NUMH,NUMTH)
      REAL REM,GRMP,RAMP,ZP(24),RE(24),GRP(24),RAP(24),NUM(24),NU(24,3),
     *     TBZ(24),PRZ(24),PRM,TBI,TBO,TM(24),T(24,3),MASS,QF,MMH20,
     *     Z(24),FF,ITBZ(3),IRE(3),IPRZ(3),IZP(3),IGRP(3),INU(3,3),
     *     IRAP(3),INUM(3),NUMH(24),NUMTH(24)
      REAL DH/0.0304/,AFL/972.2908E-6/,DEN(385),CP(385),
     *     PR(385),EXPC(385),VIS(385),KF(385),TBM,AWE/599.6853E-3/,
     *     X1,X2,X3,X4,U,R,TZ,ANU,AKF,ADEN,FP
      INTEGER I
C
      TBM=(TBI+TBO)/2.0; U=FP(VIS,TBM)
      R=MASS*DH*1000000.0/AFL; REM=R/U; ADEN=FP(DEN,TBM)
      X1=(U**2)*FP(KF,TBM)*AWE
      GRMP=(ADEN**2)*FP(EXPC,TBM)*1000000.0*9.81*QF*(DH**4)/X1
      PRM=FP(PR,TBM)
      RAMP=PRM*GRMP
      FF=MMH20*9.7891/2.0*DH*ADEN*(AFL**2)/(4.898*MASS**2)
C
      ANU=QF*DH/AWE
      DO 10 I=3,21
         TBZ(I)=TBI+(TBO-TBI)*Z(I+1)/4688.0
         TZ=TBZ(I)
         RE(I)=R/FP(VIS,TZ)
         PRZ(I)=FP(PR,TZ); AKF=FP(KF,TZ)
         ZP(I)=Z(I+1)/1000.0/DH/RE(I)/PRZ(I)
         X1=(FP(VIS,TZ)**2)*AKF*AWE
         GRP(I)=(FP(DEN,TZ)**2)*1000000.*FP(EXPC,TZ)*9.81*QF*(DH**4)/X1
         RAP(I)=PRZ(I)*GRP(I)
         NU(I,1)=ANU/AKF/(T(I,1)-TBZ(I))
```

```
         NU(I,2)=ANU/AKF/(T(I,2)-TBZ(I))
         NU(I,3)=ANU/AKF/(T(I,3)-TBZ(I))
10       NUM(I)=ANU/AKF/(TM(I)-TBZ(I))
C
C--INTERPOLATED VALUES FOR STATION 0 TO 2 (NOT MEASURED)
      DO 20 I=1,3
         ITBZ(I)=TBI+(TBO-TBI)*Z(I)/4688.0
         TZ=ITBZ(I)
         IRE(I)=R/FP(VIS,TZ)
         IPRZ(I)=FP(PR,TZ); AKF=FP(KF,TZ)
         IZP(I)=Z(I)/1000.0/DH/IRE(I)/IPRZ(I)
         X1=(FP(VIS,TZ)**2)*AKF*AWE
         IGRP(I)=(FP(DEN,TZ)**2)*1000000.*FP(EXPC,TZ)*9.81*QF*(DH**4)/X1
         IRAP(I)=IPRZ(I)*IGRP(I)
       INU(I,1)=ANU/AKF/(T(2,1)+(T(3,1)-T(2,1))/90.*(35.+Z(I))-ITBZ(I))
       INU(I,2)=ANU/AKF/(T(2,1)+(T(3,2)-T(2,1))/90.*(35.+Z(I))-ITBZ(I))
       INU(I,3)=ANU/AKF/(T(2,2)+(T(3,3)-T(2,2))/90.*(35.+Z(I))-ITBZ(I))
       INUM(I)=ANU/AKF/(TM(2)+(TM(3)-TM(2))/90.*(35.+Z(I))-ITBZ(I))
20     CONTINUE
C
C--CALCULATE NUMH BASED ON AVERAGE HEAT TRANSFER COEFFICIENT
C  AND NUMTH
C
      DO 30 I=1,3
         NUMH(I)=(INU(I,1)+INU(I,2)+2.0*INU(I,3))/4.0
30    NUMTH(I)=(INUM(I)+NUMH(I))/2.0
      DO 40 I=4,22
         NUMH(I)=(NU(I-1,1)+NU(I-1,2)+2.0*NU(I-1,3))/4.0
40    NUMTH(I)=(NUM(I-1)+NUMH(I))/2.0
      RETURN
      END
C=====================================================================
C* "OUTPUT" PRINTS THE RESULTS IN A DESIRED FORMAT                   *
C=====================================================================
      SUBROUTINE OUTPUT(TITLE,QE,QF,ER,MMH20,FF,REM,GRMP,RAMP,PRM,TIN,
     *                TOUT,TBI,TBO,MASS,Z,ZP,T,TM,TBZ,RE,PRZ,RAP,NU,NUM,
     *           ITBZ,IRE,IPRZ,IZP,IGRP,IRAP,INU,INUM,NUMH,NUMTH)
      REAL QE,QF,ER,MMH20,FF,REM,GRMP,RAMP,PRM,TIN,TOUT,TBI,TBO,MASS,
     *     Z(24),ZP(24),T(24,3),TM(24),TBZ(24),PRZ(24),RAP(24),RE(24),
     *     NU(24,3),NUM(24),ITBZ(3),IRE(3),IZP(3),IGRP(3),IRAP(3),
     *     INU(3,3),INUM(3),IPRZ(3),IT(3,3),ITM(3),AVEA,AVEB,AVEC,AVEM,
     *     NUMH(24),NUMTH(24)
      REAL AVEH,AVETH,AVEZP,AVERAP,AVEPR,AVERE,AVETBK,AVETM,AVETC,AVETB,
     *     AVETA,AVEZ
      CHARACTER TITLE*80
      INTEGER I,J
C
      DO 5 I=1,3
         ITM(I)=TM(2)+(TM(3)-TM(2))/90.*(35.+Z(I))
         IT(I,1)=T(2,1)+(T(3,1)-T(2,1))/90.*(35.+Z(I))
         IT(I,2)=T(2,1)+(T(3,2)-T(2,1))/90.*(35.+Z(I))
5        IT(I,3)=T(2,2)+(T(3,3)-T(2,2))/90.*(35.+Z(I))
C
      WRITE(13,10) TITLE
10    FORMAT(////T42,A80/)
      WRITE(13,20) QE,QF,ER
20    FORMAT(T9,'INPUT ELECTRIC POWER = ',F6.1,' W',14X,'HEAT RATE ',
     * 'GAINED BY WATER = ',F6.1,' W',14X,'HEAT BALANCE ERROR = ',F5.2,
     * '%')
C
      WRITE(13,30) MASS*1000,MMH20,FF,FF*REM
30    FORMAT(T9,'MASS FLOW RATE = ',F7.4,' G/S',8X,'PRESSURE DROP ',
     * '= ',F6.4,' MM H2O',8X,'FRICTION FACTOR = ',
     * F8.6,8X,'FREM = ',F8.4/)
C
      WRITE(13,40) REM,GRMP,TIN,TOUT
40    FORMAT(T9,'REM = ',F6.1,4X,'GRM+ = ',E11.5,4X,
     * T47,'UPSTREAM BULK TEMPERATURE = ',F5.2,' DEG C',T90,
     * 'DOWNSTREAM BULK TEMPERATURE = ',F5.2,' DEG C')
C
      WRITE(13,50) PRM,RAMP,TBI,TBO
50    FORMAT(T9,'PRM = ',F6.3,4X,'RAM+ = ',E11.5,4X,T47,
     * 'INLET BULK TEMPERATURE    = ',F5.2,' DEG C',T90,
     * 'OUTLET BULK TEMPERATURE     = ',F5.2,' DEG C'/)
C
       WRITE(13,54)
54     FORMAT(T9,
     * '_____________________________________________________________'
     * ,'_____________________________________________________________')
      WRITE(13,60)
60    FORMAT(T9,'STA-',T14,' Z',T20,'-WALL TEMPERATURE (DEG C)-'
     *,T49,'TB',T57,' RE',T65,'PR',T73,'RA+',T84,'Z+',T91,'-----'
     * ,'------- NUSSELT NUMBER ------------'/
     * T9,'TION',T14,' CM',T21,' A      B      C    AVER-',T49,'(C)',
     * T91,'  A      B      C    ----- AVERAGE -----'
```

```
      * /T9,'NO.',T41,'  AGE',T114,'T      H      T+H'/T9,'---',
      * '-------------------------------------------------------------',
      * ,'-----------------------------------------------------------')
C
        WRITE(12,62) TITLE
 62     FORMAT(T2,A26)
        WRITE(12,63) QF,ER,REM,GRMP,RAMP,FF*REM
 63     FORMAT(T2,'QF=',F6.1,'W;',1X,'E=',F4.1,'%;',1X,'REM=',F6.1/
      *        T2,'GRM=',E11.5,';',1X,'RAM=',E11.5,';',1X,'FREM=',F8.4)
       DO 65 I=1,3
       WRITE(13,90) I-1,Z(I)/10,IT(I,1),IT(I,2),IT(I,3),ITM(I),ITBZ(I),
      *IRE(I),IPRZ(I),IRAP(I),IZP(I),INU(I,1),INU(I,2),INU(I,3),INUM(I),
      * NUMH(I),NUMTH(I)
        WRITE(12,75) Z(I)/30.4,IZP(I),IT(I,1),IT(I,2),IT(I,3),
      *       ITBZ(I),INU(I,1),INU(I,2),INU(I,3),INUM(I),
      *       NUMH(I),NUMTH(I)
65     CONTINUE
75     FORMAT(F6.2,1X,F8.6,1X,4(F4.1,1X),6(F5.2,1X))
C
       DO 80 I=3,21
        WRITE(13,90) I,Z(I+1)/10.,T(I,1),T(I,2),T(I,3),TM(I),TBZ(I),
      *      RE(I),PRZ(I),RAP(I),ZP(I),NU(I,1),NU(I,2),NU(I,3),NUM(I),
      *      NUMH(I+1),NUMTH(I+1)
        WRITE (12,75) Z(I+1)/30.4,ZP(I),T(I,1),T(I,2),T(I,3),
      *      TBZ(I),NU(I,1),NU(I,2),NU(I,3),NUM(I),NUMH(I+1),NUMTH(I+1)
80     CONTINUE
90     FORMAT(T9,I2,T13,F5.1,T19,4(F6.2,1X),F6.2,T56,F6.1,T64,F4.2,
      * T69,E10.3,T81,F7.5,T91,6(F5.2,2X)/)
C
C--CALCULATE AVERAGE VALUES OVER STATIONS 15 TO 20
C
       AVEA=AVEB=AVEC=AVEM=0.0
       AVEH=AVETH=0.0
       DO 95 I=15,20
          AVEA=AVEA+NU(I,1)
          AVEB=AVEB+NU(I,2)
          AVEC=AVEC+NU(I,3)
          AVEM=AVEM+NUM(I)
          AVEH=AVEH+NUMH(I+1)
95        AVETH=AVETH+NUMTH(I+1)
       AVEA=AVEA/6.0; AVEB=AVEB/6.0
       AVEC=AVEC/6.0; AVEM=AVEM/6.0
       AVEH=AVEH/6.0; AVETH=AVETH/6.0
C
       AVEZ=AVETA=AVETB=AVETC=AVETM=0.0
       AVETBK=AVERE=AVEPR=AVERAP=AVEZP=0.0
       DO 96 I=15,20
          AVEZ=AVEZ+Z(I+1)/10.0; AVETA=AVETA+T(I,1)
          AVETB=AVETB+T(I,2); AVETC=AVETC+T(I,3)
          AVETM=AVETM+TM(I); AVETBK=AVETBK+TBZ(I)
          AVERE=AVERE+RE(I); AVEPR=AVEPR+PRZ(I)
          AVERAP=AVERAP+RAP(I); AVEZP=AVEZP+ZP(I)
96     CONTINUE
       AVEZ=AVEZ/6.0; AVETA=AVETA/6.0
       AVETB=AVETB/6.0; AVETC=AVETC/6.0
       AVETM=AVETM/6.0; AVETBK=AVETBK/6.0
       AVERE=AVERE/6.0; AVEPR=AVEPR/6.0
       AVERAP=AVERAP/6.0; AVEZP=AVEZP/6.0
C
       WRITE(13,100)
       WRITE(13,110) AVEZ,AVETA,AVETB,AVETC,AVETM,AVETBK,AVERE,AVEPR,
      * AVERAP,AVEZP,AVEA,AVEB,AVEC,AVEM,AVEH,AVETH
        WRITE(12,100)
        WRITE(12,75) AVEZ/3.1,AVEZP,AVETA,AVETB,AVETC,AVETBK,
      *    AVEA,AVEB,AVEC,AVEM,AVEH,AVETH
100    FORMAT(T9,'AVERAGE VALUES THROUGH STATIONS 15 TO 20:')
110    FORMAT(T13,F5.1,T19,4(F6.2,1X),F6.2,T56,F6.1,T64,F4.2,
      * T69,E10.3,T81,F7.5,T91,6(F5.2,2X)/T9,
      * '-------------------------------------------------------------',
      * ,'-----------------------------------------------------------')
C
       RETURN
       END
$ENTRY
========== EXPERIMENT OR81  --- DEC. 23, 1987 ==========
 79.75   78.70  -10.00 <-- TEMP INPUT FOR EXP OR81
 84.70   82.00  -10.00
107.75  108.40  103.00
114.20  112.65  105.55
118.70  119.30  108.20
123.30  122.10  111.30
126.80  125.65  114.30
130.90  129.40  119.30
133.10  131.05  118.30
135.65  134.35  123.90
140.65  138.95  127.10
```

```
146.45  145.80  135.10
150.10  147.90  135.70
154.55  154.45  143.10
158.10  158.50  143.30
164.80  165.80  150.30
165.40  164.90  152.10
169.40  167.70  153.00
170.50  167.30  156.20
175.75  176.20  160.40
174.40  174.85  160.00
159.20  145.40  -10.00
154.80  143.25  -10.00 <-- END OF TEMP INPUT FOR OR81
75.08  141.20  0.027709  4580.18  0.5546
```

Appendix E

List of the Experimental Data

The following experimental data were collected at the Heat Transfer Laboratory of Mechanical Engineering Department at the University of Manitoba. The flat surface of the horizontal semicircular duct was at the top (0R: zero rotation). Stations 0 to 2 give interpolated values and the measured data are listed from station 3. The symbols used in the tables are defined as follow:

A, B, C	= A and B: symmetrically at the top surface; C: at bottom
PR, RA+, RE	= local Prandtl, Rayleigh (Ra), and Reynolds numbers (Re)
FREM, GRM+, PRM, RAM+, REM	= fRe, Gr, Pr, Ra, and Re, respectively, based on the average of upstream bulk temperature and downstream bulk temperature
T, H	= indicating average Nusselt numbers based on average wall temperature (T) and average heat transfer coefficient (H)
T+H	= average of the above two Nusselt numbers
TB	= bulk temperature
Z, Z+	= axial length, Z+= $X/(D_h RePr)$

========== EXPERIMENT OR1 --- NOV. 12, 1987 ==========

INPUT ELECTRIC POWER = 134.0 W HEAT RATE GAINED BY WATER = 128.9 W HEAT BALANCE ERROR = 3.79%
MASS FLOW RATE = 11.4590 G/S PRESSURE DROP = 0.1299 MM H2O FRICTION FACTOR = 0.028335 FREM = 11.3775

REM = 401.5 GRM+ = 0.95353E 06 UPSTREAM BULK TEMPERATURE = 23.71 DEG C DOWNSTREAM BULK TEMPERATURE = 26.41 DEG C
PRM = 6.113 RAM+ = 0.58292E 07 INLET BULK TEMPERATURE = 23.71 DEG C OUTLET BULK TEMPERATURE = 26.40 DEG C

STATION NO.	Z CM	WALL TEMPERATURE (DEG C) A	B	C	AVERAGE	TB (C)	RE	PR	RA+	Z+	NUSSELT NUMBER A	B	C	AVERAGE T	H	T+H
0	0.0	24.27	24.26	24.23	24.25	23.71	389.3	6.33	0.540E 07	0.00001	19.35	19.57	20.65	20.04	20.06	20.05
1	1.5	24.32	24.32	24.30	24.31	23.72	389.4	6.32	0.541E 07	0.00020	17.78	18.04	18.63	18.26	18.27	18.27
2	2.5	24.36	24.35	24.34	24.35	23.73	389.4	6.32	0.541E 07	0.00033	16.83	17.11	17.45	17.21	17.21	17.21
3	5.5	24.48	24.47	24.48	24.48	23.74	389.6	6.32	0.541E 07	0.00073	14.52	14.83	14.67	14.67	14.67	14.67
4	15.5	24.79	24.76	24.69	24.73	23.80	390.1	6.31	0.543E 07	0.00207	10.83	11.21	12.03	11.50	11.53	11.52
5	25.5	24.92	24.94	24.78	24.85	23.86	390.6	6.30	0.545E 07	0.00341	10.14	9.89	11.68	10.79	10.85	10.82
6	45.5	25.16	25.17	24.95	25.06	23.97	391.6	6.28	0.548E 07	0.00608	9.00	8.97	11.01	9.90	10.00	9.95
7	75.5	25.36	25.27	25.22	25.27	24.15	393.2	6.26	0.554E 07	0.01009	8.66	9.55	9.96	9.50	9.53	9.52
8	105.5	25.55	25.54	25.45	25.50	24.32	394.7	6.23	0.559E 07	0.01411	8.71	8.78	9.50	9.11	9.12	9.11
9	135.5	25.80	25.82	25.43	25.62	24.49	396.3	6.20	0.565E 07	0.01813	8.19	8.06	11.37	9.48	9.75	9.61
10	165.2	25.89	25.87	25.67	25.77	24.66	397.8	6.18	0.570E 07	0.02212	8.69	8.85	10.64	9.61	9.70	9.66
11	205.2	26.02	26.05	25.83	25.93	24.89	400.0	6.14	0.577E 07	0.02749	9.48	9.21	11.36	10.26	10.35	10.31
12	245.2	26.43	26.59	26.14	26.33	25.12	402.1	6.10	0.585E 07	0.03286	8.14	7.27	10.48	8.86	9.09	8.98
13	275.2	26.51	26.59	26.36	26.45	25.29	403.7	6.08	0.591E 07	0.03690	8.82	8.24	10.00	9.20	9.27	9.23
14	305.2	26.81	26.81	26.56	26.68	25.46	405.4	6.05	0.596E 07	0.04094	7.92	7.96	9.80	8.77	8.87	8.82
15	333.3	26.99	26.96	26.66	26.82	25.63	406.9	6.02	0.602E 07	0.04473	7.86	7.98	10.35	8.97	9.14	9.06
16	363.3	27.08	27.05	26.75	26.91	25.80	408.6	6.00	0.607E 07	0.04878	8.32	8.53	11.17	9.60	9.80	9.70
17	383.3	27.17	27.11	26.82	26.98	25.91	409.7	5.98	0.611E 07	0.05146	8.49	8.92	11.75	10.00	10.23	10.11
18	403.3	27.22	27.21	27.00	27.11	26.03	410.8	5.96	0.615E 07	0.05418	8.94	9.00	11.00	9.88	9.99	9.93
19	423.3	27.32	27.41	27.11	27.24	26.14	411.9	5.94	0.619E 07	0.05689	9.06	8.40	11.06	9.75	9.90	9.82
20	443.3	27.56	27.73	27.31	27.48	26.26	413.1	5.92	0.623E 07	0.05959	8.17	7.26	10.14	8.75	8.93	8.84
21	463.3	27.62	27.60	27.25	27.43	26.37	414.2	5.91	0.627E 07	0.06230	8.56	8.72	12.10	10.08	10.37	10.23
AVERAGE VALUES THROUGH STATIONS 15 TO 20:																
	391.6	27.22	27.25	26.94	27.09	25.96	410.2	5.97	0.613E 07	0.05261	8.47	8.35	10.91	9.49	9.66	9.58

========== EXPERIMENT OR2 --- NOV. 14, 1987 ==========

INPUT ELECTRIC POWER = 250.0 W HEAT RATE GAINED BY WATER = 245.6 W HEAT BALANCE ERROR = 1.78%
MASS FLOW RATE = 11.0490 G/S PRESSURE DROP = 0.0931 MM H2O FRICTION FACTOR = 0.021836 FREM = 8.7642

REM = 401.4 GRM+ = 0.20546E 07 UPSTREAM BULK TEMPERATURE = 23.91 DEG C DOWNSTREAM BULK TEMPERATURE = 29.24 DEG C
PRM = 5.874 RAM+ = 0.12068E 08 INLET BULK TEMPERATURE = 23.92 DEG C OUTLET BULK TEMPERATURE = 29.23 DEG C

STATION NO.	Z CM	WALL TEMPERATURE (DEG C) A	B	C	AVERAGE	TB (C)	RE	PR	RA+	Z+	NUSSELT NUMBER A	B	C	AVERAGE T	H	T+H
0	0.0	24.91	24.93	24.86	24.89	23.92	377.1	6.29	0.104E 08	0.00001	20.64	20.10	21.77	21.04	21.07	21.06
1	1.5	25.04	25.08	25.01	25.04	23.93	377.3	6.29	0.104E 08	0.00021	18.42	17.82	18.91	18.51	18.52	18.51
2	2.5	25.14	25.18	25.12	25.14	23.94	377.4	6.29	0.104E 08	0.00035	17.15	16.53	17.34	17.08	17.09	17.09
3	5.5	25.42	25.48	25.45	25.45	23.98	377.7	6.28	0.104E 08	0.00076	14.21	13.57	13.88	13.88	13.89	13.89
4	15.5	26.01	25.94	25.80	25.89	24.09	378.6	6.27	0.105E 08	0.00215	10.64	11.04	11.98	11.38	11.41	11.40
5	25.5	26.27	26.33	25.99	26.14	24.20	379.6	6.25	0.106E 08	0.00354	9.90	9.61	11.46	10.54	10.61	10.57
6	45.5	26.63	26.63	26.28	26.45	24.43	381.6	6.21	0.107E 08	0.00631	9.30	9.27	11.06	10.09	10.17	10.13
7	75.5	26.99	26.84	26.57	26.74	24.77	384.6	6.16	0.109E 08	0.01049	9.18	9.87	11.32	10.34	10.43	10.38
8	105.5	27.29	27.25	27.02	27.14	25.11	387.7	6.10	0.111E 08	0.01466	9.35	9.55	10.69	10.03	10.07	10.05
9	135.5	27.66	27.66	27.04	27.35	25.45	390.8	6.05	0.113E 08	0.01885	9.21	9.23	12.86	10.74	11.04	10.89
10	165.2	27.86	27.81	27.43	27.63	25.79	393.9	6.00	0.116E 08	0.02300	9.85	10.07	12.42	11.05	11.19	11.12
11	205.2	28.16	28.16	27.69	27.92	26.24	398.2	5.93	0.119E 08	0.02861	10.60	10.60	14.08	12.09	12.34	12.22
12	245.2	28.82	28.94	28.40	28.64	26.70	402.5	5.85	0.121E 08	0.03423	9.57	9.05	11.93	10.46	10.62	10.54
13	275.2	29.12	29.06	28.69	28.89	27.04	405.6	5.81	0.124E 08	0.03844	9.75	10.02	12.25	10.94	11.07	11.00
14	305.2	29.51	29.50	29.07	29.29	27.38	408.4	5.76	0.126E 08	0.04265	9.52	9.56	11.95	10.61	10.74	10.68
15	333.3	29.82	29.84	29.36	29.60	27.70	411.0	5.72	0.128E 08	0.04660	9.54	9.46	12.17	10.67	10.83	10.75
16	363.3	30.28	30.22	29.76	30.01	28.04	413.9	5.68	0.130E 08	0.05083	9.02	9.26	11.72	10.27	10.43	10.35
17	383.3	30.52	30.46	29.93	30.21	28.26	415.9	5.65	0.131E 08	0.05364	8.96	9.21	12.12	10.38	10.60	10.49
18	403.3	30.72	30.66	30.26	30.48	28.49	417.8	5.62	0.132E 08	0.05646	9.06	9.31	11.42	10.18	10.30	10.24
19	423.3	30.81	30.77	30.38	30.59	28.72	419.8	5.59	0.134E 08	0.05928	9.67	9.83	12.15	10.82	10.95	10.88
20	443.3	31.23	31.41	30.76	31.04	28.94	421.8	5.57	0.135E 08	0.06211	8.84	8.20	11.11	9.64	9.81	9.72
21	463.3	31.27	31.31	30.81	31.05	29.17	423.8	5.54	0.137E 08	0.06493	9.63	9.42	12.36	10.76	10.94	10.85
AVERAGE VALUES THROUGH STATIONS 15 TO 20:																
	391.6	30.57	30.56	30.08	30.32	28.36	416.7	5.64	0.132E 08	0.05482	9.18	9.21	11.78	10.32	10.49	10.41

========== EXPERIMENT OR3 --- NOV. 15, 1987 ==========

INPUT ELECTRIC POWER = 613.8 W HEAT RATE GAINED BY WATER = 593.6 W HEAT BALANCE ERROR = 3.30%
MASS FLOW RATE = 10.1100 G/S PRESSURE DROP = 0.0881 MM H2O FRICTION FACTOR = 0.024635 FREM = 9.9993

REM = 405.9 GRM+ = 0.69015E 07 UPSTREAM BULK TEMPERATURE = 24.23 DEG C DOWNSTREAM BULK TEMPERATURE = 38.32 DEG C
PRM = 5.272 RAM+ = 0.36382E 08 INLET BULK TEMPERATURE = 24.26 DEG C OUTLET BULK TEMPERATURE = 38.31 DEG C

STATION NO.	Z CM	WALL TEMPERATURE (DEG C) A	B	C	AVERAGE	TB (C)	RE	PR	RA+	Z+	NUSSELT NUMBER A	B	C	AVERAGE T	H	T+H
0	0.0	26.43	26.44	26.23	26.33	24.26	347.8	6.24	0.257E 08	0.00001	22.76	22.62	24.97	23.77	23.83	23.80
1	1.5	26.78	26.80	26.65	26.72	24.30	348.1	6.23	0.257E 08	0.00023	19.90	19.74	21.05	20.41	20.43	20.42
2	2.5	27.03	27.05	26.93	26.98	24.33	348.4	6.23	0.258E 08	0.00038	18.31	18.15	18.99	18.60	18.61	18.61
3	5.5	27.76	27.80	27.78	27.78	24.42	349.1	6.21	0.259E 08	0.00083	14.77	14.61	14.69	14.69	14.69	14.69
4	15.5	28.88	28.76	28.23	28.53	24.72	351.5	6.17	0.263E 08	0.00235	11.86	12.20	14.06	12.96	13.04	13.00
5	25.5	29.42	29.50	28.58	29.02	25.02	354.0	6.12	0.268E 08	0.00387	11.20	10.99	13.86	12.32	12.48	12.40
6	45.5	30.14	30.07	29.11	29.61	25.62	359.0	6.02	0.277E 08	0.00692	10.88	11.05	14.12	12.34	12.54	12.44
7	75.5	31.00	30.77	29.84	30.36	26.52	366.8	5.88	0.291E 08	0.01151	10.96	11.57	14.79	12.78	13.03	12.90
8	105.5	31.82	31.75	30.94	31.36	27.42	374.0	5.76	0.304E 08	0.01611	11.14	11.31	13.92	12.43	12.57	12.50
9	135.5	32.67	32.55	31.28	31.95	28.32	381.0	5.65	0.317E 08	0.02073	11.24	11.55	16.49	13.47	13.94	13.71
10	165.2	33.18	33.07	32.09	32.61	29.21	388.1	5.53	0.331E 08	0.02531	12.28	12.64	16.96	14.36	14.71	14.54
11	205.2	34.39	34.32	33.36	33.86	30.41	398.2	5.38	0.350E 08	0.03150	12.21	12.44	16.47	14.10	14.40	14.25
12	245.2	35.97	35.96	35.00	35.48	31.61	408.8	5.23	0.369E 08	0.03772	11.12	11.16	14.29	12.52	12.71	12.62
13	275.2	36.68	36.54	35.58	36.09	32.50	416.3	5.12	0.383E 08	0.04244	11.62	12.02	15.75	13.50	13.79	13.64
14	305.2	37.65	37.63	36.69	37.16	33.40	423.7	5.02	0.396E 08	0.04720	11.39	11.43	14.72	12.86	13.06	12.96
15	333.3	38.39	38.44	37.16	37.78	34.25	430.9	4.92	0.409E 08	0.05169	11.65	11.51	16.56	13.63	14.07	13.85
16	363.3	39.62	39.63	38.37	39.00	35.15	438.9	4.82	0.423E 08	0.05652	10.75	10.73	14.90	12.48	12.82	12.65
17	383.3	40.27	40.09	39.02	39.60	35.74	444.4	4.75	0.433E 08	0.05976	10.63	11.07	14.68	12.47	12.76	12.62
18	403.3	40.86	40.73	39.60	40.20	36.34	450.0	4.68	0.442E 08	0.06301	10.62	10.93	14.73	12.44	12.75	12.60
19	423.3	41.16	41.05	40.01	40.56	36.94	455.6	4.61	0.452E 08	0.06628	11.36	11.66	15.64	13.26	13.58	13.42
20	443.3	42.07	42.28	40.87	41.52	37.54	460.7	4.56	0.462E 08	0.06947	10.58	10.09	14.39	12.03	12.36	12.19
21	463.3	42.14	42.38	41.06	41.66	38.14	465.9	4.50	0.472E 08	0.07267	11.96	11.27	16.41	13.59	14.01	13.80
AVERAGE VALUES THROUGH STATIONS 15 TO 20:																
	391.6	40.39	40.37	39.17	39.78	35.99	446.7	4.72	0.437E 08	0.06112	10.93	11.00	15.15	12.72	13.06	12.89

========== EXPERIMENT OR4 NOV. 16, 1987 ==========

INPUT ELECTRIC POWER = 977.0 W HEAT RATE GAINED BY WATER = 927.7 W HEAT BALANCE ERROR = 5.05%
MASS FLOW RATE = 9.0130 G/S PRESSURE DROP = 0.1172 MM H2O FRICTION FACTOR = 0.041154 FREM = 16.4508

REM = 399.7 GRM+ = 0.14624E 08 UPSTREAM BULK TEMPERATURE = 23.82 DEG C DOWNSTREAM BULK TEMPERATURE = 48.52 DEG C
PRM = 4.698 RAM+ = 0.68704E 08 INLET BULK TEMPERATURE = 23.86 DEG C OUTLET BULK TEMPERATURE = 48.49 DEG C

STATION NO.	Z CM	-WALL TEMPERATURE (DEG C)- A	B	C	AVERAGE	TB (C)	RE	PR	RA+	Z+	NUSSELT NUMBER A	B	C	AVERAGE T	H	T+H
0	0.0	27.28	27.31	26.99	27.14	23.86	307.3	6.30	0.392E 08	0.00001	22.61	22.38	24.65	23.53	23.57	23.55
1	1.5	27.84	27.89	27.65	27.76	23.94	307.8	6.29	0.394E 08	0.00025	19.78	19.53	20.82	20.22	20.23	20.23
2	2.5	28.23	28.29	28.10	28.18	23.99	308.2	6.28	0.395E 08	0.00042	18.20	17.95	18.80	18.43	18.44	18.43
3	5.5	29.40	29.49	29.45	29.45	24.15	309.3	6.26	0.399E 08	0.00093	14.69	14.44	14.56	14.56	14.56	14.56
4	15.5	30.92	30.74	29.64	30.24	24.67	313.0	6.17	0.411E 08	0.00264	12.33	12.72	15.51	13.86	14.02	13.94
5	25.5	31.56	31.66	29.90	30.76	25.20	316.9	6.09	0.423E 08	0.00435	12.10	11.92	16.38	13.86	14.19	14.03
6	45.5	32.73	32.64	30.92	31.80	26.25	324.8	5.92	0.448E 08	0.00778	11.85	12.02	16.46	13.84	14.20	14.02
7	75.5	34.28	34.08	32.54	33.36	27.83	336.2	5.71	0.485E 08	0.01294	11.87	12.25	16.23	13.83	14.14	13.99
8	105.5	35.84	35.70	34.32	35.04	29.40	347.4	5.51	0.522E 08	0.01813	11.85	12.11	15.52	13.52	13.75	13.64
9	135.5	37.19	37.03	35.11	36.11	30.98	359.5	5.31	0.561E 08	0.02335	12.23	12.57	18.39	14.81	15.40	15.10
10	165.2	38.34	38.19	36.72	37.49	32.54	371.4	5.12	0.599E 08	0.02858	13.05	13.41	18.13	15.29	15.68	15.48
11	205.2	40.40	40.31	38.70	39.53	34.64	387.3	4.88	0.649E 08	0.03575	13.08	13.28	18.55	15.41	15.87	15.64
12	245.2	42.93	42.83	41.35	42.11	36.74	404.6	4.63	0.702E 08	0.04304	12.11	12.30	16.26	13.94	14.23	14.09
13	275.2	44.26	44.04	42.44	43.29	38.32	416.8	4.48	0.742E 08	0.04843	12.57	13.06	16.14	15.02	15.48	15.25
14	305.2	45.98	45.99	44.39	45.19	39.90	429.6	4.34	0.784E 08	0.05385	12.23	12.22	16.58	14.07	14.40	14.24
15	333.3	47.43	47.43	45.35	46.39	41.37	442.3	4.20	0.826E 08	0.05896	12.26	12.26	18.65	14.80	15.46	15.13
16	363.3	49.39	49.46	47.27	48.35	42.95	455.2	4.07	0.869E 08	0.06444	11.49	11.36	17.15	13.71	14.29	14.00
17	383.3	50.29	49.91	48.10	49.10	44.00	463.7	3.99	0.898E 08	0.06811	11.74	12.51	18.01	14.48	15.07	14.77
18	403.3	51.23	51.00	49.14	50.13	45.05	472.5	3.91	0.927E 08	0.07180	11.94	12.39	18.05	14.53	15.10	14.82
19	423.3	51.94	51.70	50.13	50.98	46.10	481.7	3.83	0.957E 08	0.07551	12.61	13.15	18.25	15.10	15.57	15.33
20	443.3	53.46	53.70	51.57	52.58	47.15	490.9	3.75	0.988E 08	0.07924	11.64	11.22	16.63	13.54	14.03	13.79
21	463.3	53.62	54.11	51.91	52.89	48.20	499.9	3.68	0.102E 09	0.08295	13.53	12.41	19.77	15.65	16.37	16.01
AVERAGE VALUES THROUGH STATIONS 15 TO 20:																
	391.6	50.62	50.53	48.59	49.59	44.44	467.7	3.96	0.911E 08	0.06968	11.95	12.15	17.79	14.36	14.92	14.64

========== EXPERIMENT OR5 NOV. 16, 1987 ==========

INPUT ELECTRIC POWER = 1313.3 W HEAT RATE GAINED BY WATER = 1240.1 W HEAT BALANCE ERROR = 5.57%
MASS FLOW RATE = 7.9320 G/S PRESSURE DROP = 0.1023 MM H2O FRICTION FACTOR = 0.046258 FREM = 18.4858

REM = 399.6 GRM+ = 0.28318E 08 UPSTREAM BULK TEMPERATURE = 24.05 DEG C DOWNSTREAM BULK TEMPERATURE = 61.56 DEG C
PRM = 4.085 RAM+ = 0.11567E 09 INLET BULK TEMPERATURE = 24.11 DEG C OUTLET BULK TEMPERATURE = 61.52 DEG C

STATION NO.	Z CM	-WALL TEMPERATURE (DEG C)- A	B	C	AVERAGE	TB (C)	RE	PR	RA+	Z+	NUSSELT NUMBER A	B	C	AVERAGE T	H	T+H
0	0.0	28.90	28.94	28.49	28.70	24.11	272.0	6.26	0.532E 08	0.00001	21.57	21.37	23.60	22.48	22.53	22.51
1	1.5	29.70	29.76	29.42	29.57	24.23	272.7	6.24	0.535E 08	0.00029	18.85	18.64	19.89	19.30	19.32	19.31
2	2.5	30.26	30.33	30.06	30.17	24.31	273.2	6.23	0.538E 08	0.00048	17.34	17.13	17.95	17.58	17.59	17.59
3	5.5	31.92	32.03	31.98	31.98	24.55	274.7	6.19	0.545E 08	0.00106	13.98	13.77	13.86	13.88	13.88	13.88
4	15.5	33.85	33.56	31.79	32.76	25.35	279.8	6.07	0.570E 08	0.00300	12.10	12.49	15.96	13.89	14.13	14.01
5	25.5	34.94	35.11	32.57	33.80	26.14	285.2	5.94	0.595E 08	0.00495	11.67	11.45	15.97	13.41	13.77	13.59
6	45.5	36.53	36.39	34.00	35.23	27.74	295.4	5.72	0.645E 08	0.00886	11.64	11.83	16.35	13.67	14.04	13.85
7	75.5	38.65	38.34	36.18	37.33	30.13	310.6	5.42	0.721E 08	0.01476	11.95	12.41	16.85	14.14	14.52	14.33
8	105.5	40.90	40.66	38.72	39.75	32.53	326.8	5.12	0.801E 08	0.02074	12.09	12.45	16.34	14.02	14.31	14.16
9	135.5	42.88	42.60	39.98	41.36	34.92	342.8	4.84	0.876E 08	0.02685	12.65	13.10	19.90	15.63	16.39	16.01
10	165.2	44.96	44.71	42.60	43.72	37.29	359.8	4.58	0.957E 08	0.03298	13.04	13.49	18.85	15.57	16.06	15.82
11	205.2	48.10	47.96	45.58	46.81	40.48	382.4	4.29	0.107E 09	0.04118	13.06	13.30	19.49	15.72	16.34	16.03
12	245.2	51.90	51.61	49.55	50.65	43.66	405.7	4.02	0.119E 09	0.04948	12.02	12.46	16.81	14.16	14.52	14.34
13	275.2	53.59	53.28	51.11	52.27	46.07	423.6	3.83	0.128E 09	0.05578	13.08	13.65	19.50	15.86	16.43	16.14
14	305.2	56.09	56.11	53.90	55.00	48.46	441.9	3.66	0.137E 09	0.06212	12.85	12.81	18.04	15.00	15.43	15.22
15	333.3	58.71	58.81	55.97	57.37	50.71	459.9	3.50	0.146E 09	0.06811	12.19	12.04	18.56	14.66	15.34	15.00
16	363.3	61.45	61.54	58.61	60.05	53.10	478.5	3.35	0.156E 09	0.07449	11.65	11.53	17.67	14.00	14.63	14.31
17	383.3	62.82	62.32	59.88	61.22	54.70	490.3	3.27	0.162E 09	0.07873	11.94	12.73	18.73	14.87	15.53	15.20
18	403.3	64.42	64.10	61.40	62.83	56.29	502.7	3.18	0.169E 09	0.08299	11.91	12.39	18.96	14.81	15.56	15.18
19	423.3	65.50	65.03	62.89	64.08	57.89	515.0	3.09	0.175E 09	0.08738	12.69	13.52	19.29	15.60	16.19	15.90
20	443.3	67.71	67.95	65.02	66.42	59.48	527.6	3.01	0.182E 09	0.09189	11.70	11.37	17.40	13.87	14.47	14.17
21	463.3	67.97	68.73	65.83	67.09	61.08	540.9	2.92	0.188E 09	0.09645	13.92	12.55	20.20	15.97	16.72	16.34
AVERAGE VALUES THROUGH STATIONS 15 TO 20:																
	391.6	63.44	63.29	60.63	61.99	55.36	495.7	3.23	0.165E 09	0.08060	12.01	12.27	18.43	14.63	15.29	14.96

========== EXPERIMENT OR6 NOV. 17, 1987 ==========

INPUT ELECTRIC POWER = 1599.4 W HEAT RATE GAINED BY WATER = 1487.5 W HEAT BALANCE ERROR = 6.99%
MASS FLOW RATE = 7.1020 G/S PRESSURE DROP = 0.2083 MM H2O FRICTION FACTOR = 0.117205 FREM = 46.9342

REM = 400.4 GRM+ = 0.46506E 08 UPSTREAM BULK TEMPERATURE = 24.00 DEG C DOWNSTREAM BULK TEMPERATURE = 74.24 DEG C
PRM = 3.609 RAM+ = 0.16786E 09 INLET BULK TEMPERATURE = 24.10 DEG C OUTLET BULK TEMPERATURE = 74.19 DEG C

STATION NO.	Z CM	-WALL TEMPERATURE (DEG C)- A	B	C	AVERAGE	TB (C)	RE	PR	RA+	Z+	NUSSELT NUMBER A	B	C	AVERAGE T	H	T+H
0	0.0	30.31	30.34	29.63	29.98	24.10	243.4	6.26	0.637E 08	0.00001	19.95	19.85	22.37	21.07	21.14	21.10
1	1.5	31.33	31.37	30.85	31.10	24.26	244.3	6.24	0.643E 08	0.00032	17.50	17.39	18.77	18.08	18.11	18.09
2	2.5	32.04	32.09	31.68	31.87	24.36	244.9	6.22	0.647E 08	0.00054	16.12	16.01	16.90	16.47	16.48	16.48
3	5.5	34.15	34.24	34.19	34.19	24.68	246.7	6.17	0.659E 08	0.00119	13.05	12.94	13.00	13.00	13.00	13.00
4	15.5	36.23	35.90	33.32	34.69	25.75	253.0	6.00	0.699E 08	0.00336	11.77	12.16	16.29	13.79	14.13	13.96
5	25.5	37.51	37.64	34.35	35.96	26.82	259.5	5.83	0.741E 08	0.00554	11.51	11.38	16.34	13.46	13.89	13.68
6	45.5	39.31	39.07	35.92	37.56	28.96	271.2	5.56	0.820E 08	0.00992	11.82	12.11	17.58	14.24	14.77	14.50
7	75.5	42.18	41.82	38.85	40.42	32.16	290.5	5.16	0.947E 08	0.01656	12.13	12.59	18.18	14.71	15.27	14.99
8	105.5	45.17	44.88	42.30	43.66	35.37	309.7	4.79	0.107E 09	0.02338	12.30	12.67	17.40	14.54	14.94	14.74
9	135.5	47.82	47.47	44.25	45.95	38.58	330.0	4.46	0.120E 09	0.03028	12.94	13.46	21.08	16.23	17.14	16.68
10	165.2	51.49	51.26	48.45	49.91	41.75	351.2	4.17	0.134E 09	0.03711	12.21	12.51	17.76	14.57	15.06	14.82
11	205.2	55.37	55.16	52.07	53.67	46.02	379.0	3.83	0.153E 09	0.04645	12.63	12.91	19.51	15.43	16.14	15.79
12	245.2	60.53	60.13	57.33	58.83	50.30	408.8	3.53	0.174E 09	0.05592	11.46	11.92	16.67	13.74	14.18	13.96
13	275.2	62.75	62.47	59.48	61.04	53.50	431.1	3.33	0.189E 09	0.06305	12.62	13.01	19.52	15.47	16.17	15.82
14	305.2	66.42	66.46	63.32	64.88	56.71	453.1	3.16	0.205E 09	0.07017	11.96	11.90	17.55	14.21	14.74	14.47
15	333.3	70.00	70.09	66.13	68.09	59.71	474.1	3.00	0.219E 09	0.07721	11.22	11.12	18.00	13.78	14.58	14.18
16	363.3	73.03	73.15	69.35	71.22	62.92	497.9	2.83	0.235E 09	0.08472	11.36	11.22	17.84	13.83	14.56	14.20
17	383.3	75.06	74.37	71.18	72.95	65.06	514.2	2.74	0.247E 09	0.08953	11.44	12.30	18.71	14.51	15.29	14.90
18	403.3	77.04	76.58	73.21	75.01	67.19	531.4	2.65	0.260E 09	0.09437	11.59	12.16	18.99	14.61	15.43	15.02
19	423.3	78.55	78.02	75.15	76.72	69.33	548.8	2.56	0.271E 09	0.09927	12.32	13.06	19.52	15.38	16.11	15.74
20	443.3	81.31	81.54	77.84	79.63	71.47	567.4	2.47	0.284E 09	0.10422	11.48	11.22	17.73	13.84	14.54	14.19
21	463.3	81.51	82.49	78.85	80.43	73.61	583.5	2.39	0.296E 09	0.10911	14.28	12.71	21.52	16.55	17.51	17.03
AVERAGE VALUES THROUGH STATIONS 15 TO 20:																
	391.6	75.83	75.63	72.14	73.94	65.95	522.3	2.71	0.253E 09	0.09155	11.57	11.85	18.47	14.32	15.09	14.70

========== EXPERIMENT 0R7   NOV. 18, 1987 ==========

INPUT ELECTRIC POWER = 133.5 W   HEAT RATE GAINED BY WATER = 128.0 W   HEAT BALANCE ERROR = 4.18%
MASS FLOW RATE = 14.1400 G/S   PRESSURE DROP = 0.1833 MM H2O   FRICTION FACTOR = 0.026259   FREM = 12.9788

REM = 494.3   GRM+ = 0.93824E 06   UPSTREAM BULK TEMPERATURE = 23.87 DEG C   DOWNSTREAM BULK TEMPERATURE = 26.04 DEG C
PRM = 6.130   RAM+ = 0.57514E 07   INLET BULK TEMPERATURE = 23.87 DEG C   OUTLET BULK TEMPERATURE = 26.03 DEG C

STATION NO.	Z CM	WALL TEMPERATURE (DEG C) A	B	C	AVERAGE	TB (C)	RE	PR	RA+	Z+	NUSSELT NUMBER A	B	C	AVERAGE T	H	T+H
0	0.0	24.40	24.40	24.33	24.37	23.87	482.1	6.30	0.541E 07	0.00001	19.99	20.23	22.94	21.43	21.53	21.48
1	1.5	24.45	24.44	24.39	24.42	23.88	482.2	6.30	0.541E 07	0.00016	18.68	18.97	20.57	19.66	19.70	19.68
2	2.5	24.48	24.47	24.44	24.45	23.88	482.2	6.30	0.541E 07	0.00027	17.87	18.19	19.20	18.60	18.62	18.61
3	5.5	24.57	24.55	24.56	24.56	23.89	482.4	6.30	0.542E 07	0.00060	15.82	16.20	16.01	16.01	16.01	16.01
4	15.5	24.93	24.93	24.86	24.90	23.94	482.9	6.29	0.543E 07	0.00168	10.72	10.80	11.55	11.14	11.16	11.15
5	25.5	25.11	25.11	24.95	25.03	23.99	483.4	6.28	0.545E 07	0.00276	9.45	9.46	11.10	10.21	10.28	10.25
6	45.5	25.31	25.28	25.12	25.21	24.08	484.4	6.27	0.548E 07	0.00493	8.68	8.86	10.25	9.45	9.51	9.48
7	75.5	25.50	25.38	25.33	25.39	24.22	486.0	6.25	0.552E 07	0.00818	8.32	9.16	9.53	9.11	9.13	9.12
8	105.5	25.61	25.62	25.50	25.56	24.36	487.5	6.22	0.556E 07	0.01144	8.52	8.40	9.28	8.85	8.87	8.86
9	135.5	25.83	25.85	25.43	25.63	24.49	489.1	6.20	0.561E 07	0.01469	7.99	7.86	11.34	9.33	9.63	9.48
10	165.2	25.84	25.82	25.61	25.72	24.63	490.6	6.18	0.565E 07	0.01792	8.82	8.99	10.87	9.79	9.89	9.84
11	205.2	25.91	25.94	25.69	25.81	24.82	492.7	6.15	0.571E 07	0.02227	9.75	9.46	12.14	10.73	10.86	10.80
12	245.2	26.26	26.45	26.06	26.21	25.00	494.8	6.12	0.577E 07	0.02663	8.41	7.32	10.08	8.81	8.97	8.89
13	275.2	26.45	26.45	26.25	26.35	25.14	496.4	6.10	0.581E 07	0.02989	8.11	8.11	9.59	8.79	8.85	8.82
14	305.2	26.70	26.70	26.39	26.54	25.28	498.0	6.08	0.586E 07	0.03316	7.46	7.49	9.59	8.40	8.53	8.47
15	333.3	26.79	26.80	26.43	26.61	25.41	499.6	6.06	0.590E 07	0.03623	7.69	7.65	10.38	8.82	9.03	8.92
16	363.3	26.88	26.82	26.50	26.68	25.55	501.2	6.04	0.594E 07	0.03950	7.93	8.31	11.12	9.38	9.62	9.50
17	383.3	26.94	26.86	26.54	26.72	25.64	502.3	6.02	0.597E 07	0.04169	8.13	8.71	11.76	9.81	10.09	9.95
18	403.3	26.94	26.93	26.71	26.83	25.73	503.4	6.01	0.601E 07	0.04387	8.78	8.83	10.79	9.70	9.80	9.75
19	423.3	26.95	27.02	26.74	26.87	25.82	504.5	5.99	0.604E 07	0.04606	9.38	8.86	11.53	10.18	10.32	10.25
20	443.3	27.14	27.30	26.94	27.08	25.92	505.6	5.98	0.607E 07	0.04825	8.67	7.65	10.34	9.10	9.25	9.18
21	463.3	27.23	27.20	26.85	27.03	26.01	506.7	5.96	0.610E 07	0.05044	8.71	8.93	12.60	10.38	10.71	10.55
AVERAGE VALUES THROUGH STATIONS 15 TO 20:																
	391.6	26.94	26.96	26.65	26.80	25.68	502.7	6.02	0.599E 07	0.04260	8.43	8.33	10.99	9.50	9.68	9.59

========== EXPERIMENT 0R8   --- NOV. 19, 1987 ==========

INPUT ELECTRIC POWER = 254.8 W   HEAT RATE GAINED BY WATER = 251.0 W   HEAT BALANCE ERROR = 1.50%
MASS FLOW RATE = 13.8970 G/S   PRESSURE DROP = 0.1766 MM H2O   FRICTION FACTOR = 0.026187   FREM = 13.0042

REM = 496.6   GRM+ = 0.19864E 07   UPSTREAM BULK TEMPERATURE = 23.72 DEG C   DOWNSTREAM BULK TEMPERATURE = 28.06 DEG C
PRM = 5.982   RAM+ = 0.11882E 08   INLET BULK TEMPERATURE = 23.73 DEG C   OUTLET BULK TEMPERATURE = 28.05 DEG C

STATION NO.	Z CM	WALL TEMPERATURE (DEG C) A	B	C	AVERAGE	TB (C)	RE	PR	RA+	Z+	NUSSELT NUMBER A	B	C	AVERAGE T	H	T+H
0	0.0	24.65	24.65	24.62	24.63	23.73	472.3	6.32	0.105E 08	0.00001	22.76	22.65	23.50	23.10	23.10	23.10
1	1.5	24.79	24.80	24.77	24.78	23.74	472.5	6.32	0.105E 08	0.00017	19.92	19.80	20.30	20.08	20.08	20.08
2	2.5	24.89	24.90	24.88	24.89	23.75	472.6	6.32	0.105E 08	0.00028	18.34	18.22	18.56	18.42	18.42	18.42
3	5.5	25.19	25.20	25.20	25.20	23.78	472.9	6.32	0.106E 08	0.00061	14.82	14.70	14.76	14.76	14.76	14.76
4	15.5	25.70	25.72	25.54	25.63	23.87	473.9	6.30	0.106E 08	0.00171	11.43	11.33	12.51	11.92	11.94	11.93
5	25.5	25.96	26.02	25.71	25.85	23.96	474.6	6.29	0.107E 08	0.00281	10.47	10.16	11.99	11.09	11.15	11.12
6	45.5	26.35	26.27	25.94	26.12	24.15	476.9	6.26	0.108E 08	0.00502	9.50	9.85	11.67	10.58	10.67	10.62
7	75.5	26.65	26.50	26.24	26.41	24.42	479.9	6.21	0.110E 08	0.00833	9.36	10.05	11.52	10.53	10.61	10.57
8	105.5	26.84	26.80	26.53	26.68	24.70	482.9	6.17	0.111E 08	0.01165	9.74	9.94	11.38	10.56	10.61	10.58
9	135.5	27.10	27.09	26.53	26.81	24.98	486.1	6.13	0.113E 08	0.01497	9.83	9.85	13.43	11.36	11.63	11.50
10	165.2	27.30	27.25	26.89	27.08	25.25	489.2	6.08	0.115E 08	0.01826	10.19	10.43	12.72	11.39	11.52	11.45
11	205.2	27.51	27.54	27.07	27.30	25.62	493.4	6.02	0.117E 08	0.02271	10.99	10.82	14.37	12.40	12.64	12.52
12	245.2	28.00	28.16	27.66	27.87	25.99	497.8	5.97	0.119E 08	0.02716	10.36	9.59	12.47	11.07	11.22	11.15
13	275.2	28.33	28.33	27.95	28.14	26.27	501.1	5.92	0.121E 08	0.03051	10.06	10.06	12.30	11.07	11.18	11.12
14	305.2	28.75	28.74	28.25	28.50	26.54	504.4	5.88	0.123E 08	0.03386	9.40	9.44	12.13	10.61	10.78	10.69
15	333.3	28.92	28.94	28.39	28.66	26.80	507.6	5.84	0.125E 08	0.03700	9.78	9.72	13.03	11.15	11.39	11.27
16	363.3	29.18	29.12	28.58	28.87	27.08	510.5	5.80	0.127E 08	0.04035	9.88	10.16	13.78	11.60	11.90	11.75
17	383.3	29.33	29.28	28.81	29.06	27.26	512.4	5.78	0.128E 08	0.04258	10.02	10.28	13.37	11.54	11.76	11.65
18	403.3	29.51	29.46	29.01	29.25	27.45	514.4	5.75	0.129E 08	0.04482	10.04	10.30	13.22	11.50	11.70	11.60
19	423.3	29.54	29.60	29.15	29.36	27.63	516.3	5.73	0.130E 08	0.04705	10.83	10.53	13.63	11.98	12.16	12.07
20	443.3	29.88	30.08	29.40	29.69	27.81	518.3	5.71	0.131E 08	0.04929	10.04	9.15	13.03	11.04	11.31	11.18
21	463.3	29.87	29.88	29.30	29.59	28.00	520.2	5.69	0.132E 08	0.05153	11.09	10.98	15.86	13.02	13.45	13.23
AVERAGE VALUES THROUGH STATIONS 15 TO 20:																
	391.6	29.39	29.41	28.89	29.15	27.34	513.2	5.77	0.128E 08	0.04352	10.10	10.02	13.34	11.47	11.70	11.59

========== EXPERIMENT 0R9   --- NOV. 20, 1987 ==========

INPUT ELECTRIC POWER = 648.5 W   HEAT RATE GAINED BY WATER = 631.4 W   HEAT BALANCE ERROR = 2.64%
MASS FLOW RATE = 13.0170 G/S   PRESSURE DROP = 0.1903 MM H2O   FRICTION FACTOR = 0.032123   FREM = 16.1354

REM = 502.3   GRM+ = 0.64678E 07   UPSTREAM BULK TEMPERATURE = 23.63 DEG C   DOWNSTREAM BULK TEMPERATURE = 35.27 DEG C
PRM = 5.502   RAM+ = 0.35588E 08   INLET BULK TEMPERATURE = 23.65 DEG C   OUTLET BULK TEMPERATURE = 35.26 DEG C

STATION NO.	Z CM	WALL TEMPERATURE (DEG C) A	B	C	AVERAGE	TB (C)	RE	PR	RA+	Z+	NUSSELT NUMBER A	B	C	AVERAGE T	H	T+H
0	0.0	25.93	25.94	25.77	25.85	23.65	441.6	6.34	0.264E 08	0.00001	23.10	22.95	24.83	23.89	23.93	23.91
1	1.5	26.29	26.31	26.18	26.24	23.68	442.0	6.33	0.264E 08	0.00018	20.15	20.00	21.05	20.55	20.56	20.56
2	2.5	26.55	26.57	26.47	26.51	23.71	442.2	6.33	0.265E 08	0.00029	18.52	18.37	19.05	18.74	18.75	18.75
3	5.5	27.31	27.35	27.33	27.33	23.78	443.0	6.31	0.266E 08	0.00065	14.91	14.75	14.83	14.83	14.83	14.83
4	15.5	28.34	28.25	27.72	28.01	24.03	445.5	6.28	0.269E 08	0.00182	12.19	12.44	14.24	13.21	13.28	13.25
5	25.5	28.89	28.99	28.04	28.49	24.28	448.0	6.24	0.273E 08	0.00300	11.39	11.14	13.95	12.47	12.61	12.54
6	45.5	29.61	29.51	28.60	29.08	24.77	453.1	6.16	0.281E 08	0.00536	10.85	11.07	13.72	12.19	12.34	12.26
7	75.5	30.27	30.04	29.16	29.66	25.52	461.1	6.04	0.293E 08	0.00892	11.02	11.59	14.36	12.65	12.83	12.74
8	105.5	30.95	30.86	29.97	30.43	26.26	469.3	5.92	0.305E 08	0.01248	11.15	11.37	14.10	12.52	12.68	12.60
9	135.5	31.59	31.48	30.13	30.83	27.00	477.5	5.81	0.317E 08	0.01606	11.37	11.66	16.68	13.62	14.10	13.86
10	165.2	31.92	31.80	30.75	31.31	27.74	484.7	5.72	0.329E 08	0.01961	12.45	12.81	17.29	14.60	14.96	14.78
11	205.2	32.87	32.75	31.65	32.23	28.73	494.7	5.59	0.344E 08	0.02439	12.55	12.94	17.80	14.85	15.27	15.06
12	245.2	34.27	34.20	33.23	33.73	29.72	505.2	5.47	0.360E 08	0.02920	11.40	11.59	14.77	12.93	13.13	13.03
13	275.2	34.79	34.68	33.65	34.19	30.46	513.3	5.38	0.373E 08	0.03281	11.95	12.27	16.27	13.88	14.19	14.04
14	305.2	35.63	35.61	34.65	35.14	31.20	521.7	5.28	0.386E 08	0.03644	11.69	11.73	15.00	13.15	13.35	13.25
15	333.3	36.28	36.32	35.00	35.65	31.90	529.8	5.19	0.398E 08	0.03984	11.79	11.67	16.67	13.77	14.20	13.99
16	363.3	37.33	37.39	36.01	36.69	32.64	537.4	5.11	0.409E 08	0.04353	10.99	10.84	15.29	12.74	13.11	12.92
17	383.3	37.80	37.61	36.44	37.07	33.14	542.7	5.05	0.417E 08	0.04600	11.05	11.51	15.59	13.08	13.43	13.26
18	403.3	38.26	38.10	36.96	37.57	33.63	548.1	4.99	0.425E 08	0.04848	11.09	11.51	15.44	13.05	13.37	13.21
19	423.3	38.52	38.39	37.32	37.89	34.13	553.5	4.94	0.433E 08	0.05097	11.69	12.04	16.08	13.65	13.97	13.81
20	443.3	39.30	39.51	38.07	38.74	34.62	559.1	4.88	0.441E 08	0.05347	10.96	10.49	14.89	12.47	12.81	12.64
21	463.3	39.13	39.38	38.08	38.67	35.12	564.8	4.82	0.450E 08	0.05597	12.75	12.01	17.28	14.42	14.83	14.62
AVERAGE VALUES THROUGH STATIONS 15 TO 20:																
	391.6	37.91	37.89	36.63	37.27	33.34	545.1	5.03	0.421E 08	0.04705	11.26	11.34	15.66	13.13	13.48	13.30

========== EXPERIMENT 0R10 --- NOV. 20, 1987 ==========

INPUT ELECTRIC POWER = 1065.7 W HEAT RATE GAINED BY WATER = 1019.3 W HEAT BALANCE ERROR = 4.35%
MASS FLOW RATE = 11.6940 G/S PRESSURE DROP = 0.1273 MM H2O FRICTION FACTOR = 0.026576 FREM = 13.2012

REM = 496.7 GRM+ = 0.14121E 08 UPSTREAM BULK TEMPERATURE = 23.61 DEG C DOWNSTREAM BULK TEMPERATURE = 44.53 DEG C
PRM = 4.942 RAM+ = 0.69786E 08 INLET BULK TEMPERATURE = 23.64 DEG C OUTLET BULK TEMPERATURE = 44.51 DEG C

STATION NO.	Z CM	WALL TEMPERATURE (DEG C) A	B	C	AVERAGE	TB (C)	RE	PR	RA+	Z+	NUSSELT NUMBER A	B	C	AVERAGE T	H	T+H
0	0.0	27.18	27.20	26.89	27.04	23.64	396.7	6.34	0.426E 08	0.00001	24.05	23.89	26.19	25.03	25.08	25.06
1	1.5	27.77	27.80	27.56	27.67	23.71	397.3	6.33	0.427E 08	0.00020	20.92	20.75	22.02	21.41	21.43	21.42
2	2.5	28.18	28.22	28.03	28.11	23.75	397.7	6.32	0.428E 08	0.00033	19.19	19.02	19.85	19.47	19.48	19.47
3	5.5	29.40	29.46	29.43	29.43	23.89	398.9	6.30	0.432E 08	0.00072	15.39	15.22	15.30	15.30	15.30	15.30
4	15.5	30.90	30.74	29.67	30.24	24.33	403.0	6.23	0.443E 08	0.00203	12.92	13.24	15.88	14.34	14.48	14.41
5	25.5	31.62	31.71	29.87	30.77	24.78	407.1	6.16	0.454E 08	0.00335	12.38	12.21	16.63	14.14	14.46	14.30
6	45.5	32.70	32.58	30.92	31.78	25.67	415.7	6.02	0.477E 08	0.00598	12.01	12.22	16.10	13.83	14.11	13.97
7	75.5	34.02	33.77	32.18	33.04	27.00	429.0	5.81	0.512E 08	0.00996	12.01	12.46	16.29	13.97	14.26	14.11
8	105.5	35.28	35.11	33.69	34.44	28.34	440.8	5.64	0.546E 08	0.01395	12.11	12.40	15.71	13.77	13.98	13.87
9	135.5	36.43	36.20	34.13	35.22	29.67	453.4	5.47	0.580E 08	0.01796	12.40	12.82	18.81	15.10	15.71	15.40
10	165.2	37.19	37.00	35.41	36.25	30.99	466.5	5.31	0.617E 08	0.02195	13.47	13.89	18.91	15.88	16.30	16.09
11	205.2	38.93	38.79	37.16	38.01	32.78	484.1	5.09	0.664E 08	0.02738	13.50	13.82	18.98	15.89	16.32	16.10
12	245.2	41.14	41.02	39.46	40.27	34.56	501.6	4.89	0.711E 08	0.03291	12.57	12.81	16.86	14.48	14.78	14.63
13	275.2	42.15	41.93	40.22	41.13	35.89	515.5	4.73	0.747E 08	0.03711	13.17	13.66	19.06	15.74	16.24	15.99
14	305.2	43.60	43.58	41.95	42.77	37.23	529.7	4.59	0.784E 08	0.04133	12.90	12.95	17.39	14.83	15.16	14.99
15	333.3	44.79	44.83	42.74	43.77	38.48	542.3	4.47	0.820E 08	0.04522	13.00	12.90	19.26	15.48	16.10	15.79
16	363.3	46.70	46.74	44.57	45.64	39.81	556.4	4.35	0.859E 08	0.04940	11.88	11.80	17.21	14.03	14.52	14.28
17	383.3	47.42	47.07	45.16	46.20	40.70	566.2	4.27	0.886E 08	0.05220	12.15	12.83	18.33	14.85	15.41	15.13
18	403.3	48.26	48.03	45.99	47.07	41.59	576.4	4.18	0.915E 08	0.05501	12.22	12.67	18.55	14.89	15.50	15.20
19	423.3	48.81	48.48	46.78	47.71	42.48	585.8	4.11	0.941E 08	0.05783	12.85	13.58	18.95	15.57	16.08	15.83
20	443.3	50.16	50.41	48.00	49.15	43.37	594.9	4.04	0.967E 08	0.06065	11.97	11.54	17.55	14.07	14.65	14.36
21	463.3	50.14	50.54	48.30	49.32	44.26	604.4	3.97	0.994E 08	0.06349	13.80	12.93	20.07	16.04	16.72	16.38
AVERAGE VALUES THROUGH STATIONS 15 TO 20:																
	391.6	47.69	47.59	45.54	46.59	41.07	570.4	4.24	0.898E 08	0.05338	12.34	12.55	18.31	14.82	15.38	15.10

========== EXPERIMENT 0R11 --- NOV. 21, 1987 ==========

INPUT ELECTRIC POWER = 1456.2 W HEAT RATE GAINED BY WATER = 1382.5 W HEAT BALANCE ERROR = 5.06%
MASS FLOW RATE = 10.4960 G/S PRESSURE DROP = 0.1771 MM H2O FRICTION FACTOR = 0.045792 FREM = 22.7874

REM = 497.6 GRM+ = 0.26526E 08 UPSTREAM BULK TEMPERATURE = 23.81 DEG C DOWNSTREAM BULK TEMPERATURE = 55.42 DEG C
PRM = 4.365 RAM+ = 0.11578E 09 INLET BULK TEMPERATURE = 23.86 DEG C OUTLET BULK TEMPERATURE = 55.39 DEG C

STATION NO.	Z CM	WALL TEMPERATURE (DEG C) A	B	C	AVERAGE	TB (C)	RE	PR	RA+	Z+	NUSSELT NUMBER A	B	C	AVERAGE T	H	T+H
0	0.0	28.69	28.73	28.29	28.50	23.87	357.9	6.30	0.585E 08	0.00001	23.85	23.69	26.01	24.84	24.89	24.86
1	1.5	29.53	29.58	29.25	29.40	23.97	358.7	6.29	0.588E 08	0.00022	20.68	20.51	21.79	21.17	21.19	21.18
2	2.5	30.11	30.16	29.91	30.02	24.03	359.2	6.28	0.590E 08	0.00036	18.94	18.77	19.59	19.22	19.23	19.22
3	5.5	31.84	31.92	31.88	31.88	24.23	360.9	6.24	0.597E 08	0.00080	15.13	14.96	15.05	15.05	15.05	15.05
4	15.5	33.71	33.44	31.68	32.63	24.91	366.5	6.14	0.620E 08	0.00227	13.05	13.45	16.95	14.87	15.10	14.99
5	25.5	34.75	34.89	32.32	33.57	25.58	372.3	6.03	0.643E 08	0.00374	12.51	12.32	17.01	14.35	14.71	14.53
6	45.5	36.05	35.85	33.21	34.58	26.92	384.4	5.82	0.692E 08	0.00669	12.52	12.80	18.15	14.93	15.43	15.18
7	75.5	37.92	37.50	35.33	36.52	28.94	400.7	5.57	0.761E 08	0.01113	12.68	13.30	17.81	15.02	15.40	15.21
8	105.5	39.80	39.51	37.52	38.59	30.96	418.4	5.31	0.835E 08	0.01561	12.81	13.25	17.26	14.85	15.14	15.00
9	135.5	41.43	41.07	38.32	39.79	32.98	436.2	5.07	0.908E 08	0.02016	13.32	13.92	21.10	16.55	17.36	16.96
10	165.2	43.05	42.77	40.67	41.79	34.97	454.0	4.84	0.979E 08	0.02474	13.88	14.38	19.70	16.45	16.91	16.68
11	205.2	45.70	45.49	43.08	44.34	37.66	479.4	4.55	0.108E 09	0.03098	13.86	14.24	20.55	16.69	17.30	17.00
12	245.2	48.86	48.62	46.38	47.56	40.35	504.7	4.30	0.119E 09	0.03718	13.03	13.41	18.38	15.38	15.80	15.59
13	275.2	50.39	50.08	47.64	48.94	42.37	524.7	4.12	0.127E 09	0.04188	13.78	14.33	20.94	16.81	17.49	17.15
14	305.2	52.49	52.47	50.30	51.39	44.39	543.7	3.96	0.135E 09	0.04660	13.57	13.61	18.60	15.70	16.09	15.90
15	333.3	54.39	54.53	51.61	53.04	46.28	562.7	3.81	0.143E 09	0.05107	13.51	13.28	20.53	16.21	16.96	16.59
16	363.3	57.06	57.20	54.02	55.58	48.29	583.0	3.67	0.152E 09	0.05587	12.46	12.26	19.08	15.00	15.72	15.36
17	383.3	58.05	57.62	55.06	56.44	49.64	597.0	3.57	0.158E 09	0.05908	12.96	13.66	20.12	16.02	16.72	16.37
18	403.3	59.47	59.11	56.32	57.80	50.98	611.7	3.48	0.165E 09	0.06231	12.81	13.39	20.39	15.95	16.74	16.35
19	423.3	60.32	59.82	57.52	58.80	52.33	625.9	3.39	0.171E 09	0.06554	13.58	14.49	20.90	16.78	17.47	17.13
20	443.3	62.27	62.54	59.44	60.92	53.67	638.7	3.32	0.177E 09	0.06873	12.60	12.22	18.79	14.95	15.60	15.27
21	463.3	62.50	63.18	60.14	61.49	55.02	652.0	3.25	0.183E 09	0.07194	14.45	13.24	21.10	16.70	17.47	17.09
AVERAGE VALUES THROUGH STATIONS 15 TO 20:																
	391.6	58.59	58.47	55.66	57.10	50.20	603.2	3.54	0.161E 09	0.06043	12.99	13.22	19.97	15.82	16.54	16.18

========== EXPERIMENT 0R12 --- NOV. 22, 1987 ==========

INPUT ELECTRIC POWER = 1804.7 W HEAT RATE GAINED BY WATER = 1712.4 W HEAT BALANCE ERROR = 5.11%
MASS FLOW RATE = 9.4480 G/S PRESSURE DROP = 0.2159 MM H2O FRICTION FACTOR = 0.068736 FREM = 34.3764

REM = 500.1 GRM+ = 0.44965E 08 UPSTREAM BULK TEMPERATURE = 23.83 DEG C DOWNSTREAM BULK TEMPERATURE = 67.31 DEG C
PRM = 3.869 RAM+ = 0.17396E 09 INLET BULK TEMPERATURE = 23.90 DEG C OUTLET BULK TEMPERATURE = 67.27 DEG C

STATION NO.	Z CM	WALL TEMPERATURE (DEG C) A	B	C	AVERAGE	TB (C)	RE	PR	RA+	Z+	NUSSELT NUMBER A	B	C	AVERAGE T	H	T+H
0	0.0	30.05	30.10	29.47	29.77	23.91	322.4	6.29	0.726E 08	0.00001	23.23	23.02	25.63	24.31	24.38	24.35
1	1.5	31.10	31.18	30.70	30.92	24.04	323.4	6.27	0.731E 08	0.00024	20.19	19.97	21.42	20.73	20.75	20.74
2	2.5	31.83	31.92	31.54	31.71	24.13	324.1	6.26	0.735E 08	0.00041	18.52	18.30	19.23	18.81	18.82	18.82
3	5.5	34.01	34.15	34.08	34.08	24.41	326.2	6.22	0.747E 08	0.00089	14.83	14.62	14.73	14.73	14.73	14.73
4	15.5	36.29	35.92	33.52	34.81	25.34	333.2	6.07	0.786E 08	0.00252	12.97	13.42	17.37	15.00	15.28	15.14
5	25.5	37.73	37.92	34.52	36.17	26.26	340.6	5.92	0.827E 08	0.00416	12.36	12.16	17.18	14.31	14.72	14.52
6	45.5	39.40	39.18	35.92	37.61	28.11	354.5	5.67	0.907E 08	0.00744	12.51	12.76	18.08	14.87	15.36	15.11
7	75.5	41.78	41.31	38.31	39.93	30.89	376.0	5.32	0.103E 09	0.01241	12.88	13.46	18.89	15.51	16.03	15.77
8	105.5	44.27	43.93	41.24	42.67	33.66	398.0	4.99	0.115E 09	0.01747	13.14	13.57	18.39	15.47	15.87	15.67
9	135.5	46.55	46.08	42.59	44.46	36.44	421.3	4.67	0.128E 09	0.02266	13.68	14.35	22.47	17.26	18.24	17.75
10	165.2	49.19	48.84	46.06	47.54	39.18	444.1	4.41	0.141E 09	0.02777	13.75	14.25	20.01	16.47	17.00	16.74
11	205.2	52.64	52.35	49.26	50.88	42.88	476.6	4.08	0.160E 09	0.03472	14.01	14.44	21.42	17.09	17.82	17.46
12	245.2	57.01	56.64	53.81	55.32	46.58	509.4	3.79	0.179E 09	0.04177	13.02	13.49	18.77	15.54	16.01	15.77
13	275.2	58.87	58.45	55.50	57.08	49.36	534.8	3.59	0.194E 09	0.04710	14.21	14.86	22.02	17.50	18.28	17.89
14	305.2	61.78	61.75	58.91	60.34	52.13	561.8	3.40	0.210E 09	0.05248	13.94	13.99	19.87	16.40	16.92	16.66
15	333.3	64.89	65.04	61.18	63.07	54.73	584.4	3.26	0.225E 09	0.05748	13.19	13.00	20.80	16.07	16.95	16.51
16	363.3	68.10	68.28	64.15	66.17	57.51	610.0	3.11	0.240E 09	0.06290	12.59	12.38	20.09	15.40	16.29	15.84
17	383.3	69.55	68.96	65.60	67.43	59.36	627.3	3.01	0.250E 09	0.06668	13.04	13.84	21.30	16.47	17.37	16.92
18	403.3	71.42	70.92	67.47	69.32	61.21	645.5	2.91	0.261E 09	0.07051	12.97	13.64	21.15	16.33	17.23	16.78
19	423.3	72.59	71.95	69.08	70.67	63.06	663.8	2.83	0.272E 09	0.07421	13.87	14.87	21.96	17.36	18.16	17.76
20	443.3	75.28	75.51	71.61	73.50	64.91	682.5	2.75	0.284E 09	0.07782	12.72	12.44	19.67	15.34	16.12	15.73
21	463.3	75.44	76.25	72.62	74.23	66.76	702.3	2.66	0.296E 09	0.08145	15.14	13.85	22.46	17.60	18.48	18.04
AVERAGE VALUES THROUGH STATIONS 15 TO 20:																
	391.6	70.30	70.11	66.51	68.36	60.13	635.6	2.98	0.255E 09	0.06827	13.06	13.36	20.83	16.16	17.02	16.59

========== EXPERIMENT OR13 --- NOV. 23, 1987 ==========

INPUT ELECTRIC POWER = 136.1 W   HEAT RATE GAINED BY WATER = 135.0 W   HEAT BALANCE ERROR = 0.78%
MASS FLOW RATE = 17.0600 G/S   PRESSURE DROP = 0.2264 MM H2O   FRICTION FACTOR = 0.022282   FREM = 13.2661

REM = 595.4   GRM+ = 0.98465E 06   UPSTREAM BULK TEMPERATURE = 23.93 DEG C   DOWNSTREAM BULK TEMPERATURE = 25.83 DEG C
PRM = 6.141   RAM+ = 0.60464E 07   INLET BULK TEMPERATURE = 23.94 DEG C   OUTLET BULK TEMPERATURE = 25.83 DEG C

STATION NO.	Z CM	WALL TEMPERATURE (DEG C) A	B	C	AVERAGE	TB (C)	RE	PR	RA+	Z+	NUSSELT NUMBER A	B	C	AVERAGE T	H	T+H
0	0.0	24.45	24.47	24.41	24.44	23.94	582.6	6.29	0.573E 07	0.00000	21.83	21.17	23.66	22.53	22.59	22.56
1	1.5	24.51	24.53	24.48	24.50	23.94	582.7	6.29	0.573E 07	0.00013	19.99	19.22	20.86	20.22	20.24	20.23
2	2.5	24.54	24.57	24.53	24.54	23.95	582.7	6.29	0.574E 07	0.00022	18.89	18.07	19.31	18.88	18.90	18.89
3	5.5	24.65	24.69	24.67	24.67	23.96	582.9	6.29	0.574E 07	0.00049	16.22	15.32	15.76	15.76	15.76	15.76
4	15.5	25.02	25.04	24.95	24.99	24.00	583.4	6.28	0.575E 07	0.00139	11.03	10.81	11.86	11.37	11.39	11.38
5	25.5	25.20	25.23	25.09	25.15	24.04	583.9	6.27	0.577E 07	0.00229	9.71	9.47	10.74	10.13	10.17	10.15
6	45.5	25.39	25.37	25.23	25.30	24.12	585.0	6.26	0.579E 07	0.00409	8.86	9.02	10.13	9.50	9.53	9.51
7	75.5	25.64	25.49	25.45	25.51	24.24	586.6	6.24	0.583E 07	0.00678	8.05	8.99	9.32	8.89	8.92	8.90
8	105.5	25.72	25.73	25.62	25.67	24.36	588.3	6.22	0.587E 07	0.00948	8.29	8.19	8.95	8.58	8.60	8.59
9	135.5	25.91	25.93	25.55	25.73	24.48	589.9	6.20	0.591E 07	0.01218	7.87	7.75	10.59	8.99	9.20	9.09
10	165.2	25.95	25.90	25.72	25.82	24.60	591.5	6.18	0.595E 07	0.01485	8.34	8.67	10.03	9.20	9.27	9.23
11	205.2	25.96	26.00	25.75	25.86	24.77	593.8	6.16	0.601E 07	0.01846	9.36	9.12	11.42	10.22	10.34	10.28
12	245.2	26.18	26.37	25.97	26.12	24.93	596.0	6.13	0.606E 07	0.02206	8.96	7.78	10.76	9.39	9.57	9.48
13	275.2	26.31	26.36	26.13	26.24	25.05	597.7	6.11	0.610E 07	0.02477	8.90	8.52	10.33	9.45	9.52	9.49
14	305.2	26.53	26.53	26.22	26.37	25.17	599.4	6.10	0.614E 07	0.02748	8.22	8.26	10.72	9.32	9.48	9.40
15	333.3	26.59	26.57	26.29	26.43	25.28	601.0	6.08	0.618E 07	0.03002	8.56	8.71	11.15	9.73	9.89	9.81
16	363.3	26.69	26.60	26.36	26.50	25.40	602.7	6.06	0.622E 07	0.03273	8.74	9.39	11.72	10.22	10.39	10.31
17	383.3	26.72	26.69	26.40	26.55	25.49	603.8	6.05	0.625E 07	0.03454	9.10	9.31	12.23	10.50	10.72	10.61
18	403.3	26.77	26.77	26.57	26.67	25.57	605.0	6.03	0.628E 07	0.03635	9.30	9.34	11.13	10.15	10.23	10.19
19	423.3	26.76	26.86	26.60	26.71	25.65	606.1	6.02	0.631E 07	0.03816	10.08	9.07	11.70	10.52	10.64	10.56
20	443.3	26.97	27.10	26.71	26.88	25.73	607.3	6.01	0.634E 07	0.03997	9.01	8.14	11.34	9.75	9.96	9.85
21	463.3	26.94	26.91	26.62	26.77	25.81	608.4	5.99	0.636E 07	0.04178	9.85	10.17	13.81	11.61	11.91	11.76
AVERAGE VALUES THROUGH STATIONS 15 TO 20:	391.6	26.75	26.77	26.49	26.62	25.52	604.3	6.04	0.626E 07	0.03529	9.13	8.99	11.55	10.14	10.30	10.22

========== EXPERIMENT OR14 --- NOV. 24, 1987 ==========

INPUT ELECTRIC POWER = 260.4 W   HEAT RATE GAINED BY WATER = 242.6 W   HEAT BALANCE ERROR = 6.85%
MASS FLOW RATE = 16.9880 G/S   PRESSURE DROP = 0.2527 MM H2O   FRICTION FACTOR = 0.025078   FREM = 15.1066

REM = 602.4   GRM+ = 0.18699E 07   UPSTREAM BULK TEMPERATURE = 23.85 DEG C   DOWNSTREAM BULK TEMPERATURE = 27.28 DEG C
PRM = 6.033   RAM+ = 0.11281E 08   INLET BULK TEMPERATURE = 23.86 DEG C   OUTLET BULK TEMPERATURE = 27.27 DEG C

STATION NO.	Z CM	WALL TEMPERATURE (DEG C) A	B	C	AVERAGE	TB (C)	RE	PR	RA+	Z+	NUSSELT NUMBER A	B	C	AVERAGE T	H	T+H
0	0.0	24.72	24.72	24.64	24.68	23.86	579.1	6.30	0.103E 08	0.00000	23.53	23.41	25.94	24.64	24.71	24.66
1	1.5	24.84	24.85	24.78	24.81	23.87	579.2	6.30	0.103E 08	0.00014	20.74	20.60	22.03	21.33	21.35	21.34
2	2.5	24.93	24.94	24.89	24.91	23.87	579.3	6.30	0.103E 08	0.00023	19.17	19.03	19.95	19.51	19.52	19.52
3	5.5	25.19	25.20	25.20	25.20	23.90	579.6	6.30	0.103E 08	0.00050	15.62	15.48	15.55	15.55	15.55	15.55
4	15.5	25.76	25.77	25.63	25.70	23.97	580.5	6.29	0.103E 08	0.00140	11.30	11.20	12.19	11.70	11.72	11.71
5	25.5	26.01	26.05	25.79	25.91	24.04	581.5	6.27	0.104E 08	0.00230	10.24	10.07	11.55	10.81	10.85	10.83
6	45.5	26.40	26.36	26.08	26.24	24.19	583.4	6.25	0.104E 08	0.00410	9.11	9.20	10.67	9.86	9.92	9.89
7	75.5	26.77	26.59	26.38	26.53	24.41	586.4	6.22	0.106E 08	0.00681	8.55	9.26	10.24	9.52	9.57	9.54
8	105.5	26.95	26.91	26.62	26.78	24.63	589.3	6.18	0.107E 08	0.00953	8.66	8.82	10.11	9.38	9.43	9.40
9	135.5	27.16	27.12	26.53	26.83	24.84	592.3	6.15	0.108E 08	0.01224	8.72	8.85	11.96	10.13	10.37	10.25
10	165.2	27.18	27.11	26.75	26.95	25.06	595.3	6.11	0.110E 08	0.01493	9.49	9.84	11.95	10.68	10.81	10.74
11	205.2	27.34	27.29	26.79	27.05	25.35	599.4	6.07	0.111E 08	0.01856	10.10	10.39	14.02	11.84	12.13	11.99
12	245.2	27.71	27.82	27.23	27.50	25.64	603.5	6.02	0.113E 08	0.02220	9.73	9.23	12.70	10.85	11.09	10.97
13	275.2	27.85	27.80	27.39	27.61	25.86	606.6	5.99	0.115E 08	0.02493	10.10	10.39	13.20	11.53	11.72	11.63
14	305.2	28.13	28.10	27.72	27.92	26.08	609.8	5.95	0.116E 08	0.02766	9.79	9.96	12.29	10.95	11.08	11.02
15	333.3	28.42	28.49	28.02	28.24	26.29	612.8	5.92	0.117E 08	0.03023	9.42	9.13	11.55	10.29	10.41	10.35
16	363.3	28.84	28.84	28.30	28.57	26.50	616.0	5.88	0.119E 08	0.03297	8.60	8.61	11.17	9.72	9.89	9.81
17	383.3	29.05	29.00	28.48	28.75	26.65	618.2	5.86	0.120E 08	0.03479	8.38	8.55	10.99	9.56	9.73	9.65
18	403.3	29.20	29.15	28.70	28.94	26.80	620.4	5.84	0.121E 08	0.03662	8.35	8.52	10.53	9.37	9.48	9.43
19	423.3	29.18	29.18	28.70	28.94	26.94	622.4	5.82	0.122E 08	0.03845	8.97	8.97	11.39	10.04	10.18	10.11
20	443.3	29.43	29.54	28.89	29.19	27.09	624.2	5.80	0.122E 08	0.04028	8.58	8.18	11.09	9.54	9.74	9.64
21	463.3	29.19	29.20	28.61	28.90	27.23	626.1	5.78	0.123E 08	0.04210	10.24	10.20	14.55	12.01	12.38	12.19
AVERAGE VALUES THROUGH STATIONS 15 TO 20:	391.6	29.02	29.03	28.52	28.77	26.71	619.0	5.85	0.120E 08	0.03556	8.72	8.66	11.12	9.75	9.91	9.83

========== EXPERIMENT OR15 --- NOV. 24, 1987 ==========

INPUT ELECTRIC POWER = 674.3 W   HEAT RATE GAINED BY WATER = 652.2 W   HEAT BALANCE ERROR = 3.28%
MASS FLOW RATE = 15.8240 G/S   PRESSURE DROP = 0.2495 MM H2O   FRICTION FACTOR = 0.028507   FREM = 17.1721

REM = 602.4   GRM+ = 0.63902E 07   UPSTREAM BULK TEMPERATURE = 23.86 DEG C   DOWNSTREAM BULK TEMPERATURE = 33.75 DEG C
PRM = 5.583   RAM+ = 0.35679E 08   INLET BULK TEMPERATURE = 23.88 DEG C   OUTLET BULK TEMPERATURE = 33.74 DEG C

STATION NO.	Z CM	WALL TEMPERATURE (DEG C) A	B	C	AVERAGE	TB (C)	RE	PR	RA+	Z+	NUSSELT NUMBER A	B	C	AVERAGE T	H	T+H
0	0.0	26.17	26.19	26.00	26.09	23.88	539.6	6.30	0.276E 08	0.00000	23.70	23.45	25.60	24.54	24.59	24.57
1	1.5	26.53	26.57	26.42	26.48	23.91	540.0	6.30	0.276E 08	0.00015	20.69	20.41	21.64	21.08	21.10	21.09
2	2.5	26.78	26.83	26.70	26.75	23.93	540.3	6.29	0.277E 08	0.00024	19.02	18.74	19.56	19.21	19.22	19.21
3	5.5	27.54	27.60	27.57	27.57	23.99	541.0	6.28	0.278E 08	0.00053	15.31	15.04	15.17	15.17	15.17	15.17
4	15.5	28.54	28.48	27.89	28.20	24.20	543.6	6.25	0.281E 08	0.00150	12.51	12.68	14.71	13.57	13.65	13.61
5	25.5	29.11	29.14	28.27	28.70	24.41	546.3	6.22	0.284E 08	0.00247	11.54	11.48	14.07	12.66	12.79	12.72
6	45.5	29.75	29.65	28.77	29.23	24.83	551.6	6.15	0.291E 08	0.00441	11.02	11.24	13.77	12.31	12.45	12.38
7	75.5	30.38	30.20	29.28	29.78	25.46	559.8	6.05	0.302E 08	0.00733	11.00	11.41	14.19	12.52	12.70	12.61
8	105.5	30.95	30.89	29.94	30.43	26.10	568.2	5.95	0.312E 08	0.01027	11.14	11.28	14.06	12.47	12.63	12.55
9	135.5	31.51	31.39	30.02	30.74	26.73	576.9	5.85	0.323E 08	0.01321	11.28	11.56	16.39	13.46	13.90	13.68
10	165.2	31.73	31.61	30.50	31.08	27.35	584.6	5.77	0.333E 08	0.01612	12.32	12.66	17.13	14.44	14.81	14.63
11	205.2	32.48	32.41	31.23	31.83	28.19	594.7	5.66	0.347E 08	0.02005	12.55	12.75	17.72	14.76	15.19	14.98
12	245.2	33.59	33.64	32.49	33.05	29.03	605.3	5.55	0.361E 08	0.02399	11.79	11.66	15.54	13.36	13.63	13.50
13	275.2	34.15	34.01	33.02	33.55	29.67	613.4	5.48	0.371E 08	0.02695	11.96	12.35	15.98	13.80	14.07	13.93
14	305.2	34.95	34.94	33.97	34.46	30.30	621.8	5.40	0.382E 08	0.02992	11.49	11.52	14.56	12.86	13.04	12.95
15	333.3	35.44	35.48	34.03	34.74	30.89	629.8	5.32	0.393E 08	0.03271	11.75	11.65	17.02	13.86	14.36	14.11
16	363.3	36.31	36.32	35.00	35.66	31.52	638.7	5.24	0.404E 08	0.03570	11.14	11.12	15.34	12.90	13.23	13.07
17	383.3	36.66	36.48	35.32	35.94	31.94	644.5	5.19	0.412E 08	0.03770	11.30	11.74	15.79	13.31	13.65	13.48
18	403.3	37.02	36.92	35.71	36.34	32.36	649.8	5.14	0.418E 08	0.03972	11.42	11.68	15.89	13.38	13.72	13.55
19	423.3	37.22	37.05	36.06	36.60	32.78	655.1	5.09	0.425E 08	0.04174	11.98	12.47	16.22	13.94	14.22	14.08
20	443.3	38.00	38.21	36.76	37.43	33.20	660.6	5.04	0.432E 08	0.04377	11.07	10.62	14.92	12.56	12.88	12.72
21	463.3	37.90	38.06	36.70	37.34	33.62	666.1	4.99	0.439E 08	0.04581	12.42	11.95	17.27	14.29	14.73	14.51
AVERAGE VALUES THROUGH STATIONS 15 TO 20:	391.6	36.78	36.74	35.48	36.12	32.12	646.4	5.17	0.414E 08	0.03856	11.44	11.55	15.86	13.33	13.68	13.50

========== EXPERIMENT OR16 --- NOV. 25, 1987 ==========

INPUT ELECTRIC POWER = 1130.8 W   HEAT RATE GAINED BY WATER = 1082.0 W   HEAT BALANCE ERROR = 4.31%
MASS FLOW RATE = 14.5260 G/S   PRESSURE DROP = 0.1982 MM H2O   FRICTION FACTOR = 0.026830   FREM = 16.1522

REM = 602.0   GRM+ = 0.13897E 08   UPSTREAM BULK TEMPERATURE = 23.89 DEG C   DOWNSTREAM BULK TEMPERATURE = 41.77 DEG C
PRM = 5.086   RAM+ = 0.70675E 08   INLET BULK TEMPERATURE = 23.92 DEG C   OUTLET BULK TEMPERATURE = 41.75 DEG C

STATION NO.	Z CM	-WALL TEMPERATURE (DEG C)- A	B	C	AVERAGE	TB (C)	RE	PR	RA+	Z+	NUSSELT NUMBER A	B	C	AVERAGE T	H	T+H
0	0.0	27.40	27.45	27.14	27.28	23.92	495.9	6.29	0.459E 08	0.00001	25.91	25.57	28.00	26.82	26.87	26.85
1	1.5	28.02	28.08	27.84	27.94	23.98	496.5	6.28	0.460E 08	0.00016	22.31	21.96	23.32	22.71	22.73	22.72
2	2.5	28.44	28.52	28.32	28.40	24.02	496.9	6.28	0.461E 08	0.00026	20.36	20.00	20.91	20.54	20.54	20.54
3	5.5	29.71	29.83	29.77	29.77	24.13	498.2	6.26	0.464E 08	0.00058	16.12	15.79	15.96	15.96	15.96	15.96
4	15.5	31.26	31.02	30.07	30.60	24.51	502.6	6.20	0.474E 08	0.00164	13.32	13.83	16.19	14.76	14.88	14.82
5	25.5	31.93	32.05	30.24	31.11	24.89	507.0	6.14	0.485E 08	0.00269	12.77	12.55	16.81	14.44	14.73	14.59
6	45.5	33.01	32.92	31.23	32.10	25.65	516.1	6.02	0.506E 08	0.00482	12.19	12.34	16.09	13.92	14.18	14.05
7	75.5	34.11	33.79	32.12	33.04	26.79	530.5	5.84	0.538E 08	0.00802	12.24	12.78	16.80	14.33	14.65	14.49
8	105.5	35.28	35.08	33.66	34.42	27.93	543.0	5.69	0.568E 08	0.01122	12.16	12.48	15.59	13.76	13.96	13.86
9	135.5	36.23	35.96	33.76	34.93	29.07	556.1	5.55	0.599E 08	0.01444	12.44	12.90	19.00	15.20	15.83	15.51
10	165.2	36.72	36.50	34.87	35.74	30.20	569.6	5.41	0.631E 08	0.01764	13.63	14.11	19.03	16.04	16.45	16.25
11	205.2	38.26	38.06	36.31	37.24	31.72	589.0	5.22	0.677E 08	0.02197	13.55	13.97	19.29	16.06	16.52	16.29
12	245.2	40.09	39.98	38.41	39.22	33.25	606.9	5.04	0.718E 08	0.02638	12.88	13.09	17.09	14.76	15.04	14.90
13	275.2	40.95	40.66	38.94	39.87	34.39	620.9	4.91	0.750E 08	0.02972	13.40	14.00	19.32	16.03	16.51	16.27
14	305.2	42.22	42.20	40.54	41.37	35.53	635.6	4.77	0.782E 08	0.03309	13.09	13.13	17.50	14.99	15.30	15.15
15	333.3	43.22	43.28	41.09	42.17	36.60	650.0	4.65	0.814E 08	0.03628	13.21	13.07	19.47	15.69	16.30	16.00
16	363.3	45.03	45.07	42.79	43.92	37.74	664.3	4.54	0.848E 08	0.03964	11.96	11.89	17.25	14.10	14.59	14.34
17	383.3	45.63	45.29	43.28	44.37	38.50	673.9	4.47	0.871E 08	0.04187	12.20	12.82	18.21	14.82	15.36	15.09
18	403.3	46.40	46.09	44.06	45.15	39.26	683.8	4.40	0.895E 08	0.04411	12.18	12.72	18.12	14.76	15.29	15.02
19	423.3	46.79	46.43	44.65	45.63	40.02	694.0	4.33	0.919E 08	0.04635	12.83	13.54	16.75	15.47	15.97	15.72
20	443.3	47.93	48.20	45.65	46.86	40.78	704.5	4.26	0.944E 08	0.04861	12.12	11.68	17.79	14.26	14.84	14.55
21	463.3	47.78	48.19	45.85	46.92	41.54	715.3	4.19	0.969E 08	0.05087	13.87	13.02	20.09	16.10	16.77	16.43
AVERAGE VALUES THROUGH STATIONS 15 TO 20:																
	391.6	45.83	45.73	43.59	44.68	38.82	678.4	4.44	0.882E 08	0.04281	12.41	12.62	18.26	14.85	15.39	15.12

========== EXPERIMENT OR17 --- NOV. 25, 1987 ==========

INPUT ELECTRIC POWER = 1578.9 W   HEAT RATE GAINED BY WATER = 1516.8 W   HEAT BALANCE ERROR = 3.93%
MASS FLOW RATE = 13.1350 G/S   PRESSURE DROP = 0.2192 MM H2O   FRICTION FACTOR = 0.036219   FREM = 21.7617

REM = 600.8   GRM+ = 0.26203E 08   UPSTREAM BULK TEMPERATURE = 23.89 DEG C   DOWNSTREAM BULK TEMPERATURE = 51.59 DEG C
PRM = 4.537   RAM+ = 0.11889E 09   INLET BULK TEMPERATURE = 23.93 DEG C   OUTLET BULK TEMPERATURE = 51.57 DEG C

STATION NO.	Z CM	-WALL TEMPERATURE (DEG C)- A	B	C	AVERAGE	TB (C)	RE	PR	RA+	Z+	NUSSELT NUMBER A	B	C	AVERAGE T	H	T+H
0	0.0	28.87	28.90	28.45	28.67	23.93	448.5	6.29	0.644E 08	0.00001	25.58	25.41	27.94	26.66	26.71	26.69
1	1.5	29.72	29.77	29.42	29.56	24.02	449.4	6.28	0.647E 08	0.00017	22.15	21.96	23.35	22.69	22.70	22.69
2	2.5	30.30	30.36	30.09	30.21	24.08	450.0	6.27	0.649E 08	0.00029	20.27	20.09	20.98	20.57	20.58	20.57
3	5.5	32.06	32.15	32.10	32.10	24.25	451.8	6.24	0.656E 08	0.00064	16.16	15.99	16.07	16.07	16.07	16.07
4	15.5	33.99	33.64	31.94	32.88	24.84	458.0	6.15	0.678E 08	0.00181	13.78	14.32	17.76	15.69	15.91	15.80
5	25.5	34.89	35.03	32.43	33.70	25.43	464.3	6.05	0.700E 08	0.00298	13.31	13.11	17.97	15.23	15.59	15.41
6	45.5	36.26	36.08	33.49	34.83	26.61	477.6	5.87	0.747E 08	0.00534	12.98	13.25	18.24	15.26	15.68	15.47
7	75.5	37.86	37.47	35.11	36.38	28.38	495.6	5.64	0.813E 08	0.00889	13.18	13.75	18.59	15.61	16.03	15.82
8	105.5	39.52	39.26	37.23	38.31	30.15	514.5	5.41	0.883E 08	0.01246	13.28	13.67	17.57	15.25	15.52	15.39
9	135.5	40.98	40.62	37.61	39.21	31.92	534.7	5.19	0.956E 08	0.01605	13.68	14.25	21.76	17.01	17.86	17.44
10	165.2	42.27	42.04	39.81	40.96	33.67	553.4	4.99	0.102E 09	0.01968	14.35	14.75	20.09	16.87	17.32	17.10
11	205.2	44.57	44.28	41.73	43.08	36.03	580.7	4.72	0.112E 09	0.02465	14.36	14.87	21.49	17.39	18.05	17.72
12	245.2	47.33	47.11	44.84	46.03	38.38	606.1	4.48	0.122E 09	0.02961	13.65	13.99	18.92	15.97	16.37	16.17
13	275.2	48.73	48.33	45.91	47.22	40.15	629.2	4.32	0.129E 09	0.03334	14.19	14.87	21.14	17.22	17.84	17.53
14	305.2	50.67	50.64	48.24	49.45	41.92	651.6	4.15	0.138E 09	0.03708	13.86	13.90	19.20	16.11	16.54	16.33
15	333.3	52.17	52.25	49.05	50.63	43.56	670.7	4.03	0.145E 09	0.04061	14.07	13.94	22.08	17.14	18.04	17.59
16	363.3	54.51	54.65	51.37	52.98	45.35	692.3	3.89	0.153E 09	0.04441	13.14	12.95	19.99	15.79	16.52	16.15
17	383.3	55.35	54.89	52.25	53.69	46.53	707.5	3.80	0.159E 09	0.04696	13.62	14.37	20.99	16.79	17.50	17.14
18	403.3	56.57	56.14	53.28	54.82	47.70	722.2	3.71	0.164E 09	0.04951	13.54	14.23	21.52	16.87	17.70	17.29
19	423.3	57.25	56.77	54.28	55.64	48.88	737.2	3.63	0.170E 09	0.05207	14.31	15.19	22.21	17.72	18.48	18.10
20	443.3	59.14	59.39	56.10	57.68	50.06	752.8	3.55	0.176E 09	0.05464	13.17	12.81	19.80	15.69	16.40	16.05
21	463.3	59.13	59.75	56.56	58.00	51.24	769.1	3.46	0.182E 09	0.05723	15.13	14.03	22.43	17.66	18.51	18.08
AVERAGE VALUES THROUGH STATIONS 15 TO 20:																
	391.6	55.83	55.68	52.72	54.24	47.02	713.8	3.77	0.161E 09	0.04803	13.64	13.92	21.10	16.67	17.44	17.05

========== EXPERIMENT OR18 --- NOV. 26, 1987 ==========

INPUT ELECTRIC POWER = 1964.4 W   HEAT RATE GAINED BY WATER = 1874.3 W   HEAT BALANCE ERROR = 4.59%
MASS FLOW RATE = 12.0790 G/S   PRESSURE DROP = 0.2382 MM H2O   FRICTION FACTOR = 0.046451   FREM = 28.1390

REM = 605.8   GRM+ = 0.42238E 08   UPSTREAM BULK TEMPERATURE = 23.93 DEG C   DOWNSTREAM BULK TEMPERATURE = 61.15 DEG C
PRM = 4.105   RAM+ = 0.17340E 09   INLET BULK TEMPERATURE = 23.99 DEG C   OUTLET BULK TEMPERATURE = 61.11 DEG C

STATION NO.	Z CM	-WALL TEMPERATURE (DEG C)- A	B	C	AVERAGE	TB (C)	RE	PR	RA+	Z+	NUSSELT NUMBER A	B	C	AVERAGE T	H	T+H
0	0.0	30.20	30.25	29.66	29.94	23.99	413.0	6.28	0.798E 08	0.00001	25.11	24.94	27.53	26.22	26.28	26.25
1	1.5	31.28	31.34	30.89	31.10	24.10	414.1	6.26	0.803E 08	0.00019	21.75	21.56	22.99	22.30	22.32	22.31
2	2.5	32.02	32.09	31.74	31.90	24.18	414.8	6.25	0.807E 08	0.00032	19.91	19.72	20.63	20.22	20.22	20.22
3	5.5	34.24	34.35	34.29	34.29	24.42	417.1	6.21	0.818E 08	0.00070	15.87	15.70	15.79	15.79	15.79	15.79
4	15.5	36.43	36.04	33.72	34.98	25.21	424.8	6.09	0.855E 08	0.00197	13.87	14.37	18.29	15.94	16.21	16.07
5	25.5	37.73	37.83	34.52	36.15	26.01	432.8	5.96	0.893E 08	0.00325	13.24	13.13	18.25	15.31	15.72	15.51
6	45.5	39.31	39.04	35.70	37.44	27.59	448.4	5.74	0.968E 08	0.00582	13.20	13.51	19.08	15.71	16.22	15.97
7	75.5	41.39	40.92	37.95	39.55	29.97	471.2	5.44	0.108E 09	0.00969	13.47	14.05	19.28	16.05	16.52	16.29
8	105.5	43.60	43.20	40.44	41.92	32.34	495.8	5.14	0.120E 09	0.01361	13.60	14.09	18.90	15.98	16.37	16.18
9	135.5	45.53	45.03	41.30	43.29	34.72	519.8	4.87	0.131E 09	0.01762	14.06	14.75	23.11	17.74	18.76	18.25
10	165.2	47.54	47.21	44.36	45.87	37.07	545.6	4.60	0.143E 09	0.02165	14.44	14.91	20.75	17.19	17.71	17.45
11	205.2	50.44	50.13	46.85	48.57	40.24	579.6	4.31	0.160E 09	0.02703	14.74	15.20	22.74	18.05	18.85	18.45
12	245.2	54.20	53.82	51.04	52.52	43.41	614.9	4.04	0.178E 09	0.03248	13.85	14.35	19.57	16.39	16.83	16.61
13	275.2	55.86	55.41	52.37	54.00	45.78	641.7	3.85	0.192E 09	0.03661	14.75	15.44	22.59	18.09	18.84	18.47
14	305.2	58.42	58.38	55.48	56.94	48.16	669.4	3.68	0.206E 09	0.04077	14.44	14.49	20.23	16.87	17.35	17.11
15	333.3	60.76	60.90	56.91	58.87	50.38	696.3	3.52	0.219E 09	0.04470	14.22	14.04	22.63	17.40	18.38	17.89
16	363.3	63.83	64.00	59.70	61.81	52.76	725.0	3.37	0.234E 09	0.04890	13.29	13.08	21.18	16.25	17.19	16.72
17	383.3	64.84	64.23	60.80	62.67	54.34	742.6	3.29	0.243E 09	0.05168	13.98	14.84	22.71	17.62	18.56	18.09
18	403.3	66.48	66.01	62.34	64.29	55.93	761.1	3.20	0.253E 09	0.05447	13.87	14.52	22.84	17.50	18.52	18.01
19	423.3	67.47	66.85	63.84	65.50	57.51	779.9	3.11	0.263E 09	0.05733	14.66	15.63	23.05	18.27	19.10	18.69
20	443.3	69.94	70.21	66.15	68.11	59.10	798.7	3.03	0.272E 09	0.06028	13.42	13.09	20.64	16.14	16.95	16.55
21	463.3	70.02	70.85	66.87	68.65	60.68	818.5	2.94	0.282E 09	0.06326	15.53	14.28	23.45	18.20	19.18	18.69
AVERAGE VALUES THROUGH STATIONS 15 TO 20:																
	391.6	65.55	65.37	61.62	63.54	55.00	750.6	3.25	0.248E 09	0.05289	13.91	14.20	22.18	17.20	18.12	17.66

========== EXPERIMENT OR19 --- NOV. 26, 1987 ==========

INPUT ELECTRIC POWER = 2277.5 W　　HEAT RATE GAINED BY WATER = 2167.4 W　　HEAT BALANCE ERROR = 4.83%
MASS FLOW RATE = 10.9310 G/S　　PRESSURE DROP = 0.2959 MM H2O　　FRICTION FACTOR = 0.070321　　FREM = 42.2465

REM = 600.8　　GRM+ = 0.63155E 08　　UPSTREAM BULK TEMPERATURE = 23.89 DEG C　　DOWNSTREAM BULK TEMPERATURE = 71.43 DEG C
PRM = 3.712　　RAM+ = 0.23444E 09　　INLET BULK TEMPERATURE = 23.96 DEG C　　OUTLET BULK TEMPERATURE = 71.39 DEG C

STA-TION NO.	Z CM	-WALL TEMPERATURE (DEG C)- A	B	C	AVER-AGE	TB (C)	RE	PR	RA+	Z+	NUSSELT NUMBER A	B	C	AVERAGE T	H	T+H
0	0.0	31.40	31.44	30.69	31.06	23.97	373.5	6.29	0.922E 08	0.00001	24.26	24.13	26.85	25.45	25.52	25.48
1	1.5	32.67	32.73	32.16	32.43	24.11	374.8	6.26	0.929E 08	0.00021	21.08	20.94	22.42	21.69	21.71	21.70
2	2.5	33.54	33.61	33.17	33.37	24.21	375.6	6.25	0.935E 08	0.00035	19.33	19.19	20.13	19.68	19.69	19.69
3	5.5	36.16	36.27	36.22	36.22	24.52	378.3	6.20	0.951E 08	0.00077	15.47	15.34	15.40	15.40	15.40	15.40
4	15.5	38.67	38.21	35.25	36.84	25.53	387.3	6.04	0.101E 09	0.00218	13.68	14.18	18.50	15.89	16.22	16.05
5	25.5	40.29	40.44	36.26	38.31	26.54	396.7	5.88	0.106E 09	0.00360	13.04	12.90	18.45	15.23	15.71	15.47
6	45.5	42.02	41.69	37.59	39.72	28.56	414.0	5.61	0.117E 09	0.00644	13.27	13.60	19.78	16.00	16.61	16.30
7	75.5	44.69	44.12	40.37	42.39	31.60	442.0	5.23	0.135E 09	0.01074	13.54	14.17	20.22	16.44	17.04	16.74
8	105.5	47.36	46.95	43.61	45.39	34.64	469.6	4.88	0.152E 09	0.01515	13.82	14.28	19.60	16.37	16.82	16.60
9	135.5	49.80	49.25	44.96	47.24	37.67	499.3	4.54	0.169E 09	0.01964	14.40	15.09	23.97	18.25	19.36	18.80
10	165.2	52.70	52.33	48.93	50.72	40.68	529.0	4.27	0.188E 09	0.02407	14.45	14.91	21.04	17.29	17.86	17.57
11	205.2	56.39	55.98	52.07	54.13	44.72	569.6	3.94	0.214E 09	0.03011	14.78	15.32	23.45	18.33	19.25	18.79
12	245.2	61.32	60.78	57.19	59.12	46.77	612.3	3.64	0.242E 09	0.03623	13.64	14.26	20.33	16.54	17.14	16.84
13	275.2	63.17	62.63	59.00	60.95	51.81	646.8	3.42	0.264E 09	0.04089	14.99	15.73	23.69	18.63	19.53	19.08
14	305.2	66.36	66.35	62.84	64.60	54.84	677.2	3.26	0.285E 09	0.04550	14.72	14.74	21.20	17.38	17.96	17.67
15	333.3	69.78	69.95	65.16	67.51	57.68	707.6	3.10	0.305E 09	0.04990	13.96	13.76	22.58	17.18	18.22	17.70
16	363.3	73.20	73.41	68.43	70.86	60.72	741.1	2.94	0.326E 09	0.05483	13.45	13.23	21.78	16.54	17.56	17.05
17	383.3	74.64	73.92	69.94	72.11	62.74	764.4	2.84	0.342E 09	0.05806	14.07	14.96	23.23	17.86	18.88	18.37
18	403.3	76.70	76.11	71.76	74.08	64.77	787.9	2.75	0.358E 09	0.06119	13.98	14.72	23.87	17.92	19.11	18.51
19	423.3	77.96	77.18	73.64	75.60	66.79	813.0	2.66	0.375E 09	0.06433	14.90	16.02	24.32	18.89	19.89	19.39
20	443.3	81.20	81.48	76.57	78.95	68.81	838.0	2.58	0.391E 09	0.06751	13.38	13.08	21.37	16.34	17.30	16.82
21	463.3	81.29	82.32	77.64	79.72	70.84	864.6	2.49	0.408E 09	0.07072	15.78	14.36	24.24	18.56	19.66	19.11
AVERAGE VALUES THROUGH STATIONS 15 TO 20:																
	391.6	75.58	75.34	70.91	73.19	63.59	775.3	2.81	0.350E 09	0.05930	13.96	14.30	22.86	17.45	18.49	17.97

========== EXPERIMENT OR20 --- NOV. 27, 1987 ==========

INPUT ELECTRIC POWER = 138.0 W　　HEAT RATE GAINED BY WATER = 127.9 W　　HEAT BALANCE ERROR = 7.32%
MASS FLOW RATE = 20.2010 G/S　　PRESSURE DROP = 0.3063 MM H2O　　FRICTION FACTOR = 0.021500　　FREM = 15.1202

REM = 703.3　　GRM+ = 0.92457E 06　　UPSTREAM BULK TEMPERATURE = 24.02 DEG C　　DOWNSTREAM BULK TEMPERATURE = 25.54 DEG C
PRM = 6.157　　RAM+ = 0.56930E 07　　INLET BULK TEMPERATURE = 24.02 DEG C　　OUTLET BULK TEMPERATURE = 25.53 DEG C

STA-TION NO.	Z CM	-WALL TEMPERATURE (DEG C)- A	B	C	AVER-AGE	TB (C)	RE	PR	RA+	Z+	NUSSELT NUMBER A	B	C	AVERAGE T	H	T+H
0	0.0	24.42	24.42	24.36	24.39	24.02	691.1	6.28	0.546E 07	0.00000	26.71	26.38	31.71	28.90	29.13	29.01
1	1.5	24.46	24.47	24.41	24.44	24.03	691.2	6.28	0.546E 07	0.00011	24.56	24.17	27.37	25.78	25.87	25.82
2	2.5	24.49	24.49	24.45	24.47	24.03	691.3	6.28	0.546E 07	0.00019	23.27	22.85	25.00	23.99	24.03	24.01
3	5.5	24.57	24.58	24.57	24.57	24.04	691.4	6.27	0.546E 07	0.00042	20.09	19.63	19.86	19.86	19.86	19.86
4	15.5	24.91	24.93	24.89	24.90	24.07	691.9	6.27	0.547E 07	0.00118	12.75	12.42	12.97	12.77	12.78	12.78
5	25.5	25.06	25.08	24.97	25.02	24.10	692.4	6.26	0.548E 07	0.00193	11.15	10.84	12.21	11.57	11.60	11.59
6	45.5	25.25	25.25	25.15	25.20	24.17	693.5	6.25	0.550E 07	0.00345	9.84	9.80	10.87	10.32	10.35	10.33
7	75.5	25.47	25.32	25.31	25.35	24.26	695.0	6.24	0.553E 07	0.00573	8.83	10.04	10.21	9.79	9.82	9.80
8	105.5	25.58	25.62	25.47	25.54	24.36	696.6	6.22	0.556E 07	0.00801	8.75	8.43	9.55	9.04	9.07	9.06
9	135.5	25.74	25.79	25.43	25.60	24.46	698.1	6.21	0.559E 07	0.01026	8.28	7.97	10.91	9.32	9.52	9.42
10	165.2	25.84	25.76	25.55	25.68	24.55	699.6	6.19	0.562E 07	0.01254	8.28	8.82	10.64	9.48	9.60	9.54
11	205.2	25.85	25.88	25.61	25.74	24.68	701.7	6.17	0.566E 07	0.01558	9.11	8.86	11.50	10.09	10.24	10.16
12	245.2	26.04	26.20	25.80	25.96	24.81	703.8	6.15	0.570E 07	0.01863	8.68	7.65	10.78	9.27	9.47	9.37
13	275.2	26.20	26.14	25.91	26.04	24.91	705.4	6.14	0.574E 07	0.02091	8.26	8.63	10.66	9.42	9.55	9.48
14	305.2	26.31	26.33	26.02	26.17	25.01	707.0	6.12	0.577E 07	0.02320	8.15	8.02	10.50	9.14	9.29	9.21
15	333.3	26.45	26.40	26.12	26.27	25.10	708.5	6.11	0.580E 07	0.02534	7.84	8.15	10.40	9.04	9.20	9.12
16	363.3	26.52	26.46	26.16	26.32	25.19	710.1	6.09	0.583E 07	0.02763	8.03	8.41	10.95	9.39	9.59	9.49
17	383.3	26.55	26.46	26.23	26.37	25.26	711.2	6.08	0.585E 07	0.02915	8.24	8.81	10.90	9.56	9.71	9.64
18	403.3	26.54	26.54	26.29	26.42	25.32	712.3	6.07	0.587E 07	0.03068	8.69	8.72	10.99	9.72	9.85	9.78
19	423.3	26.53	26.63	26.35	26.47	25.39	713.4	6.06	0.589E 07	0.03221	9.27	8.55	11.01	9.84	9.96	9.90
20	443.3	26.72	26.88	26.52	26.66	25.45	714.4	6.05	0.591E 07	0.03373	8.39	7.45	9.97	8.81	8.95	8.88
21	463.3	26.78	26.71	26.42	26.58	25.52	715.5	6.04	0.593E 07	0.03526	8.43	8.90	11.79	9.99	10.23	10.11
AVERAGE VALUES THROUGH STATIONS 15 TO 20:																
	391.6	26.55	26.56	26.28	26.42	25.29	711.6	6.08	0.586E 07	0.02979	8.41	8.35	10.70	9.39	9.54	9.47

========== EXPERIMENT OR21 --- NOV. 27, 1987 ==========

INPUT ELECTRIC POWER = 263.4 W　　HEAT RATE GAINED BY WATER = 251.9 W　　HEAT BALANCE ERROR = 4.38%
MASS FLOW RATE = 19.7750 G/S　　PRESSURE DROP = 0.2779 MM H2O　　FRICTION FACTOR = 0.020353　　FREM = 14.2533

REM = 700.3　　GRM+ = 0.19328E 07　　UPSTREAM BULK TEMPERATURE = 23.98 DEG C　　DOWNSTREAM BULK TEMPERATURE = 27.04 DEG C
PRM = 6.042　　RAM+ = 0.11678E 08　　INLET BULK TEMPERATURE = 23.99 DEG C　　OUTLET BULK TEMPERATURE = 27.03 DEG C

STA-TION NO.	Z CM	-WALL TEMPERATURE (DEG C)- A	B	C	AVER-AGE	TB (C)	RE	PR	RA+	Z+	NUSSELT NUMBER A	B	C	AVERAGE T	H	T+H
0	0.0	24.79	24.79	24.71	24.75	23.99	676.0	6.28	0.107E 08	0.00000	26.12	25.98	29.00	27.45	27.53	27.49
1	1.5	24.91	24.92	24.85	24.88	24.00	676.2	6.28	0.107E 08	0.00012	22.91	22.76	24.43	23.61	23.63	23.62
2	2.5	24.99	25.00	24.95	24.98	24.00	676.3	6.28	0.107E 08	0.00019	21.12	20.96	22.04	21.53	21.54	21.54
3	5.5	25.25	25.26	25.25	25.25	24.02	676.6	6.28	0.107E 08	0.00043	17.11	16.96	17.03	17.03	17.03	17.03
4	15.5	25.81	25.77	25.68	25.74	24.09	677.6	6.27	0.108E 08	0.00120	12.13	12.43	13.13	12.69	12.70	12.70
5	25.5	26.01	26.05	25.79	25.91	24.15	678.6	6.26	0.108E 08	0.00198	11.25	11.05	12.79	11.91	11.97	11.94
6	45.5	26.35	26.32	25.99	26.17	24.28	680.6	6.24	0.109E 08	0.00353	10.15	10.25	12.23	11.12	11.22	11.17
7	75.5	26.65	26.50	26.26	26.42	24.48	683.7	6.21	0.110E 08	0.00585	9.62	10.34	11.72	10.77	10.85	10.81
8	105.5	26.84	26.80	26.56	26.69	24.67	686.7	6.17	0.111E 08	0.00818	9.64	9.84	11.07	10.37	10.41	10.39
9	135.5	27.04	27.04	26.50	26.77	24.87	689.9	6.14	0.113E 08	0.01052	9.62	9.64	12.80	10.99	11.21	11.10
10	165.2	27.13	27.11	26.75	26.93	25.06	693.0	6.11	0.114E 08	0.01283	10.12	10.21	12.40	11.17	11.28	11.22
11	205.2	27.32	27.35	26.87	27.10	25.32	697.2	6.07	0.116E 08	0.01595	10.47	10.32	13.46	11.73	11.93	11.83
12	245.2	27.71	27.82	27.26	27.51	25.58	701.5	6.03	0.117E 08	0.01907	9.80	9.32	12.46	10.81	11.01	10.91
13	275.2	27.88	27.83	27.41	27.63	25.77	704.7	6.00	0.118E 08	0.02141	9.91	10.18	12.74	11.23	11.39	11.31
14	305.2	28.22	28.21	27.69	27.95	25.97	708.0	5.97	0.120E 08	0.02376	9.29	9.32	12.15	10.54	10.72	10.63
15	333.3	28.33	28.32	27.77	28.05	26.15	711.1	5.94	0.121E 08	0.02596	9.57	9.64	12.91	11.01	11.26	11.13
16	363.3	28.44	28.38	27.82	28.12	26.35	714.4	5.91	0.122E 08	0.02831	9.96	10.25	14.13	11.78	12.11	11.95
17	383.3	28.59	28.52	28.03	28.29	26.48	716.6	5.89	0.123E 08	0.02988	9.86	10.22	13.45	11.49	11.74	11.62
18	403.3	28.69	28.67	28.22	28.45	26.61	718.9	5.87	0.124E 08	0.03145	10.00	10.09	12.93	11.31	11.49	11.40
19	423.3	28.76	28.76	28.31	28.53	26.74	721.2	5.85	0.125E 08	0.03302	10.33	10.31	13.24	11.60	11.78	11.69
20	443.3	29.09	29.26	28.55	28.86	26.87	723.4	5.83	0.126E 08	0.03459	9.39	8.72	12.34	10.44	10.70	10.57
21	463.3	29.05	29.05	28.47	28.76	27.00	725.3	5.81	0.127E 08	0.03616	10.14	10.12	14.17	11.82	12.15	11.98
AVERAGE VALUES THROUGH STATIONS 15 TO 20:																
	391.6	28.65	28.65	28.12	28.38	26.53	717.6	5.88	0.124E 08	0.03053	9.85	9.87	13.17	11.27	11.51	11.39

========== EXPERIMENT OR22 --- NOV. 28, 1987 ==========

INPUT ELECTRIC POWER = 692.6 W HEAT RATE GAINED BY WATER = 665.9 W HEAT BALANCE ERROR = 3.86%
MASS FLOW RATE = 18.7350 G/S PRESSURE DROP = 0.2752 MM H2O FRICTION FACTOR = 0.022436 FREM = 15.8218

REM = 705.2 GRM+ = 0.62845E 07 UPSTREAM BULK TEMPERATURE = 24.00 DEG C DOWNSTREAM BULK TEMPERATURE = 32.53 DEG C
PRM = 5.652 RAM+ = 0.35518E 08 INLET BULK TEMPERATURE = 24.01 DEG C OUTLET BULK TEMPERATURE = 32.52 DEG C

STATION NO.	Z CM	WALL TEMPERATURE (DEG C) A	B	C	AVERAGE	TB (C)	RE	PR	RA+	Z+	NUSSELT NUMBER A	B	C	AVERAGE T	H	T+H
0	0.0	26.12	26.13	25.98	26.05	24.01	640.9	6.28	0.284E 08	0.00000	26.35	26.18	28.25	27.22	27.26	27.24
1	1.5	26.49	26.51	26.40	26.45	24.04	641.3	6.27	0.284E 08	0.00012	22.58	22.40	23.52	22.99	23.01	23.00
2	2.5	26.76	26.78	26.69	26.73	24.06	641.5	6.27	0.285E 08	0.00020	20.55	20.37	21.09	20.77	20.77	20.77
3	5.5	27.54	27.57	27.55	27.55	24.11	642.3	6.26	0.286E 08	0.00045	16.18	16.01	16.10	16.10	16.10	16.10
4	15.5	28.65	28.51	28.06	28.32	24.29	645.0	6.23	0.288E 08	0.00127	12.71	13.14	14.71	13.76	13.82	13.79
5	25.5	29.17	29.28	28.38	28.80	24.48	647.7	6.21	0.291E 08	0.00209	11.79	11.53	14.18	12.80	12.92	12.86
6	45.5	29.86	29.76	28.88	29.35	24.84	653.1	6.15	0.297E 08	0.00373	11.01	11.23	13.69	12.27	12.40	12.34
7	75.5	30.44	30.20	29.33	29.83	25.38	661.5	6.06	0.307E 08	0.00619	10.93	11.46	13.99	12.43	12.59	12.51
8	105.5	30.95	30.77	29.97	30.41	25.93	670.1	5.98	0.316E 08	0.00867	10.99	11.38	13.66	12.30	12.42	12.36
9	135.5	31.37	31.25	29.88	30.59	26.47	678.9	5.89	0.325E 08	0.01115	11.25	11.53	16.18	13.37	13.78	13.58
10	165.2	31.53	31.41	30.27	30.87	27.01	687.3	5.81	0.335E 08	0.01361	12.18	12.51	16.89	14.26	14.62	14.44
11	205.2	32.19	32.07	30.95	31.54	27.74	697.5	5.72	0.346E 08	0.01692	12.33	12.68	17.12	14.45	14.81	14.63
12	245.2	33.25	33.27	32.23	32.75	28.46	708.1	5.63	0.358E 08	0.02024	11.46	11.40	14.56	12.81	12.99	12.90
13	275.2	33.61	33.44	32.36	32.95	29.01	716.2	5.56	0.368E 08	0.02274	11.89	12.34	16.31	13.90	14.22	14.06
14	305.2	34.31	34.30	33.24	33.77	29.55	724.5	5.49	0.377E 08	0.02524	11.50	11.53	14.85	12.97	13.18	13.08
15	333.3	34.71	34.74	33.32	34.02	30.06	732.4	5.43	0.386E 08	0.02759	11.76	11.67	16.78	13.80	14.25	14.02
16	363.3	35.58	35.64	34.21	34.91	30.60	741.1	5.36	0.396E 08	0.03010	10.98	10.85	15.14	12.68	13.03	12.86
17	383.3	35.89	35.72	34.50	35.16	30.97	747.0	5.31	0.402E 08	0.03178	11.08	11.47	15.42	13.02	13.35	13.19
18	403.3	36.23	36.08	34.86	35.51	31.33	753.0	5.27	0.409E 08	0.03346	11.12	11.48	15.44	13.05	13.37	13.21
19	423.3	36.32	36.18	35.08	35.67	31.69	759.1	5.22	0.416E 08	0.03514	11.76	12.14	16.07	13.71	14.01	13.86
20	443.3	37.07	37.30	35.83	36.51	32.06	764.8	5.18	0.422E 08	0.03684	10.85	10.38	14.42	12.22	12.51	12.37
21	463.3	36.91	37.09	35.74	36.37	32.42	770.2	5.13	0.428E 08	0.03854	12.09	11.63	16.35	13.75	14.11	13.93
AVERAGE VALUES THROUGH STATIONS 15 TO 20:																
	391.6	35.97	35.94	34.63	35.29	31.12	749.5	5.29	0.405E 08	0.03249	11.26	11.33	15.55	13.08	13.42	13.25

========== EXPERIMENT OR23 --- NOV. 28, 1987 ==========

INPUT ELECTRIC POWER = 1182.6 W HEAT RATE GAINED BY WATER = 1134.7 W HEAT BALANCE ERROR = 4.05%
MASS FLOW RATE = 17.2760 G/S PRESSURE DROP = 0.2585 MM H2O FRICTION FACTOR = 0.024749 FREM = 17.3717

REM = 701.9 GRM+ = 0.13693E 08 UPSTREAM BULK TEMPERATURE = 23.93 DEG C DOWNSTREAM BULK TEMPERATURE = 39.69 DEG C
PRM = 5.204 RAM+ = 0.71260E 08 INLET BULK TEMPERATURE = 23.96 DEG C OUTLET BULK TEMPERATURE = 39.68 DEG C

STATION NO.	Z CM	WALL TEMPERATURE (DEG C) A	B	C	AVERAGE	TB (C)	RE	PR	RA+	Z+	NUSSELT NUMBER A	B	C	AVERAGE T	H	T+H
0	0.0	27.54	27.57	27.27	27.42	23.96	590.3	6.29	0.482E 08	0.00000	26.38	26.13	28.49	27.33	27.37	27.35
1	1.5	28.16	28.23	28.00	28.10	24.01	590.9	6.28	0.484E 08	0.00013	22.65	22.38	23.68	23.08	23.10	23.09
2	2.5	28.62	28.68	28.49	28.57	24.04	591.4	6.27	0.485E 08	0.00022	20.63	20.37	21.22	20.85	20.86	20.85
3	5.5	29.94	30.03	29.98	29.98	24.14	592.7	6.26	0.487E 08	0.00049	16.28	16.04	16.16	16.16	16.16	16.16
4	15.5	31.55	31.30	30.35	30.89	24.48	597.3	6.20	0.497E 08	0.00138	13.34	13.83	16.06	14.72	14.82	14.77
5	25.5	32.27	32.39	30.58	31.45	24.81	601.9	6.15	0.506E 08	0.00227	12.65	12.43	16.36	14.20	14.45	14.32
6	45.5	33.18	33.04	31.26	32.20	25.48	611.4	6.05	0.525E 08	0.00405	12.23	12.46	16.23	14.02	14.29	14.15
7	75.5	34.22	33.91	32.32	33.19	26.49	626.3	5.89	0.555E 08	0.00674	12.15	12.66	16.11	14.02	14.26	14.14
8	105.5	35.19	35.00	33.57	34.33	27.50	640.1	5.75	0.584E 08	0.00943	12.18	12.48	15.42	13.70	13.88	13.79
9	135.5	36.01	35.75	33.51	34.69	28.50	653.5	5.62	0.612E 08	0.01213	12.46	12.89	18.68	15.10	15.68	15.39
10	165.2	36.35	36.22	34.42	35.35	29.50	667.3	5.50	0.641E 08	0.01482	13.61	13.88	18.96	15.94	16.35	16.14
11	205.2	37.78	37.64	35.81	36.76	30.84	686.9	5.33	0.682E 08	0.01845	13.40	13.67	18.72	15.71	16.13	15.92
12	245.2	39.38	39.28	37.66	38.50	32.18	706.9	5.16	0.723E 08	0.02211	12.88	13.05	16.91	14.68	14.94	14.81
13	275.2	40.13	39.85	38.06	39.02	33.19	721.0	5.05	0.751E 08	0.02489	13.31	13.87	18.99	15.84	16.29	16.07
14	305.2	41.32	41.31	39.57	40.44	34.19	735.6	4.93	0.780E 08	0.02769	12.93	12.96	17.13	14.75	15.04	14.89
15	333.3	42.04	42.10	39.75	40.91	35.13	749.8	4.82	0.808E 08	0.03034	13.33	13.21	19.94	15.93	16.60	16.27
16	363.3	43.73	43.83	41.36	42.57	36.14	765.6	4.70	0.839E 08	0.03319	12.09	11.94	17.59	14.28	14.80	14.54
17	383.3	44.21	43.94	41.85	42.96	36.81	776.6	4.62	0.860E 08	0.03511	12.37	12.85	18.18	14.89	15.39	15.14
18	403.3	44.90	44.63	42.52	43.65	37.48	786.4	4.56	0.881E 08	0.03698	12.33	12.79	18.14	14.84	15.35	15.10
19	423.3	45.18	44.86	42.97	44.00	38.15	796.3	4.50	0.902E 08	0.03886	12.99	13.62	18.96	15.63	16.13	15.88
20	443.3	46.33	46.62	43.98	45.23	38.82	806.5	4.44	0.924E 08	0.04074	12.16	11.71	17.68	14.25	14.81	14.53
21	463.3	46.15	46.59	44.23	45.30	39.49	817.0	4.38	0.946E 08	0.04262	13.68	12.84	19.23	15.69	16.25	15.97
AVERAGE VALUES THROUGH STATIONS 15 TO 20:																
	391.6	44.40	44.33	42.07	43.22	37.09	780.2	4.61	0.869E 08	0.03587	12.55	12.68	18.42	14.97	15.52	15.24

========== EXPERIMENT OR24 --- NOV. 29, 1987 ==========

INPUT ELECTRIC POWER = 1674.8 W HEAT RATE GAINED BY WATER = 1604.2 W HEAT BALANCE ERROR = 4.22%
MASS FLOW RATE = 15.7960 G/S PRESSURE DROP = 0.2234 MM H2O FRICTION FACTOR = 0.025540 FREM = 17.8919

REM = 700.6 GRM+ = 0.25287E 08 UPSTREAM BULK TEMPERATURE = 23.99 DEG C DOWNSTREAM BULK TEMPERATURE = 48.35 DEG C
PRM = 4.698 RAM+ = 0.11881E 09 INLET BULK TEMPERATURE = 24.02 DEG C OUTLET BULK TEMPERATURE = 48.33 DEG C

STATION NO.	Z CM	WALL TEMPERATURE (DEG C) A	B	C	AVERAGE	TB (C)	RE	PR	RA+	Z+	NUSSELT NUMBER A	B	C	AVERAGE T	H	T+H
0	0.0	29.02	29.07	28.66	28.86	24.02	540.5	6.28	0.684E 08	0.00000	26.73	26.43	28.77	27.63	27.68	27.65
1	1.5	29.92	30.00	29.68	29.82	24.10	541.4	6.26	0.687E 08	0.00015	22.94	22.63	23.93	23.34	23.36	23.35
2	2.5	30.54	30.63	30.38	30.48	24.15	542.0	6.26	0.689E 08	0.00024	20.89	20.59	21.44	21.09	21.09	21.09
3	5.5	32.40	32.54	32.47	32.47	24.31	544.0	6.23	0.695E 08	0.00053	16.48	16.20	16.34	16.34	16.34	16.34
4	15.5	34.44	34.12	32.47	33.38	24.82	550.5	6.15	0.716E 08	0.00151	13.86	14.34	17.43	15.58	15.76	15.67
5	25.5	35.37	35.57	32.86	34.16	25.34	557.2	6.07	0.737E 08	0.00248	13.28	13.02	17.72	15.10	15.44	15.27
6	45.5	36.73	36.50	33.97	35.29	26.38	571.1	5.90	0.780E 08	0.00444	12.84	13.12	17.49	14.90	15.24	15.07
7	75.5	38.03	37.67	35.30	36.57	27.94	590.5	5.69	0.843E 08	0.00739	13.11	13.60	17.97	15.32	15.66	15.49
8	105.5	39.46	39.12	37.06	38.18	29.49	610.1	5.50	0.906E 08	0.01035	13.22	13.70	17.42	15.18	15.44	15.31
9	135.5	40.67	40.28	37.02	38.75	31.05	630.9	5.30	0.973E 08	0.01333	13.65	14.23	21.99	17.06	17.96	17.51
10	165.2	41.68	41.42	39.13	40.34	32.59	651.5	5.11	0.104E 09	0.01631	14.40	14.82	20.00	16.89	17.31	17.10
11	205.2	43.75	43.46	40.84	42.22	34.66	679.0	4.87	0.112E 09	0.02040	14.32	14.80	21.09	17.22	17.82	17.52
12	245.2	46.16	45.91	43.58	44.81	36.74	708.9	4.63	0.121E 09	0.02456	13.74	14.12	18.92	16.05	16.43	16.24
13	275.2	47.35	46.93	44.34	45.74	38.29	730.0	4.49	0.128E 09	0.02763	14.25	14.95	21.34	17.33	17.97	17.65
14	305.2	48.99	48.96	46.37	47.67	39.85	752.1	4.34	0.135E 09	0.03073	14.09	14.13	19.74	16.46	16.92	16.69
15	333.3	50.29	50.42	47.06	48.71	41.30	774.1	4.21	0.142E 09	0.03364	14.29	14.09	22.30	17.34	18.24	17.79
16	363.3	52.65	52.84	49.49	51.12	42.86	796.4	4.08	0.150E 09	0.03676	13.08	12.83	19.31	15.51	16.13	15.82
17	383.3	53.36	52.95	50.07	51.61	43.90	811.1	4.00	0.155E 09	0.03886	13.50	14.12	20.71	16.56	17.26	16.91
18	403.3	54.42	54.03	51.10	52.66	44.93	826.3	3.92	0.160E 09	0.04096	13.44	14.02	20.69	16.50	17.21	16.86
19	423.3	54.92	54.33	51.84	53.23	45.97	842.1	3.84	0.165E 09	0.04308	14.22	15.22	21.68	17.52	18.20	17.86
20	443.3	56.60	56.90	53.44	55.09	47.01	858.2	3.76	0.170E 09	0.04520	13.25	12.84	19.75	15.71	16.40	16.05
21	463.3	56.52	57.09	53.76	55.28	48.04	873.7	3.69	0.175E 09	0.04732	14.97	14.02	22.19	17.52	18.34	17.93
AVERAGE VALUES THROUGH STATIONS 15 TO 20:																
	391.6	53.71	53.58	50.50	52.07	44.33	818.0	3.97	0.157E 09	0.03975	13.63	13.85	20.74	16.52	17.24	16.88

========== EXPERIMENT 0R25 --- NOV. 30, 1987 ==========

INPUT ELECTRIC POWER = 139.1 W   HEAT RATE GAINED BY WATER = 128.1 W   HEAT BALANCE ERROR = 7.87%
MASS FLOW RATE = 23.2110 G/S   PRESSURE DROP = 0.3461 MM H2O   FRICTION FACTOR = 0.018402   FREM = 14.8236

REM = 805.6   GRM+ = 0.91612E 06   UPSTREAM BULK TEMPERATURE = 23.98 DEG C   DOWNSTREAM BULK TEMPERATURE = 25.31 DEG C
PRM = 6.179   RAM+ = 0.56604E 07   INLET BULK TEMPERATURE = 23.98 DEG C   OUTLET BULK TEMPERATURE = 25.30 DEG C

STATION NO.	Z CM	WALL TEMPERATURE (DEG C) A	B	C	AVERAGE	TB (C)	RE	PR	RA+	Z+	NUSSELT NUMBER A	B	C	AVERAGE T	H	T+H
0	0.0	24.33	24.35	24.26	24.31	23.98	793.5	6.28	0.545E 07	0.00000	30.34	29.01	36.28	32.64	32.98	32.81
1	1.5	24.37	24.40	24.34	24.36	23.99	793.5	6.28	0.545E 07	0.00010	27.57	26.04	30.46	28.51	28.63	28.57
2	2.5	24.40	24.43	24.38	24.40	23.99	793.6	6.28	0.546E 07	0.00016	25.93	24.32	27.43	26.22	26.28	26.25
3	5.5	24.48	24.52	24.50	24.50	24.00	793.7	6.28	0.546E 07	0.00036	22.02	20.30	21.12	21.12	21.14	21.13
4	15.5	24.82	24.81	24.78	24.80	24.03	794.2	6.28	0.547E 07	0.00102	13.44	13.54	14.20	13.83	13.84	13.84
5	25.5	25.00	25.00	24.89	24.94	24.05	794.8	6.27	0.548E 07	0.00168	11.27	11.29	12.77	11.98	12.03	12.00
6	45.5	25.19	25.20	25.03	25.11	24.11	795.8	6.26	0.549E 07	0.00300	9.86	9.82	11.57	10.63	10.70	10.67
7	75.5	25.41	25.27	25.25	25.30	24.20	797.3	6.25	0.552E 07	0.00498	8.76	9.94	10.11	9.70	9.73	9.71
8	105.5	25.49	25.51	25.39	25.45	24.28	798.9	6.24	0.555E 07	0.00697	8.79	8.66	9.61	9.15	9.17	9.16
9	135.5	25.69	25.68	25.32	25.50	24.36	800.4	6.22	0.557E 07	0.00895	8.07	8.11	11.16	9.38	9.62	9.50
10	165.2	25.73	25.67	25.44	25.57	24.45	801.9	6.21	0.560E 07	0.01091	8.34	8.69	10.75	9.50	9.63	9.56
11	205.2	25.71	25.74	25.50	25.61	24.56	804.0	6.19	0.563E 07	0.01356	9.28	9.01	11.40	10.15	10.27	10.21
12	245.2	25.92	26.03	25.66	25.82	24.67	806.1	6.17	0.567E 07	0.01621	8.52	7.83	10.85	9.32	9.51	9.41
13	275.2	25.97	25.97	25.79	25.86	24.76	807.7	6.16	0.570E 07	0.01819	8.77	8.77	10.29	9.47	9.53	9.50
14	305.2	26.20	26.19	25.85	26.02	24.84	809.3	6.15	0.572E 07	0.02018	7.86	7.89	10.59	9.03	9.23	9.13
15	333.3	26.26	26.26	25.95	26.10	24.92	810.8	6.13	0.575E 07	0.02204	7.98	7.95	10.38	9.02	9.17	9.09
16	363.3	26.29	26.23	25.99	26.13	25.01	812.4	6.12	0.578E 07	0.02403	8.29	8.70	10.77	9.49	9.63	9.56
17	383.3	26.32	26.29	26.01	26.16	25.06	813.4	6.11	0.579E 07	0.02536	8.47	8.64	11.25	9.72	9.90	9.81
18	403.3	26.32	26.32	26.12	26.22	25.12	814.5	6.10	0.581E 07	0.02669	8.87	8.89	10.64	9.68	9.76	9.72
19	423.3	26.31	26.40	26.13	26.24	25.18	815.6	6.09	0.583E 07	0.02801	9.40	8.65	11.16	9.97	10.09	10.03
20	443.3	26.49	26.65	26.29	26.43	25.23	816.6	6.09	0.585E 07	0.02934	8.45	7.50	10.05	8.87	9.01	8.94
21	463.3	26.55	26.51	26.13	26.33	25.29	817.7	6.08	0.587E 07	0.03067	8.42	8.71	12.66	10.22	10.61	10.41
AVERAGE VALUES THROUGH STATIONS 15 TO 20:																
	391.6	26.33	26.36	26.08	26.21	25.09	813.9	6.11	0.580E 07	0.02591	8.57	8.39	10.71	9.46	9.59	9.53

========== EXPERIMENT 0R26 --- NOV. 30, 1987 ==========

INPUT ELECTRIC POWER = 267.8 W   HEAT RATE GAINED BY WATER = 255.8 W   HEAT BALANCE ERROR = 4.51%
MASS FLOW RATE = 22.7350 G/S   PRESSURE DROP = 0.3199 MM H2O   FRICTION FACTOR = 0.017726   FREM = 14.1984

REM = 801.0   GRM+ = 0.19277E 07   UPSTREAM BULK TEMPERATURE = 23.94 DEG C   DOWNSTREAM BULK TEMPERATURE = 26.64 DEG C
PRM = 6.077   RAM+ = 0.11714E 08   INLET BULK TEMPERATURE = 23.94 DEG C   OUTLET BULK TEMPERATURE = 26.64 DEG C

STATION NO.	Z CM	WALL TEMPERATURE (DEG C) A	B	C	AVERAGE	TB (C)	RE	PR	RA+	Z+	NUSSELT NUMBER A	B	C	AVERAGE T	H	T+H
0	0.0	24.75	24.76	24.68	24.72	23.94	776.5	6.29	0.109E 08	0.00000	26.45	25.94	29.13	27.58	27.66	27.62
1	1.5	24.87	24.89	24.82	24.85	23.95	776.6	6.29	0.109E 08	0.00010	23.29	22.75	24.62	23.79	23.82	23.81
2	2.5	24.95	24.97	24.92	24.94	23.96	776.7	6.29	0.109E 08	0.00017	21.53	20.97	22.24	21.73	21.74	21.74
3	5.5	25.19	25.23	25.21	25.21	23.98	777.0	6.28	0.109E 08	0.00037	17.53	16.98	17.25	17.25	17.25	17.25
4	15.5	25.76	25.72	25.60	25.67	24.03	778.1	6.28	0.109E 08	0.00104	12.35	12.64	13.60	13.02	13.05	13.03
5	25.5	25.99	26.02	25.73	25.87	24.09	779.1	6.27	0.110E 08	0.00172	11.22	11.03	12.95	11.97	12.04	12.00
6	45.5	26.29	26.27	25.99	26.14	24.21	781.1	6.25	0.110E 08	0.00307	10.21	10.31	11.89	11.02	11.08	11.05
7	75.5	26.60	26.45	26.24	26.38	24.38	784.2	6.22	0.111E 08	0.00509	9.58	10.28	11.45	10.63	10.69	10.66
8	105.5	26.76	26.74	26.48	26.61	24.55	787.3	6.19	0.112E 08	0.00712	9.63	9.70	11.04	10.30	10.35	10.33
9	135.5	26.99	26.95	26.42	26.69	24.72	790.5	6.17	0.113E 08	0.00914	9.39	9.53	12.54	10.78	11.00	10.89
10	165.2	27.04	27.02	26.63	26.83	24.89	793.6	6.14	0.115E 08	0.01115	9.88	9.97	12.21	10.95	11.06	11.01
11	205.2	27.20	27.21	26.76	26.98	25.12	797.8	6.10	0.116E 08	0.01386	10.20	10.19	12.97	11.42	11.58	11.50
12	245.2	27.57	27.71	27.11	27.38	25.35	802.1	6.07	0.118E 08	0.01657	9.57	9.00	12.05	10.48	10.67	10.57
13	275.2	27.71	27.69	27.22	27.46	25.52	805.4	6.04	0.119E 08	0.01861	9.69	9.82	12.54	10.97	11.15	11.06
14	305.2	27.96	27.96	27.52	27.74	25.70	808.7	6.01	0.120E 08	0.02065	9.35	9.38	11.64	10.38	10.50	10.44
15	333.3	28.14	28.09	27.54	27.83	25.86	811.8	5.99	0.121E 08	0.02256	9.30	9.49	12.60	10.76	10.99	10.88
16	363.3	28.22	28.16	27.57	27.88	26.03	815.1	5.96	0.122E 08	0.02460	9.70	9.97	13.75	11.47	11.79	11.63
17	383.3	28.28	28.26	27.72	28.00	26.14	817.4	5.94	0.123E 08	0.02596	9.92	9.99	13.46	11.45	11.71	11.58
18	403.3	28.41	28.36	27.88	28.13	26.26	819.6	5.92	0.124E 08	0.02733	9.86	10.06	13.08	11.31	11.52	11.41
19	423.3	28.39	28.42	27.95	28.18	26.37	821.9	5.91	0.124E 08	0.02869	10.51	10.34	13.46	11.75	11.94	11.85
20	443.3	28.72	28.89	28.22	28.51	26.49	824.2	5.89	0.125E 08	0.03006	9.49	8.82	12.26	10.48	10.71	10.59
21	463.3	28.69	28.65	28.09	28.38	26.60	826.4	5.87	0.126E 08	0.03142	10.17	10.32	14.23	11.91	12.23	12.07
AVERAGE VALUES THROUGH STATIONS 15 TO 20:																
	391.6	28.36	28.36	27.81	28.09	26.19	818.3	5.93	0.123E 08	0.02653	9.80	9.78	13.10	11.20	11.44	11.32

========== EXPERIMENT 0R27 --- DEC. 1, 1987 ==========

INPUT ELECTRIC POWER = 706.8 W   HEAT RATE GAINED BY WATER = 681.1 W   HEAT BALANCE ERROR = 3.63%
MASS FLOW RATE = 21.3920 G/S   PRESSURE DROP = 0.3071 MM H2O   FRICTION FACTOR = 0.019208   FREM = 15.2959

REM = 796.3   GRM+ = 0.61937E 07   UPSTREAM BULK TEMPERATURE = 23.91 DEG C   DOWNSTREAM BULK TEMPERATURE = 31.55 DEG C
PRM = 5.719   RAM+ = 0.35424E 08   INLET BULK TEMPERATURE = 23.92 DEG C   OUTLET BULK TEMPERATURE = 31.54 DEG C

STATION NO.	Z CM	WALL TEMPERATURE (DEG C) A	B	C	AVERAGE	TB (C)	RE	PR	RA+	Z+	NUSSELT NUMBER A	B	C	AVERAGE T	H	T+H
0	0.0	25.96	26.00	25.83	25.91	23.92	730.2	6.29	0.289E 08	0.00000	27.72	27.23	29.60	28.50	28.54	28.52
1	1.5	26.34	26.39	26.25	26.31	23.94	730.6	6.29	0.289E 08	0.00011	23.67	23.17	24.52	23.96	23.97	23.97
2	2.5	26.60	26.66	26.54	26.59	23.96	730.9	6.29	0.290E 08	0.00018	21.50	21.01	21.93	21.59	21.59	21.59
3	5.5	27.37	27.46	27.41	27.41	24.01	731.7	6.28	0.290E 08	0.00039	16.87	16.42	16.64	16.64	16.65	16.64
4	15.5	28.45	28.34	27.89	28.14	24.17	734.4	6.25	0.293E 08	0.00111	13.23	13.59	15.23	14.26	14.32	14.29
5	25.5	29.00	29.05	28.24	28.63	24.33	737.1	6.23	0.296E 08	0.00183	12.14	12.01	14.50	13.17	13.29	13.23
6	45.5	29.67	29.54	28.71	29.16	24.66	742.7	6.18	0.301E 08	0.00326	11.30	11.60	13.97	12.58	12.71	12.65
7	75.5	30.27	30.04	29.19	29.67	25.14	751.1	6.10	0.309E 08	0.00542	11.04	11.56	13.97	12.49	12.64	12.56
8	105.5	30.75	30.63	29.74	30.21	25.63	759.8	6.02	0.318E 08	0.00758	11.04	11.29	13.76	12.33	12.46	12.40
9	135.5	31.14	31.00	29.65	30.36	26.12	768.6	5.95	0.327E 08	0.00975	11.23	11.57	15.97	13.30	13.69	13.49
10	165.2	31.28	31.19	30.04	30.64	26.60	777.6	5.87	0.335E 08	0.01191	12.06	12.30	16.39	13.97	14.28	14.13
11	205.2	31.77	31.71	30.55	31.15	27.25	788.7	5.78	0.346E 08	0.01481	12.46	12.64	17.06	14.46	14.80	14.63
12	245.2	32.68	32.74	31.63	32.17	27.90	799.2	5.70	0.357E 08	0.01771	11.76	11.61	15.08	13.17	13.38	13.28
13	275.2	33.22	33.05	31.97	32.55	28.39	807.3	5.64	0.365E 08	0.01990	11.62	12.04	15.70	13.49	13.77	13.63
14	305.2	33.83	33.82	32.78	33.30	28.88	815.6	5.57	0.374E 08	0.02208	11.32	11.35	14.36	12.67	12.85	12.76
15	333.3	34.17	34.21	32.72	33.46	29.34	823.4	5.52	0.382E 08	0.02413	11.58	11.49	16.55	13.59	14.04	13.82
16	363.3	34.67	34.73	33.20	33.95	29.82	832.0	5.46	0.391E 08	0.02633	11.54	11.40	16.58	13.56	14.02	13.79
17	383.3	35.01	34.85	33.61	34.27	30.15	837.9	5.41	0.396E 08	0.02779	11.50	11.89	16.16	13.57	13.93	13.75
18	403.3	35.38	35.21	33.95	34.62	30.47	843.8	5.37	0.402E 08	0.02926	11.37	11.80	16.06	13.46	13.82	13.64
19	423.3	35.54	35.37	34.30	34.87	30.80	849.8	5.33	0.408E 08	0.03073	11.78	12.22	15.95	13.69	13.97	13.83
20	443.3	36.25	36.45	34.95	35.65	31.12	855.8	5.29	0.415E 08	0.03220	10.87	10.47	14.57	12.32	12.62	12.47
21	463.3	36.07	36.21	34.73	35.44	31.45	862.0	5.25	0.421E 08	0.03367	12.06	11.72	16.97	13.98	14.43	14.20
AVERAGE VALUES THROUGH STATIONS 15 TO 20:																
	391.6	35.17	35.14	33.79	34.47	30.28	840.5	5.40	0.399E 08	0.02841	11.44	11.54	15.98	13.36	13.73	13.55

========== EXPERIMENT 0R28 --- DEC. 1, 1987 ==========

INPUT ELECTRIC POWER = 1224.7 W   HEAT RATE GAINED BY WATER = 1172.3 W   HEAT BALANCE ERROR = 4.28%
MASS FLOW RATE = 20.0630 G/S   PRESSURE DROP = 0.2878 MM H2O   FRICTION FACTOR = 0.020438   FREM = 16.3450

REM = 799.7   GRM+ = 0.13326E 08   UPSTREAM BULK TEMPERATURE = 23.94 DEG C   DOWNSTREAM BULK TEMPERATURE = 37.96 DEG C
PRM = 5.313   RAM+ = 0.70798E 08   INLET BULK TEMPERATURE = 23.96 DEG C   OUTLET BULK TEMPERATURE = 37.95 DEG C

STATION NO.	Z CM	WALL TEMPERATURE (DEG C) A	B	C	AVERAGE	TB (C)	RE	PR	RA+	Z+	NUSSELT NUMBER A	B	C	AVERAGE T	H	T+H
0	0.0	27.44	27.47	27.21	27.33	23.97	685.6	6.29	0.498E 08	0.00000	28.10	27.82	30.10	28.99	29.03	29.01
1	1.5	28.08	28.13	27.92	28.01	24.01	686.2	6.28	0.500E 08	0.00011	23.96	23.67	24.92	24.36	24.37	24.36
2	2.5	28.53	28.58	28.42	28.49	24.04	686.7	6.27	0.501E 08	0.00019	21.75	21.46	22.28	21.94	21.94	21.94
3	5.5	29.86	29.94	29.90	29.90	24.13	688.1	6.26	0.503E 08	0.00042	17.03	16.77	16.90	16.90	16.90	16.90
4	15.5	31.41	31.19	30.24	30.77	24.43	692.8	6.21	0.512E 08	0.00118	13.97	14.42	16.77	15.37	15.48	15.43
5	25.5	32.18	32.28	30.52	31.38	24.72	697.6	6.17	0.520E 08	0.00195	13.06	12.89	16.81	14.65	14.89	14.77
6	45.5	33.07	32.92	31.20	32.10	25.32	707.4	6.07	0.538E 08	0.00348	12.56	12.80	16.55	14.36	14.61	14.48
7	75.5	34.05	33.74	32.18	33.04	26.22	722.5	5.93	0.565E 08	0.00580	12.39	12.91	16.29	14.24	14.47	14.35
8	105.5	34.94	34.72	33.31	34.07	27.11	737.5	5.80	0.592E 08	0.00812	12.38	12.73	15.62	13.92	14.09	14.00
9	135.5	35.69	35.44	33.14	34.35	28.01	751.1	5.68	0.618E 08	0.01044	12.58	13.01	18.83	15.23	15.81	15.52
10	165.2	35.99	35.85	34.02	34.97	28.89	765.1	5.57	0.644E 08	0.01275	13.60	13.86	18.82	15.88	16.28	16.08
11	205.2	37.18	36.99	35.08	36.08	30.05	784.7	5.42	0.680E 08	0.01586	13.55	13.93	19.28	16.05	16.51	16.28
12	245.2	38.73	38.64	36.92	37.80	31.28	805.4	5.27	0.718E 08	0.01900	12.89	13.04	17.01	14.71	14.99	14.85
13	275.2	39.34	39.09	37.26	38.24	32.17	820.8	5.16	0.747E 08	0.02136	13.35	13.84	18.83	15.79	16.22	16.00
14	305.2	40.43	40.41	38.56	39.49	33.07	835.3	5.06	0.773E 08	0.02376	12.99	13.02	17.41	14.89	15.21	15.05
15	333.3	41.05	41.11	38.58	39.83	33.91	849.3	4.96	0.797E 08	0.02602	13.34	13.23	20.39	16.09	16.84	16.46
16	363.3	42.43	42.55	40.12	41.30	34.80	864.9	4.86	0.825E 08	0.02845	12.48	12.28	17.89	14.63	15.13	14.88
17	383.3	42.82	42.59	40.50	41.61	35.40	875.5	4.79	0.843E 08	0.03008	12.79	13.21	18.60	15.30	15.80	15.55
18	403.3	43.52	43.20	41.05	42.20	35.99	886.4	4.72	0.862E 08	0.03171	12.61	13.16	18.77	15.27	15.82	15.55
19	423.3	43.72	43.35	41.43	42.48	36.59	897.6	4.65	0.882E 08	0.03336	13.28	14.01	19.56	16.07	16.60	16.33
20	443.3	44.89	45.17	42.43	43.73	37.19	908.2	4.59	0.901E 08	0.03499	12.28	11.84	18.05	14.46	15.06	14.76
21	463.3	44.58	44.93	42.41	43.56	37.78	918.4	4.53	0.920E 08	0.03660	13.90	13.22	20.41	16.29	16.98	16.63
AVERAGE VALUES THROUGH STATIONS 15 TO 20:																
	391.6	43.07	43.00	40.69	41.86	35.65	880.3	4.76	0.852E 08	0.03077	12.80	12.95	18.86	15.30	15.86	15.59

========== EXPERIMENT 0R29 --- DEC. 1, 1987 ==========

INPUT ELECTRIC POWER = 1750.5 W   HEAT RATE GAINED BY WATER = 1666.3 W   HEAT BALANCE ERROR = 4.81%
MASS FLOW RATE = 18.5620 G/S   PRESSURE DROP = 0.2702 MM H2O   FRICTION FACTOR = 0.022383   FREM = 17.8893

REM = 799.2   GRM+ = 0.24053E 08   UPSTREAM BULK TEMPERATURE = 23.97 DEG C   DOWNSTREAM BULK TEMPERATURE = 45.51 DEG C
PRM = 4.864   RAM+ = 0.11700E 09   INLET BULK TEMPERATURE = 24.00 DEG C   OUTLET BULK TEMPERATURE = 45.49 DEG C

STATION NO.	Z CM	WALL TEMPERATURE (DEG C) A	B	C	AVERAGE	TB (C)	RE	PR	RA+	Z+	NUSSELT NUMBER A	B	C	AVERAGE T	H	T+H
0	0.0	28.98	29.04	28.62	28.82	24.00	634.8	6.28	0.710E 08	0.00000	27.88	27.57	30.02	28.83	28.87	28.85
1	1.5	29.90	29.98	29.66	29.80	24.07	635.8	6.27	0.713E 08	0.00012	23.80	23.49	24.83	24.22	24.24	24.23
2	2.5	30.53	30.62	30.37	30.47	24.12	636.5	6.26	0.715E 08	0.00021	21.62	21.31	22.19	21.82	21.83	21.82
3	5.5	32.43	32.57	32.50	32.50	24.25	638.5	6.24	0.720E 08	0.00045	16.96	16.67	16.81	16.81	16.81	16.81
4	15.5	34.44	34.09	32.56	33.41	24.71	645.2	6.17	0.739E 08	0.00128	14.23	14.77	17.65	15.92	16.07	16.00
5	25.5	35.37	35.51	32.83	34.13	25.17	652.2	6.10	0.758E 08	0.00211	13.57	13.38	18.07	15.44	15.77	15.60
6	45.5	36.64	36.39	33.97	35.24	26.09	666.4	5.95	0.797E 08	0.00377	13.08	13.40	17.51	15.08	15.37	15.23
7	75.5	37.89	37.50	35.08	36.38	27.46	687.3	5.75	0.856E 08	0.00628	13.20	13.71	18.07	15.42	15.76	15.59
8	105.5	39.18	38.86	36.75	37.89	28.84	707.1	5.58	0.913E 08	0.00880	13.26	13.68	17.34	15.16	15.41	15.28
9	135.5	40.22	39.83	36.69	38.35	30.21	728.0	5.41	0.973E 08	0.01132	13.67	14.22	21.13	16.80	17.54	17.17
10	165.2	41.01	40.77	38.42	39.66	31.57	750.1	5.23	0.104E 09	0.01384	14.45	14.82	19.91	16.87	17.27	17.07
11	205.2	42.80	42.48	39.82	41.23	33.41	778.0	5.02	0.111E 09	0.01728	14.45	14.96	21.15	17.35	17.93	17.64
12	245.2	45.03	44.82	42.47	43.69	35.24	807.4	4.81	0.119E 09	0.02078	13.80	14.10	18.70	15.98	16.32	16.15
13	275.2	46.06	45.67	42.92	44.39	36.62	830.9	4.65	0.125E 09	0.02344	14.25	14.87	21.35	17.31	17.96	17.63
14	305.2	47.67	47.61	44.98	46.31	37.99	853.0	4.52	0.132E 09	0.02607	13.87	13.95	19.20	16.13	16.55	16.34
15	333.3	48.66	48.75	45.21	46.96	39.28	874.2	4.40	0.138E 09	0.02853	14.27	14.13	22.57	17.43	18.38	17.91
16	363.3	50.83	50.94	47.38	49.13	40.65	898.0	4.27	0.145E 09	0.03117	13.12	12.98	19.86	15.75	16.45	16.10
17	383.3	51.26	50.95	47.96	49.53	41.57	914.6	4.19	0.149E 09	0.03294	13.76	14.21	20.86	16.74	17.42	17.08
18	403.3	52.27	51.87	48.82	50.45	42.49	929.9	4.11	0.154E 09	0.03471	13.60	14.18	21.00	16.71	17.44	17.08
19	423.3	52.72	52.17	49.52	50.98	43.40	944.9	4.04	0.158E 09	0.03649	14.25	15.15	21.72	17.53	18.21	17.87
20	443.3	54.37	54.66	50.98	52.75	44.32	960.4	3.97	0.163E 09	0.03827	13.20	12.82	19.93	15.74	16.47	16.11
21	463.3	54.10	54.63	51.31	52.84	45.24	976.4	3.90	0.167E 09	0.04007	14.94	14.10	21.81	17.42	18.16	17.79
AVERAGE VALUES THROUGH STATIONS 15 TO 20:																
	391.6	51.69	51.56	48.31	49.97	41.95	920.3	4.16	0.151E 09	0.03368	13.70	13.91	20.99	16.65	17.40	17.02

========== EXPERIMENT 0R30 --- DEC. 1, 1987 ==========

INPUT ELECTRIC POWER = 138.2 W   HEAT RATE GAINED BY WATER = 128.5 W   HEAT BALANCE ERROR = 7.01%
MASS FLOW RATE = 25.6520 G/S   PRESSURE DROP = 0.3710 MM H2O   FRICTION FACTOR = 0.016150   FREM = 14.3950

REM = 891.3   GRM+ = 0.92278E 06   UPSTREAM BULK TEMPERATURE = 24.09 DEG C   DOWNSTREAM BULK TEMPERATURE = 25.30 DEG C
PRM = 6.171   RAM+ = 0.56940E 07   INLET BULK TEMPERATURE = 24.10 DEG C   OUTLET BULK TEMPERATURE = 25.29 DEG C

STATION NO.	Z CM	WALL TEMPERATURE (DEG C) A	B	C	AVERAGE	TB (C)	RE	PR	RA+	Z+	NUSSELT NUMBER A	B	C	AVERAGE T	H	T+H
0	0.0	24.46	24.46	24.43	24.45	24.10	879.2	6.27	0.551E 07	0.00000	29.50	29.11	32.04	30.61	30.67	30.64
1	1.5	24.50	24.51	24.48	24.49	24.10	879.2	6.26	0.551E 07	0.00009	26.54	26.10	27.88	27.08	27.10	27.09
2	2.5	24.53	24.54	24.52	24.53	24.10	879.3	6.26	0.551E 07	0.00015	24.82	24.35	25.59	25.08	25.09	25.09
3	5.5	24.62	24.64	24.63	24.63	24.11	879.4	6.26	0.551E 07	0.00033	20.78	20.29	20.53	20.53	20.54	20.54
4	15.5	24.99	24.98	24.95	24.97	24.14	879.9	6.26	0.552E 07	0.00093	12.50	12.61	13.17	12.85	12.86	12.86
5	25.5	25.14	25.17	25.09	25.12	24.16	880.5	6.25	0.553E 07	0.00152	10.90	10.60	11.55	11.13	11.15	11.14
6	45.5	25.39	25.37	25.23	25.30	24.21	881.5	6.25	0.554E 07	0.00272	9.08	9.26	10.50	9.79	9.83	9.81
7	75.5	25.53	25.38	25.39	25.42	24.29	883.0	6.23	0.557E 07	0.00451	8.64	9.80	9.70	9.43	9.46	9.45
8	105.5	25.61	25.62	25.56	25.59	24.37	884.6	6.22	0.559E 07	0.00630	8.62	8.50	8.94	8.75	8.75	8.75
9	135.5	25.80	25.82	25.49	25.65	24.44	886.2	6.21	0.561E 07	0.00810	7.88	7.76	10.21	8.85	9.01	8.93
10	165.2	25.81	25.79	25.61	25.70	24.52	887.7	6.20	0.564E 07	0.00988	8.27	8.42	9.78	9.01	9.06	9.04
11	205.2	25.85	25.88	25.64	25.75	24.62	889.8	6.18	0.567E 07	0.01227	8.69	8.46	10.52	9.44	9.55	9.49
12	245.2	25.98	26.15	25.71	25.89	24.72	891.9	6.17	0.570E 07	0.01467	8.49	7.51	10.79	9.17	9.39	9.28
13	275.2	26.03	26.03	25.82	25.92	24.80	893.5	6.15	0.573E 07	0.01646	8.69	8.69	10.45	9.49	9.57	9.53
14	305.2	26.17	26.16	25.82	25.99	24.88	895.1	6.14	0.575E 07	0.01826	8.26	8.29	11.31	9.56	9.79	9.68
15	333.3	26.26	26.26	25.98	26.12	24.95	896.6	6.13	0.578E 07	0.01995	8.16	8.14	10.39	9.13	9.27	9.20
16	363.3	26.38	26.31	26.05	26.20	25.02	898.2	6.12	0.580E 07	0.02175	7.90	8.28	10.40	9.10	9.24	9.17
17	383.3	26.43	26.41	26.09	26.26	25.08	899.2	6.11	0.582E 07	0.02295	7.86	8.01	10.49	9.04	9.21	9.13
18	403.3	26.43	26.40	26.20	26.31	25.13	900.3	6.10	0.583E 07	0.02415	8.18	8.38	9.91	9.02	9.09	9.06
19	423.3	26.36	26.46	26.16	26.28	25.18	901.4	6.09	0.585E 07	0.02535	9.00	8.31	10.90	9.64	9.78	9.71
20	443.3	26.52	26.71	26.32	26.47	25.23	902.5	6.09	0.587E 07	0.02655	8.27	7.22	9.79	8.62	8.77	8.70
21	463.3	26.58	26.57	26.30	26.44	25.28	903.6	6.08	0.588E 07	0.02775	8.21	8.30	10.45	9.22	9.35	9.28
AVERAGE VALUES THROUGH STATIONS 15 TO 20:																
	391.6	26.40	26.42	26.13	26.27	25.10	899.7	6.11	0.582E 07	0.02345	8.23	8.06	10.31	9.09	9.23	9.16

========== EXPERIMENT 0R31 --- DEC. 2, 1987 ==========

INPUT ELECTRIC POWER = 268.5 W HEAT RATE GAINED BY WATER = 256.0 W HEAT BALANCE ERROR = 4.63%
MASS FLOW RATE = 25.6950 G/S PRESSURE DROP = 0.3627 MM H2O FRICTION FACTOR = 0.016602 FREM = 15.0056

REM = 903.8 GRM+ = 0.19194E 07 UPSTREAM BULK TEMPERATURE = 24.03 DEG C DOWNSTREAM BULK TEMPERATURE = 26.42 DEG C
PRM = 6.087 RAM+ = 0.11684E 08 INLET BULK TEMPERATURE = 24.03 DEG C OUTLET BULK TEMPERATURE = 26.41 DEG C

STATION NO.	Z CM	-WALL TEMPERATURE (DEG C)- A	B	C	AVERAGE	TB (C)	RE	PR	RA+	Z+	NUSSELT NUMBER A	B	C	AVERAGE T	H	T+H
0	0.0	24.79	24.80	24.73	24.76	24.03	879.3	6.28	0.109E 08	0.00000	27.91	27.74	30.40	29.06	29.11	29.08
1	1.5	24.91	24.91	24.86	24.89	24.04	879.5	6.27	0.109E 08	0.00009	24.52	24.35	25.84	25.12	25.14	25.13
2	2.5	24.98	24.99	24.95	24.97	24.04	879.6	6.27	0.109E 08	0.00015	22.63	22.45	23.42	22.97	22.98	22.98
3	5.5	25.22	25.23	25.22	25.22	24.06	879.9	6.27	0.109E 08	0.00033	18.38	18.20	18.29	18.29	18.29	18.29
4	15.5	25.73	25.72	25.63	25.67	24.11	880.9	6.26	0.110E 08	0.00092	13.16	13.26	14.04	13.61	13.63	13.62
5	25.5	25.99	26.02	25.79	25.90	24.16	881.9	6.26	0.110E 08	0.00152	11.66	11.46	13.07	12.27	12.31	12.29
6	45.5	26.32	26.32	26.02	26.17	24.26	884.0	6.24	0.111E 08	0.00271	10.36	10.33	12.10	11.15	11.22	11.18
7	75.5	26.60	26.50	26.32	26.44	24.41	887.1	6.21	0.112E 08	0.00450	9.75	10.20	11.17	10.54	10.57	10.56
8	105.5	26.79	26.77	26.56	26.67	24.57	890.2	6.19	0.113E 08	0.00630	9.59	9.66	10.67	10.12	10.15	10.13
9	135.5	27.04	27.04	26.50	26.77	24.72	893.3	6.17	0.114E 08	0.00809	9.16	9.18	11.94	10.37	10.56	10.47
10	165.2	27.10	27.08	26.69	26.89	24.87	896.5	6.14	0.115E 08	0.00987	9.54	9.63	11.69	10.53	10.64	10.59
11	205.2	27.18	27.18	26.76	26.97	25.07	900.7	6.11	0.116E 08	0.01226	10.12	10.11	12.61	11.23	11.36	11.29
12	245.2	27.40	27.54	26.94	27.21	25.28	905.0	6.08	0.117E 08	0.01466	10.01	9.38	12.77	11.02	11.23	11.12
13	275.2	27.54	27.54	27.07	27.31	25.43	908.3	6.05	0.118E 08	0.01646	10.05	10.05	12.93	11.31	11.49	11.40
14	305.2	27.80	27.79	27.29	27.54	25.58	911.5	6.03	0.119E 08	0.01826	9.59	9.62	12.43	10.84	11.02	10.93
15	333.3	27.94	27.92	27.37	27.65	25.73	914.6	6.01	0.120E 08	0.01995	9.58	9.66	12.91	11.03	11.27	11.15
16	363.3	28.05	27.96	27.37	27.69	25.88	917.9	5.98	0.121E 08	0.02176	9.79	10.21	14.19	11.73	12.10	11.91
17	383.3	28.08	28.01	27.47	27.76	25.98	920.2	5.97	0.122E 08	0.02296	10.10	10.44	14.27	11.94	12.27	12.11
18	403.3	28.18	28.14	27.65	27.91	26.08	922.4	5.95	0.122E 08	0.02417	10.10	10.31	13.51	11.63	11.86	11.74
19	423.3	28.11	28.20	27.70	27.92	26.18	924.6	5.94	0.123E 08	0.02537	11.02	10.53	14.03	12.18	12.40	12.29
20	443.3	28.44	28.58	27.93	28.22	26.28	926.9	5.92	0.124E 08	0.02658	9.85	9.25	12.87	10.96	11.21	11.08
21	463.3	28.43	28.40	27.80	28.11	26.39	929.2	5.90	0.125E 08	0.02778	10.36	10.55	14.97	12.31	12.71	12.51
AVERAGE VALUES THROUGH STATIONS 15 TO 20:																
	391.6	28.13	28.13	27.58	27.86	26.02	921.1	5.96	0.122E 08	0.02347	10.07	10.07	13.63	11.58	11.85	11.71

========== EXPERIMENT 0R32 --- DEC. 2, 1987 ==========

INPUT ELECTRIC POWER = 720.1 W HEAT RATE GAINED BY WATER = 681.8 W HEAT BALANCE ERROR = 5.32%
MASS FLOW RATE = 24.5330 G/S PRESSURE DROP = 0.3650 MM H2O FRICTION FACTOR = 0.017361 FREM = 15.7105

REM = 904.9 GRM+ = 0.60095E 07 UPSTREAM BULK TEMPERATURE = 23.94 DEG C DOWNSTREAM BULK TEMPERATURE = 30.61 DEG C
PRM = 5.776 RAM+ = 0.34711E 08 INLET BULK TEMPERATURE = 23.95 DEG C OUTLET BULK TEMPERATURE = 30.60 DEG C

STATION NO.	Z CM	-WALL TEMPERATURE (DEG C)- A	B	C	AVERAGE	TB (C)	RE	PR	RA+	Z+	NUSSELT NUMBER A	B	C	AVERAGE T	H	T+H
0	0.0	25.85	25.88	25.73	25.80	23.95	838.1	6.29	0.290E 08	0.00000	29.99	29.42	31.90	30.76	30.80	30.78
1	1.5	26.21	26.26	26.14	26.18	23.97	838.5	6.28	0.290E 08	0.00009	25.43	24.86	26.27	25.69	25.71	25.70
2	2.5	26.45	26.52	26.41	26.45	23.99	838.8	6.28	0.290E 08	0.00016	23.02	22.46	23.42	23.07	23.08	23.07
3	5.5	27.20	27.29	27.24	27.24	24.03	839.6	6.28	0.291E 08	0.00034	17.92	17.41	17.66	17.66	17.66	17.66
4	15.5	28.37	28.25	27.83	28.07	24.17	842.3	6.25	0.293E 08	0.00097	13.52	13.90	15.50	14.55	14.60	14.58
5	25.5	28.94	28.97	28.15	28.55	24.32	845.0	6.23	0.296E 08	0.00159	12.25	12.19	14.77	13.38	13.50	13.44
6	45.5	29.53	29.45	28.65	29.07	24.60	850.6	6.19	0.300E 08	0.00284	11.50	11.67	13.98	12.67	12.78	12.73
7	75.5	30.15	29.92	29.11	29.57	25.02	859.0	6.12	0.308E 08	0.00473	11.04	11.56	13.87	12.45	12.58	12.51
8	105.5	30.61	30.49	29.68	30.12	25.45	867.6	6.05	0.315E 08	0.00661	10.96	11.21	13.37	12.12	12.23	12.18
9	135.5	30.94	30.86	29.51	30.21	25.88	876.4	5.98	0.323E 08	0.00850	11.15	11.34	15.54	13.05	13.39	13.22
10	165.2	31.14	31.02	29.93	30.50	26.30	885.2	5.92	0.330E 08	0.01037	11.66	11.96	15.55	13.42	13.68	13.55
11	205.2	31.49	31.40	30.19	30.82	26.86	897.4	5.83	0.340E 08	0.01291	12.19	12.44	16.97	14.27	14.64	14.46
12	245.2	32.28	32.29	31.17	31.73	27.43	907.8	5.76	0.350E 08	0.01543	11.61	11.58	15.05	13.10	13.32	13.21
13	275.2	32.57	32.41	31.31	31.90	27.86	915.7	5.70	0.357E 08	0.01733	11.93	12.37	16.28	13.91	14.21	14.06
14	305.2	33.27	33.26	32.19	32.73	28.28	923.8	5.65	0.364E 08	0.01924	11.27	11.30	14.39	12.65	12.84	12.74
15	333.3	33.53	33.56	32.06	32.80	28.68	931.5	5.60	0.371E 08	0.02102	11.58	11.51	16.59	13.62	14.07	13.84
16	363.3	34.22	34.28	32.80	33.53	29.11	939.8	5.55	0.378E 08	0.02293	10.98	10.85	15.17	12.70	13.04	12.87
17	383.3	34.44	34.29	33.02	33.69	29.39	945.5	5.51	0.383E 08	0.02420	11.09	11.45	15.45	13.03	13.36	13.20
18	403.3	34.73	34.56	33.33	33.99	29.67	951.2	5.47	0.388E 08	0.02548	11.07	11.46	15.33	12.99	13.30	13.14
19	423.3	34.75	34.64	33.51	34.10	29.96	957.0	5.44	0.393E 08	0.02675	11.69	11.96	15.74	13.50	13.78	13.64
20	443.3	35.52	35.71	34.19	34.90	30.24	962.8	5.40	0.399E 08	0.02803	10.60	10.22	14.18	12.00	12.29	12.15
21	463.3	35.26	35.38	33.98	34.65	30.53	968.8	5.37	0.404E 08	0.02931	11.82	11.53	16.18	13.56	13.92	13.74
AVERAGE VALUES THROUGH STATIONS 15 TO 20:																
	391.6	34.53	34.51	33.15	33.84	29.51	948.0	5.49	0.385E 08	0.02474	11.17	11.24	15.41	12.97	13.31	13.14

========== EXPERIMENT 0R33 --- DEC. 2, 1987 ==========

INPUT ELECTRIC POWER = 1265.5 W HEAT RATE GAINED BY WATER = 1206.4 W HEAT BALANCE ERROR = 4.67%
MASS FLOW RATE = 23.0520 G/S PRESSURE DROP = 0.3262 MM H2O FRICTION FACTOR = 0.017553 FREM = 15.8627

REM = 903.7 GRM+ = 0.13007E 08 UPSTREAM BULK TEMPERATURE = 23.91 DEG C DOWNSTREAM BULK TEMPERATURE = 36.47 DEG C
PRM = 5.409 RAM+ = 0.70356E 08 INLET BULK TEMPERATURE = 23.93 DEG C OUTLET BULK TEMPERATURE = 36.45 DEG C

STATION NO.	Z CM	-WALL TEMPERATURE (DEG C)- A	B	C	AVERAGE	TB (C)	RE	PR	RA+	Z+	NUSSELT NUMBER A	B	C	AVERAGE T	H	T+H
0	0.0	27.38	27.44	27.14	27.28	23.93	787.1	6.29	0.512E 08	0.00000	29.14	28.58	31.24	30.00	30.05	30.03
1	1.5	28.03	28.12	27.88	27.98	23.97	787.8	6.29	0.513E 08	0.00010	24.74	24.16	25.67	25.04	25.06	25.05
2	2.5	28.48	28.59	28.39	28.46	24.00	788.2	6.28	0.514E 08	0.00017	22.40	21.84	22.85	22.48	22.49	22.48
3	5.5	29.83	30.00	29.91	29.91	24.08	789.7	6.27	0.516E 08	0.00037	17.45	16.95	17.20	17.20	17.20	17.20
4	15.5	31.49	31.27	30.38	30.88	24.34	794.5	6.23	0.524E 08	0.00103	14.04	14.48	16.62	15.35	15.44	15.39
5	25.5	32.35	32.48	30.86	31.64	24.61	799.4	6.18	0.532E 08	0.00170	12.95	12.74	16.05	14.27	14.45	14.36
6	45.5	33.32	33.15	31.48	32.36	25.14	809.4	6.10	0.548E 08	0.00303	12.25	12.51	15.80	13.88	14.09	13.99
7	75.5	34.30	33.91	32.32	33.21	25.95	824.8	5.97	0.573E 08	0.00504	11.96	12.56	15.69	13.76	13.97	13.87
8	105.5	35.11	34.86	33.37	34.18	26.75	840.9	5.85	0.598E 08	0.00706	11.94	12.30	15.06	13.43	13.59	13.51
9	135.5	35.58	35.30	33.03	34.23	27.55	855.0	5.74	0.622E 08	0.00908	12.40	12.85	18.18	14.90	15.40	15.15
10	165.2	35.76	35.60	33.68	34.68	28.34	869.1	5.64	0.646E 08	0.01108	13.40	13.70	18.64	15.69	16.09	15.89
11	205.2	36.82	36.60	34.65	35.68	29.41	888.8	5.51	0.679E 08	0.01379	13.39	13.80	18.92	15.82	16.25	16.04
12	245.2	38.19	38.05	36.32	37.22	30.48	909.4	5.37	0.713E 08	0.01651	12.84	13.07	16.95	14.68	14.95	14.82
13	275.2	38.73	38.45	36.49	37.54	31.28	925.5	5.27	0.739E 08	0.01855	13.27	13.79	18.96	15.79	16.24	16.01
14	305.2	39.67	39.65	37.91	38.78	32.08	941.5	5.17	0.766E 08	0.02061	13.00	13.03	16.93	14.71	14.97	14.84
15	333.3	40.24	40.30	37.78	39.03	32.83	955.3	5.09	0.788E 08	0.02256	13.29	13.18	19.87	15.89	16.55	16.22
16	363.3	41.66	41.76	39.19	40.45	33.64	970.6	4.99	0.812E 08	0.02466	12.23	12.09	17.67	14.41	14.92	14.66
17	383.3	42.03	41.83	39.58	40.75	34.17	981.0	4.93	0.829E 08	0.02606	12.48	12.80	18.13	14.89	15.38	15.14
18	403.3	42.67	42.33	40.17	41.34	34.70	991.7	4.87	0.846E 08	0.02747	12.29	12.83	17.92	14.77	15.24	15.00
19	423.3	42.74	42.37	40.43	41.49	35.24	1002.6	4.81	0.863E 08	0.02889	13.04	13.71	18.85	15.64	16.11	15.88
20	443.3	43.84	44.07	41.29	42.63	35.77	1013.8	4.75	0.880E 08	0.03031	12.10	11.77	17.69	14.25	14.81	14.53
21	463.3	43.51	43.81	41.37	42.52	36.31	1025.2	4.68	0.898E 08	0.03174	13.53	12.99	19.25	15.70	16.25	15.98
AVERAGE VALUES THROUGH STATIONS 15 TO 20:																
	391.6	42.20	42.11	39.74	40.95	34.39	985.9	4.91	0.836E 08	0.02666	12.57	12.73	18.35	14.97	15.50	15.24

========== EXPERIMENT 0R34 --- DEC. 3, 1987 ==========

INPUT ELECTRIC POWER = 1828.0 W   HEAT RATE GAINED BY WATER = 1758.7 W   HEAT BALANCE ERROR = 3.79%
MASS FLOW RATE = 21.3190 G/S   PRESSURE DROP = 0.3083 MM H2O   FRICTION FACTOR = 0.019367   FREM = 17.4637

REM = 901.7   GRM+ = 0.24048E 08   UPSTREAM BULK TEMPERATURE = 23.96 DEG C   DOWNSTREAM BULK TEMPERATURE = 43.75 DEG C
PRM = 4.967   RAM+ = 0.11944E 09   INLET BULK TEMPERATURE = 23.99 DEG C   OUTLET BULK TEMPERATURE = 43.73 DEG C

STA-	Z	-WALL TEMPERATURE (DEG C)-				TB	RE	PR	RA+	Z+	NUSSELT NUMBER					
TION	CM	A	B	C	AVER-	(C)					A	B	C	----- AVERAGE -----		
NO.					AGE									T	H	T+H
0	0.0	29.07	29.12	28.70	28.90	23.99	728.9	6.28	0.749E 08	0.00000	28.83	28.52	31.11	29.84	29.89	29.87
1	1.5	30.00	30.08	29.75	29.89	24.05	729.9	6.27	0.752E 08	0.00011	24.61	24.29	25.71	25.06	25.08	25.07
2	2.5	30.64	30.74	30.47	30.58	24.09	730.6	6.27	0.753E 08	0.00018	22.35	22.03	22.96	22.57	22.57	22.57
3	5.5	32.57	32.71	32.64	32.64	24.22	732.7	6.25	0.759E 08	0.00040	17.52	17.23	17.38	17.38	17.38	17.38
4	15.5	34.59	34.20	32.70	33.55	24.64	739.9	6.18	0.777E 08	0.00112	14.70	15.29	18.14	16.41	16.57	16.49
5	25.5	35.51	35.65	33.00	34.29	25.06	747.1	6.11	0.795E 08	0.00184	13.98	13.79	18.41	15.83	16.15	15.99
6	45.5	36.73	36.47	33.97	35.29	25.91	762.1	5.98	0.833E 08	0.00328	13.47	13.79	18.07	15.54	15.85	15.69
7	75.5	38.00	37.61	35.08	36.44	27.17	784.6	5.79	0.891E 08	0.00547	13.42	13.92	18.38	15.67	16.02	15.85
8	105.5	39.24	38.92	36.80	37.94	28.43	805.2	5.63	0.945E 08	0.00765	13.41	13.82	17.31	15.24	15.46	15.35
9	135.5	40.19	39.80	36.57	38.28	29.70	827.0	5.47	0.100E 09	0.00985	13.77	14.30	21.01	16.83	17.52	17.17
10	165.2	40.81	40.60	38.17	39.44	30.95	849.6	5.31	0.106E 09	0.01204	14.61	14.92	19.96	16.97	17.36	17.17
11	205.2	42.51	42.17	39.29	40.82	32.63	880.0	5.11	0.114E 09	0.01501	14.52	15.05	21.55	17.53	18.17	17.85
12	245.2	44.55	44.31	41.95	43.19	34.32	910.0	4.91	0.122E 09	0.01804	13.97	14.29	18.72	16.10	16.42	16.26
13	275.2	45.47	45.08	42.27	43.77	35.56	933.8	4.77	0.127E 09	0.02033	14.40	15.00	21.30	17.39	18.00	17.70
14	305.2	46.97	46.91	44.16	45.55	36.84	959.0	4.62	0.134E 09	0.02266	14.03	14.10	19.40	16.31	16.73	16.52
15	333.3	47.82	47.88	44.16	46.00	38.03	980.3	4.51	0.139E 09	0.02479	14.46	14.38	23.10	17.76	18.76	18.26
16	363.3	49.87	50.06	46.37	48.17	39.29	1004.2	4.40	0.146E 09	0.02707	13.35	13.12	19.97	15.92	16.60	16.26
17	383.3	50.35	49.96	46.78	48.47	40.13	1020.8	4.32	0.150E 09	0.02860	13.81	14.35	21.21	16.92	17.64	17.28
18	403.3	51.23	50.81	47.46	49.24	40.98	1037.9	4.24	0.154E 09	0.03014	13.74	14.33	21.71	17.04	17.87	17.46
19	423.3	51.51	50.94	48.06	49.65	41.82	1055.7	4.16	0.159E 09	0.03168	14.50	15.41	22.51	17.96	18.74	18.35
20	443.3	53.10	53.39	49.56	51.40	42.66	1071.2	4.10	0.163E 09	0.03323	13.45	13.09	20.35	16.06	16.81	16.44
21	463.3	52.75	53.23	49.80	51.40	43.50	1087.1	4.03	0.168E 09	0.03478	15.15	14.42	22.24	17.76	18.51	18.13
AVERAGE VALUES THROUGH STATIONS 15 TO 20:																
	391.6	50.65	50.51	47.07	48.82	40.48	1028.4	4.29	0.152E 09	0.02925	13.89	14.11	21.48	16.94	17.74	17.34

========== EXPERIMENT 0R35 --- DEC. 3, 1987 ==========

INPUT ELECTRIC POWER = 136.6 W   HEAT RATE GAINED BY WATER = 128.7 W   HEAT BALANCE ERROR = 7.14%
MASS FLOW RATE = 28.9370 G/S   PRESSURE DROP = 0.4112 MM H2O   FRICTION FACTOR = 0.014067   FREM = 14.0646

REM = 999.8   GRM+ = 0.90592E 06   UPSTREAM BULK TEMPERATURE = 23.92 DEG C   DOWNSTREAM BULK TEMPERATURE = 24.98 DEG C
PRM = 6.209   RAM+ = 0.56251E 07   INLET BULK TEMPERATURE = 23.92 DEG C   OUTLET BULK TEMPERATURE = 24.98 DEG C

STA-	Z	-WALL TEMPERATURE (DEG C)-				TB	RE	PR	RA+	Z+	NUSSELT NUMBER					
TION	CM	A	B	C	AVER-	(C)					A	B	C	----- AVERAGE -----		
NO.					AGE									T	H	T+H
0	0.0	24.28	24.28	24.25	24.27	23.92	987.7	6.29	0.546E 07	0.00000	29.71	29.31	32.32	30.85	30.91	30.88
1	1.5	24.32	24.32	24.30	24.31	23.92	987.8	6.29	0.546E 07	0.00008	27.01	26.54	28.42	27.57	27.60	27.58
2	2.5	24.34	24.35	24.33	24.34	23.92	987.9	6.29	0.546E 07	0.00013	25.42	24.91	26.23	25.69	25.70	25.69
3	5.5	24.43	24.44	24.43	24.43	23.93	988.0	6.29	0.546E 07	0.00029	21.59	21.05	21.32	21.32	21.32	21.32
4	15.5	24.76	24.76	24.75	24.76	23.95	988.5	6.29	0.547E 07	0.00082	13.22	13.31	13.45	13.35	13.36	13.36
5	25.5	24.94	24.97	24.89	24.92	23.98	989.0	6.28	0.548E 07	0.00135	11.06	10.76	11.72	11.30	11.31	11.31
6	45.5	25.14	25.14	25.03	25.09	24.02	990.0	6.28	0.549E 07	0.00241	9.60	9.57	10.59	10.06	10.09	10.07
7	75.5	25.30	25.21	25.22	25.24	24.09	991.6	6.27	0.551E 07	0.00400	8.85	9.54	9.46	9.32	9.32	9.32
8	105.5	25.41	25.40	25.33	25.37	24.16	993.1	6.26	0.553E 07	0.00559	8.56	8.62	9.12	8.85	8.86	8.85
9	135.5	25.54	25.59	25.26	25.42	24.23	994.7	6.24	0.555E 07	0.00718	8.12	7.83	10.31	8.99	9.14	9.07
10	165.2	25.59	25.56	25.35	25.46	24.29	996.2	6.23	0.558E 07	0.00875	8.28	8.43	10.08	9.14	9.22	9.18
11	205.2	25.62	25.63	25.38	25.51	24.38	998.3	6.22	0.560E 07	0.01087	8.63	8.58	10.71	9.54	9.66	9.60
12	245.2	25.81	25.98	25.51	25.70	24.47	1000.4	6.21	0.563E 07	0.01299	8.01	7.12	10.31	8.71	8.94	8.82
13	275.2	25.86	25.86	25.62	25.74	24.54	1001.9	6.19	0.565E 07	0.01459	8.13	8.13	9.91	8.93	9.02	8.97
14	305.2	25.94	25.94	25.65	25.80	24.61	1003.5	6.18	0.568E 07	0.01618	8.02	8.05	10.29	9.03	9.17	9.10
15	333.3	26.00	26.01	25.72	25.86	24.67	1005.0	6.17	0.570E 07	0.01767	8.05	8.03	10.23	9.01	9.14	9.07
16	363.3	26.12	26.06	25.77	25.93	24.74	1006.6	6.16	0.572E 07	0.01926	7.76	8.12	10.41	9.01	9.18	9.09
17	383.3	26.09	26.07	25.76	25.93	24.79	1007.6	6.16	0.573E 07	0.02033	8.20	8.34	10.73	9.34	9.50	9.42
18	403.3	26.09	26.06	25.83	25.96	24.83	1008.7	6.15	0.575E 07	0.02139	8.49	8.69	10.68	9.52	9.63	9.58
19	423.3	26.03	26.10	25.79	25.93	24.88	1009.8	6.14	0.576E 07	0.02245	9.32	8.78	11.70	10.20	10.37	10.28
20	443.3	26.18	26.31	25.92	26.08	24.92	1010.8	6.13	0.578E 07	0.02352	8.51	7.71	10.71	9.22	9.41	9.31
21	463.3	26.19	26.14	25.84	26.00	24.97	1011.9	6.13	0.579E 07	0.02458	8.78	9.16	12.29	10.37	10.63	10.50
AVERAGE VALUES THROUGH STATIONS 15 TO 20:																
	391.6	26.09	26.10	25.80	25.95	24.81	1008.1	6.15	0.574E 07	0.02077	8.39	8.28	10.74	9.38	9.54	9.46

========== EXPERIMENT 0R36 --- DEC. 3, 1987 ==========

INPUT ELECTRIC POWER = 272.6 W   HEAT RATE GAINED BY WATER = 262.2 W   HEAT BALANCE ERROR = 3.82%
MASS FLOW RATE = 28.5400 G/S   PRESSURE DROP = 0.4110 MM H2O   FRICTION FACTOR = 0.014453   FREM = 14.4342

REM = 998.7   GRM+ = 0.19300E 07   UPSTREAM BULK TEMPERATURE = 23.90 DEG C   DOWNSTREAM BULK TEMPERATURE = 26.10 DEG C
PRM = 6.122   RAM+ = 0.11816E 08   INLET BULK TEMPERATURE = 23.90 DEG C   OUTLET BULK TEMPERATURE = 26.10 DEG C

STA-	Z	-WALL TEMPERATURE (DEG C)-				TB	RE	PR	RA+	Z+	NUSSELT NUMBER					
TION	CM	A	B	C	AVER-	(C)					A	B	C	----- AVERAGE -----		
NO.					AGE									T	H	T+H
0	0.0	24.65	24.66	24.59	24.62	23.90	973.8	6.30	0.111E 08	0.00000	29.23	28.63	31.67	30.24	30.30	30.27
1	1.5	24.77	24.79	24.73	24.76	23.91	974.0	6.29	0.111E 08	0.00008	25.34	24.70	26.47	25.72	25.74	25.73
2	2.5	24.85	24.88	24.83	24.85	23.91	974.1	6.29	0.111E 08	0.00013	23.20	22.57	23.78	23.32	23.33	23.33
3	5.5	25.11	25.14	25.13	25.13	23.93	974.4	6.29	0.111E 08	0.00030	18.52	17.92	18.22	18.22	18.22	18.22
4	15.5	25.64	25.63	25.57	25.60	23.97	975.4	6.28	0.112E 08	0.00083	13.07	13.16	13.67	13.39	13.39	13.39
5	25.5	25.93	26.02	25.73	25.85	24.02	976.5	6.28	0.112E 08	0.00137	11.43	10.92	12.74	11.90	11.95	11.93
6	45.5	26.26	26.27	25.94	26.10	24.11	978.5	6.26	0.112E 08	0.00244	10.16	10.13	11.96	10.98	11.05	11.02
7	75.5	26.54	26.39	26.24	26.35	24.26	981.7	6.24	0.113E 08	0.00405	9.54	10.22	11.01	10.41	10.44	10.43
8	105.5	26.70	26.69	26.45	26.57	24.40	984.9	6.22	0.114E 08	0.00567	9.46	9.52	10.63	10.02	10.06	10.04
9	135.5	26.90	26.90	26.33	26.62	24.54	988.1	6.20	0.115E 08	0.00728	9.22	9.24	12.13	10.48	10.68	10.58
10	165.2	26.96	26.86	26.55	26.73	24.68	991.2	6.17	0.116E 08	0.00888	9.54	9.99	11.64	10.62	10.70	10.66
11	205.2	27.03	27.04	26.59	26.81	24.86	995.5	6.14	0.117E 08	0.01104	10.03	10.02	12.60	11.17	11.31	11.24
12	245.2	27.29	27.40	26.77	27.06	25.05	999.9	6.11	0.118E 08	0.01319	9.74	9.26	12.66	10.85	11.08	10.96
13	275.2	27.32	27.26	26.82	27.05	25.19	1003.2	6.09	0.119E 08	0.01481	10.22	10.50	13.39	11.68	11.87	11.78
14	305.2	27.49	27.48	27.01	27.25	25.33	1006.5	6.07	0.120E 08	0.01643	10.09	10.12	12.98	11.36	11.54	11.45
15	333.3	27.66	27.67	27.17	27.42	25.46	1009.6	6.05	0.121E 08	0.01795	9.90	9.86	12.74	11.13	11.31	11.22
16	363.3	27.85	27.79	27.20	27.51	25.60	1013.0	6.03	0.122E 08	0.01958	9.69	9.96	13.59	11.40	11.71	11.56
17	383.3	27.91	27.87	27.30	27.59	25.70	1015.2	6.01	0.123E 08	0.02066	9.83	10.01	13.58	11.46	11.75	11.61
18	403.3	28.01	28.00	27.48	27.74	25.79	1017.5	6.00	0.123E 08	0.02174	9.78	9.84	12.87	11.14	11.34	11.24
19	423.3	27.94	28.00	27.50	27.73	25.89	1019.7	5.98	0.124E 08	0.02282	10.58	10.27	13.46	11.75	11.94	11.85
20	443.3	28.30	28.46	27.76	28.07	25.98	1022.0	5.97	0.125E 08	0.02391	9.37	8.75	12.18	10.39	10.62	10.50
21	463.3	28.18	28.17	27.63	27.90	26.07	1024.3	5.95	0.125E 08	0.02499	10.31	10.37	13.95	11.88	12.15	12.01
AVERAGE VALUES THROUGH STATIONS 15 TO 20:																
	391.6	27.94	27.97	27.40	27.68	25.74	1016.2	6.01	0.123E 08	0.02111	9.86	9.78	13.07	11.21	11.45	11.33

========== EXPERIMENT 0R37 --- DEC. 5, 1987 ==========

INPUT ELECTRIC POWER = 732.6 W　HEAT RATE GAINED BY WATER = 689.5 W　HEAT BALANCE ERROR = 5.89%
MASS FLOW RATE = 27.2400 G/S　PRESSURE DROP = 0.3950 MM H2O　FRICTION FACTOR = 0.015242　FREM = 15.1839

REM = 996.2　GRM+ = 0.59010E 07　UPSTREAM BULK TEMPERATURE = 23.82 DEG C　DOWNSTREAM BULK TEMPERATURE = 29.89 DEG C
PRM = 5.830　RAM+ = 0.34400E 08　INLET BULK TEMPERATURE = 23.83 DEG C　OUTLET BULK TEMPERATURE = 29.88 DEG C

STATION NO.	Z CM	-WALL TEMPERATURE (DEG C)- A	B	C	AVERAGE	TB (C)	RE	PR	RA+	Z+	NUSSELT NUMBER A	B	C	AVERAGE T	H	T+H
0	0.0	25.81	25.85	25.68	25.76	23.83	927.9	6.31	0.291E 08	0.00000	28.89	28.37	30.93	29.73	29.78	29.76
1	1.5	26.18	26.23	26.10	26.15	23.84	928.3	6.30	0.291E 08	0.00008	24.57	24.04	25.48	24.88	24.89	24.88
2	2.5	26.44	26.50	26.38	26.43	23.86	928.5	6.30	0.291E 08	0.00014	22.27	21.75	22.72	22.36	22.36	22.36
3	5.5	27.20	27.29	27.24	27.24	23.90	929.3	6.30	0.292E 08	0.00031	17.39	16.91	17.15	17.15	17.15	17.15
4	15.5	28.40	28.25	27.89	28.11	24.03	932.1	6.28	0.294E 08	0.00087	13.13	13.57	14.85	14.06	14.10	14.08
5	25.5	28.94	28.99	28.18	28.56	24.15	934.6	6.26	0.296E 08	0.00143	11.98	11.85	14.24	12.97	13.08	13.03
6	45.5	29.53	29.48	28.65	29.08	24.41	940.4	6.22	0.301E 08	0.00256	11.22	11.31	13.52	12.29	12.39	12.34
7	75.5	30.15	29.92	29.14	29.59	24.80	948.8	6.15	0.307E 08	0.00425	10.70	11.18	13.21	11.97	12.08	12.02
8	105.5	30.61	30.47	29.68	30.11	25.19	957.4	6.09	0.314E 08	0.00595	10.56	10.84	12.74	11.63	11.72	11.68
9	135.5	30.94	30.83	29.46	30.17	25.58	966.2	6.03	0.321E 08	0.00765	10.65	10.89	14.74	12.44	12.75	12.60
10	165.2	31.05	30.90	29.93	30.45	25.96	975.0	5.97	0.328E 08	0.00933	11.22	11.55	14.40	12.71	12.89	12.80
11	205.2	31.29	31.23	29.93	30.60	26.48	987.2	5.89	0.337E 08	0.01161	11.85	12.01	16.50	13.85	14.22	14.03
12	245.2	31.97	31.99	30.83	31.40	26.99	999.0	5.81	0.346E 08	0.01389	11.45	11.41	14.86	12.92	13.14	13.03
13	275.2	32.24	32.04	30.91	31.53	27.38	1006.9	5.76	0.353E 08	0.01560	11.73	12.22	16.12	13.74	14.05	13.89
14	305.2	32.74	32.75	31.59	32.17	27.77	1014.9	5.71	0.359E 08	0.01731	11.45	11.41	14.87	12.93	13.15	13.04
15	333.3	33.05	33.08	31.61	32.34	28.13	1022.5	5.67	0.365E 08	0.01892	11.56	11.49	16.34	13.52	13.93	13.72
16	363.3	33.76	33.85	32.38	33.09	28.52	1030.7	5.62	0.372E 08	0.02063	10.83	10.65	14.70	12.41	12.72	12.57
17	383.3	34.07	33.95	32.71	33.36	28.78	1036.3	5.59	0.377E 08	0.02178	10.72	10.97	14.44	12.38	12.64	12.51
18	403.3	34.40	34.23	32.93	33.62	29.04	1041.9	5.55	0.381E 08	0.02292	10.58	10.93	14.57	12.37	12.66	12.52
19	423.3	34.24	34.14	32.96	33.57	29.29	1047.6	5.52	0.386E 08	0.02407	11.46	11.71	15.49	13.26	13.54	13.40
20	443.3	34.90	35.12	33.54	34.27	29.55	1053.4	5.49	0.390E 08	0.02522	10.60	10.18	14.22	12.00	12.31	12.15
21	463.3	34.67	34.78	33.29	34.01	29.81	1059.2	5.46	0.395E 08	0.02637	11.66	11.41	16.28	13.50	13.91	13.71
AVERAGE VALUES THROUGH STATIONS 15 TO 20:																
	391.6	34.07	34.06	32.69	33.38	28.86	1038.7	5.57	0.379E 08	0.02226	10.96	10.99	14.96	12.66	12.97	12.81

========== EXPERIMENT 0R38 --- DEC. 5, 1987 ==========

INPUT ELECTRIC POWER = 1292.5 W　HEAT RATE GAINED BY WATER = 1223.4 W　HEAT BALANCE ERROR = 5.35%
MASS FLOW RATE = 25.8320 G/S　PRESSURE DROP = 0.3863 MM H2O　FRICTION FACTOR = 0.016557　FREM = 16.5529

REM = 999.7　GRM+ = 0.12653E 08　UPSTREAM BULK TEMPERATURE = 23.91 DEG C　DOWNSTREAM BULK TEMPERATURE = 35.27 DEG C
PRM = 5.485　RAM+ = 0.69398E 08　INLET BULK TEMPERATURE = 23.92 DEG C　OUTLET BULK TEMPERATURE = 35.26 DEG C

STATION NO.	Z CM	-WALL TEMPERATURE (DEG C)- A	B	C	AVERAGE	TB (C)	RE	PR	RA+	Z+	NUSSELT NUMBER A	B	C	AVERAGE T	H	T+H
0	0.0	27.36	27.42	27.16	27.27	23.92	881.9	6.29	0.519E 08	0.00000	29.65	29.16	31.51	30.42	30.46	30.44
1	1.5	28.02	28.10	27.89	27.97	23.96	882.6	6.29	0.520E 08	0.00009	25.10	24.61	25.93	25.38	25.40	25.39
2	2.5	28.47	28.57	28.39	28.45	23.98	883.1	6.28	0.521E 08	0.00015	22.70	22.22	23.11	22.78	22.79	22.78
3	5.5	29.83	29.97	29.90	29.90	24.06	884.5	6.27	0.523E 08	0.00033	17.64	17.21	17.42	17.42	17.42	17.42
4	15.5	31.55	31.30	30.44	30.93	24.30	889.4	6.23	0.530E 08	0.00092	14.03	14.53	16.58	15.34	15.43	15.39
5	25.5	32.35	32.51	30.86	31.64	24.54	894.4	6.20	0.537E 08	0.00151	13.02	12.76	16.10	14.32	14.49	14.41
6	45.5	33.35	33.15	31.60	32.42	25.02	904.4	6.12	0.552E 08	0.00270	12.20	12.50	15.46	13.73	13.90	13.82
7	75.5	34.28	33.96	32.37	33.25	25.75	920.0	6.00	0.575E 08	0.00450	11.89	12.35	15.31	13.53	13.71	13.62
8	105.5	35.05	34.86	33.40	34.18	26.47	936.1	5.89	0.598E 08	0.00629	11.81	12.07	14.62	13.14	13.28	13.21
9	135.5	35.52	35.21	32.92	34.14	27.20	951.3	5.79	0.620E 08	0.00810	12.14	12.61	17.68	14.56	15.03	14.79
10	165.2	35.54	35.37	33.46	34.47	27.92	965.4	5.70	0.642E 08	0.00988	13.24	13.53	18.15	15.41	15.77	15.59
11	205.2	36.45	36.26	34.21	35.28	28.88	984.9	5.57	0.672E 08	0.01230	13.31	13.65	18.92	15.74	16.20	15.97
12	245.2	37.62	37.55	35.80	36.69	29.85	1005.3	5.45	0.702E 08	0.01472	12.93	13.05	16.88	14.68	14.94	14.81
13	275.2	38.14	37.83	35.92	36.95	30.58	1021.2	5.36	0.726E 08	0.01654	13.27	13.83	18.77	15.73	16.16	15.95
14	305.2	38.99	38.98	37.14	38.06	31.30	1037.6	5.27	0.751E 08	0.01836	13.02	13.05	17.15	14.81	15.09	14.95
15	333.3	39.45	39.54	36.93	38.21	31.98	1052.9	5.18	0.773E 08	0.02008	13.38	13.24	20.20	16.05	16.75	16.40
16	363.3	40.78	40.91	38.32	39.58	32.71	1067.9	5.10	0.795E 08	0.02194	12.36	12.17	17.78	14.51	15.02	14.77
17	383.3	41.18	40.93	38.71	39.88	33.19	1078.1	5.04	0.810E 08	0.02318	12.48	12.88	18.06	14.90	15.37	15.13
18	403.3	41.68	41.41	39.12	40.33	33.67	1088.5	4.99	0.825E 08	0.02443	12.43	12.87	18.29	14.95	15.47	15.21
19	423.3	41.75	41.36	39.39	40.47	34.16	1099.1	4.93	0.840E 08	0.02569	13.09	13.80	19.00	15.74	16.22	15.98
20	443.3	42.74	43.02	40.30	41.59	34.64	1109.9	4.88	0.856E 08	0.02694	12.26	11.85	17.54	14.28	14.80	14.54
21	463.3	42.31	42.70	40.22	41.36	35.12	1120.9	4.82	0.871E 08	0.02821	13.81	13.09	19.47	15.90	16.46	16.18
AVERAGE VALUES THROUGH STATIONS 15 TO 20:																
	391.6	41.26	41.19	38.80	40.01	33.39	1082.7	5.02	0.816E 08	0.02371	12.67	12.80	18.48	15.07	15.61	15.34

========== EXPERIMENT 0R39 --- DEC. 5, 1987 ==========

INPUT ELECTRIC POWER = 1879.0 W　HEAT RATE GAINED BY WATER = 1763.7 W　HEAT BALANCE ERROR = 6.13%
MASS FLOW RATE = 24.0780 G/S　PRESSURE DROP = 0.3239 MM H2O　FRICTION FACTOR = 0.015959　FREM = 15.8883

REM = 995.6　GRM+ = 0.22489E 08　UPSTREAM BULK TEMPERATURE = 23.93 DEG C　DOWNSTREAM BULK TEMPERATURE = 41.50 DEG C
PRM = 5.099　RAM+ = 0.11468E 09　INLET BULK TEMPERATURE = 23.95 DEG C　OUTLET BULK TEMPERATURE = 41.48 DEG C

STATION NO.	Z CM	-WALL TEMPERATURE (DEG C)- A	B	C	AVERAGE	TB (C)	RE	PR	RA+	Z+	NUSSELT NUMBER A	B	C	AVERAGE T	H	T+H
0	0.0	28.80	28.85	28.49	28.66	23.95	822.5	6.29	0.749E 08	0.00000	30.29	29.95	32.33	31.19	31.22	31.20
1	1.5	29.76	29.84	29.55	29.67	24.01	823.5	6.28	0.752E 08	0.00010	25.53	25.19	26.47	25.90	25.91	25.91
2	2.5	30.42	30.51	30.28	30.37	24.04	824.2	6.27	0.753E 08	0.00016	23.03	22.70	23.53	23.19	23.20	23.19
3	5.5	32.40	32.54	32.47	32.47	24.16	826.3	6.26	0.758E 08	0.00035	17.80	17.50	17.65	17.65	17.65	17.65
4	15.5	34.50	34.12	32.76	33.53	24.53	833.5	6.20	0.774E 08	0.00099	14.71	15.29	17.82	16.29	16.41	16.35
5	25.5	35.56	35.79	33.22	34.45	24.90	840.7	6.14	0.791E 08	0.00163	13.75	13.45	17.61	15.35	15.61	15.48
6	45.5	36.78	36.53	34.17	35.41	25.65	855.6	6.02	0.824E 08	0.00291	13.14	13.44	17.17	14.98	15.23	15.11
7	75.5	38.06	37.64	35.25	36.55	26.77	878.9	5.84	0.876E 08	0.00484	12.93	13.43	17.22	14.93	15.20	15.06
8	105.5	39.21	38.84	36.80	37.91	27.90	899.4	5.70	0.925E 08	0.00677	12.86	13.30	16.33	14.52	14.71	14.62
9	135.5	39.99	39.54	36.24	38.00	29.02	920.7	5.56	0.974E 08	0.00871	13.23	13.79	20.11	16.15	16.81	16.48
10	165.2	40.39	40.15	37.71	38.99	30.13	942.7	5.42	0.103E 09	0.01064	14.11	14.44	19.09	16.33	16.68	16.51
11	205.2	41.84	41.46	38.70	40.18	31.62	974.1	5.23	0.110E 09	0.01325	14.13	14.66	20.39	16.87	17.39	17.13
12	245.2	43.58	43.36	40.84	42.15	33.12	1003.5	5.05	0.116E 09	0.01591	13.74	14.03	18.63	15.91	16.26	16.09
13	275.2	44.40	43.92	41.10	42.63	34.24	1026.2	4.92	0.122E 09	0.01792	14.11	14.80	20.90	17.09	17.68	17.38
14	305.2	45.67	45.65	42.83	44.25	35.36	1050.0	4.79	0.127E 09	0.01995	13.86	13.89	19.14	16.09	16.51	16.30
15	333.3	46.47	46.58	43.02	44.77	36.42	1073.3	4.67	0.132E 09	0.02187	14.17	14.02	21.58	17.05	17.84	17.45
16	363.3	48.60	48.81	45.02	46.86	37.54	1097.1	4.56	0.137E 09	0.02391	12.86	12.61	19.01	15.25	15.87	15.56
17	383.3	48.99	48.67	45.52	47.18	38.29	1112.6	4.49	0.141E 09	0.02525	13.27	13.67	19.62	15.97	16.54	16.26
18	403.3	49.90	49.43	46.10	47.88	39.03	1128.6	4.42	0.145E 09	0.02660	13.05	13.64	20.06	16.02	16.70	16.36
19	423.3	50.05	49.43	46.39	48.06	39.78	1145.0	4.35	0.149E 09	0.02795	13.78	14.68	21.44	17.10	17.83	17.47
20	443.3	51.55	51.80	47.92	49.80	40.53	1161.9	4.28	0.152E 09	0.02931	12.83	12.54	19.13	15.26	15.91	15.58
21	463.3	51.04	51.51	48.01	49.64	41.28	1179.4	4.21	0.157E 09	0.03067	14.46	13.80	20.95	16.87	17.54	17.21
AVERAGE VALUES THROUGH STATIONS 15 TO 20:																
	391.6	49.26	49.12	45.66	47.43	38.60	1119.8	4.46	0.143E 09	0.02582	13.33	13.53	20.14	16.11	16.78	16.45

========== EXPERIMENT 0R40 --- DEC. 6, 1987 ==========

INPUT ELECTRIC POWER = 139.3 W HEAT RATE GAINED BY WATER = 133.8 W HEAT BALANCE ERROR = 3.89%
MASS FLOW RATE = 34.6770 G/S PRESSURE DROP = 0.5398 MM H2O FRICTION FACTOR = 0.012860 FREM = 15.3564

REM = 1194.2 GRM+ = 0.93101E 06 UPSTREAM BULK TEMPERATURE = 23.84 DEG C DOWNSTREAM BULK TEMPERATURE = 24.77 DEG C
PRM = 6.232 RAM+ = 0.58021E 07 INLET BULK TEMPERATURE = 23.84 DEG C OUTLET BULK TEMPERATURE = 24.77 DEG C

STA-	Z	-WALL TEMPERATURE (DEG C)-				TB	RE	PR	RA+	Z+	NUSSELT NUMBER					
TION	CM	A	B	C	AVER-	(C)					A	B	C	AVERAGE		
NO.					AGE									T	H	T+H
0	0.0	24.22	24.23	24.19	24.21	23.84	1181.7	6.31	0.565E 07	0.00000	29.45	29.06	31.91	30.52	30.58	30.55
1	1.5	24.26	24.27	24.24	24.25	23.85	1181.7	6.30	0.565E 07	0.00007	26.86	26.41	28.20	27.40	27.42	27.41
2	2.5	24.29	24.30	24.28	24.28	23.85	1181.8	6.30	0.565E 07	0.00011	25.33	24.85	26.11	25.59	25.60	25.59
3	5.5	24.37	24.38	24.38	24.38	23.85	1182.0	6.30	0.566E 07	0.00024	21.62	21.10	21.36	21.36	21.36	21.36
4	15.5	24.71	24.70	24.69	24.70	23.87	1182.5	6.30	0.566E 07	0.00068	13.38	13.47	13.61	13.52	13.52	13.52
5	25.5	24.86	24.91	24.83	24.86	23.89	1183.0	6.30	0.567E 07	0.00113	11.53	10.92	11.86	11.53	11.54	11.54
6	45.5	25.14	25.14	25.00	25.07	23.93	1184.1	6.29	0.568E 07	0.00201	9.26	9.23	10.40	9.79	9.82	9.81
7	75.5	25.36	25.21	25.22	25.25	23.99	1185.7	6.28	0.570E 07	0.00333	8.17	9.14	9.06	8.84	8.86	8.85
8	105.5	25.44	25.45	25.33	25.39	24.05	1187.3	6.27	0.572E 07	0.00466	8.04	7.94	8.70	8.33	8.35	8.34
9	135.5	25.60	25.62	25.26	25.44	24.11	1188.9	6.26	0.574E 07	0.00599	7.48	7.37	9.66	8.39	8.54	8.47
10	165.2	25.61	25.56	25.38	25.49	24.17	1190.4	6.25	0.576E 07	0.00730	7.71	7.99	9.17	8.46	8.51	8.49
11	205.2	25.57	25.60	25.33	25.46	24.25	1192.6	6.24	0.578E 07	0.00907	8.43	8.22	10.32	9.22	9.32	9.27
12	245.2	25.64	25.78	25.34	25.53	24.33	1194.7	6.23	0.581E 07	0.01084	8.48	7.65	10.98	9.28	9.52	9.40
13	275.2	25.63	25.63	25.42	25.53	24.39	1196.4	6.22	0.583E 07	0.01217	8.91	8.91	10.73	9.74	9.82	9.78
14	305.2	25.75	25.74	25.48	25.61	24.44	1198.0	6.21	0.585E 07	0.01349	8.54	8.58	10.75	9.53	9.65	9.59
15	333.3	25.86	25.84	25.55	25.70	24.50	1199.5	6.20	0.587E 07	0.01474	8.17	8.32	10.61	9.26	9.43	9.36
16	363.3	25.89	25.89	25.63	25.76	24.56	1201.2	6.19	0.589E 07	0.01607	8.34	8.37	10.40	9.27	9.38	9.32
17	383.3	25.95	25.96	25.62	25.78	24.60	1202.2	6.19	0.590E 07	0.01695	8.23	8.19	10.93	9.38	9.57	9.48
18	403.3	25.92	25.92	25.72	25.82	24.64	1203.3	6.18	0.591E 07	0.01784	8.66	8.65	10.27	9.39	9.46	9.43
19	423.3	25.86	25.96	25.62	25.77	24.68	1204.4	6.17	0.592E 07	0.01873	9.43	8.69	11.74	10.22	10.40	10.31
20	443.3	25.98	26.14	25.72	25.89	24.72	1205.5	6.17	0.594E 07	0.01961	8.78	7.81	11.04	9.46	9.67	9.56
21	463.3	26.05	25.99	25.67	25.84	24.76	1206.6	6.16	0.595E 07	0.02050	8.62	8.99	12.22	10.23	10.51	10.37
AVERAGE VALUES THROUGH STATIONS 15 TO 20:																
	391.6	25.91	25.95	25.64	25.79	24.61	1202.7	6.18	0.590E 07	0.01732	8.60	8.34	10.83	9.50	9.65	9.58

========== EXPERIMENT 0R41 --- DEC. 6, 1987 ==========

INPUT ELECTRIC POWER = 273.9 W HEAT RATE GAINED BY WATER = 257.8 W HEAT BALANCE ERROR = 5.88%
MASS FLOW RATE = 34.4240 G/S PRESSURE DROP = 0.5332 MM H2O FRICTION FACTOR = 0.012888 FREM = 15.4491

REM = 1198.7 GRM+ = 0.18650E 07 UPSTREAM BULK TEMPERATURE = 23.89 DEG C DOWNSTREAM BULK TEMPERATURE = 25.68 DEG C
PRM = 6.156 RAM+ = 0.11481E 08 INLET BULK TEMPERATURE = 23.89 DEG C OUTLET BULK TEMPERATURE = 25.68 DEG C

STA-	Z	-WALL TEMPERATURE (DEG C)-				TB	RE	PR	RA+	Z+	NUSSELT NUMBER					
TION	CM	A	B	C	AVER-	(C)					A	B	C	AVERAGE		
NO.					AGE									T	H	T+H
0	0.0	24.51	24.52	24.45	24.48	23.89	1174.3	6.30	0.109E 08	0.00000	34.51	34.25	38.41	36.28	36.39	36.34
1	1.5	24.63	24.63	24.58	24.60	23.90	1174.5	6.30	0.109E 08	0.00007	29.45	29.19	31.38	30.31	30.35	30.33
2	2.5	24.70	24.71	24.67	24.69	23.90	1174.6	6.30	0.109E 08	0.00011	26.75	26.48	27.86	27.22	27.24	27.23
3	5.5	24.94	24.95	24.94	24.94	23.91	1174.9	6.29	0.109E 08	0.00024	20.97	20.73	20.85	20.85	20.85	20.85
4	15.5	25.50	25.46	25.43	25.46	23.95	1175.9	6.29	0.110E 08	0.00069	13.83	14.19	14.52	14.26	14.26	14.26
5	25.5	25.79	25.82	25.62	25.71	23.99	1176.9	6.28	0.110E 08	0.00113	11.91	11.71	13.14	12.44	12.48	12.46
6	45.5	26.15	26.10	25.82	25.97	24.06	1179.0	6.27	0.110E 08	0.00202	10.29	10.55	12.19	11.23	11.30	11.27
7	75.5	26.43	26.28	26.09	26.22	24.18	1182.0	6.25	0.111E 08	0.00336	9.54	10.22	11.20	10.49	10.54	10.52
8	105.5	26.62	26.57	26.39	26.49	24.29	1185.1	6.23	0.112E 08	0.00470	9.23	9.40	10.23	9.75	9.77	9.76
9	135.5	26.82	26.81	26.30	26.56	24.41	1188.3	6.22	0.112E 08	0.00603	8.90	8.93	11.31	9.97	10.11	10.04
10	165.2	26.85	26.80	26.52	26.67	24.52	1191.4	6.20	0.113E 08	0.00736	9.22	9.41	10.73	9.97	10.02	10.00
11	205.2	26.92	26.92	26.53	26.73	24.68	1195.6	6.17	0.114E 08	0.00914	9.54	9.53	11.52	10.43	10.53	10.48
12	245.2	27.09	27.21	26.68	26.92	24.83	1199.8	6.15	0.115E 08	0.01093	9.48	9.00	11.54	10.26	10.39	10.32
13	275.2	27.15	27.10	26.70	26.91	24.94	1203.0	6.13	0.116E 08	0.01227	9.69	9.95	12.16	10.87	10.99	10.93
14	305.2	27.32	27.34	26.84	27.08	25.06	1206.2	6.11	0.117E 08	0.01361	9.46	9.37	12.02	10.56	10.72	10.64
15	333.3	27.46	27.47	26.97	27.22	25.16	1209.3	6.10	0.117E 08	0.01487	9.31	9.28	11.85	10.42	10.57	10.49
16	363.3	27.59	27.59	26.98	27.29	25.28	1212.5	6.08	0.118E 08	0.01622	9.25	9.26	12.59	10.67	10.92	10.79
17	383.3	27.68	27.59	27.02	27.33	25.36	1214.7	6.07	0.119E 08	0.01711	9.19	9.58	12.87	10.85	11.13	10.99
18	403.3	27.73	27.72	27.23	27.48	25.43	1216.9	6.05	0.119E 08	0.01801	9.31	9.35	11.93	10.47	10.63	10.55
19	423.3	27.66	27.72	27.19	27.44	25.51	1219.1	6.04	0.120E 08	0.01890	9.95	9.66	12.71	11.07	11.26	11.16
20	443.3	27.96	28.12	27.42	27.73	25.59	1221.3	6.03	0.120E 08	0.01980	9.01	8.42	11.64	9.96	10.18	10.07
21	463.3	27.90	27.88	27.28	27.59	25.66	1223.5	6.02	0.121E 08	0.02070	9.55	9.63	13.18	11.10	11.39	11.25
AVERAGE VALUES THROUGH STATIONS 15 TO 20:																
	391.6	27.68	27.70	27.13	27.41	25.39	1215.6	6.06	0.119E 08	0.01749	9.34	9.26	12.26	10.57	10.78	10.68

========== EXPERIMENT 0R42 --- DEC. 6, 1987 ==========

INPUT ELECTRIC POWER = 750.5 W HEAT RATE GAINED BY WATER = 715.0 W HEAT BALANCE ERROR = 4.73%
MASS FLOW RATE = 33.0160 G/S PRESSURE DROP = 0.5148 MM H2O FRICTION FACTOR = 0.013523 FREM = 16.1840

REM = 1196.8 GRM+ = 0.59397E 07 UPSTREAM BULK TEMPERATURE = 23.89 DEG C DOWNSTREAM BULK TEMPERATURE = 29.08 DEG C
PRM = 5.887 RAM+ = 0.34970E 08 INLET BULK TEMPERATURE = 23.90 DEG C OUTLET BULK TEMPERATURE = 29.08 DEG C

STA-	Z	-WALL TEMPERATURE (DEG C)-				TB	RE	PR	RA+	Z+	NUSSELT NUMBER					
TION	CM	A	B	C	AVER-	(C)					A	B	C	AVERAGE		
NO.					AGE									T	H	T+H
0	0.0	25.85	25.88	25.73	25.80	23.90	1126.4	6.30	0.303E 08	0.00000	30.52	29.96	32.40	31.28	31.32	31.30
1	1.5	26.21	26.26	26.14	26.18	23.91	1126.8	6.29	0.303E 08	0.00007	25.95	25.38	26.78	26.21	26.22	26.21
2	2.5	26.45	26.52	26.41	26.45	23.92	1127.1	6.29	0.303E 08	0.00012	23.52	22.96	23.91	23.57	23.58	23.57
3	5.5	27.20	27.29	27.24	27.24	23.96	1128.0	6.29	0.304E 08	0.00026	18.36	17.85	18.10	18.10	18.11	18.10
4	15.5	28.40	28.25	27.89	28.11	24.07	1130.8	6.27	0.306E 08	0.00072	13.74	14.21	15.56	14.73	14.77	14.75
5	25.5	28.94	29.05	28.21	28.60	24.18	1133.6	6.25	0.308E 08	0.00118	12.48	12.21	14.75	13.44	13.55	13.49
6	45.5	29.53	29.43	28.63	29.05	24.40	1139.4	6.22	0.312E 08	0.00211	11.60	11.83	14.07	12.78	12.89	12.84
7	75.5	30.10	29.87	29.14	29.56	24.73	1148.1	6.16	0.317E 08	0.00351	11.07	11.56	13.49	12.30	12.40	12.35
8	105.5	30.55	30.44	29.71	30.10	25.06	1157.0	6.11	0.323E 08	0.00491	10.81	11.04	12.77	11.78	11.85	11.81
9	135.5	30.89	30.77	29.46	30.14	25.39	1166.0	6.06	0.329E 08	0.00631	10.80	11.03	14.60	12.49	12.76	12.62
10	165.2	31.00	30.88	29.96	30.45	25.72	1175.1	6.01	0.335E 08	0.00770	11.24	11.50	14.00	12.55	12.68	12.62
11	205.2	31.12	31.00	29.71	30.39	26.16	1187.5	5.94	0.344E 08	0.00957	11.94	12.24	16.70	14.03	14.40	14.21
12	245.2	31.71	31.76	30.60	31.17	26.61	1200.2	5.87	0.352E 08	0.01145	11.58	11.47	14.81	12.96	13.17	13.06
13	275.2	31.93	31.76	30.57	31.21	26.94	1209.5	5.82	0.358E 08	0.01286	11.85	12.26	16.26	13.84	14.16	14.00
14	305.2	32.37	32.36	31.25	31.81	27.27	1217.6	5.78	0.364E 08	0.01427	11.58	11.60	14.82	13.01	13.21	13.11
15	333.3	32.69	32.71	31.35	32.03	27.58	1225.3	5.74	0.369E 08	0.01559	11.56	11.50	15.64	13.27	13.58	13.43
16	363.3	33.42	33.48	31.96	32.71	27.91	1233.7	5.70	0.375E 08	0.01701	10.70	10.59	14.57	12.30	12.61	12.45
17	383.3	33.53	33.44	32.06	32.78	28.13	1239.3	5.67	0.379E 08	0.01795	10.91	11.10	14.99	12.69	13.00	12.85
18	403.3	33.83	33.67	32.31	33.03	28.35	1245.0	5.64	0.383E 08	0.01889	10.76	11.09	14.91	12.61	12.92	12.76
19	423.3	33.73	33.58	32.37	33.01	28.57	1250.7	5.61	0.387E 08	0.01983	11.41	11.78	15.53	13.27	13.56	13.42
20	443.3	34.33	34.58	32.86	33.66	28.80	1256.5	5.58	0.391E 08	0.02078	10.63	10.17	14.49	12.11	12.45	12.28
21	463.3	34.02	34.17	32.65	33.38	29.02	1262.4	5.56	0.395E 08	0.02172	11.76	11.41	16.18	13.50	13.88	13.69
AVERAGE VALUES THROUGH STATIONS 15 TO 20:																
	391.6	33.59	33.58	32.15	32.87	28.22	1241.8	5.66	0.381E 08	0.01834	11.00	11.04	15.02	12.71	13.02	12.86

========== EXPERIMENT 0R43 --- DEC. 7, 1987 ==========

INPUT ELECTRIC POWER = 1345.5 W HEAT RATE GAINED BY WATER = 1278.3 W HEAT BALANCE ERROR = 4.99%
MASS FLOW RATE = 31.4490 G/S PRESSURE DROP = 0.5204 MM H2O FRICTION FACTOR = 0.015053 FREM = 18.0716

REM = 1200.6 GRM+ = 0.12642E 08 UPSTREAM BULK TEMPERATURE = 24.06 DEG C DOWNSTREAM BULK TEMPERATURE = 33.81 DEG C
PRM = 5.567 RAM+ = 0.70371E 08 INLET BULK TEMPERATURE = 24.08 DEG C OUTLET BULK TEMPERATURE = 33.81 DEG C

STATION NO.	Z CM	WALL TEMPERATURE (DEG C) A	B	C	AVERAGE	TB (C)	RE	PR	RA+	Z+	NUSSELT NUMBER A	B	C	AVERAGE T	H	T+H
0	0.0	27.37	27.41	27.17	27.28	24.08	1077.4	6.27	0.547E 08	0.00000	32.37	31.92	34.37	33.22	33.26	33.24
1	1.5	28.01	28.08	27.89	27.97	24.11	1078.1	6.26	0.548E 08	0.00007	27.25	26.80	28.15	27.57	27.59	27.58
2	2.5	28.46	28.54	28.38	28.44	24.13	1078.7	6.26	0.549E 08	0.00012	24.57	24.13	25.02	24.68	24.69	24.68
3	5.5	29.80	29.92	29.86	29.86	24.19	1080.2	6.25	0.551E 08	0.00027	18.97	18.58	18.77	18.77	18.77	18.77
4	15.5	31.49	31.24	30.44	30.90	24.40	1085.3	6.22	0.557E 08	0.00076	14.99	15.53	17.61	16.35	16.43	16.39
5	25.5	32.27	32.39	30.86	31.59	24.61	1090.5	6.18	0.564E 08	0.00124	13.87	13.64	17.00	15.21	15.38	15.29
6	45.5	33.24	33.09	31.60	32.38	25.02	1101.1	6.12	0.577E 08	0.00222	12.92	13.15	16.15	14.43	14.59	14.51
7	75.5	34.25	33.96	32.40	33.25	25.64	1117.3	6.02	0.597E 08	0.00369	12.32	12.74	15.69	13.93	14.11	14.02
8	105.5	35.05	34.83	33.46	34.20	26.27	1134.0	5.92	0.618E 08	0.00517	12.05	12.36	14.72	13.34	13.46	13.40
9	135.5	35.52	35.21	33.00	34.19	26.89	1151.0	5.83	0.639E 08	0.00665	12.24	12.70	17.30	14.49	14.88	14.69
10	165.2	35.45	35.29	33.34	34.35	27.51	1165.4	5.75	0.658E 08	0.00811	13.28	13.56	18.10	15.41	15.76	15.59
11	205.2	36.20	36.01	33.98	35.04	28.34	1185.5	5.64	0.684E 08	0.01009	13.40	13.73	18.66	15.71	16.11	15.91
12	245.2	37.36	37.27	35.49	36.40	29.17	1206.2	5.54	0.711E 08	0.01207	12.83	12.98	16.63	14.53	14.76	14.65
13	275.2	37.80	37.43	35.47	36.54	29.79	1222.3	5.46	0.732E 08	0.01357	13.11	13.73	18.49	15.55	15.96	15.75
14	305.2	38.55	38.50	36.57	37.55	30.41	1238.8	5.38	0.753E 08	0.01506	12.89	12.96	17.01	14.69	14.97	14.83
15	333.3	38.81	38.89	36.30	37.58	30.99	1254.6	5.31	0.773E 08	0.01646	13.40	13.27	19.72	15.91	16.53	16.22
16	363.3	39.99	40.14	37.47	38.77	31.62	1272.0	5.23	0.796E 08	0.01797	12.49	12.27	17.85	14.62	15.11	14.86
17	383.3	40.27	40.06	37.78	38.97	32.03	1283.1	5.18	0.810E 08	0.01897	12.69	13.02	18.16	15.05	15.50	15.28
18	403.3	40.83	40.51	38.21	39.44	32.45	1293.5	5.13	0.823E 08	0.01999	12.44	12.94	18.11	14.92	15.40	15.16
19	423.3	40.82	40.41	38.38	39.50	32.86	1304.0	5.08	0.836E 08	0.02101	13.09	13.81	18.88	15.70	16.16	15.93
20	443.3	41.81	42.09	39.20	40.57	33.28	1314.7	5.03	0.849E 08	0.02203	12.20	11.82	17.58	14.27	14.80	14.53
21	463.3	41.32	41.67	39.06	40.28	33.69	1325.6	4.99	0.863E 08	0.02306	13.63	13.04	19.36	15.79	16.35	16.07
AVERAGE VALUES THROUGH STATIONS 15 TO 20:																
	391.6	40.42	40.35	37.89	39.14	32.20	1287.0	5.16	0.814E 08	0.01940	12.72	12.85	18.38	15.08	15.58	15.33

========== EXPERIMENT 0R44 --- DEC. 8, 1987 ==========

INPUT ELECTRIC POWER = 140.4 W HEAT RATE GAINED BY WATER = 131.0 W HEAT BALANCE ERROR = 6.73%
MASS FLOW RATE = 40.6690 G/S PRESSURE DROP = 0.6208 MM H2O FRICTION FACTOR = 0.010752 FREM = 15.0882

REM = 1403.3 GRM+ = 0.91753E 06 UPSTREAM BULK TEMPERATURE = 24.01 DEG C DOWNSTREAM BULK TEMPERATURE = 24.78 DEG C
PRM = 6.218 RAM+ = 0.57057E 07 INLET BULK TEMPERATURE = 24.01 DEG C OUTLET BULK TEMPERATURE = 24.78 DEG C

STATION NO.	Z CM	WALL TEMPERATURE (DEG C) A	B	C	AVERAGE	TB (C)	RE	PR	RA+	Z+	NUSSELT NUMBER A	B	C	AVERAGE T	H	T+H
0	0.0	24.34	24.35	24.31	24.33	24.01	1391.0	6.28	0.558E 07	0.00000	32.61	32.13	35.70	33.95	34.03	33.99
1	1.5	24.37	24.38	24.35	24.36	24.01	1391.1	6.28	0.558E 07	0.00006	30.09	29.52	31.80	30.77	30.81	30.79
2	2.5	24.39	24.40	24.38	24.39	24.01	1391.1	6.28	0.558E 07	0.00009	28.57	27.95	29.58	28.90	28.92	28.91
3	5.5	24.45	24.47	24.46	24.46	24.02	1391.3	6.28	0.559E 07	0.00021	24.80	24.11	24.45	24.45	24.45	24.45
4	15.5	24.71	24.70	24.72	24.71	24.03	1391.8	6.28	0.559E 07	0.00058	16.15	16.27	15.81	16.01	16.01	16.01
5	25.5	24.89	24.86	24.83	24.85	24.05	1392.3	6.27	0.560E 07	0.00096	12.97	13.46	13.88	13.54	13.55	13.54
6	45.5	25.14	25.14	25.03	25.09	24.08	1393.3	6.27	0.561E 07	0.00171	10.32	10.29	11.45	10.85	10.88	10.86
7	75.5	25.33	25.18	25.22	25.24	24.13	1394.9	6.26	0.562E 07	0.00284	9.10	10.35	9.98	9.83	9.85	9.84
8	105.5	25.38	25.40	25.33	25.36	24.18	1396.5	6.25	0.564E 07	0.00397	9.07	8.94	9.46	9.23	9.23	9.23
9	135.5	25.57	25.59	25.32	25.45	24.23	1398.1	6.24	0.565E 07	0.00511	8.11	7.98	9.99	8.91	9.02	8.97
10	165.2	25.61	25.56	25.38	25.49	24.28	1399.6	6.24	0.567E 07	0.00623	8.16	8.48	9.86	9.02	9.09	9.06
11	205.2	25.62	25.66	25.44	25.54	24.34	1401.7	6.23	0.569E 07	0.00773	8.50	8.28	9.94	9.10	9.17	9.13
12	245.2	25.70	25.92	25.46	25.63	24.41	1403.8	6.22	0.571E 07	0.00924	8.46	7.20	10.41	8.91	9.12	9.01
13	275.2	25.80	25.75	25.56	25.67	24.46	1405.4	6.21	0.573E 07	0.01038	8.10	8.45	9.84	8.99	9.06	9.02
14	305.2	25.86	25.85	25.59	25.73	24.51	1407.0	6.20	0.574E 07	0.01151	8.05	8.09	10.03	8.94	9.05	9.00
15	333.3	25.95	25.95	25.72	25.83	24.55	1408.5	6.19	0.576E 07	0.01257	7.82	7.80	9.34	8.51	8.58	8.54
16	363.3	26.06	26.00	25.77	25.90	24.60	1410.1	6.19	0.577E 07	0.01370	7.45	7.78	9.34	8.39	8.48	8.43
17	383.3	26.09	26.01	25.73	25.89	24.64	1411.2	6.18	0.578E 07	0.01446	7.48	7.91	9.97	8.68	8.83	8.75
18	403.3	26.01	25.98	25.78	25.89	24.67	1412.3	6.17	0.580E 07	0.01521	8.13	8.31	9.82	8.95	9.02	8.98
19	423.3	25.94	26.01	25.74	25.86	24.70	1413.3	6.17	0.581E 07	0.01597	8.78	8.30	10.52	9.42	9.53	9.48
20	443.3	26.07	26.23	25.84	25.99	24.73	1414.4	6.16	0.582E 07	0.01672	8.17	7.30	9.87	8.66	8.80	8.73
21	463.3	26.13	26.08	25.72	25.91	24.77	1415.5	6.16	0.583E 07	0.01748	7.99	8.30	11.38	9.49	9.76	9.63
AVERAGE VALUES THROUGH STATIONS 15 TO 20:																
	391.6	26.02	26.03	25.76	25.89	24.65	1411.7	6.18	0.579E 07	0.01477	7.97	7.90	9.81	8.77	8.87	8.82

========== EXPERIMENT 0R45 --- DEC. 8, 1987 ==========

INPUT ELECTRIC POWER = 275.5 W HEAT RATE GAINED BY WATER = 257.7 W HEAT BALANCE ERROR = 6.46%
MASS FLOW RATE = 40.3080 G/S PRESSURE DROP = 0.6425 MM H2O FRICTION FACTOR = 0.011328 FREM = 15.8426

REM = 1398.6 GRM+ = 0.18414E 07 UPSTREAM BULK TEMPERATURE = 23.87 DEG C DOWNSTREAM BULK TEMPERATURE = 25.40 DEG C
PRM = 6.180 RAM+ = 0.11380E 08 INLET BULK TEMPERATURE = 23.87 DEG C OUTLET BULK TEMPERATURE = 25.40 DEG C

STATION NO.	Z CM	WALL TEMPERATURE (DEG C) A	B	C	AVERAGE	TB (C)	RE	PR	RA+	Z+	NUSSELT NUMBER A	B	C	AVERAGE T	H	T+H
0	0.0	24.46	24.47	24.42	24.44	23.87	1374.3	6.30	0.109E 08	0.00000	36.11	35.83	39.16	37.50	37.56	37.53
1	1.5	24.57	24.57	24.53	24.55	23.87	1374.5	6.30	0.109E 08	0.00006	30.98	30.68	32.49	31.64	31.66	31.65
2	2.5	24.64	24.65	24.61	24.63	23.88	1374.6	6.30	0.109E 08	0.00009	28.21	27.92	29.08	28.56	28.57	28.57
3	5.5	24.85	24.86	24.86	24.86	23.89	1374.9	6.30	0.109E 08	0.00021	22.25	21.98	22.11	22.11	22.11	22.11
4	15.5	25.33	25.32	25.32	25.32	23.92	1375.9	6.29	0.109E 08	0.00059	15.19	15.29	15.36	15.30	15.30	15.30
5	25.5	25.68	25.76	25.57	25.64	23.95	1376.9	6.29	0.110E 08	0.00097	12.43	11.83	13.30	12.68	12.72	12.70
6	45.5	26.07	26.07	25.82	25.95	24.02	1379.0	6.28	0.110E 08	0.00173	10.47	10.44	11.87	11.12	11.16	11.14
7	75.5	26.37	26.22	26.09	26.20	24.11	1382.0	6.26	0.111E 08	0.00287	9.50	10.18	10.83	10.31	10.34	10.32
8	105.5	26.53	26.52	26.36	26.44	24.21	1385.1	6.25	0.111E 08	0.00401	9.24	9.30	9.98	9.61	9.62	9.62
9	135.5	26.76	26.75	26.22	26.49	24.31	1388.2	6.23	0.112E 08	0.00515	8.75	8.77	11.22	9.84	9.99	9.92
10	165.2	26.76	26.69	26.41	26.57	24.41	1391.3	6.22	0.112E 08	0.00628	9.10	9.40	10.73	9.93	9.99	9.96
11	205.2	26.81	26.81	26.42	26.62	24.54	1395.5	6.20	0.113E 08	0.00781	9.44	9.42	11.37	10.31	10.40	10.35
12	245.2	27.06	27.15	26.66	26.88	24.67	1399.7	6.17	0.114E 08	0.00933	8.96	8.63	10.78	9.68	9.79	9.73
13	275.2	27.04	26.98	26.65	26.83	24.77	1402.9	6.16	0.115E 08	0.01048	9.42	9.66	11.39	10.38	10.47	10.43
14	305.2	27.21	27.20	26.78	26.99	24.86	1406.1	6.14	0.115E 08	0.01162	9.14	9.16	11.16	10.06	10.16	10.11
15	333.3	27.35	27.36	26.89	27.12	24.96	1409.1	6.13	0.116E 08	0.01269	8.94	8.91	11.09	9.89	10.01	9.95
16	363.3	27.48	27.42	26.89	27.17	25.05	1412.3	6.11	0.117E 08	0.01384	8.82	9.05	11.62	10.10	10.28	10.19
17	383.3	27.46	27.42	26.85	27.14	25.12	1414.4	6.10	0.117E 08	0.01460	9.16	9.30	12.36	10.57	10.80	10.68
18	403.3	27.56	27.55	27.00	27.28	25.18	1416.6	6.09	0.117E 08	0.01537	9.00	9.04	11.79	10.22	10.41	10.32
19	423.3	27.55	27.53	27.00	27.27	25.25	1418.8	6.08	0.118E 08	0.01613	9.32	9.40	12.25	10.61	10.81	10.71
20	443.3	27.79	27.92	27.20	27.53	25.31	1420.9	6.07	0.118E 08	0.01690	8.65	8.19	11.37	9.67	9.89	9.78
21	463.3	27.67	27.65	27.11	27.39	25.38	1423.1	6.06	0.119E 08	0.01766	9.32	9.41	12.36	10.66	10.86	10.76
AVERAGE VALUES THROUGH STATIONS 15 TO 20:																
	391.6	27.53	27.53	26.97	27.25	25.15	1415.4	6.10	0.117E 08	0.01492	8.98	8.98	11.75	10.18	10.36	10.27

========== EXPERIMENT OR46 --- DEC. 8, 1987 ==========

INPUT ELECTRIC POWER = 765.0 W   HEAT RATE GAINED BY WATER = 739.8 W   HEAT BALANCE ERROR = 3.29%
MASS FLOW RATE = 38.9800 G/S   PRESSURE DROP = 0.6764 MM H2O   FRICTION FACTOR = 0.012748   FREM = 17.8358

REM = 1399.1   GRM+ = 0.59446E 07   UPSTREAM BULK TEMPERATURE = 23.80 DEG C   DOWNSTREAM BULK TEMPERATURE = 28.35 DEG C
PRM = 5.952   RAM+ = 0.35384E 08   INLET BULK TEMPERATURE = 23.81 DEG C   OUTLET BULK TEMPERATURE = 28.35 DEG C

STATION NO.	Z CM	WALL TEMPERATURE (DEG C) A	B	C	AVERAGE	TB (C)	RE	PR	RA+	Z+	NUSSELT NUMBER A	B	C	AVERAGE T	H	T+H
0	0.0	25.70	25.73	25.60	25.66	23.81	1327.2	6.31	0.312E 08	0.00000	32.51	32.08	34.37	33.30	33.33	33.31
1	1.5	26.05	26.08	25.98	26.02	23.82	1327.6	6.31	0.312E 08	0.00006	27.67	27.23	28.52	27.97	27.98	27.98
2	2.5	26.28	26.33	26.24	26.27	23.83	1327.9	6.31	0.312E 08	0.00010	25.09	24.66	25.53	25.20	25.20	25.20
3	5.5	27.00	27.06	27.03	27.03	23.86	1328.8	6.30	0.313E 08	0.00022	19.61	19.21	19.41	19.41	19.41	19.41
4	15.5	26.17	28.03	27.75	27.92	23.96	1331.7	6.29	0.314E 08	0.00061	14.61	15.12	16.24	15.52	15.55	15.54
5	25.5	28.75	28.82	28.04	28.41	24.05	1334.6	6.27	0.316E 08	0.00100	13.12	12.90	15.43	14.12	14.22	14.17
6	45.5	29.30	29.20	28.43	28.84	24.25	1340.5	6.24	0.320E 08	0.00179	12.18	12.42	14.72	13.40	13.51	13.46
7	75.5	29.87	29.64	28.94	29.35	24.54	1349.5	6.20	0.325E 08	0.00297	11.53	12.04	13.97	12.78	12.88	12.83
8	105.5	30.33	30.21	29.51	29.89	24.83	1358.6	6.15	0.330E 08	0.00415	11.17	11.41	13.13	12.14	12.21	12.18
9	135.5	30.69	30.55	29.26	29.94	25.12	1367.8	6.10	0.336E 08	0.00534	11.02	11.32	14.83	12.74	13.00	12.87
10	165.2	30.77	30.62	29.76	30.23	25.41	1377.1	6.06	0.341E 08	0.00651	11.44	11.77	14.11	12.73	12.85	12.79
11	205.2	30.81	30.69	29.46	30.10	25.79	1389.7	6.00	0.348E 08	0.00810	12.22	12.52	16.74	14.22	14.55	14.39
12	245.2	31.43	31.46	30.32	30.88	26.18	1402.6	5.94	0.356E 08	0.00969	11.67	11.62	14.82	13.04	13.23	13.14
13	275.2	31.59	31.42	30.29	30.90	26.47	1412.4	5.89	0.362E 08	0.01088	11.96	12.37	16.04	13.84	14.10	13.97
14	305.2	32.01	31.97	30.86	31.42	26.76	1422.4	5.84	0.367E 08	0.01208	11.67	11.75	14.94	13.13	13.33	13.23
15	333.3	32.21	32.26	30.93	31.58	27.03	1430.7	5.81	0.372E 08	0.01320	11.82	11.69	15.71	13.45	13.73	13.59
16	363.3	32.74	32.80	31.28	32.03	27.32	1439.2	5.77	0.377E 08	0.01439	11.28	11.16	15.43	12.99	13.32	13.16
17	383.3	32.91	32.77	31.45	32.14	27.52	1444.9	5.75	0.381E 08	0.01519	11.33	11.64	15.55	13.21	13.51	13.36
18	403.3	33.24	33.05	31.80	32.47	27.71	1450.6	5.72	0.384E 08	0.01598	11.05	11.44	14.96	12.84	13.10	12.97
19	423.3	33.12	32.93	31.75	32.39	27.91	1456.4	5.70	0.388E 08	0.01678	11.72	12.15	15.87	13.62	13.90	13.76
20	443.3	33.77	33.96	32.29	33.08	28.10	1462.2	5.67	0.392E 08	0.01756	10.76	10.41	14.55	12.25	12.57	12.41
21	463.3	33.35	33.43	32.02	32.70	28.29	1468.1	5.65	0.395E 08	0.01838	12.07	11.87	16.37	13.83	14.17	14.00
AVERAGE VALUES THROUGH STATIONS 15 TO 20:																
	391.6	33.00	32.96	31.56	32.28	27.60	1447.3	5.74	0.382E 08	0.01552	11.33	11.41	15.34	13.06	13.36	13.21

========== EXPERIMENT OR47 --- DEC. 9, 1987 ==========

INPUT ELECTRIC POWER = 1381.9 W   HEAT RATE GAINED BY WATER = 1332.6 W   HEAT BALANCE ERROR = 3.57%
MASS FLOW RATE = 37.2760 G/S   PRESSURE DROP = 0.6259 MM H2O   FRICTION FACTOR = 0.012891   FREM = 18.0534

REM = 1400.5   GRM+ = 0.12500E 08   UPSTREAM BULK TEMPERATURE = 23.89 DEG C   DOWNSTREAM BULK TEMPERATURE = 32.46 DEG C
PRM = 5.663   RAM+ = 0.70785E 08   INLET BULK TEMPERATURE = 23.90 DEG C   OUTLET BULK TEMPERATURE = 32.45 DEG C

STATION NO.	Z CM	WALL TEMPERATURE (DEG C) A	B	C	AVERAGE	TB (C)	RE	PR	RA+	Z+	NUSSELT NUMBER A	B	C	AVERAGE T	H	T+H
0	0.0	27.19	27.21	27.04	27.12	23.90	1271.9	6.30	0.565E 08	0.00000	33.72	33.48	35.35	34.45	34.48	34.46
1	1.5	27.85	27.88	27.74	27.80	23.93	1272.6	6.29	0.565E 08	0.00006	28.30	28.06	29.07	28.62	28.62	28.62
2	2.5	28.30	28.34	28.23	28.27	23.94	1273.2	6.29	0.566E 08	0.00010	25.47	25.24	25.89	25.62	25.62	25.62
3	5.5	29.66	29.72	29.69	29.69	24.00	1274.7	6.28	0.568E 08	0.00023	19.60	19.40	19.50	19.50	19.50	19.50
4	15.5	31.32	31.05	30.32	30.75	24.18	1280.1	6.25	0.574E 08	0.00064	15.53	16.15	18.06	16.87	16.95	16.91
5	25.5	32.07	32.17	30.69	31.40	24.36	1285.4	6.22	0.580E 08	0.00105	14.38	14.20	17.53	15.75	15.91	15.83
6	45.5	33.01	32.87	31.37	32.15	24.73	1296.3	6.17	0.592E 08	0.00187	13.37	13.61	16.68	14.91	15.08	15.00
7	75.5	33.99	33.65	32.12	32.97	25.28	1312.9	6.08	0.610E 08	0.00311	12.69	13.20	16.16	14.37	14.55	14.46
8	105.5	34.83	34.58	33.29	33.99	25.82	1330.0	5.99	0.629E 08	0.00435	12.27	12.61	14.81	13.52	13.62	13.57
9	135.5	35.30	35.02	32.83	33.99	26.37	1347.5	5.91	0.648E 08	0.00560	12.36	12.76	17.08	14.47	14.82	14.65
10	165.2	35.37	35.12	33.37	34.31	26.91	1364.9	5.82	0.667E 08	0.00684	13.03	13.43	17.08	14.91	15.15	15.03
11	205.2	35.83	35.56	33.47	34.58	27.64	1385.3	5.73	0.690E 08	0.00850	13.44	13.90	18.87	15.85	16.27	16.06
12	245.2	36.85	36.79	35.09	35.96	28.37	1406.2	5.64	0.714E 08	0.01017	12.95	13.04	16.35	14.48	14.68	14.58
13	275.2	37.24	36.90	34.95	36.01	28.92	1422.4	5.57	0.733E 08	0.01143	13.19	13.75	18.18	15.47	15.82	15.65
14	305.2	37.98	37.94	36.07	37.01	29.47	1436.9	5.50	0.752E 08	0.01269	12.86	12.93	16.61	14.52	14.75	14.64
15	333.3	38.19	38.24	35.62	36.92	29.98	1454.8	5.44	0.770E 08	0.01387	13.33	13.25	19.40	15.77	16.35	16.06
16	363.3	39.14	39.26	36.52	37.86	30.53	1472.1	5.37	0.789E 08	0.01513	12.69	12.51	18.25	14.91	15.42	15.17
17	383.3	39.33	39.13	36.78	38.00	30.89	1483.9	5.32	0.803E 08	0.01597	12.95	13.26	18.57	15.36	15.83	15.60
18	403.3	39.82	39.53	37.19	38.43	31.26	1495.8	5.27	0.816E 08	0.01682	12.75	13.19	18.40	15.21	15.69	15.45
19	423.3	39.78	39.37	37.24	38.41	31.62	1508.0	5.23	0.830E 08	0.01766	13.36	14.07	19.42	16.07	16.57	16.32
20	443.3	40.80	41.10	38.18	39.56	31.99	1519.6	5.18	0.843E 08	0.01851	12.37	11.96	17.59	14.38	14.88	14.63
21	463.3	40.20	40.53	37.97	39.16	32.35	1530.4	5.14	0.855E 08	0.01937	13.87	13.32	19.39	15.98	16.49	16.23
AVERAGE VALUES THROUGH STATIONS 15 TO 20:																
	391.6	39.51	39.44	36.92	38.20	31.05	1489.0	5.30	0.808E 08	0.01633	12.91	13.04	18.61	15.28	15.79	15.54

========== EXPERIMENT OR48 --- DEC. 9, 1987 ==========

INPUT ELECTRIC POWER = 140.2 W   HEAT RATE GAINED BY WATER = 136.1 W   HEAT BALANCE ERROR = 2.91%
MASS FLOW RATE = 46.3730 G/S   PRESSURE DROP = 0.7384 MM H2O   FRICTION FACTOR = 0.009837   FREM = 15.6851

REM = 1594.6   GRM+ = 0.94197E 06   UPSTREAM BULK TEMPERATURE = 23.89 DEG C   DOWNSTREAM BULK TEMPERATURE = 24.59 DEG C
PRM = 6.242   RAM+ = 0.58801E 07   INLET BULK TEMPERATURE = 23.89 DEG C   OUTLET BULK TEMPERATURE = 24.59 DEG C

STATION NO.	Z CM	WALL TEMPERATURE (DEG C) A	B	C	AVERAGE	TB (C)	RE	PR	RA+	Z+	NUSSELT NUMBER A	B	C	AVERAGE T	H	T+H
0	0.0	24.17	24.18	24.11	24.14	23.89	1581.9	6.30	0.576E 07	0.00000	40.17	39.45	51.80	45.02	45.80	45.41
1	1.5	24.20	24.21	24.16	24.18	23.89	1581.9	6.30	0.576E 07	0.00005	36.55	35.72	42.71	39.15	39.42	39.28
2	2.5	24.22	24.23	24.19	24.21	23.89	1582.0	6.30	0.577E 07	0.00008	34.41	33.53	38.10	35.91	36.04	35.97
3	5.5	24.29	24.30	24.29	24.29	23.90	1582.2	6.30	0.577E 07	0.00018	29.26	28.32	28.78	28.78	28.79	28.78
4	15.5	24.56	24.59	24.55	24.56	23.91	1582.7	6.29	0.577E 07	0.00051	17.38	16.76	17.74	17.40	17.41	17.40
5	25.5	24.72	24.74	24.72	24.73	23.93	1583.2	6.29	0.578E 07	0.00084	14.32	13.87	14.29	14.19	14.19	14.19
6	45.5	24.97	24.97	24.86	24.92	23.96	1584.3	6.29	0.579E 07	0.00150	11.22	11.18	12.52	11.82	11.86	11.84
7	75.5	25.21	25.07	25.11	25.13	24.00	1585.9	6.28	0.580E 07	0.00249	9.35	10.60	10.24	10.08	10.11	10.10
8	105.5	25.24	25.26	25.22	25.23	24.05	1587.6	6.27	0.582E 07	0.00348	9.50	9.35	9.69	9.56	9.56	9.56
9	135.5	25.40	25.42	25.15	25.28	24.09	1589.2	6.27	0.583E 07	0.00448	8.65	8.51	10.70	9.52	9.64	9.58
10	165.2	25.44	25.42	25.27	25.35	24.14	1590.8	6.26	0.585E 07	0.00546	8.66	8.82	10.00	9.33	9.37	9.35
11	205.2	25.48	25.49	25.30	25.39	24.20	1593.0	6.25	0.587E 07	0.00678	8.80	8.76	10.28	9.47	9.53	9.50
12	245.2	25.50	25.70	25.40	25.50	24.26	1595.2	6.24	0.589E 07	0.00810	9.13	7.86	9.92	9.13	9.21	9.17
13	275.2	25.63	25.63	25.48	25.56	24.30	1596.8	6.23	0.590E 07	0.00910	8.50	8.50	9.61	9.02	9.06	9.04
14	305.2	25.78	25.77	25.48	25.63	24.35	1598.5	6.23	0.592E 07	0.01009	7.92	7.95	9.99	8.85	8.96	8.91
15	333.3	25.78	25.78	25.49	25.64	24.39	1600.0	6.22	0.593E 07	0.01102	8.15	8.13	10.27	9.08	9.20	9.14
16	363.3	25.78	25.72	25.46	25.60	24.43	1601.7	6.21	0.594E 07	0.01201	8.40	8.81	11.03	9.67	9.82	9.74
17	383.3	25.75	25.73	25.45	25.59	24.46	1602.8	6.21	0.595E 07	0.01267	8.79	8.93	11.50	10.01	10.18	10.10
18	403.3	25.75	25.76	25.55	25.65	24.49	1603.9	6.20	0.596E 07	0.01334	8.98	8.97	10.71	9.77	9.84	9.81
19	423.3	25.74	25.82	25.48	25.63	24.52	1605.0	6.20	0.597E 07	0.01400	9.27	8.75	11.78	10.20	10.39	10.30
20	443.3	25.87	26.03	25.55	25.75	24.55	1606.1	6.19	0.598E 07	0.01466	8.60	7.68	11.31	9.45	9.72	9.59
21	463.3	25.88	25.82	25.49	25.67	24.58	1607.2	6.19	0.599E 07	0.01532	8.75	9.14	12.45	10.40	10.69	10.55
AVERAGE VALUES THROUGH STATIONS 15 TO 20:																
	391.6	25.78	25.81	25.50	25.65	24.48	1603.2	6.21	0.596E 07	0.01295	8.70	8.55	11.10	9.70	9.86	9.78

========== EXPERIMENT 0R49 --- DEC. 9, 1987 ==========

INPUT ELECTRIC POWER = 276.7 W HEAT RATE GAINED BY WATER = 269.3 W HEAT BALANCE ERROR = 2.67%
MASS FLOW RATE = 46.1200 G/S PRESSURE DROP = 0.7563 MM H2O FRICTION FACTOR = 0.010185 FREM = 16.2573

REM = 1596.2 GRM+ = 0.19066E 07 UPSTREAM BULK TEMPERATURE = 23.82 DEG C DOWNSTREAM BULK TEMPERATURE = 25.22 DEG C
PRM = 6.198 RAM+ = 0.11817E 08 INLET BULK TEMPERATURE = 23.82 DEG C OUTLET BULK TEMPERATURE = 25.22 DEG C

STATION NO.	Z CM	WALL TEMPERATURE (DEG C) A	B	C	AVERAGE	TB (C)	RE	PR	RA+	Z+	NUSSELT NUMBER A	B	C	AVERAGE T	H	T+H
0	0.0	24.48	24.51	24.46	24.48	23.82	1570.9	6.31	0.114E 08	0.00000	34.19	32.84	35.15	34.31	34.33	34.32
1	1.5	24.58	24.62	24.57	24.59	23.83	1571.1	6.31	0.114E 08	0.00005	29.89	28.45	30.05	29.59	29.61	29.60
2	2.5	24.65	24.69	24.65	24.66	23.83	1571.2	6.31	0.114E 08	0.00008	27.50	26.05	27.32	27.03	27.05	27.04
3	5.5	24.85	24.92	24.86	24.88	23.84	1571.5	6.31	0.114E 08	0.00018	22.19	20.78	21.46	21.46	21.47	21.47
4	15.5	25.33	25.32	25.32	25.32	23.87	1572.5	6.30	0.114E 08	0.00051	15.34	15.44	15.51	15.45	15.45	15.45
5	25.5	25.65	25.68	25.57	25.61	23.90	1573.6	6.30	0.114E 08	0.00085	12.82	12.60	13.46	13.07	13.08	13.08
6	45.5	25.98	25.93	25.71	25.83	23.96	1575.7	6.29	0.114E 08	0.00151	11.09	11.37	12.79	11.96	12.01	11.99
7	75.5	26.26	26.08	25.93	26.05	24.05	1578.9	6.27	0.115E 08	0.00251	10.14	11.03	11.94	11.21	11.26	11.24
8	105.5	26.39	26.29	26.13	26.24	24.14	1582.2	6.26	0.116E 08	0.00350	9.94	10.39	11.23	10.67	10.70	10.68
9	135.5	26.53	26.50	26.05	26.28	24.23	1585.4	6.24	0.116E 08	0.00450	9.71	9.86	12.28	10.89	11.04	10.96
10	165.2	26.62	26.57	26.29	26.45	24.32	1588.6	6.23	0.117E 08	0.00549	9.71	9.92	11.33	10.52	10.57	10.55
11	205.2	26.70	26.70	26.28	26.49	24.44	1593.0	6.21	0.118E 08	0.00682	9.90	9.89	12.12	10.90	11.01	10.95
12	245.2	26.95	27.10	26.60	26.81	24.55	1597.3	6.19	0.118E 08	0.00815	9.36	8.81	10.95	9.93	10.02	9.97
13	275.2	27.01	26.98	26.65	26.82	24.64	1600.6	6.18	0.119E 08	0.00915	9.45	9.57	11.18	10.28	10.34	10.31
14	305.2	27.21	27.20	26.73	26.96	24.73	1603.9	6.16	0.120E 08	0.01015	9.05	9.07	11.23	10.03	10.14	10.09
15	333.3	27.24	27.25	26.69	26.96	24.82	1607.1	6.15	0.120E 08	0.01109	9.24	9.21	11.96	10.42	10.59	10.51
16	363.3	27.25	27.19	26.64	26.93	24.91	1610.4	6.14	0.121E 08	0.01209	9.53	9.78	12.89	11.04	11.27	11.16
17	383.3	27.17	27.14	26.57	26.86	24.97	1612.6	6.13	0.121E 08	0.01276	10.14	10.29	13.95	11.79	12.08	11.94
18	403.3	27.19	27.19	26.69	26.94	25.03	1614.9	6.12	0.122E 08	0.01343	10.31	10.35	13.47	11.69	11.90	11.80
19	423.3	27.15	27.19	26.72	26.94	25.08	1617.1	6.11	0.122E 08	0.01410	10.82	10.63	13.71	12.03	12.22	12.12
20	443.3	27.45	27.61	26.88	27.21	25.14	1619.4	6.10	0.122E 08	0.01476	9.70	9.06	12.85	10.83	11.11	10.97
21	463.3	27.37	27.34	26.82	27.09	25.20	1621.6	6.09	0.123E 08	0.01543	10.34	10.48	13.83	11.88	12.12	12.00
AVERAGE VALUES THROUGH STATIONS 15 TO 20:	391.6	27.24	27.26	26.70	26.97	24.99	1613.6	6.12	0.121E 08	0.01304	9.96	9.89	13.14	11.30	11.53	11.42

========== EXPERIMENT 0R50 --- DEC. 9, 1987 ==========

INPUT ELECTRIC POWER = 778.1 W HEAT RATE GAINED BY WATER = 748.4 W HEAT BALANCE ERROR = 3.82%
MASS FLOW RATE = 44.8210 G/S PRESSURE DROP = 0.7572 MM H2O FRICTION FACTOR = 0.010794 FREM = 17.2717

REM = 1600.1 GRM+ = 0.59039E 07 UPSTREAM BULK TEMPERATURE = 23.85 DEG C DOWNSTREAM BULK TEMPERATURE = 27.85 DEG C
PRM = 5.988 RAM+ = 0.35353E 08 INLET BULK TEMPERATURE = 23.85 DEG C OUTLET BULK TEMPERATURE = 27.85 DEG C

STATION NO.	Z CM	WALL TEMPERATURE (DEG C) A	B	C	AVERAGE	TB (C)	RE	PR	RA+	Z+	NUSSELT NUMBER A	B	C	AVERAGE T	H	T+H
0	0.0	25.66	25.71	25.60	25.64	23.85	1527.6	6.30	0.316E 08	0.00000	34.56	33.46	35.57	34.77	34.79	34.78
1	1.5	26.01	26.09	25.99	26.02	23.86	1528.1	6.30	0.316E 08	0.00005	29.10	28.02	29.35	28.95	28.96	28.95
2	2.5	26.25	26.35	26.25	26.27	23.87	1528.4	6.30	0.317E 08	0.00009	26.25	25.19	26.19	25.95	25.96	25.95
3	5.5	26.97	27.12	27.05	27.05	23.90	1529.3	6.30	0.317E 08	0.00019	20.28	19.34	19.80	19.80	19.80	19.80
4	15.5	28.20	28.03	27.83	27.97	23.98	1532.2	6.28	0.319E 08	0.00053	14.78	15.40	16.18	15.62	15.64	15.63
5	25.5	28.83	28.94	28.15	28.52	24.07	1535.2	6.27	0.320E 08	0.00087	13.08	12.79	15.25	14.00	14.09	14.04
6	45.5	29.30	29.17	28.43	28.83	24.24	1541.2	6.24	0.323E 08	0.00156	12.30	12.62	14.87	13.56	13.67	13.61
7	75.5	29.82	29.59	28.94	29.32	24.50	1550.2	6.20	0.328E 08	0.00258	11.70	12.22	14.00	12.90	12.98	12.94
8	105.5	30.27	30.16	29.57	29.89	24.75	1559.4	6.16	0.333E 08	0.00361	11.26	11.50	12.92	12.10	12.15	12.12
9	135.5	30.66	30.49	29.26	29.92	25.01	1568.7	6.12	0.337E 08	0.00464	10.99	11.34	14.62	12.66	12.89	12.77
10	165.2	30.72	30.62	29.76	30.21	25.26	1578.0	6.08	0.342E 08	0.00566	11.38	11.58	13.81	12.54	12.65	12.59
11	205.2	30.81	30.72	29.46	30.11	25.60	1590.7	6.03	0.349E 08	0.00704	11.91	12.12	16.10	13.76	14.06	13.91
12	245.2	31.32	31.34	30.26	30.79	25.94	1603.6	5.97	0.355E 08	0.00842	11.54	11.48	14.37	12.78	12.94	12.86
13	275.2	31.48	31.25	30.17	30.77	26.20	1613.4	5.93	0.360E 08	0.00946	11.74	12.26	15.59	13.56	13.79	13.67
14	305.2	31.81	31.80	30.69	31.25	26.45	1623.4	5.89	0.365E 08	0.01049	11.56	11.59	14.63	12.92	13.10	13.01
15	333.3	32.01	32.09	30.73	31.39	26.69	1632.8	5.85	0.370E 08	0.01147	11.64	11.46	15.34	13.18	13.45	13.31
16	363.3	32.52	32.58	30.95	31.75	26.95	1642.3	5.82	0.375E 08	0.01251	11.11	10.99	15.47	12.89	13.26	13.08
17	383.3	32.60	32.49	31.11	31.83	27.12	1647.9	5.80	0.378E 08	0.01320	11.29	11.52	15.49	13.14	13.45	13.29
18	403.3	32.90	32.77	31.45	32.14	27.29	1653.6	5.77	0.381E 08	0.01389	11.02	11.28	14.84	12.73	13.00	12.87
19	423.3	32.83	32.57	31.44	32.07	27.46	1659.4	5.75	0.384E 08	0.01459	11.50	12.10	15.51	13.40	13.65	13.53
20	443.3	33.38	33.62	31.95	32.72	27.63	1665.2	5.73	0.387E 08	0.01528	10.75	10.32	14.29	12.13	12.41	12.27
21	463.3	33.07	33.14	31.73	32.42	27.80	1671.0	5.71	0.391E 08	0.01597	11.73	11.55	15.72	13.37	13.68	13.53
AVERAGE VALUES THROUGH STATIONS 15 TO 20:	391.6	32.71	32.68	31.27	31.98	27.19	1650.2	5.79	0.379E 08	0.01349	11.22	11.28	15.16	12.91	13.20	13.06

========== EXPERIMENT 0R51 --- DEC. 10, 1987 ==========

INPUT ELECTRIC POWER = 1416.9 W HEAT RATE GAINED BY WATER = 1379.3 W HEAT BALANCE ERROR = 2.65%
MASS FLOW RATE = 42.8350 G/S PRESSURE DROP = 0.6994 MM H2O FRICTION FACTOR = 0.010910 FREM = 17.4017

REM = 1595.0 GRM+ = 0.12554E 08 UPSTREAM BULK TEMPERATURE = 23.88 DEG C DOWNSTREAM BULK TEMPERATURE = 31.60 DEG C
PRM = 5.718 RAM+ = 0.71781E 08 INLET BULK TEMPERATURE = 23.89 DEG C OUTLET BULK TEMPERATURE = 31.59 DEG C

STATION NO.	Z CM	WALL TEMPERATURE (DEG C) A	B	C	AVERAGE	TB (C)	RE	PR	RA+	Z+	NUSSELT NUMBER A	B	C	AVERAGE T	H	T+H
0	0.0	27.14	27.20	26.94	27.05	23.89	1461.2	6.30	0.584E 08	0.00000	35.33	34.71	37.69	36.30	36.36	36.33
1	1.5	27.79	27.87	27.66	27.74	23.91	1462.0	6.29	0.585E 08	0.00005	29.64	29.04	30.67	29.99	30.00	30.00
2	2.5	28.23	28.33	28.15	28.22	23.93	1462.5	6.29	0.585E 08	0.00009	26.68	26.09	27.18	26.78	26.78	26.78
3	5.5	29.57	29.72	29.65	29.65	23.98	1464.2	6.28	0.587E 08	0.00020	20.52	20.01	20.26	20.26	20.26	20.26
4	15.5	31.35	31.10	30.44	30.83	24.14	1469.7	6.26	0.592E 08	0.00055	15.93	16.49	18.24	17.16	17.22	17.19
5	25.5	32.15	32.31	30.80	31.52	24.31	1475.2	6.23	0.598E 08	0.00091	14.62	14.34	17.67	15.92	16.07	16.00
6	45.5	33.01	32.87	31.37	32.15	24.64	1486.4	6.18	0.609E 08	0.00163	13.69	13.93	17.03	15.25	15.42	15.33
7	75.5	33.99	33.63	32.09	32.95	25.13	1503.5	6.10	0.626E 08	0.00271	12.92	13.48	16.45	14.64	14.82	14.73
8	105.5	34.80	34.55	33.23	33.95	25.62	1521.0	6.02	0.643E 08	0.00379	12.47	12.81	15.04	13.73	13.84	13.79
9	135.5	35.24	34.96	32.75	33.92	26.12	1538.9	5.95	0.661E 08	0.00487	12.52	12.92	17.23	14.63	14.97	14.80
10	165.2	35.23	34.98	33.28	34.19	26.60	1557.1	5.87	0.679E 08	0.00595	13.23	13.62	17.10	15.04	15.26	15.15
11	205.2	35.66	35.42	33.42	34.48	27.26	1579.5	5.78	0.702E 08	0.00740	13.57	13.97	18.51	15.79	16.14	15.96
12	245.2	36.71	36.60	34.89	35.77	27.92	1600.8	5.70	0.724E 08	0.00885	12.94	13.11	16.32	14.49	14.68	14.58
13	275.2	36.96	36.59	34.50	35.64	28.41	1617.2	5.63	0.741E 08	0.00994	13.30	13.90	18.67	15.73	16.14	15.93
14	305.2	37.59	37.58	35.61	36.60	28.91	1634.0	5.57	0.758E 08	0.01103	13.07	13.09	16.93	14.76	15.00	14.88
15	333.3	37.80	37.87	35.28	36.56	29.37	1650.0	5.51	0.774E 08	0.01205	13.46	13.33	19.18	15.77	16.29	16.03
16	363.3	38.63	38.78	35.87	37.29	29.86	1667.4	5.45	0.792E 08	0.01315	12.91	12.70	18.85	15.25	15.83	15.54
17	383.3	38.76	38.51	36.10	37.37	30.19	1679.2	5.41	0.804E 08	0.01388	13.21	13.61	19.14	15.77	16.27	16.02
18	403.3	39.20	38.88	36.51	37.77	30.52	1691.2	5.37	0.817E 08	0.01461	13.03	13.52	18.89	15.59	16.08	15.84
19	423.3	39.11	38.70	36.59	37.75	30.85	1703.4	5.33	0.829E 08	0.01535	13.68	14.39	19.67	16.38	16.85	16.62
20	443.3	40.15	40.47	37.53	38.92	31.18	1715.7	5.29	0.841E 08	0.01608	12.59	12.15	17.78	14.59	15.07	14.83
21	463.3	39.58	39.84	37.27	38.49	31.50	1728.2	5.24	0.854E 08	0.01682	13.97	13.54	19.56	16.15	16.66	16.41
AVERAGE VALUES THROUGH STATIONS 15 TO 20:	391.6	38.94	38.87	36.31	37.61	30.33	1684.5	5.39	0.810E 08	0.01419	13.15	13.28	18.92	15.56	16.07	15.81

========== EXPERIMENT 0R52 --- DEC. 10, 1987 ==========

INPUT ELECTRIC POWER = 2133.8 W HEAT RATE GAINED BY WATER = 2056.1 W HEAT BALANCE ERROR = 3.64%
MASS FLOW RATE = 41.0300 G/S PRESSURE DROP = 0.6942 MM H2O FRICTION FACTOR = 0.011793 FREM = 18.8099

REM = 1595.0 GRM+ = 0.21574E 08 UPSTREAM BULK TEMPERATURE = 23.79 DEG C DOWNSTREAM BULK TEMPERATURE = 35.81 DEG C
PRM = 5.459 RAM+ = 0.11776E 09 INLET BULK TEMPERATURE = 23.80 DEG C OUTLET BULK TEMPERATURE = 35.79 DEG C

STATION NO.	Z CM	WALL TEMPERATURE (DEG C) A	B	C	AVERAGE	TB (C)	RE	PR	RA+	Z+	NUSSELT NUMBER A	B	C	AVERAGE T	H	T+H
0	0.0	28.79	28.89	28.50	28.67	23.80	1396.9	6.31	0.866E 08	0.00000	34.35	33.68	36.42	35.17	35.22	35.19
1	1.5	29.76	29.90	29.59	29.71	23.84	1398.0	6.31	0.868E 08	0.00006	28.90	28.23	29.78	29.16	29.17	29.16
2	2.5	30.44	30.61	30.34	30.43	23.87	1398.9	6.30	0.869E 08	0.00009	26.05	25.40	26.45	26.08	26.09	26.08
3	5.5	32.46	32.71	32.58	32.58	23.94	1401.3	6.29	0.873E 08	0.00021	20.10	19.52	19.81	19.81	19.81	19.81
4	15.5	34.73	34.34	33.15	33.84	24.20	1409.5	6.25	0.886E 08	0.00058	16.25	16.86	19.10	17.73	17.83	17.78
5	25.5	35.76	35.96	33.56	34.71	24.45	1417.8	6.21	0.899E 08	0.00095	15.12	14.85	18.78	16.67	16.88	16.78
6	45.5	36.98	36.67	34.42	35.63	24.97	1434.6	6.13	0.925E 08	0.00170	14.21	14.59	18.05	16.02	16.23	16.12
7	75.5	38.20	37.72	35.41	36.69	25.73	1460.7	6.01	0.965E 08	0.00283	13.67	14.22	17.61	15.56	15.78	15.67
8	105.5	39.30	38.89	36.95	38.02	26.50	1487.8	5.89	0.101E 09	0.00396	13.30	13.73	16.29	14.77	14.90	14.84
9	135.5	39.79	39.29	35.95	37.75	27.27	1513.1	5.78	0.105E 09	0.00510	13.56	14.13	19.55	16.21	16.70	16.45
10	165.2	39.80	39.39	36.86	38.23	28.03	1536.8	5.68	0.108E 09	0.00622	14.40	14.92	19.20	16.62	16.93	16.78
11	205.2	40.79	40.34	37.35	38.96	29.05	1569.9	5.55	0.114E 09	0.00774	14.41	14.99	20.38	17.07	17.54	17.31
12	245.2	42.16	41.97	39.46	40.76	30.07	1604.5	5.42	0.119E 09	0.00927	13.96	14.19	17.98	15.79	16.03	15.91
13	275.2	42.55	41.99	38.94	40.60	30.84	1631.4	5.33	0.124E 09	0.01042	14.39	15.12	20.81	17.26	17.79	17.53
14	305.2	43.51	43.44	40.57	42.02	31.61	1659.3	5.23	0.128E 09	0.01157	14.13	14.22	18.76	16.16	16.48	16.32
15	333.3	43.86	43.93	39.78	41.84	32.33	1683.7	5.14	0.132E 09	0.01266	14.56	14.47	22.54	17.66	18.53	18.09
16	363.3	45.37	45.64	41.36	43.43	33.10	1709.2	5.06	0.136E 09	0.01383	13.65	13.36	20.28	16.21	16.89	16.55
17	383.3	45.58	45.26	41.65	43.54	33.61	1726.6	5.00	0.138E 09	0.01462	13.98	14.36	20.80	16.85	17.48	17.17
18	403.3	46.26	45.73	41.98	43.99	34.12	1744.4	4.94	0.141E 09	0.01541	13.77	14.40	21.25	16.93	17.67	17.30
19	423.3	46.11	45.42	42.24	44.01	34.63	1762.5	4.86	0.144E 09	0.01620	14.54	15.47	21.92	17.80	18.46	18.13
20	443.3	47.54	47.89	43.50	45.61	35.14	1781.1	4.82	0.147E 09	0.01699	13.45	13.07	19.94	15.93	16.60	16.26
21	463.3	46.72	47.16	43.28	45.11	35.65	1800.0	4.76	0.149E 09	0.01779	15.05	14.47	21.83	17.61	18.30	17.95
AVERAGE VALUES THROUGH STATIONS 15 TO 20:																
	391.6	45.79	45.65	41.75	43.73	33.82	1734.6	4.97	0.139E 09	0.01495	13.99	14.19	21.12	16.90	17.61	17.25

========== EXPERIMENT 0R53 --- DEC. 10, 1987 ==========

INPUT ELECTRIC POWER = 2875.8 W HEAT RATE GAINED BY WATER = 2759.4 W HEAT BALANCE ERROR = 4.05%
MASS FLOW RATE = 39.0810 G/S PRESSURE DROP = 0.6367 MM H2O FRICTION FACTOR = 0.011910 FREM = 19.0642

REM = 1600.7 GRM+ = 0.34155E 08 UPSTREAM BULK TEMPERATURE = 23.76 DEG C DOWNSTREAM BULK TEMPERATURE = 40.69 DEG C
PRM = 5.156 RAM+ = 0.17610E 09 INLET BULK TEMPERATURE = 23.78 DEG C OUTLET BULK TEMPERATURE = 40.68 DEG C

STATION NO.	Z CM	WALL TEMPERATURE (DEG C) A	B	C	AVERAGE	TB (C)	RE	PR	RA+	Z+	NUSSELT NUMBER A	B	C	AVERAGE T	H	T+H
0	0.0	30.38	30.48	29.98	30.20	23.78	1329.9	6.31	0.116E 09	0.00000	34.84	34.33	37.09	35.79	35.84	35.81
1	1.5	31.68	31.82	31.42	31.59	23.83	1331.4	6.31	0.116E 09	0.00006	29.27	28.77	30.26	29.63	29.65	29.64
2	2.5	32.58	32.75	32.42	32.54	23.87	1332.5	6.30	0.117E 09	0.00010	26.37	25.87	26.87	26.49	26.50	26.49
3	5.5	35.29	35.53	35.41	35.41	23.98	1335.8	6.28	0.117E 09	0.00022	20.31	19.88	20.09	20.09	20.09	20.09
4	15.5	37.85	37.28	35.39	36.48	24.34	1346.8	6.23	0.120E 09	0.00061	16.98	17.74	20.77	18.91	19.07	18.99
5	25.5	39.14	39.42	36.04	37.66	24.70	1358.1	6.17	0.122E 09	0.00100	15.88	15.58	20.23	17.70	17.98	17.84
6	45.5	40.72	40.37	37.20	38.87	25.42	1381.1	6.06	0.127E 09	0.00179	14.96	15.32	19.44	17.02	17.29	17.16
7	75.5	42.32	41.62	38.40	40.18	26.50	1417.1	5.89	0.135E 09	0.00298	14.44	15.11	19.19	16.69	16.98	16.84
8	105.5	43.82	43.20	40.44	41.98	27.58	1450.5	5.74	0.143E 09	0.00417	14.03	14.58	17.72	15.83	16.01	15.92
9	135.5	44.35	43.65	39.11	41.55	28.66	1483.3	5.60	0.150E 09	0.00536	14.49	15.17	21.76	17.63	18.30	17.97
10	165.2	44.51	44.12	40.55	42.43	29.73	1517.2	5.47	0.158E 09	0.00655	15.34	15.76	20.96	17.85	18.26	18.05
11	205.2	46.04	45.46	41.34	43.55	31.18	1565.4	5.28	0.168E 09	0.00816	15.20	15.82	22.23	18.27	18.87	18.57
12	245.2	47.90	47.50	44.09	45.90	32.62	1612.8	5.11	0.179E 09	0.00979	14.74	15.13	19.62	16.96	17.28	17.12
13	275.2	48.56	47.77	43.69	45.93	33.70	1647.6	4.99	0.186E 09	0.01102	15.11	15.96	22.48	18.36	19.01	18.69
14	305.2	49.72	49.63	45.83	47.75	34.78	1684.0	4.86	0.194E 09	0.01227	14.99	15.08	20.27	17.26	17.65	17.46
15	333.3	50.32	50.53	45.18	47.80	35.79	1719.5	4.74	0.201E 09	0.01344	15.38	15.16	23.79	18.60	19.53	19.06
16	363.3	52.56	52.87	47.27	49.99	36.88	1759.0	4.62	0.210E 09	0.01471	14.20	13.93	21.44	16.99	17.75	17.37
17	383.3	52.65	52.33	47.60	50.04	37.60	1782.7	4.55	0.215E 09	0.01554	14.78	15.10	22.24	17.87	18.59	18.23
18	403.3	53.69	52.97	48.09	50.71	38.32	1807.0	4.48	0.221E 09	0.01637	14.45	15.16	22.74	17.93	18.77	18.35
19	423.3	53.57	52.51	48.23	50.64	39.04	1832.0	4.42	0.226E 09	0.01720	15.27	16.47	24.13	19.13	20.00	19.56
20	443.3	55.36	55.77	50.01	52.79	39.76	1857.7	4.35	0.232E 09	0.01804	14.20	13.84	21.61	17.00	17.81	17.41
21	463.3	54.47	55.17	50.09	52.46	40.48	1884.2	4.29	0.238E 09	0.01887	15.82	15.06	23.01	18.47	19.23	18.85
AVERAGE VALUES THROUGH STATIONS 15 TO 20:																
	391.6	53.02	52.83	47.73	50.33	37.90	1793.0	4.53	0.218E 09	0.01588	14.71	14.94	22.66	17.92	18.74	18.33

========== EXPERIMENT 0R54 --- DEC. 11, 1987 ==========

INPUT ELECTRIC POWER = 3495.8 W HEAT RATE GAINED BY WATER = 3355.2 W HEAT BALANCE ERROR = 4.02%
MASS FLOW RATE = 37.2030 G/S PRESSURE DROP = 0.5974 MM H2O FRICTION FACTOR = 0.012320 FREM = 19.7008

REM = 1599.1 GRM+ = 0.48181E 08 UPSTREAM BULK TEMPERATURE = 23.84 DEG C DOWNSTREAM BULK TEMPERATURE = 45.47 DEG C
PRM = 4.874 RAM+ = 0.23483E 09 INLET BULK TEMPERATURE = 23.87 DEG C OUTLET BULK TEMPERATURE = 45.45 DEG C

STATION NO.	Z CM	WALL TEMPERATURE (DEG C) A	B	C	AVERAGE	TB (C)	RE	PR	RA+	Z+	NUSSELT NUMBER A	B	C	AVERAGE T	H	T+H
0	0.0	31.75	31.85	31.23	31.52	23.87	1268.5	6.30	0.142E 09	0.00000	35.48	35.00	37.95	36.54	36.59	36.57
1	1.5	33.31	33.46	32.97	33.18	23.94	1270.4	6.29	0.142E 09	0.00006	29.80	29.32	30.92	30.22	30.24	30.23
2	2.5	34.39	34.57	34.17	34.33	23.98	1271.8	6.28	0.143E 09	0.00010	26.83	26.37	27.42	27.00	27.01	27.01
3	5.5	37.63	37.91	37.77	37.77	24.12	1275.8	6.26	0.144E 09	0.00023	20.66	20.26	20.46	20.46	20.46	20.46
4	15.5	40.49	39.76	37.34	38.73	24.58	1289.3	6.19	0.148E 09	0.00064	17.53	18.38	21.86	19.71	19.91	19.81
5	25.5	42.18	42.54	38.15	40.25	25.04	1303.2	6.12	0.152E 09	0.00105	16.26	15.93	21.26	18.32	18.68	18.50
6	45.5	44.10	43.64	39.52	41.69	25.96	1331.7	5.97	0.159E 09	0.00188	15.33	15.73	20.51	17.68	18.02	17.85
7	75.5	45.96	45.18	41.02	43.29	27.34	1374.1	5.77	0.171E 09	0.00313	14.89	15.54	20.27	17.38	17.74	17.56
8	105.5	47.56	46.87	43.36	45.29	28.73	1413.8	5.59	0.183E 09	0.00439	14.67	15.23	18.88	16.68	16.92	16.80
9	135.5	48.36	47.47	41.75	44.83	30.11	1455.9	5.42	0.195E 09	0.00565	15.09	15.87	23.65	18.70	19.57	19.13
10	165.2	48.66	48.11	43.85	46.12	31.47	1500.0	5.25	0.207E 09	0.00690	15.98	16.51	22.19	18.75	19.22	18.98
11	205.2	50.47	49.68	44.71	47.39	33.32	1556.5	5.03	0.223E 09	0.00862	15.94	16.70	23.98	19.42	20.15	19.78
12	245.2	52.55	51.97	47.93	50.09	35.16	1615.5	4.82	0.239E 09	0.01037	15.64	16.18	21.31	18.21	18.61	18.41
13	275.2	53.36	52.41	47.53	50.21	36.54	1662.7	4.66	0.252E 09	0.01169	16.11	17.08	24.66	19.83	20.63	20.23
14	305.2	54.82	54.74	50.27	52.53	37.92	1707.3	4.52	0.265E 09	0.01300	15.99	16.07	21.88	18.50	18.96	18.73
15	333.3	55.82	56.05	49.79	52.87	39.21	1749.9	4.40	0.277E 09	0.01423	16.23	16.01	25.49	19.75	20.81	20.28
16	363.3	58.62	59.16	52.33	55.61	40.60	1797.7	4.28	0.291E 09	0.01555	14.92	14.49	22.92	17.91	18.81	18.36
17	383.3	58.81	58.32	52.76	55.66	41.52	1831.1	4.19	0.300E 09	0.01643	15.52	15.97	23.88	18.98	19.82	19.40
18	403.3	60.04	59.16	53.31	56.46	42.44	1862.2	4.11	0.309E 09	0.01732	15.22	16.02	24.65	19.12	20.14	19.63
19	423.3	60.04	58.64	53.60	56.47	43.36	1892.3	4.04	0.318E 09	0.01820	16.04	17.50	26.11	20.40	21.44	20.92
20	443.3	62.18	62.71	55.50	58.97	44.28	1923.4	3.97	0.327E 09	0.01909	14.92	14.49	23.79	18.17	19.25	18.71
21	463.3	61.21	62.04	55.87	58.74	45.20	1955.6	3.90	0.337E 09	0.01999	16.66	15.83	24.99	19.68	20.62	20.15
AVERAGE VALUES THROUGH STATIONS 15 TO 20:																
	391.6	59.25	59.01	52.88	56.01	41.90	1842.8	4.17	0.304E 09	0.01680	15.48	15.75	24.47	19.06	20.04	19.55

========== EXPERIMENT 0R55 --- DEC. 11, 1987 ==========

INPUT ELECTRIC POWER = 2062.5 W HEAT RATE GAINED BY WATER = 1961.5 W HEAT BALANCE ERROR = 3.93%
MASS FLOW RATE = 35.3260 G/S PRESSURE DROP = 0.5351 MM H2O FRICTION FACTOR = 0.012259 FREM = 17.1415

REM = 1398.3 GRM+ = 0.22032E 08 UPSTREAM BULK TEMPERATURE = 23.91 DEG C DOWNSTREAM BULK TEMPERATURE = 37.36 DEG C
PRM = 5.353 RAM+ = 0.11794E 09 INLET BULK TEMPERATURE = 23.92 DEG C OUTLET BULK TEMPERATURE = 37.35 DEG C

STATION NO.	Z CM	WALL TEMPERATURE (DEG C) A	B	C	AVERAGE	TB (C)	RE	PR	RA+	Z+	NUSSELT NUMBER A	B	C	AVERAGE T	H	T+H
0	0.0	28.80	28.87	28.52	28.68	23.93	1206.0	6.29	0.841E 08	0.00000	33.81	33.36	35.89	34.70	34.74	34.72
1	1.5	29.78	29.87	29.59	29.71	23.97	1207.1	6.29	0.843E 08	0.00007	28.39	27.94	29.33	28.73	28.75	28.74
2	2.5	30.45	30.56	30.33	30.42	24.00	1207.9	6.28	0.844E 08	0.00011	25.57	25.13	26.04	25.69	25.69	25.69
3	5.5	32.46	32.63	32.54	32.54	24.08	1210.3	6.27	0.848E 08	0.00024	19.69	19.30	19.49	19.49	19.49	19.49
4	15.5	34.59	34.20	32.87	33.63	24.37	1218.3	6.22	0.862E 08	0.00067	16.13	16.75	19.38	17.79	17.91	17.85
5	25.5	35.65	35.91	33.45	34.61	24.65	1226.3	6.18	0.876E 08	0.00111	14.98	14.63	18.73	16.54	16.77	16.65
6	45.5	36.98	36.70	34.42	35.63	25.23	1242.7	6.09	0.904E 08	0.00198	13.99	14.34	17.88	15.81	16.02	15.92
7	75.5	38.28	37.78	35.41	36.72	26.09	1268.2	5.95	0.948E 08	0.00329	13.46	14.04	17.60	15.43	15.67	15.55
8	105.5	39.44	39.06	37.09	38.17	26.94	1294.3	5.82	0.993E 08	0.00461	13.12	13.52	16.15	14.60	14.73	14.66
9	135.5	40.02	39.52	36.18	37.97	27.80	1317.1	5.71	0.103E 09	0.00593	13.38	13.96	19.52	16.08	16.60	16.34
10	165.2	40.05	39.73	36.97	36.43	28.65	1340.5	5.60	0.108E 09	0.00724	14.32	14.73	19.62	16.69	17.07	16.88
11	205.2	41.16	40.73	37.69	39.32	29.80	1373.3	5.46	0.113E 09	0.00900	14.33	14.89	20.63	17.10	17.62	17.36
12	245.2	42.56	42.27	39.78	41.10	30.95	1407.8	5.31	0.120E 09	0.01078	13.98	14.33	18.38	15.99	16.27	16.13
13	275.2	43.05	42.49	39.56	41.17	31.80	1434.8	5.21	0.124E 09	0.01212	14.40	15.16	20.88	17.31	17.83	17.57
14	305.2	44.13	44.03	41.22	42.65	32.66	1459.1	5.11	0.129E 09	0.01348	14.10	14.23	18.90	16.19	16.53	16.36
15	333.3	44.53	44.69	40.66	42.64	33.47	1482.5	5.01	0.133E 09	0.01476	14.58	14.37	22.44	17.60	18.46	18.03
16	363.3	46.30	46.52	42.43	44.42	34.33	1508.2	4.91	0.137E 09	0.01613	13.44	13.21	19.86	15.95	16.60	16.28
17	383.3	46.57	46.28	42.83	44.63	34.90	1525.9	4.85	0.140E 09	0.01705	13.77	14.13	20.27	16.52	17.11	16.82
18	403.3	47.33	46.85	43.15	45.12	35.47	1543.9	4.78	0.143E 09	0.01798	13.54	14.11	20.91	16.64	17.37	17.00
19	423.3	47.35	46.57	43.53	45.25	36.05	1562.5	4.71	0.146E 09	0.01891	14.18	15.23	21.41	17.42	18.06	17.74
20	443.3	48.72	49.08	44.75	46.83	36.62	1581.4	4.65	0.149E 09	0.01984	13.22	12.84	19.69	15.68	16.36	16.02
21	463.3	48.01	48.42	44.64	46.42	37.19	1599.3	4.59	0.152E 09	0.02077	14.78	14.24	21.47	17.31	17.99	17.65
AVERAGE VALUES THROUGH STATIONS 15 TO 20:																
	391.6	46.80	46.67	42.89	44.81	35.14	1534.1	4.82	0.141E 09	0.01744	13.79	13.98	20.77	16.64	17.33	16.98

========== EXPERIMENT 0R56 --- DEC. 11, 1987 ==========

INPUT ELECTRIC POWER = 2767.8 W HEAT RATE GAINED BY WATER = 2621.2 W HEAT BALANCE ERROR = 5.30%
MASS FLOW RATE = 33.3770 G/S PRESSURE DROP = 0.5087 MM H2O FRICTION FACTOR = 0.013041 FREM = 18.1563

REM = 1392.2 GRM+ = 0.34343E 08 UPSTREAM BULK TEMPERATURE = 23.74 DEG C DOWNSTREAM BULK TEMPERATURE = 42.58 DEG C
PRM = 5.048 RAM+ = 0.17336E 09 INLET BULK TEMPERATURE = 23.76 DEG C OUTLET BULK TEMPERATURE = 42.56 DEG C

STATION NO.	Z CM	WALL TEMPERATURE (DEG C) A	B	C	AVERAGE	TB (C)	RE	PR	RA+	Z+	NUSSELT NUMBER A	B	C	AVERAGE T	H	T+H
0	0.0	30.30	30.40	29.88	30.11	23.77	1135.4	6.32	0.110E 09	0.00000	33.41	32.92	35.70	34.38	34.43	34.41
1	1.5	31.60	31.73	31.32	31.49	23.82	1136.9	6.31	0.111E 09	0.00007	28.09	27.60	29.11	28.46	28.48	28.47
2	2.5	32.49	32.66	32.32	32.44	23.86	1137.9	6.30	0.111E 09	0.00011	25.30	24.83	25.82	25.44	25.44	25.44
3	5.5	35.17	35.42	35.30	35.30	23.98	1141.0	6.28	0.112E 09	0.00025	19.50	19.08	19.29	19.29	19.29	19.29
4	15.5	37.74	37.16	35.27	36.36	24.39	1151.5	6.22	0.114E 09	0.00071	16.33	17.06	20.02	18.20	18.36	18.28
5	25.5	39.08	39.42	36.06	37.66	24.79	1162.2	6.16	0.117E 09	0.00117	15.23	14.88	19.31	16.92	17.18	17.05
6	45.5	40.81	40.37	37.14	38.86	25.59	1184.2	6.03	0.122E 09	0.00210	14.29	14.71	18.82	16.38	16.66	16.52
7	75.5	42.32	41.65	38.29	40.14	26.79	1218.8	5.84	0.130E 09	0.00349	13.96	14.59	18.86	16.25	16.57	16.41
8	105.5	43.74	43.20	40.44	41.95	27.99	1249.3	5.69	0.138E 09	0.00489	13.73	14.22	17.37	15.49	15.67	15.58
9	135.5	44.29	43.56	39.02	41.47	29.20	1281.0	5.53	0.146E 09	0.00629	14.29	15.01	21.95	17.56	18.30	17.93
10	165.2	44.62	44.17	40.81	42.60	30.39	1314.1	5.38	0.154E 09	0.00768	15.10	15.60	20.64	17.60	17.99	17.80
11	205.2	46.15	45.54	41.62	43.73	31.99	1360.8	5.18	0.166E 09	0.00957	15.13	15.81	22.25	18.24	18.86	18.55
12	245.2	48.24	47.78	44.52	46.27	33.60	1404.2	5.00	0.176E 09	0.01149	14.57	15.04	19.52	16.84	17.17	17.00
13	275.2	48.98	48.22	44.23	46.42	34.80	1438.7	4.86	0.184E 09	0.01295	15.00	15.85	22.55	18.31	18.99	18.65
14	305.2	50.33	50.22	46.34	48.31	36.00	1474.9	4.72	0.193E 09	0.01443	14.79	14.91	20.51	17.23	17.68	17.46
15	333.3	51.13	51.35	46.21	48.72	37.13	1509.3	4.59	0.201E 09	0.01581	15.10	14.87	23.29	18.24	19.14	18.69
16	363.3	53.61	53.94	48.50	51.14	38.33	1543.6	4.48	0.210E 09	0.01727	13.81	13.52	20.74	16.47	17.20	16.84
17	383.3	53.90	53.45	48.92	51.30	39.13	1567.4	4.41	0.216E 09	0.01824	14.27	14.71	21.53	17.32	18.01	17.67
18	403.3	54.87	54.17	49.56	52.04	39.93	1592.0	4.34	0.222E 09	0.01922	14.08	14.77	21.85	17.37	18.14	17.76
19	423.3	54.83	53.80	49.74	52.03	40.74	1617.3	4.26	0.228E 09	0.02020	14.90	16.08	23.32	18.60	19.40	19.00
20	443.3	56.63	57.10	51.46	54.16	41.54	1643.5	4.19	0.235E 09	0.02118	13.90	13.48	21.14	16.62	17.42	17.02
21	463.3	55.87	56.49	51.65	53.92	42.34	1667.8	4.12	0.241E 09	0.02217	15.48	14.80	22.49	18.09	18.81	18.45
AVERAGE VALUES THROUGH STATIONS 15 TO 20:																
	391.6	54.16	53.97	49.06	51.56	39.47	1578.9	4.38	0.219E 09	0.01865	14.34	14.57	21.98	17.44	18.22	17.83

========== EXPERIMENT 0R57 --- DEC. 14, 1987 ==========

INPUT ELECTRIC POWER = 3340.2 W HEAT RATE GAINED BY WATER = 3191.1 W HEAT BALANCE ERROR = 4.47%
MASS FLOW RATE = 31.7160 G/S PRESSURE DROP = 0.5199 MM H2O FRICTION FACTOR = 0.014745 FREM = 20.6295

REM = 1399.1 GRM+ = 0.49515E 08 UPSTREAM BULK TEMPERATURE = 23.85 DEG C DOWNSTREAM BULK TEMPERATURE = 47.98 DEG C
PRM = 4.728 RAM+ = 0.23410E 09 INLET BULK TEMPERATURE = 23.88 DEG C OUTLET BULK TEMPERATURE = 47.96 DEG C

STATION NO.	Z CM	WALL TEMPERATURE (DEG C) A	B	C	AVERAGE	TB (C)	RE	PR	RA+	Z+	NUSSELT NUMBER A	B	C	AVERAGE T	H	T+H
0	0.0	31.84	31.92	31.26	31.57	23.88	1081.7	6.30	0.135E 09	0.00000	33.40	33.05	36.01	34.56	34.62	34.59
1	1.5	33.37	33.49	32.98	33.20	23.96	1083.5	6.29	0.136E 09	0.00007	28.22	27.86	29.45	28.73	28.74	28.74
2	2.5	34.43	34.57	34.16	34.33	24.01	1084.8	6.28	0.136E 09	0.00012	25.49	25.14	26.16	25.73	25.74	25.73
3	5.5	37.60	37.82	37.71	37.71	24.16	1088.6	6.25	0.137E 09	0.00027	19.75	19.44	19.59	19.59	19.60	19.59
4	15.5	40.29	39.62	37.17	38.56	24.68	1101.5	6.17	0.141E 09	0.00075	16.98	17.75	21.23	19.10	19.30	19.20
5	25.5	41.98	42.28	37.87	40.00	25.19	1114.8	6.09	0.145E 09	0.00124	15.77	15.50	20.90	17.89	18.27	18.08
6	45.5	43.90	43.47	39.35	41.51	26.22	1142.2	5.93	0.154E 09	0.00221	14.94	15.32	20.13	17.27	17.63	17.45
7	75.5	45.57	44.90	40.74	42.99	27.76	1181.4	5.72	0.166E 09	0.00368	14.79	15.36	20.29	17.29	17.68	17.49
8	105.5	47.39	46.79	43.24	45.17	29.30	1219.9	5.52	0.179E 09	0.00515	14.50	15.01	18.82	16.54	16.79	16.66
9	135.5	48.28	47.52	42.03	44.97	30.84	1261.0	5.33	0.192E 09	0.00663	15.00	15.68	23.37	18.51	19.35	18.93
10	165.2	48.86	48.39	44.27	46.45	32.37	1302.4	5.14	0.205E 09	0.00812	15.80	16.26	21.88	18.50	18.96	18.73
11	205.2	50.86	50.13	45.22	47.86	34.42	1356.6	4.90	0.221E 09	0.01015	15.77	16.50	24.00	19.29	20.07	19.68
12	245.2	53.35	52.78	48.84	50.95	36.48	1415.5	4.66	0.239E 09	0.01222	15.28	15.81	20.85	17.81	18.20	18.00
13	275.2	54.35	53.50	48.84	51.38	38.02	1458.1	4.51	0.253E 09	0.01376	15.74	16.59	23.75	19.23	19.96	19.59
14	305.2	56.00	55.86	51.52	53.72	39.56	1501.7	4.37	0.267E 09	0.01530	15.58	15.72	21.42	18.09	18.54	18.31
15	333.3	57.17	57.29	51.27	54.25	41.00	1544.9	4.24	0.280E 09	0.01674	15.81	15.69	24.88	19.29	20.31	19.80
16	363.3	59.92	60.35	53.85	56.99	42.54	1590.4	4.11	0.295E 09	0.01830	14.66	14.31	22.53	17.63	18.51	18.07
17	383.3	60.15	59.62	54.27	57.08	43.57	1619.2	4.03	0.305E 09	0.01934	15.34	15.85	23.76	18.83	19.68	19.25
18	403.3	61.42	60.57	54.90	57.95	44.60	1649.1	3.95	0.314E 09	0.02039	15.08	15.89	24.64	19.01	20.06	19.54
19	423.3	61.56	60.24	55.42	58.16	45.62	1680.1	3.87	0.325E 09	0.02144	15.90	17.33	25.85	20.21	21.24	20.72
20	443.3	63.68	64.18	57.37	60.65	46.65	1712.2	3.79	0.335E 09	0.02250	14.85	14.43	23.58	18.06	19.11	18.59
21	463.3	62.89	63.70	57.83	60.56	47.68	1743.1	3.71	0.345E 09	0.02355	16.59	15.76	24.86	19.59	20.52	20.06
AVERAGE VALUES THROUGH STATIONS 15 TO 20:																
	391.6	60.65	60.37	54.51	57.51	44.00	1632.6	3.99	0.309E 09	0.01979	15.27	15.58	24.21	18.84	19.82	19.33

========== EXPERIMENT 0R58 --- DEC. 15, 1987 ==========

INPUT ELECTRIC POWER = 1972.5 W　　HEAT RATE GAINED BY WATER = 1873.9 W　　HEAT BALANCE ERROR = 5.00%
MASS FLOW RATE = 29.8750 G/S　　PRESSURE DROP = 0.4424 MM H2O　　FRICTION FACTOR = 0.014167　　FREM = 17.0277

REM = 1202.0　　GRM+ = 0.21934E 08　　UPSTREAM BULK TEMPERATURE = 23.85 DEG C　　DOWNSTREAM BULK TEMPERATURE = 38.90 DEG C
PRM = 5.260　　RAM+ = 0.11536E 09　　INLET BULK TEMPERATURE = 23.87 DEG C　　OUTLET BULK TEMPERATURE = 38.88 DEG C

STA- TION NO.	Z CM	-WALL TEMPERATURE (DEG C)- A	B	C	AVER- AGE	TB (C)	RE	PR	RA+	Z+	NUSSELT NUMBER A	B	C	AVERAGE T	H	T+H
0	0.0	28.93	28.98	28.61	28.78	23.87	1018.7	6.30	0.793E 08	0.00000	30.86	30.53	32.96	31.78	31.83	31.80
1	1.5	29.88	29.96	29.67	29.79	23.92	1019.8	6.29	0.795E 08	0.00008	26.16	25.82	27.15	26.56	26.57	26.57
2	2.5	30.54	30.63	30.39	30.49	23.95	1020.5	6.29	0.796E 08	0.00013	23.67	23.34	24.21	23.85	23.86	23.86
3	5.5	32.51	32.65	32.58	32.58	24.05	1022.7	6.27	0.801E 08	0.00028	18.42	18.12	18.27	18.27	18.27	18.27
4	15.5	34.56	34.12	32.87	33.60	24.37	1030.3	6.22	0.815E 08	0.00080	15.29	15.98	18.33	16.87	16.98	16.93
5	25.5	35.62	35.82	33.45	34.58	24.69	1037.9	6.17	0.830E 08	0.00131	14.25	13.99	17.78	15.74	15.95	15.84
6	45.5	36.90	36.64	34.31	35.54	25.33	1053.5	6.07	0.860E 08	0.00234	13.44	13.74	17.31	15.23	15.45	15.34
7	75.5	38.14	37.72	35.39	36.66	26.29	1077.8	5.92	0.907E 08	0.00389	13.09	13.57	17.06	14.96	15.19	15.08
8	105.5	39.27	38.92	36.86	37.98	27.25	1101.3	5.78	0.953E 08	0.00545	12.88	13.27	16.11	14.43	14.59	14.51
9	135.5	40.02	39.54	36.29	38.04	28.21	1123.2	5.66	0.997E 08	0.00701	13.08	13.63	19.11	15.72	16.24	15.98
10	165.2	40.19	39.90	37.14	38.60	29.16	1145.8	5.54	0.104E 09	0.00856	13.97	14.35	19.31	16.34	16.74	16.54
11	205.2	41.36	41.01	38.00	39.59	30.44	1177.6	5.38	0.111E 09	0.01066	14.08	14.54	20.34	16.80	17.33	17.06
12	245.2	42.79	42.58	40.12	41.40	31.72	1211.2	5.22	0.117E 09	0.01277	13.85	14.12	18.25	15.84	16.12	15.98
13	275.2	43.59	43.05	40.13	41.73	32.68	1234.5	5.10	0.122E 09	0.01437	14.02	14.75	20.53	16.91	17.46	17.18
14	305.2	44.80	44.70	41.81	43.28	33.64	1258.1	4.99	0.126E 09	0.01599	13.67	13.80	18.68	15.83	16.20	16.02
15	333.3	45.24	45.37	41.37	43.34	34.54	1281.1	4.89	0.131E 09	0.01751	14.23	14.06	22.29	17.31	18.22	17.76
16	363.3	47.01	47.20	43.24	45.17	35.51	1306.6	4.78	0.135E 09	0.01915	13.19	12.98	19.62	15.70	16.35	16.03
17	383.3	47.28	46.98	43.62	45.37	36.15	1324.1	4.70	0.139E 09	0.02025	13.61	13.99	20.29	16.42	17.04	16.73
18	403.3	48.12	47.69	44.17	46.04	36.79	1342.2	4.63	0.142E 09	0.02136	13.35	13.87	20.49	16.35	17.05	16.70
19	423.3	48.14	47.47	44.54	46.17	37.43	1358.4	4.57	0.145E 09	0.02244	14.11	15.05	21.25	17.28	17.91	17.60
20	443.3	49.60	49.99	45.77	47.78	38.07	1374.8	4.51	0.149E 09	0.02353	13.09	12.66	19.60	15.54	16.24	15.89
21	463.3	48.99	49.45	45.59	47.40	38.71	1391.6	4.45	0.152E 09	0.02461	14.66	14.03	21.90	17.33	18.13	17.73
AVERAGE VALUES THROUGH STATIONS 15 TO 20:																
	391.6	47.57	47.45	43.78	45.65	36.41	1331.2	4.68	0.140E 09	0.02071	13.60	13.77	20.59	16.43	17.14	16.78

========== EXPERIMENT 0R59 --- DEC. 15, 1987 ==========

INPUT ELECTRIC POWER = 2623.2 W　　HEAT RATE GAINED BY WATER = 2477.8 W　　HEAT BALANCE ERROR = 5.54%
MASS FLOW RATE = 27.8180 G/S　　PRESSURE DROP = 0.3909 MM H2O　　FRICTION FACTOR = 0.014419　　FREM = 17.1996

REM = 1192.9　　GRM+ = 0.35326E 08　　UPSTREAM BULK TEMPERATURE = 23.86 DEG C　　DOWNSTREAM BULK TEMPERATURE = 45.22 DEG C
PRM = 4.888　　RAM+ = 0.17266E 09　　INLET BULK TEMPERATURE = 23.88 DEG C　　OUTLET BULK TEMPERATURE = 45.20 DEG C

STA- TION NO.	Z CM	-WALL TEMPERATURE (DEG C)- A	B	C	AVER- AGE	TB (C)	RE	PR	RA+	Z+	NUSSELT NUMBER A	B	C	AVERAGE T	H	T+H
0	0.0	30.47	30.52	30.01	30.25	23.89	948.9	6.30	0.105E 09	0.00000	31.34	31.09	33.67	32.40	32.44	32.42
1	1.5	31.72	31.80	31.40	31.58	23.95	950.3	6.29	0.105E 09	0.00008	26.55	26.30	27.68	27.04	27.05	27.05
2	2.5	32.58	32.67	32.36	32.50	24.00	951.3	6.28	0.106E 09	0.00014	24.02	23.77	24.66	24.27	24.28	24.27
3	5.5	35.17	35.31	35.24	35.24	24.13	954.2	6.26	0.106E 09	0.00030	18.66	18.45	18.56	18.56	18.57	18.56
4	15.5	37.51	36.94	35.08	36.15	24.55	964.2	6.19	0.109E 09	0.00085	15.94	16.68	19.64	17.82	17.97	17.89
5	25.5	38.83	39.11	35.70	37.33	25.04	974.4	6.12	0.112E 09	0.00141	14.93	14.63	19.31	16.74	17.04	16.89
6	45.5	40.52	40.17	36.83	38.59	25.95	995.5	5.97	0.118E 09	0.00252	14.09	14.44	18.88	16.25	16.57	16.41
7	75.5	42.04	41.42	38.20	39.97	27.32	1026.9	5.77	0.126E 09	0.00419	13.90	14.51	18.80	16.18	16.51	16.34
8	105.5	43.57	43.06	40.32	41.82	28.68	1056.2	5.60	0.135E 09	0.00587	13.71	14.19	17.53	15.53	15.74	15.63
9	135.5	44.35	43.67	39.39	41.70	30.05	1087.2	5.43	0.144E 09	0.00755	14.22	14.93	21.78	17.46	18.16	17.82
10	165.2	44.96	44.60	41.18	42.98	31.40	1119.7	5.26	0.153E 09	0.00923	14.95	15.36	20.74	17.51	17.95	17.73
11	205.2	46.69	46.13	42.18	44.30	33.22	1161.6	5.04	0.164E 09	0.01153	14.99	15.63	22.51	18.22	18.91	18.56
12	245.2	48.75	48.37	45.07	46.81	35.03	1204.9	4.83	0.176E 09	0.01386	14.65	15.07	20.03	17.06	17.45	17.25
13	275.2	49.80	49.18	45.45	47.47	36.40	1239.6	4.67	0.185E 09	0.01563	14.95	15.67	22.12	18.09	18.71	18.40
14	305.2	51.32	51.23	47.56	49.42	37.76	1272.9	4.54	0.194E 09	0.01739	14.73	14.82	20.39	17.14	17.58	17.36
15	333.3	52.28	52.42	47.49	49.92	39.04	1304.1	4.42	0.203E 09	0.01903	15.04	14.89	23.58	18.31	19.27	18.79
16	363.3	54.71	54.96	49.85	52.35	40.41	1339.2	4.29	0.213E 09	0.02079	13.89	13.65	21.02	16.64	17.40	17.02
17	383.3	54.95	54.52	50.23	52.49	41.32	1363.6	4.21	0.220E 09	0.02197	14.54	15.01	22.24	17.75	18.51	18.13
18	403.3	56.06	55.43	51.01	53.38	42.22	1387.3	4.13	0.227E 09	0.02315	14.31	14.99	22.53	17.75	18.59	18.17
19	423.3	56.27	55.34	51.42	53.61	43.13	1409.4	4.06	0.233E 09	0.02434	15.05	16.20	23.85	18.86	19.73	19.30
20	443.3	58.15	58.57	53.21	55.79	44.04	1432.2	3.99	0.240E 09	0.02553	13.99	13.58	21.52	16.80	17.65	17.23
21	463.3	57.44	58.09	53.33	55.55	44.95	1455.7	3.92	0.247E 09	0.02672	15.77	15.00	23.52	18.59	19.45	19.02
AVERAGE VALUES THROUGH STATIONS 15 TO 20:																
	391.6	55.40	55.21	50.54	52.92	41.69	1372.6	4.18	0.223E 09	0.02247	14.47	14.72	22.46	17.69	18.53	18.11

========== EXPERIMENT 0R60 --- DEC. 15, 1987 ==========

INPUT ELECTRIC POWER = 3145.7 W　　HEAT RATE GAINED BY WATER = 2969.4 W　　HEAT BALANCE ERROR = 5.60%
MASS FLOW RATE = 26.1720 G/S　　PRESSURE DROP = 0.3802 MM H2O　　FRICTION FACTOR = 0.015825　　FREM = 18.8169

REM = 1189.0　　GRM+ = 0.50263E 08　　UPSTREAM BULK TEMPERATURE = 23.77 DEG C　　DOWNSTREAM BULK TEMPERATURE = 50.98 DEG C
PRM = 4.571　　RAM+ = 0.22976E 09　　INLET BULK TEMPERATURE = 23.80 DEG C　　OUTLET BULK TEMPERATURE = 50.96 DEG C

STA- TION NO.	Z CM	-WALL TEMPERATURE (DEG C)- A	B	C	AVER- AGE	TB (C)	RE	PR	RA+	Z+	NUSSELT NUMBER A	B	C	AVERAGE T	H	T+H
0	0.0	31.44	31.56	30.94	31.22	23.81	891.1	6.31	0.125E 09	0.00000	32.38	31.88	34.69	33.36	33.41	33.38
1	1.5	32.93	33.10	32.60	32.81	23.89	892.8	6.30	0.126E 09	0.00009	27.34	26.84	28.39	27.72	27.74	27.73
2	2.5	33.96	34.16	33.75	33.90	23.95	894.0	6.29	0.126E 09	0.00015	24.69	24.21	25.23	24.83	24.84	24.83
3	5.5	37.04	37.34	37.19	37.19	24.12	897.5	6.26	0.127E 09	0.00032	19.13	18.69	18.91	18.91	18.91	18.91
4	15.5	39.95	39.28	36.86	38.24	24.70	909.5	6.17	0.132E 09	0.00091	16.18	16.93	20.30	18.23	18.43	18.33
5	25.5	41.62	42.00	37.58	39.70	25.28	921.9	6.08	0.136E 09	0.00150	15.08	14.74	20.03	17.09	17.47	17.28
6	45.5	43.65	43.19	39.06	41.24	26.44	947.6	5.90	0.145E 09	0.00268	14.28	14.68	19.47	16.61	16.97	16.79
7	75.5	45.34	44.62	40.31	42.65	28.18	983.3	5.66	0.158E 09	0.00446	14.26	14.89	20.17	16.92	17.37	17.15
8	105.5	47.17	46.48	43.01	44.92	29.91	1019.9	5.44	0.171E 09	0.00625	14.13	14.72	18.62	16.25	16.52	16.39
9	135.5	48.16	47.35	41.98	44.87	31.65	1059.4	5.22	0.185E 09	0.00805	14.71	15.47	23.53	18.38	19.31	18.84
10	165.2	48.91	48.45	44.36	46.52	33.37	1096.2	5.02	0.198E 09	0.00987	15.56	16.04	22.01	18.40	18.91	18.65
11	205.2	51.14	50.46	45.56	48.18	35.69	1149.0	4.75	0.216E 09	0.01236	15.56	16.27	24.37	19.25	20.14	19.69
12	245.2	53.77	53.20	49.53	51.51	38.01	1203.0	4.51	0.235E 09	0.01485	15.17	15.74	20.76	17.72	18.11	17.91
13	275.2	54.96	54.09	49.63	52.08	39.74	1243.7	4.35	0.250E 09	0.01672	15.66	16.61	24.10	19.32	20.12	19.72
14	305.2	56.82	56.70	52.57	54.66	41.48	1287.2	4.19	0.265E 09	0.01860	15.49	15.61	21.44	18.03	18.49	18.26
15	333.3	58.18	58.50	52.92	55.63	43.11	1325.4	4.06	0.280E 09	0.02037	15.72	15.39	24.14	18.91	19.84	19.38
16	363.3	61.39	61.82	55.59	58.60	44.85	1367.0	3.93	0.295E 09	0.02227	14.27	13.91	21.97	17.17	18.03	17.60
17	383.3	61.85	61.33	56.04	58.82	46.01	1396.1	3.84	0.306E 09	0.02354	14.86	15.37	23.48	18.39	19.30	18.85
18	403.3	63.29	62.47	57.06	59.97	47.16	1425.8	3.75	0.316E 09	0.02483	14.58	15.35	23.77	18.36	19.37	18.86
19	423.3	63.53	62.26	57.63	60.26	48.32	1454.6	3.67	0.327E 09	0.02611	15.43	16.84	25.21	19.65	20.67	20.16
20	443.3	65.71	66.19	59.75	62.85	49.48	1484.5	3.59	0.338E 09	0.02739	14.43	14.02	22.81	17.52	18.52	18.02
21	463.3	64.91	65.70	60.08	62.69	50.64	1515.8	3.50	0.350E 09	0.02869	16.38	15.53	24.76	19.40	20.36	19.88
AVERAGE VALUES THROUGH STATIONS 15 TO 20:																
	391.6	62.33	62.10	56.50	59.36	46.49	1408.9	3.80	0.310E 09	0.02408	14.88	15.15	23.56	18.33	19.29	18.81

========== EXPERIMENT 0R61 --- DEC. 15, 1987 ==========

INPUT ELECTRIC POWER = 3609.0 W   HEAT RATE GAINED BY WATER = 3387.4 W   HEAT BALANCE ERROR = 6.14%
MASS FLOW RATE = 25.0450 G/S   PRESSURE DROP = 0.3744 MM H2O   FRICTION FACTOR = 0.017000   FREM = 20.3349

REM = 1196.2   GRM+ = 0.66389E 08   UPSTREAM BULK TEMPERATURE = 23.78 DEG C   DOWNSTREAM BULK TEMPERATURE = 56.21 DEG C
PRM = 4.330   RAM+ = 0.28746E 09   INLET BULK TEMPERATURE = 23.82 DEG C   OUTLET BULK TEMPERATURE = 56.19 DEG C

STATION NO.	Z CM	WALL TEMPERATURE (DEG C) A	B	C	AVERAGE	TB (C)	RE	PR	RA+	Z+	NUSSELT NUMBER A	B	C	AVERAGE T	H	T+H
0	0.0	32.66	32.75	32.02	32.36	23.82	853.0	6.31	0.143E 09	0.00000	31.92	31.58	34.40	33.02	33.08	33.05
1	1.5	34.36	34.49	33.92	34.17	23.92	855.0	6.29	0.144E 09	0.00009	27.02	26.68	28.20	27.51	27.52	27.52
2	2.5	35.53	35.69	35.23	35.42	23.99	856.3	6.28	0.144E 09	0.00015	24.44	24.10	25.08	24.67	24.67	24.67
3	5.5	39.05	39.29	39.17	39.17	24.20	860.4	6.25	0.146E 09	0.00034	18.98	18.68	18.83	18.83	18.83	18.83
4	15.5	42.25	41.51	38.44	40.16	24.89	874.2	6.14	0.152E 09	0.00095	16.21	16.93	20.76	18.43	18.67	18.55
5	25.5	44.15	44.55	39.33	41.84	25.58	888.4	6.03	0.158E 09	0.00157	15.13	14.81	20.43	17.28	17.70	17.49
6	45.5	46.26	45.81	40.93	43.48	26.96	917.9	5.82	0.170E 09	0.00280	14.51	14.86	20.05	16.95	17.37	17.16
7	75.5	48.22	47.43	42.59	45.21	29.03	957.9	5.56	0.187E 09	0.00467	14.53	15.15	20.55	17.23	17.70	17.46
8	105.5	50.17	49.39	45.24	47.51	31.10	1001.6	5.29	0.206E 09	0.00654	14.55	15.17	19.62	16.91	17.24	17.07
9	135.5	51.50	50.61	44.40	47.72	33.17	1044.9	5.05	0.224E 09	0.00845	15.06	15.83	24.60	18.97	20.02	19.50
10	165.2	52.45	51.93	47.40	49.79	35.22	1089.0	4.81	0.242E 09	0.01038	15.94	16.43	22.56	18.85	19.37	19.11
11	205.2	55.06	54.26	49.04	51.85	37.99	1150.8	4.52	0.268E 09	0.01299	15.98	16.76	24.66	19.68	20.53	20.10
12	245.2	58.43	57.73	53.41	55.75	40.75	1213.9	4.26	0.295E 09	0.01559	15.35	15.98	21.43	18.10	18.55	18.32
13	275.2	59.80	58.84	53.76	56.54	42.82	1261.9	4.08	0.316E 09	0.01756	15.92	16.87	24.71	19.70	20.55	20.13
14	305.2	61.93	61.83	57.07	59.47	44.89	1309.1	3.92	0.337E 09	0.01955	15.81	15.90	22.12	18.47	18.99	18.73
15	333.3	63.71	64.00	57.50	60.68	46.83	1356.6	3.77	0.358E 09	0.02143	15.89	15.63	25.14	19.37	20.45	19.91
16	363.3	67.28	67.71	60.52	64.01	48.90	1406.1	3.63	0.380E 09	0.02344	14.55	14.22	23.02	17.71	18.70	18.20
17	383.3	67.71	67.10	61.11	64.26	50.28	1441.2	3.53	0.395E 09	0.02479	15.32	15.87	24.64	19.10	20.12	19.61
18	403.3	69.33	68.39	62.31	65.58	51.66	1478.0	3.43	0.411E 09	0.02615	15.07	15.92	25.02	19.13	20.26	19.69
19	423.3	69.75	68.36	63.23	66.14	53.04	1509.7	3.36	0.426E 09	0.02749	15.91	17.35	26.09	20.29	21.36	20.83
20	443.3	72.31	72.82	65.70	69.13	54.43	1541.7	3.28	0.441E 09	0.02883	14.82	14.42	23.53	18.03	19.08	18.55
21	463.3	71.79	72.68	66.26	69.25	55.81	1575.1	3.21	0.456E 09	0.03018	16.55	15.68	25.31	19.66	20.71	20.20
AVERAGE VALUES THROUGH STATIONS 15 TO 20:																
	391.6	66.35	68.07	61.73	64.97	50.86	1455.6	3.50	0.402E 09	0.02535	15.26	15.57	24.58	18.94	19.99	19.47

========== EXPERIMENT 0R62 --- DEC. 16, 1987 ==========

INPUT ELECTRIC POWER = 2457.7 W   HEAT RATE GAINED BY WATER = 2322.1 W   HEAT BALANCE ERROR = 5.52%
MASS FLOW RATE = 22.4030 G/S   PRESSURE DROP = 0.3290 MM H2O   FRICTION FACTOR = 0.018698   FREM = 18.5885

REM = 994.1   GRM+ = 0.36662E 08   UPSTREAM BULK TEMPERATURE = 23.76 DEG C   DOWNSTREAM BULK TEMPERATURE = 48.63 DEG C
PRM = 4.695   RAM+ = 0.17214E 09   INLET BULK TEMPERATURE = 23.80 DEG C   OUTLET BULK TEMPERATURE = 48.61 DEG C

STATION NO.	Z CM	WALL TEMPERATURE (DEG C) A	B	C	AVERAGE	TB (C)	RE	PR	RA+	Z+	NUSSELT NUMBER A	B	C	AVERAGE T	H	T+H
0	0.0	30.15	30.21	29.71	29.95	23.80	762.7	6.31	0.978E 08	0.00000	30.46	30.15	32.69	31.45	31.50	31.47
1	1.5	31.37	31.46	31.08	31.25	23.88	764.0	6.30	0.982E 08	0.00010	25.79	25.48	26.85	26.23	26.25	26.24
2	2.5	32.22	32.33	32.01	32.14	23.93	764.9	6.29	0.985E 08	0.00017	23.33	23.02	23.91	23.54	23.54	23.54
3	5.5	34.75	34.91	34.83	34.83	24.09	767.7	6.27	0.994E 08	0.00038	18.13	17.85	17.99	17.99	17.99	17.99
4	15.5	37.23	36.71	34.77	35.87	24.62	777.0	6.18	0.102E 09	0.00106	15.31	15.96	19.02	17.16	17.33	17.24
5	25.5	38.52	38.77	35.36	37.00	25.15	786.6	6.10	0.106E 09	0.00175	14.42	14.15	18.87	16.26	16.58	16.42
6	45.5	40.16	39.83	36.38	38.19	26.20	806.6	5.93	0.112E 09	0.00313	13.78	14.11	18.91	16.05	16.43	16.24
7	75.5	41.67	41.14	37.84	39.62	27.79	835.1	5.71	0.121E 09	0.00521	13.81	14.35	19.08	16.20	16.58	16.39
8	105.5	43.34	42.84	40.12	41.61	29.38	863.2	5.51	0.130E 09	0.00730	13.67	14.19	17.77	15.61	15.85	15.73
9	135.5	44.40	43.76	39.44	41.76	30.97	893.2	5.31	0.140E 09	0.00940	14.16	14.87	22.44	17.62	18.48	18.05
10	165.2	45.18	44.85	41.57	43.30	32.54	923.1	5.12	0.150E 09	0.01150	14.99	15.40	20.98	17.62	18.08	17.85
11	205.2	47.17	46.61	42.94	44.92	34.66	962.9	4.87	0.162E 09	0.01438	15.07	15.77	22.75	18.37	19.08	18.73
12	245.2	49.66	49.23	46.10	47.77	36.77	1006.2	4.63	0.176E 09	0.01732	14.55	15.05	20.11	17.05	17.45	17.25
13	275.2	50.75	50.13	46.51	48.47	38.36	1036.7	4.48	0.186E 09	0.01949	15.08	15.88	22.95	18.48	19.21	18.85
14	305.2	52.52	52.44	49.08	50.78	39.95	1068.8	4.34	0.197E 09	0.02167	14.82	14.92	20.39	17.20	17.63	17.41
15	333.3	53.69	53.91	49.34	51.57	41.43	1100.8	4.20	0.207E 09	0.02372	15.16	14.89	23.51	18.34	19.27	18.80
16	363.3	56.47	56.72	51.94	54.26	43.02	1132.8	4.07	0.218E 09	0.02593	13.78	13.53	20.78	16.48	17.22	16.85
17	383.3	56.94	56.52	52.36	54.55	44.08	1154.1	3.99	0.225E 09	0.02741	14.38	14.86	22.32	17.66	18.47	18.07
18	403.3	58.18	57.51	53.25	55.55	45.14	1176.3	3.90	0.233E 09	0.02889	14.15	14.92	22.74	17.73	18.64	18.18
19	423.3	58.55	57.66	53.94	56.02	46.20	1199.3	3.82	0.240E 09	0.03039	14.91	16.06	23.79	18.74	19.64	19.19
20	443.3	60.46	60.81	55.67	58.15	47.26	1222.4	3.74	0.248E 09	0.03188	13.92	13.56	21.83	16.87	17.79	17.33
21	463.3	59.86	60.61	56.16	58.19	48.31	1244.9	3.67	0.256E 09	0.03338	15.90	14.93	23.40	18.57	19.41	18.99
AVERAGE VALUES THROUGH STATIONS 15 TO 20:																
	391.6	57.38	57.19	52.75	55.02	44.52	1164.3	3.95	0.229E 09	0.02804	14.38	14.64	22.50	17.64	18.50	18.07

========== EXPERIMENT 0R63 --- DEC. 16, 1987 ==========

INPUT ELECTRIC POWER = 2897.6 W   HEAT RATE GAINED BY WATER = 2749.3 W   HEAT BALANCE ERROR = 5.12%
MASS FLOW RATE = 20.9590 G/S   PRESSURE DROP = 0.2718 MM H2O   FRICTION FACTOR = 0.017626   FREM = 17.4588

REM = 990.5   GRM+ = 0.52263E 08   UPSTREAM BULK TEMPERATURE = 23.72 DEG C   DOWNSTREAM BULK TEMPERATURE = 55.18 DEG C
PRM = 4.380   RAM+ = 0.22891E 09   INLET BULK TEMPERATURE = 23.76 DEG C   OUTLET BULK TEMPERATURE = 55.16 DEG C

STATION NO.	Z CM	WALL TEMPERATURE (DEG C) A	B	C	AVERAGE	TB (C)	RE	PR	RA+	Z+	NUSSELT NUMBER A	B	C	AVERAGE T	H	T+H
0	0.0	31.40	31.46	30.85	31.14	23.77	713.0	6.32	0.116E 09	0.00000	30.00	29.75	32.34	31.06	31.11	31.08
1	1.5	32.82	32.91	32.44	32.65	23.86	714.5	6.30	0.116E 09	0.00011	25.55	25.29	26.69	26.04	26.06	26.05
2	2.5	33.81	33.91	33.54	33.70	23.93	715.6	6.29	0.117E 09	0.00018	23.17	22.92	23.82	23.43	23.44	23.43
3	5.5	36.76	36.92	36.84	36.84	24.13	718.9	6.26	0.118E 09	0.00040	18.12	17.89	18.01	18.01	18.01	18.01
4	15.5	39.55	38.97	36.38	37.82	24.80	730.1	6.15	0.123E 09	0.00113	15.48	16.12	19.73	17.55	17.77	17.66
5	25.5	41.05	41.40	37.13	39.18	25.47	741.6	6.05	0.127E 09	0.00187	14.64	14.32	19.55	16.63	17.02	16.82
6	45.5	43.03	42.59	38.47	40.64	26.81	765.7	5.84	0.137E 09	0.00335	14.02	14.41	19.50	16.44	16.86	16.65
7	75.5	44.86	44.17	40.12	42.32	28.82	798.1	5.58	0.150E 09	0.00558	14.11	14.74	20.03	16.77	17.23	17.00
8	105.5	46.74	46.14	42.78	44.61	30.83	833.1	5.33	0.165E 09	0.00782	14.16	14.71	18.84	16.34	16.64	16.49
9	135.5	48.16	47.38	42.20	44.99	32.84	868.7	5.09	0.180E 09	0.01009	14.63	15.42	23.95	18.46	19.48	18.97
10	165.2	49.33	48.93	45.13	47.13	34.83	903.9	4.85	0.194E 09	0.01238	15.38	15.82	21.66	18.13	18.63	18.38
11	205.2	51.73	51.08	46.71	49.06	37.50	954.4	4.56	0.214E 09	0.01551	15.58	16.32	24.08	19.18	20.02	19.60
12	245.2	54.82	54.26	50.73	52.64	40.18	1004.6	4.31	0.235E 09	0.01861	15.06	15.66	20.91	17.71	18.14	17.92
13	275.2	56.26	55.53	51.40	53.65	42.19	1044.6	4.13	0.252E 09	0.02097	15.62	16.47	23.86	19.18	19.95	19.57
14	305.2	58.36	58.21	54.29	56.29	44.20	1082.1	3.98	0.268E 09	0.02333	15.46	15.62	21.69	18.10	18.61	18.36
15	333.3	60.03	60.28	54.97	57.56	46.08	1119.6	3.83	0.284E 09	0.02557	15.63	15.36	24.53	18.99	20.01	19.50
16	363.3	63.32	63.63	57.73	60.60	48.09	1160.2	3.68	0.301E 09	0.02797	14.27	13.98	22.54	17.37	18.34	17.85
17	383.3	63.90	63.39	58.56	61.10	49.43	1187.8	3.59	0.313E 09	0.02957	14.99	15.54	23.76	18.58	19.51	19.05
18	403.3	65.49	64.72	59.67	62.39	50.77	1216.7	3.50	0.325E 09	0.03119	14.70	15.52	24.33	18.63	19.72	19.18
19	423.3	65.98	64.86	60.65	63.04	52.11	1245.9	3.41	0.338E 09	0.03281	15.58	16.94	25.28	19.77	20.77	20.27
20	443.3	68.31	68.68	62.86	65.68	53.45	1271.1	3.33	0.349E 09	0.03441	14.51	14.15	22.89	17.62	18.61	18.12
21	463.3	67.83	68.64	63.38	65.81	54.79	1297.4	3.26	0.361E 09	0.03602	16.49	15.52	25.05	19.52	20.53	20.02
AVERAGE VALUES THROUGH STATIONS 15 TO 20:																
	391.6	64.50	64.26	59.08	61.73	49.99	1200.2	3.56	0.318E 09	0.03025	14.95	15.25	23.89	18.49	19.49	18.99

========== EXPERIMENT 0R64 --- DEC. 16, 1987 ==========

INPUT ELECTRIC POWER = 3315.5 W HEAT RATE GAINED BY WATER = 3123.7 W HEAT BALANCE ERROR = 5.79%
MASS FLOW RATE = 19.9190 G/S PRESSURE DROP = 0.2895 MM H2O FRICTION FACTOR = 0.020759 FREM = 20.7683

REM = 1000.4 GRM+ = 0.70690E 08 UPSTREAM BULK TEMPERATURE = 23.82 DEG C DOWNSTREAM BULK TEMPERATURE = 61.43 DEG C
PRM = 4.099 RAM+ = 0.28975E 09 INLET BULK TEMPERATURE = 23.87 DEG C OUTLET BULK TEMPERATURE = 61.40 DEG C

STATION NO.	Z CM	-WALL TEMPERATURE (DEG C)- A	B	C	AVERAGE	TB (C)	RE	PR	RA+	Z+	NUSSELT NUMBER A	B	C	AVERAGE T	H	T+H
0	0.0	32.59	32.69	31.92	32.28	23.88	679.3	6.30	0.132E 09	0.00000	29.84	29.51	32.32	30.94	31.00	30.97
1	1.5	34.22	34.35	33.76	34.02	23.99	681.1	6.28	0.133E 09	0.00012	25.42	25.09	26.62	25.92	25.94	25.93
2	2.5	35.34	35.50	35.03	35.22	24.07	682.3	6.27	0.134E 09	0.00019	23.07	22.74	23.73	23.31	23.32	23.31
3	5.5	38.71	38.95	38.83	38.83	24.31	686.1	6.23	0.135E 09	0.00042	18.05	17.75	17.90	17.90	17.90	17.90
4	15.5	41.91	41.17	38.02	39.78	25.11	698.9	6.10	0.142E 09	0.00120	15.44	16.15	20.10	17.68	17.95	17.81
5	25.5	43.76	44.04	38.96	41.43	25.91	712.2	5.98	0.148E 09	0.00197	14.51	14.28	19.84	16.68	17.12	16.90
6	45.5	45.84	45.44	40.48	43.06	27.51	738.3	5.75	0.161E 09	0.00353	14.07	14.39	19.90	16.59	17.06	16.83
7	75.5	47.91	47.15	42.40	44.96	29.92	776.3	5.44	0.180E 09	0.00588	14.26	14.89	20.55	17.05	17.56	17.30
8	105.5	50.06	49.36	45.19	47.45	32.32	817.2	5.15	0.200E 09	0.00825	14.38	14.97	19.82	16.86	17.25	17.05
9	135.5	51.70	50.89	45.01	48.15	34.72	857.2	4.87	0.219E 09	0.01068	14.93	15.68	24.62	18.87	19.96	19.42
10	165.2	53.26	52.78	48.56	50.79	37.10	900.2	4.60	0.239E 09	0.01313	15.59	16.07	21.98	18.40	18.91	18.65
11	205.2	56.08	55.41	50.33	53.04	40.30	956.8	4.30	0.268E 09	0.01639	15.88	16.57	24.96	19.66	20.59	20.13
12	245.2	59.87	59.24	55.10	57.33	43.50	1015.7	4.03	0.298E 09	0.01970	15.20	15.82	21.46	18.00	18.49	18.24
13	275.2	61.60	60.78	55.95	58.57	45.90	1060.5	3.84	0.320E 09	0.02221	15.79	16.66	24.66	19.56	20.44	20.00
14	305.2	64.11	63.99	59.47	61.76	48.30	1106.6	3.67	0.344E 09	0.02473	15.61	15.73	22.10	18.34	18.89	18.61
15	333.3	66.32	66.59	60.52	63.49	50.55	1151.7	3.51	0.367E 09	0.02711	15.60	15.33	24.67	19.01	20.07	19.54
16	363.3	70.03	70.41	63.53	66.87	52.95	1199.0	3.36	0.392E 09	0.02966	14.35	14.04	23.17	17.61	18.68	18.14
17	383.3	70.69	70.09	64.59	67.49	54.55	1228.6	3.27	0.408E 09	0.03135	15.15	15.74	24.36	18.90	19.90	19.40
18	403.3	72.47	71.59	65.85	68.94	56.15	1259.6	3.19	0.424E 09	0.03304	14.95	15.80	25.14	19.07	20.26	19.66
19	423.3	73.15	71.89	67.15	69.83	57.75	1290.8	3.10	0.441E 09	0.03478	15.80	17.20	25.90	20.14	21.20	20.67
20	443.3	75.92	76.30	69.77	72.94	59.36	1322.4	3.01	0.457E 09	0.03656	14.63	14.31	23.28	17.85	18.88	18.36
21	463.3	75.58	76.51	70.59	73.32	60.96	1355.6	2.93	0.473E 09	0.03839	16.53	15.54	25.09	19.55	20.56	20.06
AVERAGE VALUES THROUGH STATIONS 15 TO 20:																
	391.6	71.43	71.14	65.24	68.26	55.22	1242.0	3.24	0.415E 09	0.03209	15.08	15.40	24.42	18.76	19.83	19.30

========== EXPERIMENT 0R65 --- DEC. 17, 1987 ==========

INPUT ELECTRIC POWER = 3624.1 W HEAT RATE GAINED BY WATER = 3426.2 W HEAT BALANCE ERROR = 5.46%
MASS FLOW RATE = 18.9370 G/S PRESSURE DROP = 0.3183 MM H2O FRICTION FACTOR = 0.025224 FREM = 25.3002

REM = 1003.0 GRM+ = 0.90114E 08 UPSTREAM BULK TEMPERATURE = 23.92 DEG C DOWNSTREAM BULK TEMPERATURE = 67.30 DEG C
PRM = 3.866 RAM+ = 0.34840E 09 INLET BULK TEMPERATURE = 23.97 DEG C OUTLET BULK TEMPERATURE = 67.26 DEG C

STATION NO.	Z CM	-WALL TEMPERATURE (DEG C)- A	B	C	AVERAGE	TB (C)	RE	PR	RA+	Z+	NUSSELT NUMBER A	B	C	AVERAGE T	H	T+H
0	0.0	33.56	33.64	32.73	33.16	23.98	647.3	6.28	0.146E 09	0.00000	29.77	29.52	32.59	31.05	31.12	31.08
1	1.5	35.33	35.44	34.75	35.07	24.11	649.3	6.26	0.147E 09	0.00012	25.42	25.16	26.81	26.03	26.05	26.04
2	2.5	36.55	36.69	36.14	36.38	24.20	650.6	6.25	0.148E 09	0.00020	23.10	22.84	23.89	23.42	23.43	23.42
3	5.5	40.21	40.42	40.31	40.31	24.48	654.8	6.20	0.150E 09	0.00045	18.12	17.88	18.00	18.00	18.00	18.00
4	15.5	43.64	42.86	39.18	41.21	25.41	669.0	6.06	0.158E 09	0.00126	15.59	16.29	20.64	17.98	18.29	18.13
5	25.5	45.65	45.94	40.29	43.04	26.33	683.8	5.91	0.166E 09	0.00207	14.69	14.47	20.32	16.98	17.45	17.21
6	45.5	47.98	47.50	42.01	44.87	28.18	711.5	5.66	0.182E 09	0.00371	14.26	14.62	20.43	16.92	17.43	17.18
7	75.5	50.22	49.45	44.03	46.93	30.95	754.7	5.31	0.207E 09	0.00619	14.56	15.17	21.45	17.56	18.16	17.86
8	105.5	52.51	51.80	47.42	49.79	33.72	798.6	4.98	0.231E 09	0.00872	14.84	15.42	20.34	17.35	17.74	17.54
9	135.5	54.47	53.63	47.32	50.69	36.49	845.4	4.66	0.257E 09	0.01131	15.39	16.14	25.55	19.49	20.66	20.08
10	165.2	56.46	55.95	51.23	53.72	39.23	890.9	4.40	0.283E 09	0.01386	15.98	16.46	22.93	19.00	19.58	19.29
11	205.2	59.83	59.01	53.31	56.37	42.92	955.9	4.08	0.321E 09	0.01732	16.17	16.99	26.32	20.34	21.45	20.89
12	245.2	64.08	63.32	58.70	61.20	46.61	1021.6	3.79	0.359E 09	0.02084	15.55	16.25	22.46	18.61	19.18	18.90
13	275.2	65.98	65.08	59.82	62.67	49.38	1072.3	3.59	0.389E 09	0.02350	16.29	17.22	25.90	20.34	21.33	20.84
14	305.2	68.80	68.70	63.69	66.22	52.15	1126.5	3.40	0.421E 09	0.02619	16.17	16.27	23.34	19.14	19.78	19.46
15	333.3	71.41	71.70	64.99	68.27	54.75	1171.6	3.26	0.449E 09	0.02868	16.09	15.82	26.18	19.83	21.07	20.45
16	363.3	75.49	75.87	68.51	72.10	57.52	1222.9	3.11	0.481E 09	0.03138	14.85	14.54	24.28	18.31	19.49	18.90
17	383.3	76.14	75.43	69.41	72.60	59.37	1257.4	3.01	0.501E 09	0.03327	15.85	16.55	26.48	20.10	21.34	20.72
18	403.3	78.28	77.29	71.02	74.40	61.21	1293.9	2.91	0.522E 09	0.03518	15.53	16.49	27.03	20.10	21.52	20.81
19	423.3	79.09	77.66	72.52	75.45	63.06	1330.5	2.83	0.544E 09	0.03702	16.50	18.11	27.95	21.34	22.63	21.99
20	443.3	82.41	82.84	75.43	79.03	64.91	1368.0	2.75	0.568E 09	0.03883	15.07	14.71	25.06	18.67	19.97	19.32
21	463.3	82.04	83.09	76.48	79.53	66.75	1407.6	2.66	0.592E 09	0.04064	17.21	16.11	27.04	20.61	21.85	21.23
AVERAGE VALUES THROUGH STATIONS 15 TO 20:																
	391.6	77.14	76.80	70.31	73.64	60.14	1274.0	2.98	0.511E 09	0.03406	15.65	16.04	26.16	19.73	21.00	20.36

========== EXPERIMENT 0R66 --- DEC. 17, 1987 ========== (CHECK 0R34)

INPUT ELECTRIC POWER = 1813.0 W HEAT RATE GAINED BY WATER = 1718.2 W HEAT BALANCE ERROR = 5.22%
MASS FLOW RATE = 21.3630 G/S PRESSURE DROP = 0.2756 MM H2O FRICTION FACTOR = 0.017244 FREM = 15.4847

REM = 898.0 GRM+ = 0.23052E 08 UPSTREAM BULK TEMPERATURE = 23.90 DEG C DOWNSTREAM BULK TEMPERATURE = 43.19 DEG C
PRM = 5.003 RAM+ = 0.11532E 09 INLET BULK TEMPERATURE = 23.92 DEG C OUTLET BULK TEMPERATURE = 43.18 DEG C

STATION NO.	Z CM	-WALL TEMPERATURE (DEG C)- A	B	C	AVERAGE	TB (C)	RE	PR	RA+	Z+	NUSSELT NUMBER A	B	C	AVERAGE T	H	T+H
0	0.0	28.96	29.01	28.64	28.81	23.93	729.4	6.29	0.729E 08	0.00000	28.44	28.13	30.38	29.29	29.33	29.31
1	1.5	29.89	29.97	29.67	29.80	23.99	730.3	6.28	0.732E 08	0.00011	24.23	23.92	25.16	24.61	24.62	24.61
2	2.5	30.53	30.62	30.39	30.48	24.03	731.0	6.28	0.733E 08	0.00018	21.99	21.68	22.49	22.16	22.16	22.16
3	5.5	32.46	32.60	32.53	32.53	24.15	733.1	6.26	0.738E 08	0.00039	17.21	16.93	17.07	17.07	17.07	17.07
4	15.5	34.50	34.12	32.70	33.50	24.56	740.0	6.19	0.756E 08	0.00111	14.37	14.95	17.55	15.97	16.10	16.04
5	25.5	35.51	35.68	33.11	34.35	24.97	747.1	6.13	0.773E 08	0.00183	13.55	13.33	17.54	15.21	15.49	15.35
6	45.5	36.73	36.53	34.06	35.34	25.79	761.6	6.00	0.809E 08	0.00328	13.03	13.26	17.24	14.92	15.19	15.05
7	75.5	37.97	37.61	35.27	36.53	27.03	784.0	5.81	0.864E 08	0.00545	12.97	13.42	17.22	14.94	15.21	15.07
8	105.5	39.35	39.00	36.98	38.08	28.26	804.0	5.65	0.916E 08	0.00764	12.77	13.18	16.24	14.42	14.61	14.52
9	135.5	40.13	39.71	36.49	38.21	29.49	825.0	5.50	0.970E 08	0.00983	13.27	13.81	20.18	16.20	16.86	16.53
10	165.2	40.73	40.49	37.91	39.26	30.71	847.0	5.34	0.103E 09	0.01201	14.06	14.40	19.56	16.47	16.89	16.68
11	205.2	42.29	41.97	39.21	40.67	32.35	877.0	5.14	0.110E 09	0.01497	14.12	14.59	20.47	16.87	17.41	17.14
12	245.2	44.23	44.03	41.58	42.86	33.99	906.0	4.95	0.117E 09	0.01798	13.64	13.92	18.42	15.76	16.10	15.93
13	275.2	45.16	44.77	42.12	43.54	35.23	928.9	4.81	0.123E 09	0.02027	14.02	14.60	20.19	16.74	17.25	17.00
14	305.2	46.63	46.61	43.93	45.28	36.46	953.1	4.67	0.129E 09	0.02258	13.65	13.68	18.57	15.75	16.12	15.93
15	333.3	47.48	47.57	43.82	45.67	37.61	974.7	4.55	0.134E 09	0.02472	14.03	13.91	22.32	17.18	18.14	17.66
16	363.3	49.50	49.69	46.00	47.80	38.84	997.7	4.44	0.140E 09	0.02700	12.96	12.74	19.31	15.43	16.08	15.75
17	383.3	49.95	49.60	46.48	48.13	39.66	1013.6	4.36	0.144E 09	0.02852	13.41	13.89	20.25	16.31	16.95	16.63
18	403.3	50.89	50.47	47.35	49.01	40.49	1030.0	4.29	0.148E 09	0.03005	13.24	13.80	20.07	16.15	16.80	16.47
19	423.3	51.18	50.58	47.78	49.33	41.31	1047.0	4.21	0.153E 09	0.03159	13.93	14.84	21.23	17.14	17.81	17.48
20	443.3	52.65	52.99	49.22	51.02	42.13	1063.6	4.14	0.157E 09	0.03313	13.06	12.64	19.36	15.44	16.11	15.78
21	463.3	52.33	52.77	49.23	50.89	42.95	1078.9	4.07	0.161E 09	0.03467	14.61	13.96	21.84	17.27	18.06	17.67
AVERAGE VALUES THROUGH STATIONS 15 TO 20:																
	391.6	50.28	50.15	46.77	48.49	40.01	1021.1	4.33	0.146E 09	0.02917	13.44	13.64	20.42	16.28	16.98	16.63

========== EXPERIMENT OR67 --- DEC. 17, 1987 ==========

INPUT ELECTRIC POWER = 2375.5 W HEAT RATE GAINED BY WATER = 2260.8 W HEAT BALANCE ERROR = 4.83%
MASS FLOW RATE = 19.7670 G/S PRESSURE DROP = 0.2397 MM H2O FRICTION FACTOR = 0.017489 FREM = 15.7764

REM = 902.1 GRM+ = 0.38783E 08 UPSTREAM BULK TEMPERATURE = 23.90 DEG C DOWNSTREAM BULK TEMPERATURE = 51.33 DEG C
PRM = 4.549 RAM+ = 0.17643E 09 INLET BULK TEMPERATURE = 23.94 DEG C OUTLET BULK TEMPERATURE = 51.31 DEG C

STATION NO.	Z CM	WALL TEMPERATURE (DEG C) A	B	C	AVERAGE	TB (C)	RE	PR	RA+	Z+	NUSSELT NUMBER A	B	C	AVERAGE T	H	T+H
0	0.0	30.57	30.63	30.03	30.31	23.94	675.0	6.29	0.960E 08	0.00000	28.40	28.12	30.89	29.52	29.57	29.54
1	1.5	31.75	31.85	31.38	31.59	24.02	676.3	6.28	0.964E 08	0.00012	24.34	24.05	25.57	24.86	24.88	24.87
2	2.5	32.57	32.68	32.32	32.47	24.08	677.2	6.27	0.968E 08	0.00019	22.16	21.87	22.85	22.42	22.43	22.43
3	5.5	35.03	35.20	35.11	35.11	24.26	679.9	6.24	0.977E 08	0.00043	17.45	17.19	17.32	17.32	17.32	17.32
4	15.5	37.43	36.88	34.79	35.97	24.84	689.2	6.15	0.101E 09	0.00120	14.92	15.60	16.87	16.87	17.07	16.97
5	25.5	38.72	38.88	35.39	37.09	25.42	698.6	6.06	0.104E 09	0.00198	14.11	13.94	16.82	16.07	16.42	16.25
6	45.5	40.33	40.03	36.63	38.40	26.59	718.3	5.87	0.111E 09	0.00355	13.62	13.92	18.63	15.84	16.20	16.02
7	75.5	42.01	41.48	38.23	39.99	28.34	745.2	5.64	0.121E 09	0.00591	13.63	14.18	18.85	16.00	16.38	16.19
8	105.5	43.76	43.32	40.52	42.03	30.10	773.3	5.42	0.131E 09	0.00828	13.58	14.04	17.80	15.55	15.80	15.67
9	135.5	45.05	44.47	40.29	42.52	31.85	803.6	5.20	0.142E 09	0.01067	14.00	14.65	21.90	17.31	18.11	17.71
10	165.2	46.08	45.75	42.57	44.24	33.58	831.4	5.00	0.152E 09	0.01307	14.72	15.12	20.48	17.26	17.70	17.48
11	205.2	48.12	47.65	44.04	45.96	35.92	871.9	4.73	0.166E 09	0.01637	14.98	15.59	22.52	18.21	18.90	18.56
12	245.2	50.73	50.35	47.30	48.92	38.25	912.8	4.49	0.180E 09	0.01967	14.58	15.04	20.12	17.06	17.47	17.27
13	275.2	52.04	51.54	48.07	49.93	40.00	944.1	4.33	0.192E 09	0.02215	15.07	15.73	22.49	18.28	18.94	18.61
14	305.2	54.07	54.04	50.73	52.39	41.76	977.6	4.17	0.204E 09	0.02464	14.69	14.72	20.15	17.00	17.43	17.22
15	333.3	55.51	55.63	51.13	53.35	43.40	1006.1	4.04	0.215E 09	0.02698	14.87	14.73	23.31	18.11	19.06	18.58
16	363.3	58.08	58.36	53.57	55.90	45.15	1038.1	3.90	0.227E 09	0.02950	13.89	13.60	21.33	16.72	17.54	17.13
17	383.3	58.76	58.27	54.38	56.45	46.32	1060.5	3.81	0.235E 09	0.03119	14.41	15.00	22.22	17.69	18.46	18.08
18	403.3	60.01	59.42	55.30	57.51	47.48	1082.8	3.73	0.243E 09	0.03289	14.28	14.99	22.90	17.85	18.77	18.31
19	423.3	60.57	59.71	56.18	58.16	48.65	1104.9	3.64	0.252E 09	0.03458	14.98	16.15	23.73	18.78	19.65	19.21
20	443.3	62.69	63.05	58.05	60.46	49.82	1128.0	3.56	0.260E 09	0.03629	13.85	13.48	21.65	16.75	17.66	17.20
21	463.3	62.27	63.01	58.52	60.58	50.99	1152.1	3.48	0.269E 09	0.03801	15.76	14.80	23.60	18.54	19.44	18.99
AVERAGE VALUES THROUGH STATIONS 15 TO 20:																
	391.6	59.27	59.07	54.77	56.97	46.80	1070.1	3.78	0.238E 09	0.03190	14.38	14.66	22.52	17.65	18.52	18.09

========== EXPERIMENT OR68 --- DEC. 18, 1987 ==========

INPUT ELECTRIC POWER = 2805.6 W HEAT RATE GAINED BY WATER = 2646.5 W HEAT BALANCE ERROR = 5.67%
MASS FLOW RATE = 18.4320 G/S PRESSURE DROP = 0.2845 MM H2O FRICTION FACTOR = 0.023839 FREM = 21.4997

REM = 901.9 GRM+ = 0.55584E 08 UPSTREAM BULK TEMPERATURE = 24.00 DEG C DOWNSTREAM BULK TEMPERATURE = 58.44 DEG C
PRM = 4.217 RAM+ = 0.23442E 09 INLET BULK TEMPERATURE = 24.05 DEG C OUTLET BULK TEMPERATURE = 58.41 DEG C

STATION NO.	Z CM	WALL TEMPERATURE (DEG C) A	B	C	AVERAGE	TB (C)	RE	PR	RA+	Z+	NUSSELT NUMBER A	B	C	AVERAGE T	H	T+H
0	0.0	31.80	31.86	31.13	31.48	24.05	631.1	6.27	0.113E 09	0.00000	28.42	28.19	31.12	29.65	29.71	29.68
1	1.5	33.19	33.28	32.72	32.98	24.16	632.6	6.26	0.114E 09	0.00012	24.37	24.13	25.71	24.96	24.98	24.97
2	2.5	34.15	34.26	33.82	34.02	24.23	633.6	6.24	0.114E 09	0.00021	22.18	21.95	22.95	22.50	22.51	22.50
3	5.5	37.04	37.20	37.12	37.12	24.45	636.8	6.21	0.116E 09	0.00046	17.48	17.26	17.37	17.37	17.37	17.37
4	15.5	39.78	39.14	36.49	37.98	25.18	647.8	6.09	0.120E 09	0.00129	15.05	15.74	19.43	17.17	17.41	17.29
5	25.5	41.34	41.57	37.33	39.39	25.92	659.0	5.98	0.125E 09	0.00213	14.22	14.01	19.21	16.27	16.66	16.47
6	45.5	43.39	43.02	38.75	40.98	27.38	681.3	5.76	0.135E 09	0.00381	13.65	13.98	19.22	16.08	16.52	16.30
7	75.5	45.23	44.68	40.71	42.83	29.58	713.2	5.49	0.150E 09	0.00635	13.90	14.41	19.54	16.41	16.85	16.63
8	105.5	47.25	46.70	43.21	45.10	31.78	748.2	5.21	0.166E 09	0.00890	13.99	14.50	18.93	16.25	16.59	16.42
9	135.5	48.87	48.20	43.19	45.86	33.98	781.4	4.95	0.181E 09	0.01152	14.45	15.13	23.37	18.11	19.08	18.59
10	165.2	50.46	50.08	46.35	48.31	36.15	817.1	4.70	0.196E 09	0.01415	14.96	15.37	21.00	17.61	18.08	17.85
11	205.2	53.03	52.43	48.00	50.37	39.09	864.8	4.41	0.217E 09	0.01768	15.25	15.94	23.86	18.86	19.73	19.29
12	245.2	56.21	55.75	52.24	54.11	42.02	915.9	4.15	0.241E 09	0.02123	14.90	15.41	20.69	17.49	17.92	17.71
13	275.2	57.91	57.30	53.16	55.38	44.22	951.9	3.98	0.258E 09	0.02392	15.38	16.11	23.55	18.86	19.64	19.25
14	305.2	60.35	60.29	56.33	58.33	46.41	990.7	3.80	0.276E 09	0.02664	15.05	15.12	21.16	17.61	18.12	17.87
15	333.3	62.28	62.42	57.16	59.76	48.47	1027.1	3.66	0.293E 09	0.02919	15.14	14.99	24.07	18.53	19.57	19.05
16	363.3	65.55	65.81	60.04	62.86	50.67	1068.1	3.50	0.312E 09	0.03194	14.00	13.76	22.24	17.09	18.06	17.58
17	383.3	66.29	65.70	60.86	63.43	52.14	1096.2	3.40	0.325E 09	0.03379	14.70	15.33	23.84	18.42	19.43	18.92
18	403.3	67.92	67.22	62.11	64.84	53.60	1120.5	3.33	0.337E 09	0.03560	14.49	15.24	24.39	18.47	19.63	19.05
19	423.3	68.59	67.52	63.40	65.73	55.07	1146.0	3.25	0.350E 09	0.03743	15.31	16.62	24.86	19.42	20.41	19.92
20	443.3	71.16	71.54	65.87	68.61	56.54	1172.7	3.17	0.363E 09	0.03927	14.12	13.76	22.13	17.11	18.04	17.57
21	463.3	70.87	71.76	66.32	68.82	58.00	1198.9	3.09	0.375E 09	0.04117	16.01	14.97	24.76	19.04	20.12	19.58
AVERAGE VALUES THROUGH STATIONS 15 TO 20:																
	391.6	66.96	66.70	61.57	64.20	52.75	1105.1	3.38	0.330E 09	0.03454	14.63	14.95	23.59	18.17	19.19	18.68

========== EXPERIMENT OR69 --- DEC. 18, 1987 ==========

INPUT ELECTRIC POWER = 3133.0 W HEAT RATE GAINED BY WATER = 2959.7 W HEAT BALANCE ERROR = 5.53%
MASS FLOW RATE = 17.3490 G/S PRESSURE DROP = 0.3057 MM H2O FRICTION FACTOR = 0.028876 FREM = 25.9947

REM = 900.2 GRM+ = 0.73492E 08 UPSTREAM BULK TEMPERATURE = 24.02 DEG C DOWNSTREAM BULK TEMPERATURE = 64.93 DEG C
PRM = 3.955 RAM+ = 0.29064E 09 INLET BULK TEMPERATURE = 24.07 DEG C OUTLET BULK TEMPERATURE = 64.89 DEG C

STATION NO.	Z CM	WALL TEMPERATURE (DEG C) A	B	C	AVERAGE	TB (C)	RE	PR	RA+	Z+	NUSSELT NUMBER A	B	C	AVERAGE T	H	T+H
0	0.0	32.77	32.83	32.03	32.42	24.08	594.3	6.27	0.127E 09	0.00000	28.32	28.16	30.97	29.54	29.61	29.57
1	1.5	34.34	34.41	33.81	34.09	24.20	596.1	6.25	0.128E 09	0.00013	24.30	24.13	25.64	24.90	24.92	24.91
2	2.5	35.42	35.50	35.04	35.25	24.29	597.3	6.23	0.128E 09	0.00022	22.13	21.96	22.91	22.47	22.48	22.47
3	5.5	38.65	38.78	38.72	38.72	24.55	600.8	6.19	0.130E 09	0.00049	17.45	17.29	17.37	17.37	17.37	17.37
4	15.5	41.60	40.97	37.79	39.54	25.42	613.1	6.06	0.137E 09	0.00137	15.18	15.79	19.85	17.40	17.67	17.53
5	25.5	43.45	43.73	38.77	41.18	26.29	626.0	5.92	0.143E 09	0.00226	14.29	14.06	19.65	16.47	16.91	16.69
6	45.5	45.64	45.19	40.31	42.86	28.04	649.9	5.68	0.156E 09	0.00405	13.86	14.23	19.89	16.46	16.97	16.72
7	75.5	47.66	47.03	42.34	44.84	30.65	686.9	5.35	0.176E 09	0.00676	14.27	14.81	20.75	17.09	17.64	17.37
8	105.5	50.09	49.36	45.42	47.57	33.26	725.0	5.04	0.196E 09	0.00950	14.33	14.97	19.83	16.85	17.24	17.04
9	135.5	51.98	51.23	45.72	48.66	35.87	764.6	4.73	0.217E 09	0.01232	14.87	15.60	24.33	18.73	19.78	19.25
10	165.2	53.93	53.48	49.39	51.55	38.46	804.3	4.47	0.238E 09	0.01511	15.39	15.86	21.79	18.20	18.71	18.45
11	205.2	57.01	56.34	51.51	54.09	41.94	861.0	4.15	0.269E 09	0.01888	15.70	16.43	24.72	19.47	20.39	19.93
12	245.2	60.87	60.27	56.24	58.41	45.42	915.6	3.88	0.299E 09	0.02270	15.22	15.83	21.72	18.10	18.62	18.36
13	275.2	62.72	61.96	57.40	59.87	48.03	959.4	3.69	0.323E 09	0.02559	15.94	16.80	24.98	19.77	20.68	20.22
14	305.2	65.57	65.48	61.06	63.29	50.65	1004.9	3.50	0.349E 09	0.02851	15.61	15.71	22.39	18.43	19.03	18.73
15	333.3	68.01	68.20	62.20	65.15	53.09	1046.6	3.35	0.373E 09	0.03124	15.57	15.37	25.50	19.25	20.48	19.87
16	363.3	71.78	72.05	65.56	68.74	55.71	1089.4	3.21	0.398E 09	0.03416	14.38	14.15	23.48	17.75	18.87	18.31
17	383.3	72.53	71.89	66.69	69.45	57.45	1119.1	3.12	0.415E 09	0.03614	15.28	15.97	24.94	19.21	20.28	19.75
18	403.3	74.47	73.70	68.18	71.13	59.19	1148.8	3.02	0.431E 09	0.03819	15.04	15.84	25.56	19.24	20.50	19.87
19	423.3	75.34	74.16	69.55	72.15	60.93	1180.2	2.93	0.448E 09	0.04027	15.89	17.32	26.57	20.42	21.59	21.00
20	443.3	78.44	78.82	72.38	75.50	62.67	1211.9	2.84	0.466E 09	0.04231	14.49	14.15	23.54	17.81	18.93	18.37
21	463.3	78.11	79.08	73.19	75.90	64.41	1243.9	2.77	0.485E 09	0.04428	16.64	15.54	25.97	19.86	21.03	20.44
AVERAGE VALUES THROUGH STATIONS 15 TO 20:																
	391.6	73.43	73.14	67.43	70.35	58.17	1132.7	3.08	0.422E 09	0.03705	15.11	15.47	24.93	18.95	20.11	19.53

========== EXPERIMENT OR70 --- DEC. 18, 1987 ==========

INPUT ELECTRIC POWER = 3430.5 W   HEAT RATE GAINED BY WATER = 3215.1 W   HEAT BALANCE ERROR = 6.28%
MASS FLOW RATE = 16.4460 G/S   PRESSURE DROP = 0.3109 MM H2O   FRICTION FACTOR = 0.032645   FREM = 29.3437

REM = 898.9   GRM+ = 0.92252E 08   UPSTREAM BULK TEMPERATURE = 23.91 DEG C   DOWNSTREAM BULK TEMPERATURE = 70.78 DEG C
PRM = 3.735   RAM+ = 0.34453E 09   INLET BULK TEMPERATURE = 23.97 DEG C   OUTLET BULK TEMPERATURE = 70.74 DEG C

STATION NO.	Z CM	WALL TEMPERATURE (DEG C) A	B	C	AVERAGE	TB (C)	RE	PR	RA+	Z+	NUSSELT NUMBER A	B	C	AVERAGE T	H	T+H
0	0.0	33.72	33.76	32.85	33.29	23.98	562.1	6.28	0.137E 09	0.00000	27.48	27.37	30.16	28.73	28.79	28.76
1	1.5	35.44	35.49	34.81	35.14	24.12	564.0	6.26	0.138E 09	0.00014	23.65	23.53	25.02	24.29	24.31	24.30
2	2.5	36.62	36.69	36.17	36.41	24.22	565.3	6.25	0.139E 09	0.00023	21.57	21.46	22.39	21.94	21.95	21.95
3	5.5	40.18	40.28	40.23	40.23	24.52	569.1	6.20	0.141E 09	0.00051	17.07	16.96	17.02	17.02	17.02	17.02
4	15.5	43.47	42.66	38.95	41.01	25.52	582.5	6.04	0.149E 09	0.00145	14.85	15.56	19.85	17.21	17.53	17.37
5	25.5	45.42	45.74	40.09	42.83	26.52	596.6	5.88	0.157E 09	0.00239	14.07	13.84	19.60	16.30	16.78	16.54
6	45.5	47.64	47.19	41.61	44.51	28.51	622.2	5.62	0.173E 09	0.00426	13.85	14.18	20.22	16.55	17.12	16.83
7	75.5	50.08	49.31	44.09	46.89	31.50	663.5	5.24	0.199E 09	0.00714	14.16	14.78	20.91	17.10	17.69	17.39
8	105.5	52.54	51.88	47.62	49.91	34.50	704.5	4.89	0.224E 09	0.01007	14.47	15.02	19.89	16.93	17.32	17.13
9	135.5	54.78	54.00	47.94	51.17	37.49	748.7	4.56	0.250E 09	0.01305	14.99	15.70	24.80	18.95	20.07	19.51
10	165.2	57.13	56.60	52.06	54.46	40.45	792.4	4.29	0.277E 09	0.01599	15.45	15.96	22.21	18.40	18.96	18.68
11	205.2	60.76	59.97	54.41	57.39	44.44	852.7	3.96	0.315E 09	0.02000	15.68	16.47	25.67	19.76	20.87	20.32
12	245.2	65.44	64.72	60.19	62.63	48.43	915.8	3.66	0.355E 09	0.02407	14.94	15.60	21.61	17.89	18.44	18.16
13	275.2	67.38	66.48	61.41	64.17	51.42	966.2	3.45	0.388E 09	0.02716	15.85	16.79	25.31	19.83	20.82	20.32
14	305.2	70.34	70.27	65.56	67.93	54.42	1012.3	3.28	0.418E 09	0.03022	15.80	15.87	22.59	18.62	19.22	18.92
15	333.3	73.43	73.72	67.35	70.46	57.22	1057.3	3.13	0.448E 09	0.03313	15.46	15.18	24.74	18.92	20.03	19.48
16	363.3	77.67	77.97	70.85	74.33	60.21	1106.3	2.97	0.479E 09	0.03639	14.28	14.03	23.44	17.65	18.80	18.22
17	383.3	78.59	77.83	71.99	75.10	62.21	1141.1	2.86	0.501E 09	0.03858	15.16	15.90	25.39	19.27	20.46	19.86
18	403.3	80.74	79.87	73.72	77.01	64.20	1175.4	2.78	0.524E 09	0.04065	14.98	15.82	26.04	19.34	20.72	20.03
19	423.3	81.79	80.43	75.34	78.23	66.20	1211.9	2.69	0.549E 09	0.04273	15.86	17.36	27.03	20.55	21.82	21.18
20	443.3	85.29	85.70	78.55	82.02	68.19	1249.1	2.60	0.573E 09	0.04484	14.40	14.06	23.77	17.80	19.00	18.40
21	463.3	85.02	86.12	79.72	82.64	70.19	1287.8	2.52	0.597E 09	0.04697	16.52	15.38	25.71	19.67	20.83	20.25
AVERAGE VALUES THROUGH STATIONS 15 TO 20:																
	391.6	79.58	79.25	72.97	76.19	63.04	1156.9	2.84	0.512E 09	0.03939	15.02	15.39	25.07	18.92	20.14	19.53

========== EXPERIMENT OR71 --- DEC. 19, 1987 ==========

INPUT ELECTRIC POWER = 2258.2 W   HEAT RATE GAINED BY WATER = 2121.7 W   HEAT BALANCE ERROR = 6.04%
MASS FLOW RATE = 17.0240 G/S   PRESSURE DROP = 0.2412 MM H2O   FRICTION FACTOR = 0.023715   FREM = 18.8387

REM = 794.4   GRM+ = 0.38868E 08   UPSTREAM BULK TEMPERATURE = 23.84 DEG C   DOWNSTREAM BULK TEMPERATURE = 53.74 DEG C
PRM = 4.441   RAM+ = 0.17260E 09   INLET BULK TEMPERATURE = 23.89 DEG C   OUTLET BULK TEMPERATURE = 53.71 DEG C

STATION NO.	Z CM	WALL TEMPERATURE (DEG C) A	B	C	AVERAGE	TB (C)	RE	PR	RA+	Z+	NUSSELT NUMBER A	B	C	AVERAGE T	H	T+H
0	0.0	30.27	30.36	29.79	30.05	23.89	580.7	6.30	0.898E 08	0.00000	27.69	27.32	29.91	28.66	28.71	28.68
1	1.5	31.44	31.56	31.12	31.31	23.98	581.9	6.28	0.903E 08	0.00013	23.68	23.30	24.74	24.10	24.12	24.11
2	2.5	32.24	32.39	32.03	32.18	24.04	582.8	6.27	0.906E 08	0.00022	21.54	21.16	22.11	21.72	21.73	21.72
3	5.5	34.66	34.88	34.77	34.77	24.24	585.3	6.24	0.916E 08	0.00050	16.93	16.57	16.75	16.75	16.75	16.75
4	15.5	37.17	36.74	34.57	35.76	24.87	594.0	6.14	0.949E 08	0.00140	14.33	14.85	18.18	16.19	16.38	16.29
5	25.5	38.46	38.66	35.19	36.88	25.51	602.9	6.04	0.984E 08	0.00230	13.58	13.39	18.17	15.48	15.83	15.66
6	45.5	40.13	39.83	36.43	38.21	26.78	621.5	5.84	0.105E 09	0.00412	13.15	13.45	18.18	15.36	15.74	15.55
7	75.5	41.78	41.26	37.98	39.75	28.69	646.5	5.60	0.115E 09	0.00686	13.34	13.90	18.81	15.80	16.22	16.01
8	105.5	43.60	43.12	40.30	41.83	30.60	673.3	5.36	0.126E 09	0.00962	13.38	13.89	17.94	15.49	15.79	15.64
9	135.5	45.00	44.41	40.23	42.47	32.51	701.0	5.12	0.137E 09	0.01241	13.87	14.55	22.42	17.39	18.31	17.85
10	165.2	46.25	45.86	42.85	44.45	34.40	727.8	4.90	0.147E 09	0.01522	14.54	15.03	20.38	17.14	17.58	17.36
11	205.2	48.55	48.10	44.60	46.46	36.94	767.2	4.61	0.162E 09	0.01908	14.75	15.34	22.36	17.98	18.70	18.34
12	245.2	51.53	51.16	48.15	49.75	39.49	805.0	4.38	0.177E 09	0.02289	14.15	14.60	19.66	16.60	17.02	16.81
13	275.2	52.89	52.32	48.98	50.79	41.40	835.8	4.20	0.189E 09	0.02578	14.78	15.54	22.38	18.07	18.77	18.42
14	305.2	54.91	54.88	51.69	53.29	43.30	865.1	4.05	0.201E 09	0.02868	14.58	14.62	20.18	16.94	17.39	17.16
15	333.3	56.58	56.73	52.50	54.58	45.09	893.1	3.91	0.212E 09	0.03142	14.68	14.49	22.77	17.78	18.68	18.23
16	363.3	59.50	59.67	55.12	57.35	47.00	924.9	3.76	0.225E 09	0.03437	13.45	13.27	20.70	16.24	17.03	16.63
17	383.3	60.26	59.73	55.95	57.97	48.27	945.3	3.67	0.233E 09	0.03634	13.98	14.64	21.83	17.28	18.07	17.68
18	403.3	61.62	61.04	57.00	59.17	49.55	966.7	3.58	0.242E 09	0.03832	13.86	14.55	22.45	17.40	18.33	17.86
19	423.3	62.32	61.50	58.14	60.02	50.82	989.2	3.49	0.251E 09	0.04031	14.52	15.64	22.82	18.15	18.95	18.55
20	443.3	64.64	64.97	60.20	62.50	52.09	1011.7	3.41	0.260E 09	0.04231	13.28	12.94	20.55	16.01	16.83	16.42
21	463.3	64.18	64.90	60.55	62.54	53.36	1031.1	3.34	0.269E 09	0.04427	15.38	14.42	23.16	18.12	19.03	18.58
AVERAGE VALUES THROUGH STATIONS 15 TO 20:																
	391.6	60.82	60.61	56.48	58.60	48.80	955.1	3.64	0.237E 09	0.03718	13.96	14.25	21.86	17.14	17.98	17.56

========== EXPERIMENT OR72 --- DEC. 19, 1987 ==========

INPUT ELECTRIC POWER = 2640.0 W   HEAT RATE GAINED BY WATER = 2498.2 W   HEAT BALANCE ERROR = 5.37%
MASS FLOW RATE = 16.0130 G/S   PRESSURE DROP = 0.2665 MM H2O   FRICTION FACTOR = 0.029571   FREM = 23.7596

REM = 803.5   GRM+ = 0.56381E 08   UPSTREAM BULK TEMPERATURE = 23.86 DEG C   DOWNSTREAM BULK TEMPERATURE = 61.28 DEG C
PRM = 4.103   RAM+ = 0.23134E 09   INLET BULK TEMPERATURE = 23.91 DEG C   OUTLET BULK TEMPERATURE = 61.24 DEG C

STATION NO.	Z CM	WALL TEMPERATURE (DEG C) A	B	C	AVERAGE	TB (C)	RE	PR	RA+	Z+	NUSSELT NUMBER A	B	C	AVERAGE T	H	T+H
0	0.0	31.42	31.48	30.85	31.15	23.92	546.6	6.29	0.106E 09	0.00000	27.71	27.52	30.01	28.77	28.82	28.79
1	1.5	32.81	32.89	32.41	32.63	24.03	548.0	6.28	0.107E 09	0.00014	23.69	23.49	24.83	24.19	24.21	24.20
2	2.5	33.77	33.86	33.48	33.65	24.11	549.0	6.26	0.107E 09	0.00024	21.53	21.33	22.19	21.80	21.81	21.81
3	5.5	36.64	36.78	36.71	36.71	24.35	552.0	6.22	0.109E 09	0.00053	16.90	16.72	16.81	16.81	16.81	16.81
4	15.5	39.41	38.83	36.15	37.64	25.15	562.3	6.10	0.114E 09	0.00149	14.54	15.16	18.85	16.61	16.85	16.73
5	25.5	40.97	41.18	36.97	39.02	25.94	573.0	5.97	0.119E 09	0.00245	13.78	13.59	18.78	15.83	16.23	16.03
6	45.5	42.83	42.48	38.27	40.46	27.54	593.8	5.74	0.129E 09	0.00439	13.49	13.80	19.22	15.96	16.43	16.19
7	75.5	44.83	44.23	40.31	42.42	29.93	624.2	5.44	0.144E 09	0.00731	13.76	14.34	19.75	16.42	16.90	16.66
8	105.5	46.97	46.45	43.16	44.93	32.32	656.9	5.15	0.160E 09	0.01027	13.92	14.43	18.82	16.17	16.50	16.33
9	135.5	48.79	48.17	43.41	45.95	34.70	688.9	4.87	0.175E 09	0.01329	14.40	15.05	23.29	18.04	19.01	18.52
10	165.2	50.57	50.22	46.57	48.48	37.07	723.3	4.60	0.191E 09	0.01633	14.93	15.33	21.21	17.66	18.17	17.91
11	205.2	53.45	52.91	48.65	50.91	40.25	768.6	4.31	0.214E 09	0.02039	15.18	15.83	23.87	18.79	19.69	19.24
12	245.2	57.06	56.53	53.01	54.91	43.44	815.6	4.04	0.238E 09	0.02450	14.62	15.22	20.80	17.37	17.86	17.61
13	275.2	58.73	58.08	54.07	56.24	45.83	851.4	3.85	0.256E 09	0.02762	15.37	16.18	24.05	19.04	19.91	19.48
14	305.2	61.22	61.16	57.32	59.26	48.22	888.3	3.67	0.274E 09	0.03076	15.18	15.26	21.69	17.89	18.45	18.17
15	333.3	63.49	63.69	58.61	61.10	50.45	924.3	3.52	0.293E 09	0.03372	15.10	14.87	24.12	18.48	19.55	19.02
16	363.3	67.00	67.26	61.67	64.40	52.84	962.4	3.37	0.312E 09	0.03689	13.85	13.60	22.20	16.96	17.96	17.46
17	383.3	67.96	67.33	62.82	65.23	54.44	985.9	3.28	0.325E 09	0.03899	14.46	15.17	23.32	18.11	19.07	18.59
18	403.3	69.64	68.95	64.27	66.78	56.03	1010.6	3.19	0.338E 09	0.04109	14.33	15.09	23.69	18.14	19.20	18.67
19	423.3	70.59	69.59	65.63	67.86	57.62	1035.6	3.11	0.351E 09	0.04326	15.00	16.25	24.28	19.00	19.95	19.47
20	443.3	73.44	73.75	68.19	70.89	59.21	1060.8	3.02	0.364E 09	0.04548	13.63	13.34	21.62	16.61	17.55	17.08
21	463.3	72.92	73.82	68.80	71.09	60.81	1087.2	2.94	0.377E 09	0.04774	15.97	14.86	24.19	18.82	19.80	19.31
AVERAGE VALUES THROUGH STATIONS 15 TO 20:																
	391.6	68.69	68.43	63.53	66.05	55.10	996.6	3.25	0.331E 09	0.03990	14.40	14.72	23.20	17.88	18.88	18.38

========== EXPERIMENT 0R73 --- DEC. 19, 1987 ==========

INPUT ELECTRIC POWER = 2957.1 W HEAT RATE GAINED BY WATER = 2811.1 W HEAT BALANCE ERROR = 4.94%
MASS FLOW RATE = 14.9360 G/S PRESSURE DROP = 0.2736 MM H2O FRICTION FACTOR = 0.034843 FREM = 27.9751

REM = 802.9 GRM+ = 0.77029E 08 UPSTREAM BULK TEMPERATURE = 23.84 DEG C DOWNSTREAM BULK TEMPERATURE = 68.97 DEG C
PRM = 3.804 RAM+ = 0.29298E 09 INLET BULK TEMPERATURE = 23.91 DEG C OUTLET BULK TEMPERATURE = 68.93 DEG C

STATION NO.	Z CM	WALL TEMPERATURE (DEG C) A	B	C	AVERAGE	TB (C)	RE	PR	RA+	Z+	NUSSELT NUMBER A	B	C	AVERAGE T	H	T+H
0	0.0	32.39	32.47	31.63	32.03	23.91	509.7	6.29	0.119E 09	0.00001	27.60	27.36	30.34	28.84	28.91	28.87
1	1.5	33.94	34.04	33.40	33.69	24.05	511.4	6.27	0.120E 09	0.00015	23.66	23.42	25.03	24.26	24.28	24.27
2	2.5	35.00	35.13	34.62	34.84	24.15	512.5	6.26	0.121E 09	0.00026	21.55	21.30	22.33	21.87	21.88	21.87
3	5.5	38.20	38.39	38.29	38.29	24.44	515.9	6.21	0.123E 09	0.00056	16.98	16.76	16.87	16.87	16.87	16.87
4	15.5	41.29	40.66	37.37	39.17	25.40	527.5	6.06	0.130E 09	0.00159	14.68	15.28	19.48	16.93	17.23	17.08
5	25.5	43.14	43.42	38.51	40.90	26.36	539.7	5.91	0.137E 09	0.00263	13.87	13.64	19.14	16.01	16.45	16.23
6	45.5	45.19	44.85	40.00	42.51	28.28	562.3	5.65	0.150E 09	0.00471	13.70	13.98	19.77	16.28	16.81	16.54
7	75.5	47.63	46.92	42.29	44.78	31.16	598.0	5.29	0.171E 09	0.00785	13.98	14.60	20.69	16.90	17.49	17.20
8	105.5	50.09	49.45	45.62	47.69	34.04	634.0	4.95	0.192E 09	0.01107	14.24	14.83	19.74	16.74	17.14	16.94
9	135.5	52.24	51.51	46.22	49.05	36.92	672.8	4.61	0.214E 09	0.01436	14.82	15.55	24.39	18.71	19.79	19.25
10	165.2	54.61	54.13	50.15	52.26	39.77	710.2	4.35	0.237E 09	0.01759	15.21	15.72	21.74	18.07	18.60	18.34
11	205.2	58.02	57.50	52.69	55.23	43.62	763.1	4.02	0.269E 09	0.02199	15.55	16.14	24.68	19.30	20.26	19.78
12	245.2	62.57	61.95	57.96	60.11	47.46	817.8	3.73	0.302E 09	0.02646	14.72	15.35	21.18	17.58	18.11	17.84
13	275.2	64.40	63.67	59.31	61.67	50.34	860.3	3.53	0.328E 09	0.02984	15.74	16.61	24.69	19.54	20.43	19.98
14	305.2	67.40	67.36	62.95	65.17	53.22	902.7	3.35	0.355E 09	0.03324	15.55	15.60	22.65	18.46	19.11	18.78
15	333.3	70.45	70.65	64.93	67.74	55.92	941.0	3.20	0.380E 09	0.03641	15.11	14.90	24.36	18.57	19.68	19.13
16	363.3	74.33	74.60	68.40	71.43	58.80	983.2	3.04	0.406E 09	0.03992	14.07	13.83	22.76	17.30	18.35	17.83
17	383.3	75.46	74.70	69.64	72.36	60.72	1012.7	2.94	0.423E 09	0.04233	14.77	15.57	24.42	18.71	19.79	19.25
18	403.3	77.49	76.67	71.42	74.25	62.64	1042.9	2.85	0.442E 09	0.04471	14.61	15.47	24.73	18.70	19.89	19.29
19	423.3	78.58	77.49	72.97	75.50	64.56	1073.3	2.76	0.462E 09	0.04695	15.45	16.75	25.77	19.80	20.93	20.36
20	443.3	82.05	82.33	75.94	79.07	66.48	1105.5	2.68	0.483E 09	0.04929	13.88	13.63	22.84	17.17	18.30	17.73
21	463.3	81.51	82.52	77.00	79.51	68.41	1138.0	2.59	0.503E 09	0.05161	16.41	15.24	25.01	19.37	20.42	19.90
AVERAGE VALUES THROUGH STATIONS 15 TO 20:																
	391.6	76.39	76.07	70.55	73.39	61.52	1026.5	2.91	0.433E 09	0.04328	14.65	15.02	24.15	18.37	19.49	18.93

========== EXPERIMENT 0R74 --- DEC. 20, 1987 ==========

INPUT ELECTRIC POWER = 2131.8 W HEAT RATE GAINED BY WATER = 2025.6 W HEAT BALANCE ERROR = 4.98%
MASS FLOW RATE = 14.5120 G/S PRESSURE DROP = 0.2482 MM H2O FRICTION FACTOR = 0.033557 FREM = 23.5601

REM = 702.1 GRM+ = 0.41193E 08 UPSTREAM BULK TEMPERATURE = 23.91 DEG C DOWNSTREAM BULK TEMPERATURE = 57.39 DEG C
PRM = 4.270 RAM+ = 0.17589E 09 INLET BULK TEMPERATURE = 23.96 DEG C OUTLET BULK TEMPERATURE = 57.36 DEG C

STATION NO.	Z CM	WALL TEMPERATURE (DEG C) A	B	C	AVERAGE	TB (C)	RE	PR	RA+	Z+	NUSSELT NUMBER A	B	C	AVERAGE T	H	T+H
0	0.0	30.25	30.30	29.74	30.01	23.96	495.8	6.29	0.861E 08	0.00001	26.82	26.59	29.17	27.88	27.94	27.91
1	1.5	31.38	31.46	31.03	31.23	24.06	497.0	6.27	0.866E 08	0.00016	23.03	22.79	24.20	23.53	23.55	23.54
2	2.5	32.17	32.26	31.92	32.07	24.13	497.8	6.26	0.870E 08	0.00026	20.98	20.74	21.65	21.25	21.25	21.25
3	5.5	34.52	34.66	34.59	34.59	24.35	500.2	6.23	0.880E 08	0.00058	16.56	16.34	16.45	16.45	16.45	16.45
4	15.5	36.91	36.52	34.28	35.50	25.06	508.5	6.11	0.916E 08	0.00164	14.19	14.68	18.23	16.11	16.34	16.22
5	25.5	38.27	38.49	35.08	36.73	25.77	517.1	6.00	0.953E 08	0.00270	13.44	13.21	18.04	15.33	15.68	15.51
6	45.5	39.91	39.66	36.23	38.01	27.20	534.4	5.79	0.103E 09	0.00484	13.17	13.43	18.52	15.48	15.91	15.70
7	75.5	41.76	41.28	38.06	39.79	29.34	558.6	5.52	0.114E 09	0.00806	13.41	13.94	19.09	15.93	16.38	16.16
8	105.5	43.76	43.37	40.61	42.09	31.47	585.1	5.25	0.125E 09	0.01130	13.49	13.93	18.14	15.61	15.92	15.77
9	135.5	45.39	44.89	40.99	43.07	33.61	610.7	5.00	0.136E 09	0.01461	13.99	14.61	22.34	17.43	18.32	17.88
10	165.2	47.09	46.73	43.82	45.37	35.73	637.6	4.75	0.148E 09	0.01794	14.43	14.90	20.26	17.01	17.46	17.24
11	205.2	49.70	49.31	45.84	47.67	38.58	674.3	4.46	0.163E 09	0.02244	14.65	15.18	22.45	17.92	18.68	18.30
12	245.2	52.98	52.56	49.78	51.28	41.43	712.9	4.20	0.181E 09	0.02694	14.03	14.56	19.40	16.46	16.85	16.65
13	275.2	54.49	54.01	50.77	52.51	43.56	740.8	4.03	0.193E 09	0.03035	14.78	15.46	22.39	18.04	18.76	18.40
14	305.2	56.79	56.76	53.70	55.24	45.70	769.8	3.86	0.207E 09	0.03379	14.50	14.54	20.11	16.86	17.32	17.09
15	333.3	58.77	58.96	54.86	56.86	47.70	797.9	3.71	0.219E 09	0.03703	14.48	14.24	22.40	17.50	18.38	17.94
16	363.3	61.87	62.02	57.56	59.76	49.84	828.5	3.56	0.233E 09	0.04051	13.27	13.12	20.68	16.11	16.94	16.52
17	383.3	62.88	62.29	58.56	60.57	51.27	850.1	3.46	0.243E 09	0.04285	13.72	14.45	21.84	17.12	17.97	17.54
18	403.3	64.39	63.77	59.89	61.99	52.69	870.2	3.37	0.252E 09	0.04518	13.59	14.36	22.07	17.11	18.02	17.56
19	423.3	65.24	64.41	61.16	62.99	54.12	889.1	3.30	0.262E 09	0.04749	14.26	15.41	22.53	17.87	18.68	18.28
20	443.3	67.69	67.92	63.40	65.60	55.54	908.9	3.22	0.271E 09	0.04981	13.03	12.79	20.14	15.73	16.52	16.13
21	463.3	67.36	68.07	63.90	65.80	56.97	929.5	3.14	0.281E 09	0.05216	15.20	14.22	22.79	17.87	18.75	18.31
AVERAGE VALUES THROUGH STATIONS 15 TO 20:																
	391.6	63.47	63.23	59.24	61.29	51.86	857.5	3.44	0.247E 09	0.04381	13.73	14.06	21.61	16.91	17.75	17.33

========== EXPERIMENT 0R75 --- DEC. 20, 1987 ==========

INPUT ELECTRIC POWER = 2472.0 W HEAT RATE GAINED BY WATER = 2359.5 W HEAT BALANCE ERROR = 4.55%
MASS FLOW RATE = 13.4620 G/S PRESSURE DROP = 0.2585 MM H2O FRICTION FACTOR = 0.040548 FREM = 28.5247

REM = 703.5 GRM+ = 0.59764E 08 UPSTREAM BULK TEMPERATURE = 23.85 DEG C DOWNSTREAM BULK TEMPERATURE = 65.88 DEG C
PRM = 3.924 RAM+ = 0.23451E 09 INLET BULK TEMPERATURE = 23.91 DEG C OUTLET BULK TEMPERATURE = 65.84 DEG C

STATION NO.	Z CM	WALL TEMPERATURE (DEG C) A	B	C	AVERAGE	TB (C)	RE	PR	RA+	Z+	NUSSELT NUMBER A	B	C	AVERAGE T	H	T+H
0	0.0	31.37	31.43	30.73	31.07	23.91	459.5	6.29	0.100E 09	0.00001	26.33	26.15	28.81	27.47	27.53	27.50
1	1.5	32.71	32.78	32.25	32.50	24.04	460.8	6.27	0.101E 09	0.00017	22.66	22.47	23.92	23.22	23.24	23.23
2	2.5	33.63	33.72	33.30	33.49	24.13	461.8	6.26	0.101E 09	0.00028	20.68	20.48	21.41	20.99	20.99	20.99
3	5.5	36.39	36.52	36.46	36.46	24.40	464.6	6.22	0.103E 09	0.00063	16.37	16.19	16.28	16.28	16.28	16.28
4	15.5	39.10	38.60	35.81	37.33	25.30	474.3	6.08	0.108E 09	0.00177	14.18	14.72	18.62	16.27	16.53	16.40
5	25.5	40.69	40.89	36.74	38.77	26.19	484.5	5.93	0.114E 09	0.00292	13.48	13.29	18.52	15.54	15.95	15.75
6	45.5	42.47	42.14	37.93	40.12	27.98	503.7	5.69	0.124E 09	0.00522	13.43	13.74	19.55	16.03	16.57	16.30
7	75.5	44.83	44.28	40.51	42.53	30.66	533.2	5.35	0.141E 09	0.00871	13.65	14.20	19.64	16.29	16.78	16.54
8	105.5	47.19	46.67	43.41	45.17	33.35	563.6	5.03	0.157E 09	0.01225	13.88	14.42	19.09	16.25	16.62	16.43
9	135.5	49.24	48.63	44.17	46.55	36.03	595.2	4.72	0.174E 09	0.01588	14.45	15.15	23.44	18.14	19.12	18.63
10	165.2	51.47	51.12	47.71	49.50	38.69	626.8	4.45	0.191E 09	0.01948	14.85	15.27	21.03	17.55	18.05	17.80
11	205.2	54.81	54.32	50.30	52.43	42.26	671.8	4.13	0.216E 09	0.02434	15.03	15.64	23.45	18.54	19.39	18.96
12	245.2	58.88	58.35	54.93	56.77	45.84	716.0	3.85	0.242E 09	0.02927	14.36	14.98	20.60	17.13	17.64	17.38
13	275.2	60.64	60.08	56.32	58.34	48.53	750.8	3.65	0.262E 09	0.03301	15.39	16.14	23.91	18.99	19.84	19.41
14	305.2	63.44	63.37	59.81	61.61	51.21	787.8	3.46	0.283E 09	0.03678	15.18	15.26	21.58	17.85	18.40	18.12
15	333.3	66.30	66.45	61.57	63.97	53.72	819.8	3.32	0.302E 09	0.04029	14.71	14.52	23.55	18.04	19.08	18.56
16	363.3	69.86	70.04	64.88	67.41	56.41	854.7	3.17	0.323E 09	0.04405	13.69	13.51	21.73	16.73	17.66	17.20
17	383.3	71.06	70.34	66.05	68.37	58.19	878.1	3.08	0.336E 09	0.04666	14.27	15.11	23.38	18.03	19.03	18.53
18	403.3	72.89	72.21	67.76	70.15	59.98	902.4	2.98	0.350E 09	0.04932	14.18	14.97	23.54	17.99	19.05	18.52
19	423.3	74.05	73.12	69.33	71.46	61.77	928.0	2.88	0.364E 09	0.05202	14.85	16.07	24.14	18.83	19.80	19.31
20	443.3	76.88	77.15	72.04	74.53	63.56	952.9	2.80	0.379E 09	0.05456	13.66	13.39	21.47	16.59	17.50	17.05
21	463.3	76.60	77.48	72.79	74.91	65.35	979.1	2.73	0.395E 09	0.05710	16.15	14.97	24.41	18.99	19.98	19.48
AVERAGE VALUES THROUGH STATIONS 15 TO 20:																
	391.6	71.84	71.55	66.94	69.32	58.94	889.3	3.04	0.342E 09	0.04782	14.23	14.59	22.97	17.70	18.69	18.20

========== EXPERIMENT 0R76 --- DEC. 20, 1987 ==========

INPUT ELECTRIC POWER = 2753.2 W HEAT RATE GAINED BY WATER = 2599.8 W HEAT BALANCE ERROR = 5.57%
MASS FLOW RATE = 12.5480 G/S PRESSURE DROP = 0.3094 MM H2O FRICTION FACTOR = 0.055777 FREM = 39.1786

REM = 702.4 GRM+ = 0.79686E 08 UPSTREAM BULK TEMPERATURE = 23.88 DEG C DOWNSTREAM BULK TEMPERATURE = 73.56 DEG C
PRM = 3.638 RAM+ = 0.28991E 09 INLET BULK TEMPERATURE = 23.95 DEG C OUTLET BULK TEMPERATURE = 73.51 DEG C

STA-TION NO.	Z CM	-WALL TEMPERATURE (DEG C)- A	B	C	AVER-AGE	TB (C)	RE	PR	RA+	Z+	NUSSELT NUMBER A	B	C	AVERAGE T	H	T+H
0	0.0	32.43	32.50	31.66	32.06	23.96	428.7	6.29	0.111E 09	0.00001	25.54	25.35	28.10	26.71	26.78	26.74
1	1.5	33.94	34.03	33.39	33.69	24.11	430.2	6.26	0.111E 09	0.00018	22.02	21.83	23.32	22.60	22.62	22.61
2	2.5	34.97	35.08	34.56	34.61	24.22	431.3	6.25	0.112E 09	0.00031	20.11	19.91	20.87	20.43	20.44	20.43
3	5.5	38.09	38.24	38.16	38.16	24.54	434.4	6.20	0.114E 09	0.00067	15.95	15.77	15.86	15.86	15.86	15.86
4	15.5	41.12	40.55	37.14	38.99	25.59	445.2	6.03	0.121E 09	0.00190	13.89	14.42	18.67	16.10	16.41	16.25
5	25.5	42.94	43.19	38.32	40.69	26.65	456.6	5.86	0.128E 09	0.00313	13.20	13.01	18.44	15.32	15.77	15.54
6	45.5	44.80	44.43	39.57	42.09	28.76	477.2	5.59	0.142E 09	0.00561	13.35	13.67	19.80	16.06	16.66	16.36
7	75.5	47.57	46.92	42.54	44.89	31.94	511.0	5.19	0.164E 09	0.00936	13.59	14.18	20.04	16.40	16.97	16.68
8	105.5	50.26	49.70	45.99	47.98	35.11	544.3	4.82	0.185E 09	0.01322	13.91	14.45	19.37	16.37	16.76	16.57
9	135.5	52.69	52.02	46.98	49.67	38.28	579.8	4.49	0.208E 09	0.01713	14.52	15.23	24.04	18.37	19.46	18.92
10	165.2	55.61	55.14	51.29	53.33	41.42	616.4	4.20	0.232E 09	0.02099	14.65	15.16	21.08	17.46	17.99	17.73
11	205.2	59.43	58.93	54.27	56.72	45.65	665.0	3.86	0.265E 09	0.02627	14.97	15.54	23.95	18.63	19.60	19.12
12	245.2	64.59	63.94	59.88	62.07	49.87	716.8	3.56	0.300E 09	0.03162	13.93	14.58	20.50	16.81	17.37	17.09
13	275.2	66.46	65.75	61.44	63.77	53.05	756.4	3.36	0.327E 09	0.03567	15.21	16.05	24.29	19.01	19.96	19.49
14	305.2	69.64	69.60	65.59	67.60	56.22	794.3	3.18	0.354E 09	0.03969	15.12	15.17	21.67	17.83	18.40	18.12
15	333.3	73.26	73.44	67.92	70.64	59.19	830.9	3.02	0.379E 09	0.04364	14.35	14.16	23.12	17.64	18.69	18.16
16	363.3	77.13	77.38	71.44	74.35	62.36	872.5	2.86	0.406E 09	0.04793	13.59	13.37	22.12	16.75	17.80	17.28
17	383.3	78.67	77.91	73.06	75.67	64.47	900.5	2.76	0.426E 09	0.05065	14.11	14.90	23.34	17.88	18.92	18.40
18	403.3	80.91	80.12	75.02	77.77	66.59	930.3	2.67	0.448E 09	0.05338	13.95	14.76	23.68	17.87	19.02	18.44
19	423.3	82.41	81.39	76.91	79.40	68.70	960.4	2.58	0.468E 09	0.05615	14.51	15.67	24.22	18.58	19.66	19.12
20	443.3	85.77	86.04	80.05	82.98	70.82	992.2	2.49	0.489E 09	0.05894	13.23	12.99	21.43	16.26	17.27	16.77
21	463.3	85.25	86.35	81.05	83.42	72.93	1022.2	2.42	0.511E 09	0.06173	16.02	14.70	24.31	18.81	19.84	19.32
AVERAGE VALUES THROUGH STATIONS 15 TO 20:																
	391.6	79.69	79.38	74.07	76.80	65.35	914.5	2.73	0.436E 09	0.05178	13.95	14.31	22.99	17.50	18.56	18.03

========== EXPERIMENT 0R77 --- DEC. 21, 1987 ==========

INPUT ELECTRIC POWER = 4019.4 W HEAT RATE GAINED BY WATER = 3850.0 W HEAT BALANCE ERROR = 4.22%
MASS FLOW RATE = 35.3990 G/S PRESSURE DROP = 0.6986 MM H2O FRICTION FACTOR = 0.015898 FREM = 25.3320

REM = 1593.4 GRM+ = 0.63382E 08 UPSTREAM BULK TEMPERATURE = 23.83 DEG C DOWNSTREAM BULK TEMPERATURE = 49.92 DEG C
PRM = 4.617 RAM+ = 0.29265E 09 INLET BULK TEMPERATURE = 23.86 DEG C OUTLET BULK TEMPERATURE = 49.90 DEG C

STA-TION NO.	Z CM	-WALL TEMPERATURE (DEG C)- A	B	C	AVER-AGE	TB (C)	RE	PR	RA+	Z+	NUSSELT NUMBER A	B	C	AVERAGE T	H	T+H
0	0.0	32.99	33.10	32.36	32.70	23.87	1206.9	6.30	0.163E 09	0.00000	35.14	34.74	37.76	36.29	36.35	36.32
1	1.5	34.79	34.94	34.36	34.61	23.95	1209.1	6.29	0.164E 09	0.00006	29.56	29.16	30.78	30.05	30.07	30.06
2	2.5	36.03	36.21	35.74	35.93	24.00	1210.6	6.28	0.164E 09	0.00011	26.65	26.25	27.30	26.87	26.87	26.87
3	5.5	39.75	40.02	39.89	39.89	24.17	1215.2	6.25	0.166E 09	0.00024	20.56	20.21	20.38	20.38	20.38	20.38
4	15.5	42.88	42.07	39.18	40.83	24.72	1230.9	6.17	0.171E 09	0.00067	17.63	18.45	22.13	19.87	20.09	19.98
5	25.5	44.80	45.23	39.84	42.43	25.28	1246.9	6.08	0.176E 09	0.00111	16.37	16.02	21.95	18.64	19.07	18.85
6	45.5	47.02	46.46	41.58	44.16	26.39	1280.2	5.90	0.187E 09	0.00198	15.45	15.88	20.98	17.94	18.32	18.13
7	75.5	48.84	47.99	42.96	45.69	28.06	1326.7	5.68	0.203E 09	0.00330	15.28	15.93	21.30	18.01	18.45	18.23
8	105.5	50.74	49.98	45.90	48.13	29.72	1373.9	5.47	0.220E 09	0.00462	15.05	15.62	19.55	17.18	17.44	17.31
9	135.5	51.67	50.75	44.28	47.75	31.39	1424.5	5.26	0.237E 09	0.00595	15.54	16.28	24.44	19.26	20.17	19.72
10	165.2	52.14	51.54	46.74	49.29	33.04	1472.9	5.06	0.253E 09	0.00729	16.43	16.96	22.90	19.31	19.80	19.55
11	205.2	54.24	53.31	47.72	50.75	35.26	1540.3	4.80	0.276E 09	0.00912	16.44	17.29	25.04	20.15	20.95	20.55
12	245.2	56.84	56.14	51.61	54.05	37.48	1611.2	4.56	0.299E 09	0.01097	16.04	16.64	21.96	18.73	19.15	18.94
13	275.2	57.89	56.85	51.37	54.37	39.15	1662.8	4.41	0.317E 09	0.01235	16.51	17.48	25.31	20.33	21.15	20.74
14	305.2	59.68	59.59	54.35	56.99	40.81	1717.8	4.26	0.336E 09	0.01373	16.35	16.43	22.78	19.06	19.59	19.32
15	333.3	60.90	61.27	54.23	57.66	42.37	1769.8	4.12	0.354E 09	0.01504	16.59	16.28	25.93	20.12	21.18	20.65
16	363.3	64.20	64.71	56.86	60.66	44.04	1822.3	3.99	0.373E 09	0.01644	15.21	14.83	23.91	18.45	19.46	18.95
17	383.3	64.58	63.90	57.21	60.73	45.15	1859.0	3.90	0.386E 09	0.01738	15.74	16.32	25.35	19.64	20.69	20.16
18	403.3	65.94	64.97	58.13	61.80	46.26	1897.2	3.82	0.399E 09	0.01832	15.51	16.31	25.71	19.65	20.81	20.23
19	423.3	66.00	64.47	58.81	62.02	47.37	1935.2	3.73	0.413E 09	0.01927	16.35	17.82	26.64	20.79	21.86	21.33
20	443.3	68.48	69.02	60.94	64.84	48.48	1972.8	3.66	0.426E 09	0.02022	15.21	14.81	24.41	18.59	19.71	19.15
21	463.3	67.38	68.27	61.12	64.48	49.59	2011.8	3.58	0.440E 09	0.02117	17.06	16.25	26.33	20.40	21.49	20.95
AVERAGE VALUES THROUGH STATIONS 15 TO 20:																
	391.6	65.02	64.72	57.70	61.28	45.61	1876.0	3.87	0.392E 09	0.01778	15.77	16.06	25.32	19.54	20.62	20.08

========== EXPERIMENT 0R78 --- DEC. 21, 1987 ==========

INPUT ELECTRIC POWER = 4499.4 W HEAT RATE GAINED BY WATER = 4300.2 W HEAT BALANCE ERROR = 4.43%
MASS FLOW RATE = 34.1350 G/S PRESSURE DROP = 0.6578 MM H2O FRICTION FACTOR = 0.016085 FREM = 25.7526

REM = 1601.1 GRM+ = 0.79970E 08 UPSTREAM BULK TEMPERATURE = 23.96 DEG C DOWNSTREAM BULK TEMPERATURE = 54.17 DEG C
PRM = 4.416 RAM+ = 0.35314E 09 INLET BULK TEMPERATURE = 23.99 DEG C OUTLET BULK TEMPERATURE = 54.14 DEG C

STA-TION NO.	Z CM	-WALL TEMPERATURE (DEG C)- A	B	C	AVER-AGE	TB (C)	RE	PR	RA+	Z+	NUSSELT NUMBER A	B	C	AVERAGE T	H	T+H
0	0.0	34.14	34.26	33.43	33.82	24.00	1167.3	6.28	0.183E 09	0.00000	35.28	34.88	37.93	36.45	36.50	36.48
1	1.5	36.14	36.30	35.66	35.94	24.09	1169.7	6.27	0.184E 09	0.00007	29.70	29.30	30.94	30.20	30.22	30.21
2	2.5	37.52	37.71	37.19	37.40	24.15	1171.5	6.26	0.185E 09	0.00011	26.78	26.39	27.44	27.01	27.01	27.01
3	5.5	41.65	41.94	41.80	41.80	24.35	1176.6	6.23	0.187E 09	0.00025	20.67	20.33	20.50	20.50	20.50	20.50
4	15.5	45.12	44.10	40.73	42.67	24.99	1194.2	6.12	0.194E 09	0.00070	17.74	18.69	22.66	20.20	20.45	20.32
5	25.5	47.31	47.75	41.78	44.65	25.63	1212.4	6.02	0.201E 09	0.00115	16.45	16.12	22.09	18.75	19.19	18.97
6	45.5	49.78	49.16	43.59	46.53	26.92	1250.0	5.82	0.215E 09	0.00206	15.55	15.99	21.33	18.13	18.55	18.34
7	75.5	51.75	50.74	45.10	48.17	28.85	1300.6	5.58	0.236E 09	0.00342	15.46	16.17	21.78	18.32	18.80	18.56
8	105.5	53.80	52.83	48.28	50.80	30.78	1355.4	5.34	0.258E 09	0.00480	15.31	15.98	20.14	17.61	17.89	17.75
9	135.5	54.84	53.72	46.65	50.46	32.71	1411.2	5.10	0.280E 09	0.00619	15.85	16.70	25.17	19.76	20.72	20.24
10	165.2	55.50	54.91	49.70	52.45	34.62	1466.0	4.88	0.300E 09	0.00760	16.72	17.20	23.15	19.57	20.05	19.81
11	205.2	57.94	56.85	50.61	54.00	37.19	1545.3	4.59	0.330E 09	0.00952	16.72	17.65	25.84	20.63	21.51	21.07
12	245.2	60.90	60.22	55.24	57.90	39.76	1622.7	4.35	0.362E 09	0.01142	16.33	16.88	22.30	19.03	19.45	19.24
13	275.2	62.33	61.06	54.90	58.30	41.69	1686.0	4.17	0.387E 09	0.01286	16.67	17.76	26.04	20.71	21.63	21.17
14	305.2	64.37	64.22	58.45	61.37	43.62	1744.3	4.02	0.411E 09	0.01431	16.52	16.64	23.11	19.31	19.84	19.57
15	333.3	65.90	66.20	58.10	62.08	45.43	1801.8	3.88	0.435E 09	0.01568	16.68	16.44	26.95	20.51	21.75	21.13
16	363.3	69.55	70.01	61.11	65.44	47.36	1865.8	3.73	0.461E 09	0.01715	15.34	15.03	24.75	18.82	19.97	19.39
17	383.3	69.75	69.07	61.50	65.46	48.64	1907.8	3.64	0.478E 09	0.01813	16.09	16.63	26.41	20.20	21.39	20.79
18	403.3	71.34	70.25	62.56	66.68	49.93	1951.8	3.55	0.496E 09	0.01912	15.84	16.69	26.84	20.24	21.55	20.90
19	423.3	71.43	69.62	63.45	66.99	51.22	1997.9	3.46	0.515E 09	0.02012	16.73	18.38	27.65	21.45	22.60	22.03
20	443.3	74.15	74.72	65.92	70.18	52.50	2041.0	3.38	0.533E 09	0.02111	15.60	15.20	25.16	19.10	20.28	19.69
21	463.3	73.14	74.11	66.38	70.00	53.79	2081.0	3.32	0.551E 09	0.02209	17.41	16.58	26.76	20.78	21.88	21.33
AVERAGE VALUES THROUGH STATIONS 15 TO 20:																
	391.6	70.35	69.98	62.11	66.14	49.18	1927.7	3.61	0.486E 09	0.01855	16.05	16.39	26.29	20.05	21.26	20.66

========== EXPERIMENT 0R79 --- DEC. 23, 1987 ==========

INPUT ELECTRIC POWER = 3855.9 W   HEAT RATE GAINED BY WATER = 3641.8 W   HEAT BALANCE ERROR = 5.55%
MASS FLOW RATE = 30.3450 G/S   PRESSURE DROP = 0.5923 MM H2O   FRICTION FACTOR = 0.018333   FREM = 25.6647

REM = 1399.9   GRM+ = 0.64510E 08   UPSTREAM BULK TEMPERATURE = 23.80 DEG C   DOWNSTREAM BULK TEMPERATURE = 52.58 DEG C
PRM = 4.496   RAM+ = 0.29004E 09   INLET BULK TEMPERATURE = 23.84 DEG C   OUTLET BULK TEMPERATURE = 52.56 DEG C

STATION NO.	Z CM	WALL TEMPERATURE (DEG C) A	B	C	AVERAGE	TB (C)	RE	PR	RA+	Z+	NUSSELT NUMBER A	B	C	AVERAGE T	H	T+H
0	0.0	32.77	32.89	32.14	32.49	23.84	1034.0	6.31	0.154E 09	0.00000	33.95	33.51	36.52	35.07	35.13	35.10
1	1.5	34.54	34.70	34.12	34.37	23.93	1036.0	6.29	0.155E 09	0.00006	28.56	28.14	29.75	29.04	29.06	29.05
2	2.5	35.76	35.96	35.48	35.67	23.99	1037.5	6.28	0.155E 09	0.00013	25.76	25.33	26.38	25.96	25.97	25.96
3	5.5	39.41	39.71	39.56	39.56	24.17	1041.8	6.25	0.157E 09	0.00028	19.88	19.50	19.69	19.69	19.69	19.69
4	15.5	42.65	41.82	38.87	40.55	24.79	1056.6	6.16	0.162E 09	0.00078	16.94	17.77	21.49	19.20	19.42	19.31
5	25.5	44.57	45.00	39.75	42.27	25.40	1071.8	6.06	0.168E 09	0.00129	15.76	15.41	21.05	17.91	18.32	18.11
6	45.5	46.80	46.26	41.38	43.96	26.62	1103.6	5.87	0.179E 09	0.00231	14.94	15.35	20.42	17.39	17.78	17.58
7	75.5	48.73	47.79	42.82	45.54	28.46	1146.9	5.63	0.196E 09	0.00385	14.81	15.52	20.90	17.57	18.03	17.80
8	105.5	50.65	49.87	45.76	48.01	30.30	1192.4	5.40	0.213E 09	0.00539	14.68	15.27	19.33	16.87	17.15	17.01
9	135.5	51.70	50.75	44.45	47.84	32.14	1240.7	5.17	0.232E 09	0.00695	15.21	15.99	24.16	18.95	19.88	19.42
10	165.2	52.36	51.85	47.09	49.60	33.96	1286.0	4.96	0.248E 09	0.00853	16.09	16.55	22.56	18.94	19.44	19.19
11	205.2	54.69	53.78	48.25	51.25	36.41	1352.4	4.67	0.272E 09	0.01068	16.09	16.94	24.85	19.84	20.68	20.26
12	245.2	57.52	56.86	52.33	54.76	38.86	1417.6	4.44	0.297E 09	0.01283	15.69	16.27	21.74	18.42	18.86	18.64
13	275.2	58.70	57.63	52.28	55.22	40.70	1469.3	4.27	0.317E 09	0.01444	16.21	17.23	25.19	20.09	20.96	20.52
14	305.2	60.63	60.51	55.42	58.00	42.54	1521.5	4.11	0.337E 09	0.01607	16.07	16.18	22.56	18.81	19.34	19.07
15	333.3	62.17	62.53	55.71	59.03	44.26	1568.2	3.97	0.355E 09	0.01760	16.18	15.86	25.31	19.62	20.66	20.14
16	363.3	65.72	66.18	58.63	62.29	46.10	1621.4	3.83	0.376E 09	0.01925	14.72	14.38	23.04	17.83	18.79	18.31
17	383.3	66.20	65.58	59.21	62.55	47.32	1657.6	3.74	0.390E 09	0.02035	15.27	15.78	24.25	18.93	19.89	19.41
18	403.3	67.64	66.65	60.06	63.61	48.55	1693.1	3.65	0.404E 09	0.02146	15.07	15.89	24.98	19.10	20.23	19.67
19	423.3	67.83	66.26	60.65	63.85	49.77	1730.2	3.57	0.418E 09	0.02257	15.90	17.41	26.38	20.40	21.52	20.96
20	443.3	70.22	70.72	62.92	66.70	51.00	1768.9	3.48	0.434E 09	0.02369	14.91	14.53	24.04	18.25	19.38	18.82
21	463.3	69.32	70.22	63.29	66.53	52.22	1806.9	3.40	0.449E 09	0.02481	16.73	15.90	25.85	19.99	21.08	20.54
AVERAGE VALUES THROUGH STATIONS 15 TO 20:	391.6	66.63	66.32	59.53	63.00	47.83	1673.2	3.71	0.396E 09	0.02082	15.34	15.64	24.67	19.02	20.08	19.55

========== EXPERIMENT 0R80 --- DEC. 23, 1987 ==========

INPUT ELECTRIC POWER = 4252.3 W   HEAT RATE GAINED BY WATER = 3971.0 W   HEAT BALANCE ERROR = 6.62%
MASS FLOW RATE = 28.7200 G/S   PRESSURE DROP = 0.5615 MM H2O   FRICTION FACTOR = 0.019385   FREM = 26.8274

REM = 1383.9   GRM+ = 0.79844E 08   UPSTREAM BULK TEMPERATURE = 23.87 DEG C   DOWNSTREAM BULK TEMPERATURE = 57.03 DEG C
PRM = 4.288   RAM+ = 0.34239E 09   INLET BULK TEMPERATURE = 23.91 DEG C   OUTLET BULK TEMPERATURE = 57.00 DEG C

STATION NO.	Z CM	WALL TEMPERATURE (DEG C) A	B	C	AVERAGE	TB (C)	RE	PR	RA+	Z+	NUSSELT NUMBER A	B	C	AVERAGE T	H	T+H
0	0.0	33.72	33.83	33.01	33.39	23.92	980.3	6.29	0.168E 09	0.00000	33.71	33.35	36.37	34.89	34.95	34.92
1	1.5	35.67	35.82	35.18	35.47	24.02	982.6	6.28	0.169E 09	0.00006	26.36	28.00	29.60	28.87	28.89	28.88
2	2.5	37.02	37.20	36.68	36.90	24.09	984.1	6.27	0.170E 09	0.00013	25.56	25.21	26.24	25.80	25.81	25.81
3	5.5	41.05	41.32	41.19	41.19	24.30	988.9	6.23	0.172E 09	0.00029	19.71	19.41	19.56	19.56	19.56	19.56
4	15.5	44.52	43.56	40.14	42.09	25.01	1005.2	6.12	0.179E 09	0.00083	16.90	17.77	21.79	19.30	19.56	19.43
5	25.5	46.63	47.10	41.22	44.04	25.71	1021.9	6.01	0.186E 09	0.00137	15.74	15.40	21.24	17.96	18.40	18.18
6	45.5	49.05	48.46	42.77	45.76	27.12	1056.1	5.80	0.201E 09	0.00245	14.97	15.38	20.98	17.61	18.08	17.84
7	75.5	51.04	50.12	44.42	47.50	29.24	1103.3	5.53	0.222E 09	0.00407	14.98	15.64	21.51	17.88	18.41	18.15
8	105.5	53.10	52.22	47.73	50.20	31.36	1155.0	5.26	0.244E 09	0.00571	14.95	15.58	19.85	17.25	17.56	17.41
9	135.5	54.41	53.41	46.42	50.17	33.48	1205.4	5.01	0.266E 09	0.00738	15.44	16.22	24.98	19.37	20.40	19.89
10	165.2	55.31	54.72	49.53	52.27	35.57	1257.8	4.77	0.288E 09	0.00906	16.30	16.80	23.04	19.26	19.79	19.53
11	205.2	58.02	57.02	50.95	54.24	38.40	1329.9	4.48	0.318E 09	0.01133	16.28	17.16	25.46	20.18	21.09	20.63
12	245.2	61.21	60.44	55.47	58.15	41.22	1405.1	4.22	0.352E 09	0.01361	15.90	16.54	22.30	18.78	19.26	19.02
13	275.2	62.63	61.48	55.55	58.81	43.34	1460.2	4.04	0.376E 09	0.01533	16.41	17.45	25.92	20.47	21.42	20.94
14	305.2	64.87	64.78	59.16	61.99	45.45	1516.6	3.88	0.402E 09	0.01707	16.24	16.32	23.01	19.07	19.64	19.36
15	333.3	66.69	67.02	59.30	63.07	47.44	1571.9	3.73	0.427E 09	0.01870	16.32	16.05	26.50	20.09	21.34	20.72
16	363.3	70.45	70.92	62.40	66.54	49.55	1631.2	3.58	0.453E 09	0.02046	14.99	14.66	24.37	18.44	19.60	19.02
17	383.3	71.03	70.26	63.30	66.97	50.97	1673.2	3.48	0.472E 09	0.02164	15.58	16.20	25.34	19.53	20.61	20.07
18	403.3	72.64	71.51	64.38	68.23	52.38	1714.0	3.39	0.491E 09	0.02282	15.39	16.30	25.98	19.68	20.92	20.30
19	423.3	72.95	71.16	65.24	68.65	53.79	1750.8	3.32	0.509E 09	0.02399	16.24	17.91	27.17	20.94	22.12	21.53
20	443.3	75.70	76.27	67.90	71.94	55.20	1789.3	3.24	0.527E 09	0.02516	15.15	14.73	24.44	18.54	19.69	19.12
21	463.3	74.97	76.00	68.63	72.06	56.61	1829.4	3.16	0.546E 09	0.02634	16.88	15.98	25.78	20.06	21.10	20.58
AVERAGE VALUES THROUGH STATIONS 15 TO 20:	391.6	71.58	71.19	63.75	67.57	51.55	1688.4	3.46	0.480E 09	0.02213	15.61	15.98	25.63	19.54	20.71	20.12

========== EXPERIMENT 0R81 --- DEC. 23, 1987 ==========

INPUT ELECTRIC POWER = 4580.2 W   HEAT RATE GAINED BY WATER = 4244.8 W   HEAT BALANCE ERROR = 7.32%
MASS FLOW RATE = 27.7090 G/S   PRESSURE DROP = 0.5546 MM H2O   FRICTION FACTOR = 0.020554   FREM = 28.4432

REM = 1383.8   GRM+ = 0.94511E 08   UPSTREAM BULK TEMPERATURE = 23.93 DEG C   DOWNSTREAM BULK TEMPERATURE = 60.67 DEG C
PRM = 4.124   RAM+ = 0.38979E 09   INLET BULK TEMPERATURE = 23.98 DEG C   OUTLET BULK TEMPERATURE = 60.64 DEG C

STATION NO.	Z CM	WALL TEMPERATURE (DEG C) A	B	C	AVERAGE	TB (C)	RE	PR	RA+	Z+	NUSSELT NUMBER A	B	C	AVERAGE T	H	T+H
0	0.0	34.57	34.70	33.73	34.18	23.98	947.2	6.28	0.181E 09	0.00000	33.38	32.98	36.26	34.65	34.72	34.68
1	1.5	36.65	36.83	36.07	36.41	24.10	949.7	6.27	0.182E 09	0.00008	28.14	27.75	29.49	28.70	28.72	28.71
2	2.5	38.08	38.30	37.69	37.94	24.17	951.4	6.25	0.183E 09	0.00014	25.40	25.01	26.13	25.66	25.67	25.66
3	5.5	42.38	42.70	42.54	42.54	24.41	956.5	6.22	0.185E 09	0.00030	19.64	19.29	19.47	19.47	19.47	19.47
4	15.5	46.20	45.14	41.22	43.44	25.19	974.0	6.09	0.193E 09	0.00086	16.77	17.66	21.99	19.31	19.60	19.45
5	25.5	48.43	48.94	42.51	45.60	25.97	992.1	5.97	0.202E 09	0.00142	15.66	15.32	21.27	17.92	18.38	18.15
6	45.5	51.02	50.40	44.38	47.55	27.54	1027.5	5.74	0.219E 09	0.00254	14.93	15.33	20.81	17.52	17.97	17.74
7	75.5	53.13	52.17	46.06	49.35	29.88	1079.1	5.45	0.244E 09	0.00422	15.00	15.64	21.55	17.90	18.44	18.17
8	105.5	55.29	54.35	49.36	52.09	32.23	1134.9	5.16	0.271E 09	0.00593	15.04	15.68	20.23	17.46	17.80	17.63
9	135.5	56.84	55.76	48.28	52.29	34.57	1188.9	4.88	0.296E 09	0.00768	15.48	16.27	25.15	19.46	20.51	19.98
10	165.2	57.94	57.30	51.74	54.68	36.90	1247.6	4.62	0.323E 09	0.00944	16.28	16.79	23.08	19.26	19.81	19.53
11	205.2	60.95	59.94	53.20	56.82	40.02	1324.0	4.33	0.361E 09	0.01178	16.27	17.10	25.85	20.27	21.27	20.77
12	245.2	64.50	63.66	58.22	61.15	43.15	1404.3	4.06	0.400E 09	0.01415	15.86	16.51	22.47	18.81	19.33	19.07
13	275.2	66.09	64.85	58.45	61.96	45.50	1464.4	3.88	0.430E 09	0.01595	16.37	17.41	26.02	20.47	21.45	20.96
14	305.2	68.55	68.45	62.39	65.44	47.84	1527.3	3.70	0.461E 09	0.01776	16.21	16.29	23.08	19.07	19.67	19.37
15	333.3	70.59	70.99	62.83	66.81	50.04	1587.5	3.55	0.492E 09	0.01947	16.28	15.97	26.17	19.95	21.15	20.55
16	363.3	74.81	75.36	66.29	70.69	52.39	1653.9	3.39	0.525E 09	0.02131	14.87	14.51	23.98	18.22	19.33	18.77
17	383.3	75.35	74.59	67.17	71.07	53.95	1693.4	3.31	0.546E 09	0.02252	15.54	16.11	25.16	19.43	20.49	19.96
18	403.3	77.27	75.97	68.30	72.46	55.51	1734.7	3.22	0.568E 09	0.02373	15.25	16.22	25.96	19.58	20.85	20.21
19	423.3	77.62	75.70	69.38	73.02	57.08	1777.7	3.14	0.590E 09	0.02496	16.11	17.77	26.89	20.75	21.92	21.33
20	443.3	80.81	81.43	72.32	76.72	58.64	1819.7	3.05	0.611E 09	0.02625	14.89	14.48	24.12	18.25	19.40	18.83
21	463.3	79.97	81.17	73.19	76.88	60.21	1863.8	2.97	0.632E 09	0.02754	16.65	15.69	25.33	19.73	20.75	20.24
AVERAGE VALUES THROUGH STATIONS 15 TO 20:	391.6	76.07	75.67	67.71	71.79	54.60	1711.2	3.28	0.555E 09	0.02304	15.49	15.84	25.38	19.36	20.52	19.94

========== EXPERIMENT OR82 --- JAN. 4, 1988 ==========

INPUT ELECTRIC POWER = 3954.2 W HEAT RATE GAINED BY WATER = 3711.9 W HEAT BALANCE ERROR = 6.13%
MASS FLOW RATE = 23.8470 G/S PRESSURE DROP = 0.4858 MM H2O FRICTION FACTOR = 0.024306 FREM = 29.0501

REM = 1195.2 GRM+ = 0.83494E 08 UPSTREAM BULK TEMPERATURE = 23.84 DEG C DOWNSTREAM BULK TEMPERATURE = 61.17 DEG C
PRM = 4.108 RAM+ = 0.34302E 09 INLET BULK TEMPERATURE = 23.89 DEG C OUTLET BULK TEMPERATURE = 61.14 DEG C

STATION NO.	Z CM	WALL TEMPERATURE (DEG C) A	B	C	AVERAGE	TB (C)	RE	PR	RA+	Z+	NUSSELT NUMBER A	B	C	AVERAGE T	H	T+H
0	0.0	33.79	33.88	33.00	33.42	23.89	813.5	6.30	0.157E 09	0.00000	31.22	30.96	33.95	32.46	32.52	32.49
1	1.5	35.63	35.75	35.08	35.39	24.01	815.7	6.28	0.158E 09	0.00010	26.58	26.31	27.91	27.16	27.18	27.17
2	2.5	36.90	37.05	36.51	36.74	24.09	817.2	6.27	0.159E 09	0.00016	24.10	23.84	24.86	24.41	24.42	24.41
3	5.5	40.72	40.93	40.82	40.82	24.33	821.6	6.23	0.161E 09	0.00035	18.84	18.60	18.72	18.72	18.72	18.72
4	15.5	44.01	43.14	39.66	41.62	25.12	836.9	6.10	0.168E 09	0.00100	16.31	17.10	21.20	18.68	18.95	18.82
5	25.5	46.04	46.39	40.65	43.43	25.92	852.7	5.98	0.176E 09	0.00165	15.29	15.02	20.87	17.56	18.01	17.79
6	45.5	48.49	47.92	42.43	45.32	27.50	883.7	5.75	0.191E 09	0.00295	14.61	15.01	20.54	17.21	17.67	17.44
7	75.5	50.51	49.67	44.17	47.13	29.89	928.8	5.45	0.213E 09	0.00491	14.79	15.41	21.34	17.68	18.22	17.95
8	105.5	52.70	51.94	47.39	49.86	32.27	977.5	5.15	0.237E 09	0.00689	14.84	15.42	20.05	17.24	17.59	17.42
9	135.5	54.36	53.38	46.73	50.30	34.66	1024.9	4.87	0.260E 09	0.00892	15.29	16.09	24.95	19.26	20.32	19.79
10	165.2	55.70	55.08	50.15	52.77	37.01	1076.1	4.60	0.284E 09	0.01097	16.03	16.58	22.80	19.01	19.55	19.28
11	205.2	56.53	57.61	51.77	54.92	40.19	1143.2	4.31	0.317E 09	0.01369	16.24	17.10	25.73	20.22	21.20	20.71
12	245.2	62.12	61.36	56.56	59.15	43.37	1213.2	4.04	0.352E 09	0.01645	15.79	16.45	22.44	18.76	19.28	19.02
13	275.2	63.84	62.77	57.09	60.20	45.75	1266.2	3.86	0.379E 09	0.01854	16.29	17.31	25.99	20.40	21.40	20.90
14	305.2	66.39	66.29	61.03	63.68	48.14	1321.1	3.68	0.407E 09	0.02065	16.08	16.16	22.76	18.87	19.44	19.16
15	333.3	68.51	68.82	61.63	65.15	50.37	1374.4	3.52	0.434E 09	0.02264	16.12	15.85	25.97	19.79	20.97	20.38
16	363.3	72.32	72.73	64.74	68.63	52.75	1431.2	3.37	0.463E 09	0.02477	14.89	14.58	24.31	18.35	19.52	18.93
17	383.3	73.16	72.40	65.79	69.29	54.34	1466.1	3.29	0.482E 09	0.02618	15.44	16.10	25.38	19.45	20.57	20.01
18	403.3	74.78	73.72	66.96	70.61	55.93	1502.7	3.20	0.502E 09	0.02759	15.38	16.29	26.28	19.75	21.06	20.41
19	423.3	75.26	73.63	68.15	71.30	57.52	1540.0	3.11	0.521E 09	0.02904	16.30	17.95	27.19	20.99	22.16	21.57
20	443.3	78.24	76.74	70.85	74.67	59.11	1577.2	3.03	0.540E 09	0.03053	15.07	14.69	24.56	18.53	19.72	19.12
21	463.3	77.61	78.74	71.52	74.85	60.70	1616.4	2.94	0.559E 09	0.03205	17.00	15.93	26.57	20.32	21.52	20.92
AVERAGE VALUES THROUGH STATIONS 15 TO 20:																
	391.6	73.71	73.34	66.35	69.94	55.00	1481.9	3.25	0.490E 09	0.02679	15.53	15.91	25.61	19.47	20.67	20.07

========== EXPERIMENT OR83 --- JAN. 4, 1988 ==========

INPUT ELECTRIC POWER = 4294.2 W HEAT RATE GAINED BY WATER = 4031.2 W HEAT BALANCE ERROR = 6.13%
MASS FLOW RATE = 23.0160 G/S PRESSURE DROP = 0.4785 MM H2O FRICTION FACTOR = 0.025679 FREM = 30.8156

REM = 1200.0 GRM+ = 0.10147E 09 UPSTREAM BULK TEMPERATURE = 23.75 DEG C DOWNSTREAM BULK TEMPERATURE = 65.74 DEG C
PRM = 3.934 RAM+ = 0.39914E 09 INLET BULK TEMPERATURE = 23.80 DEG C OUTLET BULK TEMPERATURE = 65.70 DEG C

STATION NO.	Z CM	WALL TEMPERATURE (DEG C) A	B	C	AVERAGE	TB (C)	RE	PR	RA+	Z+	NUSSELT NUMBER A	B	C	AVERAGE T	H	T+H
0	0.0	34.46	34.56	33.61	34.06	23.80	783.6	6.31	0.170E 09	0.00000	31.51	31.20	34.24	32.73	32.80	32.77
1	1.5	36.47	36.62	35.88	36.21	23.93	785.9	6.29	0.171E 09	0.00010	26.77	26.46	28.09	27.33	27.35	27.34
2	2.5	37.86	38.03	37.45	37.70	24.02	787.5	6.28	0.172E 09	0.00017	24.25	23.95	24.99	24.54	24.55	24.54
3	5.5	42.02	42.28	42.15	42.15	24.29	792.3	6.23	0.175E 09	0.00037	18.92	18.64	18.78	18.78	18.78	18.78
4	15.5	45.77	44.86	40.82	43.07	25.18	808.9	6.09	0.184E 09	0.00103	16.25	17.01	21.40	18.71	19.02	18.86
5	25.5	47.95	48.37	41.98	45.07	26.08	826.2	5.95	0.193E 09	0.00171	15.27	14.98	21.01	17.58	18.06	17.82
6	45.5	50.43	49.90	43.79	46.97	27.87	859.2	5.70	0.211E 09	0.00305	14.74	15.10	20.89	17.41	17.91	17.66
7	75.5	52.68	51.72	45.61	48.90	30.55	909.3	5.36	0.239E 09	0.00509	14.94	15.62	21.95	18.01	18.61	18.31
8	105.5	54.92	54.04	49.25	51.87	33.23	961.3	5.04	0.267E 09	0.00716	15.14	15.78	20.50	17.62	17.98	17.80
9	135.5	56.82	55.79	48.73	52.51	35.91	1015.1	4.73	0.296E 09	0.00928	15.60	16.41	25.45	19.65	20.73	20.19
10	165.2	58.33	57.70	52.31	55.16	38.57	1069.2	4.46	0.325E 09	0.01139	16.41	16.95	23.60	19.54	20.14	19.84
11	205.2	61.63	60.67	54.18	57.67	42.14	1146.2	4.14	0.368E 09	0.01423	16.53	17.38	26.76	20.75	21.86	21.30
12	245.2	65.78	64.94	59.68	62.52	45.72	1221.3	3.86	0.411E 09	0.01712	15.95	16.64	22.92	19.05	19.61	19.33
13	275.2	67.61	66.43	60.22	63.62	48.40	1280.9	3.66	0.445E 09	0.01930	16.58	17.67	26.95	20.93	22.04	21.48
14	305.2	70.26	70.16	64.51	67.36	51.08	1343.7	3.47	0.481E 09	0.02151	16.54	16.62	23.62	19.48	20.10	19.79
15	333.3	72.75	73.22	65.50	69.24	53.59	1398.9	3.33	0.514E 09	0.02356	16.49	16.10	26.53	20.19	21.41	20.80
16	363.3	77.30	77.77	69.04	73.29	56.27	1458.2	3.18	0.549E 09	0.02576	14.96	14.64	24.64	18.49	19.72	19.11
17	383.3	78.22	77.40	70.25	74.03	58.06	1498.4	3.08	0.573E 09	0.02728	15.56	16.22	25.73	19.64	20.81	20.23
18	403.3	80.06	78.89	71.42	75.45	59.85	1539.6	2.99	0.596E 09	0.02884	15.47	16.42	27.03	20.05	21.49	20.77
19	423.3	80.69	78.92	72.80	76.30	61.64	1583.2	2.89	0.620E 09	0.03042	16.36	18.03	27.92	21.25	22.56	21.90
20	443.3	84.28	84.71	75.86	80.18	63.42	1625.9	2.81	0.645E 09	0.03191	14.91	14.60	25.01	18.56	19.88	19.22
21	463.3	83.36	84.58	76.72	80.34	65.21	1670.4	2.73	0.673E 09	0.03339	17.09	16.02	26.97	20.50	21.76	21.13
AVERAGE VALUES THROUGH STATIONS 15 TO 20:																
	391.6	78.88	78.49	70.81	74.75	58.81	1517.4	3.05	0.583E 09	0.02796	15.63	16.00	26.14	19.70	20.98	20.34

========== EXPERIMENT OR84 --- JAN. 5, 1988 ==========

INPUT ELECTRIC POWER = 4578.3 W HEAT RATE GAINED BY WATER = 4295.9 W HEAT BALANCE ERROR = 6.17%
MASS FLOW RATE = 22.0420 G/S PRESSURE DROP = 0.4526 MM H2O FRICTION FACTOR = 0.026459 FREM = 31.7444

REM = 1199.8 GRM+ = 0.12186E 09 UPSTREAM BULK TEMPERATURE = 23.74 DEG C DOWNSTREAM BULK TEMPERATURE = 70.46 DEG C
PRM = 3.752 RAM+ = 0.45716E 09 INLET BULK TEMPERATURE = 23.80 DEG C OUTLET BULK TEMPERATURE = 70.43 DEG C

STATION NO.	Z CM	WALL TEMPERATURE (DEG C) A	B	C	AVERAGE	TB (C)	RE	PR	RA+	Z+	NUSSELT NUMBER A	B	C	AVERAGE T	H	T+H
0	0.0	35.12	35.25	34.19	34.69	23.81	750.5	6.31	0.181E 09	0.00000	31.62	31.27	34.44	32.87	32.94	32.91
1	1.5	37.29	37.46	36.65	37.01	23.95	752.9	6.29	0.183E 09	0.00010	26.82	26.47	28.16	27.38	27.40	27.39
2	2.5	38.78	38.99	38.34	38.61	24.05	754.6	6.27	0.184E 09	0.00017	24.27	23.93	25.02	24.55	24.56	24.55
3	5.5	43.26	43.58	43.42	43.42	24.35	759.8	6.23	0.187E 09	0.00038	18.89	18.58	18.73	18.73	18.73	18.73
4	15.5	47.33	46.38	41.87	44.36	25.34	777.5	6.07	0.197E 09	0.00108	16.21	16.94	21.57	18.74	19.08	18.91
5	25.5	49.79	50.27	43.21	46.62	26.34	796.1	5.91	0.208E 09	0.00178	15.17	14.86	21.07	17.53	18.04	17.79
6	45.5	52.34	51.76	45.06	48.55	28.33	830.7	5.64	0.230E 09	0.00319	14.74	15.11	21.16	17.50	18.04	17.77
7	75.5	54.71	53.71	47.10	50.66	31.31	885.5	5.27	0.264E 09	0.00532	15.03	15.70	22.27	18.18	18.82	18.50
8	105.5	57.17	56.25	50.82	53.77	34.29	940.4	4.92	0.297E 09	0.00751	15.26	15.90	21.12	17.92	18.35	18.13
9	135.5	59.28	58.11	50.30	54.50	37.28	999.5	4.58	0.331E 09	0.00974	15.75	16.64	26.60	20.12	21.40	20.76
10	165.2	61.11	60.45	54.73	57.75	40.23	1057.5	4.31	0.367E 09	0.01193	16.50	17.04	23.77	19.66	20.27	19.97
11	205.2	64.90	63.82	56.85	60.61	44.21	1138.1	3.98	0.418E 09	0.01492	16.53	17.43	27.05	20.85	22.02	21.44
12	245.2	69.61	68.69	63.02	66.08	48.19	1222.2	3.68	0.472E 09	0.01795	15.85	16.56	22.89	18.97	19.55	19.26
13	275.2	71.48	70.14	63.63	67.22	51.17	1289.0	3.47	0.514E 09	0.02025	16.64	17.82	27.12	21.06	22.18	21.62
14	305.2	74.36	74.25	68.22	71.26	54.15	1351.3	3.30	0.555E 09	0.02254	16.65	16.74	23.92	19.67	20.31	19.99
15	333.3	77.39	77.87	69.51	73.57	56.95	1411.4	3.14	0.595E 09	0.02470	16.39	16.01	26.66	20.15	21.43	20.79
16	363.3	82.48	82.96	73.60	78.16	59.93	1476.4	2.98	0.636E 09	0.02713	14.77	14.47	24.37	18.28	19.50	18.89
17	383.3	83.30	82.58	74.71	78.83	61.92	1523.0	2.88	0.665E 09	0.02878	15.53	16.07	25.96	19.64	20.88	20.26
18	403.3	85.49	84.33	76.30	80.60	63.91	1568.5	2.79	0.696E 09	0.03032	15.35	16.22	26.73	19.84	21.26	20.55
19	423.3	86.48	84.61	77.72	81.63	65.90	1616.8	2.70	0.728E 09	0.03188	16.05	17.66	27.94	21.00	22.40	21.70
20	443.3	90.43	90.77	81.21	85.90	67.89	1666.5	2.62	0.761E 09	0.03345	14.60	14.38	24.71	18.27	19.60	18.94
21	463.3	88.70	90.01	81.86	85.61	69.88	1717.7	2.53	0.793E 09	0.03503	17.40	16.27	27.35	20.83	22.09	21.46
AVERAGE VALUES THROUGH STATIONS 15 TO 20:																
	391.6	84.26	83.85	75.51	79.78	62.75	1543.7	2.85	0.680E 09	0.02938	15.45	15.80	26.06	19.53	20.84	20.19

========== EXPERIMENT OR85 --- JAN. 5, 1988 ==========

INPUT ELECTRIC POWER = 3900.1 W   HEAT RATE GAINED BY WATER = 3641.9 W   HEAT BALANCE ERROR = 6.62%
MASS FLOW RATE = 18.0710 G/S   PRESSURE DROP = 0.4258 MM H2O   FRICTION FACTOR = 0.037021   FREM = 36.9647

REM = 998.5   GRM+ = 0.10769E 09   UPSTREAM BULK TEMPERATURE = 23.81 DEG C   DOWNSTREAM BULK TEMPERATURE = 72.13 DEG C
PRM = 3.691   RAM+ = 0.39744E 09   INLET BULK TEMPERATURE = 23.88 DEG C   OUTLET BULK TEMPERATURE = 72.09 DEG C

STATION NO.	Z CM	-WALL TEMPERATURE (DEG C)- A	B	C	AVERAGE	TB (C)	RE	PR	RA+	Z+	NUSSELT NUMBER A	B	C	AVERAGE T	H	T+H
0	0.0	34.37	34.41	33.42	33.90	23.89	616.4	6.30	0.154E 09	0.00000	28.92	28.82	31.81	30.27	30.34	30.30
1	1.5	36.30	36.35	35.61	35.97	24.03	618.5	6.27	0.155E 09	0.00013	24.72	24.61	26.18	25.40	25.42	25.41
2	2.5	37.63	37.69	37.13	37.39	24.14	619.9	6.26	0.156E 09	0.00021	22.46	22.36	23.33	22.86	22.87	22.87
3	5.5	41.62	41.72	41.67	41.67	24.45	624.3	6.21	0.159E 09	0.00047	17.63	17.53	17.56	17.58	17.58	17.58
4	15.5	45.20	44.38	40.23	42.51	25.47	639.4	6.05	0.169E 09	0.00132	15.31	15.98	20.48	17.74	18.06	17.90
5	25.5	47.36	47.69	41.44	44.48	26.50	655.3	5.88	0.178E 09	0.00218	14.45	14.22	20.18	16.76	17.26	17.01
6	45.5	49.69	49.22	42.97	46.21	28.56	684.4	5.61	0.197E 09	0.00390	14.19	14.52	20.82	17.00	17.59	17.29
7	75.5	52.06	51.24	45.38	48.52	31.64	731.4	5.23	0.227E 09	0.00650	14.59	15.20	21.69	17.66	18.29	17.97
8	105.5	54.64	53.84	48.91	51.57	34.73	777.8	4.87	0.256E 09	0.00917	14.84	15.47	20.85	17.55	18.00	17.77
9	135.5	56.82	55.93	49.23	52.80	37.81	827.7	4.53	0.286E 09	0.01188	15.44	16.20	25.70	19.58	20.76	20.17
10	165.2	59.20	58.65	53.50	56.22	40.87	877.9	4.25	0.319E 09	0.01456	15.91	16.40	23.09	19.01	19.62	19.32
11	205.2	62.98	62.11	56.12	59.33	44.96	946.1	3.92	0.363E 09	0.01822	16.08	16.90	25.99	20.17	21.24	20.71
12	245.2	67.96	67.16	61.99	64.78	49.10	1018.1	3.61	0.410E 09	0.02193	15.23	15.90	22.29	18.33	18.93	18.63
13	275.2	69.83	68.84	63.04	66.19	52.18	1075.4	3.40	0.448E 09	0.02474	16.21	17.17	26.36	20.43	21.52	20.98
14	305.2	72.96	72.82	67.48	70.19	55.27	1127.0	3.24	0.484E 09	0.02753	16.10	16.22	23.31	19.08	19.73	19.41
15	333.3	76.18	76.52	69.14	72.74	58.16	1176.1	3.08	0.518E 09	0.03022	15.72	15.43	25.79	19.42	20.68	20.05
16	363.3	80.70	81.03	72.93	76.90	61.24	1235.3	2.91	0.555E 09	0.03321	14.48	14.24	24.11	18.00	19.23	18.61
17	383.3	81.60	80.84	74.18	77.70	63.30	1274.1	2.82	0.581E 09	0.03514	15.35	16.02	25.82	19.51	20.75	20.13
18	403.3	83.90	82.92	75.82	79.62	65.35	1314.4	2.73	0.610E 09	0.03703	15.11	15.95	26.78	19.65	21.16	20.40
19	423.3	85.05	83.54	77.58	80.94	67.41	1356.5	2.64	0.638E 09	0.03893	15.84	17.32	27.46	20.65	22.02	21.33
20	443.3	88.54	88.93	80.93	84.83	69.47	1399.3	2.55	0.666E 09	0.04086	14.58	14.28	24.26	18.09	19.34	18.72
21	463.3	87.94	89.10	82.09	85.30	71.52	1445.0	2.46	0.696E 09	0.04281	16.85	15.74	26.19	20.07	21.24	20.66
AVERAGE VALUES THROUGH STATIONS 15 TO 20:																
	391.6	82.66	82.30	75.10	78.79	64.15	1292.9	2.79	0.595E 09	0.03590	15.18	15.54	25.70	19.22	20.53	19.88

========== EXPERIMENT OR86 --- JAN. 5, 1988 ==========

INPUT ELECTRIC POWER = 4126.3 W   HEAT RATE GAINED BY WATER = 3850.3 W   HEAT BALANCE ERROR = 6.69%
MASS FLOW RATE = 17.1680 G/S   PRESSURE DROP = 0.4023 MM H2O   FRICTION FACTOR = 0.038714   FREM = 38.5385

REM = 995.5   GRM+ = 0.12985E 09   UPSTREAM BULK TEMPERATURE = 23.81 DEG C   DOWNSTREAM BULK TEMPERATURE = 77.56 DEG C
PRM = 3.500   RAM+ = 0.45451E 09   INLET BULK TEMPERATURE = 23.89 DEG C   OUTLET BULK TEMPERATURE = 77.52 DEG C

STATION NO.	Z CM	-WALL TEMPERATURE (DEG C)- A	B	C	AVERAGE	TB (C)	RE	PR	RA+	Z+	NUSSELT NUMBER A	B	C	AVERAGE T	H	T+H
0	0.0	35.27	35.34	34.21	34.76	23.89	585.7	6.30	0.163E 09	0.00000	28.18	28.01	31.06	29.51	29.58	29.54
1	1.5	37.31	37.41	36.56	36.96	24.06	587.9	6.27	0.165E 09	0.00013	24.18	24.00	25.63	24.84	24.86	24.85
2	2.5	38.72	38.84	38.16	38.48	24.17	589.4	6.25	0.166E 09	0.00022	22.02	21.84	22.67	22.39	22.40	22.40
3	5.5	42.95	43.13	43.04	43.04	24.52	594.1	6.20	0.169E 09	0.00049	17.37	17.20	17.28	17.28	17.28	17.28
4	15.5	46.71	45.82	41.22	43.74	25.66	610.2	6.02	0.180E 09	0.00139	15.17	15.84	20.53	17.66	18.02	17.84
5	25.5	49.11	49.39	42.57	45.91	26.81	627.1	5.84	0.192E 09	0.00229	14.28	14.10	20.20	16.67	17.20	16.93
6	45.5	51.30	50.74	44.07	47.54	29.09	657.5	5.55	0.213E 09	0.00410	14.27	14.63	21.15	17.17	17.80	17.48
7	75.5	53.98	53.09	46.71	50.12	32.53	707.2	5.12	0.249E 09	0.00686	14.65	15.28	22.16	17.86	18.56	18.21
8	105.5	56.81	55.94	50.88	53.63	35.96	757.9	4.72	0.283E 09	0.00969	14.94	15.59	20.87	17.63	18.07	17.85
9	135.5	59.30	58.33	51.15	54.98	39.39	810.3	4.39	0.320E 09	0.01254	15.53	16.33	26.31	19.84	21.12	20.48
10	165.2	62.20	61.49	55.89	58.87	42.79	864.6	4.09	0.359E 09	0.01538	15.83	16.43	23.45	19.11	19.79	19.45
11	205.2	66.31	65.40	58.82	62.34	47.36	938.5	3.73	0.413E 09	0.01926	16.08	16.90	26.61	20.35	21.55	20.95
12	245.2	71.80	70.90	65.46	68.41	51.94	1018.0	3.42	0.471E 09	0.02320	15.24	15.96	22.35	18.37	18.97	18.67
13	275.2	73.79	72.72	66.59	69.92	55.37	1072.4	3.23	0.513E 09	0.02614	16.34	17.35	26.83	20.68	21.84	21.26
14	305.2	77.22	77.11	71.33	74.25	58.80	1130.2	3.04	0.556E 09	0.02918	16.25	16.34	23.89	19.37	20.09	19.73
15	333.3	81.07	81.42	73.41	77.33	62.02	1187.9	2.87	0.597E 09	0.03213	15.62	15.33	26.11	19.43	20.80	20.11
16	363.3	85.82	86.13	77.63	81.80	65.45	1250.6	2.72	0.646E 09	0.03511	14.54	14.32	24.33	18.12	19.38	18.75
17	383.3	86.62	85.82	78.78	82.50	67.74	1295.1	2.62	0.680E 09	0.03712	15.63	16.32	26.74	19.99	21.36	20.68
18	403.3	89.44	88.31	80.78	84.83	70.03	1341.0	2.53	0.713E 09	0.03916	15.12	16.05	27.28	19.83	21.43	20.63
19	423.3	90.42	88.78	82.70	86.15	72.32	1387.9	2.44	0.747E 09	0.04120	16.14	17.75	28.13	21.12	22.54	21.83
20	443.3	94.58	94.99	86.45	90.62	74.60	1428.4	2.36	0.783E 09	0.04322	14.63	14.33	24.68	18.25	19.58	18.91
21	463.3	93.78	95.10	87.63	91.04	76.89	1471.4	2.29	0.820E 09	0.04526	17.30	16.04	27.21	20.66	21.94	21.30
AVERAGE VALUES THROUGH STATIONS 15 TO 20:																
	391.6	87.99	87.58	79.96	83.87	68.69	1315.1	2.59	0.694E 09	0.03799	15.28	15.68	26.21	19.46	20.85	20.15

========== EXPERIMENT OR87 --- JAN. 6, 1988 ==========

INPUT ELECTRIC POWER = 3673.8 W   HEAT RATE GAINED BY WATER = 3479.3 W   HEAT BALANCE ERROR = 5.29%
MASS FLOW RATE = 15.6650 G/S   PRESSURE DROP = 0.4056 MM H2O   FRICTION FACTOR = 0.046886   FREM = 42.3509

REM = 903.3   GRM+ = 0.11559E 09   UPSTREAM BULK TEMPERATURE = 23.76 DEG C   DOWNSTREAM BULK TEMPERATURE = 77.00 DEG C
PRM = 3.522   RAM+ = 0.40709E 09   INLET BULK TEMPERATURE = 23.84 DEG C   OUTLET BULK TEMPERATURE = 76.96 DEG C

STATION NO.	Z CM	-WALL TEMPERATURE (DEG C)- A	B	C	AVERAGE	TB (C)	RE	PR	RA+	Z+	NUSSELT NUMBER A	B	C	AVERAGE T	H	T+H
0	0.0	34.19	34.24	33.20	33.71	23.84	533.8	6.31	0.147E 09	0.00000	28.01	27.88	30.95	29.37	29.45	29.41
1	1.5	36.07	36.14	35.37	35.74	24.01	535.8	6.28	0.148E 09	0.00015	24.00	23.87	25.49	24.69	24.71	24.70
2	2.5	37.38	37.46	36.86	37.14	24.12	537.2	6.26	0.149E 09	0.00024	21.85	21.71	22.72	22.24	22.25	22.25
3	5.5	41.28	41.41	41.34	41.34	24.46	541.4	6.21	0.152E 09	0.00054	17.20	17.07	17.14	17.14	17.14	17.14
4	15.5	44.86	44.07	39.86	42.16	25.59	555.9	6.03	0.162E 09	0.00152	14.98	15.62	20.23	17.42	17.76	17.59
5	25.5	47.11	47.38	41.19	44.22	26.73	571.1	5.85	0.172E 09	0.00251	14.12	13.93	19.90	16.46	16.97	16.71
6	45.5	49.33	48.82	42.63	45.85	28.99	598.7	5.56	0.192E 09	0.00450	14.08	14.44	21.00	16.98	17.63	17.31
7	75.5	51.97	51.13	45.44	48.49	32.39	643.6	5.14	0.223E 09	0.00751	14.51	15.16	21.78	17.64	18.31	17.97
8	105.5	54.76	54.01	49.31	51.85	35.79	689.2	4.74	0.254E 09	0.01062	14.85	15.46	20.84	17.54	18.00	17.77
9	135.5	57.24	56.41	49.91	53.37	39.19	736.5	4.40	0.287E 09	0.01374	15.49	16.24	26.09	19.72	20.98	20.35
10	165.2	60.21	59.55	54.64	57.26	42.56	785.7	4.10	0.322E 09	0.01685	15.73	16.35	22.99	18.89	19.52	19.20
11	205.2	64.37	63.60	57.69	60.84	47.09	852.3	3.75	0.370E 09	0.02110	15.95	16.69	25.98	20.04	21.15	20.59
12	245.2	69.84	69.05	64.05	66.75	51.62	923.7	3.44	0.422E 09	0.02541	15.02	15.69	22.01	18.09	18.68	18.38
13	275.2	71.82	70.87	65.31	68.33	55.02	973.2	3.25	0.460E 09	0.02863	16.20	17.17	26.44	20.45	21.56	21.01
14	305.2	75.14	75.04	69.80	72.45	58.42	1025.3	3.07	0.498E 09	0.03194	16.18	16.28	23.77	19.29	20.00	19.64
15	333.3	79.13	79.42	72.22	75.74	61.60	1077.0	2.89	0.534E 09	0.03518	15.35	15.10	25.35	19.02	20.29	19.65
16	363.3	83.76	83.98	76.22	80.04	65.00	1133.3	2.74	0.578E 09	0.03847	14.28	14.11	23.88	17.81	19.04	18.42
17	383.3	85.03	84.22	77.65	81.14	67.27	1173.4	2.64	0.608E 09	0.04066	15.03	15.75	25.71	19.25	20.55	19.90
18	403.3	87.43	86.46	79.65	83.30	69.53	1214.3	2.55	0.637E 09	0.04289	14.83	15.69	26.25	19.29	20.76	20.02
19	423.3	88.57	87.13	81.64	84.74	71.80	1258.1	2.45	0.668E 09	0.04514	15.75	17.23	26.84	20.40	21.67	21.03
20	443.3	92.52	92.87	85.17	88.93	74.07	1294.5	2.38	0.700E 09	0.04735	14.31	14.04	23.78	17.76	18.98	18.37
21	463.3	91.99	93.16	86.19	89.38	76.33	1332.8	2.31	0.733E 09	0.04957	16.87	15.69	26.80	20.24	21.54	20.89
AVERAGE VALUES THROUGH STATIONS 15 TO 20:																
	391.6	86.07	85.68	78.76	82.32	68.21	1191.8	2.61	0.621E 09	0.04162	14.93	15.32	25.30	18.92	20.21	19.57

========== EXPERIMENT 0R88 --- JAN. 6, 1988 ==========

INPUT ELECTRIC POWER = 3202.5 W HEAT RATE GAINED BY WATER = 3042.4 W HEAT BALANCE ERROR = 5.00%
MASS FLOW RATE = 14.1400 G/S PRESSURE DROP = 0.3539 MM H2O FRICTION FACTOR = 0.050224 FREM = 40.4252

REM = 804.9 GRM+ = 0.97614E 08 UPSTREAM BULK TEMPERATURE = 23.88 DEG C DOWNSTREAM BULK TEMPERATURE = 75.45 DEG C
PRM = 3.572 RAM+ = 0.34867E 09 INLET BULK TEMPERATURE = 23.95 DEG C OUTLET BULK TEMPERATURE = 75.41 DEG C

STA-TION NO.	Z CM	-WALL TEMPERATURE (DEG C)- A	B	C	AVER-AGE	TB (C)	RE	PR	RA+	Z+	NUSSELT NUMBER A	B	C	AVERAGE T	H	T+H
0	0.0	33.54	33.59	32.63	33.10	23.96	483.1	6.29	0.129E 09	0.00001	26.42	26.28	29.20	27.70	27.77	27.73
1	1.5	35.23	35.30	34.57	34.92	24.11	484.8	6.26	0.130E 09	0.00016	22.79	22.64	24.21	23.44	23.46	23.45
2	2.5	36.39	36.47	35.91	36.17	24.22	486.0	6.24	0.131E 09	0.00027	20.81	20.67	21.66	21.19	21.20	21.19
3	5.5	39.87	39.99	39.93	39.93	24.55	489.7	6.19	0.134E 09	0.00060	16.52	16.38	16.45	16.45	16.45	16.45
4	15.5	43.02	42.30	38.53	40.59	25.65	502.4	6.02	0.142E 09	0.00169	14.53	15.16	19.59	16.89	17.22	17.05
5	25.5	45.00	45.23	39.75	42.43	26.75	515.8	5.85	0.151E 09	0.00278	13.79	13.62	19.35	16.05	16.53	16.29
6	45.5	47.02	46.57	40.99	43.89	28.94	539.8	5.57	0.168E 09	0.00498	13.85	14.21	20.79	16.75	17.41	17.08
7	75.5	49.72	49.03	43.97	46.67	32.24	579.2	5.16	0.194E 09	0.00832	14.22	14.80	21.17	17.22	17.84	17.53
8	105.5	52.54	51.88	47.73	49.97	35.53	618.7	4.77	0.220E 09	0.01175	14.49	15.07	20.19	17.06	17.49	17.28
9	135.5	55.03	54.29	48.50	51.58	38.82	660.1	4.44	0.248E 09	0.01521	15.09	15.82	25.28	19.18	20.37	19.77
10	165.2	57.97	57.42	52.94	55.31	42.08	703.5	4.14	0.277E 09	0.01865	15.31	15.86	22.40	18.38	18.99	18.69
11	205.2	61.94	61.24	55.95	58.77	46.47	760.9	3.80	0.318E 09	0.02335	15.59	16.34	25.45	19.61	20.71	20.16
12	245.2	67.34	66.65	62.11	64.55	50.87	822.3	3.49	0.361E 09	0.02811	14.54	15.17	21.31	17.50	18.08	17.79
13	275.2	69.26	66.48	63.55	66.21	54.16	866.9	3.30	0.393E 09	0.03169	15.77	16.64	25.38	19.77	20.79	20.28
14	305.2	72.59	72.52	67.93	70.24	57.45	912.2	3.12	0.426E 09	0.03530	15.66	15.73	22.61	18.53	19.15	18.84
15	333.3	76.40	76.63	70.17	73.34	60.54	956.0	2.95	0.456E 09	0.03886	14.85	14.65	24.47	18.40	19.61	19.01
16	363.3	80.59	80.72	74.00	77.32	63.83	1004.9	2.79	0.492E 09	0.04258	14.00	13.89	23.07	17.38	18.51	17.94
17	383.3	81.85	81.06	75.36	78.41	66.02	1039.2	2.70	0.517E 09	0.04500	14.78	15.55	25.07	18.89	20.12	19.51
18	403.3	84.50	83.60	77.55	80.80	68.22	1074.4	2.60	0.542E 09	0.04745	14.31	15.15	24.97	18.52	19.85	19.18
19	423.3	85.61	84.44	79.34	82.19	70.42	1111.1	2.51	0.568E 09	0.04992	15.25	16.52	25.95	19.68	20.92	20.30
20	443.3	89.21	89.50	82.74	86.05	72.61	1147.3	2.43	0.594E 09	0.05240	13.91	13.67	22.80	17.18	18.29	17.74
21	463.3	88.67	89.81	83.76	86.50	74.81	1179.5	2.36	0.621E 09	0.05485	16.65	15.39	25.78	19.74	20.90	20.32
AVERAGE VALUES THROUGH STATIONS 15 TO 20:																
	391.6	83.03	82.66	76.52	79.68	66.94	1055.5	2.66	0.528E 09	0.04604	14.51	14.90	24.39	18.34	19.55	18.95

========== EXPERIMENT 0R89 --- JAN. 6, 1988 ==========

INPUT ELECTRIC POWER = 3430.6 W HEAT RATE GAINED BY WATER = 3258.7 W HEAT BALANCE ERROR = 5.01%
MASS FLOW RATE = 13.4450 G/S PRESSURE DROP = 0.3256 MM H2O FRICTION FACTOR = 0.051034 FREM = 41.2786

REM = 808.9 GRM+ = 0.12143E 09 UPSTREAM BULK TEMPERATURE = 23.85 DEG C DOWNSTREAM BULK TEMPERATURE = 81.93 DEG C
PRM = 3.363 RAM+ = 0.40832E 09 INLET BULK TEMPERATURE = 23.94 DEG C OUTLET BULK TEMPERATURE = 81.89 DEG C

STA-TION NO.	Z CM	-WALL TEMPERATURE (DEG C)- A	B	C	AVER-AGE	TB (C)	RE	PR	RA+	Z+	NUSSELT NUMBER A	B	C	AVERAGE T	H	T+H
0	0.0	34.46	34.51	33.38	33.93	23.94	459.2	6.29	0.138E 09	0.00001	25.79	25.67	28.75	27.15	27.24	27.20
1	1.5	36.29	36.36	35.51	35.92	24.12	461.1	6.26	0.140E 09	0.00017	22.28	22.16	23.80	22.98	23.01	23.00
2	2.5	37.55	37.64	36.99	37.29	24.25	462.4	6.24	0.141E 09	0.00028	20.37	20.24	21.28	20.78	20.79	20.79
3	5.5	41.34	41.46	41.40	41.40	24.62	466.3	6.18	0.144E 09	0.00063	16.20	16.08	16.14	16.14	16.14	16.14
4	15.5	44.75	43.99	39.60	41.99	25.85	480.0	5.99	0.154E 09	0.00177	14.29	14.89	19.64	16.74	17.12	16.93
5	25.5	46.88	47.15	40.96	43.99	27.09	494.0	5.80	0.164E 09	0.00293	13.61	13.42	19.41	15.93	16.46	16.20
6	45.5	48.88	48.37	42.29	45.46	29.56	520.0	5.49	0.185E 09	0.00524	13.86	14.24	21.04	16.85	17.55	17.20
7	75.5	51.89	51.10	45.64	48.57	33.27	562.0	5.04	0.216E 09	0.00878	14.26	14.89	21.47	17.36	18.02	17.69
8	105.5	54.87	54.21	49.66	52.11	36.98	606.3	4.61	0.249E 09	0.01242	14.70	15.27	20.70	17.38	17.84	17.61
9	135.5	57.69	56.86	50.84	54.06	40.69	650.8	4.27	0.283E 09	0.01605	15.36	16.15	25.72	19.53	20.74	20.13
10	165.2	61.39	60.73	55.72	58.39	44.36	696.1	3.96	0.319E 09	0.01969	15.22	15.84	22.82	18.48	19.18	18.83
11	205.2	65.69	64.98	59.18	62.26	49.30	760.2	3.60	0.369E 09	0.02468	15.69	16.40	26.02	19.85	21.04	20.44
12	245.2	71.83	71.12	66.11	68.79	54.25	825.4	3.29	0.422E 09	0.02970	14.52	15.12	21.51	17.55	18.17	17.86
13	275.2	73.82	73.03	67.67	70.55	57.96	873.9	3.09	0.462E 09	0.03352	15.99	16.83	26.10	20.14	21.25	20.70
14	305.2	77.61	77.51	72.41	74.98	61.66	925.2	2.89	0.501E 09	0.03754	15.79	15.90	23.45	18.91	19.65	19.28
15	333.3	82.19	82.41	75.18	78.74	65.14	974.7	2.74	0.543E 09	0.04112	14.71	14.52	24.99	18.44	19.80	19.12
16	363.3	86.62	86.73	79.34	83.01	68.85	1031.3	2.58	0.589E 09	0.04498	14.02	13.93	23.73	17.59	18.85	18.22
17	383.3	88.27	87.42	81.19	84.52	71.32	1071.6	2.47	0.620E 09	0.04759	14.61	15.37	25.09	18.76	20.04	19.40
18	403.3	90.94	89.99	83.40	86.93	73.79	1107.2	2.39	0.652E 09	0.05018	14.42	15.26	25.75	18.82	20.29	19.56
19	423.3	92.14	90.88	85.44	88.48	76.26	1142.9	2.31	0.685E 09	0.05277	15.58	16.92	26.93	20.25	21.59	20.92
20	443.3	96.41	96.72	89.19	92.88	78.73	1178.5	2.23	0.717E 09	0.05540	13.97	13.72	23.61	17.45	18.73	18.09
21	463.3	95.75	97.11	90.52	93.47	81.21	1215.6	2.16	0.750E 09	0.05806	16.94	15.49	26.46	20.08	21.34	20.71
AVERAGE VALUES THROUGH STATIONS 15 TO 20:																
	391.6	89.43	89.03	82.29	85.76	72.35	1084.3	2.45	0.634E 09	0.04867	14.55	14.96	25.02	18.55	19.88	19.22

========== EXPERIMENT 0R90 --- JAN. 7, 1988 ==========

INPUT ELECTRIC POWER = 2964.8 W HEAT RATE GAINED BY WATER = 2797.9 W HEAT BALANCE ERROR = 5.63%
MASS FLOW RATE = 11.7770 G/S PRESSURE DROP = 0.2650 MM H2O FRICTION FACTOR = 0.054152 FREM = 38.0531

REM = 702.7 GRM+ = 0.10194E 09 UPSTREAM BULK TEMPERATURE = 23.87 DEG C DOWNSTREAM BULK TEMPERATURE = 80.81 DEG C
PRM = 3.392 RAM+ = 0.34582E 09 INLET BULK TEMPERATURE = 23.96 DEG C OUTLET BULK TEMPERATURE = 80.77 DEG C

STA-TION NO.	Z CM	-WALL TEMPERATURE (DEG C)- A	B	C	AVER-AGE	TB (C)	RE	PR	RA+	Z+	NUSSELT NUMBER A	B	C	AVERAGE T	H	T+H
0	0.0	33.48	33.53	32.53	33.02	23.97	402.4	6.29	0.119E 09	0.00001	24.49	24.36	27.20	25.74	25.81	25.78
1	1.5	35.13	35.20	34.45	34.81	24.14	404.0	6.26	0.120E 09	0.00020	21.19	21.05	22.58	21.82	21.85	21.84
2	2.5	36.27	36.36	35.78	36.05	24.26	405.2	6.24	0.121E 09	0.00033	19.38	19.24	20.21	19.75	19.76	19.75
3	5.5	39.70	39.83	39.76	39.76	24.63	408.6	6.18	0.123E 09	0.00072	15.43	15.30	15.37	15.37	15.37	15.37
4	15.5	42.76	42.13	38.19	40.32	25.84	420.3	5.99	0.132E 09	0.00203	13.70	14.24	18.78	16.02	16.37	16.20
5	25.5	44.77	44.97	39.53	42.20	27.05	432.4	5.80	0.141E 09	0.00334	13.05	12.90	18.54	15.27	15.76	15.51
6	45.5	46.63	46.17	40.93	43.67	29.47	454.7	5.50	0.158E 09	0.00599	13.41	13.77	20.07	16.21	16.83	16.52
7	75.5	49.66	49.00	44.00	46.67	33.11	490.7	5.05	0.185E 09	0.01001	13.78	14.35	20.93	16.82	17.50	17.16
8	105.5	52.76	52.16	48.05	50.25	36.74	528.6	4.63	0.212E 09	0.01417	14.11	14.65	19.98	16.72	17.18	16.95
9	135.5	55.49	54.79	49.43	52.29	40.38	566.6	4.30	0.241E 09	0.01831	14.68	15.56	24.78	18.84	19.99	19.42
10	165.2	59.23	58.71	54.30	56.64	43.98	605.6	3.99	0.271E 09	0.02247	14.61	15.13	21.59	17.60	18.23	17.91
11	205.2	63.58	63.04	57.86	60.58	48.82	660.3	3.63	0.313E 09	0.02815	14.98	15.55	24.45	18.79	19.85	19.32
12	245.2	69.64	68.97	64.51	66.90	53.67	716.7	3.32	0.357E 09	0.03388	13.73	14.34	20.24	16.57	17.14	16.85
13	275.2	71.65	70.98	66.17	68.74	57.31	758.1	3.13	0.391E 09	0.03821	15.20	15.95	24.61	19.07	20.09	19.58
14	305.2	75.40	75.32	70.82	73.09	60.94	801.3	2.93	0.424E 09	0.04278	14.98	15.06	21.92	17.83	18.47	18.15
15	333.3	79.80	80.01	73.64	76.77	64.35	843.5	2.77	0.458E 09	0.04692	13.95	13.76	23.20	17.35	18.53	17.94
16	363.3	84.35	84.35	77.65	81.00	67.98	891.6	2.61	0.496E 09	0.05131	13.09	13.10	22.16	16.46	17.63	17.04
17	383.3	85.77	84.95	79.56	82.46	70.41	925.3	2.51	0.522E 09	0.05427	13.87	14.65	23.27	17.68	18.77	18.22
18	403.3	88.34	87.52	81.75	84.84	72.83	958.2	2.42	0.549E 09	0.05724	13.69	14.45	23.80	17.68	18.94	18.31
19	423.3	89.75	88.64	83.91	86.55	75.25	988.1	2.34	0.576E 09	0.06020	14.65	15.86	24.54	18.80	19.90	19.35
20	443.3	93.70	93.92	87.38	90.59	77.68	1019.0	2.27	0.604E 09	0.06318	13.24	13.06	21.87	16.42	17.51	16.97
21	463.3	93.11	94.30	88.50	91.10	80.10	1050.0	2.19	0.631E 09	0.06620	16.27	14.91	25.21	19.24	20.40	19.82
AVERAGE VALUES THROUGH STATIONS 15 TO 20:																
	391.6	86.95	86.56	80.65	83.70	71.42	937.6	2.49	0.534E 09	0.05552	13.75	14.15	23.14	17.40	18.54	17.97

========== EXPERIMENT 0R91 --- JAN. 7, 1988 ==========

INPUT ELECTRIC POWER = 2506.4 W   HEAT RATE GAINED BY WATER = 2346.0 W   HEAT BALANCE ERROR = 6.40%
MASS FLOW RATE = 10.1350 G/S   PRESSURE DROP = 0.2123 MM H2O   FRICTION FACTOR = 0.058601   FREM = 35.0242

REM = 597.7   GRM+ = 0.82784E 08   UPSTREAM BULK TEMPERATURE = 23.86 DEG C   DOWNSTREAM BULK TEMPERATURE = 79.35 DEG C
PRM = 3.436   RAM+ = 0.28442E 09   INLET BULK TEMPERATURE = 23.95 DEG C   OUTLET BULK TEMPERATURE = 79.30 DEG C

STA-TION NO.	Z CM	-WALL TEMPERATURE (DEG C)- A	B	C	AVER-AGE	TB (C)	RE	PR	RA+	Z+	NUSSELT NUMBER A	B	C	AVERAGE T	H	T+H
0	0.0	32.55	32.58	31.66	32.11	23.96	346.2	6.29	0.997E 08	0.00001	22.72	22.64	25.35	23.94	24.01	23.98
1	1.5	34.00	34.04	33.36	33.69	24.13	347.6	6.26	0.101E 09	0.00023	19.77	19.69	21.15	20.41	20.44	20.43
2	2.5	35.00	35.05	34.53	34.78	24.25	348.5	6.24	0.101E 09	0.00038	18.15	18.06	18.98	18.53	18.54	18.54
3	5.5	38.00	38.07	38.04	38.04	24.60	351.4	6.19	0.103E 09	0.00083	14.55	14.47	14.51	14.51	14.51	14.51
4	15.5	40.75	40.27	36.75	38.63	25.78	361.2	6.00	0.110E 09	0.00235	12.99	13.43	17.74	15.14	15.47	15.31
5	25.5	42.52	42.71	37.95	40.28	26.96	371.5	5.82	0.118E 09	0.00388	12.47	12.32	17.65	14.56	15.02	14.79
6	45.5	44.35	44.00	39.32	41.75	29.32	390.0	5.52	0.131E 09	0.00695	12.84	13.14	19.30	15.53	16.15	15.84
7	75.5	47.43	46.87	42.62	44.89	32.86	420.3	5.08	0.153E 09	0.01163	13.14	13.66	19.61	15.92	16.50	16.21
8	105.5	50.54	50.06	46.42	48.36	36.41	451.7	4.67	0.175E 09	0.01645	13.41	13.88	18.94	15.86	16.29	16.08
9	135.5	53.31	52.70	48.02	50.51	39.95	483.5	4.33	0.199E 09	0.02126	14.09	14.76	23.31	17.82	18.87	18.34
10	165.2	57.07	56.57	52.68	54.75	43.46	516.4	4.03	0.223E 09	0.02608	13.73	14.26	20.27	16.56	17.13	16.84
11	205.2	61.26	60.79	56.26	58.64	48.18	561.9	3.68	0.257E 09	0.03267	14.17	14.71	22.94	17.72	18.69	18.21
12	245.2	67.08	66.51	62.56	64.68	52.90	609.6	3.36	0.294E 09	0.03934	12.98	13.53	19.05	15.63	16.15	15.89
13	275.2	69.21	68.65	64.46	66.69	56.44	643.8	3.17	0.321E 09	0.04433	14.34	15.00	22.84	17.86	18.76	18.31
14	305.2	73.01	72.94	68.87	70.92	59.99	679.4	2.98	0.348E 09	0.04958	13.97	14.05	20.48	16.63	17.24	16.94
15	333.3	77.13	77.30	71.85	74.53	63.30	714.7	2.82	0.375E 09	0.05448	13.08	12.93	21.18	16.12	17.09	16.60
16	363.3	81.18	81.20	75.63	78.41	66.85	754.4	2.66	0.407E 09	0.05955	12.57	12.55	20.51	15.58	16.54	16.06
17	383.3	83.04	82.25	77.43	80.04	69.21	781.7	2.56	0.427E 09	0.06298	12.95	13.74	21.79	16.54	17.57	17.05
18	403.3	85.32	84.61	79.62	82.29	71.57	811.0	2.46	0.448E 09	0.06645	12.96	13.66	22.12	16.61	17.72	17.17
19	423.3	86.74	85.84	81.72	84.01	73.93	836.1	2.38	0.470E 09	0.06988	13.90	14.95	22.84	17.67	18.63	18.15
20	443.3	90.40	90.60	85.14	87.82	76.29	861.8	2.31	0.493E 09	0.07331	12.62	12.44	20.11	15.44	16.32	15.88
21	463.3	89.94	91.07	86.19	88.34	78.65	887.5	2.24	0.516E 09	0.07680	15.75	14.31	23.59	18.34	19.31	18.83
AVERAGE VALUES THROUGH STATIONS 15 TO 20:																
	391.6	83.97	83.63	78.57	81.18	70.19	793.3	2.53	0.437E 09	0.06444	13.01	13.38	21.43	16.33	17.31	16.82

========== EXPERIMENT 0R92 --- JAN. 7, 1988 ==========

INPUT ELECTRIC POWER = 2034.5 W   HEAT RATE GAINED BY WATER = 1862.9 W   HEAT BALANCE ERROR = 8.43%
MASS FLOW RATE = 8.6190 G/S   PRESSURE DROP = 0.1800 MM H2O   FRICTION FACTOR = 0.068752   FREM = 33.7249

REM = 490.5   GRM+ = 0.59739E 08   UPSTREAM BULK TEMPERATURE = 23.73 DEG C   DOWNSTREAM BULK TEMPERATURE = 75.57 DEG C
PRM = 3.573   RAM+ = 0.21343E 09   INLET BULK TEMPERATURE = 23.82 DEG C   OUTLET BULK TEMPERATURE = 75.52 DEG C

STA-TION NO.	Z CM	-WALL TEMPERATURE (DEG C)- A	B	C	AVER-AGE	TB (C)	RE	PR	RA+	Z+	NUSSELT NUMBER A	B	C	AVERAGE T	H	T+H
0	0.0	31.16	31.19	30.40	30.79	23.83	293.6	6.31	0.786E 08	0.00001	21.17	21.08	23.60	22.29	22.36	22.33
1	1.5	32.39	32.43	31.85	32.13	23.99	294.7	6.28	0.793E 08	0.00027	18.45	18.36	19.73	19.05	19.07	19.06
2	2.5	33.24	33.29	32.84	33.06	24.10	295.4	6.27	0.798E 08	0.00044	16.95	16.86	17.73	17.31	17.32	17.31
3	5.5	35.79	35.87	35.83	35.83	24.43	297.6	6.21	0.813E 08	0.00098	13.63	13.54	13.58	13.58	13.58	13.58
4	15.5	38.28	37.90	35.02	36.55	25.53	305.4	6.04	0.865E 08	0.00276	12.12	12.50	16.28	14.02	14.30	14.16
5	25.5	39.93	40.07	36.15	38.07	26.63	313.5	5.86	0.918E 08	0.00456	11.59	11.47	16.20	13.47	13.86	13.67
6	45.5	41.76	41.49	37.85	39.74	28.84	328.3	5.58	0.102E 09	0.00817	11.87	12.12	17.02	14.07	14.51	14.29
7	75.5	44.69	44.20	40.65	42.55	32.15	352.4	5.17	0.119E 09	0.01364	12.13	12.63	17.90	14.63	15.14	14.88
8	105.5	47.70	47.29	44.33	45.91	35.45	376.6	4.78	0.134E 09	0.01927	12.32	12.75	17.01	14.43	14.77	14.60
9	135.5	50.28	49.81	45.86	47.95	38.76	401.9	4.44	0.151E 09	0.02496	13.01	13.56	21.12	16.30	17.20	16.75
10	165.2	53.79	53.45	50.27	51.94	42.04	428.5	4.15	0.170E 09	0.03060	12.67	13.05	18.10	15.03	15.48	15.25
11	205.2	57.68	57.36	53.76	55.64	46.45	463.6	3.80	0.194E 09	0.03831	13.14	13.54	20.20	16.07	16.77	16.42
12	245.2	62.97	62.51	59.19	60.96	50.86	501.2	3.49	0.221E 09	0.04612	12.11	12.59	17.61	14.51	14.98	14.74
13	275.2	65.02	64.57	61.07	62.93	54.17	528.5	3.29	0.241E 09	0.05199	13.44	14.02	21.13	16.64	17.43	17.04
14	305.2	68.63	68.59	65.16	66.89	57.48	556.2	3.12	0.261E 09	0.05792	13.01	13.06	18.88	15.42	15.96	15.69
15	333.3	72.50	72.68	68.15	70.37	60.57	583.1	2.95	0.280E 09	0.06377	12.10	11.92	19.06	14.73	15.53	15.13
16	363.3	76.06	76.16	71.66	73.88	63.88	613.0	2.79	0.301E 09	0.06986	11.80	11.70	18.46	14.36	15.11	14.73
17	383.3	78.10	77.40	73.45	75.60	66.09	634.0	2.69	0.317E 09	0.07383	11.92	12.66	19.46	15.06	15.87	15.46
18	403.3	80.26	79.61	75.53	77.74	68.29	655.6	2.60	0.333E 09	0.07785	11.91	12.60	19.70	15.10	15.98	15.54
19	423.3	81.70	80.94	77.53	79.42	70.50	678.2	2.51	0.348E 09	0.08191	12.66	13.59	20.18	15.89	16.65	16.27
20	443.3	84.84	85.02	80.47	82.70	72.70	700.1	2.42	0.364E 09	0.08597	11.65	11.48	18.20	14.14	14.88	14.51
21	463.3	84.52	85.49	81.39	83.20	74.91	719.9	2.35	0.381E 09	0.09000	14.72	13.36	21.81	17.06	17.92	17.49
AVERAGE VALUES THROUGH STATIONS 15 TO 20:																
	391.6	78.91	78.64	74.46	76.62	67.01	644.0	2.66	0.324E 09	0.07553	12.01	12.32	19.18	14.88	15.67	15.28

Figure 6.13: Wall Temperature Differences $(t_b - t_c)$ at Station 16