

THE UNIVERSITY OF MANITOBA

HEAT TRANSFER AND HYDRODYNAMICS IN
TWO-PHASE TWO-COMPONENT FLOW IN
A VERTICAL TUBE

by

KAMIEL SAMY REZKALLAH

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HEAT TRANSFER AND HYDRODYNAMICS IN TWO-PHASE

TWO COMPONENT FLOW IN A VERTICAL TUBE

BY

KAMIEL S. REZKALLAH

A thesis submitted to the Faculty of Graduate Studies of
the University of Manitoba in partial fulfillment of the requirements
of the degree of

DOCTOR OF PHILOSOPHY

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ABSTRACT

Forced-convective heat transfer and hydrodynamic aspects of co-current, two-phase, two-component flow were studied experimentally in a 0.46 in. (1.168 cm) i.d. vertical tube with essentially no evaporation. The effect of reducing the surface tension on the heat-transfer coefficients, both local and length mean, the frictional pressure drop, and the flow patterns were investigated. Three liquids (water, glycerine & water solution of 58% glycerine by weight, and silicone liquid, 5 CS viscosity grade) were used in the study. The glycerine & water solution was chosen so that it would have essentially the same Prandtl number as that for the silicone liquid, while its surface tension was 3.4 times that of the latter.

At low-to-medium liquid flow rates, the mean heat-transfer coefficient for silicone-air increased with the increase of the gas flow rate until it reached a maximum, after which there was a substantial drop as the mixture was approaching the annular-mist transition. A further increase in $\dot{m}_G$ was followed by a monotonic increase in $\bar{h}_{TP}$ with the attendant condition of the gas phase becoming more important in the heat-transfer process.

The behaviour and shape of the local heat-transfer coefficients along the test section length remained unchanged in most cases with trends that varied according to the combination of the liquid and gas flow rates.

The effect of lowering the surface tension on the flow pattern was most profound on the bubble-slug boundary, which fell considerably, expanding the bubble flow region for the silicone-air system. Smaller changes were observed for the other flow pattern transitions.

The frictional-pressure-drop data for the silicone-air were slightly lower than those for the glycerine & water-air data in terms of the ratio ϕ^2 vs V_{SG}/V_{SL} at the same liquid Reynolds numbers.

A comprehensive study and comparisons were done with most of the existing correlations that predict the mean heat-transfer coefficient in two-phase, two-component, co-current, upward flow in vertical tubes. These correlations were tested against a large set of data which included a very wide range of variables and fluid properties.

Two correlations are presented for determining the mean heat-transfer coefficient in the laminar and turbulent flow regions. These two correlations give the best combination of predictive capabilities together with minimum restrictions.

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NOMENCLATURE

A_c	Cross-sectional area of tube wall	$\text{ft}^2(\text{m}^2)$
A_T	Flow area of the tube	$\text{ft}^2(\text{m}^2)$
A_1, A_2	Constants in various equations	
$B_0, B_1,$ B_2, B_3	Constants appearing in Eq. (D.7)	
C	Circumference of the ring, defined in Section D.11, or Discharge coefficient for flow through an orifice plate	
C_p	Specific heat	$\text{Btu/lb}_m \cdot ^\circ\text{F} \cdot (\text{J/kg} \cdot \text{K})$
d	Diameter of orifice throat	$\text{ft}(\text{m})$
D	Inside diameter of the tube	$\text{ft}(\text{m})$
D_o	Outside diameter of the tube	$\text{ft}(\text{m})$
D_p	Diameter of the pipe connected to the orifice plate	$\text{ft}(\text{m})$
e	Local voltage of the heated tube	volts
$\bar{e}$	Mean deviation defined in Eq. (5.1)	
$\bar{e}_r$	Root mean square deviation, Eq. (5.2)	
E	Total voltage drop across the heated tube	volts

E_{LG}, E_{UG}	Voltage drop across the lower and upper guard heaters, respectively	volts
f	Friction factor	
F	Velocity of approach factor, Eq.(D.42), or Correction factor, Eq.(D.48)	
F_a	Thermal expansion factor of the orifice plate, Eq.(D.42)	
g	Acceleration due to gravity	$\text{ft/s}^2 (\text{m/s}^2)$
g_c	Conversion factor	$\text{lb}_m \cdot \text{ft} / \text{lb}_f \cdot \text{s}^2$
G	Mass velocity	$\text{lb}_m / \text{hr} \cdot \text{ft}^2 (\text{kg} / \text{m}^2 \cdot \text{s})$
G_{SG}	Mass velocity of the gas phase as if it were flowing alone in the tube	$\text{lb}_m / \text{hr} \cdot \text{ft}^2 (\text{kg} / \text{m}^2 \cdot \text{s})$
G_{SL}	Mass velocity of the liquid phase as if it were flowing alone in the tube	$\text{lb}_m / \text{hr} \cdot \text{ft}^2 (\text{kg} / \text{m}^2 \cdot \text{s})$
h	Enthalpy per unit mass of fluid	$\text{Btu} / \text{lb} (\text{J} / \text{kg})$
$h, h(Z)$	Local heat-transfer coefficient	$\text{Btu} / \text{hr} \cdot \text{ft}^2 \cdot ^\circ\text{F} (\text{W} / \text{m}^2 \cdot \text{K})$
$\bar{h}$	Length-mean heat-transfer coefficient	$\text{Btu} / \text{hr} \cdot \text{ft}^2 \cdot ^\circ\text{F} (\text{W} / \text{m}^2 \cdot \text{K})$
h_w	Differential pressure drop across the orifice plate	$\text{in. H}_2\text{O} (\text{cm H}_2\text{O})$
i	Axial current density	$\text{Amp} / \text{ft}^2 (\text{Amp} / \text{m}^2)$
I	Total current flowing through the tube	Amp
k	Thermal conductivity	$\text{Btu} / \text{hr} \cdot \text{ft} \cdot ^\circ\text{F} (\text{W} / \text{m} \cdot \text{K})$

k'_o, k_t	Thermal conductivity of tube material	Btu/hr.ft. ⁰ F (W/m.K)
l_E	Entrance length, Eq.(6.6)	ft(m)
L	Length of the heated test section	ft(m)
L'	Calming length	ft(m)
ΔL	Length used to calculate the length-mean heat-transfer coefficient	ft(m)
m	Variable defined in Eq.(D.9)	⁰ F/ft ² (⁰ C/m ²)
$\dot{m}$	Mass flow rate	lb _m /hr (kg/s)
n	Number of variables	
Nu	Local Nusselt number = $\frac{hD}{k_L}$	
$\bar{Nu}$	Mean Nusselt number	
P	Pressure	lb _f /in ² (kPa)
P_a	Partial pressure of dry air	lb _f /in ² (kPa)
P_{FN}	P-function, Eq.(5.12)	
P_g	Saturation pressure of vapour in air	lb _f /in ² (kPa)
P_v	Partial pressure of vapour	lb _f /in ² (kPa)
Pr	Prandtl number	
Pr_T	Turbulent Prandtl number	
ΔP	Pressure drop (total without subscripts)	lb _f /in ² (kPa)
ΔP_{SPF}	Single-phase frictional pressure drop	lb _f /in ² (kPa)
ΔP_{TPF}	Two-phase frictional pressure drop	lb _f /in ² (kPa)
$\Delta P/\Delta L$	Total pressure drop per unit length	lb _f /in ³ (N/m ³)
q''	Heat flux	Btu/hr.ft ² (W/m ²)

q_v'''	Heat generated per unit volume of the heated tube	Btu/hr.ft ³ (W/m ³)
q_w''	Heat flux at the wall	Btu/hr.ft ² (W/m ²)
Q	Volumetric flow rate	ft ³ /hr(m ³ /s)
r	Radial coordinate measured from the axis of the tube	ft(m)
R	Gas constant	ft.lbf/lb _m ⁰ R (kJ/kg.K)
R_L	Liquid volume fraction = $1 - \alpha$	
R_t	Total resistance of test tube	ohm
Re	Reynolds number	
Re_d	Reynolds number based on orifice throat diameter	
Re_{SG}	Superficial gas Reynolds number $= \rho_G V_{SG} D / \mu_G$	
Re_{SL}	Superficial liquid Reynolds number $= \rho_L V_{SL} D / \mu_L$	
S	Slip ratio, Eq.(D.32)	
S_q	Spalding function Eq.(5.11)	
St	Stanton number = $Nu / Re.Pr$	
t	Wall thickness of the tube	ft(m)
T	Temperature	⁰ F(⁰ C)
T_{AVG}	Mean temperature of tube wall, Eq.(D.11)	⁰ F(⁰ C)
T_L	Temperature of the liquid at the inlet to the mixer	⁰ F(⁰ C)
T_o	Temperature as measured by the thermocouples on the heated tube	⁰ F(⁰ C)
ΔT_w	Temperature drop across the tube wall	⁰ F(⁰ C)

V	Velocity	ft/s(m/s)
V _{EXP}	Experimental value of a variable, Eq.(5.1)	
V _{PRED}	Predicted value of a variable, Eq.(5.1)	
V _{SG}	Superficial gas velocity	ft/s(m/s)
V _{SL}	Superficial liquid velocity	ft/s(m/s)
w	Mass of vapour/mass of dry air	
W	Wattmeter	W
We _{SL}	Weber number = $\rho_L V_{SL}^2 D / \sigma_L g_c$	
x	Flow quality = $\dot{m}_G / (\dot{m}_G + \dot{m}_L)$	
X	Martinelli parameter	
y	Coordinate measured from the tube wall	ft(m)
Y	Expansion factor, Eq.(D.43)	
Z	Axial coordinate measured from the commencement of heated section	in.(cm)
z ⁺	Variable defined in Eq.(5.13)	

Greek Symbols

α	Void fraction
α'	Temperature coefficient of thermal conductivity of tube material
β	d/D , (App. D)
β'	Temperature coefficient of electri- cal resistivity of tube material

ρ	Density	$\text{lb}_m/\text{ft}^3 (\text{kg}/\text{m}^3)$
$\rho', \rho'_0,$ $\bar{\rho}, \rho'_t$	Resistivities defined in Appendix D	$\text{ohm.ft} (\text{ohm.m})$
μ	Dynamic viscosity	$\text{lb}_m/\text{hr.ft} (\text{kg}/\text{m.s})$
ν	Kinematic viscosity	$\text{ft}^2/\text{hr} (\text{m}^2/\text{s})$
σ	Surface tension	$\text{lb}_f/\text{ft} (\text{N}/\text{m})$
τ	Shear stress	$\text{lb}_f/\text{ft}^2 (\text{kPa})$
ϕ	Relative humidity	
ω	Uncertainty interval in a variable, Appendix E	
ψ^2	$= \bar{h}_{TP} / \bar{h}_{SP}$	
ϕ^2	$\Delta P_{TPF} / \Delta P_{SPF}$	
ζ	Thickness of the laminar sublayer in the liquid film	in. (cm)

Subscripts

a	Dry air or atmosphere
abs	Absolute
app	Apparent
ave	Average
B	Bulk, liquid or mixture
cw	Cooling water (heat exchanger)
EVAP	Evaporation
EXP	Experimental
G	Gas
G1, G2	At the inlet and outlet of orifice plate

i	Location at which a thermocouple is attached to the wall; or Inside
IN,OUT	At the inlet and outlet of heated tube
ℓ	Laminar
L	Liquid
LP	Lower phase
MIX	Gas-liquid mixture
o	Outside
OR	Orifice
Pred	Predicted
SG	Superficial gas
SL	Superficial liquid
SP	Single-phase (generally, liquid)
SPF	Single-phase frictional
t	Turbulent
TP	Two-phase
TPF	Two-phase frictional
UP	Upper phase
v	Vapour
W	At the wall
Z	Axial component (in the direction of flow)

Superscripts

GL	Glycerine
H ₂ O	Water
L	Liquid

Chapter 1

INTRODUCTION

1.1 BACKGROUND AND PURPOSE OF PRESENT STUDY

The applications of two-phase flow, with or without heating, in the industrial field are numerous. Many industrial processes such as power generation, refrigeration, distillation, and air conditioning depend on a detailed knowledge of two-phase flow. The flow of a liquid and a permanent gas (usually referred to as two-phase, two-component flow) also involves a wide range of industrial applications. Examples are the flow of natural gas in pipe lines, oil wells and many chemical processes. The ability to remove the large amounts of heat produced in nuclear power reactors rapidly and efficiently is another example of the importance of two-phase flow (single component in this case).

These studies and others related to the field of two-phase flow have received considerable attention in recent years due to the growing need for more economical design, optimization of operating conditions, and improving of safety aspects. A large volume of literature on two-phase flow already exists and is rapidly increasing (21, 22, 26,

68). However, among this considerable volume of work, a small fraction has dealt with heat transfer in two-phase, two-component, co-current, upward flow in vertical tubes.

Comprehensive literature reviews on the subject have been conducted by Collier(19), Michiyoshi(65) and Vijay(93), which showed that the majority of the investigators have dealt mostly with the hydrodynamic aspects of the flow (i.e. pressure drops, void fractions, and flow patterns).

For those investigations which dealt with the heat transfer aspects of the flow, the effect of changing the fluid properties on the heat-transfer coefficients was not studied exhaustively. It is fair to say that among the different fluid properties, the liquid viscosity was given the most attention (35, 27, 55, 89, 90, 69, 93, 26). On the other hand, other fluid properties such as the surface tension have received minimum attention; some investigators (69, 89, 90) dealt with its effects on the hydrodynamic aspects only.

For this reason, an attempt to investigate the effect of surface tension on the heat transfer and the hydrodynamics in two-phase, two-component flow in vertical tubes was made by adding a surface-active agent to water (107). In that work (107), some difficulties were encountered with the use of a surface-active agent, among which was the change that took place in the solution concentration (and hence its

surface tension) at high liquid flow rates. In addition, as expected in such cases, the dynamic surface tension would differ from the static at operating conditions where gas-liquid interfaces are moving.

Therefore, the present investigation was carried out using two pure liquids. The selection of those two liquids was done based on the analysis given below.

Assuming that in this case the gravitational forces are unimportant, the results of a dimensional analysis will show that the Nusselt number is a function of the following dimensionless groups:

$$Nu = f^n (Re_{SL}, Pr_L, \frac{V_{SG}}{V_{SL}}, We, \frac{\rho_G}{\rho_L}, \frac{\mu_G}{\mu_L}, \frac{k_G}{k_L}, \frac{C_{PG}}{C_{PL}}) \quad (1.1)$$

where

Nu is the Nusselt number = $\frac{hD}{k}$

Re is the superficial liquid Reynolds number

$$= \frac{\rho_L V_{SL} D}{\mu_L}$$

Pr is the liquid Prandtl number, and

We is the Weber number = $\frac{\rho_L V_{SL}^2 D}{\sigma}$.

If the tube wall is wetted and the liquid layer is thick enough to contain the main resistance to heat transfer, it is expected that at least to a first approximation, the groups $\frac{\mu_G}{\mu_L}$, $\frac{k_G}{k_L}$ and $\frac{C_{PG}}{C_{PL}}$ would be unimportant.

It could be argued that the success of the "Liquid-Acceleration Model" over a wide range of conditions (see Chapter 8) is some support for the previous statement (in this model it is implied that the effect of the gas phase is to accelerate the liquid phase while the heat-transfer coefficient is predicted using a conventional single-phase correlation with liquid properties and some adjusted liquid velocity). The Lockhart-Martinelli parameter X_{tt} is often used to correlate two-phase heat transfer (18); in that parameter ρ_G/ρ_L appears to the 0.5 power (μ_G/μ_L appears to the rather weak power of 0.1). Further, in the work in this thesis, ρ_G (or ρ_G/ρ_L) appears in the void fraction correlation used in connection with the Liquid-Acceleration Model, and there are other arguments for retaining ρ_G/ρ_L .

Based on the previous comments and in order to advance, it is therefore assumed that there will be conditions when Eq. (1.1) can be reduced to

$$Nu = f^n (Re_{SL}, Pr_L, \frac{V_{SG}}{V_{SL}}, We, \frac{\rho_G}{\rho_L}) \quad (1.2)$$

Apparently, the effect of changing We on Nu could be found by keeping Re_{SL} , Pr_L , $\frac{V_{SG}}{V_{SL}}$ and $\frac{\rho_G}{\rho_L}$ unchanged while varying We independently. The ideal situation then would be to have two (or more) liquids whose properties are identical except for the surface tension σ (σ appears only in We). However, with pure liquids, a precise match of all the other properties excepting σ appeared to be impossible during

the consideration of a number of them at the early stage of the present study. With safety aspects as a consideration, particularly for an apparatus with an electrically heated test section and requiring a large volume of liquids (35 U.S. gallons or 132 litres), the choice of liquids was even more restricted (e.g. alcohol, toluene, hexane. . . . etc., were excluded).

The two liquids which were finally chosen were a glycerine & water solution of 58% glycerine by weight and a silicone liquid, known as "Dow Corning 200", 5 CS viscosity grade.

The glycerine & water solution was chosen such that its Prandtl number would be the same as that of the silicone liquid. The ratio of the liquid densities and viscosities were 25% and 80% larger for the glycerine & water solution, while its surface tension was approximately 3.4 times that of the silicone liquid. Due to these differences in ρ_L and μ_L , when the liquid superficial Reynolds numbers were matched, the ratio of Weber numbers was 1.3. (The properties of both liquids are listed in Table C.2.)

Therefore, having the same Re_{SL} , Pr_L , $\frac{V_{SG}}{V_{SL}}$ and roughly the same $\frac{\rho_G}{\rho_L}$, differences in Nu could be basically attributed to the difference in We through changing the surface tension (which is the property that varied the most in this case). This then essentially determined how the data were taken.

It should be noted that, wherever applicable, the discussions throughout the thesis will proceed in terms of surface tension effects.

Another purpose of the present study is to assemble and examine the existing correlations which predict the mean heat-transfer coefficient in two-phase, two-component, upward vertical flow. Firstly, the large set of data taken to date on the present experimental facility was used to examine the correlations. This set of data, taken by Vijay (93), Aggour (1), Zaidi(107) and the present author, covers the widest range of liquid and gas flow rates and fluid properties that appears in the literature for heat-transfer data in two-phase, two-component, upward flow in a vertical tube for a single apparatus.

Secondly, an up-dating search was done in the literature in order to locate other experimental data taken by different investigators and reported in an analyzable form. A comprehensive comparison between this extensive set of data and the correlations was done and a thorough examination of those correlations has led to conclusions about their success, or otherwise, in predicting this large set of data.

1.2 LAYOUT OF THE THESIS

The results of up-dating the literature survey done on the topic of forced convective heat transfer in two-phase, two-component (gas-liquid) flow in vertical tubes are presented in Chapter 2. The work done in this subject by different authors is described briefly and the main conclusions drawn by some authors are also summarized.

In Chapter 3, the experimental apparatus is described and the systems used for measuring the different variables. Detailed information on the different components of the apparatus is given in Appendix A.

Chapter 4 describes the procedure which was followed in performing the experimental work. The calculation procedure is given in Appendix D. The single-phase heat-transfer and pressure-drop results are presented in Chapter 5.

The flow pattern observations and pressure-drop data for the two-phase tests are presented in Chapter 6. Samples of pictures of the flow patterns observed during the different runs are also shown in this chapter. The chapter ends with a presentation of the frictional-pressure-drop data, comparison with some existing correlations, and a discussion on the effect of surface tension on the frictional pressure drop.

Chapter 7 contains the results of the heat-transfer tests. Local and mean heat-transfer data are presented and compared with other data which appears in the literature (for the mean heat-transfer coefficients). A thorough discussion on the effect of surface tension on both local and mean heat-transfer coefficients is also given, and the chapter ends with a comparison between the mean heat-transfer coefficients and some existing correlations.

In Chapter 8, the results of a comprehensive testing of the existing correlations that predict the mean heat-transfer coefficient in two-phase, two-component upward flow are given. Chapter 9 contains the conclusions that were drawn from the present investigation.

The number of each figure, table, and equation in the body of the thesis begins with the number of the chapter or the letter of the appendix in which it appears.

The variables appearing in the body of the thesis are listed in the "Nomenclature" or defined in detail the first time they appear in the thesis. The units employed are given also in the Nomenclature.

Chapter 2

LITERATURE REVIEW

2.1 INTRODUCTORY REMARKS

As pointed out in the previous chapter, two-phase flow and heat transfer have been studied extensively during recent years because of their increasing importance in engineering applications. The subject under consideration in the present study is that for forced-convective heat transfer in two-phase, two-component, gas-liquid co-current flow in vertical tubes. Major reviews of the literature on this subject have been reported by Collier (19) and Michiyoshi (64). Also, a comprehensive survey of both experimental and theoretical work done on the subject has been presented by Vijay (93) and Aggour (1). Since these reviews summarize the work in this field thoroughly and include extensive bibliographies, only the major contributions that have a direct bearing on the present investigation will be discussed. Details of the experimental work which have been done in the past are given in Table 2.1. The correlations, which were reported by different authors for predicting the mean heat-transfer coefficients, are given in Table 2.2 in chronological order with the definitions of terms and the range of applicability, as proposed by the original authors. A

Table 2.1 Details of Experimental Work

Reference	Test Section Details	Method of Heating	Method of Temperature Measurement	Fluid used		Range of $\dot{m}_L$ and $\dot{m}_G$ (lb/hr)	Range of Re_{SL} min. max.	Range of V_{SL} (ft/s) min. max.	Range of V_{SG}/V_{SL} min. max.	h_{TP} Basis *	Flow Pattern Observed
				Liquid	Gas						
Verschoor and Stemmerding (92)	Ambraloy 927 D = 0.551 in. L = 15.75 in. L/D = 28.6	Steam at atmospheric pressure	Thermocouples soldered on to the tube wall. Fluid temps. were measured by thermometer	Water	Air	171-545 Not given	2960 9460	0.46 1.47	0.02 225.	Mean	Bubble Slug Annular
Ueda (89)	Steel D = 2.01 in. L = 3.94 in. L/D = 1.96	D.C. electrical heating by means of external resistance wire	Thermocouples inserted to the mid point of the tube wall thickness	Water	Air	441-11,025 0-99	138 3460	0.09 2.23	0.17 129	Local	Bubble Slug Annular
Katsuhara and Kazama (46)	Copper D = 148 in. L = 10.63 in. L/D = 9	Electric (Nichrome wire wound around the tube)	4 thermocouples attached on the outer surface.	Water	Air	915-4167 $\dot{m}_G$ not given	Not given	0.52 2.5	0.04 3.43	Mean	Not reported
Groothuis and Hendal (35)	Copper D = 0.551 in. L = 7.87 in. L/D = 14.3	Steam	Constantan wires were buried inside the wall to form together with the tube material 8 copper - constantan thermocouples	1. Water	Air	(1) 244-977 $\dot{m}_G$ not given	(1) 3182 16,550	(1) 0.49 2.57	(1) 1.0 210.0	Mean	Not observed
				2. Gas-oil	Air	(2) 269-513 $\dot{m}_G$ not given	(2) 1853 3538	(2) 0.87 1.66	(2) 0.7 70.-		
Knott et al. (53)	Type 304 Stainless Steel D = 0.506 in. L = 60 in. L/D = 113.6	A.C. electric heating, using the tube as a resistor	6 No. 22 copper-constantan thermocouples soldered on the tube wall	Paraffin-base Petroleum Oil	Nitrogen	5.8-140. 0.22-6.9	6.7 162.0	0.11 5.65	0.11 39.4	Mean	Bubble
Kudirka et al. (56)	Bronze D = 0.625 in. L = 11.0 in. L/D = 17.6	A.C. electric heating, using the tube as a resistor	8 Cu-Con. thermocouples attached to the inner surface of the tube wall	(1) Water (2) Ethylene glycol.	Air	(1) 480-4320 0.83-68.5 (2) 540-2400 0.8-54.5	(1) 5440 44,825 (2) 380 1700	(1) 1.0 9.0 (2) 1.0 4.5	(1) 0.16 71.0 (2) 0.25 65.0	Local at Z/D=14.3	Bubble Slug Annular

* As reported by original authors

Table 2.1 (Cont'd.)

Reference	Test Section Details	Method of Heating	Method of Temperature Measurement	Fluid used		Range of $\dot{m}_L$ and $\dot{m}_G$ (lb_m/hr)	Range of Re_{SL} min. max.	Range of V_{SL} (ft/s) min. max.	Range of V_{SG}/V_{SL} min. max.	h_{TP} Basis	Flow Pattern Observed
				Liquid	Gas						
Ueda and Hanaoka (90)	Brass D = 0.766 in. L = 51.2 in. L/D = 66.8	Hot water circulated through a jacket around the tube.	3 pairs of thermocouples soldered on the outer surface of the tube.	1. Water	Air	(1) 229-1540 1.1-13.4	(1) 2800 16,000	(1) 0.32 2.16	(1) 0.58 50.3	Local and Mean	Bubble Slug Annular
				2. Mixture of Water and Salton	Air	(2) 695-1170 1.1-11.9	(2) 680 5,000	(2) 0.99 1.69	(2) 0.72 12.9		
Domanskii et al. (23)	Copper D = 1.26 in. L = 39.37 in. L/D = 31.25	Electrically by winding Nichrome strip around the tube	6 Cu-Con. thermocouples.	1. Water 2. Alcohol 87% 3. Glycerol (54, 65, 71, 77, 85%)	Air Air Air	Not given	Not given	0.328 7.22 For all liquids used	Range of V_{SG} is 0.082 4.92	Mean	Bubble
Fedotkin and Zarudnev (27)	D = 0.394, 0.846, in. L = 39.48, 98.4 in.	Not given	Measured the wall temp. at 3 points in each chamber	Water and solutions of different μ_L	Air	Not given	700 11,400	Not given	Not given	Local	Bubble Slug Annular
Dorresteijs (24)	Stainless Steel D = 2.756 in. L = 43.3 in. L/D = 15.7	A.C. electric heating, using the tube as a resistor	Cu-Con. thermocouples	Gas-oil	Air	510-11.8x10 ⁴ 0.36-3630	300 66,000	0.066 15.2	0.004 4730	Not given	Bubble Slug Froth Mist-Annular
Ueda & Nose (91)	Stainless Steel D = 1.177 in. L = 51.2 in. L/D = 43.5	A.C. electric heating of the tube, using the tube as a resistor	12 thermocouples attached on the outer surface at equal intervals	Water	Air	35.6-2505 81.6-154.4	Re_{LF} = liquid film Reynolds number: 190 13,700	0.21 1.476	Range of V_{SG} is 32.8 164.0	Local at $Z/D=32$	Annular and Mist
Kapinos et al. (45)	L/D = 1.68 to 59.1	Not given	Not given	Water	Air	Not given	Not given	Not given	Range of V_{SG} is 131 492	Mean	Mist (fog)

Table 2.1 (Cont'd.)

Reference	Test Section Details	Method of Heating	Method of Temperature Measurement	Fluid used		Range of $\dot{m}_L$ and $\dot{m}_G$ (lb _m /hr)	Range of Re_{SL} min. max.	Range of V_{SL} (ft/s) min. max.	Range of V_{SG}/V_{SL} min. max.	h_{TP} Basis	Flow Pattern Observed
				Liquid	Gas						
Ravipudi & Godbold (76)	Copper D = 0.75 in. L = 60 in. L/D = 80	Steam	24 Cu. Con. thermocouples 9 of which were placed inside the copper tube to measure the mixture temp. along the tube.	(1) Water (2) Toluene	Air Air	1) 690-5540 10.4-182.3 2) 1050 11.4-60.0	1) 10,100 52,540 2) 2022	1) 1.0 8.05 2) 1.8	1) 1.3 88.0 2) 7.7 40.4	Mean	Bubble Slug Churn Annular and Annular-mist
Vijay (93)	Stainless Steel 304 D = 0.46 in. L = 24 in. L/D = 52.2	A.C. electric heating using the tube as a resistor	47 Cu-Con (D = 0.005") thermocouples were attached onto the outer surface of the tube: Six thermocouples were used for fluid temp. at inlet and outlet of the test section.	1. Water 2. Glycerine & water solution (75-25% by weight) 3. Glycerine	Air Air Air	1) 16.7-8996 0.75-216 2) 13.6-9120 0.32-151.6 3) 100-1240 0.19-99.3	1) 250 1.26x10 ⁵ 2) 8.0 4,500 3) 1.8 21.0	1) 0.065 34.8 2) 0.044 29.4 3) 0.31 3.8	1) 0.03 6700 2) 0.01 6700 3) 0.05 330	Local and Mean	Bubble Slug Froth Annular and Annular-mist
Aggour (1)	← same as Vijay →	as Vijay		1. Water 2. Water 3. Water	Air Helium Freon 12 vap.	1) 267-8995 0.084-200 2) 267-8995 0.02-33.7 3) 267-3600 0.84-206	1) 4150 1.28x10 ⁵ 2) 3995 1.26x10 ⁵ 3) 4230 55,200	1) 1.03 34.7 2) 1.03 34.7 3) 1.03 34.7	1) 0.02 305.8 2) 0.042 196.0 3) 0.035 114.0	Local & Mean	Bubble Slug Froth Annular and Annular-mist

Table 2.1 (Cont'd.)

Reference	Test Section Details	Method of Heating	Method of Temperature Measurement	Fluid used		Range of $\dot{m}_L$ and $\dot{m}_G$ (lb _m /hr)	Range of Re_{SL} min. max.	Range of V_{SL} (ft/s) min. max.	Range of V_{SG}/V_{SL} min. max.	h_{TP} Basis	Flow Pattern Observed
				Liquid	Gas						
Chu & Jones (16)	Stainless Steel D = 1.05 in. L = 36 in. L/D = 34.3	A.C. electric heating using 12 heating wires wound around the stainless steel tube	Three Chr-Alum. thermocouples were soldered in a recessed hole in the test section wall (at same axial location, 120° apart azimuthally)	Water	Air	1855-14,315 2.1-10.2	16,000 112,000	1.38 10.63	0.13 2.12	Mean	Bubble Slug Froth
Zaidi (107)	←	same as Vijay	→	1. Water 2. Surfactant water solution	Air Air	(1) 48-8995 0.1-198. (2) 48-5397 0.14-196	(1) 710 1.53x10 ⁵ (2) 818 8.15x10 ⁴	(1) 0.19 34.8 (2) 0.19 20.8	(1) 0.02 2033 (2) 0.05 1682	Local and Mean	Bubble Slug Churn Froth Annular and Annular-mist
Elamvaluthi and Srinivas (26)	Brass D = 0.394 in. L = 33.9 in. L/D = 86	A.C. electric heating using a Nichrome wire wound around the test section	Four Cu-Con. thermocouples were fixed to the wall at equidistant to measure wall temp. Two other thermocouples were mounted at inlet & exit of test section to measure mixture temps at those locations	1. Water 2. Aqueous glycerine	Air Air	(1) 187-997 $\dot{m}_G$ not given (2) 125-935 $\dot{m}_G$ not given	(1) 4.3 22.9 (2) 0.15 1.15	Not given	(1) 0.3 2.5 (2) 0.6 4.6	Mean	Bubble Slug

Table 2.2 Summary of the Correlations for Predicting ($\bar{h}_{TP}$)

Author	Statement of Correlation and Definition of Terms	Range of Applicability and Comments
Katsuhara & Kazama (46), 1958	$Nu_{TP} = 8.7 (1-\alpha)^{0.125} (Re_{MIX})^{0.25} (Pr_{MIX})^{0.4}$ where: $Nu_{TP} = h_{TP} D / k_{MIX}$ $k_{MIX} = \alpha (\rho_G / \rho_{MIX}) k_G + (1-\alpha) (\rho_L / \rho_{MIX}) k_L$ $\rho_{MIX} = \alpha \rho_G + (1-\alpha) \rho_L$ $Pr_{MIX} = \alpha (\rho_G / \rho_{MIX}) Pr_G + (1-\alpha) (\rho_L / \rho_{MIX}) Pr_L$ $Re_{MIX} = V_{MIX} D / \nu_{MIX}$ $V_{MIX} = (\dot{m}_G + \dot{m}_L) / A_T \rho_{MIX}$ $\nu_{MIX} = \alpha (\rho_G / \rho_{MIX}) \nu_G + (1-\alpha) (\rho_L / \rho_{MIX}) \nu_L$	$0.08 < \alpha < 0.6$
Groothuis & Hendal (35), 1959	(1) <u>Water-air</u> : $Nu_{TP} = 0.029 (Re_2)^{0.87} (Pr_L)^{1/3} (\mu_B / \mu_W)^{0.14}$ (2) <u>Gas-oil/air</u> : $Nu_{TP} = 2.6 (Re_2)^{0.39} (Pr_L)^{1/3} (\mu_B / \mu_W)^{0.14}$ where: $Re_2 = Re_{SL} + Re_{SG}$	(1) $Re_{SL} > 5000$ $Re_{SG} > 0, V_{SG}/V_{SL} \geq 1$ (2) $1400 \leq Re_{SL} \leq 3500$, $Re_{SG} > 0, V_{SG}/V_{SL} \geq 1$
Knott et al. (53), 1959	$\frac{h_{TP}}{h_L} = [1 + (V_{SG}/V_{SL})]^{1/3}$, h_L was obtained from the Sieder-Tate correlation.	$Re_{SL} \leq 1500, 0.1 \leq V_{SG}/V_{SL} \leq 40$
Kudirka et al. (56), 1965	$Nu_{TP} = 125 \left(\frac{V_{SG}}{V_{SL}} \right)^{1/3} (Re_{SL})^{1/4} (Pr_L)^{1/3} \left(\frac{\mu_G}{\mu_L} \right)^{0.6} \left(\frac{\mu_B}{\mu_W} \right)^{0.14}$	$2.5 \times 10^{-4} \leq x \leq 0.092$ $x = \text{quality} = \dot{m}_G / (\dot{m}_L + \dot{m}_G)$
Ueda & Hanaoka (90), 1967	$Nu_{TP} = 0.075 (Re_M)^{0.6} \frac{Pr_L}{1 + 0.035 (Pr_L - 1)}$ where: $Re_M = \rho_L U_M^* D / \mu_L$ $U_M^* = V_L + 1.2 Re_S^{-0.25} V_S - 12 Fr_{ED} V_{ED} + 16 Fr_S^{1.25} V_S$ $V_L = V_{SL} / (1-\alpha), V_G = V_{SG} / \alpha, V_S = V_G - V_L$ $Re_S = V_S D (1 - \sqrt{\alpha}) / \nu_L, V_{ED} = V_{SL} + V_{SG}$ $Fr_{ED} = g \alpha D (1 - \sqrt{\alpha}) / V_{ED}^2, Fr_S = g \alpha D (1 - \sqrt{\alpha}) / V_S^2$	$1.5 \times 10^3 \leq Re_M \leq 6 \times 10^4$
Domanski, et al. (23), 1969	$\frac{h_{TP} \nu_L}{k_L U^*} = \frac{Pr_L}{\bar{\Psi}}$ where: $\bar{\Psi}$ = dimensionless temperature difference, U^* = friction velocity = $[(\frac{\tau_w}{\rho_L})^2 + \xi^* \nu_L g V_S \alpha (1-\alpha)^2]^{0.25}$, τ_w = wall shear stress and ξ = a proportionality constant.	

Author	Statement of Correlation and Definition of Terms	Range of Applicability and Comments
Fedotkin & Zarudnev (27), 1970	$Nu_{TP} = C_3 Re_2^n Pr_L^{0.43} \left(\frac{Pr_L}{Pr_W} \right)^{0.25} \text{ where:}$ $C_3, n = \text{constants}$ $Pr_W = \text{Prandtl number of liquid at the tube wall,}$ $Re_2 = Re_{SL} + Re_{SG}$	$1 < Pr_L < 200$ $700 < Re_{SL} < 1.14 \times 10^4$ Values of the constants n, C_3 were given for each chamber of the three used in their study (27).
Ueda & Nose (91), 1974	(1) <u>Laminar liquid film flow:</u> $\frac{h_{TP}}{k_L} \left(\frac{v_L^2}{g} \right)^{1/3} = X^* = \frac{Re_L^*}{T^*} \text{ where}$ $Re_L^* = -\frac{4}{3} (Y_1^*)^3 + 2 \tau_1^* (Y_1^*)^2,$ $T^* = \frac{4}{3} (\tau_1^* - Y_1^*) (Y_1^*)^3 + \frac{1}{2} (Y_1^*)^4,$ $Y_1^* = Y_1 (g/v_L^2)^{1/3}, \tau_1^* = \frac{\tau_1}{\rho_L g} (g/v_L^2)^{1/3},$ $\tau_1 = -\frac{r_1}{2} \left\{ \frac{\Delta P}{\Delta L} \right\} - \frac{1}{2\pi r_1} \left\{ \frac{\Delta \dot{m}_D}{\Delta L} \right\},$ $r_1 = R - Y_1, \frac{\Delta \dot{m}_D}{\Delta L} = V_G (\Delta \dot{m}_{ED} / \Delta L) / g,$ $\dot{m}_{ED}$ = mass flow rate of the entrained droplets. (2) <u>Turbulent liquid film flow:</u> $q = -\rho_L g C_{PL} \left(\frac{v_L}{Pr_L} + \epsilon_n \right) \frac{dT}{dY} \text{ and:}$ $h_{TP} = q_w / (T_w - T_{BF}) \text{ where:}$ T_{BF} = Bulk mean temperature of the liquid film and ϵ_h = eddy diffusivity for heat transfer.	The heat transfer data were analyzed theoretically by assuming that the liquid film consisted of a laminar sublayer and a turbulent layer. The correlations are difficult to use. Authors did not present a solution for this case.
Kapinos et al. (45), 1975	$Nu_{TP} = \frac{h_{TP} D}{k_G} = 340 Re_{SG}^{0.8} G^{-0.15} K_0^{0.86} q^{-0.82}$ For $L/D < 30$, the above correlation should be multiplied by ξ_L given by: $\xi_L = 1 + 10.2/(L/D)^{1.74}$	The terms appearing in the correlation were not defined in (45).
Liquid-Acceleration Model	$\frac{h_{TP}}{h_L} = \left(\frac{1}{1-\alpha} \right)^n$	$Re_{SL} \geq 2000$ Collier (18) suggested that in the bubble regime $n = 1/3$ & 0.8 for laminar and turbulent flow, respectively. Aggour (1) used $n = 1/3$ (for $Re_{SL} \leq 1000$) and $n = 0.83$ (for $Re_{SL} \geq 2000$). Dorrestijn (24) used $n = 0.9$ in the turbulent region.
Ravipudi & Godbold (76), 1978	$Nu_{TP} = 0.56 \left(\frac{v_{SG}}{v_{SL}} \right)^{0.3} \left(\frac{\mu_G}{\mu_L} \right)^{0.2} (Re_{SL})^{0.6} (Pr_L)^{1/3} \left(\frac{\mu_B}{\mu_W} \right)^{0.14}$	$8554 < Re_{SL} < 89,626$ $1 < v_{SG}/v_{SL} < 90$

Table 2.2 (Cont'd.)

Author	Statement of Correlation and Definition of Terms	Range of Applicability and Comments
Vijay et al. (94), 1982	$\psi^2 = (\phi^2)^n$ where: n is a constant depending on the flow pattern; n = 0.427, 0.489, 0.269, 0.455 for bubble, slug, froth and annular flow, respectively. For all flow patterns including transitions, n = 0.451. A slightly better fit of the data can be obtained using the following equation instead: $\psi^2 = A(\phi^2)^P (Re_{SL})^Q$ where A, P, q are constants depending on the flow pattern. $\psi^2 = \frac{h_{TP}}{h_L}$, $\phi^2 = \frac{\Delta P_{TPF}}{\Delta P_L}$	The correlation does not apply to the annular-mist transition. Also, it does not work well for slug flow and the slug-annular transition with frictional pressure drops less than approximately 1000 Pa/m.
Elamvaluthi & Srinivas (26), 1984	$Nu_{TP} = 0.5 \left(\frac{\mu_G}{\mu_L} \right)^{0.25} (Re_2)^{0.7} (Pr_L)^{1/3} \left(\frac{\mu_B}{\mu_W} \right)^{0.14}$ where: $Re_2 = \frac{\mu_L D V_{SL} \rho_L}{\mu_L} + \frac{D V_{SG} \rho_G}{\mu_G}$	$300 < Re_2 < 16,500$ $V_{SG}/V_{SL} = 0.3 - 4.6$

comprehensive review of these correlations was done and results are presented in Chapter 8, where most of them are tested using a large set of experimental data. Therefore, no other comments on the correlations are given in this chapter.

The present investigation also includes some hydrodynamic aspects of two-phase, two-component flow in a vertical tube. The literature relating to these studies (pressure drops and flow patterns) is not reviewed in this chapter. However, the literature pertaining to these aspects which are relevant to the present work will be discussed at the appropriate places throughout the thesis.

Due to the fact that the present investigation deals only with conditions such as non-boiling, forced-convective heat transfer in circular tubes with vertically upward flow, other studies that dealt with different geometries (17,65) or where free convection existed (67) or where substantial evaporation took place (70) are excluded from this survey.

At the end of this survey, a review is given for the studies done in the past with regard to the effect of changing the surface tension on the heat transfer in two-phase, two-component vertical flow.

2.2 TWO-PHASE, TWO-COMPONENT HEAT TRANSFER IN VERTICAL TUBES

Verschoor and Stemerding (92) used a 0.55 in. (1.40 cm) i.d. tube with 15.75 in. (40.0 cm) long test section, heated by condensing steam (at atmospheric pressure) on the outside diameter to investigate two-phase heat transfer of air and water. The authors found that $\bar{h}_{TP}$ increased with increasing volumetric air-to-water ratio at constant liquid flow rate, and that introduction of air was most effective in increasing the heat-transfer rate at the lowest liquid flow rate. They also observed that $\bar{h}_{TP}$ values passed through a minimum at $V_{SG}/V_{SL} = 2$ and reached a maximum at $V_{SG}/V_{SL} = 200$. This behaviour was attributed to flow regime transitions from bubble to slug, and from slug to annular, respectively. However, as also suggested by Collier (18), $\bar{h}_{TP}$ passes through a maximum and then decreases during the transition from annular flow to the annular-mist transition.

Groothuis and Hendal (35) performed tests using a similar tube size and method of heating with water-air and gas-oil/air¹ mixtures. The authors found that introduction of the first amount of air caused a rapid increase in $\bar{h}_{TP}$, but that further additions of air increased it much more gradually. The influence of air was most profound at the lowest Reynolds numbers. This was explained by noting that

¹ With this liquid-gas combination only a "/" will be used to separate the two phases; otherwise, the convention used throughout the thesis will be dash "-" between the liquid and gas phases.

resistance to the heat transfer was mainly due to the viscous sublayer at the wall, and that eddies produced in the wake of the rising air bubbles reduced the effective thickness of the film on the wall, thus enhancing the heat-transfer rate. In general, the trends of $\bar{h}_{TP}$ observed by these authors agreed well with the results of Verschoor and Stemmerding (92), including the observation of a maximum in $\bar{h}_{TP}$ at high air-to-liquid volumetric ratios. This phenomenon was explained by the possibility of dry spots on the heated wall due to the breakdown of the film on it. They also developed a criterion for the flow conditions at which the liquid film on the wall is partly and temporarily disintegrated by the shearing stresses exerted by the flow.

Knott et al. (53) conducted an experimental study of heat transfer to oil-nitrogen mixture flowing upward in a 0.506 in. (1.29 cm) i.d. stainless steel tube, which was used as a resistance heater to provide constant-heat-flux boundary conditions. The results of their experiments indicated much lower effect of the gas phase on the $\bar{h}_{TP}$ increase than those by the previous investigators (35, 92), which were for higher initial liquid Reynolds numbers.

Kudirka (55) conducted his experimental work by bubbling air through the wall of a porous tube preceding the heated test section into water and ethylene-glycol flowing vertically at atmospheric pressure. Void fraction measurements (using the gamma-ray-attenuation technique) and local heat-transfer

coefficients at $z/D = 14.3$ were reported. The investigation showed that the effect of liquid viscosity on $\bar{h}_{TP}$ was an inverse function of viscosity. The authors also compared their results with some results of boiling-heat-transfer experiments.

Dorresteyn (24) studied the effect of tube size on the heat-transfer coefficient of a gas-oil/air mixture in a vertical tube. The test section was 2.76 in. (70.0 mm) in diameter and 3.61 ft (110.0 cm) long, which is the largest tube size reported in the literature in conjunction with two-phase, liquid-gas heat-transfer experiments. The author compared his results with those of Groothuis & Hendal (35) and concluded that for a larger tube size, $\bar{h}_{TP}$ was much lower compared to other data for smaller tube sizes. The study involved also downflow conditions in order to demonstrate the effect of flow direction on the heat-transfer behaviour. In general, the author found no significant difference in $\bar{h}_{TP}$ for these two flow orientations; however, $\bar{h}_{TP}$ dropped below the value for single-phase liquid flow in the transition from bubble to slug flow with downward flow.

Ueda and Nose (91) investigated two-phase water-air upflow in the annular and annular-mist regions. They obtained data on the pressure drop, mean liquid-film thickness, state of gas-liquid interface, droplet entrainment, and local h_{TP} (at $z/D = 32$). The heat-transfer data were analyzed theoretically by assuming that the liquid

film consisted of a laminar sublayer and a turbulent layer and theoretical expressions were obtained for the laminar and turbulent liquid film flow conditions.

Kapinos et al. (45) examined the heat transfer in the entrance section of a vertical pipe containing air flow bearing suspended water droplets. Sixteen sections of varying L/D ratios were used. On the basis of the measured values of $\bar{h}_{TP}$, it was found that the pipe length required for heat-transfer stabilization was $30D$. Expressions were given by the authors in order to correlate the experimental data for L/D ratios lower than or higher than 30.

Vijay (93) studied the effect of changing the liquid Prandtl number (through viscosity) on the two-phase local and mean heat-transfer coefficients, pressure drops, and flow patterns. The heat-transfer results agreed with those of Kudirka (55) in that $\bar{h}_{TP}$ was a reciprocal function of viscosity. The author was the first to obtain an extensive set of local $\bar{h}_{TP}$ data which were reported at seven locations along an electrically heated test section tube [0.46 in. (1.17 cm) i.d. and 2 ft (61.0 cm) long]. The range of variables involved in his study was considerably larger than any of the previously mentioned studies. For example, the author changed the liquid viscosity by 30 to 1000 times that for water (Pr_L varied from 5.6 to 7000). Also, he conducted his experiments for a very wide range of $\dot{m}_G$, $\dot{m}_L$, V_{SG}/V_{SL} and flow patterns. The author, in an attempt to

correlate his local $\bar{h}_{TP}$ data, modified the single-phase Spalding theory to predict the two-phase local-heat-transfer data. Other expressions were given for predicting the mean heat-transfer coefficients.

Other studies, which involved in them the effect of changing the liquid viscosity, were carried out by Ueda and Hanaoka (90), Domanskii et al. (23), and most recently by Elamvaluthi and Srinivas (26). The widest range of changing Pr_L among them was that by Domanskii et al. (23) who changed it from 5 to 247.

Aggour (1), utilizing the same rig used by Vijay (93), examined the effect of changing the gas density on the heat-transfer coefficients, pressure drops, and flow patterns. The author used different gases with water (air, helium, and Freon 12 vapour) allowing a change in ρ_G by a factor of 31. Significant effects of changing ρ_G on $\bar{h}_{TP}$ and ΔP_{TPF} were observed at low water flow rates [$V_{SL} \leq 3.41$ ft/s (1.04 m/s)] and gas superficial velocities higher than 5.00 ft/s (1.52 m/s), the trend of the results being that, for the same V_{SL} and V_{SG} , higher values of $\bar{h}_{TP}$ and ΔP_{TPF} were obtained with the higher gas density. The influence of changing ρ_G on the flow patterns was observed to be significant only on the slug-annular, churn-annular, and slug-churn transitions.

Chu (15) conducted water-air tests in upward and downward flows, in another attempt to examine the influence of flow direction on the heat-transfer behaviour [the first attempt was by Dorresteijs (24)]. The author found that the values of $\bar{h}_{TP}$ and $\bar{h}_{TP}/\bar{h}_L$ in downward flow were higher than those in upward flows with the same combinations of air and water superficial velocities. One of the reasons to which this was attributed was the higher void fraction in downward flow than in upward flow which induced higher liquid velocities. Void fraction measurements were obtained using two different techniques (a conducting probe and radiation beam attenuation).

Dobran (22,23) developed a theoretical model for the prediction of hydrodynamics and heat transfer in annular flow. The analysis incorporated a two-layer liquid film turbulence structure and was supplemented by using two developments for the entrainment of liquid droplets in the core.

The studies dedicated to examine the effect of surface tension on the heat transfer and hydrodynamics in two-phase, two-component, vertical flow are indeed very scanty, especially with regard to heat transfer. As mentioned earlier, the literature relating to the hydrodynamics studies will be discussed at the appropriate place in the thesis.

Domanskii et al.(23) conducted heat-transfer experiments using different liquid-gas mixtures which included alcohol(87%)-air. The authors used their experimental data to derive a semi-empirical correlation for the prediction of the heat-transfer coefficient. Unfortunately, the authors(23) did not report the results of this test in their paper.

Ravipudi (75) used a mixture of toluene and air to obtain heat-transfer results at one liquid mass velocity at low vapour pressure. These results (shown on a figure introduced later in Chapter 7), when compared with the water-air data taken by the same author at approximately the same Re_{SL} , showed essentially no effect of the surface tension on $\bar{h}_{TP}$.

Zaidi (107) was the first to study the effect of changing the surface tension on the heat transfer (both local and mean). The influence of changing σ on the frictional pressure drop and flow patterns was also studied in his work. The author lowered the static σ of water by adding a surfactant to it (in which case all other properties of water remained unchanged). Zaidi(107) observed significant effects of σ on the bubble-slug transition and a slight change in the churn-annular transition. The study concluded that the lower surface tension produced some effects on the frictional pressure drop and that little changes in $\bar{h}_{TP}$ were observed only at regions where flow pattern changes took place.

From the material presented in this chapter, the following remarks can be made on the studies done on the subject of forced-convective heat transfer in two-phase, two-component (liquid and gas) flow in vertical tubes:

1. Liquid viscosity was the only fluid property which received considerable attention from the investigators in the past.
2. The widest range of variables studied in junction with this subject were those of Vijay (93), Aggour (1), and Zaidi (107).
3. The very limited studies, which were done in order to examine the effect of changing the surface tension, focused on the hydrodynamic aspects of the flow. The present investigation is the second attempt to study thoroughly the effect of changing the surface tension on the heat transfer and hydrodynamics in two-phase, two-component flow in a vertical tube.

Chapter 3

DESCRIPTION OF THE APPARATUS

3.1 INTRODUCTORY REMARKS

In this chapter, a description of the experimental apparatus is given. This apparatus, being essentially the same as that used in the previous investigations by (93,1,107), is described in detail in Ref.(93). Some modifications were done on the apparatus in the present study in order to achieve higher accuracy in taking some of the measurements. The major modification was the replacement of the water and mercury manometers, used in the past to measure the pressure drop across the heated test section, with a set of pressure transmitters. The three transmitters covered a wide range of readings; the three ranges were: -25 to +5, 0 to 100, and 0 to 750 in. of water. A fourth transmitter was used to obtain the gauge pressure.

Other slight modifications involved the replacement of the control valves on the air-flow circuit with better valves, exchanging the gas pressure regulator with a higher-capacity regulator to obtain more stability in the gas-pressure entering the mixing chamber, and the addition of some drain points in the liquid flow loop in order to be

able to clean the rig and dry it more thoroughly. Other than the modifications mentioned above, the material presented in this chapter is essentially the same as that in (93,1,107) and is presented here for the sake of completeness. The circled numbers appearing in the figures correspond to the components used in the system which are described in detail in Appendix A.

3.2 FLOW CIRCUITRY

A simplified flow diagram of the overall system is given in Fig.3.1. Test liquids from the storage tank, after passing through the heat exchanger, were pumped by a positive-displacement gear pump to the gas-liquid mixer through a selected rotameter. Some flow was by-passed to the storage tank at the pump discharge and a large pressure drop was maintained across the control valve which allowed stable operation in two-phase flow. The air from the central compressor passed through two filters and a pressure regulator to a set of orifice meters (or a rotameter) to select the flow rate entering the mixer downstream of the orifice meters. The air was injected through the porous tube in the mixer. The back-flow of liquid into the air supply line was prevented by a check-valve installed on the air feed line. The liquid-gas mixture then passed through the calming tube to the heated test section and the transparent visualization section. From the exit of the

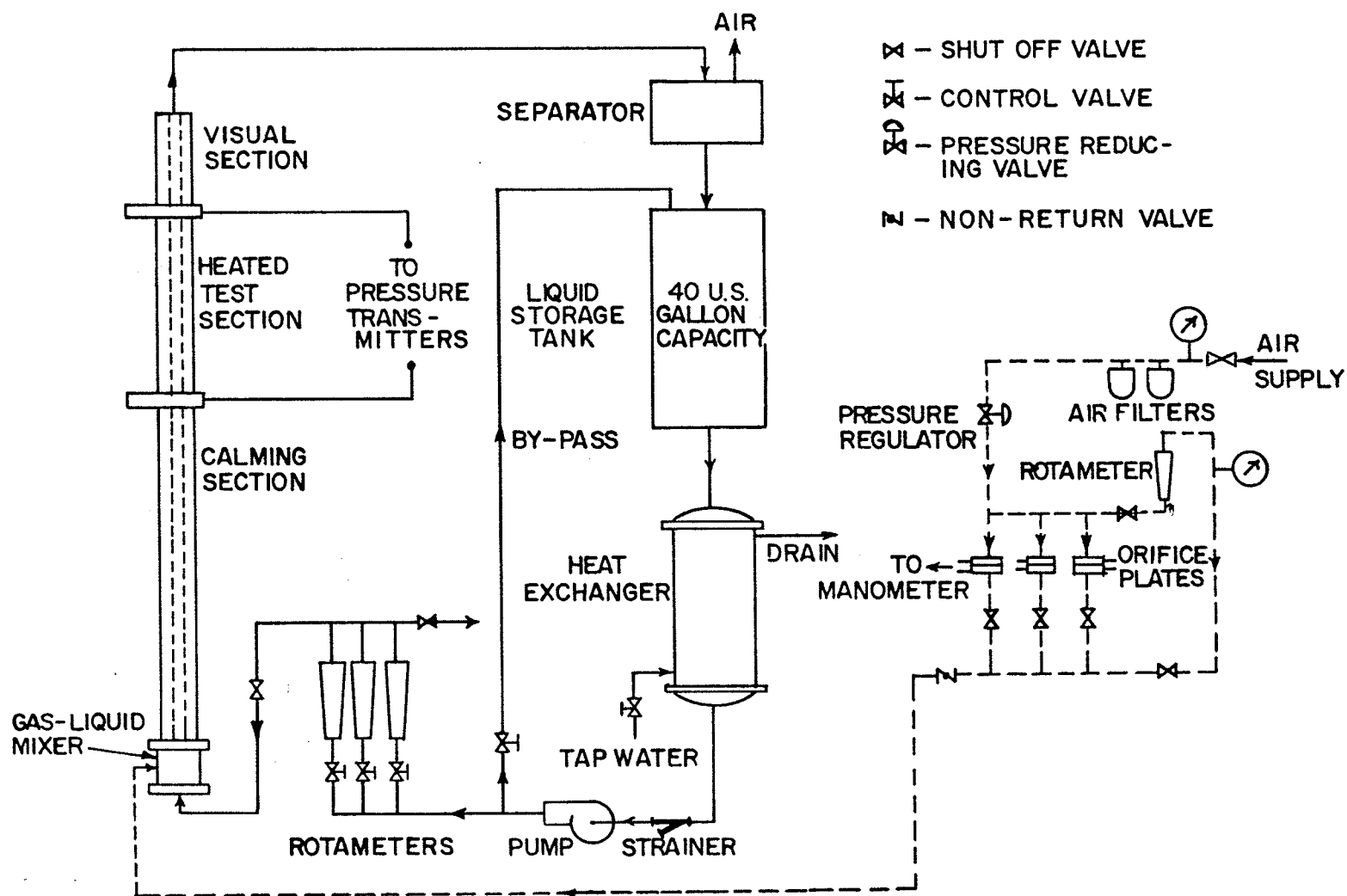


Fig. 3.1 Schematic of Two-Phase Apparatus

transparent section, the mixture continued to the separator where air escaped to the atmosphere and the liquid returned to the storage tank.

The details of the liquid flow loop and the air flow circuit are given in the following sections.

3.2.1 Liquid Flow Loop

The details of the liquid flow loop are given in Fig.

3.2. It consisted of the following:

1. A stainless steel liquid storage tank of 40 U.S. gallon (151.4 litre) capacity.
2. A liquid-to-liquid shell-and-tube-type heat exchanger to control the temperature of the liquid entering the test section.
3. A positive-displacement gear pump with a by-pass line at the discharge of the pump to allow setting the desired flow rate through the rotameters.
4. Three rotameters of varying ranges with needle control valves, in parallel, for measuring the liquid flow rates.
5. The liquid-gas mixing chamber, followed by a 5.00 ft (1.52 m) long calming section ($L=130 D$).
6. The heated test section [i.d.=0.46 in. (1.17 cm) and $L = 2.00$ ft (61.0 cm)] followed by the transparent section [1.00 ft (0.305 m) long].

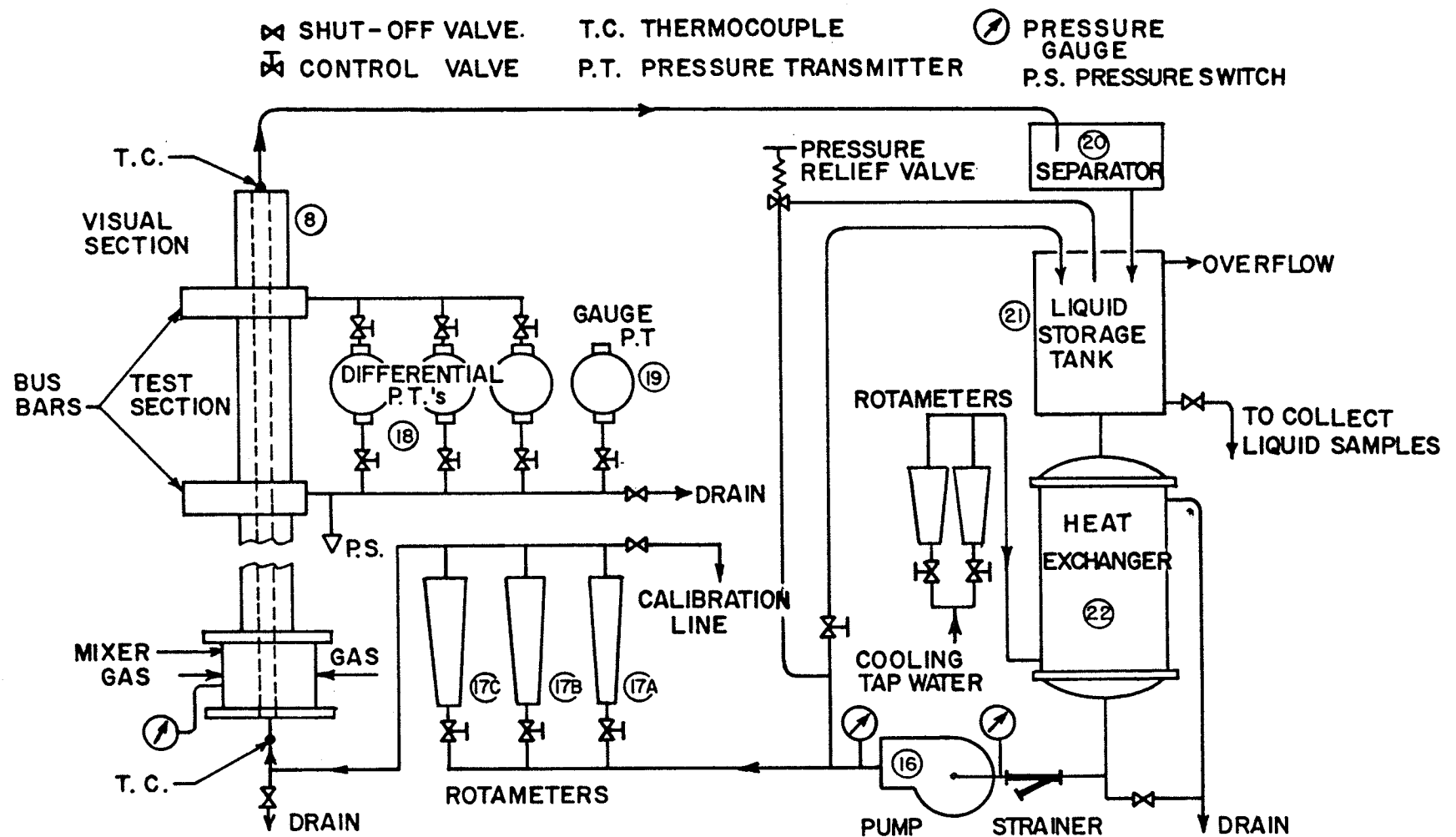


Fig. 3.2 Detailed Schematic of Liquid Flow Loop

7. The liquid-gas separator, which drained the liquid into the storage tank and vented air to the atmosphere.
8. A heat-exchanger cooling-water system consisting of two parallel rotameters, and control valves to set the cooling tap-water flow rates.
9. Three differential pressure transmitters in parallel (with the high-pressure side of these connected to a gauge-pressure transmitter) to measure the total pressure drop across the heated test section.
10. Other elements including control valves, pressure gauges, a pressure relief valve, a strainer, and provision for calibration as shown in Fig. 3.2.

The material used in constructing the liquid circuit and those of control valves and strainer were stainless steel, brass, and copper. Rubber hoses were also used wherever required for flexible joints.

3.2.2 Air Flow Circuit

The air flow circuit, as shown in Fig. 3.3, consisted of a main gas supply line having a shut-off valve; two air filters leading to a pressure regulator; a set of three orifice meters and a rotameter, all connected in parallel through four needle valves; a well-type water manometer to measure the pressure drop across the orifice plates and a check-valve on the air-line leading to the mixer to prevent any back flow of liquid into the air lines.

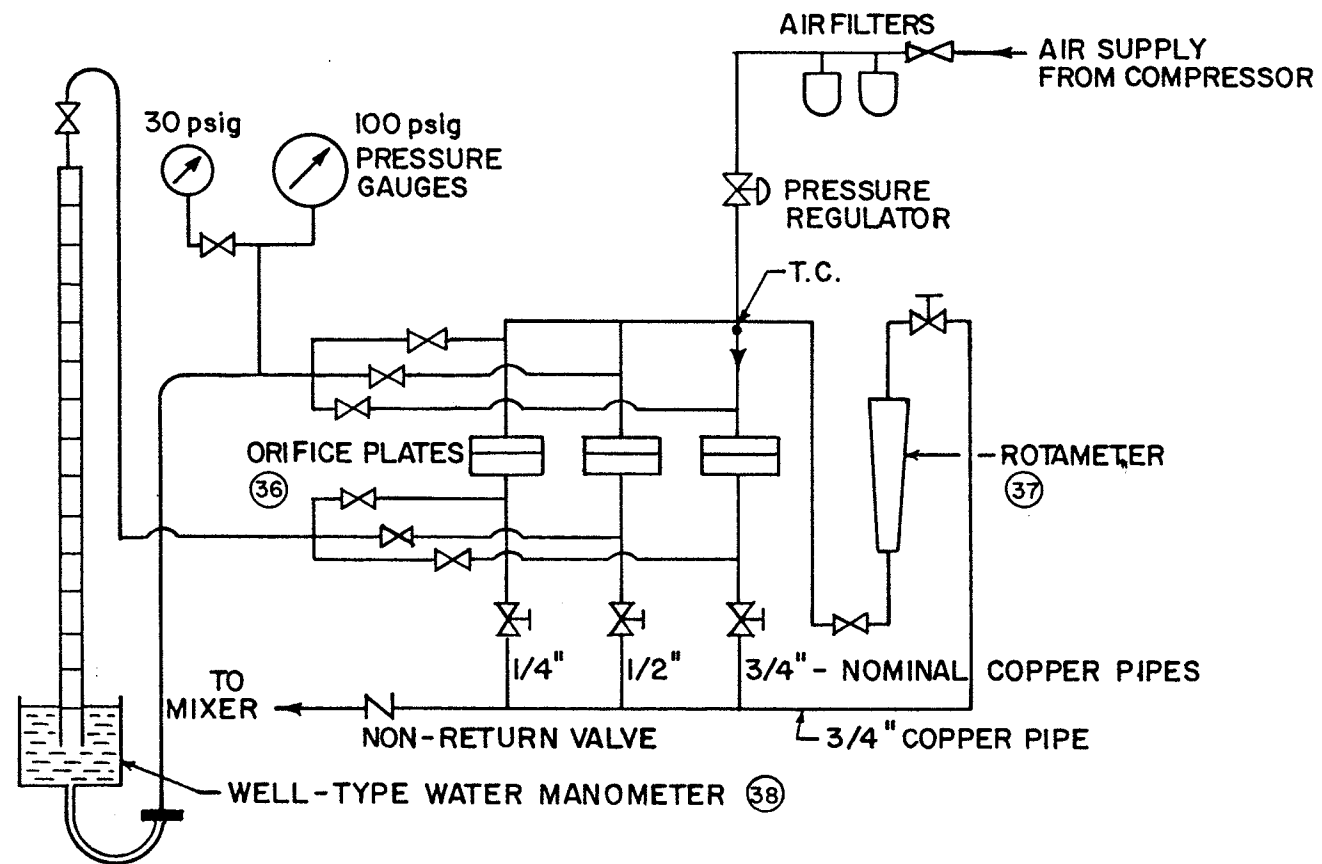


Fig. 3.3 Detailed Schematic of the Air Flow Loop

Flexible pressure hoses were used in the air-supply system and standard pressure gauges were installed at appropriate locations, as shown in Fig. 3.3.

3.3 TEST SECTION DESIGN

The test section consisted of the gas-liquid mixer, downstream of which was a 5.00 ft (1.52 m) long calming length ($L=130D$), the heated tube, and the transparent visualization section. All the sections (of the same inside diameter) were flange-connected and sealed with rubber O-rings. Details of the gas-liquid mixer and the heated test section are shown in Figs. 3.4 and 3.5 respectively, and they are discussed in the following sections.

3.3.1 Gas-Liquid Mixer

The mixer consisted of a Grade E Porosint bronze tube (supplied by Sintered Products Limited, Sutton-in-Ashfield, Notts, England) of the same inside diameter as that of the test tube. The porous tube was surrounded by a stainless steel strainer and both elements were contained in a brass cylinder of a 5.00 in. (12.7 cm) outside diameter and 6.25 in. (15.9 cm) length (as shown in Fig. 3.5). Gas or liquid could be forced through the chamber radially or axially; however, in the present investigation, the liquid flowed axially upwards while the gas was forced to diffuse through the porous tube.

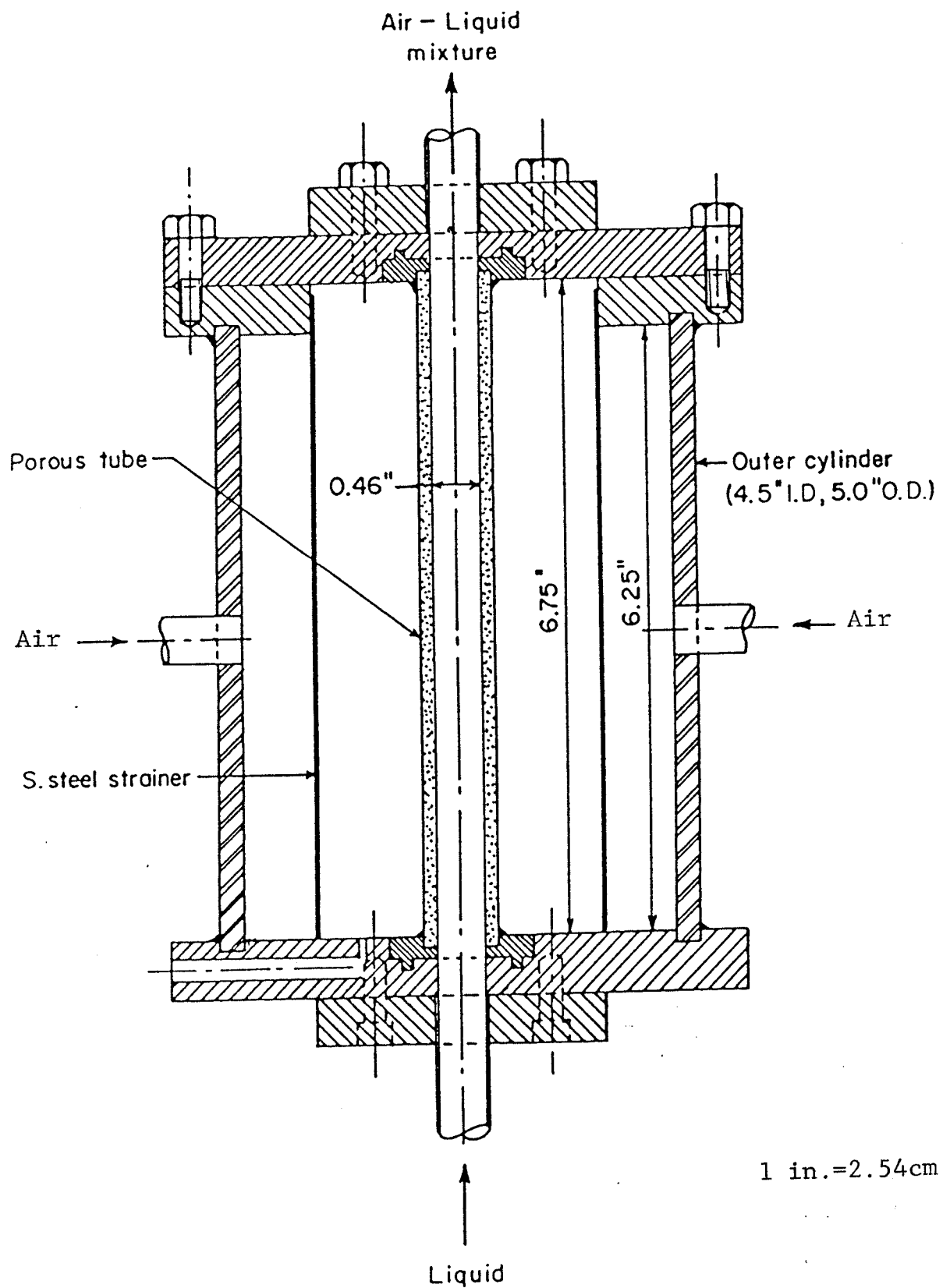


Fig. 3.4 The Mixer, From Ref. (107)

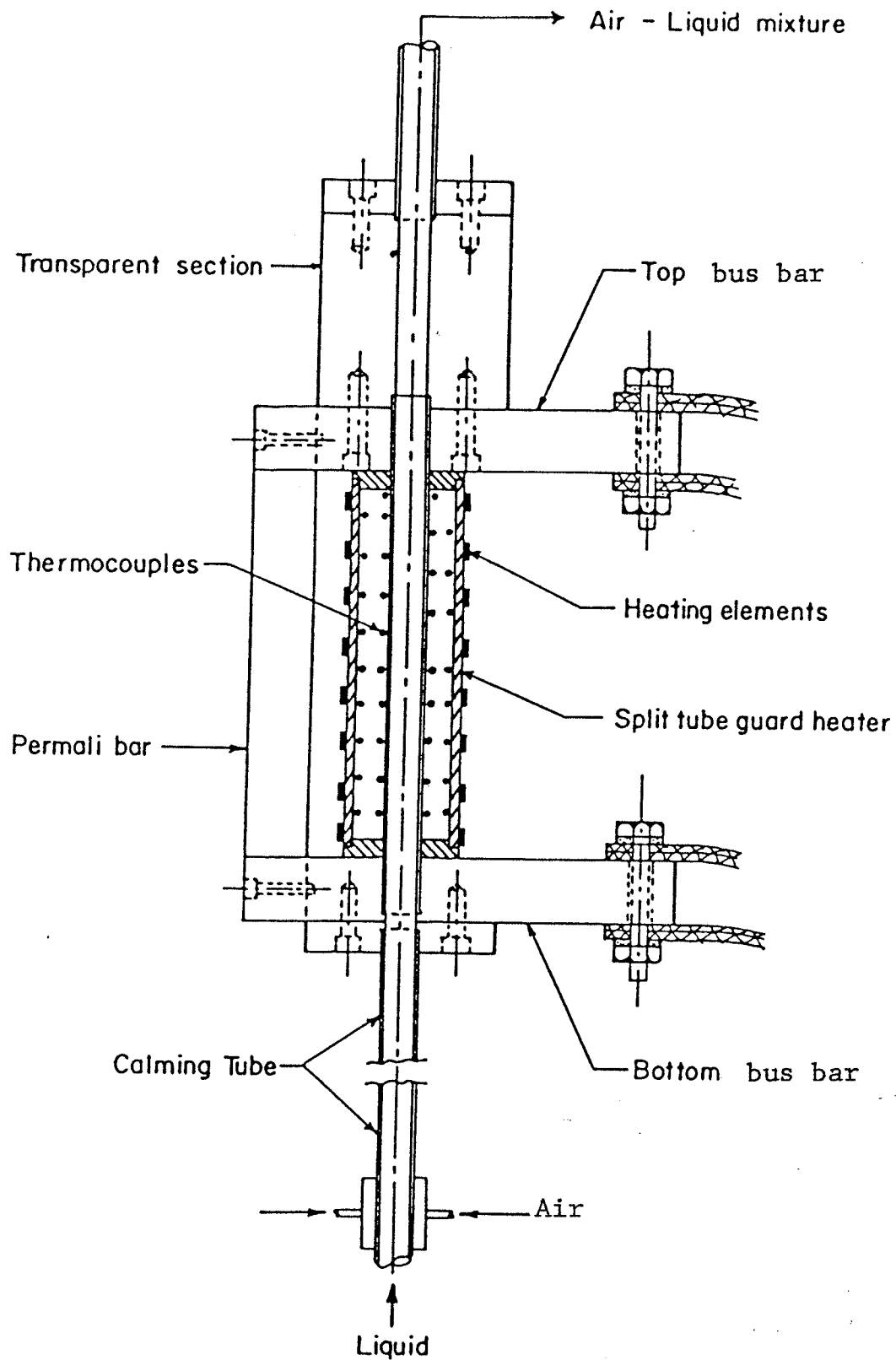


Fig. 3.5 Test Section, From Ref. (107)

3.3.2 Heated Test Section

The heated test section was made of type 304 stainless steel tube, 0.46 in. (1.17 cm) i.d., 0.50 in. (1.27 cm) o.d., and 2.00 ft (61.0 cm) long. The tube-wall thickness and the average roughness were measured (93) to be 0.020 ± 0.001 in. (0.508 ± 0.025 mm) and 40 ± 5 μ in. ($\sim 1.016 \times 10^2$ cm), respectively. Two bus bars (for power supply) were silver-soldered to the tube. A 1 in. x 1 in. x 2 ft long ($2.54 \times 2.54 \times 61.0$ cm) Permalloy electrical insulator supporting bar was firmly attached to the bus bars (vertically between them) to avoid buckling of the heated tube due to the weight of the bus bars and the power cables. Alternating-current electrical heating, using the tube as an electrical resistor, was employed. (This offered a simple and accurate means of measuring and controlling the local heat flux.)

As shown in Fig. 3.5, a split tube guard heater, which consisted of two parts (lower and upper guard heaters), was installed around each tube. Each guard heater was heated independently by a DC power supply using heating elements made of a Bristleat silicon-rubber-embedded heating tape 0.50 in. (1.27 cm) wide. The purpose of the guard heaters was to maintain a zero temperature-gradient at the outer surface of the heated-tube wall (to comply with the boundary conditions used in estimating the inner surface temperature of the tube wall), and also to eliminate the heat losses from the heated

test section to the surroundings. In order to maintain a zero temperature-gradient at the outer surface of the heated tube, the power supplied to each guard heater was adjusted so that the temperature of the inner surface of the guard heater at any position along the axial direction would match approximately the temperature of the outer surface of the heated tube at the corresponding position.

3.3.3 Observation Section

The observation section was made of a transparent cast acrylic rectangular block, 3 in. x 3 in. x 1 ft long (7.62 x 7.62 x 30.5 cm). A precision, highly polished, hole of the same inside diameter as that of the heated test section was drilled through the block. The block was placed above the heated test section and was used for both visual observations and photography of the flow patterns. Being just downstream of the heated test section, it was believed that the flow patterns observed were the same as those existing in the heated section. Clear observations and good photographs of the flow patterns were obtained with such a design of the observation section.

3.4 TEMPERATURE MEASUREMENTS

In this section, the following will be considered:

1. Fluid-temperature measurements,
2. Wall-temperature measurements, and
3. Temperature-measuring system.

3.4.1 Fluid-Temperature Measurements

Six copper-constantan AWG#30, 0.010 in. (0.254 mm) diameter (T/G-30-DT) thermocouples were used to measure the temperature of the fluid at the following locations:

1. One for measuring the temperature of air at the inlet to the orifice meters,
2. One for the liquid temperature at the inlet to the mixer,
3. Two for the mixture at the exit of the mixer, and
4. Two at the outlet of the transparent section.

3.4.2 Wall-Temperature Measurements

In the experiments, outer-wall temperatures of the test section were measured by means of thermocouples. The inner-wall temperatures were calculated from these measurements by employing the method of Kreith and Summerfield (54). In this method, the temperature drop across the tube wall was calculated from the knowledge of the tube wall thickness and

properties, and the electrical current. More details on this method are given in Appendix D.

The locations of thermocouples on the outer wall of the heated test tube and the inner wall of the guard heaters are shown in Fig. 3.6. Forty-three thermocouples (Nos. 5-47) were used to measure the wall temperature at 16 elevations along the test section, of which those at Plane Nos. 2,4,6,8,11,14, and 15 were used (93) to calculate the local heat-transfer coefficients (See Appendix D). Eighteen thermocouples (Nos. 48-65) were used to measure the guard-heater wall temperatures at nine elevations. Thermocouples Nos. 1-4 measured the temperature of the bus bars.

Copper-constantan AWG #36, 0.005 in. (0.0127 mm) diameter (T/G-36-DT) thermocouples were installed on the test tube wall and AWG #30, 0.010 in. (0.254 mm) diameter (T/G-30-DT) thermocouples were installed on the inner wall of the guard heater. At any desired location, a layer of a Scotch electrical tape No. 27 was wrapped (93) around the tube, the thermocouple head was placed in position, 2-3 turns of the wire were wrapped around the tube (to minimize the possible conduction error due to the temperature gradient along the wire). The thermocouple wires, supplied by Thermoelectric Canada Ltd., were calibrated in the laboratory at the time of installation over the temperature range involved in the present investigation (93).

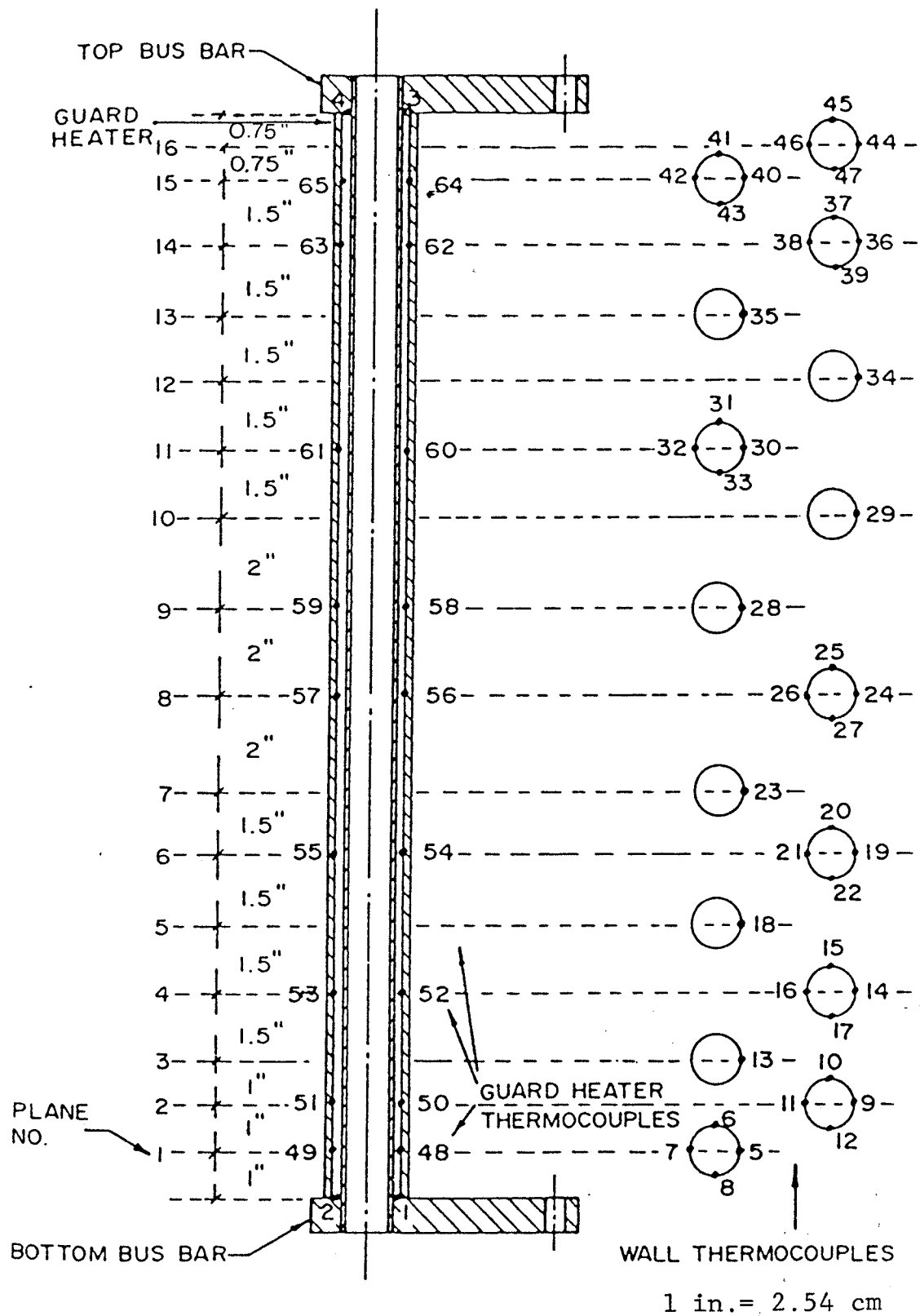


Fig. 3.6 Location of Thermocouples

3.4.3 Temperature-Measuring System

The system employed to measure the emf of the thermocouples mentioned in this section is shown in Fig.

3.7. The emf of thermocouples was measured by any one or a combination of the following temperature recording devices by selecting the appropriate switches:

1. The Fluke 2240A data logger,
2. The Keithley 181 DVM, and
3. The Honeywell two-pen strip chart recorder.

The Fluke data logger had 60 analog inputs and a scanning speed up to 15 channels per second. The first channel (No. 0) was connected to a 1 mV standard potential source, the remaining 59 channels were used to record the emf of all the wall thermocouples, fluid thermocouples, six of the guard heater thermocouples, and four for the lower and upper bus bars.

The correspondence between the data logger inputs and inputs of the multiple-point selector switch is given in Table. 3.1.

A high-precision Fluke 335A DC voltage standard was used to check accuracy and to calibrate the DVM and the recorder. The data logger then was calibrated against the DVM in the laboratory.

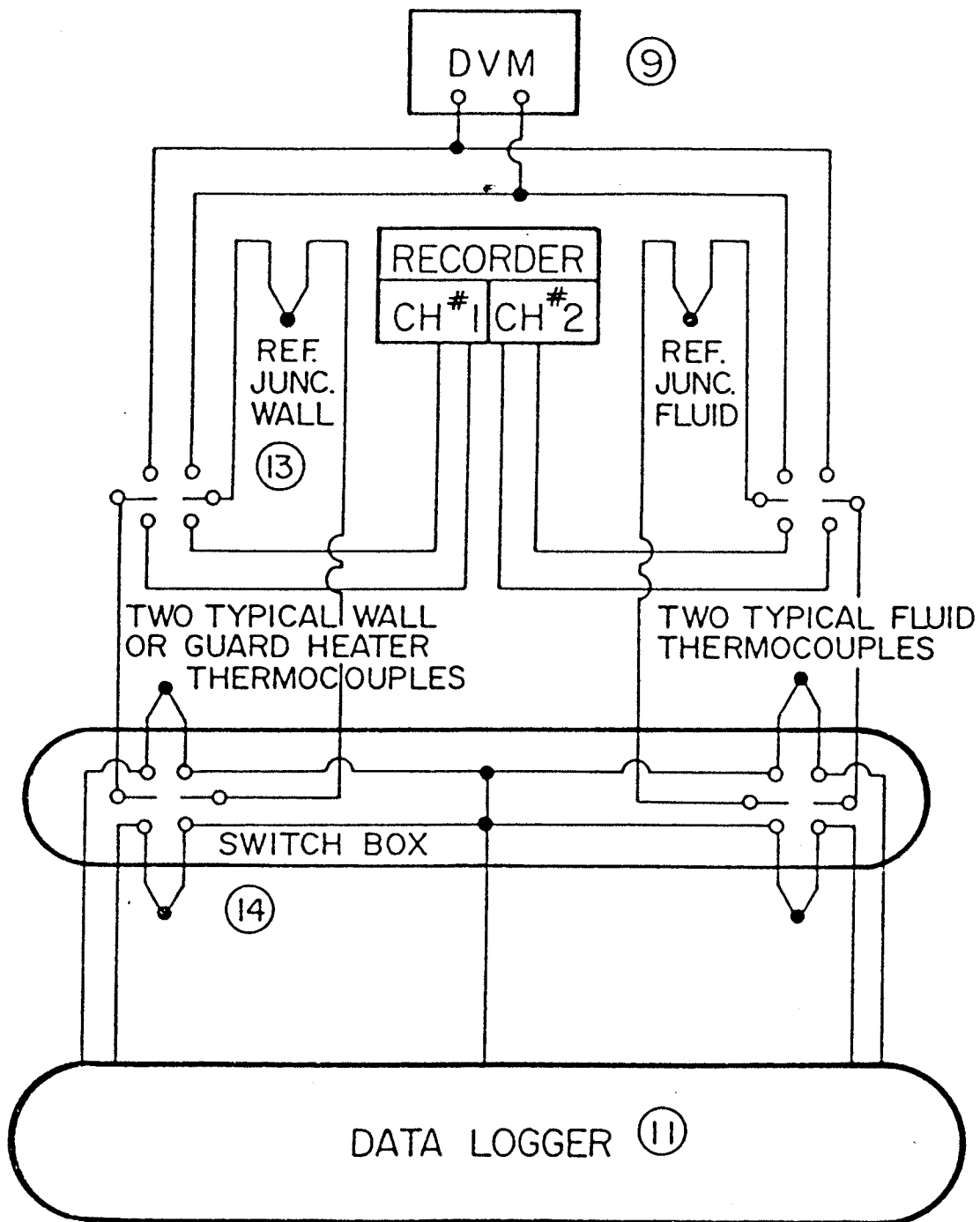


Fig. 3.7 Thermocouple emf Measuring Circuit,
From Ref.(107)

Table 3.1

Correspondence Between the Data Logger Inputs
and the Multi-point Selector Switch

TC No.	To Measure the Temperature of	Fluke Data Logger Channel No.	DVM/Recorder Selector Switch No.
1-4	lower & upper bus bars	1-4	1-4
5-47	the outer wall of the heated test tube*	5-47	5-47
52	the inner wall of the guard heater*	48	52
53	"	49	53
56	"	50	56
57	"	51	57
62	"	52	62
63	"	53	63
66-67	the mixture at the outlet of the test section	54-55	73-74
68-69	the mixture at the outlet of the mixer	56-57	75-76
70	the liquid at the inlet to the mixer	58	77
71	the gas at the inlet to the orifice plate assembly	59	79

*Location of the thermocouples given in Fig. 3.6

3.5 POWER SUPPLY CIRCUIT

A power supply system was constructed by Vijay (93) to supply, control, and measure the electric power to the test section. The same system was used in the present study, and its components are given in Fig. 3.8.

It consisted of the following:

1. A 240 volt, 100 amp, AC mains power source.
2. A power variac for control of electrical power to the test section.
3. Power-measuring circuit, which consisted of a calibrated current transformer, a potential transformer, voltmeter, ammeter, and a wattmeter. The ammeter readings were used to calculate the heat flux while the voltmeter and the wattmeter readings were used only as a check.
4. The stainless steel test section tube which served as an electric resistor.
5. A pressure flow switch to shut off the power in case of no flow in the test section.
6. A temperature controller (sensing the temperature of the middle-point on the test section) to shut off the power in case of accidental over-heating of the test section.

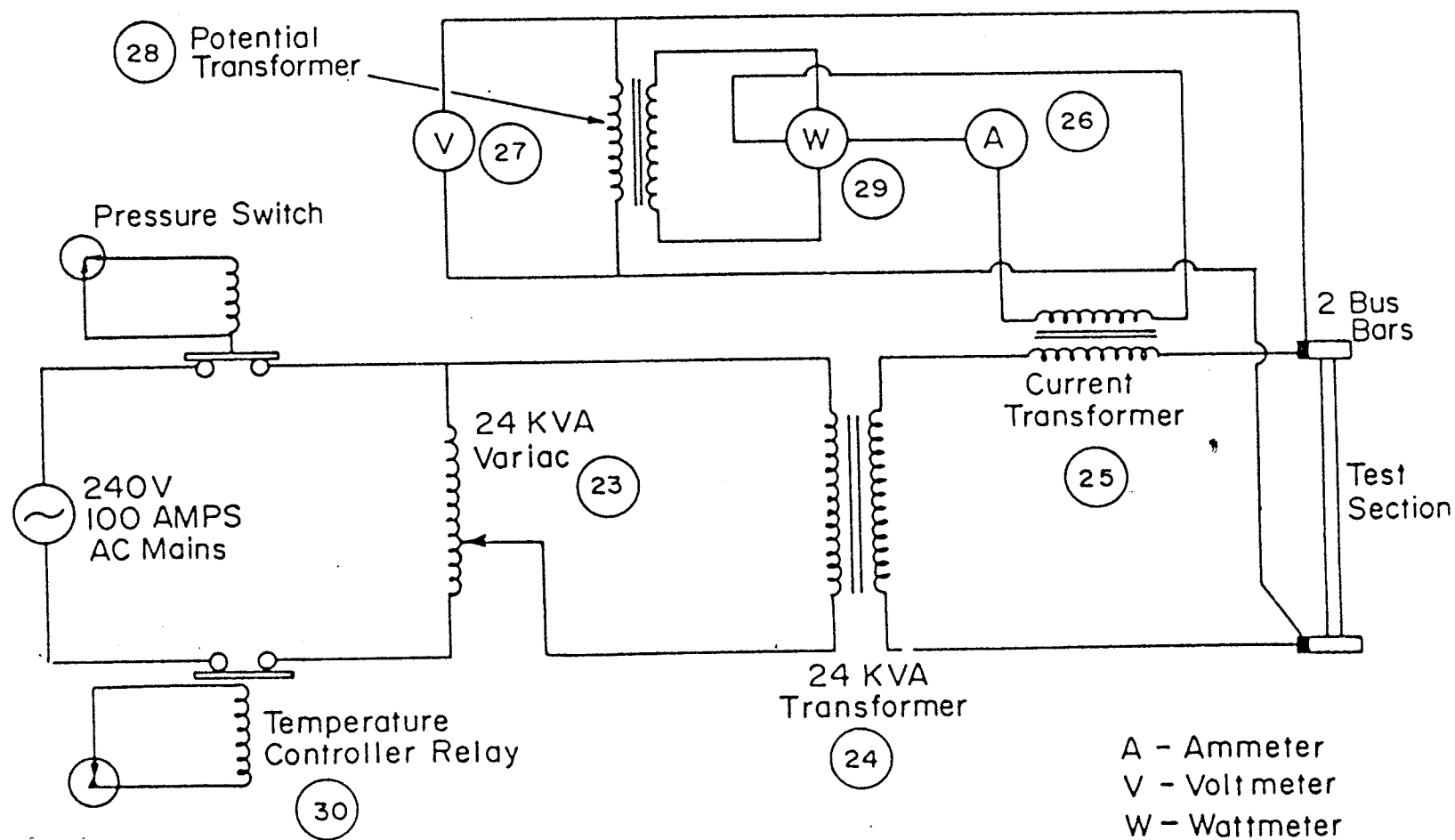


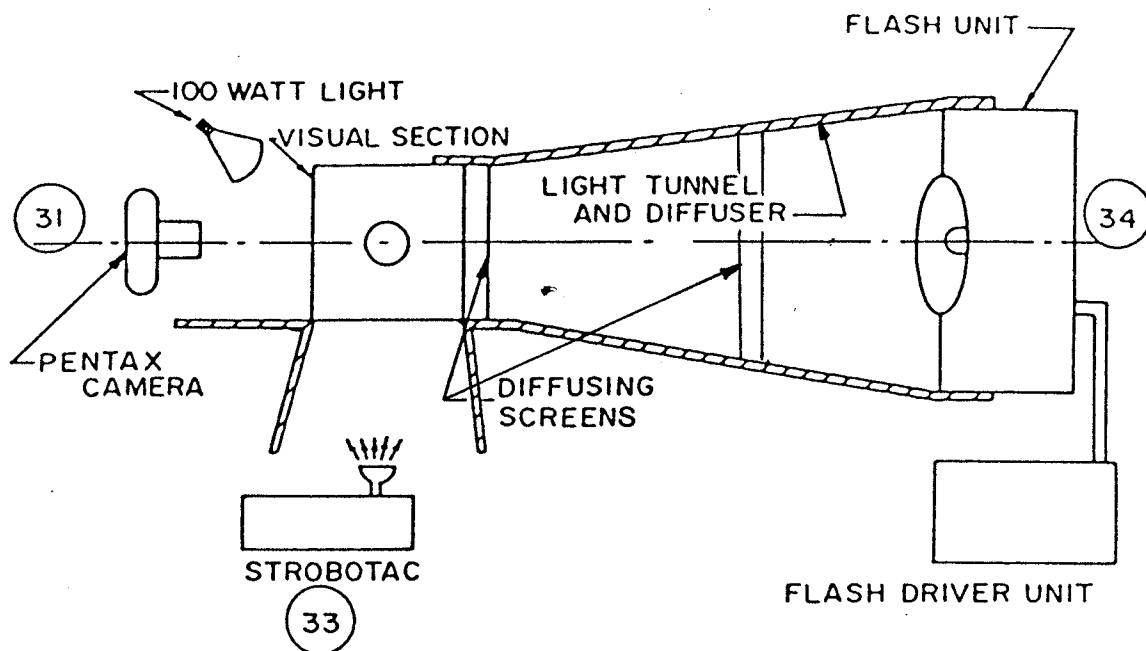
Fig. 3.8 Power Supply Circuit , From Ref.(107)

3.6 EQUIPMENT FOR PHOTOGRAPHY AND PHOTOGRAPHIC SECTION

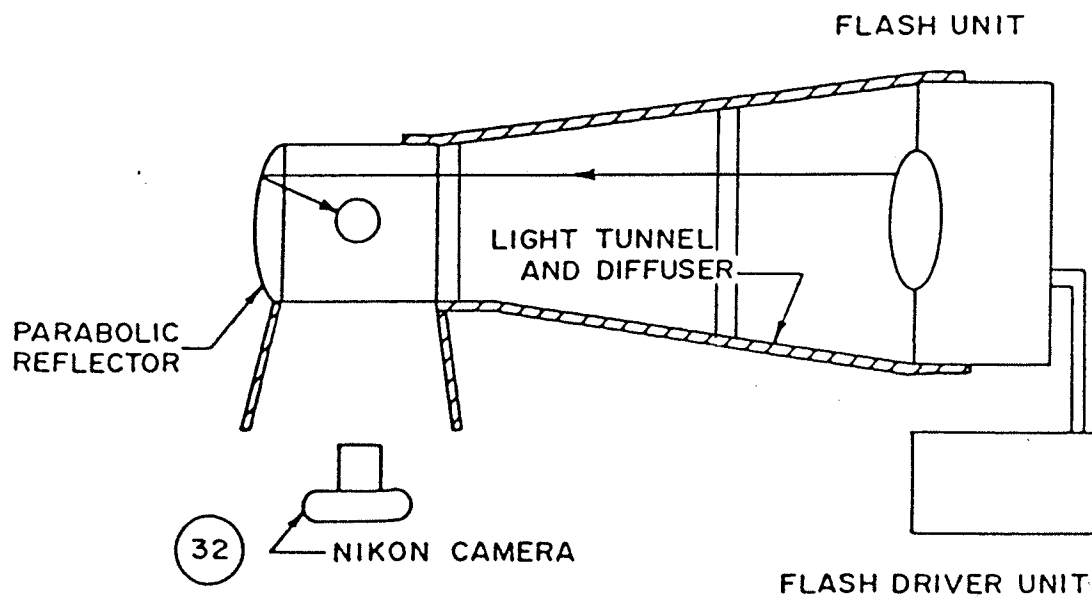
The photographic equipment consisted of the following:

1. A Pentax Spotmatic camera with Super Takumar 50 mm f/4.0 close-up lens.
2. A Nikon Photomatic FTN camera equipped with a Nikkor 50 mm f/1.0 to f/4.0 close-up lens.
3. An EG&G Microflash electronic flash unit (flash duration = 0.5 μ sec) with the driver unit (which produced a 2-KV pulse to trigger the flash). The flash unit was covered with a mylar diffuser.
4. A light guide made of cardboard lined with white paper to diffuse and direct the light towards the visual section. At two different places along that passage, two glass diffuser screens were placed in order to get even illumination of the transparent tube, thus producing clear pictures.
5. A parabolic reflector designed by (107) to focus light on the tube, thus illuminating both sides of it.
6. A General Radio type 1538-A Strobotac electronic stroboscope.
7. Kodak Plus-X Pan (ASA 125) films which were used for all the photographic work.

The two arrangements proposed by (107) were adopted in the present study and are shown in Fig. 3.9. As mentioned



(a) Arrangement with Pentax 35 mm Camera



(b) Arrangement with Nikon 35 mm Camera

Fig. 3.9 Set-Up of Photographic Section

in Ref.(107) , the arrangement shown in Fig. 3.9.b was used wherever froth flow was observed. The parabolic reflector was designed so that its focal point lay at the centre of the transparent tube. This helped a great deal to illuminate both sides of the tube and produce good quality pictures with froth flow. (Its appearance was milky and opaque.)

The Strobotac and the lamp light shown in Fig. 3.9 were not part of the photographic equipment; they were used only to observe the flow patterns.

3.7 SURFACE TENSION MEASUREMENTS

The surface tension of the liquids used in the study was continuously measured and checked during the present work using a Fisher 215 Autotensiomat Surface Tension Analyzer which operates on the principles of the du-Nouy ring method (details are given in Appendix A).

Chapter 4

EXPERIMENTAL PROCEDURE

4.1 GENERAL REMARKS

This chapter describes the procedures followed in performing the experiments; the following will be discussed:

1. Preparation of tests,
2. Start-up and shut-down procedures,
3. Acquisition of data, and
4. Flow pattern observations.

4.2 PREPARATION OF TESTS

The cooling water to the heat exchanger and all the temperature-measuring instruments were turned on several hours before performing the experiments to allow an adequate warm-up and stabilizing time. The air filters on the supply line were checked and changed if found oily or dirty. The leads from the orifice plates to the well-type manometer were checked to be clear of any liquid by bleeding air through them. The water level in the well-type manometer was checked and, if necessary, adjusted.

4.3 START-UP AND SHUT-DOWN PROCEDURES

The following steps were typically taken to start the rig:

1. The valve on the main gas supply line was opened and the gas pressure at the inlet to the orifice plate assembly was set at a constant value by adjusting the pressure regulator. To start with a dry mixer, one of the gas line control valves was opened to blow air into the mixer before turning the pump on.
2. The liquid pump was then started with the by-pass valve fully opened.
3. All pressure-transmitter leads containing liquid were checked for the presence of air and purged if necessary. This step was repeated as often as required during the course of the experiments.
4. The liquid flow rate was set to the desired value by a combination of closing the by-pass valve on the pump discharge and adjusting the control valve on the appropriate liquid flow meter. The rotameter was watched regularly during the experiment and adjusted whenever required. A large pressure difference across the control valve upstream of the liquid flow meters was maintained in order to prevent oscillations in the liquid flow rates.
5. The desired gas flow rate was set by controlling the needle valve at the outlet of the appropriate orifice plate or rotameter.

6. The power supply to the test section was turned on with the power-control setting at zero input value and the power input was slowly increased to the desired value.
7. The power supply to the lower and upper guard heaters was turned on.
8. Both channels of the two-pen recorder were then set on the monitoring position to record continuously the emf's from the inlet fluid temperature and the wall thermocouple at the mid-point of the test-section.

For single-phase-flow experiments, the same procedure described above was employed, excluding steps 1 and 5.

The rig was shut down by first turning off the power supply to the heated tube and the guard heaters. The bypass valve on the pump discharge was then opened fully, the control valve on the flow meter was closed, and the pump switched off. The cooling water to the heat exchanger was turned off and the gas flow control valves were closed. Finally, air was supplied and left flowing into the mixer and the test section for at least one hour to dry the mixer and test section.

4.4 ACQUISITION OF DATA

4.4.1 Establishing Steady Conditions

The following variables were continuously monitored and controlled to obtain steady-state conditions before taking any set of data:

1. The liquid inlet temperature to the mixer,
2. The wall temperature at six elevations along the heated test section tube,
3. The voltage supply to the lower and upper guard heaters, and
4. The power supply to the test section, and hence wall temperatures.

The liquid inlet temperature T_L , as mentioned earlier, was continuously recorded on one channel of the two-pen strip-chart recorder. An attempt was always made to maintain T_L as closely as possible to the room temperature (at which the liquid flow meters were calibrated) by controlling the cooling water rate to the heat exchanger. The thermocouple readings of the wall temperatures along the heated test section were recorded on the data logger printer every 7 to 10 minutes. Six of these readings (two near the inlet, two near the exit, and two at the middle of the test section) were continuously recorded and compared with previous readings. Steady-state conditions were deemed to prevail when the difference between the readings (for both

wall temperatures and T_L) of two successive recorded emf's was within $\pm 0.2^\circ\text{F}$ ($\pm 0.1^\circ\text{C}$).

The voltage supply to the guard heaters was controlled so as to achieve approximately a zero-temperature-gradient boundary condition at the outer wall of test section. The method for meeting such conditions was established by Vijay (93) and was adopted in the present work. This was done by controlling the power supply to the guard heaters so that at any given elevation along the heated test section, the temperature difference between the outer surface of the test section and the inner surface of the guard heater did not differ by more than $\pm 4^\circ\text{F}$ ($\pm 2.2^\circ\text{C}$). The readings of the thermocouples on the tube wall at three elevations (two near the bottom and top ends and mid-way) and the corresponding ones on the guard heaters were monitored and the power input to the guard heaters was adjusted accordingly.

The power level to the heated test section was supplied taking into account the following considerations:

1. The temperature difference between the tube wall and the bulk fluid temperature should be low enough to minimize radial variations in fluid properties,
2. This temperature difference should be large enough to determine the heat-transfer coefficient accurately.

A temperature difference of about 15°F (8.33°C) was found by (93) to be adequate to meet these requirements. Therefore,

the following procedure, as adopted in the previous works by (93,1,107), was used to adjust the power to the test section:

1. The outer wall temperature T_o (see Fig. 4.1) at $Z=24D$ (TC No.24), the liquid inlet temperature T_L (TC No.66), and the mixture temperature at the outlet of the test section T_{OUT} (TC No.69) were read from the DVM or recorder,
2. An approximate value of the inlet wall temperature T_W was estimated from a previously prepared table for the temperature drop across the tube wall ΔT_W as a function of the current I ,
3. An approximate value of the liquid bulk temperature T_B at $Z=24D$ was calculated from the knowledge of T_L and T_{OUT} ,
4. The difference $T_W - T_B$ was calculated and the power input was adjusted accordingly.

During the course of experiments, it was attempted to maintain a reasonably constant temperature difference. The spread in $(T_W - T_B)$ for the entire series of tests was as follows:

Water-air: $15 \pm 7^\circ\text{F}$ ($8.3 \pm 3.9^\circ\text{C}$)

Glycerine & water-air: $13 \pm 7^\circ\text{F}$ ($7.2 \pm 3.9^\circ\text{C}$)

Silicone-Air: $15 \pm 7^\circ\text{F}$ ($8.3 \pm 3.9^\circ\text{C}$)

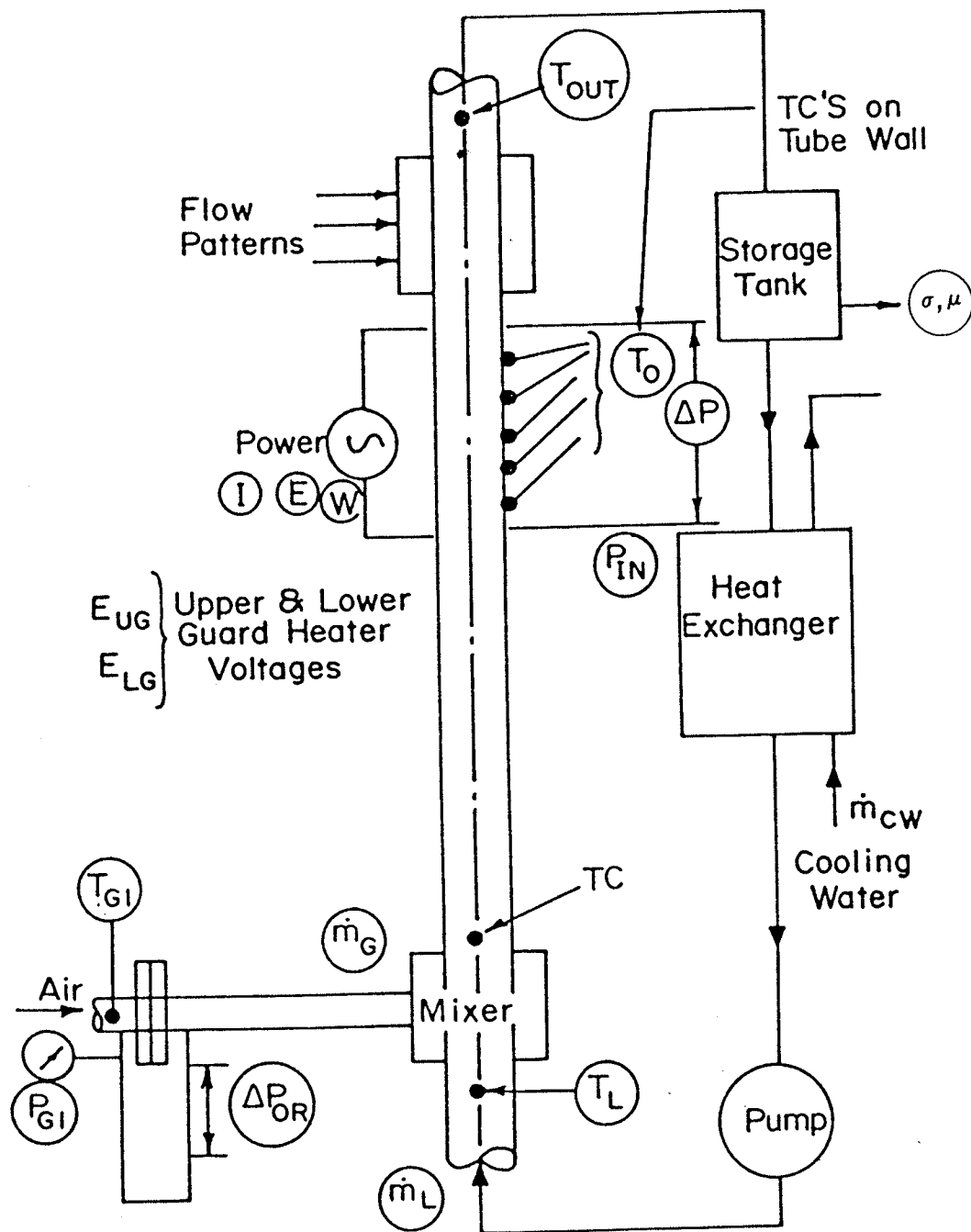


Fig. 4.1 Measured Variables, From Ref. (107)

4.4.2 Taking of Data

After equilibrium conditions had been established, instruments were read and the value of all the variables listed in Table 4.1 were recorded. Figure 4.1 shows those variables which were measured to determine the heat transfer and hydrodynamic results. The thermocouple readings were taken last in all the tests after steady temperature conditions were reached, as described earlier in Sec. 4.4.1.

The test conditions and the range of variables employed in the present study are listed in Table 4.2. Depending upon the liquid and its flow rate, the gas flow was varied to obtain flow patterns from bubble to annular-mist. The maximum air flow rate, however, was limited by the capacity of the air compressor. The data for a particular run was collected continuously to complete the whole run for any liquid flow rate (a run in this text refers to an experiment in which the liquid flow rate is fixed and the air flow rate is varied.)

4.5 FLOW PATTERN OBSERVATIONS

When the required test conditions were set, the flow patterns were first observed by naked eye using a lamp light and then with the aid of a stroboscope. These visual observations were recorded on the data sheets. Using the camera arrangements shown in Fig. 3.9 (a) or (b) (depending

Table 4.1 List of Variables Measured in the Present Experiments

Power to Test Section			Power to Guard Heater		Water Flow Rate		Test Section Pressure	
(I) Ammeter Reading	(V) Voltmeter Reading	(W) Wattmeter Reading	E_{UG} volts	E_{LG} volts	Meter No.	Reading (%)	P_{IN}	ΔP
used to calculate the local heat flux	W and VI were used to check the power input to the test section		were adjusted to control the temperature of the guard heater		used with the calibration curves to calculate m_L		Pressure at inlet to the test section	Total pressure drop across the test section
Gas Line Data					Thermocouple Readings			
O.P.N.	P_{GI}	ΔP_{OR}	P_{GL}		TC No.	To measure the temperature of		
Orifice plate or rotameter No.	Press. at inlet to the orifice or rotameter	Press. drop across the orifice plate or rotameter reading	Gas pressure in the supply line		1-4	Top and bottom bus bars		
used, together with the gas temperature at the inlet to the orifice plate assembly (T_{GI}), to calculate the gas flow rate ($\dot{m}_G$)			used to calculate the moisture content in the gas		5-47	The outer wall of the heated test tube (T_o)		
					52-63	The inner wall of the guard heater		
Other Variables					66,67	The mixture at the outlet of the test section (T_{OUT})		
Barometric Pressure	measured 2 times during the course of the experiment				68,69	The mixture at the outlet of the mixer		
Flow Pattern					70	The water at the inlet to the mixer (T_L)		
	Observed visually and photographed twice for each test				71	The gas at the inlet to the orifice plate assembly (T_{GI})		

Table 4.2

Range of Variables Investigated in the Present Study

Variable	Water-Air		Glycerine & Water-Air		Silicone-Air	
	Minimum	Maximum	Minimum	Maximum	Minimum	Maximum
$\dot{m}_L$ lb _m /hr (Kg/hr)	48 (22)	8996 (4080)	21 (9.5)	7196 (3265)	17 (7.7)	7196 (3265)
$\dot{m}_G$ lb _m /hr (Kg/hr)	0.42 (0.19)	157 (71.2)	0.09 (0.04)	149 (67.6)	0.07 (0.03)	155 (70.3)
V_{SL} ft/s (m/s)	0.185 (0.056)	34.7 (10.6)	0.073 (0.022)	24.2 (7.38)	0.073 (0.022)	30.2 (9.20)
V_{SG} ft/s (m/s)	1.08 (0.329)	425 (129)	0.190 (0.058)	344 (105)	0.170 (0.052)*	364 (111)
$\bar{q}_w''$ Btu/hr. ft ² (KW/m ²)	6490 (20.5)	60,550 (191)	853 (2.7)	13,830 (43.6)	496 (1.56)	8316 (2.6)
$\bar{T}_{MIX}$ °F (°C)	66.0 (18.9)	88.3 (31.3)	70.1 (21.2)	87.3 (30.7)	66.4 (19.1)	82.1 (27.8)
Re_{SL}	845	1.27×10^5	42	1.3×10^4	51	2.07×10^4
Re_{SG}	318	1.35×10^5	68	1.12×10^5	52	1.15×10^5
Pr_L	5.4	7.2	42.4	65.8	61.0	72.3
Pr_G	0.708	0.710	0.707	0.710	0.707	0.710
We_{SL}	0.525	1.8×10^4	0.095	1.02×10^4	0.073	1.27×10^4

upon the flow pattern observed), two photographs (at least) were taken for each flow pattern. This was done while the room was in total darkness; the aperture of the camera was held open and the microflash fired.

After an extensive testing of various settings and arrangements of the cameras, both cameras were set at an f-stop of 5.6, which gave a clear image of the flow in the transparent tube.

The final analysis of the flow patterns was done using a combination of the comments taken during the observation by naked eye and stroboscope plus the corresponding photographs taken from one side or both sides of the tube using the parabolic reflector (normally with the froth flow).

Chapter 5

REPRESENTATION AND DISCUSSION OF SINGLE-PHASE RESULTS

5.1 INTRODUCTORY REMARKS

In this chapter, the results of single-phase liquid flow for pressure drop and local and mean heat-transfer coefficients are presented. Comparisons of these results with well-known empirical correlations and theoretical expressions are also given. Two parameters, defined below, are used to denote the deviations between the experimental results and the predictions using the empirical or theoretical expressions. The same parameters are used throughout the thesis wherever required.

$\bar{e}$ = mean algebraic deviation =

$$\frac{1}{N} \sum \left\{ \frac{V_{\text{EXP}} - V_{\text{PRED}}}{V_{\text{PRED}}} \right\} \times 100 \quad (\%) \quad (5.1)$$

$\bar{e}_r$ = the r.m.s. deviation =

$$\left\{ \frac{1}{N} \sum \left\{ \frac{V_{\text{EXP}} - V_{\text{PRED}}}{V_{\text{PRED}}} \right\}^2 \right\}^{\frac{1}{2}} \times 100 \quad (\%) \quad (5.2)$$

where

N = number of experimental data points used in the comparison,

V_{PRED} = value of the variable predicted from
the theoretical or empirical expression
under consideration, and

V_{EXP} = experimental value of the same variable.

5.2 SINGLE-PHASE PRESSURE DROP

The frictional-pressure-drop data for all liquids used in the present study are calculated from the measured total pressure values. The method of calculation is discussed in Appendix D.

The friction factor f (defined as $f = \frac{\tau_w}{\rho V^2 / 2g_c}$) was calculated using the correlations for a smooth tube. These correlations, as recommended by Kays (47), are as follows:

For laminar flow ($Re_{\text{SL}} \leq 2000$):

$$f_{\text{SP}} = 16/Re_{\text{SL}} \quad (5.3)$$

For turbulent flow ($2000 < Re_{\text{SL}} < 30,000$):

$$f_{\text{SP}} = 0.079 Re_{\text{SL}}^{-0.25} \quad (5.4)$$

and for $Re_{\text{SL}} \geq 30,000$:

$$f_{\text{SP}} = 0.046 Re_{\text{SL}}^{-0.2} \quad (5.5)$$

where f_{SP} is the single-phase friction factor.

The comparison between the experimental data and the above predictions is shown in Fig. 5.1. Four data points, which appear in the heat-transfer data, were excluded from the comparison here. For these points, the pressure drop readings were less than 0.1 in. of water (1.13 KPa/m). The deviations for the three liquids are given in Table 5.1.

TABLE 5.1

Summary of Comparison of the Single-Phase Pressure-Drop Data

Liquid	Laminar Flow			Turbulent Flow		
	N	$\bar{e}(\%)$	$\bar{e}_r(\%)$	N	$\bar{e}(\%)$	$\bar{e}_r(\%)$
Water	2	34.3	43.61	13	2.4	19.5
Glycerine & water	7	23.1	30.1	9	19.8	21.4
Silicone	3	-47.8	48.0	10	-13.0	13.6

In addition to the fact that very few data points are used in the laminar flow region, the large deviations in this region were caused by fewer data points with deflections very close to the criterion mentioned earlier ($\Delta P_{SPF} < 0.1$ in. of water). Agreement in the turbulent flow region is considered reasonable.

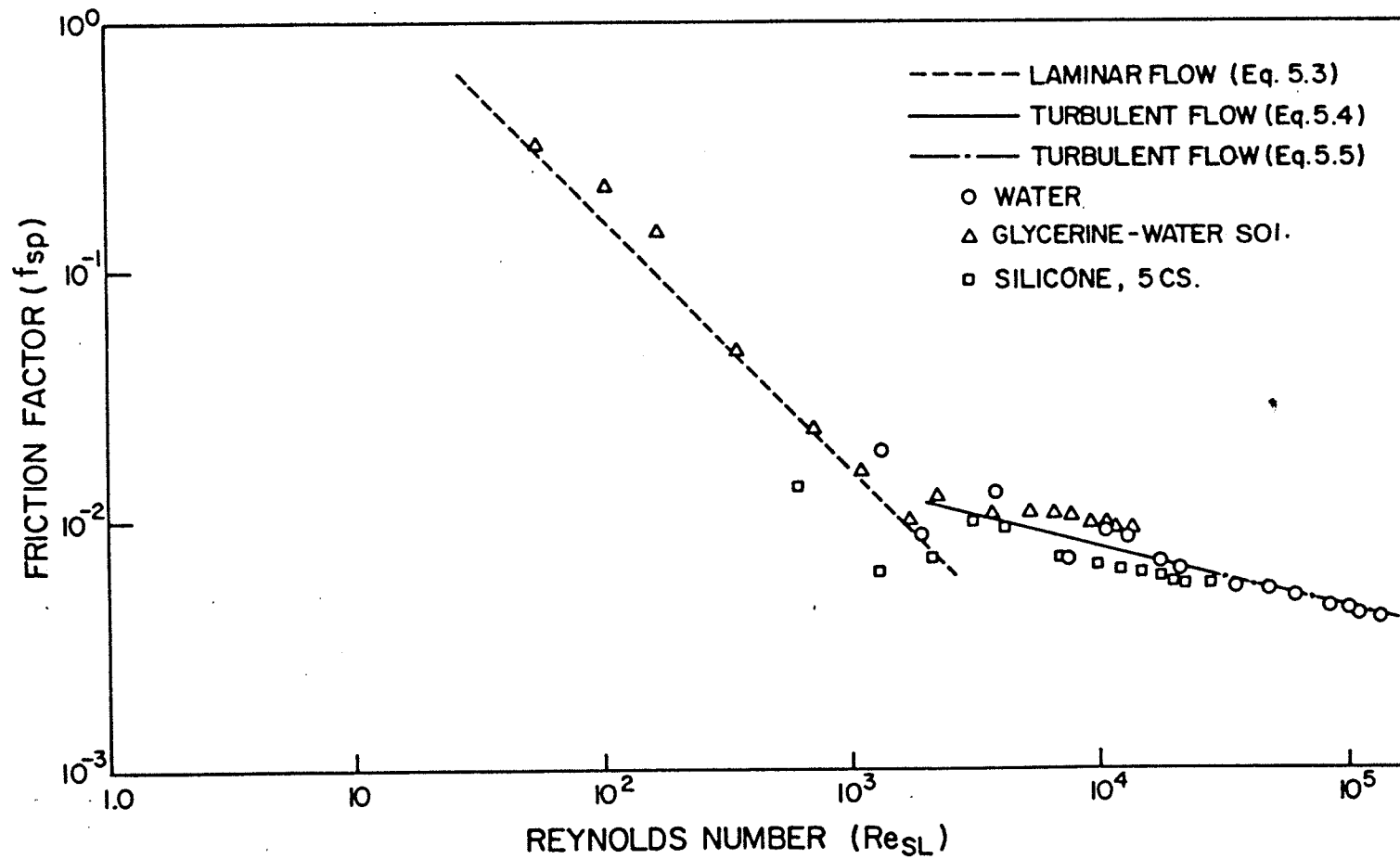


Fig. 5.1 Comparison of the Single-Phase Friction Factor with Correlations

The single-phase friction factors were not corrected for variations in fluid properties, as proposed by (47), because of the small differences between wall and bulk temperatures involved in the present investigation.

5.3 SINGLE-PHASE HEAT TRANSFER

As with the case of pressure-drop results, single-phase heat-transfer results were obtained in order to ensure the continued satisfactory performance of the experimental apparatus. The local heat-transfer coefficients were first calculated from:

$$h_{SP} = \frac{q_W''}{T_W - T_B} \quad (5.6)$$

Then, the mean heat-transfer coefficient was calculated from:

$$\bar{h}_{SP} = \frac{1}{\Delta L} \int_{L_1}^{L_2} h_{SP} \, dz \quad (5.7)$$

(Details of calculation procedures are given in Appendix D). These results are discussed in the following sections.

5.3.1 Local-Heat-Transfer Results

The local heat-transfer coefficients (measured at seven different elevations along the test section) for the three liquids used in the study are shown in Figs. 5.2 to 5.4. These plots show internal consistency in the data and their

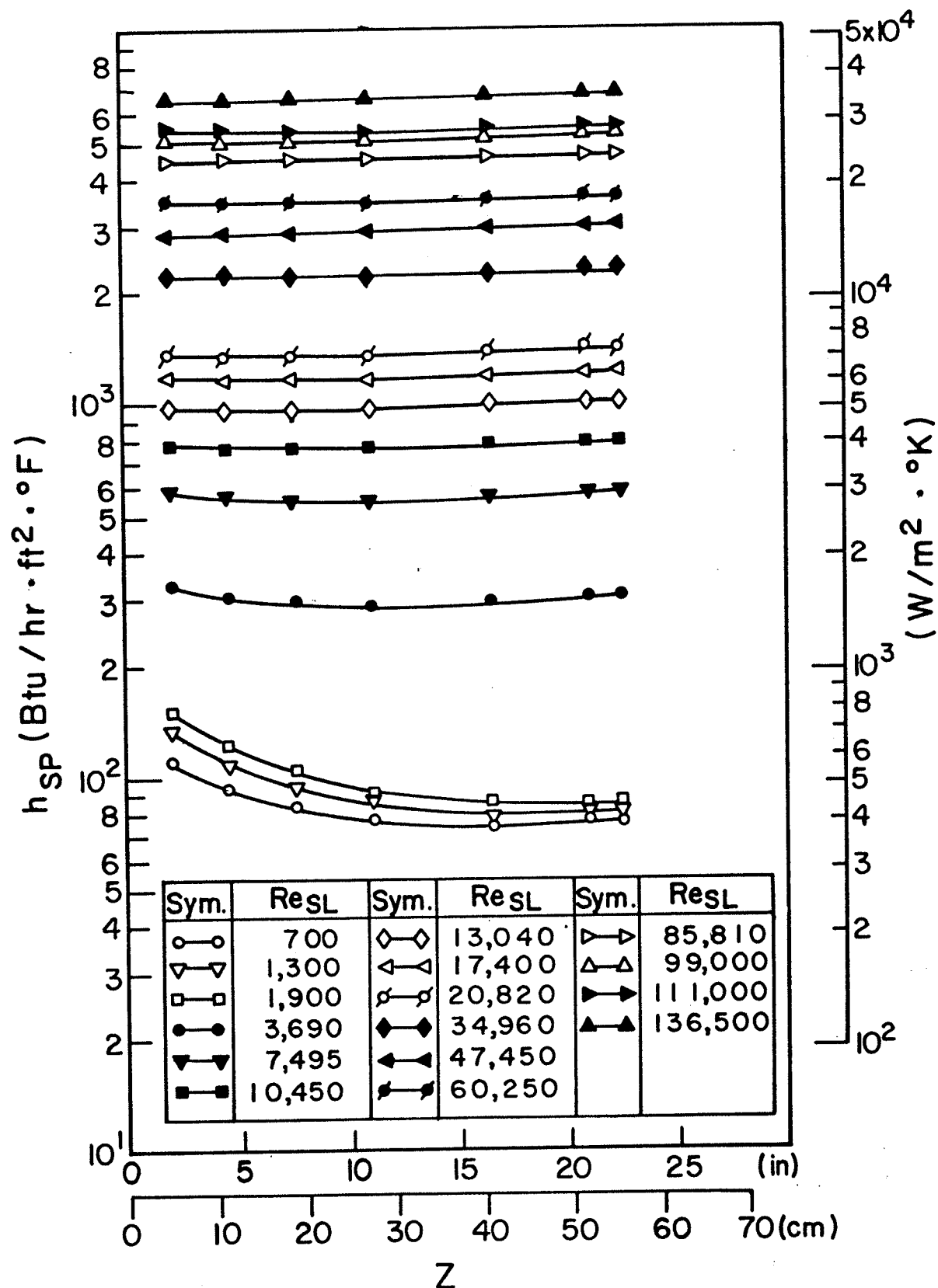


Fig. 5.2 Single-Phase Water Local-Heat-Transfer Results

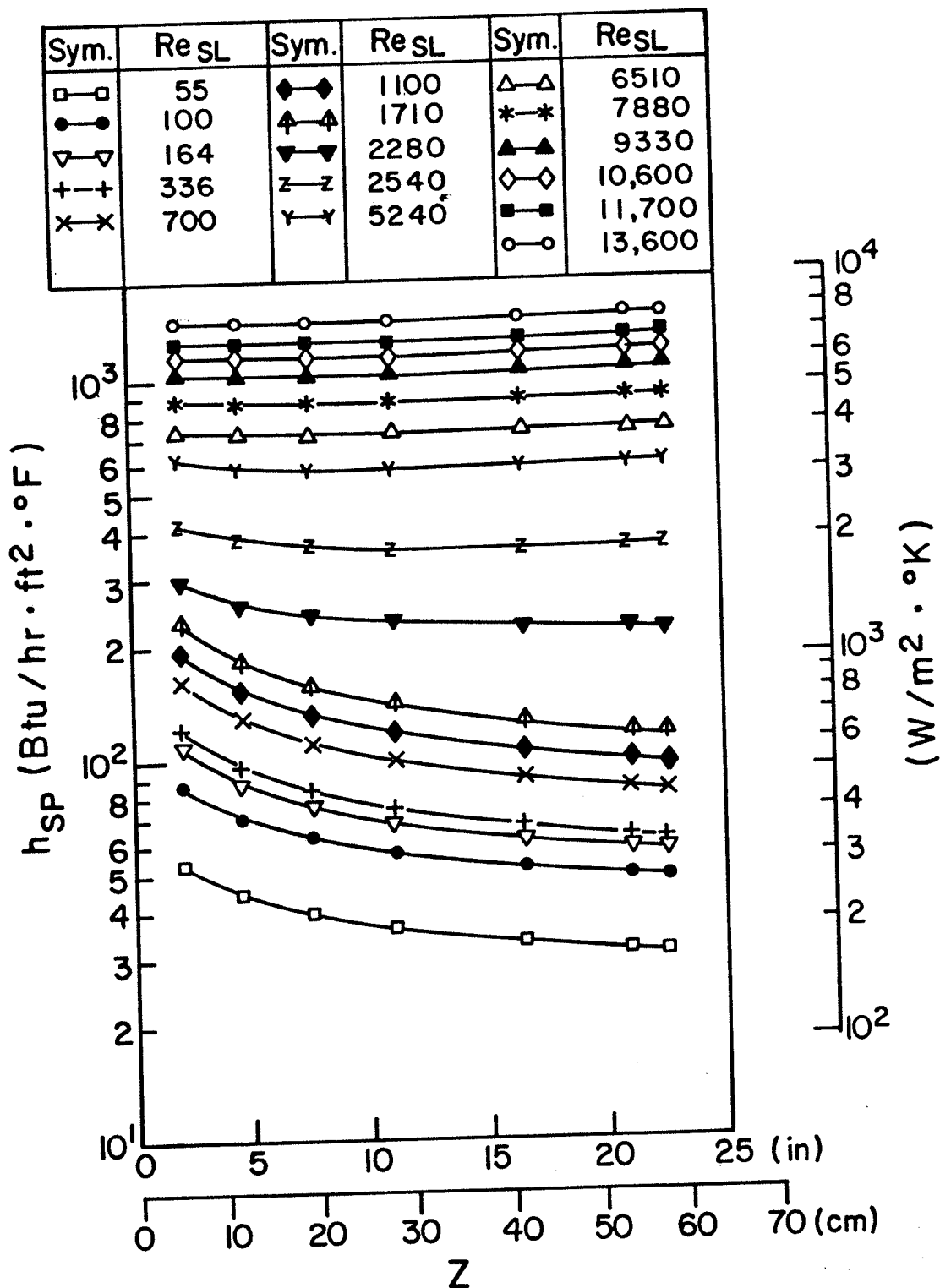


Fig. 5.3 Single-Phase Glycerine & Water Solution Local-Heat-Transfer Results

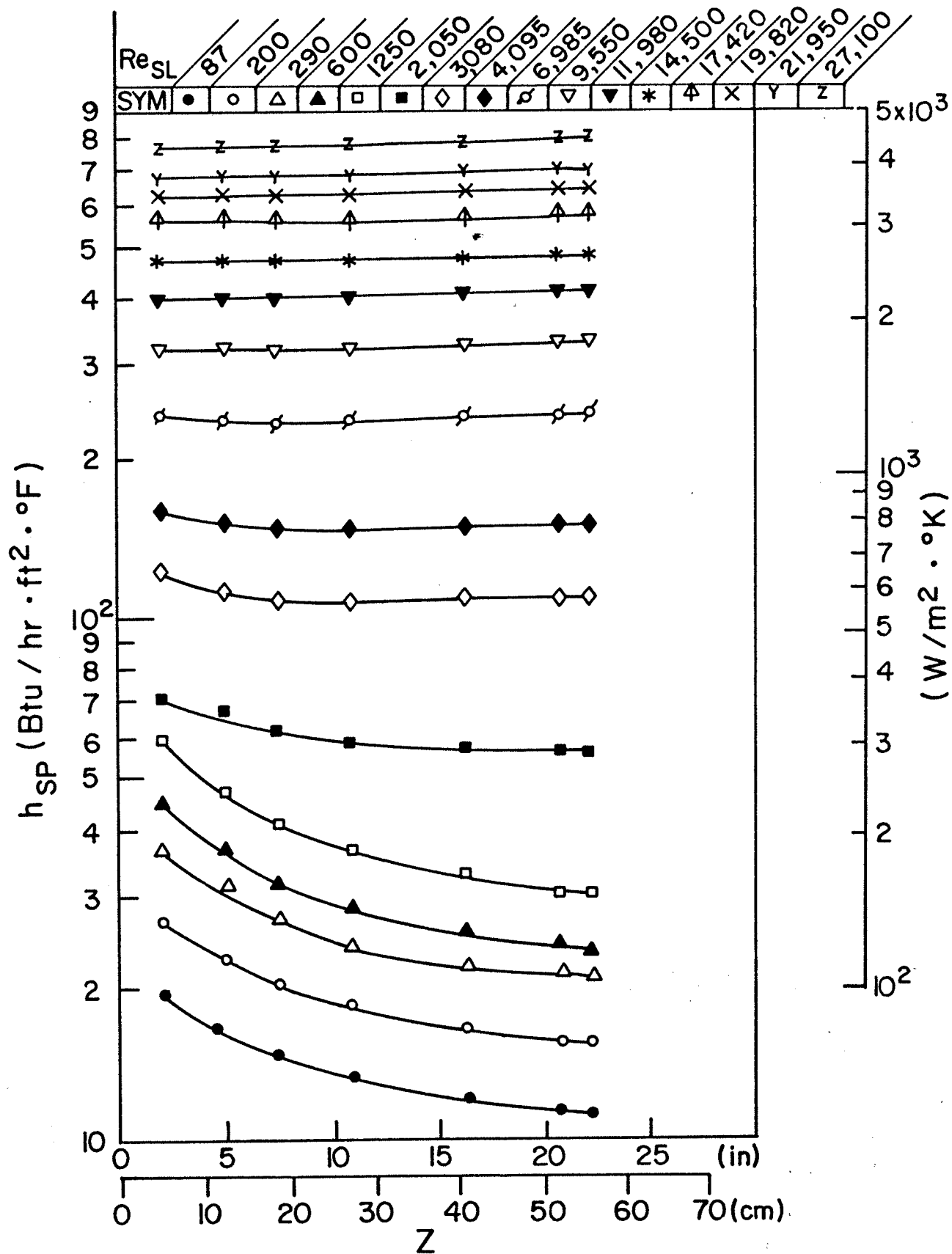


Fig. 5.4 Single-Phase Silicone Local-Heat-Transfer Results

profiles suggest qualitative agreement with the single-phase heat-transfer theory. For quantitative comparison, the data were compared with the following theories:

1. Laminar Flow ($Re_{SL} \leq 2000$):

(i) Worsøe-Schmidt (106)

In the paper, the governing differential equations were solved by using finite differences and the solutions were presented in the form of tables, listing Nu_{SP} against $\bar{Z}$, where

$$\bar{Z} = \frac{4(Z/D)}{Re_{SL} Pr_L} \quad (5.8)$$

(ii) Seigel et al.(81)

The solution was presented in the form of infinite series as given below

$$Nu_{SP}(\bar{Z}) = \left\{ \frac{11}{48} - \frac{1}{2} \sum_{n=1}^{\infty} \frac{\exp(-v_m^2 \bar{Z})}{A_m v_m^4} \right\}^{-1} \quad (5.9)$$

where

$$\bar{Z} = \frac{2(Z/D)}{Re_{SL} Pr_L} \quad (5.10)$$

The constants and the eigen values for the infinite series are given in Table 5.2.

2. Turbulent Flow ($Re_{SL} > 2000$):

The following expression recommended by Spalding (83) as being valid for the entire range of z^+ (defined

TABLE 5.2
Values of A_m and v_m in Equation(5.9)

m	A_m	v_m
1	7.630×10^{-3}	25.68
2	2.058×10^{-3}	83.86
3	0.901×10^{-3}	174.2
4	0.487×10^{-3}	296.5
5	0.297×10^{-3}	450.9
For large m, $v_m = 4m + \frac{4}{3}$ $A_m = 0.358 v_m^{-2.32}$		

below) was used to predict the local heat-transfer coefficients in this region.

$$Sq(z^+) = \left\{ \left\{ \frac{Pr_L/Pr_T}{6.64 (z^+/Pr_T)^{1/9} + P_{FN}} \right\}^4 + \left\{ 0.651 (z^+/Pr_L)^{-1/3} \right\}^4 \right\}^{1/4} \quad (5.11)$$

where

P_{FN} is the "P-Function" and is given by

$$P_{FN} = 11.57 \left\{ \left(\frac{Pr_L}{Pr_T} \right)^{0.75} - 1 \right\} \quad (5.12)$$

Pr_T is the turbulent Prandtl number and was given the value 0.887, as recommended by Spalding.

The single-phase friction factor was calculated from the expressions (5.3), (5.4), (5.5).

$$z^+ = (z/D) Re_{SL} (f_{SP}/2)^{1/2} \quad (5.13)$$

$Sq(z^+)$ is the Spalding function given by

$$Sq(z^+) = \frac{Nu_{SP}(z)}{Re_{SL} (f_{SP}/2)^{1/2}} \quad (5.14)$$

The comparisons between the experimental data and the predictions, in both the laminar and turbulent flow regions, for all three liquids are shown in Figs. 5.5 to 5.8. A summary of the deviations, both algebraic and r.m.s., is given in Tables 5.3 and 5.4 for laminar and turbulent flow,

TABLE 5.3

Summary of Comparison of the Local-Heat-Transfer Data in the Laminar Region

Liquid	Worsøe-Schmidt			Siegel et al. Eq.(5.9)	
	N	$\bar{e}\%$	$\bar{e}_r\%$	$\bar{e}\%$	$\bar{e}_r\%$
Water	21	+10.7	18.6	+7.6	13.3
Glycerine & water	49	+9.8	13.5	+12.1	16.9
Silicone	35	+1.3	8.7	+4.0	11.5
Overall	105	+7.1	13.4	+8.5	14.6

respectively.

The results showed good agreement with the theories, especially with the water data.

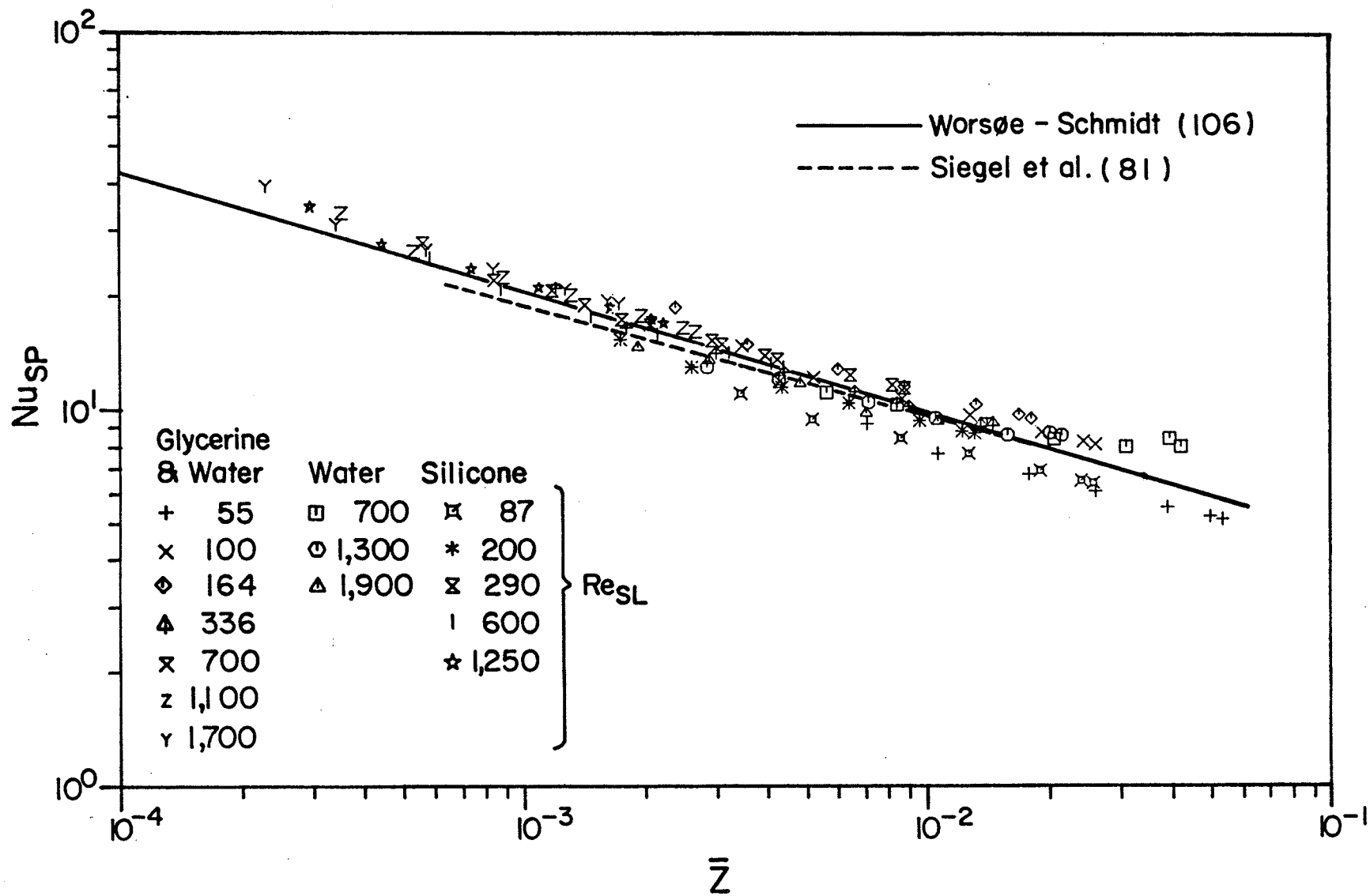


Fig. 5.5 Comparison of Single-Phase Local Heat-Transfer Data (Laminar Flow) with Some Existing Theories

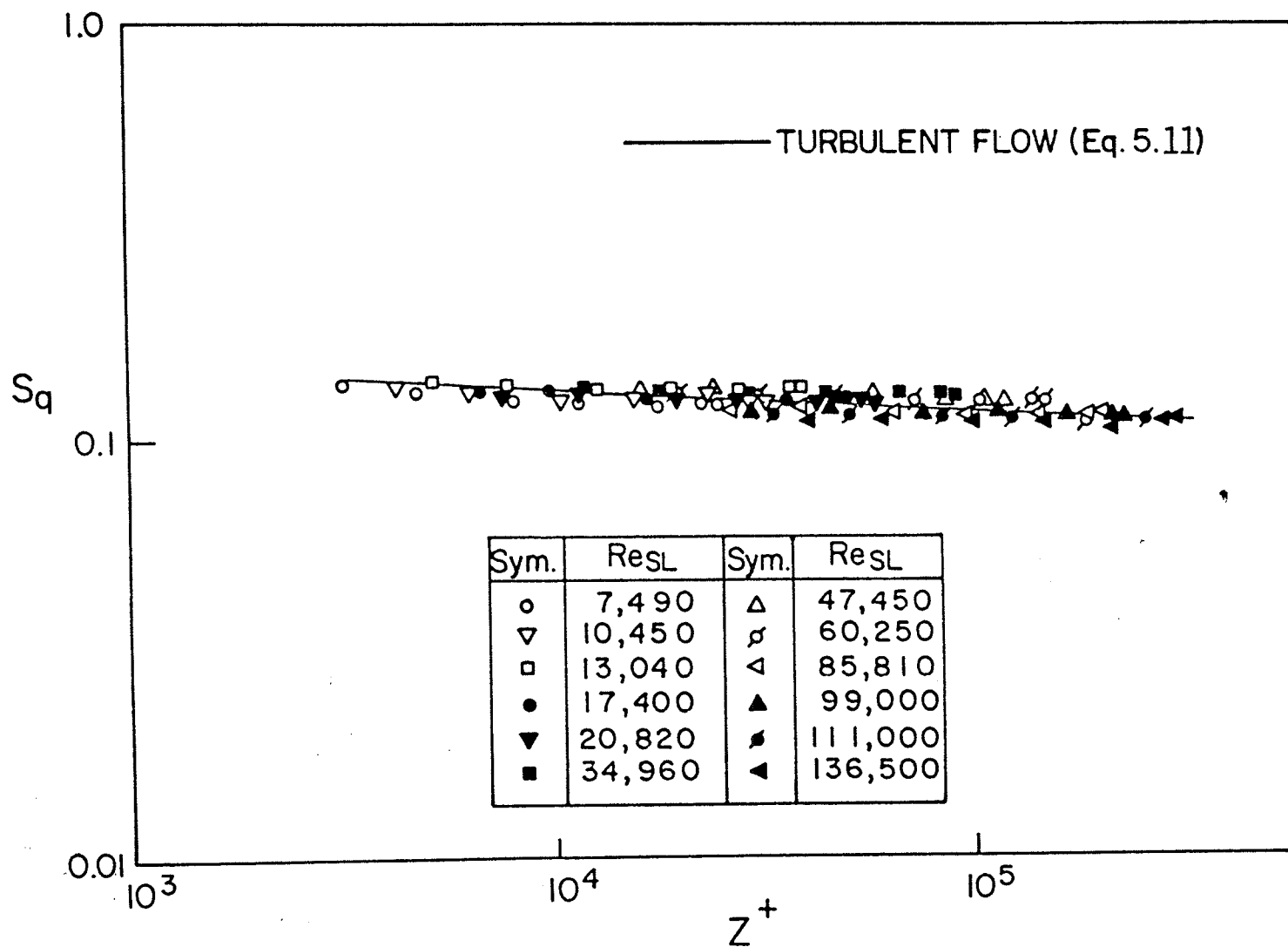


Fig. 5.6 Comparison of Single-Phase Water Local Heat-Transfer Data with Spalding Theory

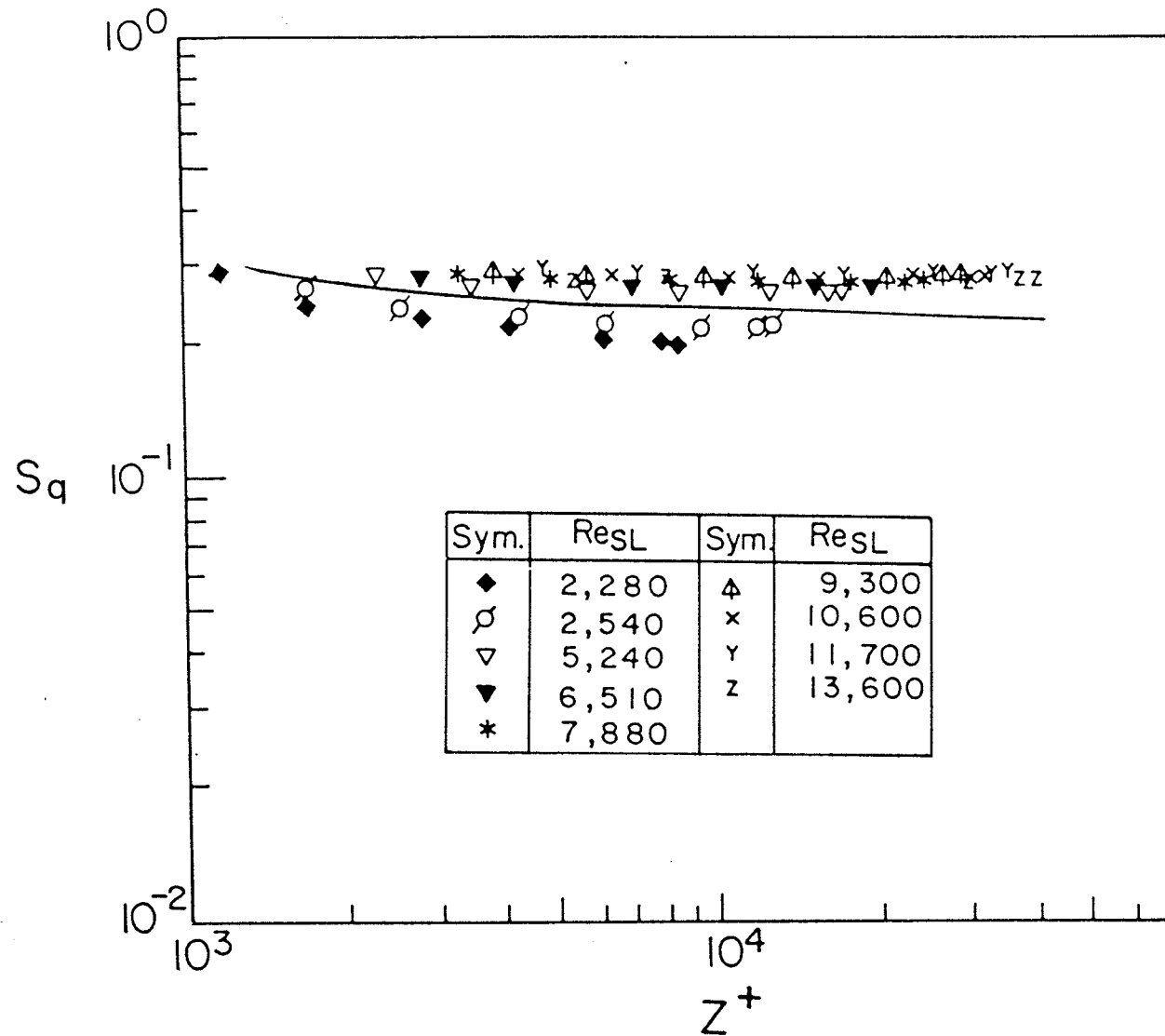


Fig. 5.7 Comparison of Single-Phase Glycerine & Water Local Heat-Transfer Data with Spalding Theory

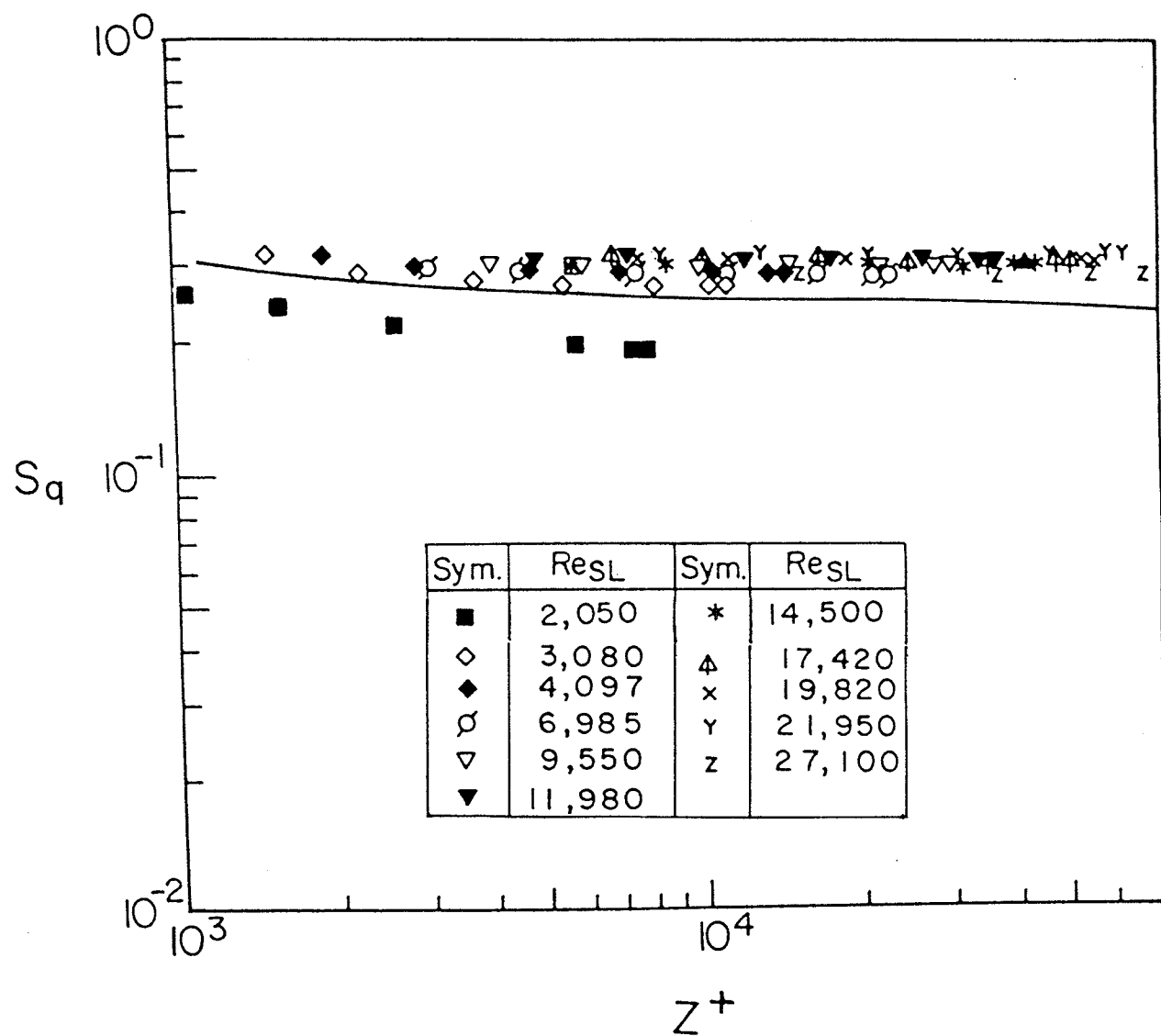


Fig. 5.8 Comparison of Single-Phase Silicone Local Heat-Transfer Data with Spalding Theory

TABLE 5.4

Summary of Comparison of the Local-Heat-Transfer Data in the Turbulent Region

Liquid	N	$\bar{e}\%$	$\bar{e}_r\%$
Water	91	-0.4	4.5
Glycerine & water	63	+9.7	15.3
Silicone	77	15.0	22.9
Overall	231	7.5	15.7

5.3.2 Mean-Heat-Transfer Results

As mentioned earlier in the chapter, the mean heat-transfer coefficients were calculated from the local values using a length-mean integration.

The mean-heat-transfer data were compared with the well-established correlation of Sieder and Tate (79) in the laminar and turbulent flow regions. These expressions for $\bar{Nu}_{SP}$ are given below:

1. For Laminar Flow ($Re_{SL} \leq 2000$)

$$\bar{Nu}_{SP} = 1.86 (Re_{SL} Pr_L \frac{D}{L})^{1/3} \left(\frac{\mu_B}{\mu_W} \right)^{0.14} \quad (5.15)$$

in which the viscosity ratio term is used to account for the variation of the fluid properties with temperature.

The agreement between the experimental data and Eq. (5.15) was such that the overall r.m.s. deviation for all three liquids was 16.1%.

2. For Turbulent Flow ($Re_{SL} > 2000$)

The Sieder-Tate equation for the single-phase heat-transfer coefficients in turbulent flow is given by:

$$\overline{Nu}_{SP} = 0.023 (Re_{SL})^{0.8} (Pr_L)^{1/3} \left(\frac{\mu_B}{\mu_W} \right)^{0.14} \quad (5.16)$$

This equation is applicable to fluids whose viscosity is sensitive to temperature (i.e. glycerine & water solutions); hence it was used here. The equation was used with all data points that have $Re_{SL} > 2000$, which covers those data points in the transition regions also.

The comparison gave excellent agreement with an overall r.m.s. deviation of 10.5% over the whole range of $Re_{SL} > 2000$. A summary of these results is given in Table 5.5. A plot of the comparisons, for all three liquids, is shown in Fig. 5.9. In this figure, the curve drawn between $Re_{SL} = 2000$ and $Re_{SL} = 10^4$ is obtained by drawing a smooth curve tangential to the theoretical line for turbulent flow, as shown in the original paper(79). From the same figure, it can be seen that the agreement was excellent with all three liquids over the entire range of Re_{SL} , including the transition region. The results in the Reynolds number range $2000 \leq Re_{SL} \leq 10^4$ could be improved if the smooth curve was used instead of the straight line.

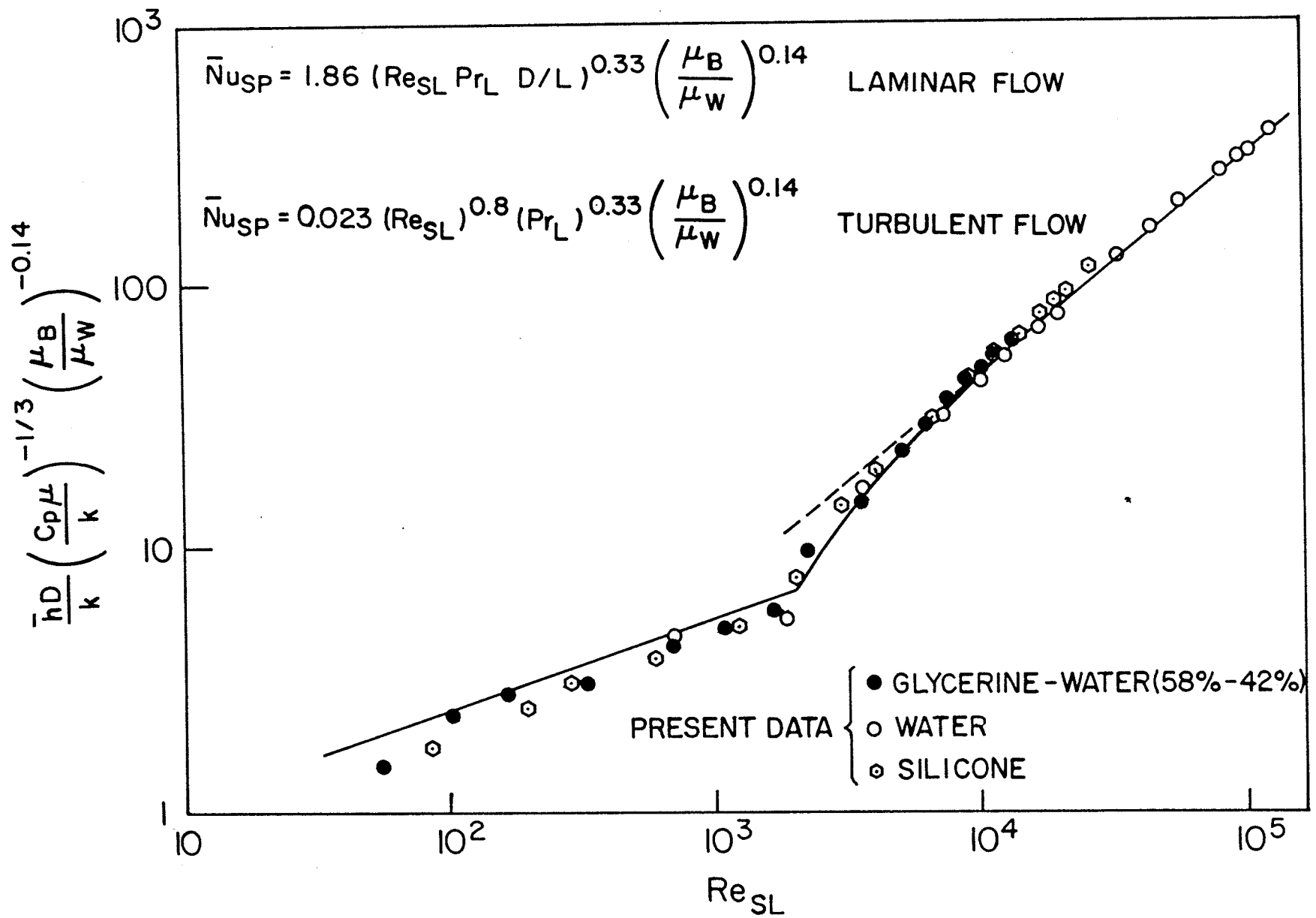


Fig. 5.9 Comparison of Single-Phase Mean Heat-Transfer Results with the Correlation of Sieder and Tate

TABLE 5.5

Summary of Comparison of the Single-Phase Mean-Heat-Transfer Data

Liquid	Laminar Flow, Eq. (5.15)			Turbulent Flow Eq. (5.16)		
	N	$\bar{e}$ (%)	$\bar{e}_r$ (%)	N	$\bar{e}$ (%)	$\bar{e}_r$ (%)
Water	3	-10.4	12.2	13	0.77	6.8
Glycerine & water	7	-12.9	14.5	9	-4.8	13.7
Silicone	5	-12.1	18.1	11	16.4	11.7
Overall	15	-13.0	16.1	33	0.93	10.5

From the material which is represented in this chapter, the following conclusions can be drawn:

1. The experimental rig continues to perform in a satisfactory way and therefore the two-phase-flow data (presented in the next chapters) are reliable.
2. The single-phase local and mean-heat-transfer data and the frictional-pressure-drop data showed good agreement when compared with some of the well-established single-phase theoretical and empirical relations.

Chapter 6

FLOW PATTERNS AND PRESSURE DROP IN TWO-PHASE FLOW

6.1 INTRODUCTORY REMARKS

Since flow patterns influence heat transfer and pressure drop in two-phase systems, they were observed and reported for all liquid-gas combinations taken in the present investigation. The primary purpose of flow-pattern observation in the present experiments was not to study two-phase flow patterns as such (although it could be done), but rather to provide information so that heat-transfer and pressure-drop results could be discussed in terms of flow patterns.

In this chapter, a description of the flow patterns in vertical channels is given together with samples of photographs of those flow patterns. This is followed by a presentation of the flow pattern maps for each liquid-gas combination, and then a comparison between the flow pattern data observed and some of the flow pattern maps which exist in the literature. Then the two-phase frictional-pressure-drop data are presented and compared with some of the theoretical and empirical correlations. Finally, the effect of surface tension on the frictional pressure drop in two-phase flow is discussed.

6.2 DESCRIPTION OF FLOW PATTERNS

Because of the multitude of flow patterns and the various interpretations accorded to them by different observers, no uniform procedure exists at present for describing and classifying them. However, in recent years, some attempts have been made to standardize their description (30,37,41,97). The characterization and description proposed by Hewitt and Hall-Taylor (41) appears to be among the best. Taitel et al. (87) and Zaidi (107) followed their lead in describing the basic flow patterns. Their description (41), with some modifications, will be used in the analysis of the results observed in the present work.

In the present investigation, the flow patterns were observed visually with and without the aid of a stroboscope through the transparent visualization section. The flow patterns were photographed (still photography) by using a high-speed microflash unit. Initial classifications were done with the water-air system and were later used to identify the flow patterns for other systems. The basic flow patterns observed are shown in Fig. 6.1 and are described below.

1. Bubble Flow: In this flow, the gas phase is distributed in the form of discrete bubbles in a continuous liquid phase. At low gas flow rates, the

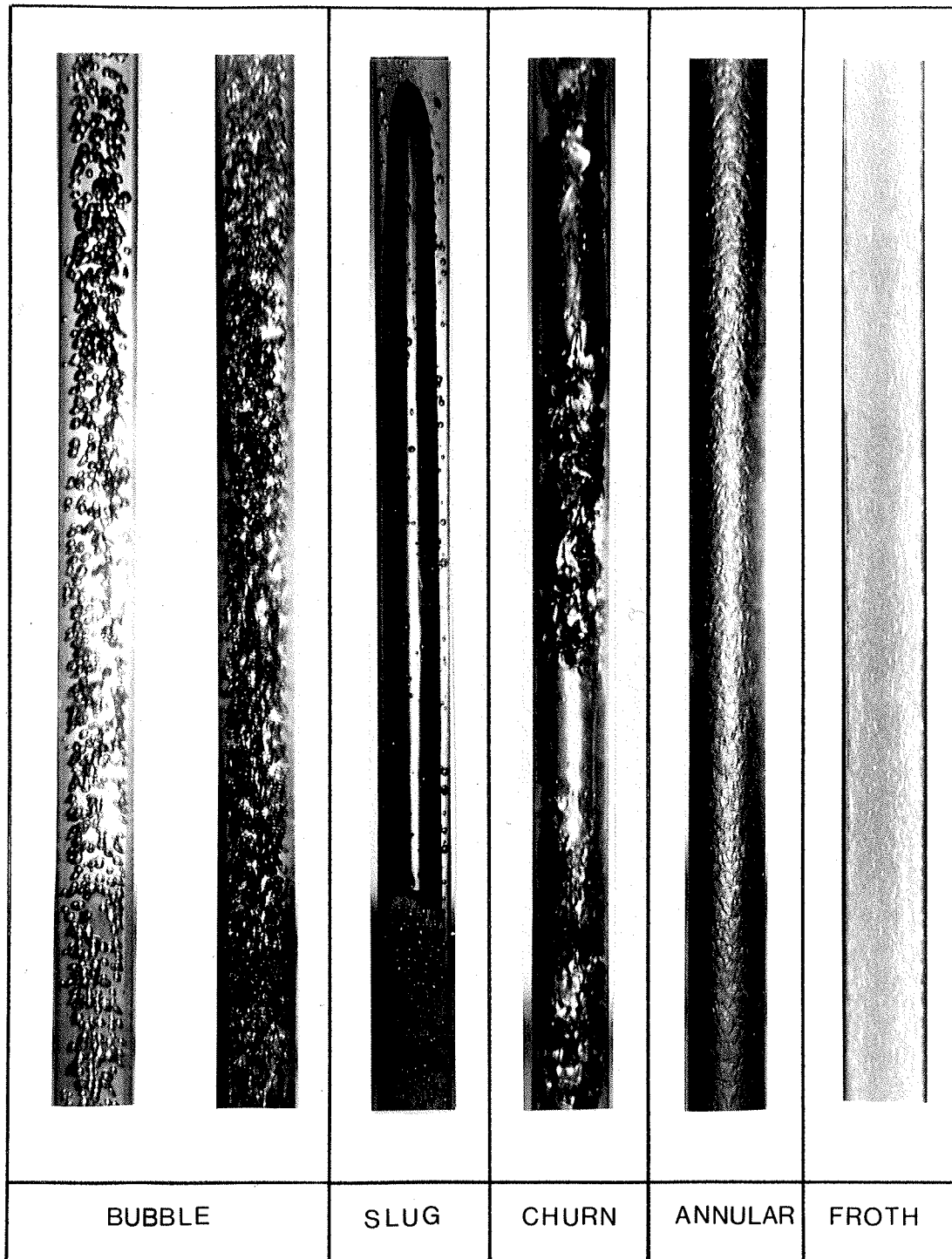


Fig.6.1 Flow Patterns in Co-Current Vertical Flow

bubbles are well spaced in the liquid phase, which is referred to in Ref. (5) as the "independent bubble" configuration. As gas flow increases, the size of the bubble decreases, and they become crowded together forming the "packed bubble" configuration (see Fig. 6.1). In the present study, both types have been observed and termed as bubble flow.

2. Slug Flow: Centrally located long bullet-shaped bubbles, sometimes called "Taylor bubbles," move uniformly upwards with a diameter almost equal to the tube diameter and a length that varies with the introduction of more gas flow into the liquid phase. Taylor bubbles are separated by slugs of continuous liquid which bridge the pipe and contain small gas bubbles. Between the Taylor bubbles and the pipe wall, liquid flows downward in the form of a thin falling film.
3. Churn Flow: As the gas flow increases, the liquid between the successive Taylor bubbles becomes discontinuous and the flow appears to be progressing with an oscillatory upward and downward motion. This pattern is characterized mainly by that oscillatory motion and the "distorted" shape of the Taylor bubbles which are repeatedly destroyed by the high local gas concentration in the slug. As the liquid falls, it forms a bridge across the tube and is again lifted by the oncoming gas flow.

4. Annular Flow: Gas flows in a continuous central core of the tube, and liquid flows in an annular wavy film on the tube wall. The gas core usually contains entrained drops of the liquid phase.
5. Mist Flow: In this case, the liquid film on the wall becomes thinner and thinner and eventually (as the gas flow continues to increase) is swept away from the wall. The liquid droplets are entrained in a continuous gas phase. This flow pattern has not been observed in the present investigation, and indeed, Hewitt and Taylor (41) suggested that this flow pattern can not be obtained in adiabatic (non-boiling) flows. However, the transition to this flow has been observed in this study.
6. Froth Flow: The gas-liquid mixture flows in a highly dispersed type of flow, with turbulence and continuous interaction occurring between the phases. This flow pattern is characterized by a homogeneous mixture that contains tiny gas bubbles and has an opaque milky appearance.

The transitions from one flow pattern to another have been observed in the present investigation. Any flow configuration which contained the elements of two basic flow patterns in it was classified as a transition between those flow patterns. An example is the annular-mist transition in

which the flow, when observed with the unaided eye, was somewhat transparent and gave the impression of a mist in the tube. A very thin film on the wall was observed when the flow was illuminated by the stroboscope; the same observations were gained from the photographs.

In addition to the above flow-pattern transition, others have been observed also, for example bubble-slug, bubble-froth, slug-churn, churn-annular, and annular-froth transitions. The numbers for the tests (data points) falling under each flow pattern and transition are summarized in Table 6.1.

6.3 PRESENTATION OF FLOW PATTERN PHOTOGRAPHS

In this section, samples of photographs that cover most of the flow patterns observed at each liquid flow rate (for the three liquids) are presented. The photographs are arranged in order of increasing gas flow rate at a fixed liquid rate.

In order to obtain detailed description of the flow patterns, the following procedure was found appropriate:

TABLE 6.1

Summary of the Flow Pattern Observations in the Present Study

Flow Pattern	Code	Number of Data Points Observed			Total
		Water-air	Glyc.&water-air 58%-42% by weight	Silicone-air	
Bubble	B	8	12	26	46
Slug	S	9	21	13	43
Churn	C	2	9	11	22
Annular	A	12	33	55	100
Froth	F	5	9	19	33
Bubble-Slug	B-S	2	6	7	15
Bubble-Froth	B-F	3	7	10	20
Slug-Churn	S-C	5	9	13	27
Slug-Annular	S-A	-	-	-	-
Slug-Froth	S-F	3	2	-	5
Churn-Annular	C-A	2	8	12	22
Froth-Annular	F-A	9	4	3	16
Annular-Mist	A-M	4	4	21	29

1. After establishing steady conditions for a specific run, a careful visual observation of the flow pattern was made first with lamp light, then using the stroboscope. Observations were recorded on the data sheet and, based on this step, a preliminary classification (or possibly more than one) of the flow pattern was done.
2. This was followed by taking a first picture of the flow pattern using the arrangement shown in Fig. 3.9 (a).
3. Due to the fact that the two-phase flow might be inherently unsteady, conditions at any plane might change with time, therefore, a second picture was taken for the same liquid-gas combination. In addition, in the case of froth flow and froth flow transitions, where the flow was very opaque, both sides of the transparent tube were illuminated using a reflector (as described in Sec. 3.6) and another picture was taken using the arrangement shown in Fig. 3.9 (b). [Examples of photographs taken with this arrangement are shown in Fig. 6.2(J,L,U).]
4. After obtaining the photographs for a certain run, a careful study of each flow pattern and transition was done using the different photographs together with the recorded comments and the descriptions taken during that run (Step 1) and a final identification and classification of the flow patterns was done.

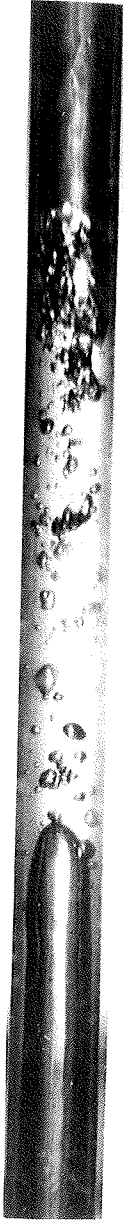
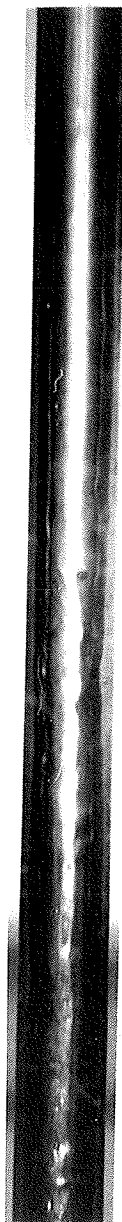
WATER- AIR			$V_{SL}=0.185$ ft/s(0.056 m/s)		
V_{SG} ft/s (m/s)					
3.47 (1.06)	9.03 (2.75)	26.6 (8.11)	42.7 (13.0)	129.4 (39.4)	290.9 (88.7)
					
I	II	III	IV	V	VI
S	S-C	C	C-A	A	A-M

FIG. 6.2(A)
FLOW PATTERN PHOTOGRAPHS

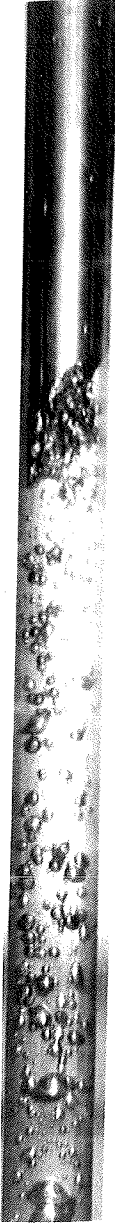
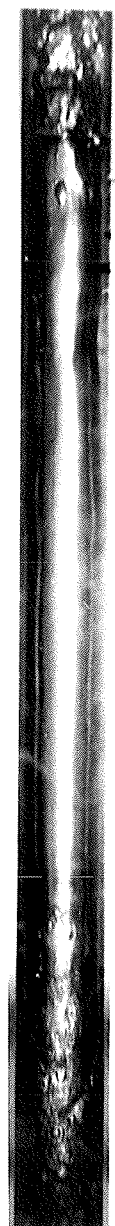
WATER-AIR					
$V_{SL} = 1.03 \text{ ft/s (0.314 m/s)}$					
$V_{SG} \text{ ft/s (m/s)}$					
2.95 (0.90)	4.82 (1.47)	8.24 (2.51)	17.1 (5.21)	63.5 (19.4)	288.9 (88.1)
					
I	II	III	IV	V	VI
S	S	S-C	C	A	A-M

FIG. 6.2(B)

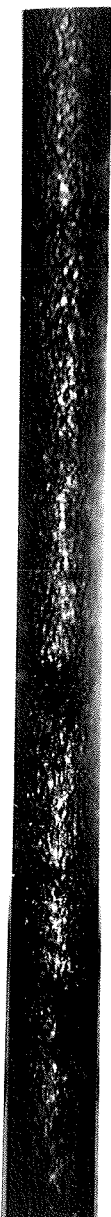
WATER- AIR			$V_{SL} = 10.4 \text{ ft/s (3.18 \text{ m/s})}$		
$V_{SG} \text{ ft/s (m/s)}$					
1.08 (0.10)	2.72 (0.38)	5.18 (1.58)	19.3 (5.86)	24.7 (7.53)	35.9 (10.9)
					
I	II	III	IV	V	VI
B	B	B-S	S-F	F-A	F-A

FIG. 6.2(C)

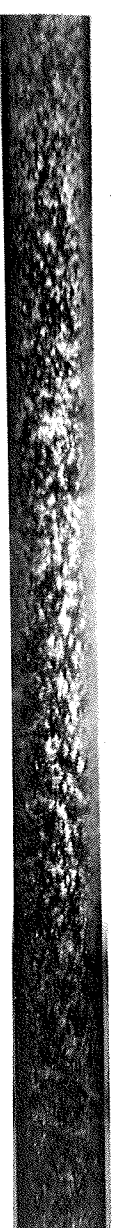
WATER- AIR			$V_{SL}= 34.7 \text{ ft/s(} 10.6 \text{ m/s)}$		
$V_{SG} \text{ ft/s (m/s)}$					
1.89 (0.58)	2.49 (0.76)	3.04 (0.93)	3.40 (1.04)	3.63 (1.11)	4.9 (1.49)
					
I	II	III	IV	V	VI
B	B	B	B-F	B-F	B-F

FIG. 6.2(D)

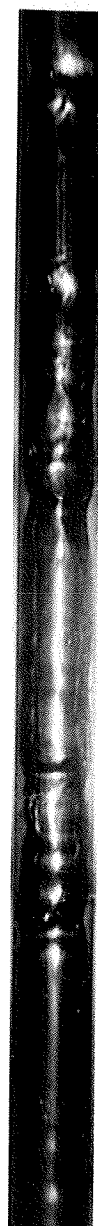
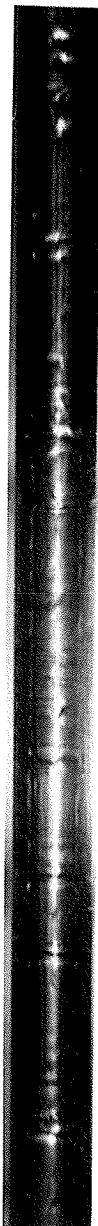
GLYCERINE & WATER MIX.-AIR			$V_{SL} = 0.073 \text{ ft/s (0.022 m/s)}$		
$V_{SG} \text{ ft/s (m/s)}$					
3.58 (1.09)	9.74 (2.97)	14.7 (4.47)	28.9 (8.81)	84.8 (25.8)	344.3 (104.9)
					
I	II	III	IV	V	VI
S	S-C	C	C-A	A	A

FIG. 6.2(E)

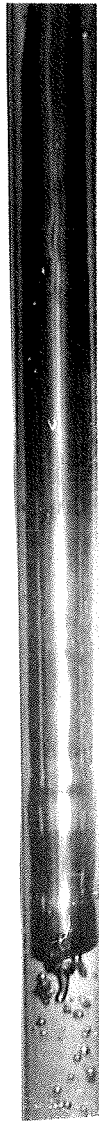
GLYCERINE & WATER MIX.-AIR				$V_{SL}=0.144$ ft/s(0.044 m/s)	
V_{SG} ft/s(m/s)					
1.76 (0.54)	6.89 (2.10)	9.65 (2.94)	31.7 (9.65)	179.5 (54.7)	299.3 (91.2)
					
I	II	III	IV	V	VI
S	S-C	S-C	C-A	A	A-M

FIG. 6.2(F)

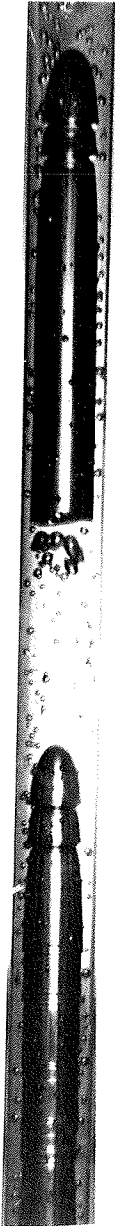
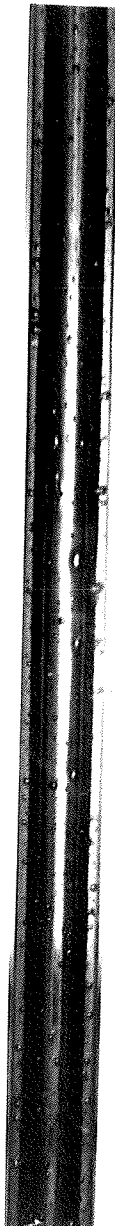
GLYCERINE & WATER MIX.-AIR						93
$V_{SL} = 0.380 \text{ ft/s} (0.116 \text{ m/s})$						
$V_{SG} \text{ ft/s (m/s)}$						
1.31 (0.40)	3.42 (1.04)	9.28 (2.83)	21.8 (6.64)	42.8 (13.0)	80.0 (24.4)	
						
I	II	III	IV	V	VI	
S	S	S-C	C	C-A	A	

FIG. 6.2 (G)

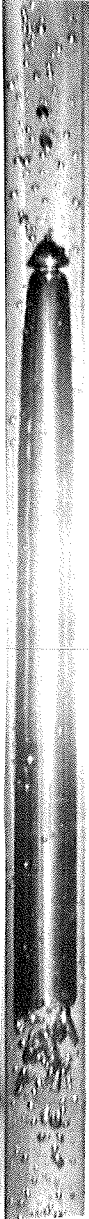
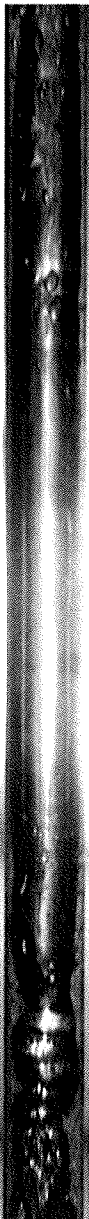
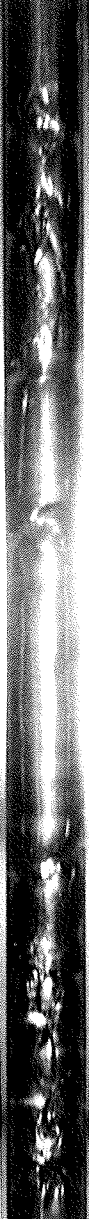
GLYCERINE & WATER MIX.-AIR					
$V_{SL} = 1.31 \text{ ft/s (0.399 m/s)}$					
$V_{SG} \text{ ft/s (m/s)}$					
2.31 (0.70)	3.26 (0.99)	9.06 (2.76)	14.5 (4.42)	39.4 (12.0)	70.9 (21.6)
					
I	II	III	IV	V	VI
S	S	S-C	C	C-A	A

FIG. 6.2(H)

GLYCERINE & WATER MIX.-AIR				$V_{SL} = 3.27 \text{ ft/s}(0.997 \text{ m/s})$	
$V_{SG} \text{ ft/s (m/s)}$					
2.41 (0.73)	4.70 (1.43)	6.52 (1.99)	16.4 (5.0)	23.1 (7.04)	113.4 (34.6)
					
I	II	III	IV	V	VI
S	S	S	C	C-A	A

FIG. 6.2(I)

GLYCERINE & WATER MIX.-AIR			$V_{SL} = 8.74 \text{ ft/s (2.66 m/s)}$		
$V_{SG} \text{ ft/s (m/s)}$					
0.18 (0.05)	4.96 (1.51)	9.83 (3.0)	13.9 (4.24)	19.3 (5.88)	55.8 (17.0)
					
I	II	III	IV	V	VI
B	B-S	S-F	S-F	F-A	A

* PICTURES WERE TAKEN USING THE ARRANGEMENT SHOWN IN FIG. 3.9(B)
FIG. 6.2(J)

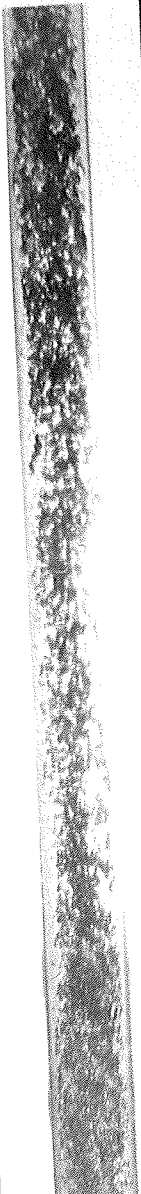
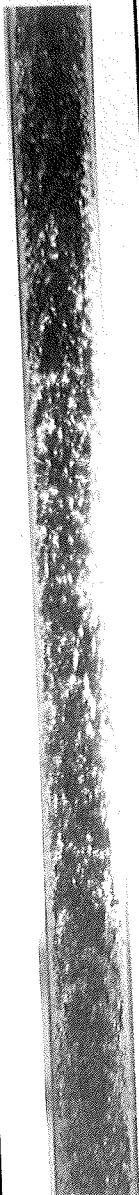
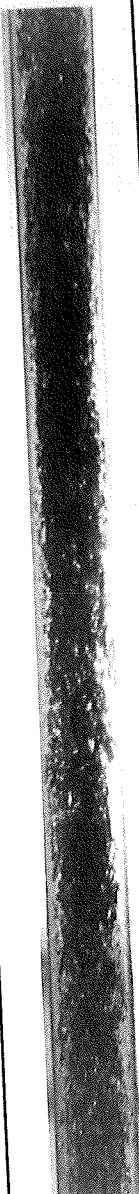
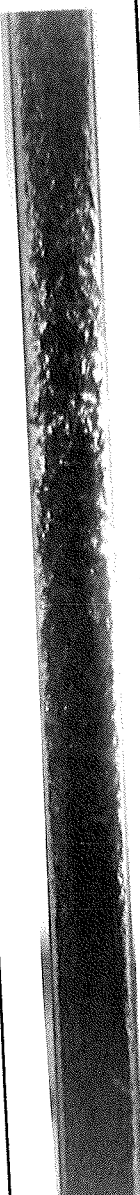
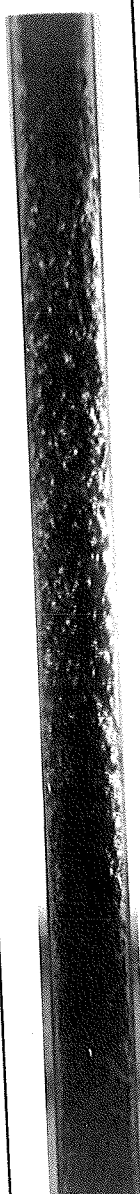
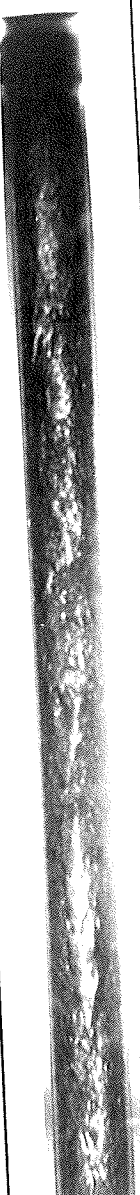
GLYCERINE & WATER MIX.-AIR					
$V_{SL} = 18.1 \text{ ft/s (5.52 m/s)}$					
$V_{SG} \text{ ft/s (m/s)}$					
1.44 (0.44)	1.96 (0.6)	2.7 (0.82)	4.89 (1.49)	9.79 (2.98)	21.1 (6.43)
					
I	II	III	IV	V	VI
B	B	B-F	B-F	F	F

FIG. 6.2 (K)

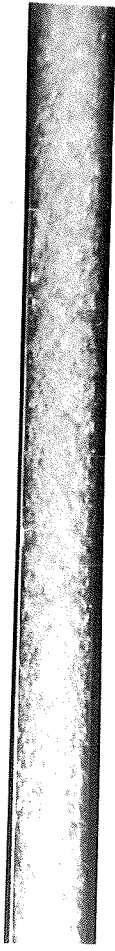
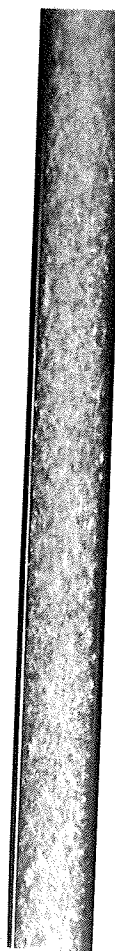
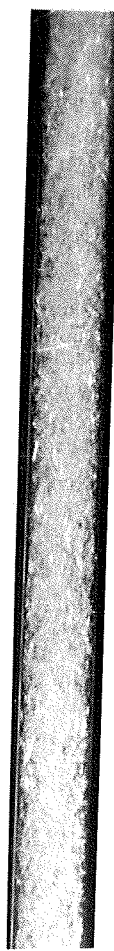
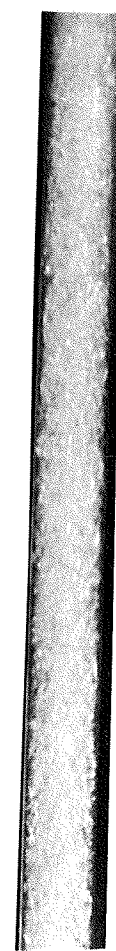
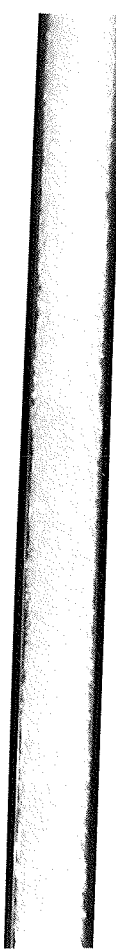
GLYCERINE & WATER MIX.-AIR					
$V_{SL} = 24.2 \text{ ft/s (7.38 m/s)}$					
$V_{SG} \text{ ft/s (m/s)}$					
1.19 (0.36)	1.68 (0.51)	2.22 (0.68)	3.0 (0.91)	6.89 (2.1)	12.9 (3.93)
					
*	*	*	*	*	*
I	II	III	IV	V	VI
B	B-F	B-F	B-F	F	F

FIG. 6.2(L)

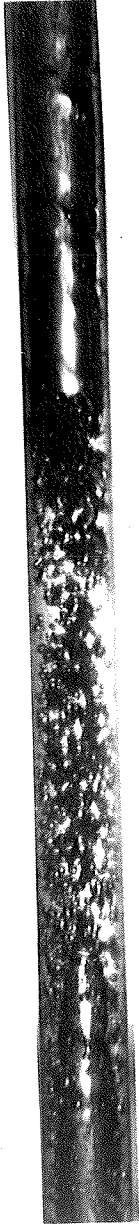
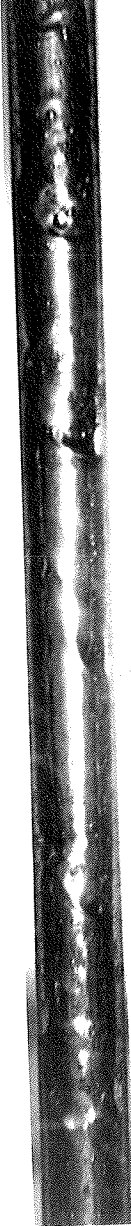
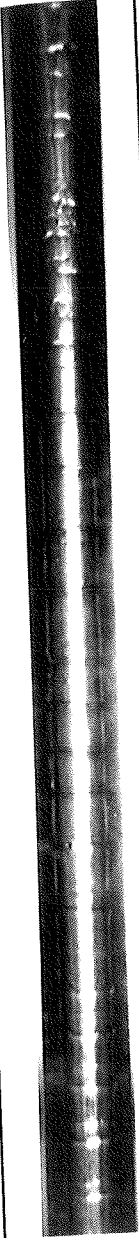
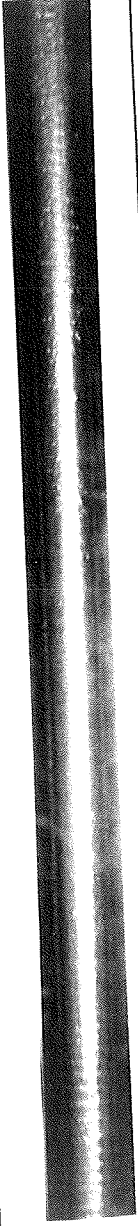
SILICONE-AIR					
$V_{SL} = 0.073 \text{ ft/s (0.022 m/s)}$					
$V_{SG} \text{ ft/s(m/s)}$					
2.53 (0.77)	5.06 (1.54)	9.73 (2.97)	14.9 (4.54)	86.5 (26.4)	279.0 (85.1)
					
I	II	III	IV	V	VI
S	S-C	C	C-A	A	A-M

FIG. 6.2(M)

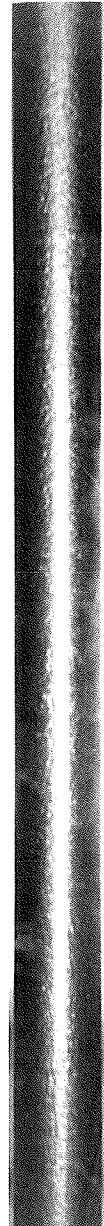
SILICONE-AIR			$V_{SL} = 0.100 \text{ ft/s (0.030 m/s)}$		
$V_{SG} \text{ ft/s(m/s)}$					
2.04 (0.62)	7.05 (2.15)	14.40 (4.39)	21.7 (6.61)	85.1 (25.9)	298.6 (91.0)
					
I	II	III	IV	V	VI
S	S-C	C	C-A	A	A-M

FIG. 6.2(N)

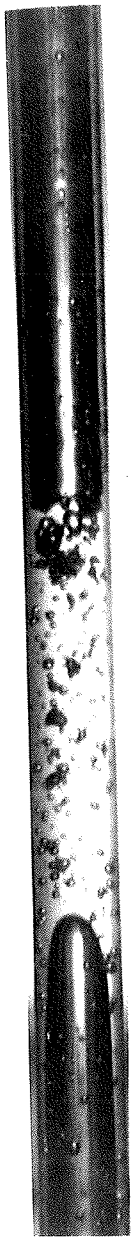
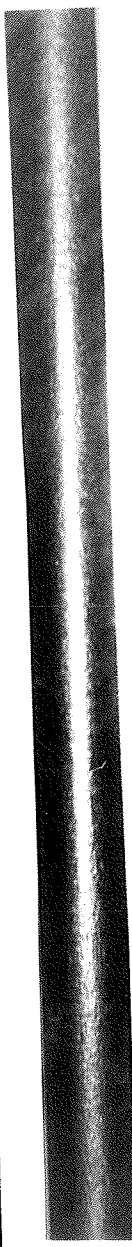
SILICONE - AIR			$V_{SL} = 0.260 \text{ ft/s (0.079 m/s)}$		
$V_{SG} \text{ ft/s(m/s)}$					
0.78 (0.24)	3.35 (1.02)	9.75 (2.97)	21.1 (6.42)	85.0 (25.9)	279.0 (85.0)
					
I	II	III	IV	V	VI
S	S	C	C-A	A	A-M

FIG. 6.2(0)

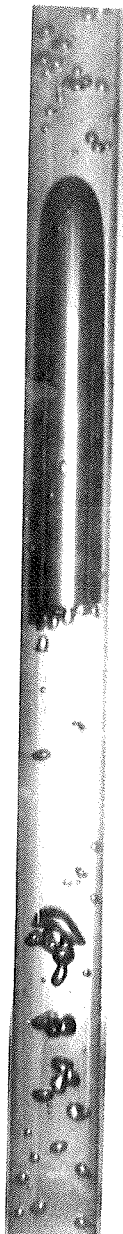
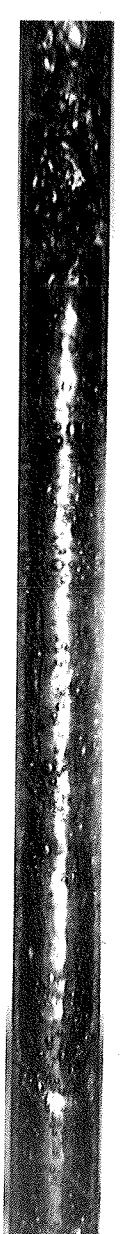
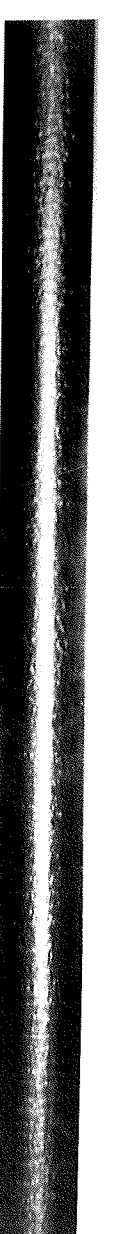
SILICONE-AIR			$V_{SL}=0.380\text{ ft/s (0.116 m/s)}$		
$V_{SG}\text{ ft/s(m/s)}$					
0.77 (0.23)	2.06 (0.63)	6.4 (1.95)	9.99 (3.04)	54.2 (16.5)	268.7 (81.9)
					
I	II	III	IV	V	VI
S	S	C	C-A	A	A-M

FIG. 6.2(P)

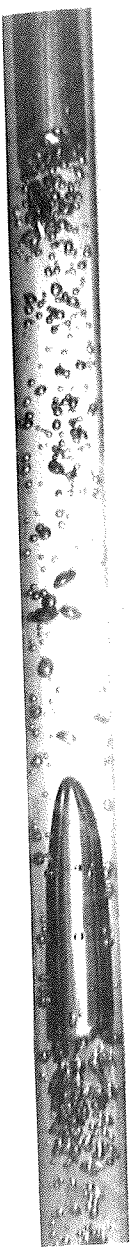
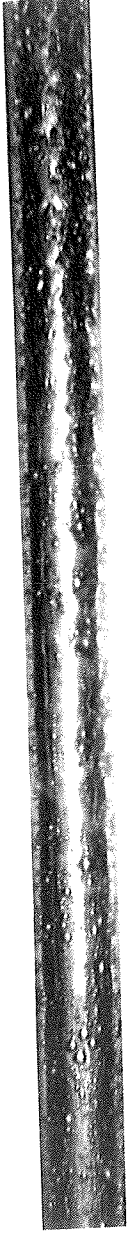
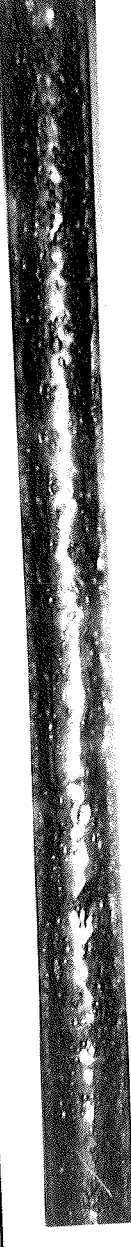
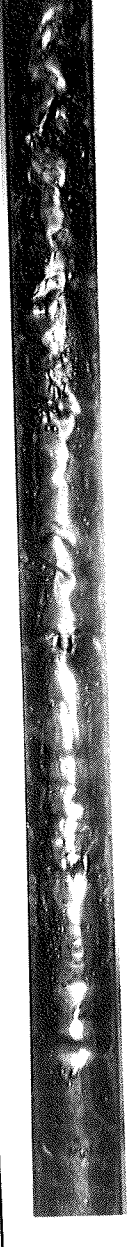
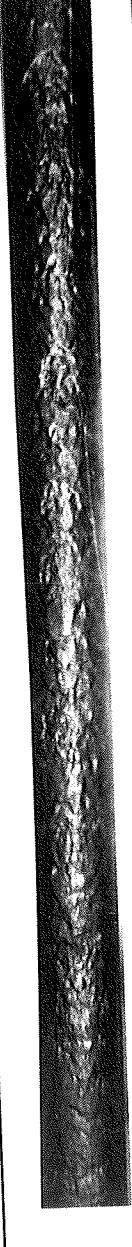
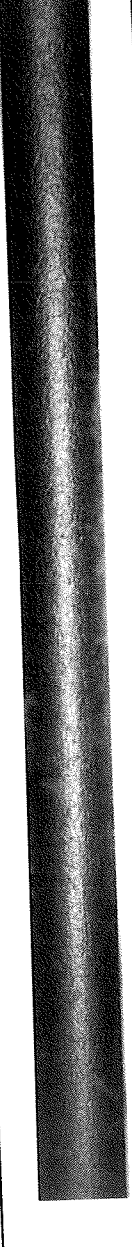
SILICONE-AIR					
$V_{SL} = 0.910 \text{ ft/s (0.277 m/s)}$					
$V_{SG} \text{ ft/s(m/s)}$					
2.14 (0.65)	4.52 (1.38)	9.22 (2.81)	20.1 (6.13)	78.4 (23.9)	292.9 (89.3)
					
I	II	III	IV	V	VI
S	S-C	C	C-A	A	A-M

FIG. 6.2(Q)

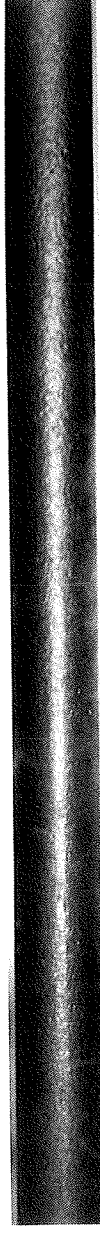
SILICONE-AIR			$V_{SL} = 1.30 \text{ ft/s (0.396 m/s)}$		
$V_{SG} \text{ ft/s(m/s)}$					
0.47 (0.14)	3.19 (0.97)	6.39 (1.95)	8.86 (2.70)	72.4 (22.1)	245.4 (74.8)
					
I	II	III	IV	V	VI
B	B-S	S-C	C	A	A-M

FIG. 6.2(R)

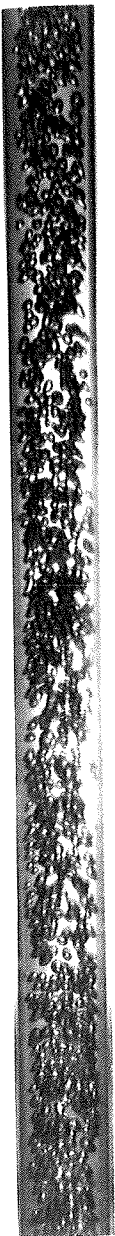
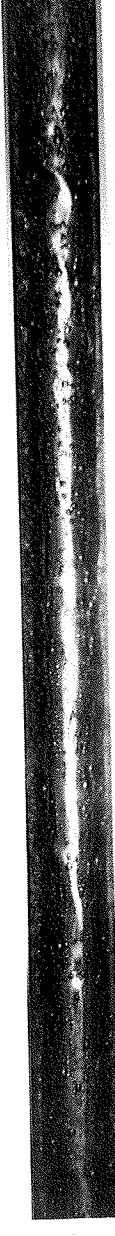
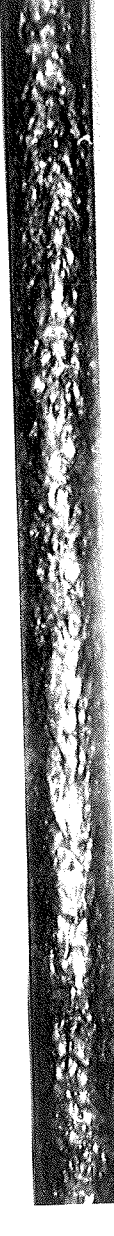
SILICONE-AIR			$V_{SL} = 2.26 \text{ ft/s (0.690 m/s)}$		
$V_{SG} \text{ ft/s(m/s)}$					
0.5 (0.15)	2.8 (0.85)	4.04 (1.23)	8.68 (2.65)	13.1 (3.99)	19.4 (5.91)
					
I	II	III	IV	V	VI
B	B	S-C	S-C	C	C-A

FIG. 6.2(S)

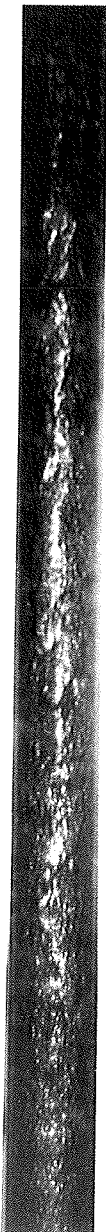
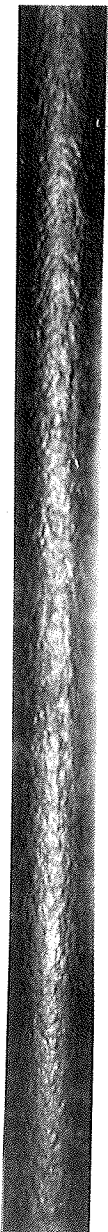
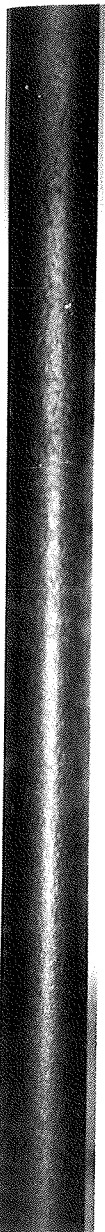
SILICONE-AIR				$V_{SL}=2.26 \text{ ft/s (0.690 m/s)}$	
$V_{SG} \text{ ft/s(m/s)}$					
27.3 (8.32)	53.4 (16.3)	145.0 (44.2)	265.0 (80.8)		
					
VII	VIII	IX	X		
A	A	A	A-M		

FIG. 6.2(S) CONT.

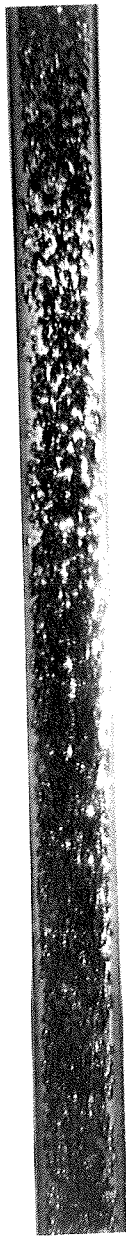
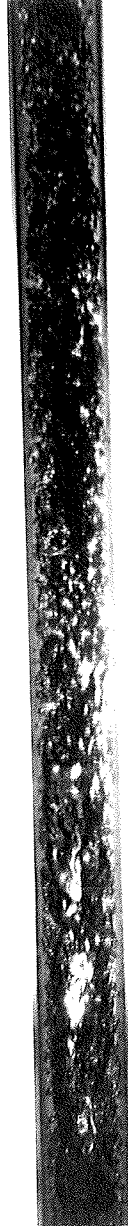
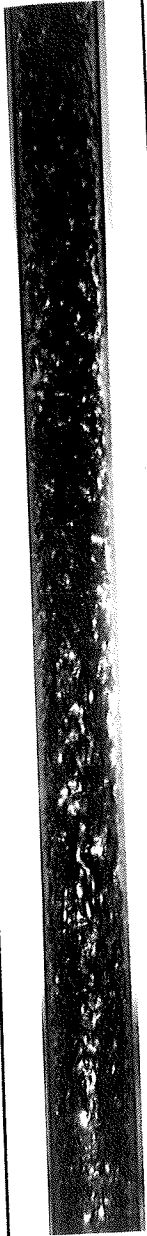
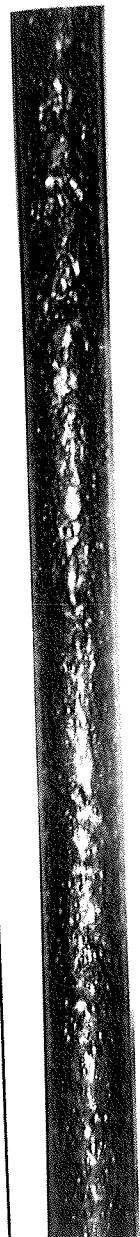
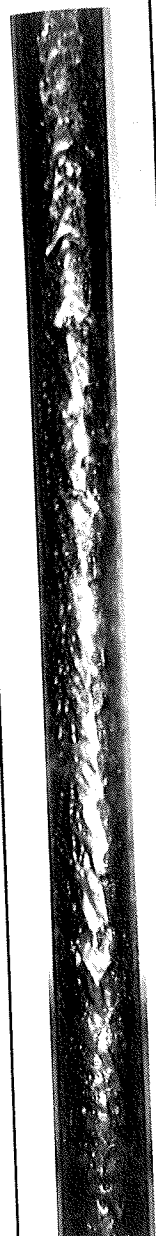
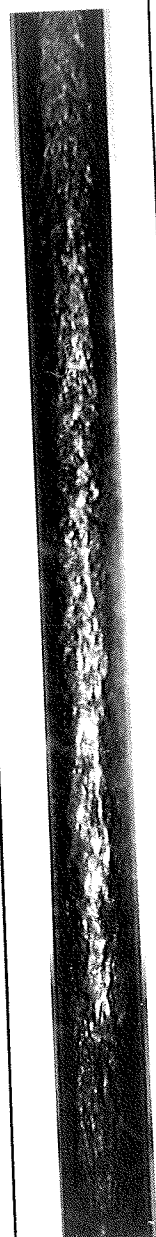
SILICONE-AIR					
$V_{SL} = 6.05 \text{ ft/s (1.84 m/s)}$					
$V_{SG} \text{ ft/s(m/s)}$					
1.69 (0.515)	3.91 (1.19)	7.97 (2.43)	11.6 (3.54)	24.1 (7.35)	32.4 (9.88)
					
I	II	III	IV	V	VI
B	B-S	S-C	C-A	A	A

FIG. 6.2(T)

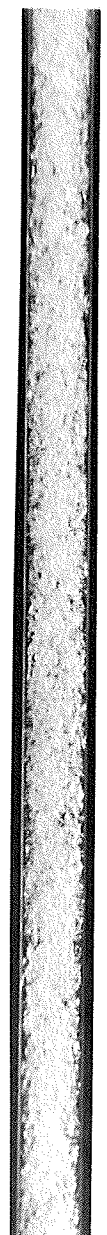
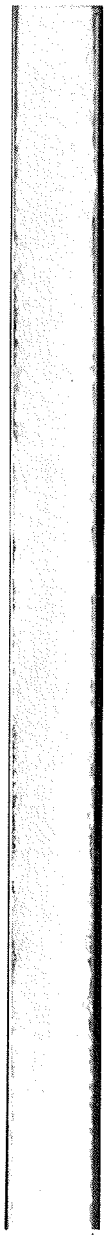
SILICONE-AIR			$V_{SL}=12.6 \text{ ft/s (3.83 m/s)}$		
$V_{SG} \text{ ft/s(m/s)}$					
1.07 (0.33)	2.23 (0.68)	2.23 (0.68)	9.4 (2.87)	18.5 (5.64)	18.5 (5.64)
					
I	II	III*	IV*	V*	VI
B	B-F	B-F	F	F-A	F-A

FIG. 6.2(U)

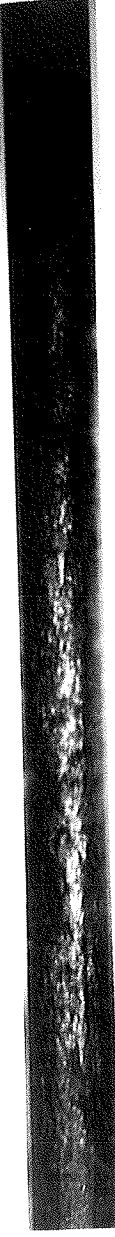
SILICONE-AIR				$V_{SL}=12.6$ ft/s (3.83 m/s)	
V_{SG} ft/s(m/s)					
32.6 (9.94)	32.6 (9.94)	40.4 (12.3)	54.6 (16.6)		
					
VII	* VIII	IX	* X		
A	A	A	A		

FIG. 6.2(U) CONT.

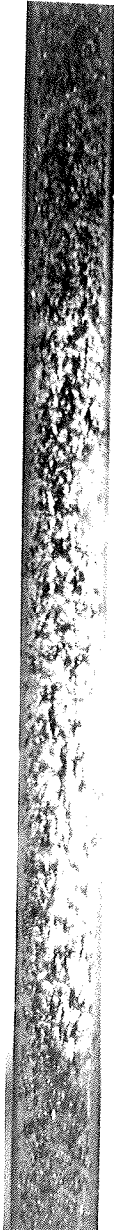
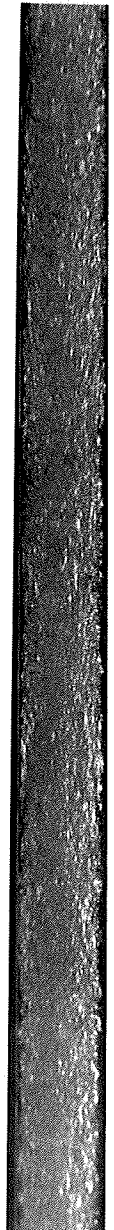
SILICONE-AIR				$V_{SL} = 16.6 \text{ ft/s (5.07 m/s)}$	
$V_{SG} \text{ ft/s(m/s)}$					
1.18 (0.36)	1.72 (0.52)	4.56 (1.39)	12.4 (3.78)	35.1 (10.7)	59.7 (18.2)
					
I	II	III	IV	V	* VI
B	B	B-F	F	F-A	F-A

FIG. 6.2(V)

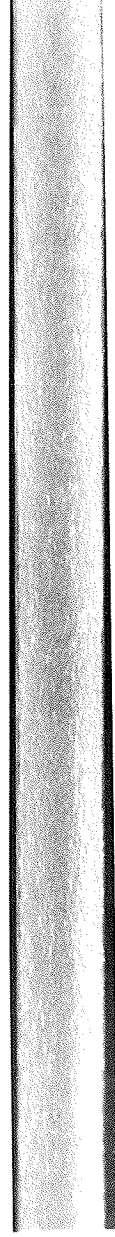
SILICONE – AIR			$V_{SL}=24.2 \text{ ft/s (7.38 m/s)}$		
$V_{SG} \text{ ft/s(m/s)}$					
2.30 (0.70)	3.16 (0.96)	6.9 (2.1)	9.15 (2.79)	15.9 (4.85)	26.5 (8.08)
					
I	II	III*	IV*	V*	VI*
B	B-F	F	F	F	F

FIG. 6.2(W)

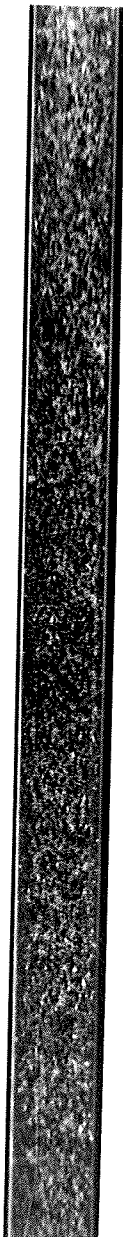
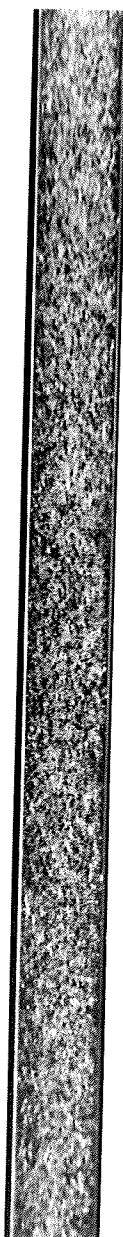
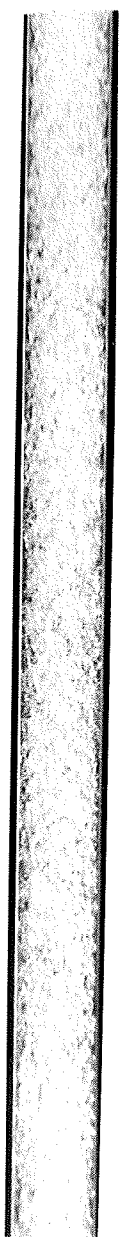
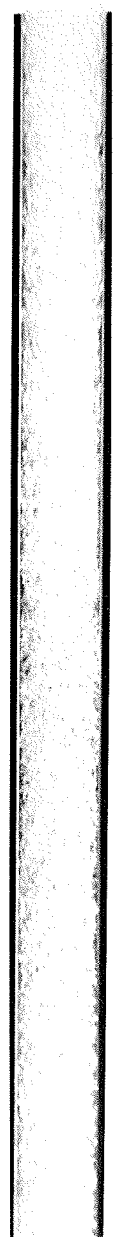
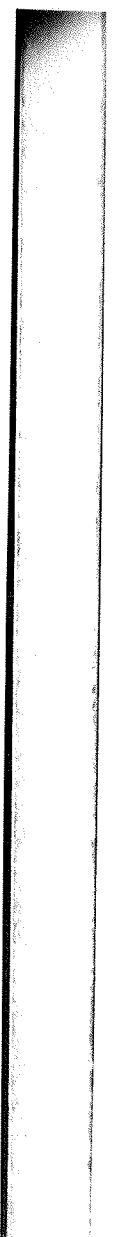
SILICONE-AIR			$V_{SL} = 30.2 \text{ ft/s (9.20 m/s)}$		
$V_{SG} \text{ ft/s(m/s)}$					
0.45 (0.14)	0.68 (0.21)	2.63 (0.80)	3.50 (1.07)	6.33 (1.93)	8.22 (2.51)
					
I	II	* III	* IV	* V	* VI
B	B	B	B-F	F	F

FIG. 6.2(X)

These are the flow patterns represented here and shown in Figs. 6.2 (A) to 6.2 (X).

6.4 PRESENT DATA ON FLOW PATTERN MAPS

The different flow pattern regions along with their transition boundaries can be represented on a two-dimensional co-ordinate system, known as a "flow-pattern map." Taitel et al.(87), in a study done on flow-pattern map systems, concluded that for the experimental flow-pattern maps there are two basic types of co-ordinates that appear in the literature. One group of investigators uses dimensional co-ordinates, such as superficial velocities or mass flow rates of both phases (30,40,97,102). The second group represents the results on dimensionless co-ordinates (25,34), among which Griffith and Wallis (34) were the only investigators who attempted to invoke theory to arrive at the dimensionless co-ordinates they used. Taitel et al.(87), Wiseman and Kang (102), Mishima & Ishii (66), and most recently McQuillan and Whalley (63) have presented an alternative to the experimental methods of obtaining the flow-pattern maps; these authors have attempted to generalize the presentation of such maps by deriving analytical expressions that determine the conditions necessary for the existence of each of the flow patterns. Also, they postulated mechanisms by which the transitions between the various flow patterns might occur. In this

section the various flow patterns observed in the present study are presented on dimensional co-ordinates, mainly the superficial liquid velocity V_{SL} and the superficial gas velocity V_{SG} . The transitions between the various flow patterns for the water-air system (Fig. 6.3) were obtained by the present author as a result of plotting most of the experimental water-air data taken previously on the same rig by (1, 93, 107) plus the present data. Due to the fact that some of the water-air data were taken at the same liquid and gas velocities, a few of them fell upon the present data, in which cases the latter only were included in the figure. Experimentally, these transitions take place over a certain range of V_{SG} while increasing the gas flow rate. Therefore, the transitions are presented by a shaded area (rather than a line) that contains most of the transitions observed.

Figure 6.4 gives the present glycerine & water (58%-42%)-air data. The boundaries drawn on this figure were obtained as a result of plotting the present observations for water-air and glycerine & water (58%-42%)-air. These boundaries differed slightly from those obtained for the water-air data (Fig. 6.3), which suggests the very small effect of liquid viscosity on the transition lines. The same conclusion was drawn by Vijay (93), who changed the liquid viscosity by a factor of 1000 times that of water (using pure glycerine as the liquid phase). Also, Wiseman and Kang (102) reported the weak

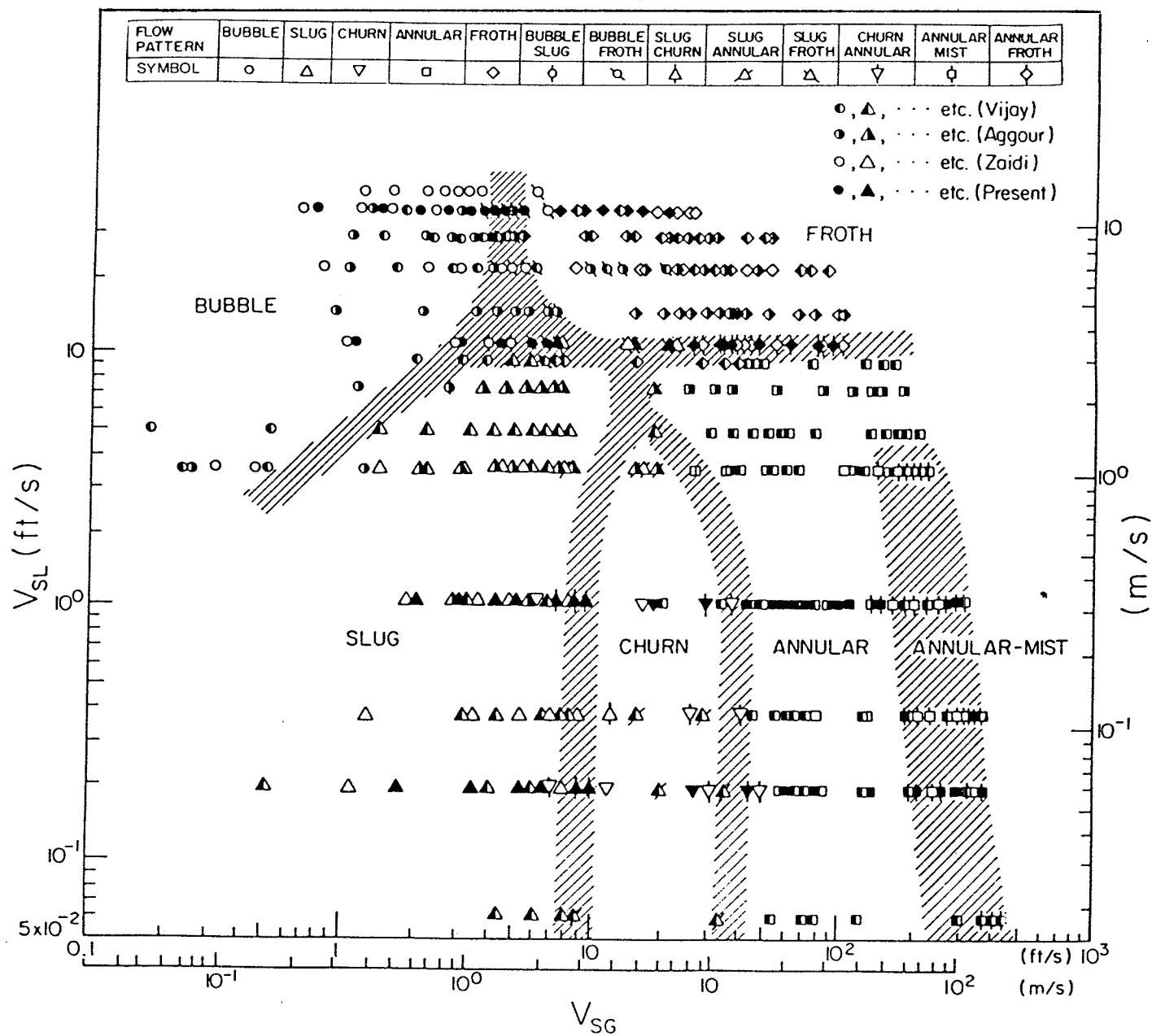


Fig. 6.3 Water-Air Flow-Pattern Data of Vijay, Aggour, Zaidi and Present

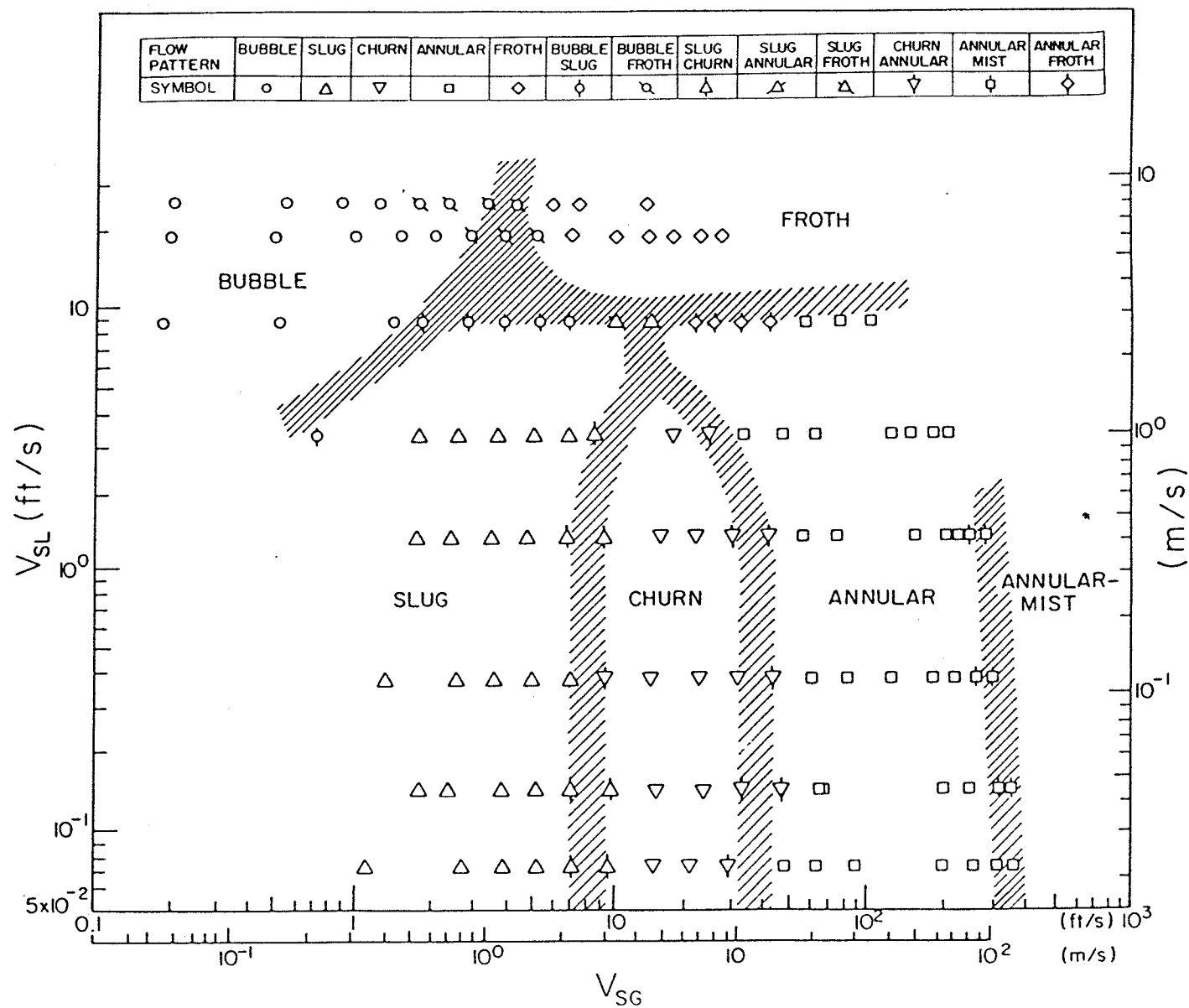


Fig. 6.4 Glycerine & Water (58%-42%)-Air Flow-Pattern Data

dependence of flow pattern transitions on the liquid viscosity.

The silicone-air data, covering a wide range of V_{SL} and V_{SG} for 12 liquid velocities, are shown in Fig. 6.5. With such a large amount of data (192 data points), transition lines between various flow patterns were obtained.

To demonstrate the effect of surface tension on the flow pattern regions and transitions, both sets of transition lines (the glycerine & water-air and silicone-air) are plotted on the same map and are shown in Fig. 6.6. In this figure, the shaded lines represent those areas which have been affected when the surface tension changed. This effect is most profound on the bubble-slug boundary in such a way that part of the region formerly occupied by slug flow has been replaced by bubble flow. The bubble-slug boundary has fallen (in terms of V_{SL}), expanding the bubble-flow region and shrinking the slug-flow region. The slug-churn and the churn-annular boundaries moved slightly toward the left on the map. Annular flow and the annular-mist transition were observed earlier (in terms of V_{SG} at the same V_{SL}) with silicone-air than with other liquids.

Also, the boundary between froth and annular flows is believed to be sloped when the flow pattern, at a constant V_{SL} , changes from bubble to froth (or froth-annular) and then to annular. This sequence [at a liquid flow velocity of

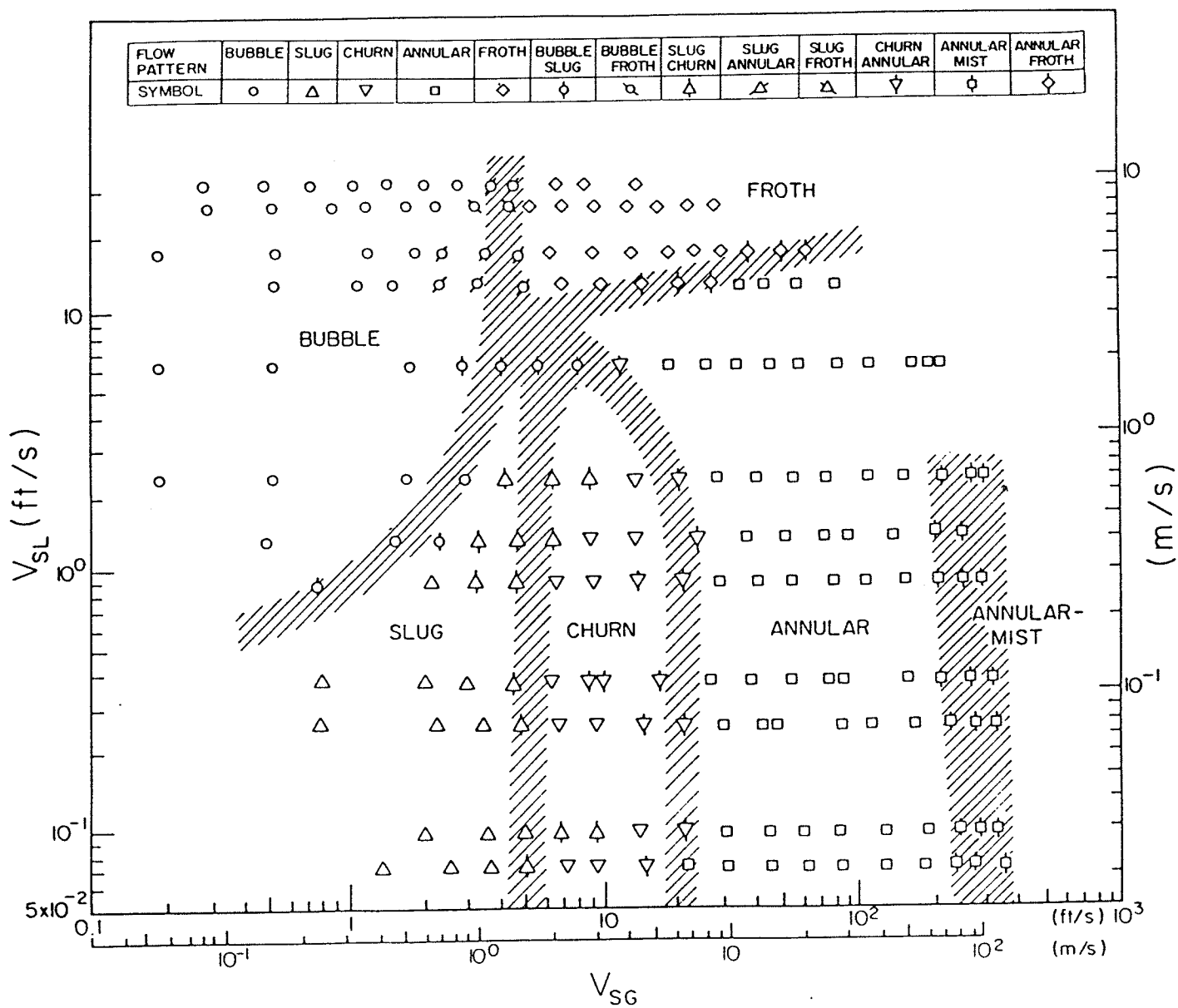


Fig. 6.5 Silicone-Air Flow-Pattern Data

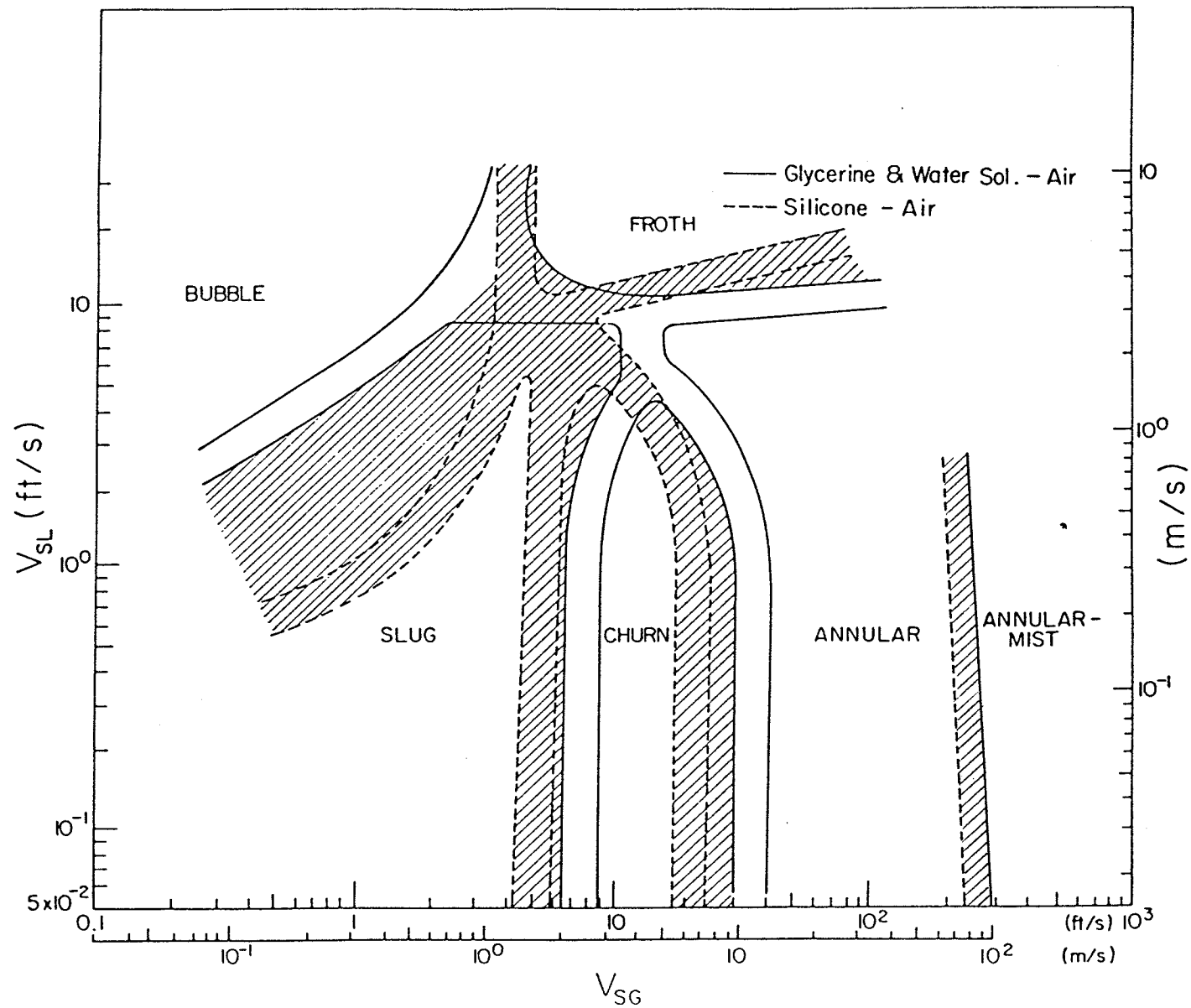


Fig. 6.6 Presentation of the Effect of Surface Tension on the Flow Pattern Boundaries

about 10.0 ft/s (3.05 m/s)] has been observed in the present study with silicone-air and glycerine & water(58%-42%)-air (see Figs. 6.4, 6.5) and also with the water-air data of Vijay(93) (Fig. 6.3) and with the surfactant-air data of Zaidi(107) [Fig.5.6 in Ref.(107)].

At this point, it is worth while to compare the present results with those obtained by Zaidi (107), who used a surfactant solution in his study. This comparison is shown in Fig. 6.7 where the continuous lines are the boundaries obtained for silicone-air. In Ref. (107), the author reported the same large effect on the bubble-slug boundary as mentioned here. The slug-churn and churn-annular boundaries were slightly affected when surfactant solution was used.

From the material presented in this section, it can be concluded that the lower surface tension produced significant change on the bubble-slug transition and less profound changes on the other flow pattern boundaries.

6.5 COMPARISON OF FLOW PATTERN MAPS

In general, most of the existing flow pattern maps in the literature for two-phase upward flow in vertical tubes are empirical. Examples of such maps are those of (13,30,34,40,69). However, analytical expressions to predict flow pattern transition are emerging (63,66,87,102).

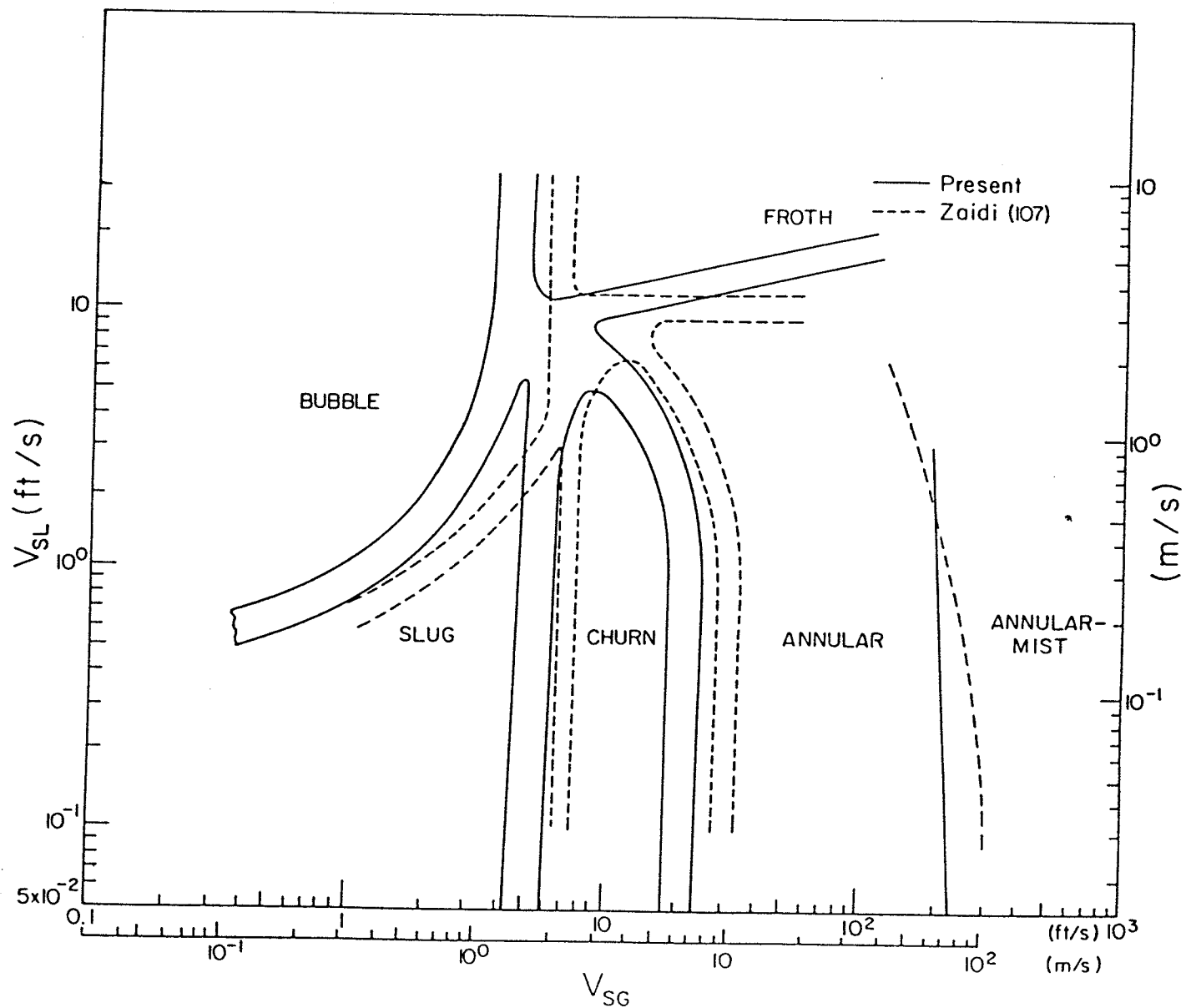


Fig. 6.7 Comparison Between the Flow Pattern Boundaries for Silicone-Air and Those for Surfactant Solution-Air of Zaidi (107)

Completely satisfactory maps of such kind have not yet been developed because of the extreme complexity of the flow mechanism and its changes with flow rate. Examination of the existing maps reveals that for any given liquid-gas system, the major factors in determining the flow pattern are the relative velocities of gas and liquid phases. Other factors include the fluid densities, viscosities and surface tension, and the pipe diameter.

A comparison was done in order to examine how closely the present flow-pattern data agree when plotted on some of the well-established flow-pattern maps in the literature. Due to the fact that the present study is basically focusing on the heat-transfer coefficients in two-phase flow and is not a study of flow patterns as such, comparisons of the present flow pattern data were made with only two of the maps that appear in the literature. The two maps selected for the comparison are believed to be well established and widely used. These are the empirical map of Govier and Aziz (30) and the analytical expressions given by Taitel et al.(87) for obtaining the boundaries for any liquid-gas combination.

The Govier and Aziz map was based upon the water-air data of Govier et al. (31) and the equations obtained by Brown et al. (7) and Duns and Ros (25). The comparison of the present data with this map is given in Fig. 6.8, where the parameters Y^* and X^* are defined by:

$$Y^* = \left\{ \frac{\rho_L \sigma_{WA}}{\rho_W \sigma_{LG}} \right\}^{1/4} \quad (6.1)$$

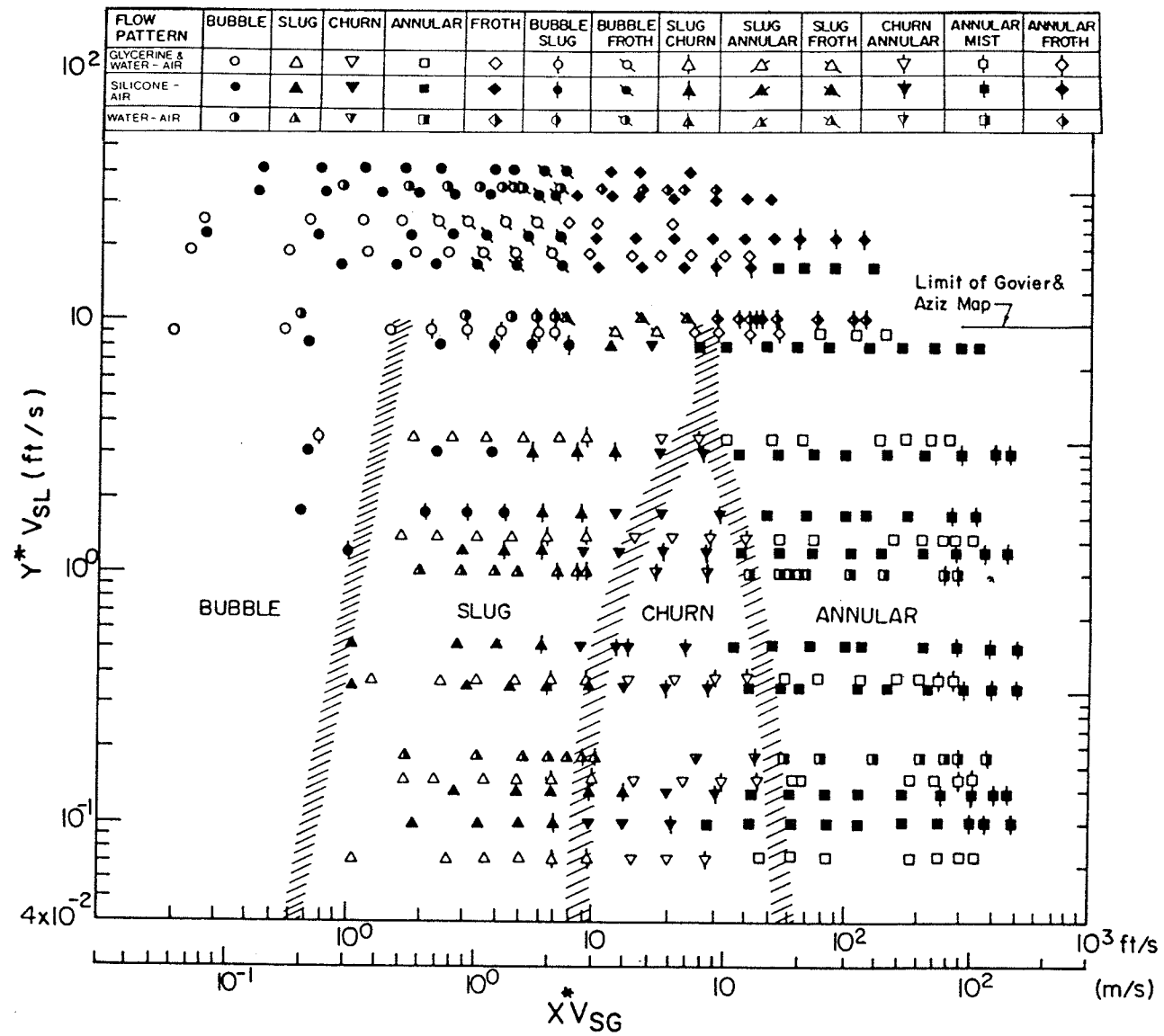


Fig. 6.8 Comparison Between Present Flow Pattern Data and the Flow Pattern Map of Govier and Aziz for Vertical Flow

and

$$X^* = Y^* \left\{ \frac{\rho_G}{\rho_A} \right\}^{1/3} \quad (6.2)$$

where

- σ_{WA} is the surface tension of the water-air system,
- σ_{LG} is the surface tension of the liquid-gas system under flowing conditions,
- ρ_L is the density of liquid under flowing conditions,
- ρ_W is the density of water at standard conditions (14.7 psia and 60°F),
- ρ_G is the density of gas under flowing conditions, and
- ρ_A is the density of air at standard conditions (14.7 psia and 60°F).

This system of co-ordinates suggests that the liquid density and surface tension, and the gas density affect the flow pattern transitions. It should be noted that the "churn flow" region in Fig. 6.8 replaces the term "froth flow" in the original map. Also, they (30) used the term "annular-mist" for the region which is occupied by both annular and annular-mist in the present study. The map is restricted to a modified liquid velocity of $Y^* V_{SL} = 10.0$ ft/s (3.05 m/s); this is equivalent to a V_{SL} of approximately 10.0 ft/s (3.05 m/s) in a water-air system.

Based on the present data, the bubble-slug boundary cannot be tested at lower fluid rates (V_{SL} and V_{SG} less than 1.0 ft/s or 0.305 m/s) since there are no bubble flow data

taken in this region. Except for very few data points for the silicone-air, the agreement between the data and the churn-annular boundary is excellent. Other than that, the agreement between the present data for water-air and glycerine & water-air with the boundaries could be considered satisfactory (especially when the difficulty of observing such boundaries is taken into consideration).

The second comparison is made between the present flow pattern data and the analytical transition boundaries proposed by Taitel et al.(87). These transition boundaries are given in terms of gas and liquid densities, superficial velocities, liquid viscosity, surface tension, tube diameter and entry length. The analytical expressions derived by the authors are given below and are shown in Fig. 6.9.

Bubble-Slug Transition (Line A)

$$V_{SL} + V_{SG} = 4.0 \left\{ \left\{ \frac{D^{0.429} (\sigma g_C)^{0.089}}{\rho_L} \right\} \left\{ \frac{g(\rho_L - \rho_G)}{\rho_L} \right\}^{0.446} \right\} \left\{ \frac{1}{v_L^{0.072}} \right\} \quad (6.3)$$

Dispersed² Bubble-Bubble Transition (Line B)

$$V_{SL} = 3.0 V_{SG} - 1.15 \left\{ \frac{g(\rho_L - \rho_G) \sigma g_C}{\rho_L^2} \right\}^{1/4} \quad (6.4)$$

² Dispersed bubble was defined in (87) as fine bubbles which do not contain any bullet-shaped bubbles (Taylor bubbles).

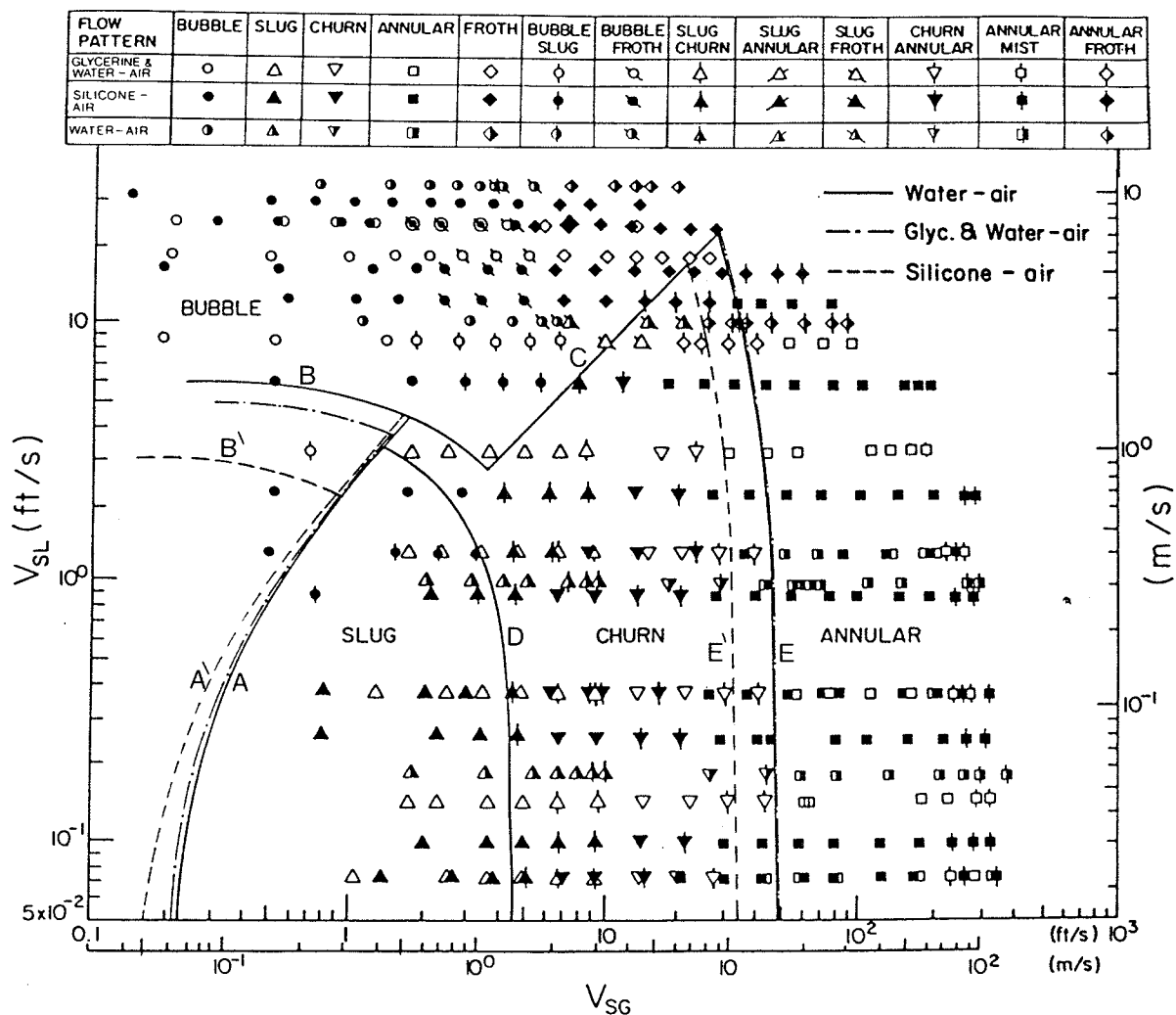


Fig. 6.9 Comparison Between Present Flow Pattern Data and the Map of Taitel et al. for Vertical Flow

Bubble-Churn Transition (Line C)

$$V_{SL} = 0.923 V_{SG} - 0.734 \left\{ \frac{g(\rho_L - \rho_G) \sigma g_c}{\rho_L^2} \right\}^{1/4} \quad (6.5)$$

Slug-Churn Transition (Line D)

$$\ell_E/D = 40.6 \left\{ \frac{V_{SG} + V_{SL}}{\sqrt{gD}} + 0.22 \right\} \quad (6.6)$$

where ℓ_E = entry length, $\ell_E/D = 182.6$ at the beginning of the present visualization section.

Churn-Annular Transition (Line E)

$$\frac{V_{SG} \rho_G^{0.5}}{\left\{ \sigma g (\rho_L - \rho_G) g_c \right\}^{0.25}} = 3.1 \quad (6.7)$$

The transition lines for all three liquids used in the present investigation were computed from the above equations and drawn on a flow pattern map with superficial gas and liquid velocities as the co-ordinates. The present flow pattern observations were plotted also on the same map; this is shown in Fig. 6.9.

According to Taitel et al. (87), bubble flow cannot exist below the curve (B) in systems having small-diameter tubes, the criterion for "small diameter" being that

$$\left\{ \frac{\rho_L^2 g D^2}{g_c (\rho_L - \rho_G) \sigma} \right\}^{0.25} \leq 4.36 \quad (6.8)$$

According to the above equation, the present experimental facility falls in the category of "small-diameter tube." However, some bubble-flow data were observed below curve (B) in the present study, as shown in Fig. 6.9. It is fair to say that more data in that region (low V_{SL} and V_{SG}) are needed to confirm the existence or non-existence of bubble flow below curve B.

The theory shows also that the churn-annular boundary (or the line to the right of which annular flow exists) has not changed with changing the liquid viscosity and that it does move to the left (lower V_{SG}) when surface tension is lowered. In this case, besides the same direction, the magnitude of the change occurring with the experimental data is close to that predicted by the theory. As clearly shown in Fig. 6.9, the majority of the present annular flow observations lie to the right of line (E) (or E') for all liquids. At higher liquid velocities, their bubble region also contained the present froth flow.

From the comparisons made in this section, the following conclusions can be drawn:

1. The data obtained in the present investigation for the water-air system were found to be consistent with those observed in the earlier work of (93,107). Together, the total set of data provided a clear picture of flow pattern behaviour in vertical tubes.

2. The agreement between the present experimental data and the flow pattern map of Govier and Aziz (30) in its range of applicability was found to be satisfactory. There was a qualitative agreement with some of the theoretical lines of Taitel et al. (87) when the surface tension was changed.

6.6 FRICTIONAL-PRESSURE-DROP RESULTS AND DISCUSSION

The method of calculating the frictional pressure drop in two-phase flow from the measured total pressure drop is discussed in Appendix D. The data for the three liquid-gas combinations used in the study are given in Figs. 6.10 to 6.13. The letter code appearing beside each data point refers to the flow pattern observed for the point and can be identified using Table 6.1. Due to the influence of flow patterns on the pressure drop, such representation of the data will be quite useful.

The four pressure transmitters (three of which were used to measure the total pressure drop across the test section) were calibrated using water or mercury manometers at room temperature. Calibration curves are given in Appendix B, from which it can be seen that the tested points fell on the manufacturer's curves. The distance between the pressure taps was 24.5 in. (62.4 cm).

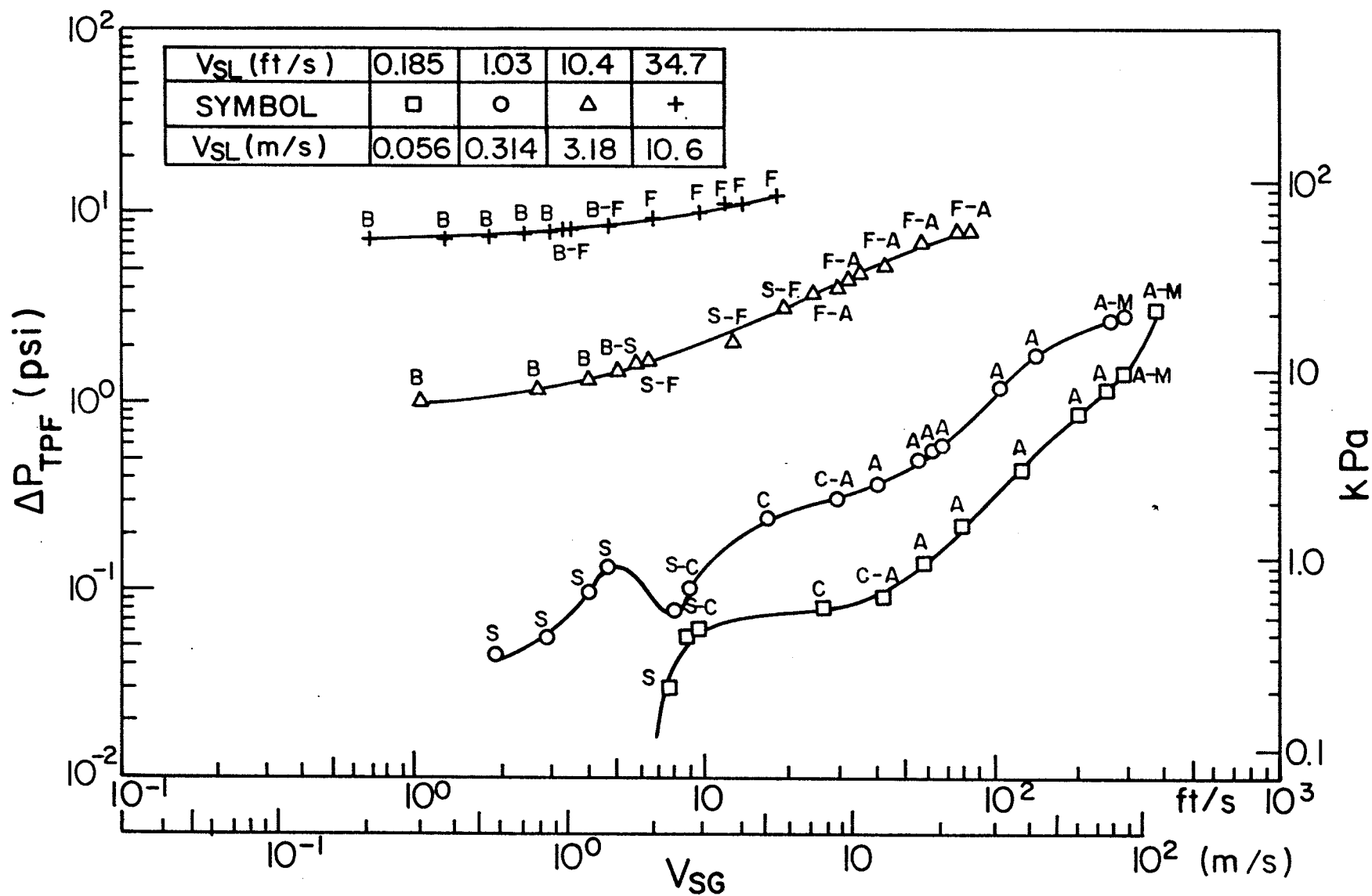


Fig. 6.10 Two-Phase Frictional Pressure-Drop Results for Water-Air

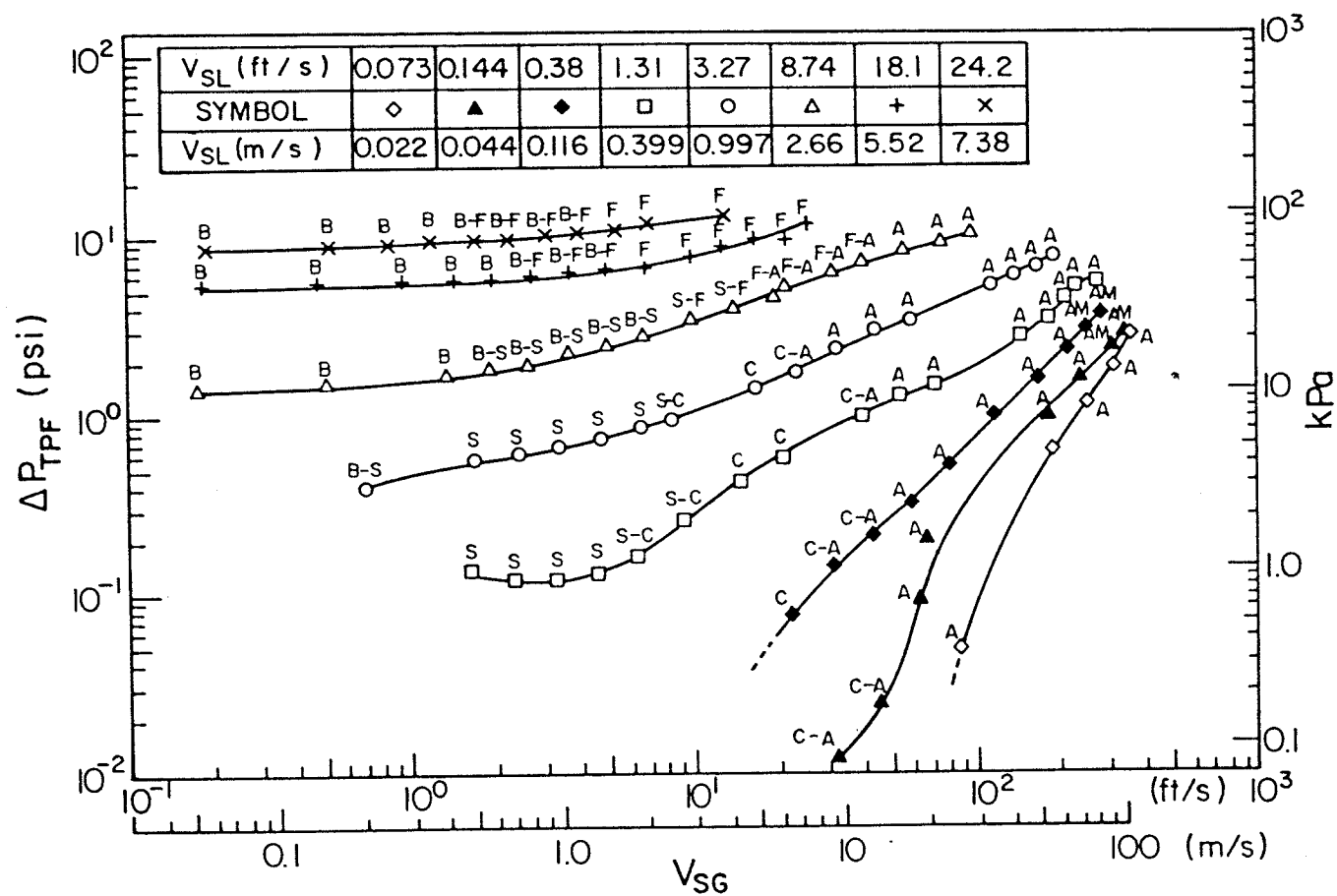


Fig. 6.11 Two-Phase Frictional Pressure-Drop Results for Glycerine & Water Air

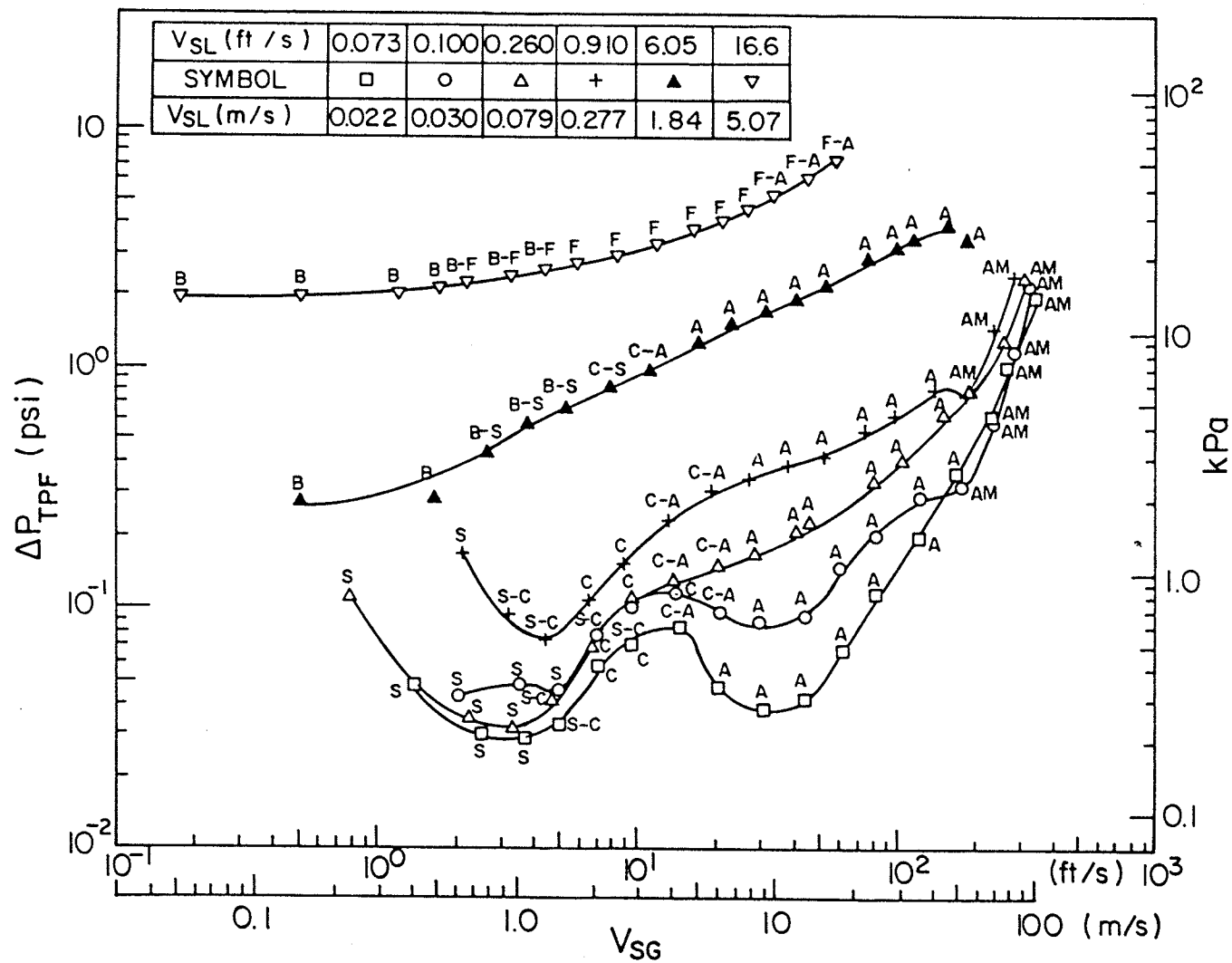


Fig. 6.12 Two-Phase Frictional Pressure-Drop Results for Silicone-Air

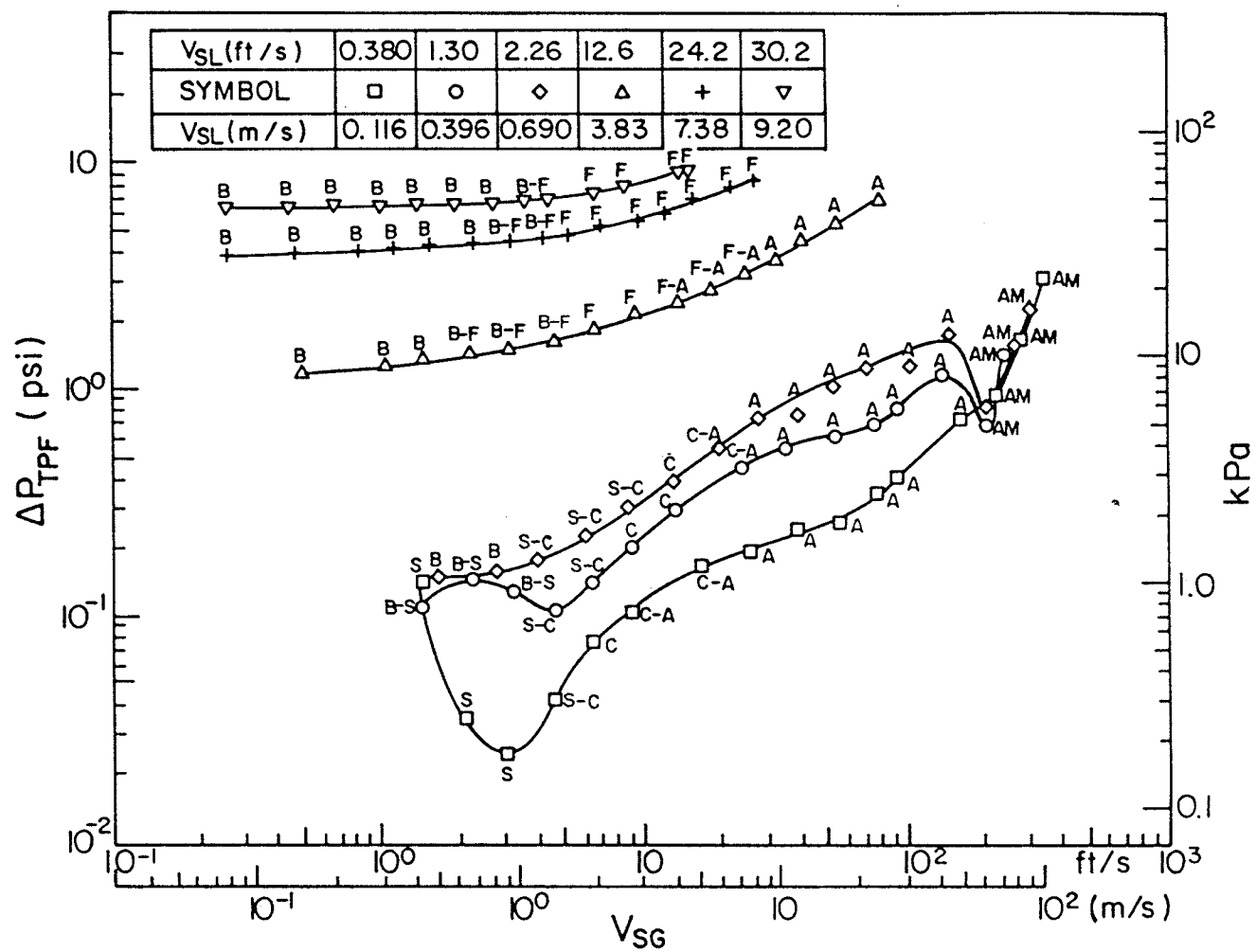


Fig. 6.13 Two-Phase Frictional Pressure-Drop Results for Silicone-Air (cont'd)

The total pressure drop was read on a DVM in terms of volts. At very low liquid and gas flow rates (typically in the bubble-slug and slug regions), the calculated frictional pressure drop gave negative or very small values (less than 0.01 psi). For such cases, the data points were excluded from the graphs and also when used with correlations that include in them the measured frictional pressure drop as a dependent variable. (The criteria for exclusion of pressure-drop data from comparisons are discussed in detail in Sec. 7.3.). The data points, which were excluded from Figs. 6.10 and 6.11, were as follows:

For water-air: 4 points at $V_{SL} = 0.185 \text{ ft/s}$ (0.017 m/s),
 $V_{SG} < 7.0 \text{ ft/s}$ (2.13 m/s)
 2 points at $V_{SL} = 1.03 \text{ ft/s}$ (1.03 m/s),
 $V_{SG} < 3.0 \text{ ft/s}$ (0.914 m/s)

For glycerine & water-air:

11 points at $V_{SL} = 0.073 \text{ ft/s}$ (0.022 m/s),
 $V_{SG} < 62.0 \text{ ft/s}$ (18.9 m/s)
 8 points at $V_{SL} = 0.144 \text{ ft/s}$ (0.044 m/s),
 $V_{SG} < 23.0 \text{ ft/s}$ (7.01 m/s)
 7 points at $V_{SL} = 0.379 \text{ ft/s}$ (0.116 m/s)
 $V_{SG} < 14.0 \text{ ft/s}$ (4.27 m/s).

For silicone-water: none

The water-air data showed excellent repeatability when compared with the previous data taken on the same rig. The local minima and maxima in the slug, churn, and churn-annular regions (shown in Figs. 6.12 and 6.13) have been observed only with the silicone-air system at superficial liquid velocities of 0.073, 0.100, 0.260, and 0.380 ft/s (0.022, 0.030, 0.079, and 0.116 m/s). For these liquid velocities, a minimum in the frictional pressure drop was reached at approximately $V_{SG} = 3.0$ ft/s (0.914 m/s) in the slug flow region. This was followed by an increase to a maximum at about 15.0 ft/s (4.57 m/s) (occurred with the lowest two velocities). Further increase in the gas flow rate resulted in a monotonic increase in ΔP_{TPF} . At yet higher liquid velocities (0.910, 1.30, and 2.26 ft/s or 0.277, 0.396, and 0.689 m/s), the increase of ΔP_{TPF} in the annular region was not continuous. At a superficial gas velocity of about 200 ft/s (61 m/s), a sudden drop in the frictional pressure drop occurred (less dramatic for $V_{SL} = 0.910$ ft/s or 0.278 m/s) which was followed again by a monotonic increase. It is believed that this behaviour of ΔP_{TPF} took place once the annular-mist transition was reached.

Similar behaviour of the frictional pressure drop was reported by Owen et al. (68) In Fig. 6.14 [taken from

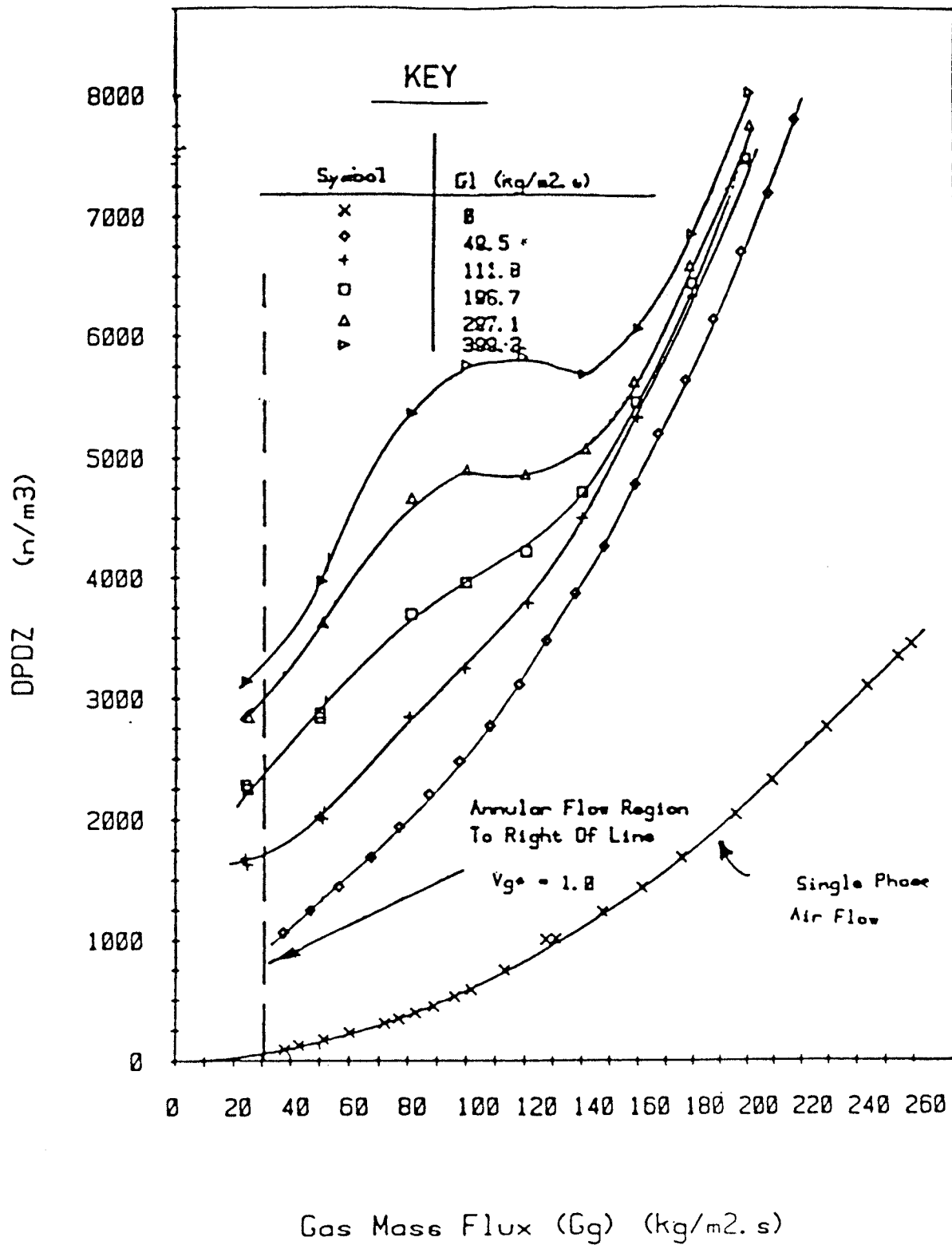


Fig. 6.14 Experimental Water-Air Pressure Drop
Results of Owen et al., Taken from Ref. (68)

Ref.(68)], this behaviour of ΔP_{TPF} can be seen with the highest water mass velocities (297.1, 399.2 kg/m²s). These mass velocities are approximately the same as those calculated for the silicone-air data at $V_{\text{SL}} = 0.260$ and 0.380 ft/s (0.080 and 0.116 m/s). This decline of the pressure drop followed by a steep rise was well explained by the same authors (68). They suggested that what takes place at the annular flow region is a result of two competing processes. The first is a tendency to increase the interfacial shear stress as the gas flow rate increases, analogous to the behaviour in single-phase flow. The second process is the rapid decrease of the amount of liquid in the film (and hence the film thickness) resulting in a reduction in wave activity on the interface and a consequent reduction in the interfacial friction factor. The authors suggested that the decrease in ΔP_{TPF} occurs when the second of these processes becomes dominant. Ultimately, when nearly all the film has been entrained away, the first process again prevails and the pressure drop increases as the gas flow rate increases. This explanation of the pressure-drop behaviour at the annular flow region was found applicable in the present study for the silicone-air results. However, this behaviour was not observed with the present water-air data and also was not reported in the earlier work of (93,1,107). It should be mentioned that with the silicone-air data, the steep rise in ΔP_{TPF} occurred at the annular-mist transition in the present investigation.

6.7 COMPARISON OF THE DATA

Figures 6.15 and 6.16 show the two sets of data plotted on dimensionless co-ordinates with the liquid superficial Reynolds number as a parameter. The abscissa is the ratio of the two-phase to the single-phase frictional pressure drop. The single-phase frictional pressure drop was taken as the best estimate of ΔP_L . In laminar flow, this was the predicted values using the single-phase equations given in Sec. 5.2, while the actual measured values were the best estimate for the data points in turbulent flow.

From the above-mentioned figures, the following observations can be made:

1. For the data at the lowest three Reynolds numbers (Fig. 6.15), the silicone-air data lie considerably above those for glycerine & water-air up to $V_{SG}/V_{SL} \sim 400$ (5 for $Re_{SL} = 611$), after which the data cross. Careful examination of the data in those regions of V_{SL} and V_{SG} showed that the head term [which was calculated using the void fraction as predicted by Chisholm(14)] was much higher than the frictional-pressure-drop term. Since the frictional pressure drop is obtained in the present investigation by subtracting the head term from the measured total pressure drop, an error can be introduced due to void fraction (since a calculated value obtained from the

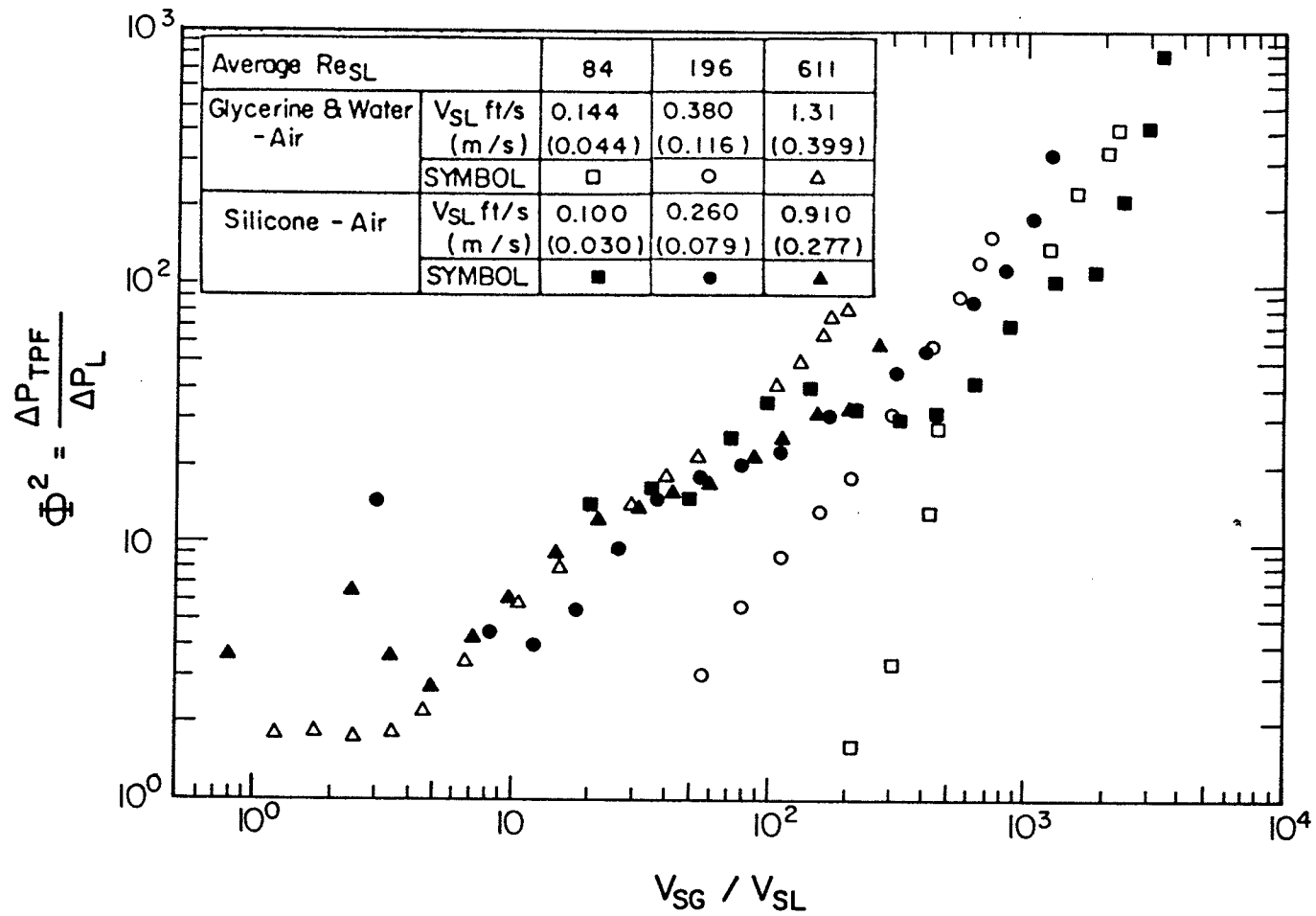


Fig. 6.15 Comparison Between Present Glycerine & Water-Air and Silicone-Air Pressure Drop Data

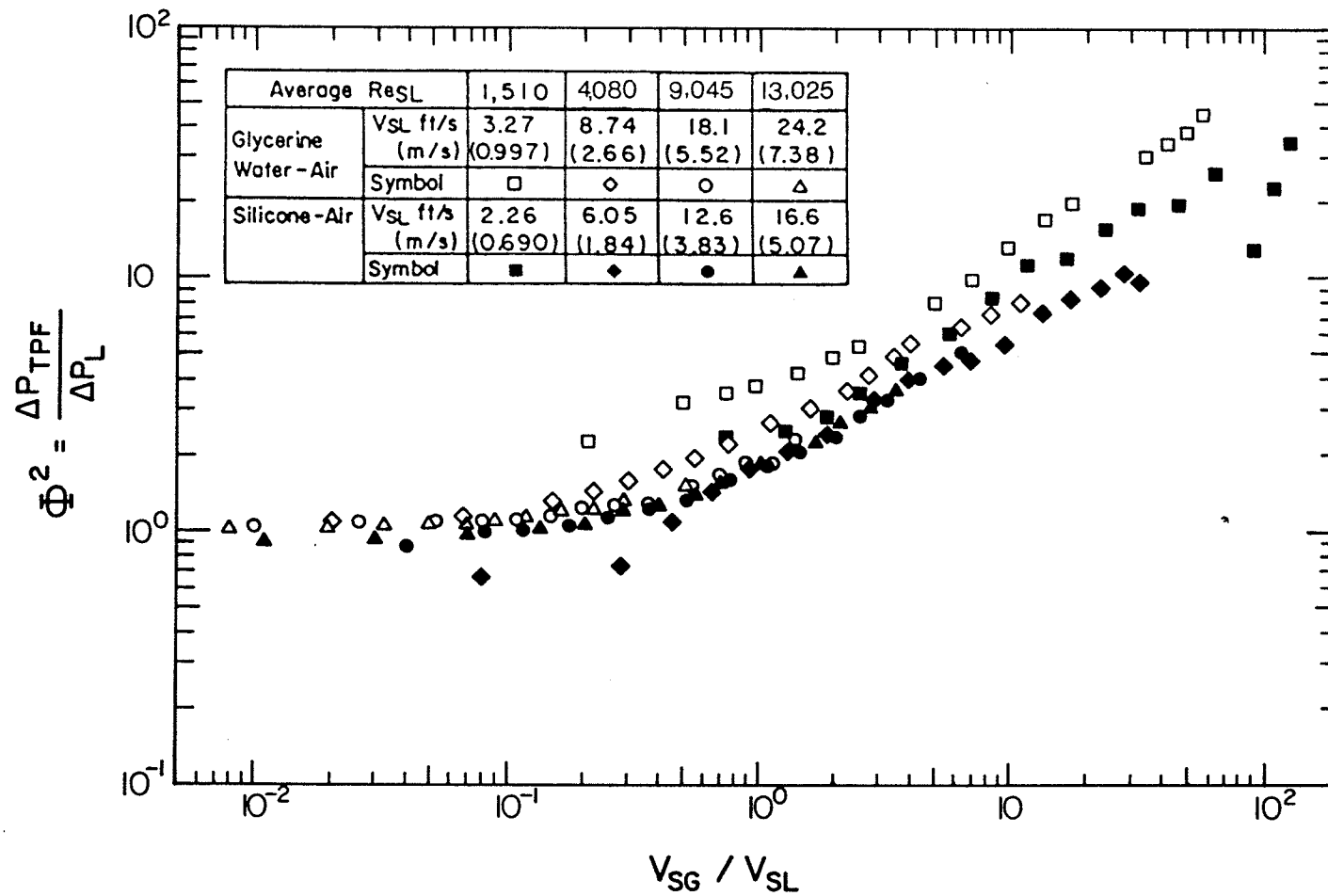


Fig. 6.16 Comparison Between Present Glycerine & Water-Air and Silicone-Air Pressure Drop Data (Cont'd)

same equation is used for both liquid-air systems as opposed to a measured value). Therefore, it would be risky to attribute these changes to the surface tension.

2. For the data with $Re_{SL} > 1500$ (Fig. 6.16), where the head term is very small compared with the measured total pressure drop (generally in the range of 2-14%), the silicone-air data appear to lie slightly below those for glycerine & water-air with differences that decrease as Re_{SL} increases. In general, these differences were small.

A search in the literature was done in order to find similar data where surface tension difference exists. The data of Whalley et al.(104) for water-air and "Genklene" (1-1-1 trichloroethane)-air, with the surface tension of Genklene ~ 0.39 that of water, was found to be pertinent to the comparisons made in this study. The Genklene has approximately the same viscosity as that for water, while its density is $\sim 30\%$ higher at the same temperature.

Figure 6.17 shows a plot of these data ($\frac{dP}{dz}$ is the gradient of the total pressure drop) for an air density of $3.0-3.5 \text{ kg/m}^3$. The range of the liquid mass flow rates G_L shown on the graph was a result of grouping the data points taken at approximately the same G_L , as their data were taken fixing G_G and varying G_L . It can be seen from this comparison that the data of Genklene-air fall below those of

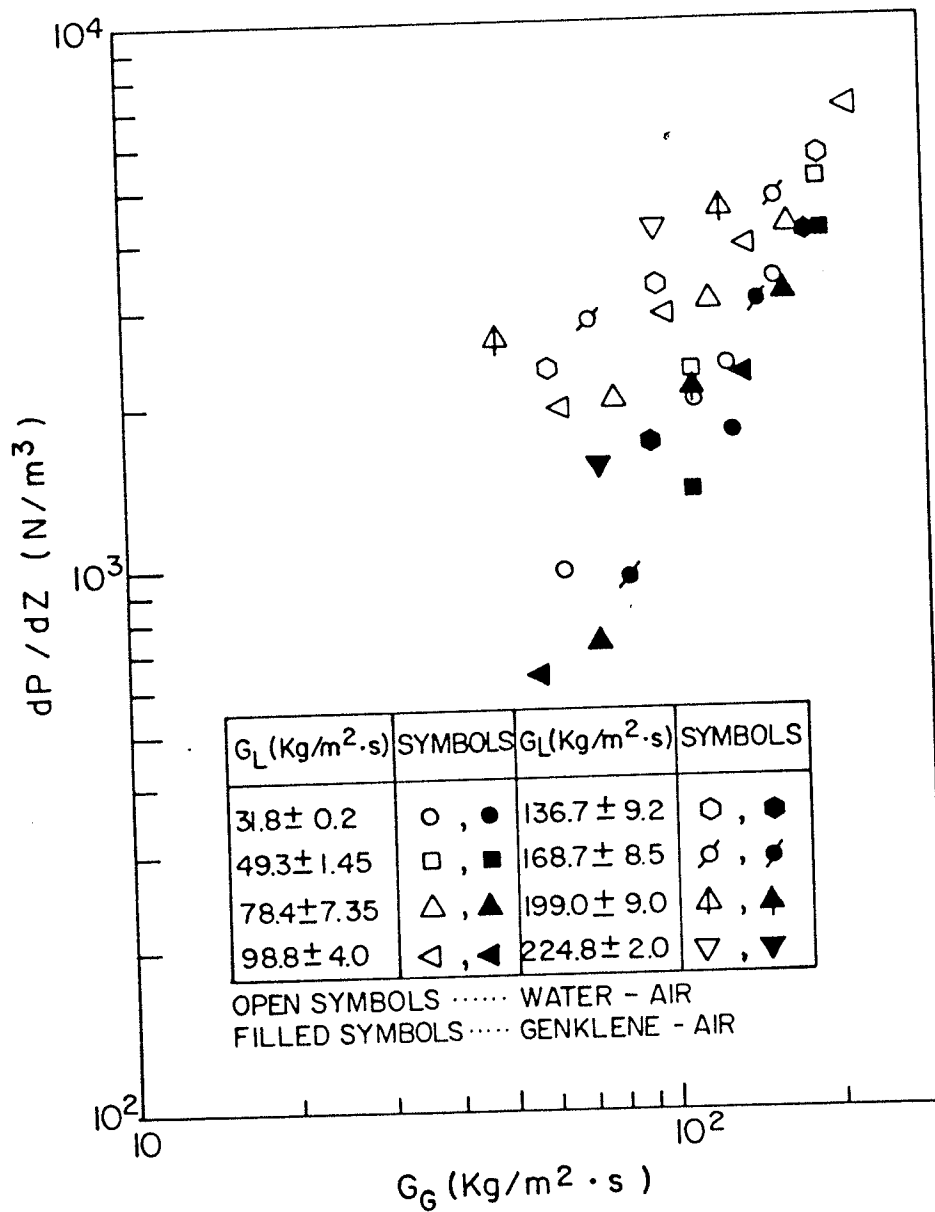


Fig. 6.17 Data of Whalley et al. (104) for Water-Air and Genklene-Air

water-air for most of the liquid flow rates. In this case, where the match of the two liquid viscosities and densities is very close, one can directly attribute the observed differences to the lower surface tension.

Similar results were also obtained with the surfactant solution-air and water-air data of Zaidi (107), who reported that there was generally a tendency in the surfactant data to be lower than those of water-air especially where a change in the flow pattern was observed.

Other comparisons were made between the present data, for all three liquids, and some of the correlations that predict the pressure drop in two-phase flow. The two correlations used in the comparisons are those by Lockhart and Martinelli(59) and Friedel(36).

The first correlation, by Lockhart and Martinelli(59), was chosen because it is widely used. Results of the comparison with this correlation are shown in Fig. 6.18. The Lockhart and Martinelli parameter X used is the appropriate parameter for the liquid and gas Reynolds numbers (X_{ll} for laminar-laminar, X_{lt} for laminar-turbulent, etc). On this figure, the data of Whalley et al.(103) were also plotted for both liquids used in their study. The total pressure gradients were reduced to frictional using the Chisholm's(14) void fraction correlation, as for the present data. Agreement was such that 66% (for glycerine &

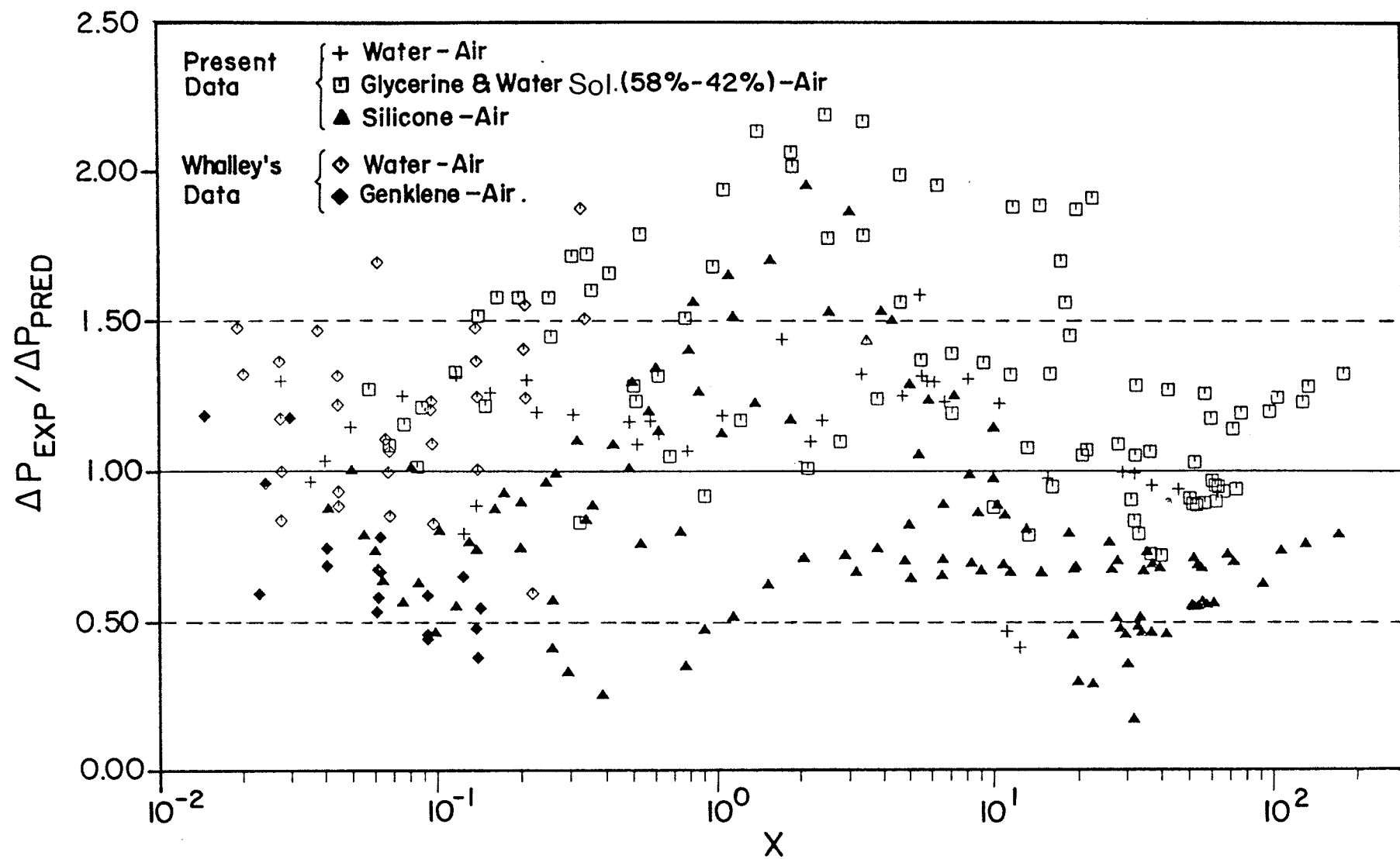


Fig. 6.18 Comparison of Experimental Data with the Correlation of Lockhart & Martinelli

water-air) to 92% (for water-air) of the present data points fell within $\pm 50\%$ of the correlation line.

From this comparison, it can be clearly seen that the large majority of the data with low surface tension (silicone-air and Genklene-air) fall below those for water-air and glycerine & water-air. In the absence of large differences in the other liquid properties with the Genklene, these results suggest that the correlation did not adequately accommodate the change in surface tension.

The second correlation used in the comparisons here was that of Friedel(59). This correlation was derived empirically using numerous data points. The comparison, shown on Fig. 6.19, still showed similar results to those obtained with the first correlation with regard to the effect of surface tension on the pressure drop. For this case, 68% (with glycerine & water air) to 82% (with water-air) of the data points were correlated within $\pm 50\%$.

Another study on the effect of surface tension on the frictional pressure drop for two-phase, gas-liquid mixtures flowing in vertical tubes was done by Ueda(89). This study was performed using an aqueous-surfactant solution. The lowest value obtained for surface tension was 33.94 dyne/cm. Ueda (89) concluded that surface tension has very little effect on frictional pressure drop. Examination of his data plotted on a small scale in the paper (89) indicated that,

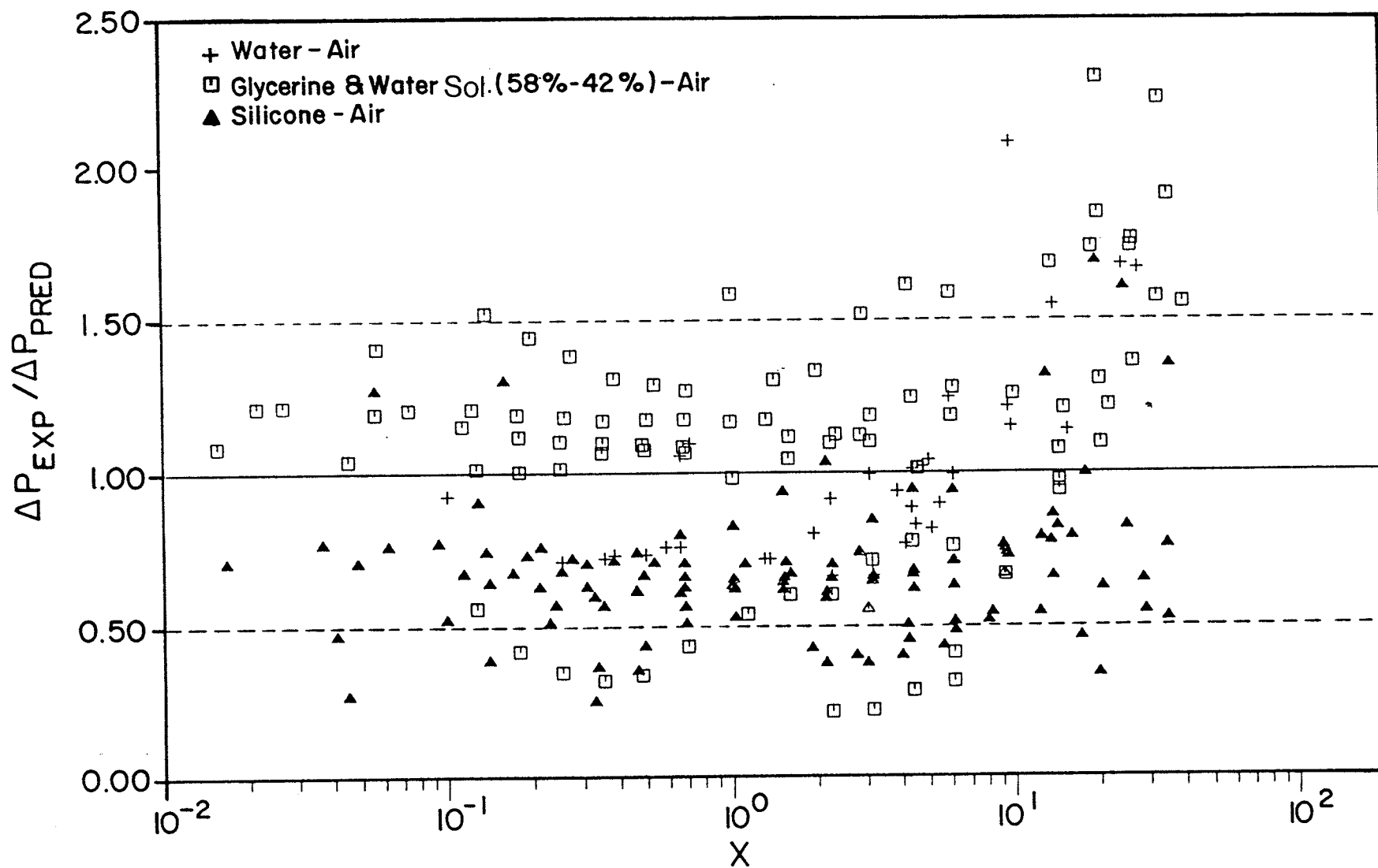


Fig. 6.19 Comparison of Experimental Data with the Correlation of Friedel

if anything, there is a tendency in the surfactant solution data to be slightly lower than those of the water-air data.

As a result of the comparisons made in this section, it can be concluded that when a silicone liquid (with a lower surface tension than that of glycerine & water solution) was used, surface tension produced small effects on the ratio Φ^2 such that it was lower for the silicone-air than for glycerine & water-air at the same Re_{SL} . These differences, produced by a pure liquid, were generally close to or slightly higher than those reported for surfactant-air systems (107,89).

Chapter 7

PRESENTATION AND DISCUSSION OF THE TWO-PHASE HEAT-TRANSFER RESULTS

3.1 GENERAL REMARKS

In this chapter, results for two-phase heat transfer are presented and discussed. The presentations will be discussed in the following order:

1. Presentation and discussion of local heat-transfer coefficients.
2. Comparison of the local heat-transfer coefficients with the modified theory of Spalding, as proposed by Vijay (93).
3. Presentation and discussion of length-mean heat-transfer coefficients.
4. Comparison of the mean-heat-transfer data with some of the correlations presented in Chapter 2.
5. Comparison between the glycerine & water-air and silicone-air heat-transfer results, followed by a discussion on the possible effect of surface tension on the heat-transfer coefficients.

The theoretical and empirical correlating expressions appearing in this chapter were presented and described in

Chapter 2. An error analysis of the results together with a discussion on their repeatability appears in Appendix E.

7.2 LOCAL HEAT-TRANSFER COEFFICIENTS

The procedure for calculating the local heat-transfer coefficient is similar to that for h_{SP} , and is discussed in detail in Appendix D. The data are presented in Figs. 7.1 (A to D), 7.2 (A to H), and 7.3 (A to L) for water-air, glycerine & water-air, and silicone-air respectively. In each figure, h_{TP} is plotted against the distance along the heated tube (Z) for a given liquid superficial velocity with the gas superficial velocity as a parameter. In order to avoid crowded figures and show clearly the effect of the addition of the gas phase on h_{TP} , not all data of the tests performed for a given liquid rate are shown in these figures. All the experimental results are, however, tabulated in Appendix F.

Examination of these figures would yield the following observations:

1. At very low liquid flow rates and low gas flow rates, h_{TP} increases along the test section with a slope that decreases with increasing the gas flow rate.
2. At medium liquid flow rates (typically $1 < V_{SL} < 10$ ft/s or $0.305 < V_{SL} < 3.05$ m/s) and low-to-medium gas flow rates (typically $1 < V_{SG} < 100$ ft/s or

$V_{SL} = 0.185 \text{ ft/s}$ (0.056 m/s) Water - Air

150

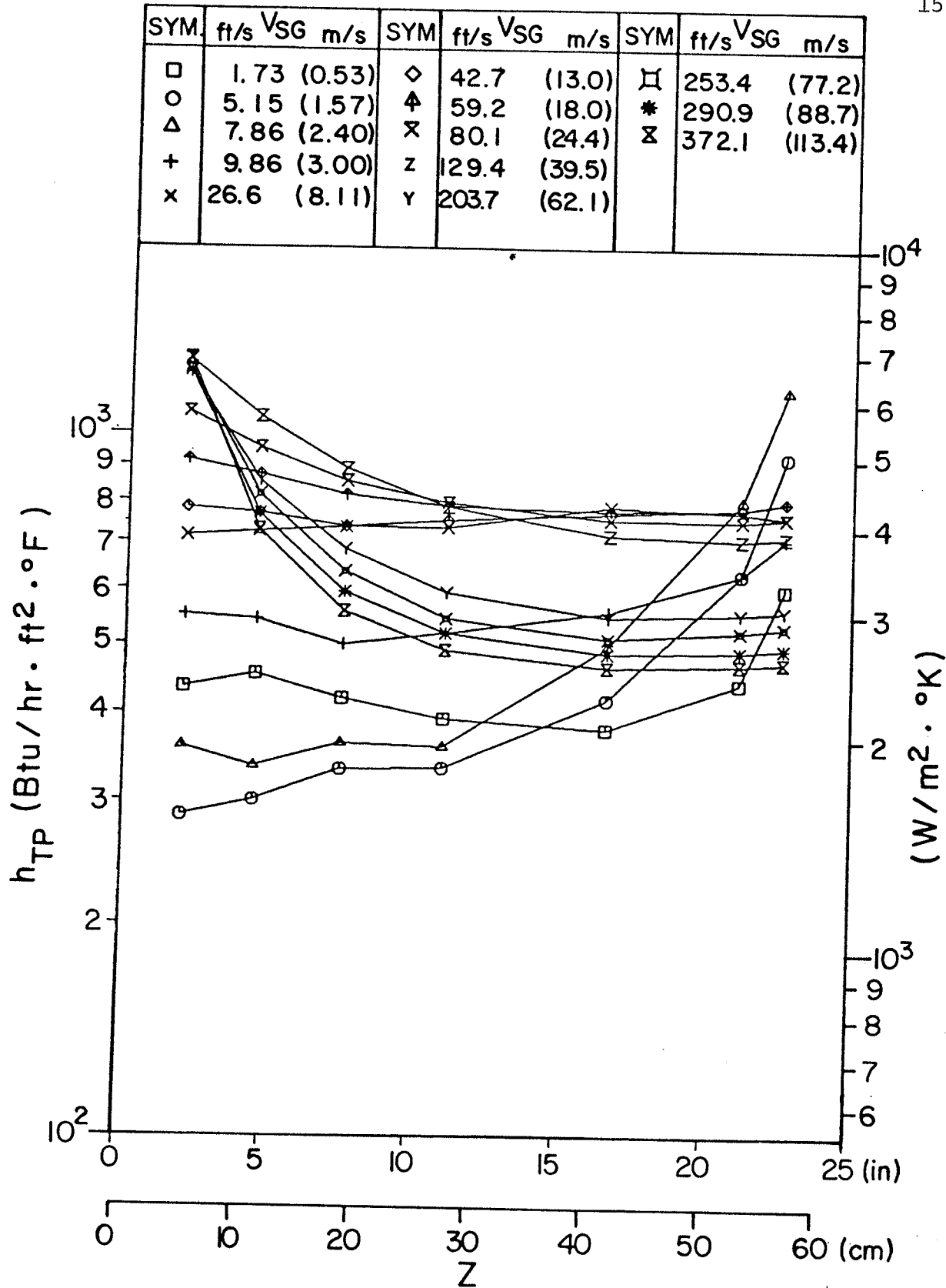


Fig. 7.1(A) Two-Phase Water-Air Local Heat-Transfer Results

$$V_{SL} = 1.03 \text{ ft/s } (0.314 \text{ m/s})$$

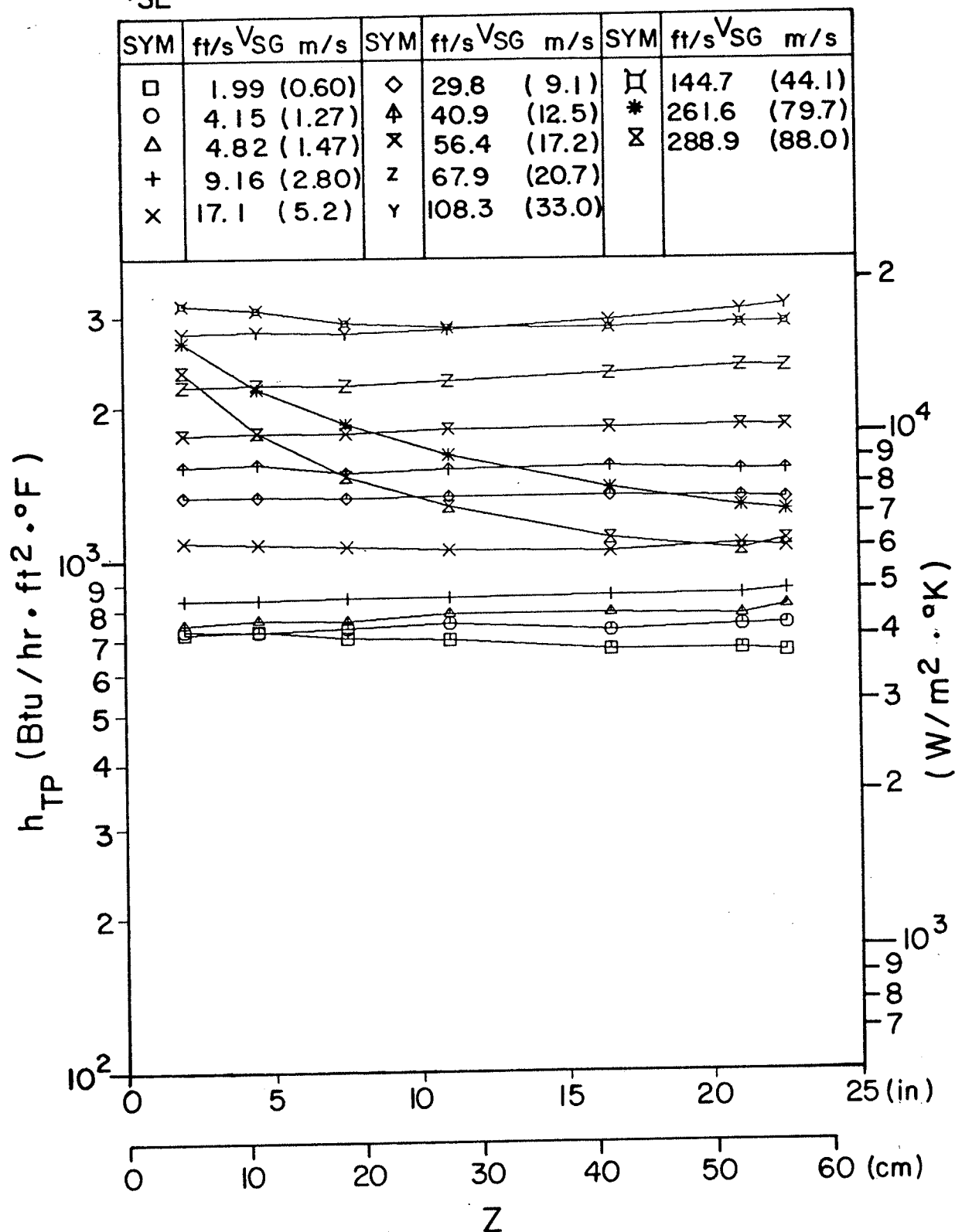


Fig. 7.1(B) Two-Phase Water-Air Local Heat-Transfer Results

$$V_{SL} = 10.4 \text{ ft/s } (3.18 \text{ m/s})$$

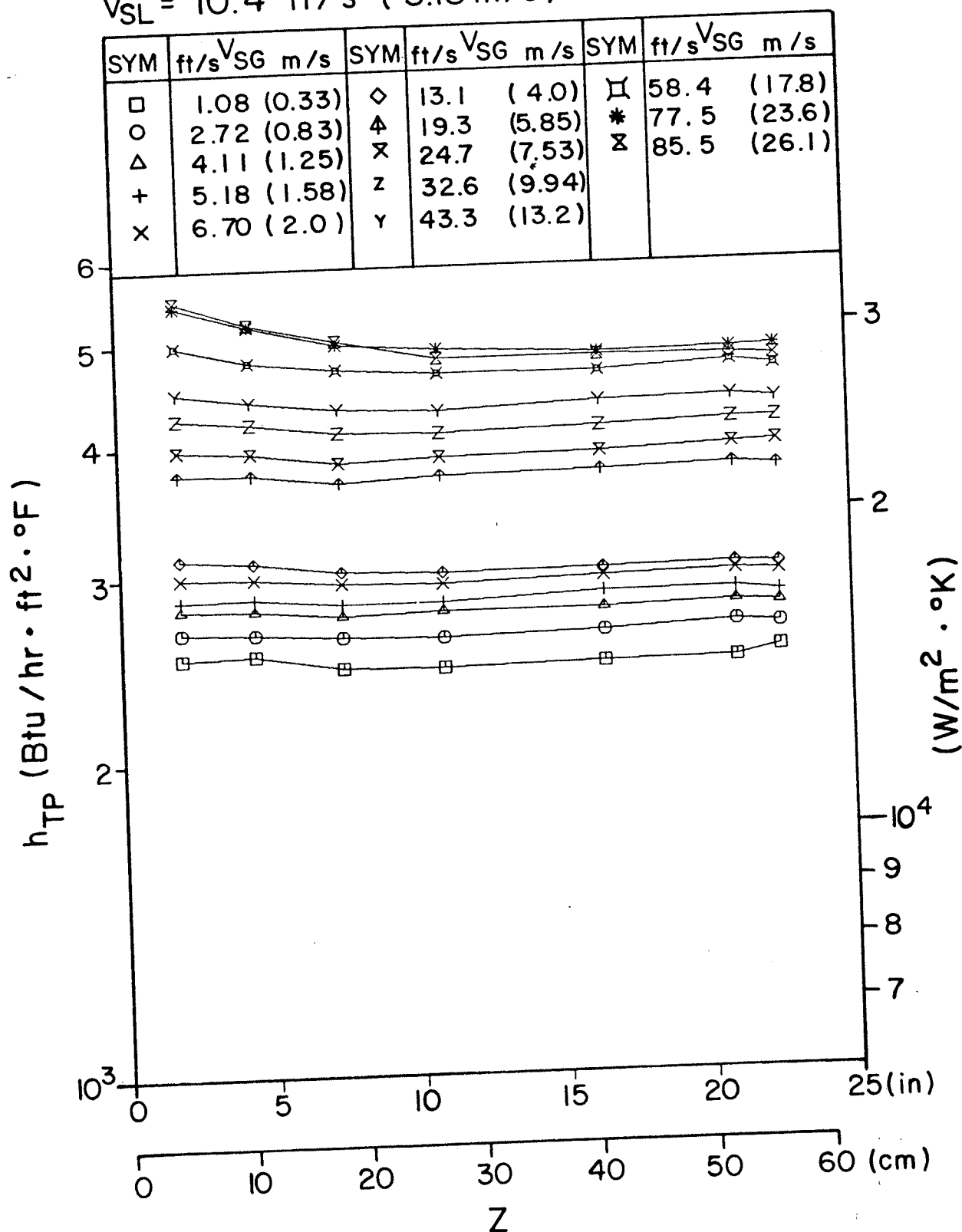


Fig. 7.1(C) Two-Phase Water-Air Local Heat-Transfer Results

$$V_{SL} = 34.7 \text{ ft/s } (10.6 \text{ m/s})$$

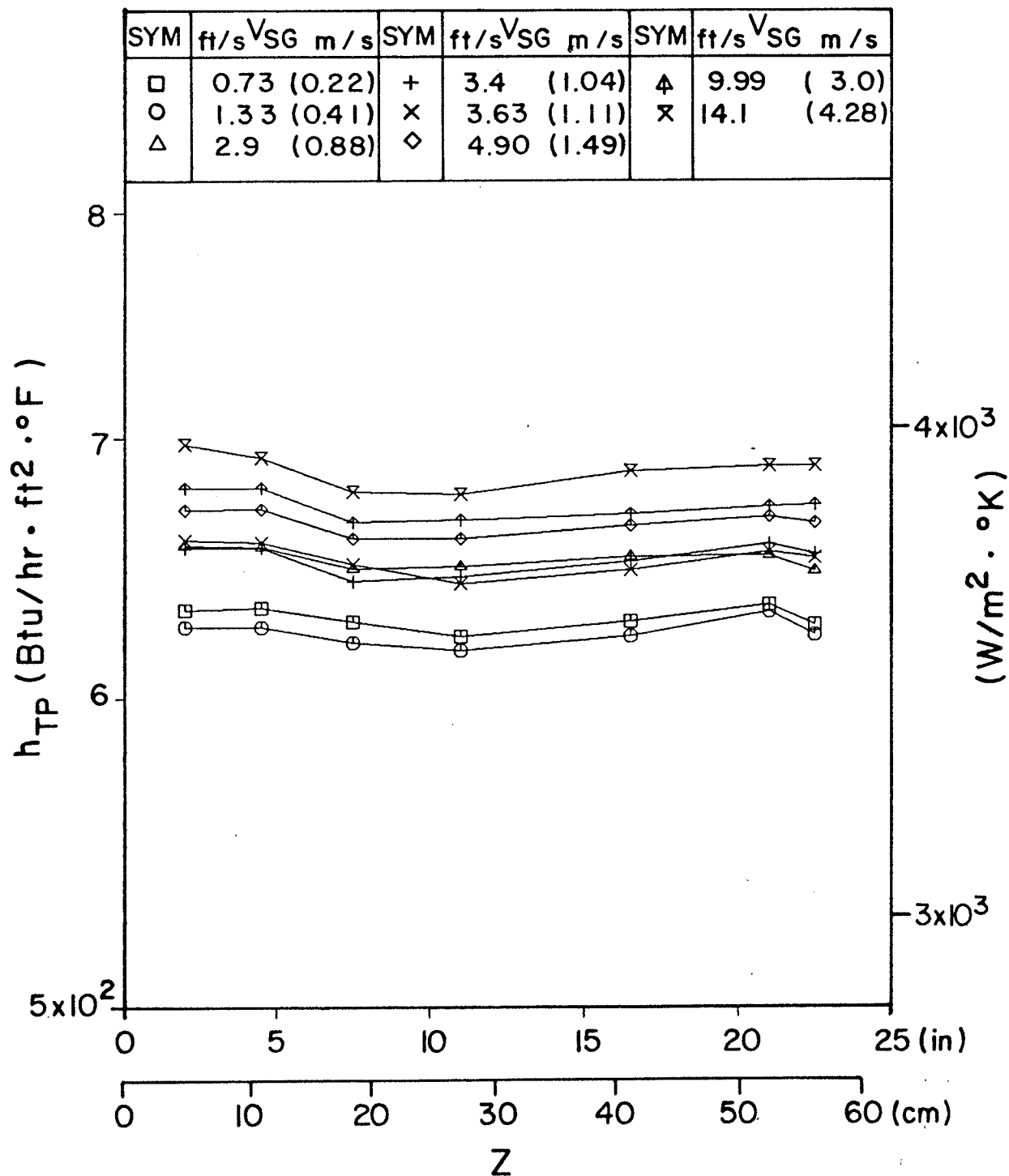


Fig. 7.1(D) Two-Phase Water-Air Local Heat-Transfer Results

$V_{SL} = 0.073 \text{ ft/s (0.022 m/s)}$ Glycerine + Water - Air

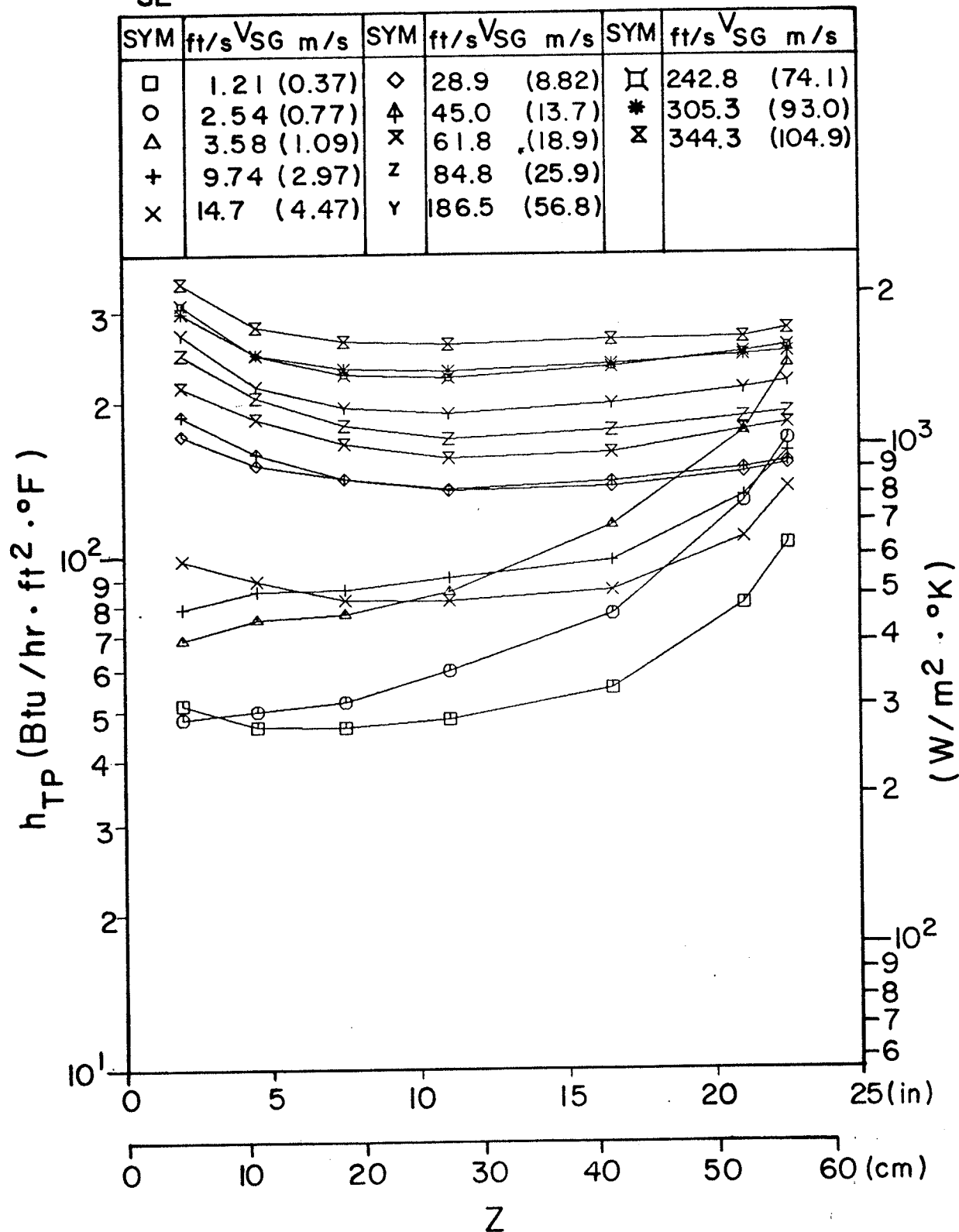


Fig. 7.2(A) Two-Phase Glycerine & Water-Air Local Heat-Transfer Results

$$V_{SL} = 0.144 \text{ ft/s (0.044 m/s)}$$

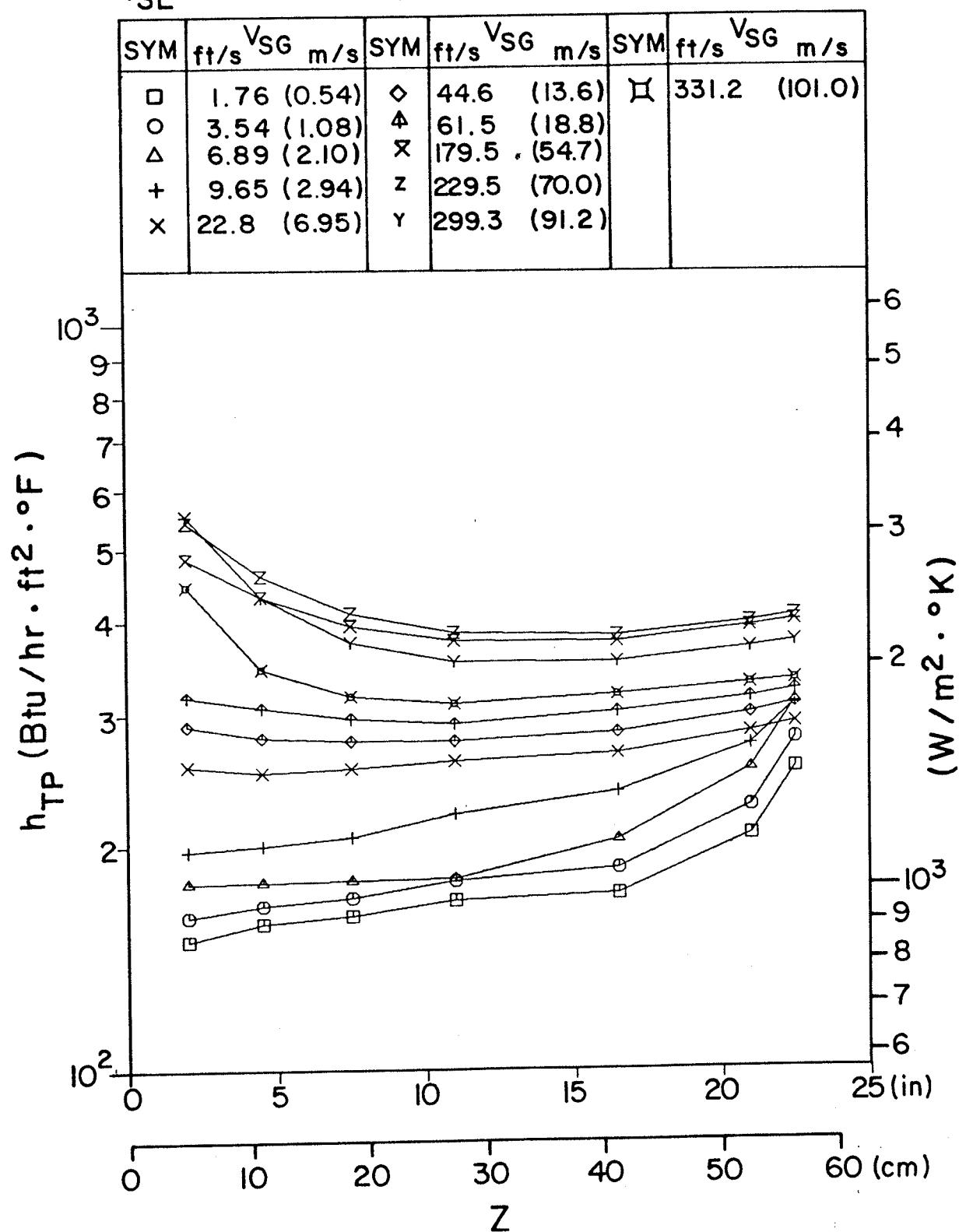


Fig. 7.2(B) Two-Phase Glycerine & Water-Air Local Heat-Transfer Results

$$V_{SL} = 0.38 \text{ ft/s (0.116 m/s)}$$

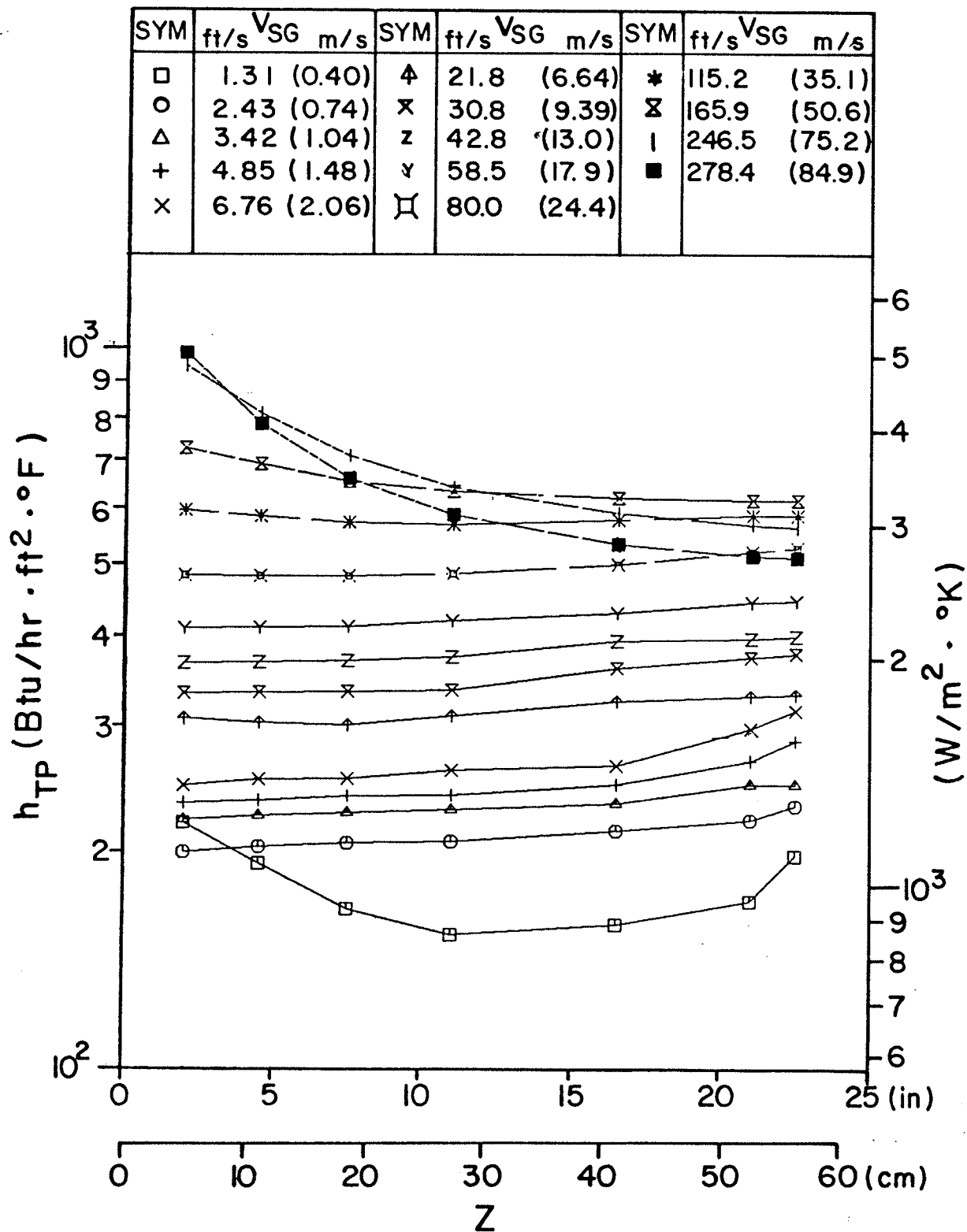


Fig. 7.2(C) Two-Phase Glycerine & Water-Air Local Heat-Transfer Results

$$V_{SL} = 1.31 \text{ ft/s (0.399 m/s)}$$

SYM	ft/s V_{SG} m/s	SYM	ft/s V_{SG} m/s	SYM	ft/s V_{SG} m/s
□	1.63 (0.50)	◇	9.06 (2.76)	⊠	144.7 (44.1)
○	2.31 (0.70)	♠	20.5 (6.25)	*	180.7 (55.1)
△	3.26 (0.99)	⌘	39.4 (12.0)	⌘	208.8 (67.3)
+	4.57 (1.39)	z	53.0 (16.2)	!	268.8 (81.9)
x	6.26 (1.91)	y	70.9 (21.6)		

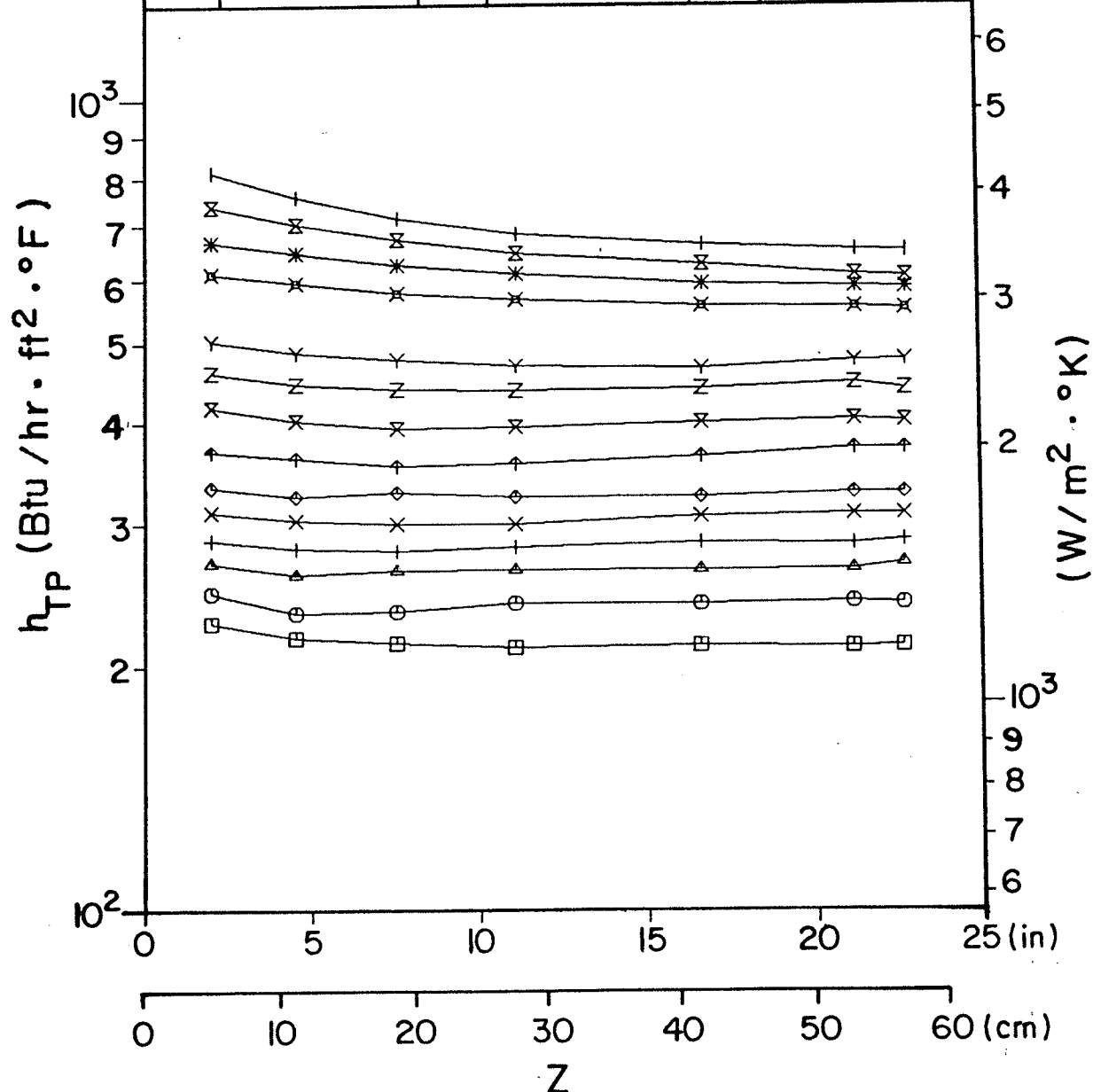


Fig. 7.2(D) Two-Phase Glycerine & Water-Air Local Heat-Transfer Results

$$V_{SL} = 3.27 \text{ ft/s } (0.997 \text{ m/s})$$

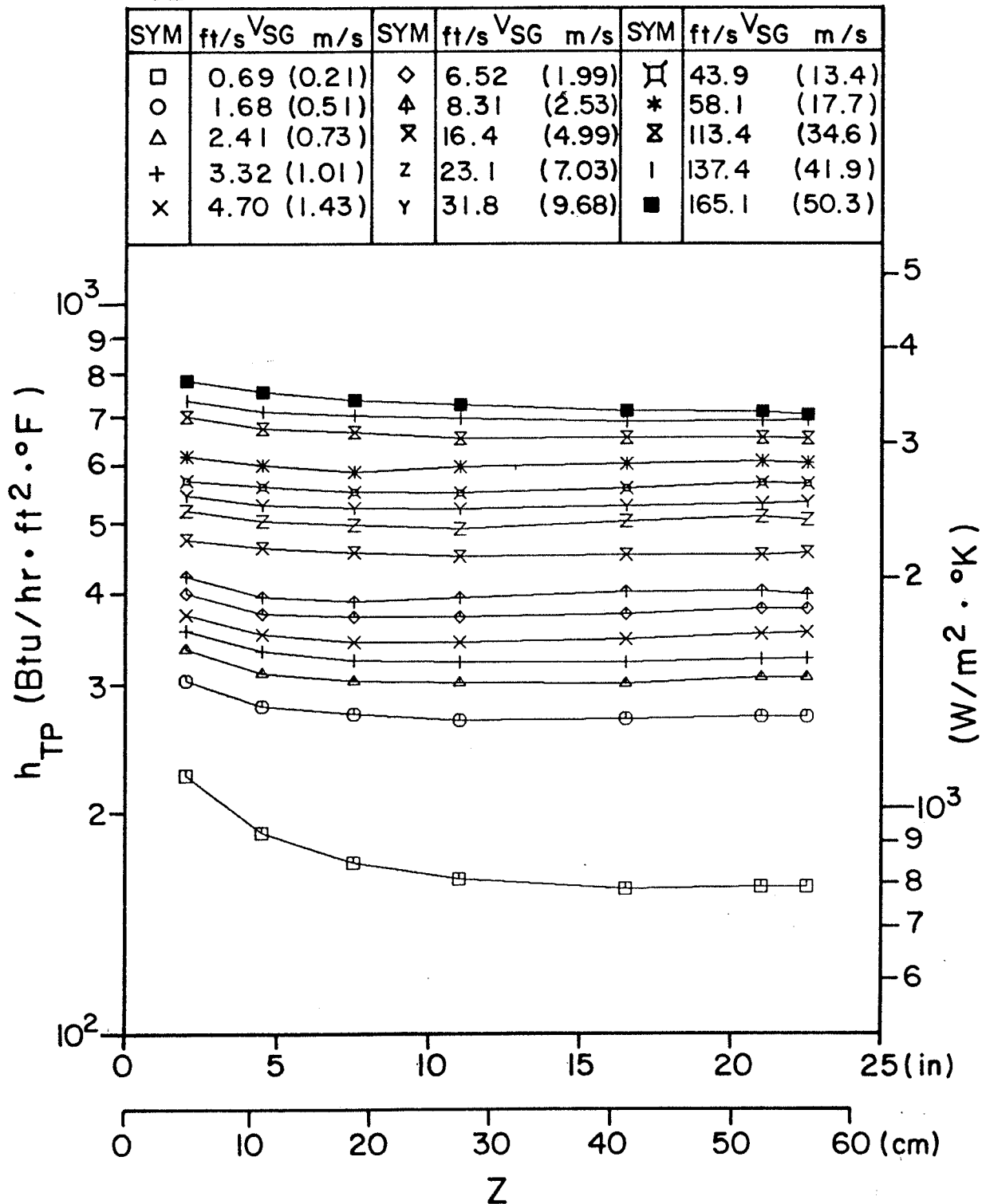


Fig. 7.2(E) Two-Phase Glycerine & Water-Air Local Heat-Transfer Results

$$V_{SL} = 8.74 \text{ ft/s } (2.66 \text{ m/s})$$

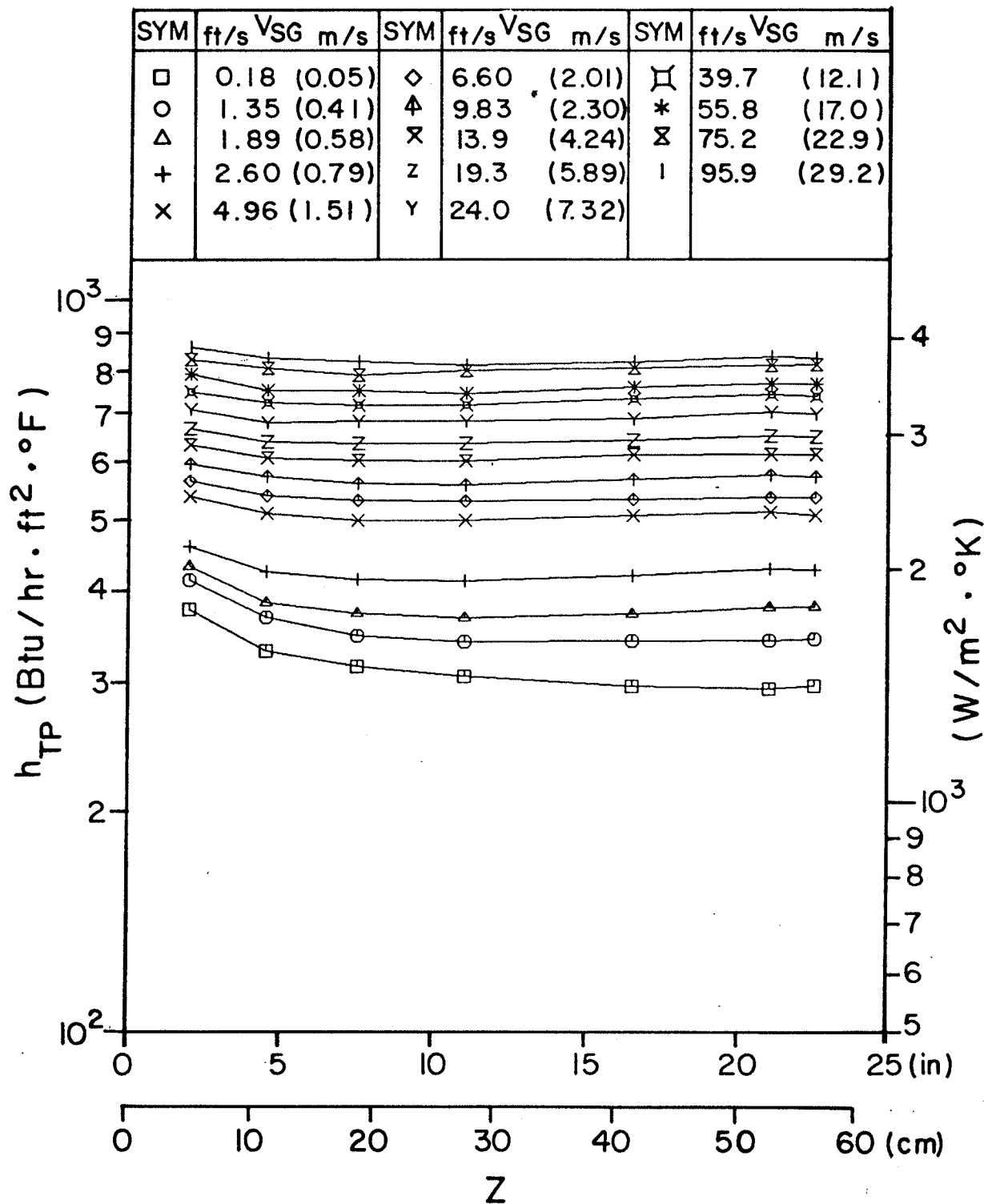


Fig. 7.2(F) Two-Phase Glycerine & Water-Air Local Heat-Transfer Results

$$V_{SL} = 18.1 \text{ ft/s } (5.52 \text{ m/s})$$

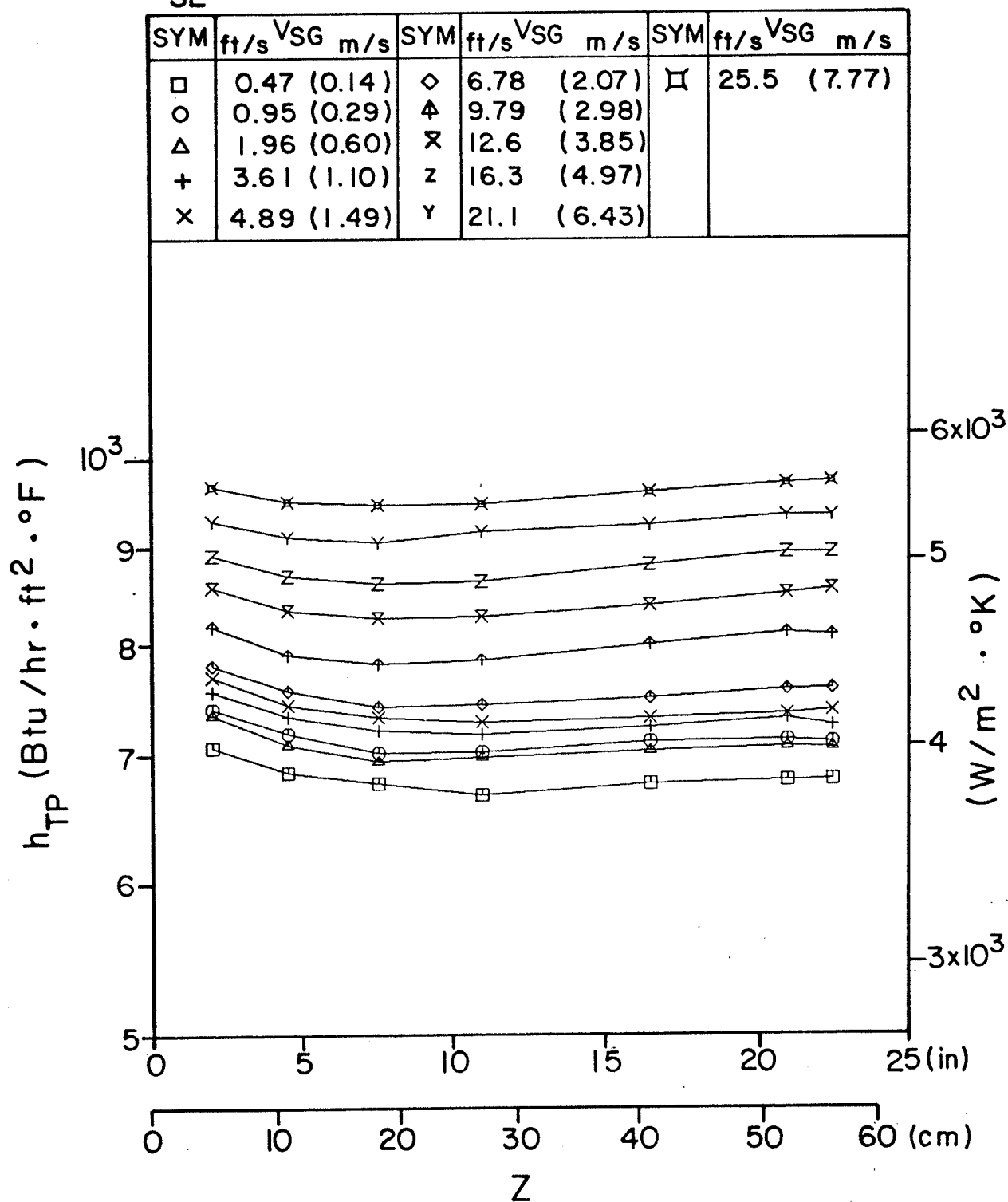


Fig. 7.2(G) Two-Phase Glycerine & Water-Air Local Heat-Transfer Results

$V_{SL} = 24.2 \text{ ft/s (7.38 m/s)}$

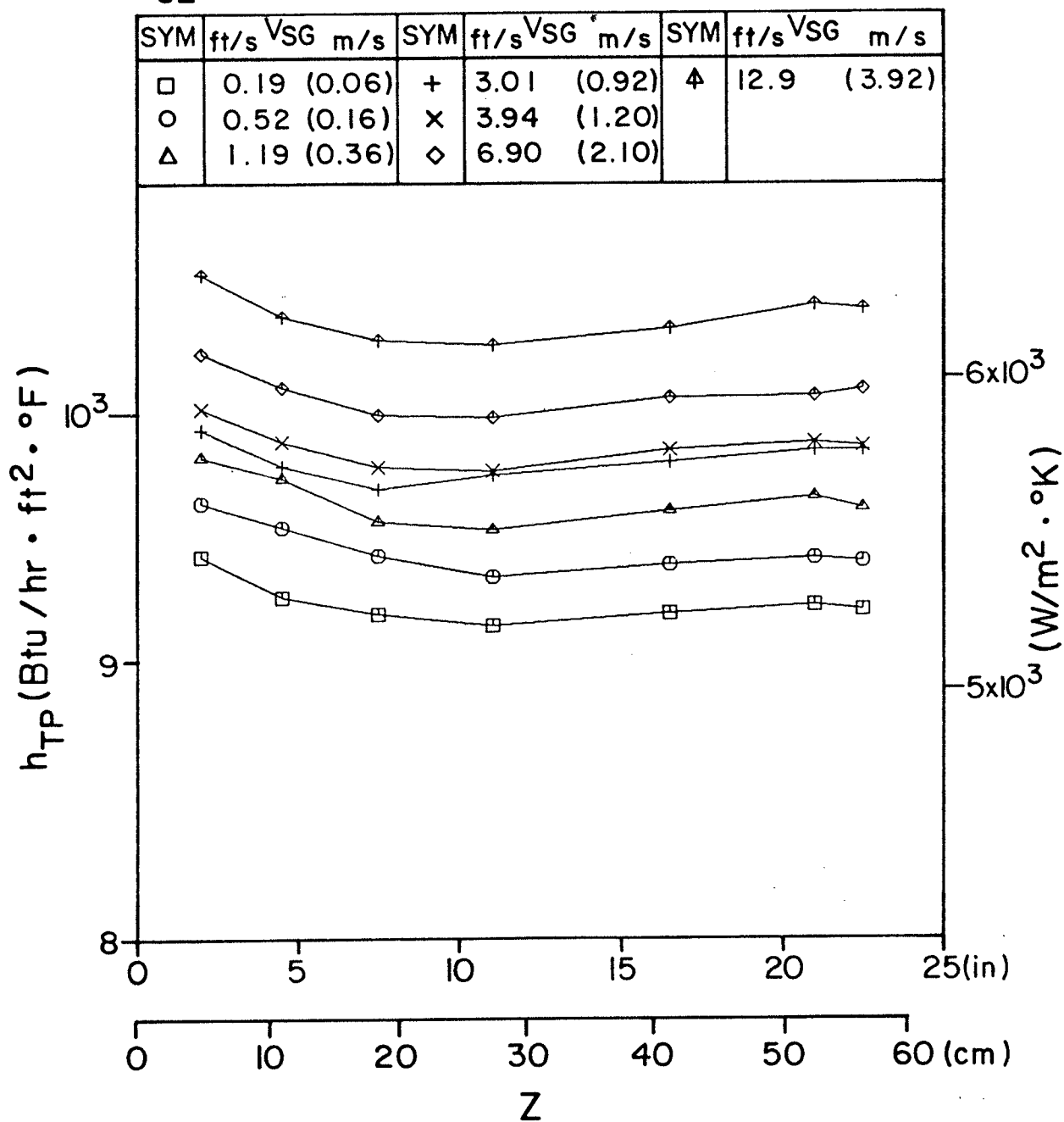


Fig. 7.2(H) Two-Phase Glycerine & Water-Air Local Heat-Transfer Results

$V_{SL} = 0.073 \text{ ft/s}$ (0.022 m/s) Silicone - Air

162

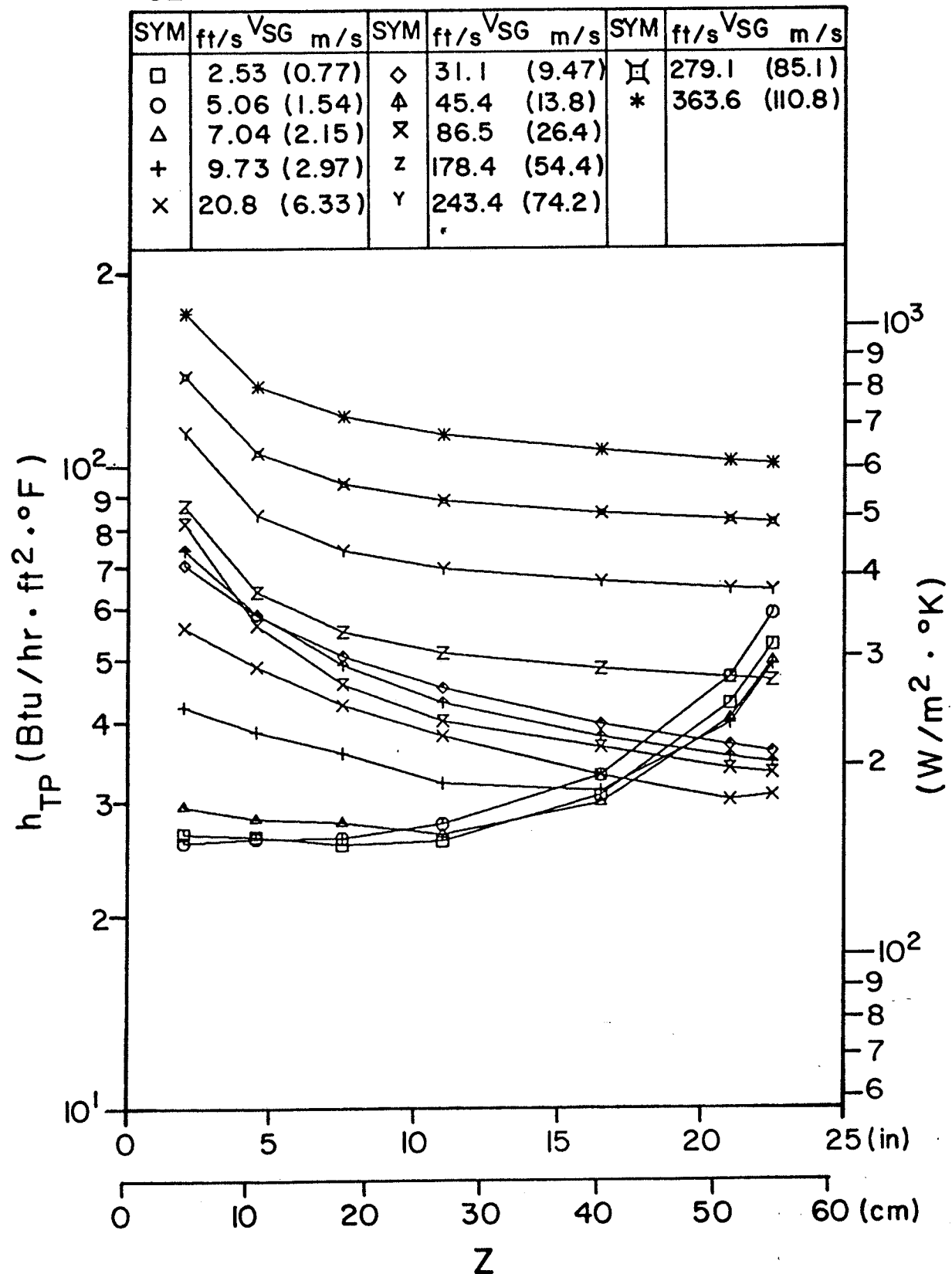


Fig. 7.3(A) Two-Phase Silicone-Air Local Heat-Transfer Results

$$V_{SL} = 0.100 \text{ ft/s } (0.030 \text{ m/s})$$

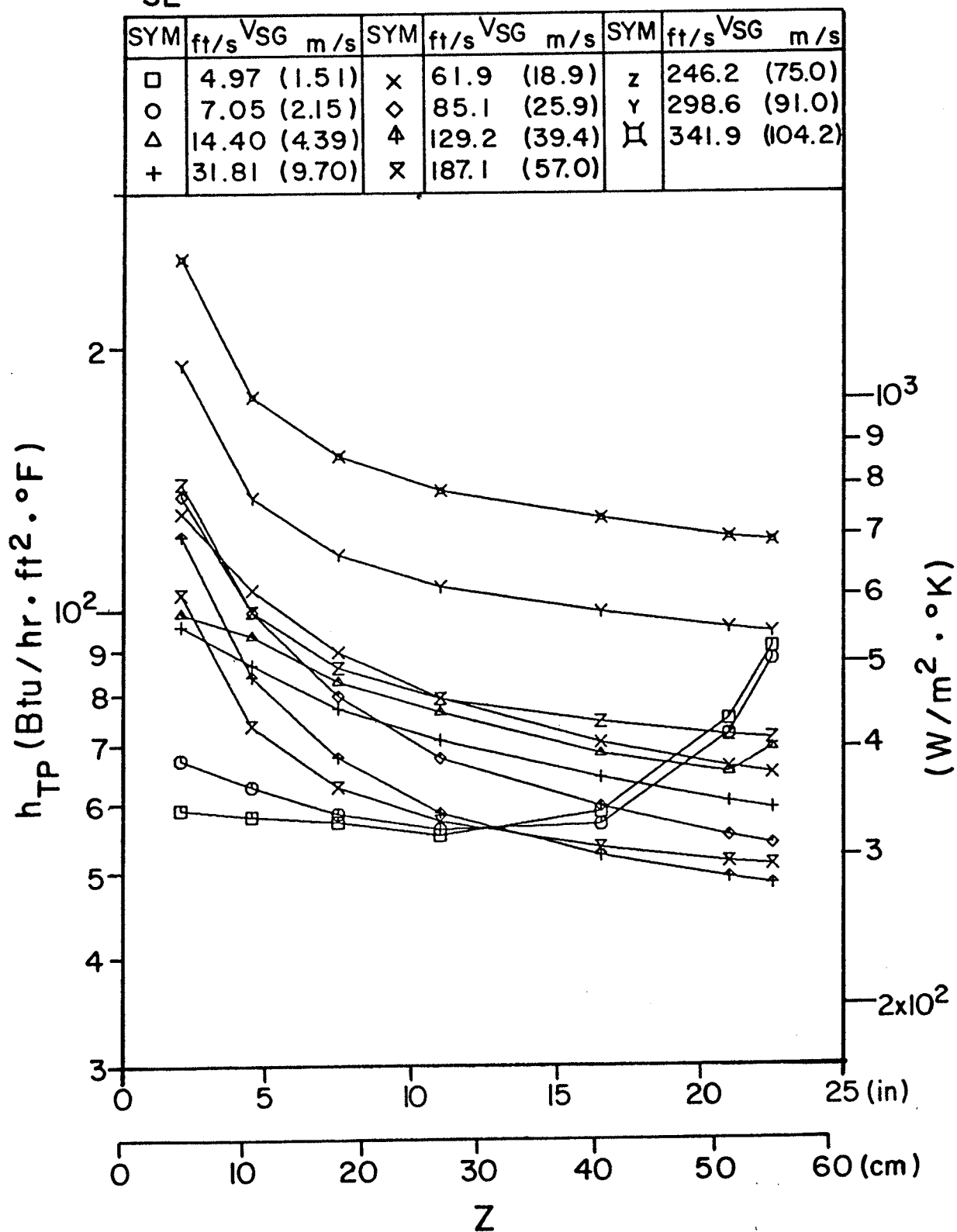


Fig. 7.3(B) Two-Phase Silicone-Air Local Heat-Transfer Results

$$V_{SL} = 0.260 \text{ ft/s } (0.079 \text{ m/s})$$

164

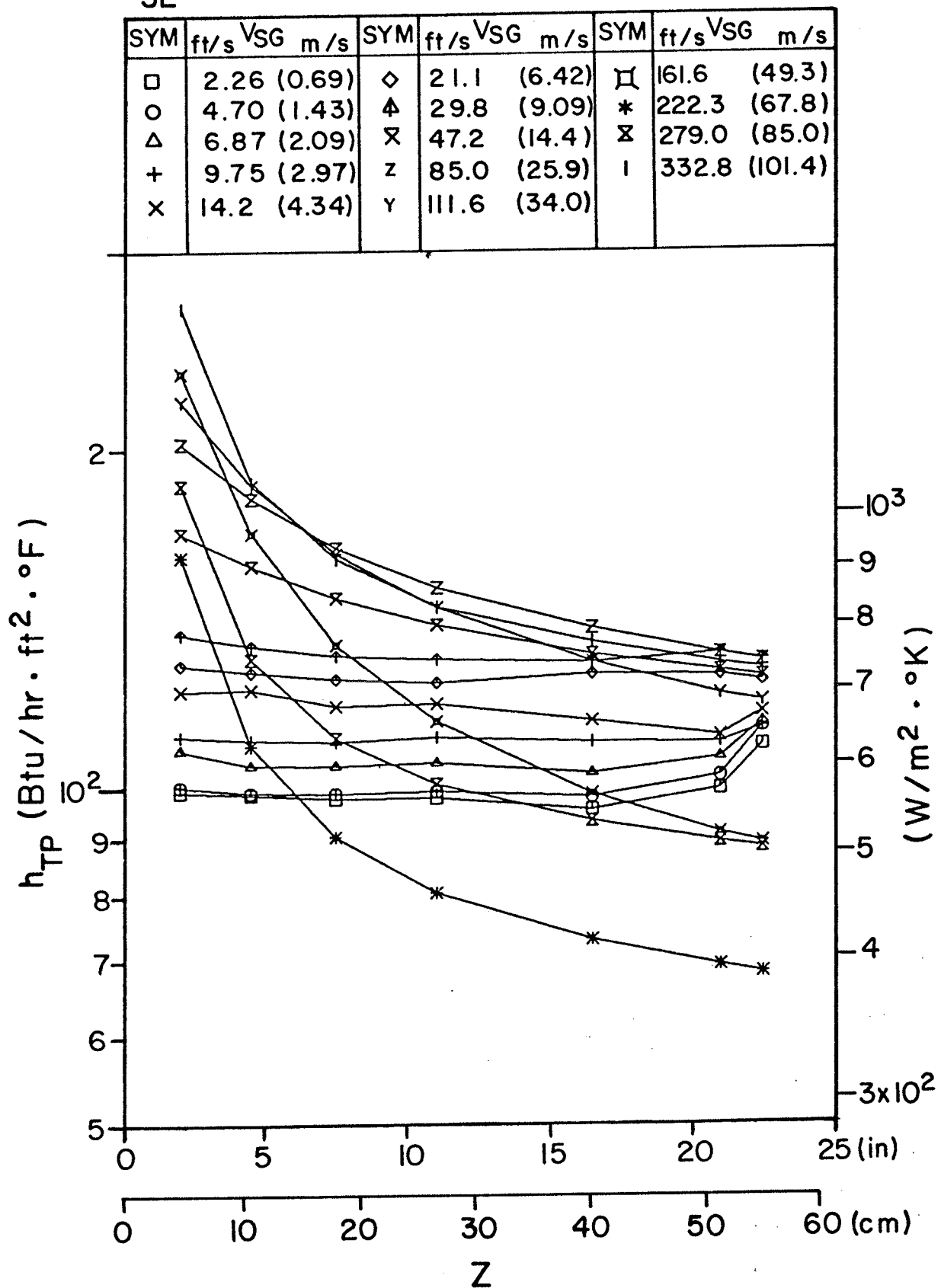


Fig. 7.3(C) Two-Phase Silicone-Air Local Heat-Transfer Results

$V_{SL} = 0.38 \text{ ft/s (0.116 m/s)}$

165

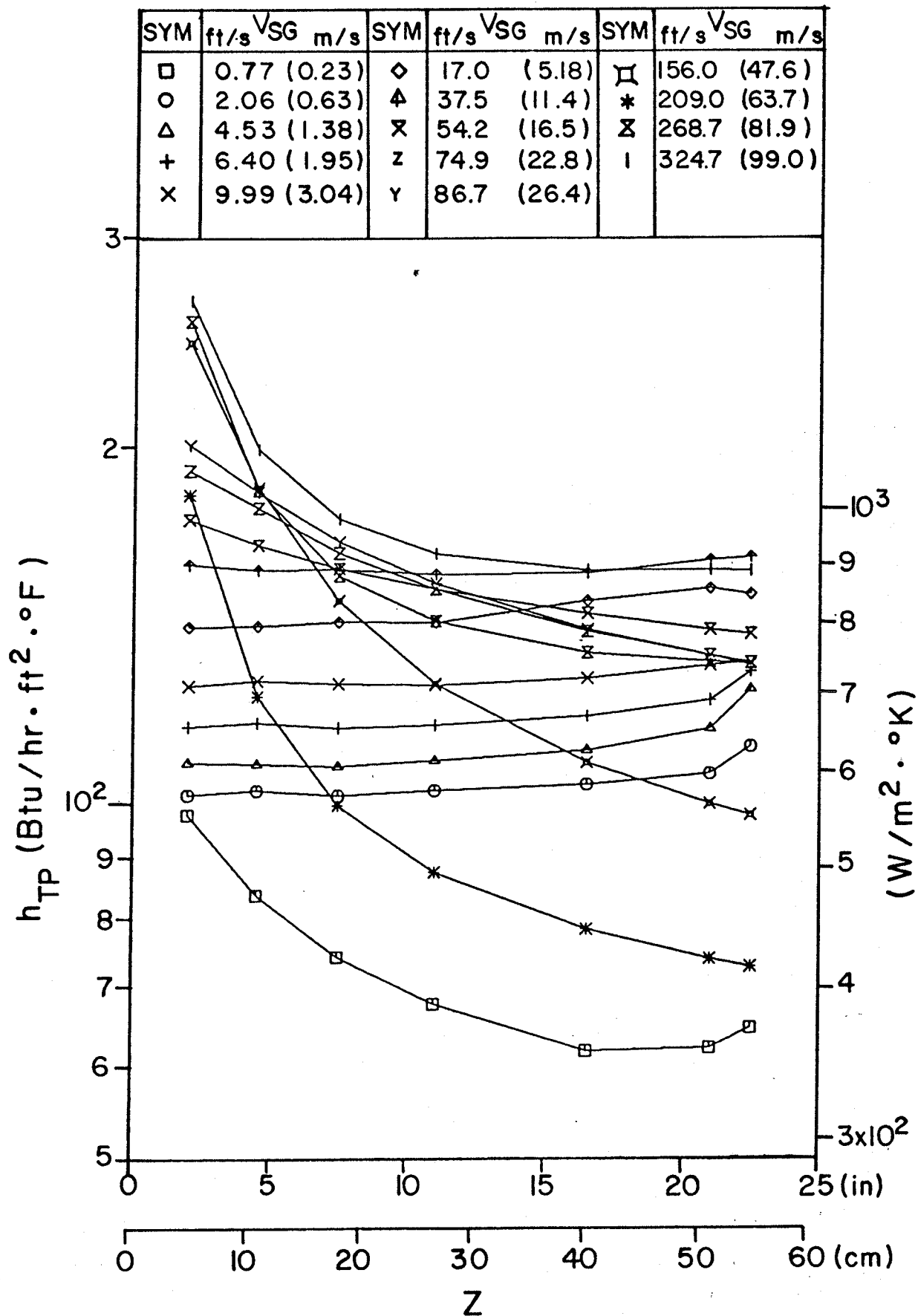


Fig. 7.3(D) Two-Phase Silicone-Air Local Heat-Transfer Results

$$V_{SL} = 0.910 \text{ ft/s } (0.277 \text{ m/s})$$

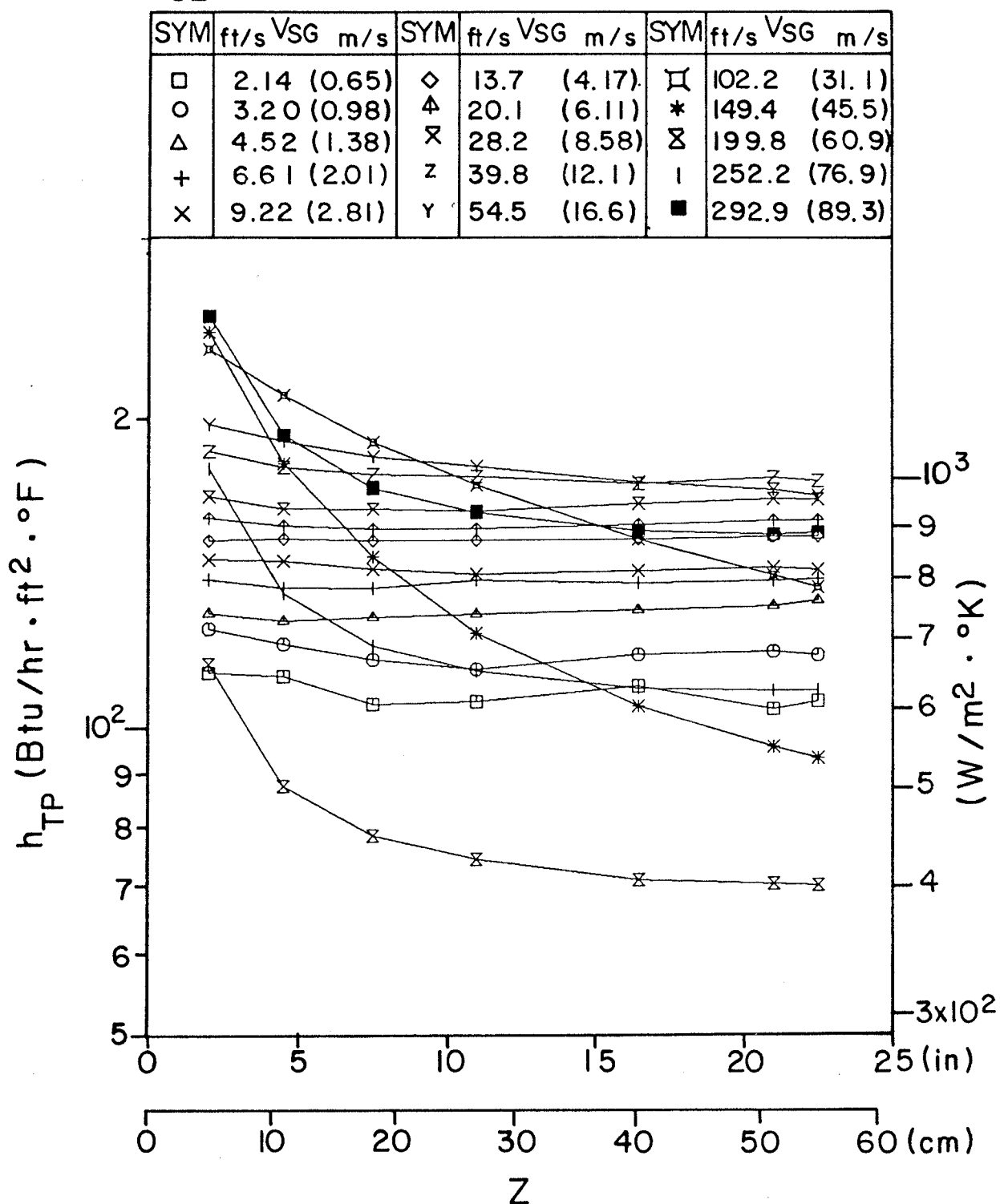


Fig. 7.3(E) Two-Phase Silicone-Air Local Heat-Transfer Results

$$V_{SL} = 1.30 \text{ ft/s } (0.396 \text{ m/s})$$

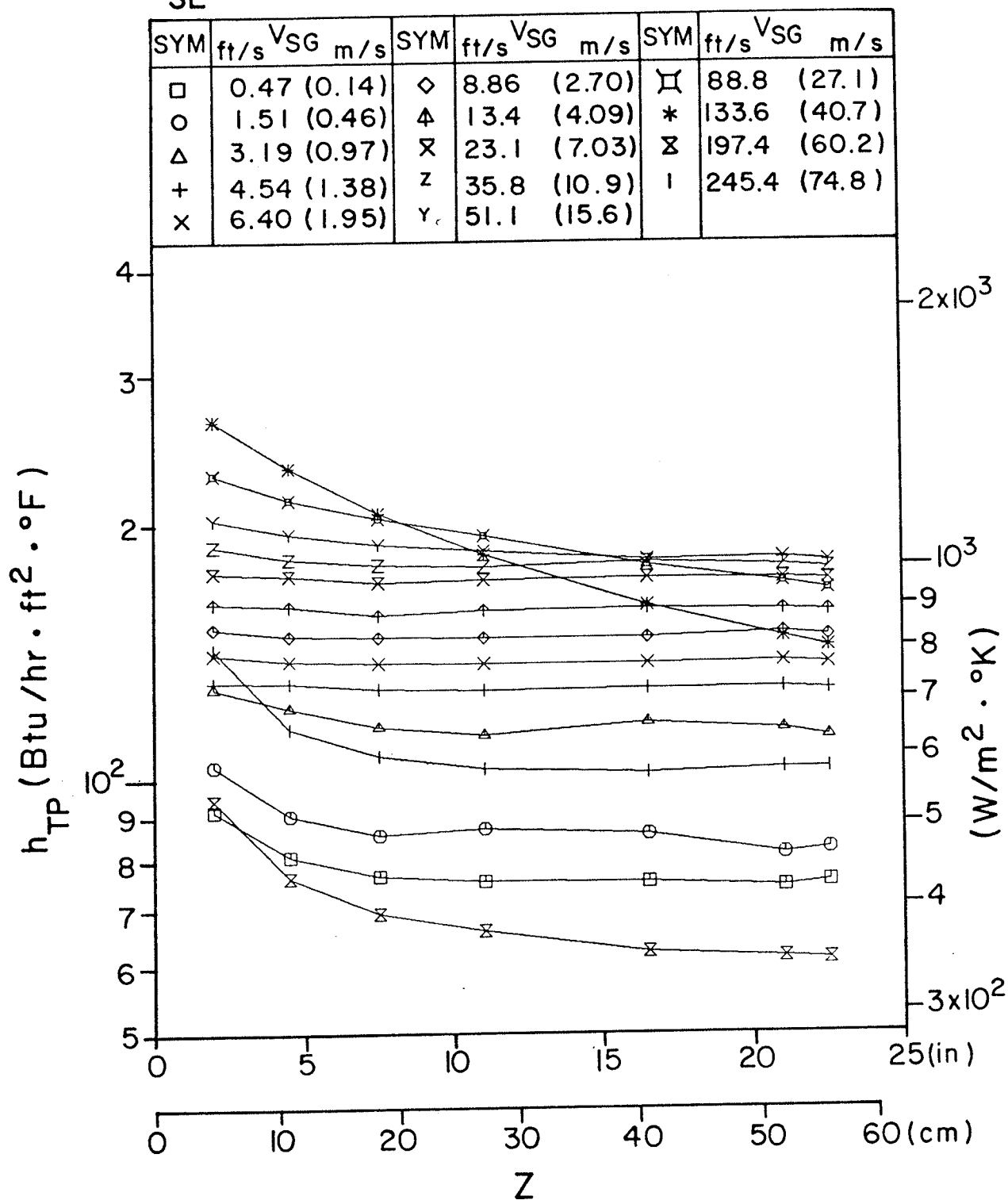


Fig. 7.3(F) Two-Phase Silicone-Air Local Heat-Transfer Results

$$V_{SL} = 2.26 \text{ ft/s (0.690 m/s)}$$

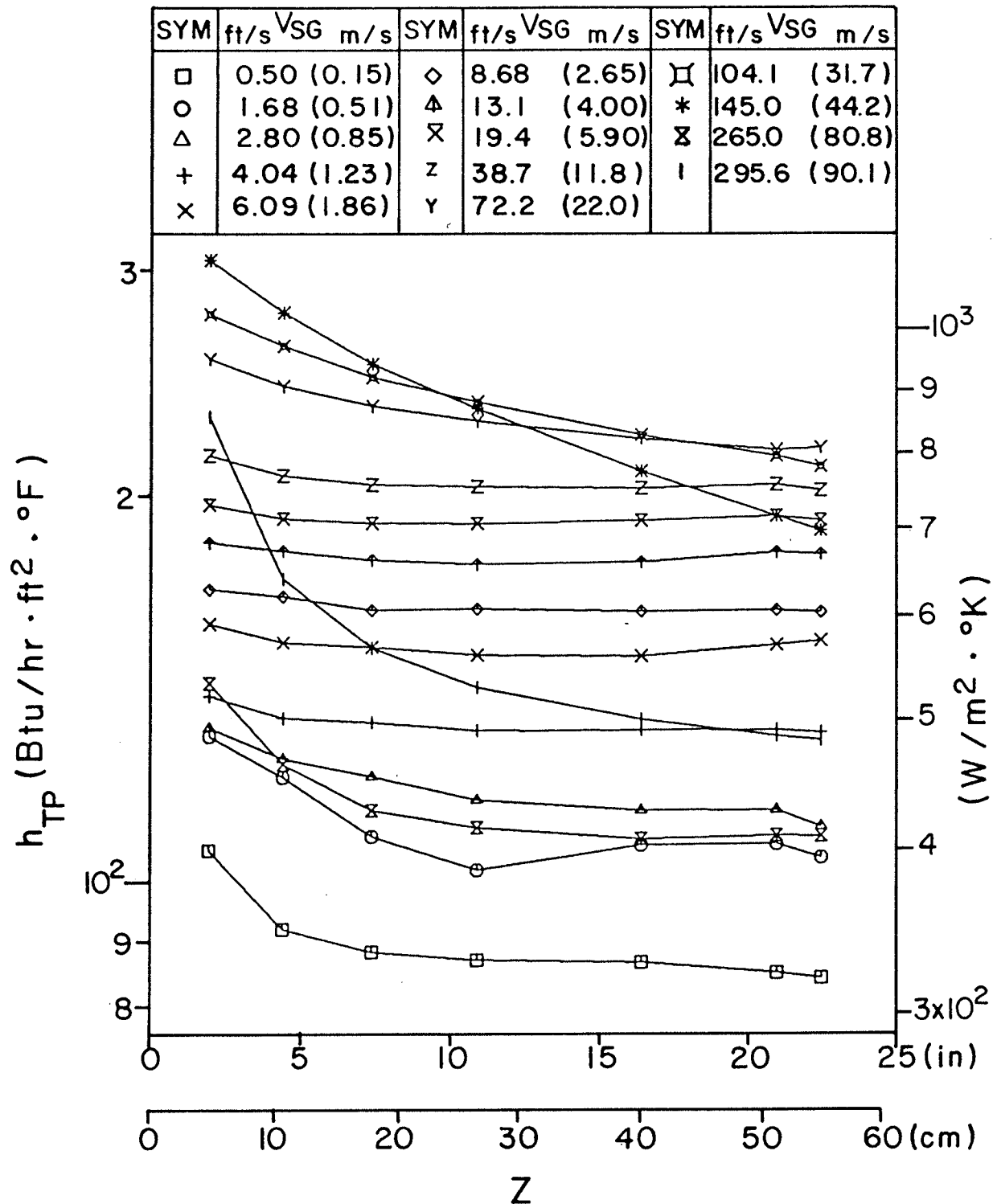


Fig. 7.3(G) Two-Phase Silicone-Air Local Heat-Transfer Results

$$V_{SL} = 6.05 \text{ ft/s} \quad (1.84 \text{ m/s})$$

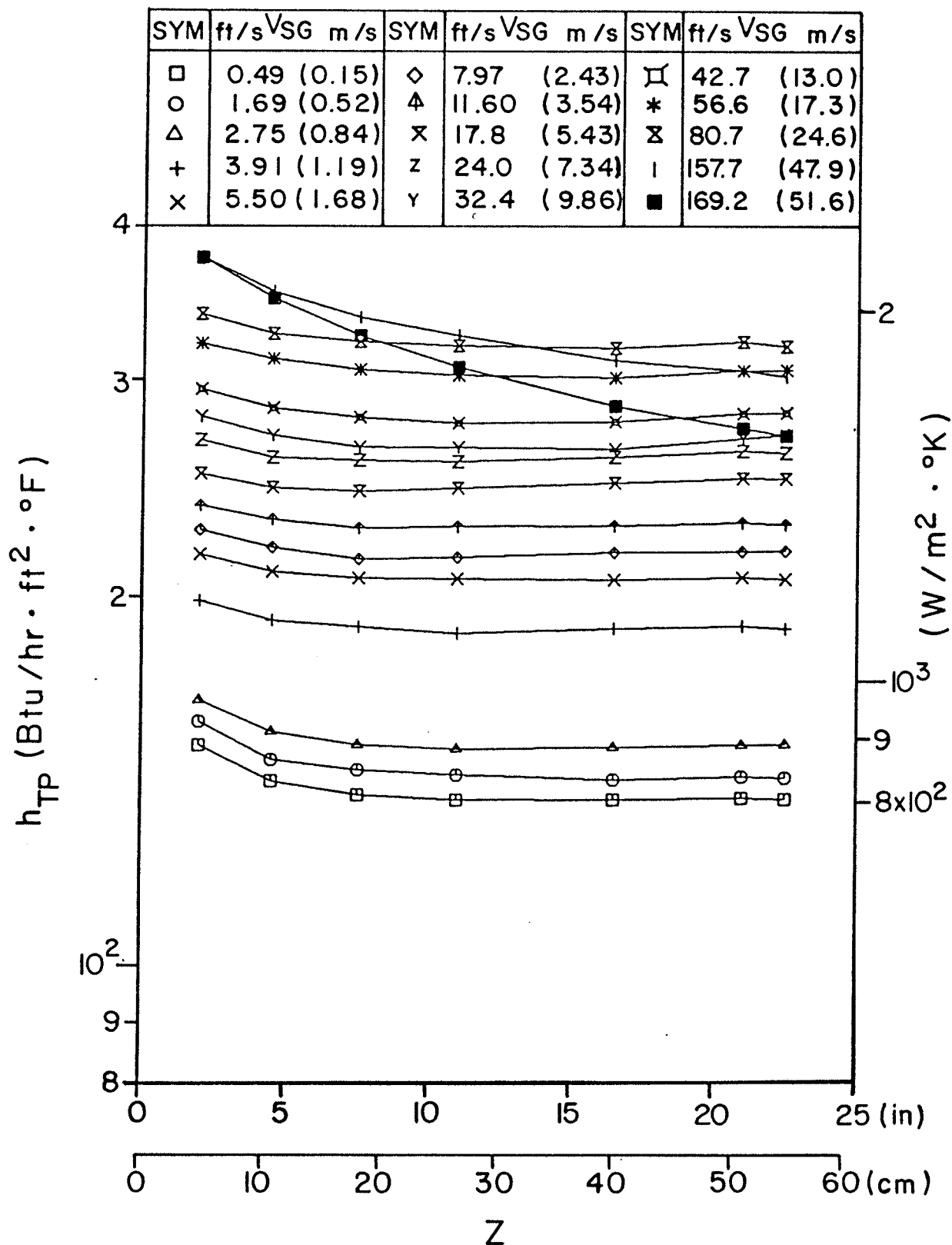


Fig. 7.3(H) Two-Phase Silicone-Air Local Heat-Transfer Results

$$V_{SL} = 12.6 \text{ ft/s } (3.83 \text{ m/s})$$

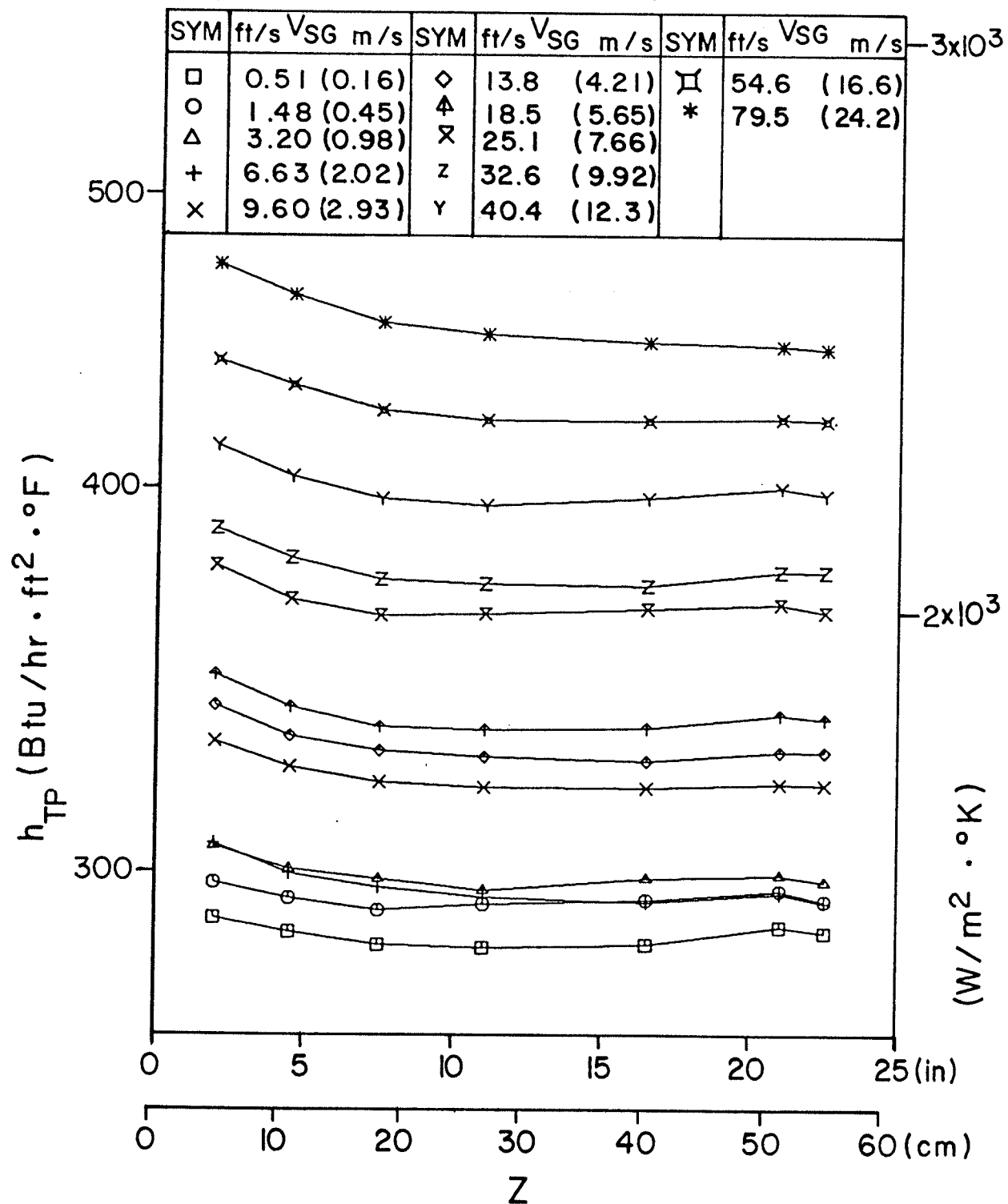


Fig. 7.3(I) Two-Phase Silicone-Air Local Heat-Transfer Results

$$V_{SL} = 16.6 \text{ ft/s } (5.07 \text{ m/s})$$

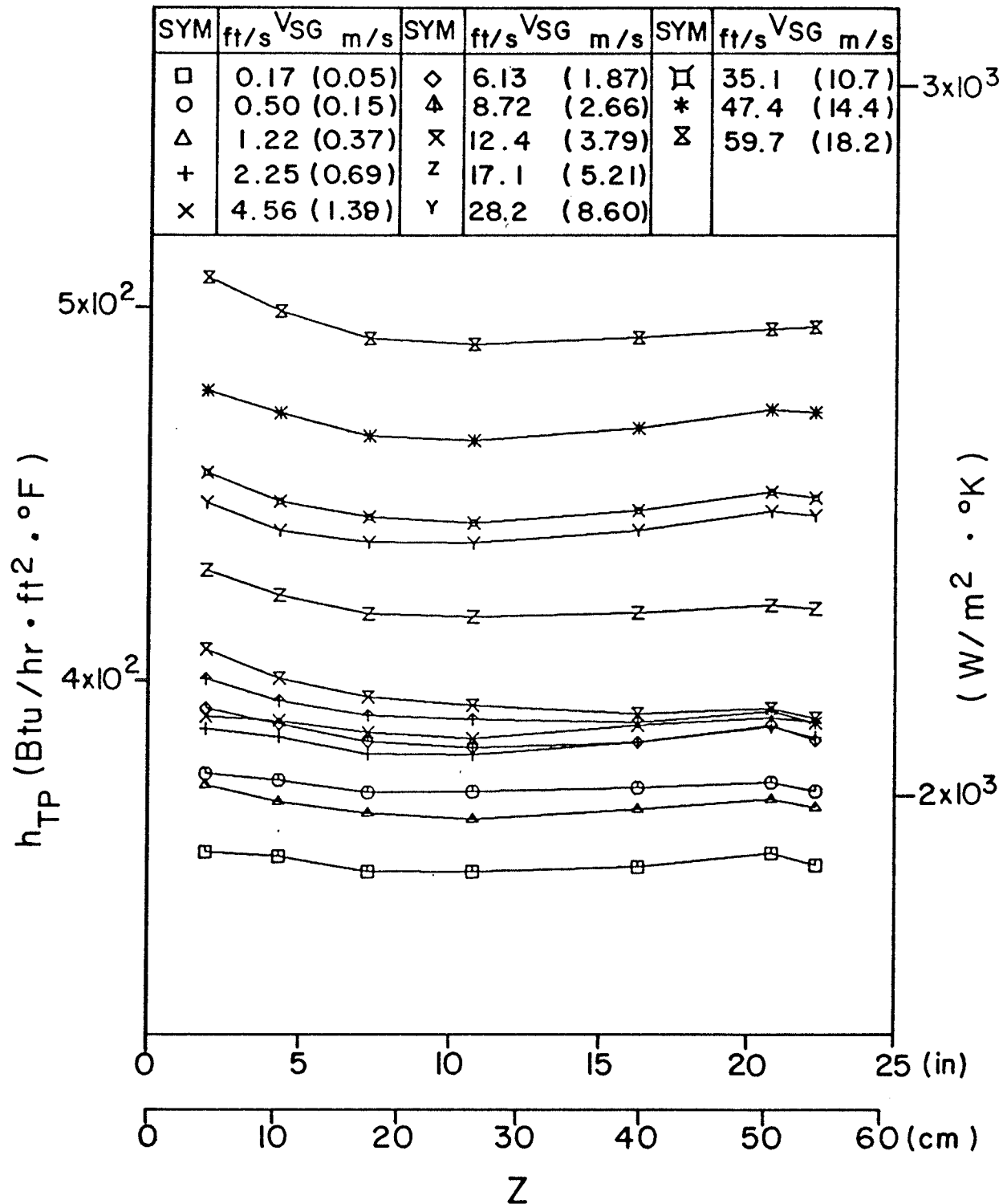


Fig. 7.3(J) Two-Phase Silicone-Air Local Heat-Transfer Results

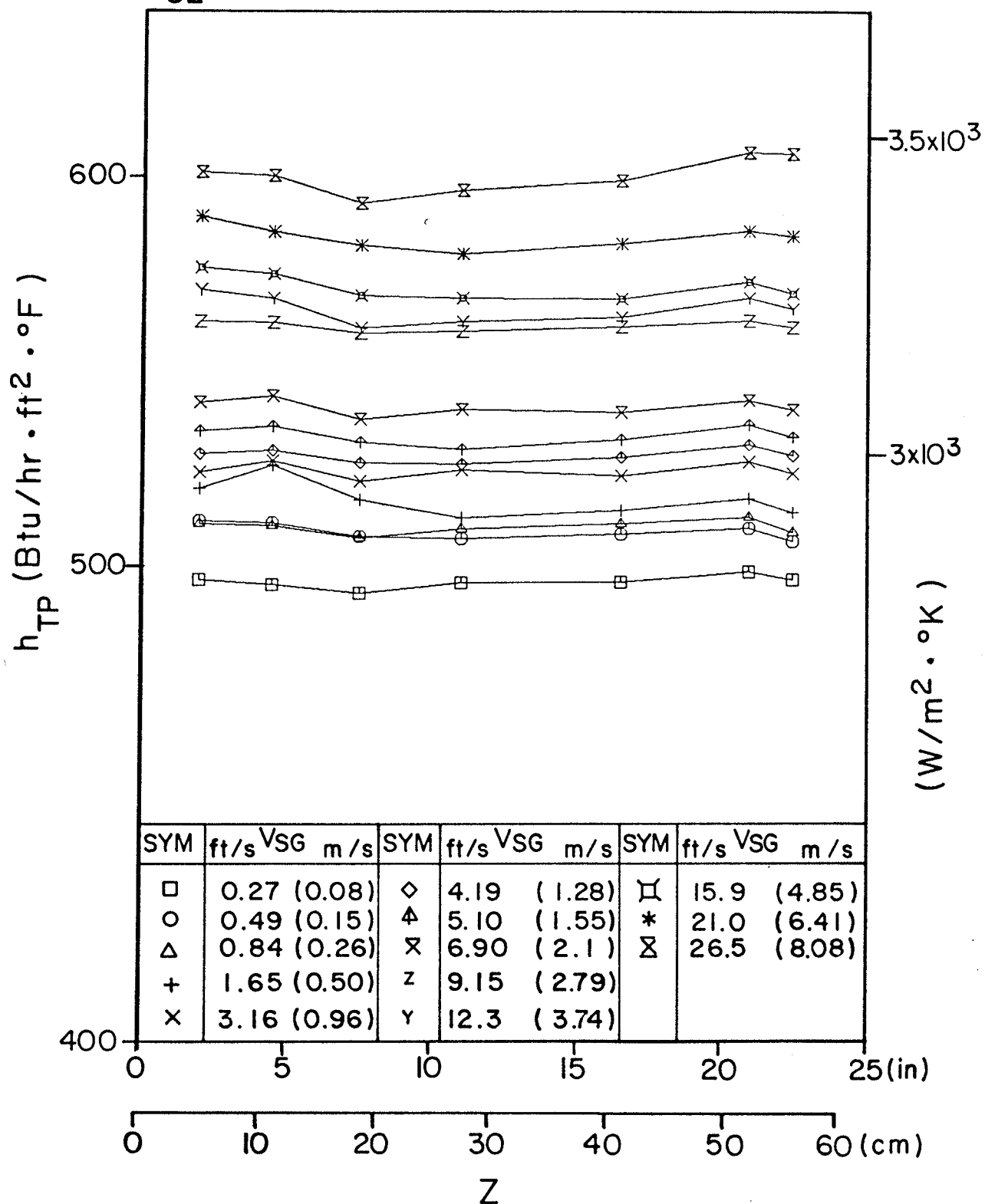
$V_{SL} = 24.2 \text{ ft/s } (7.38 \text{ m/s})$


Fig. 7.3(K) Two-Phase Silicone-Air Local Heat-Transfer Results

$$V_{SL} = 30.2 \text{ ft/s (9.20 m/s)}$$

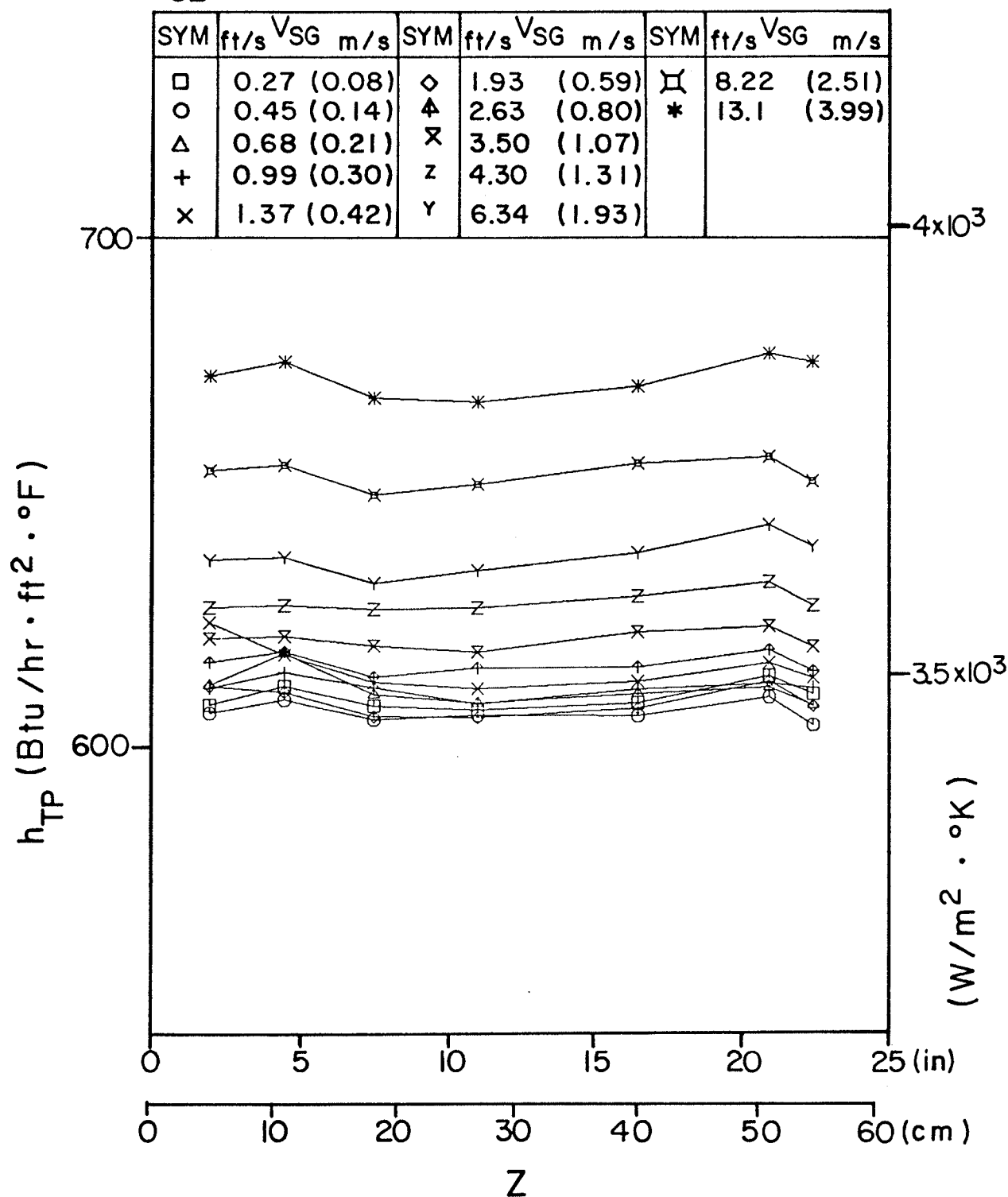


Fig. 7.3(L) Two-Phase Silicone-Air Local Heat-Transfer Results

$0.305 < V_{SG} < 30.5$ m/s), the slope of h_{TP} profiles is essentially zero.

3. At low-to-medium liquid flow rates and high gas flow rates, h_{TP} decreases along the test section. In the silicone-air case, the decrease of h_{TP} along Z is more dramatic. Also, a sudden drop in h_{TP} values at very high V_{SG} could be observed at liquid velocities $V_{SL} = 0.260$ to 2.26 ft/s (0.079 to 0.690 m/s). This large drop in h_{TP} values (hence making for a sudden drop in the mean heat-transfer coefficients) will be discussed in detail when the mean-heat-transfer data are presented.
4. At high liquid flow rates and for all gas flow rates, the $h_{TP} \sim Z$ profile is almost flat.

With regard to point 1 above, this behaviour of h_{TP} at low liquid and gas flow rates was also observed in the earlier work (1,93,107) conducted on the present rig. A theoretical explanation of the $h_{TP} \sim Z$ profiles at low Reynolds numbers in two-phase flow in vertical tube was done by Vijay et al. (95). In their paper, the full Graetz problem for single-phase fluids was solved for the two-phase flow by the addition of a certain parameter involving the product of Reynolds and Prandtl numbers and the non-dimensional vertical velocity gradient. It was suggested (93, 95) that the downflow of the liquid film at the tube wall was one of a number of possible mechanisms for this

behaviour of h_{TP} . This downflow of the liquid film was observed in slug flow in the present study, as well as in the earlier work (1, 93, 107) and was believed to take place in the bubble flow also. Aggour (1) confirmed this observation in bubble flow by conducting a visualization study using hydrogen-bubble and dye-injection methods.

Other possible reasons for the local heat-transfer coefficients behaviour at low $\dot{m}_L$ and $\dot{m}_G$ could be:

1. Variation in the fluid properties along the test section,
2. Acceleration of bubbles due to pressure gradient along the test section, as explained in Ref. (93),
3. Perhaps natural convection effects.

A comparison of Fig. 7.2 A to H for the glycerine & water-air and Fig. 7.3 A to L for the silicone-air system suggests that the behaviour and the shape of local heat-transfer coefficients along the test section remain in most cases unaffected by reducing the surface tension of the liquid. However, comparing Figs. 7.2 C and 7.3 D (for $V_{SL} = 0.380$ ft/s or 0.116 m/s) and Figs. 7.2 D and 7.3 F (for $V_{SL} = 1.30$ ft/s or 0.396 m/s) show, as pointed out earlier, a sudden drop in h_{TP} values at very high gas velocities. This large drop in the heat-transfer coefficient, followed by a rise (as will clearly be shown when the mean values are presented), is believed to occur in annular flow and the

annular-mist transition. A possible explanation of that behaviour for the heat-transfer coefficient will be discussed later in this chapter.

Other than the behaviour of h_{TP} with Z in the annular-mist transition, the silicone-air local-heat-transfer results were similar to those obtained for water-air and glycerine & water-air systems.

7.3 COMPARISON OF THE LOCAL HEAT-TRANSFER COEFFICIENTS WITH THE MODIFIED THEORY OF SPALDING

The results of the local heat-transfer coefficients were compared with the modified theory of Spalding, as proposed by Vijay(93).

Assuming the flow to be homogeneous and that the variations of wall shear stress and fluid properties with respect to Z are small (and therefore these quantities could be treated as constants), Vijay (93) defined the variables S_q and Z^+ , which appear in Spalding's theory for single-phase flows, as follows:

$$Z^+ = \int_0^Z (\tau_W \rho_{MIX} g_C)^{1/2} / \mu_{MIX} dz \quad (7.1)$$

$$= (\tau_W \rho_{MIX} g_C)^{1/2} Z / \mu_{MIX} \quad (7.2)$$

where

τ_W refers to the wall shear stress in two-phase flow and is calculated from

$$\tau_W = \frac{D}{4L} \Delta P_{TPF} \quad (7.3)$$

Experimental values³ of ΔP_{TPF} were used in the comparisons to calculate τ_W . Just as in the case of single-phase flow, the experimental values of $(Sq)_{TP}$ were calculated from

$$(Sq)_{TP} = \frac{Pr_{MIX} St_{MIX}}{(f/2)^{1/2}} \quad (7.4)$$

$$= \frac{Pr_{MIX} h_{TP}}{(C_p)_{MIX} (\tau_W \rho_{MIX} g_c)^{1/2}} \quad (7.5)$$

where:

Pr_{MIX} and St_{MIX} are the mixture Prandtl number and Stanton number, respectively.

Expected values were calculated from Eq. (5.11), taking $Pr_T = 0.887$ (the value recommended by Spalding for single-phase flows).

Examination of the Eqs. (7.1) to (7.5) reveals that a knowledge of mixture properties is required in order to correlate the two-phase local-heat-transfer data with the theory, Eq. (5.11). Vijay (93) and Aggour (1) examined different groups of fluid properties (with each group

³ These values were obtained by subtracting the head term, in which the void fraction was predicted using Chisholm's (14) correlation, from the measured total pressure.

employing different combinations of expressions for μ , ρ , k and C_p). The best agreement between the data of (1,93) and Eq. (5.11) was obtained when only liquid properties were used for the mixture with the exception of annular-mist flow. This reservation seems logical since in the annular-mist flow regime, the gas phase would be the main medium for transferring heat from the wall to the mixture. Therefore, the annular-mist data for the present study were excluded in the comparisons.

At low liquid and gas mass fluxes, a reversed behaviour or $h_{TP} \sim Z$ exists, as discussed earlier where h_{TP} increases with an increase in Z along the test section. Since the modified theory proposed by Vijay (93) is essentially a single-phase heat-transfer theory of Spalding which does not accommodate this reversed trend of heat-transfer coefficients, comparison of these data with the theory would indicate large deviations. Therefore, the data points where h_{TP} significantly increased as Z increased were excluded from comparisons.

Also, the wall-shear-stress term, which appears in Eqs. (7.1) to (7.5) was calculated using the actual two-phase frictional-pressure-drop data (Eq. 7.3). This required, therefore, that the pressure-drop data to be used in the comparisons should be reliable and in areas where the measurement errors are minimal. The data points with negative ΔP_{TPF} and those measurements outside the meters'

accuracy were excluded also from the study. Therefore, the local-heat-transfer data falling in any one or more of the following categories were excluded for the purpose of comparison:

1. The data in annular-mist flow.
2. The data for which the local heat-transfer coefficients increased with an increase in Z .
3. The data for which pressure-drop measurements were suspected to be in error. The unreliable data in this category includes the data for which the frictional pressure drop $\Delta P_{\text{TPF}} \leq 0.1$ psi, and also those data points having negative values. It should be noted that most of the data points falling in this category have a behaviour as described in category 2 above.

The comparisons between the present data and the modified theory of Spalding are given in Figs. 7.4, 7.5, and 7.6 A & B for water-air, glycerine & water-air, and silicone-air respectively. Due to the large set of data taken with the silicone liquid, the results were presented in two figures for $Re_{\text{SL}} < 2000$ (Fig. 7.6 A) and for $Re_{\text{SL}} > 2000$ (Fig. 7.6 B). Also, the range of data included in these comparisons is given in Fig. 7.7. The deviations between the experimental and the predicted values were estimated for the data points within the range of applicability of the theory, as specified above. A summary of these deviations is given in Table 7.1.

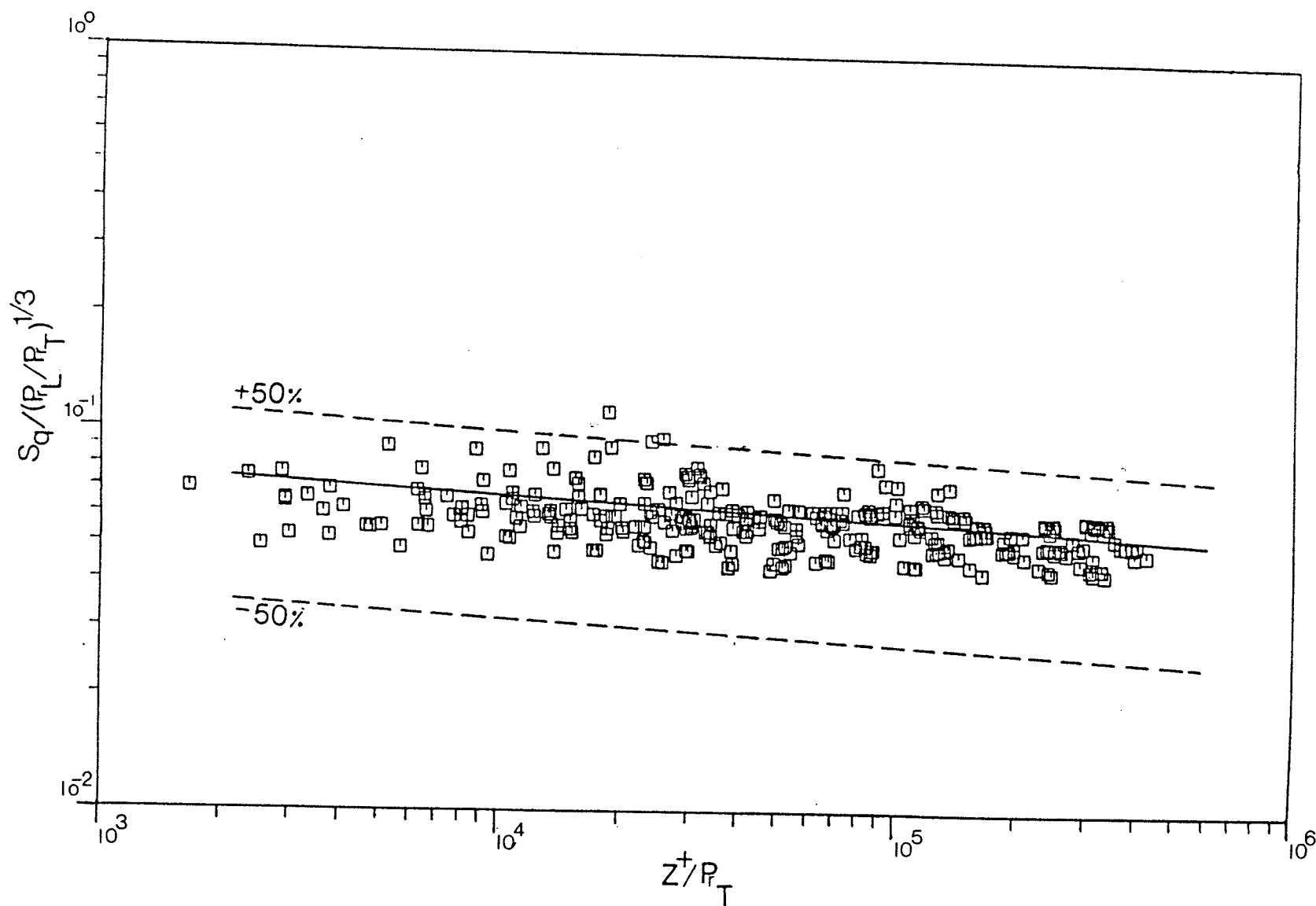


Fig. 7.4 Comparison of Water-Air Local-Heat-Transfer Coefficients with the Modified Theory of Spalding

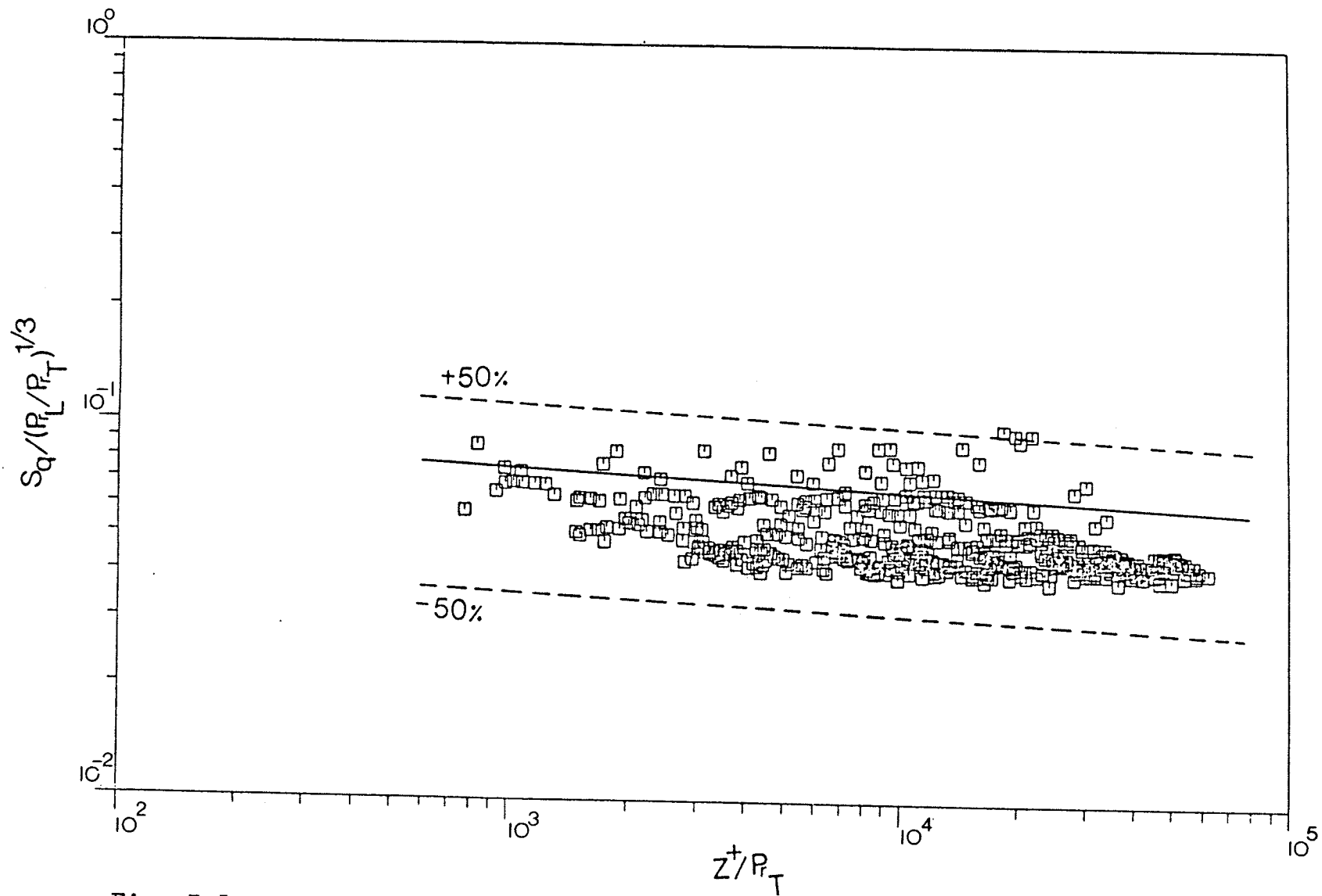


Fig. 7.5 Comparison of Glycerine & Water-Air Local-Heat-Transfer Coefficients with the Modified Theory of Spalding

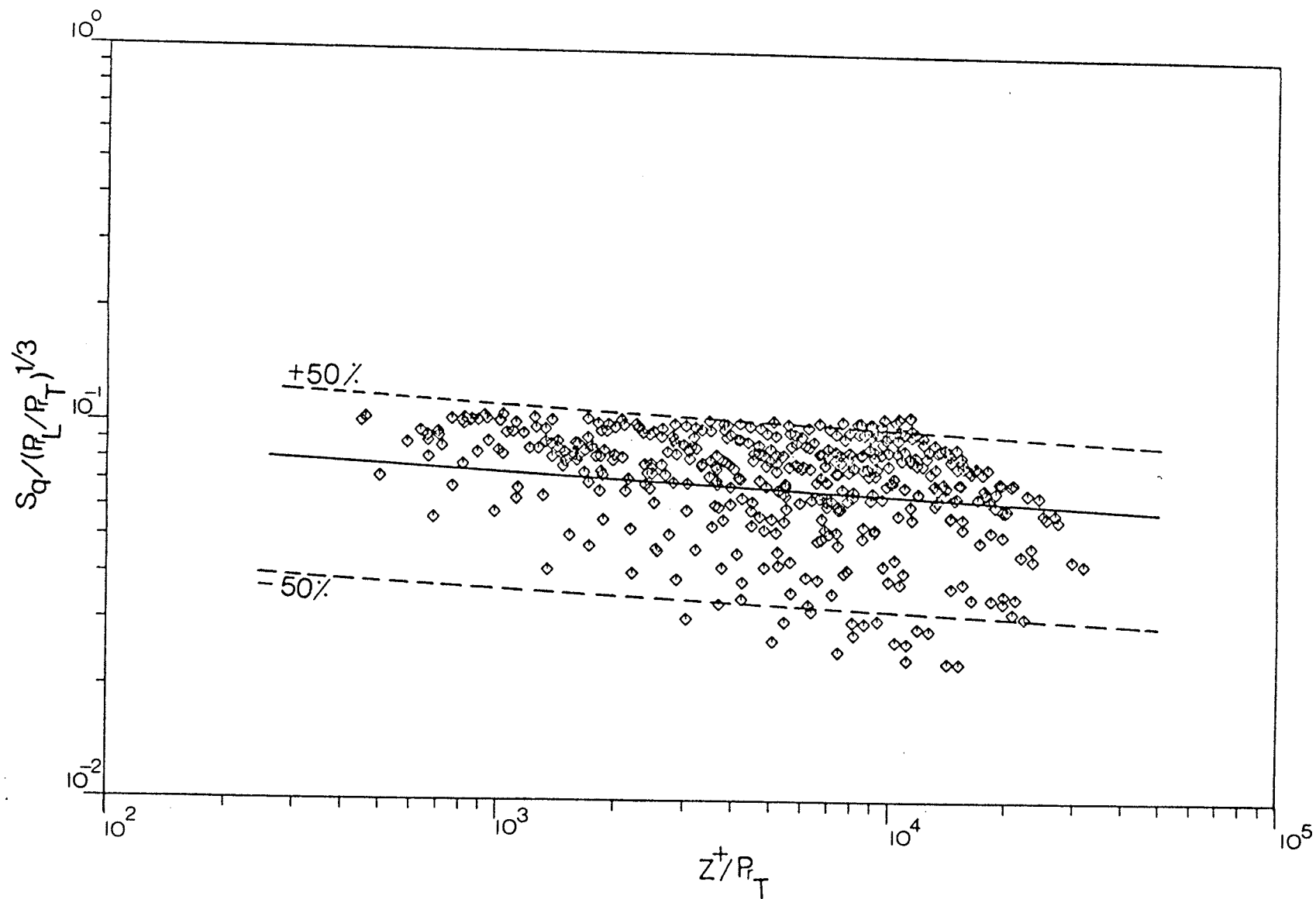


Fig. 7.6A Comparison of Silicone-Air Local-Heat-Transfer Coefficients with the Modified Theory of Spalding, $Re_{SL} < 2000$

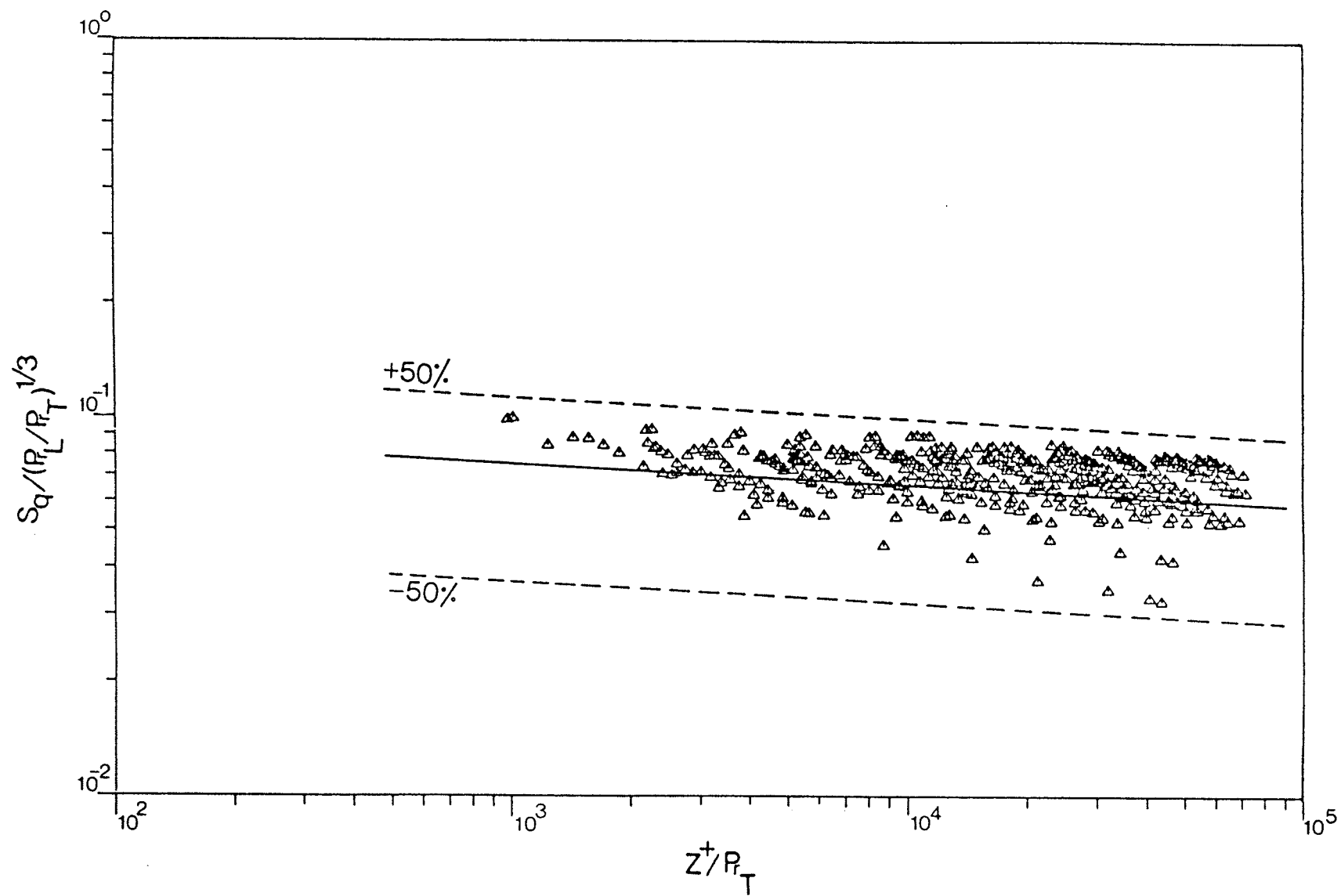


Fig. 7.6B Comparison of Silicone-Air Local-Heat-Transfer Coefficients with the Modified Theory of Spalding, $Re_{SL} > 2000$

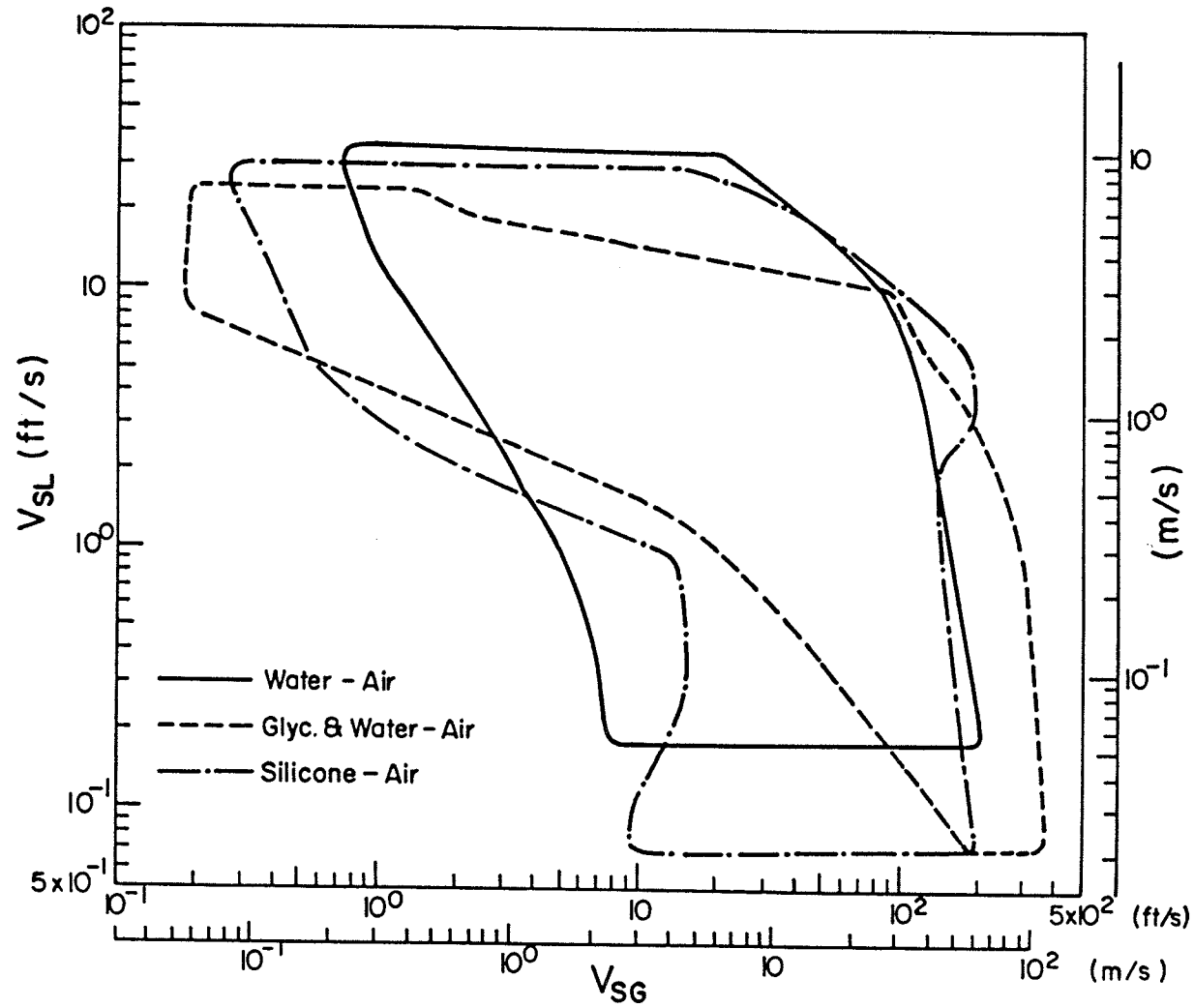


Fig. 7.7 Velocity Range of Local h_{TP} Data Used in the Comparison with the Modified Theory of Spalding

It can be seen, from the above-mentioned table, that 63.4%-97% of the data points correlated within $\pm 30\%$ of the theoretical line, while 97.3% of the data points fell within $\pm 50\%$. The overall algebraic and r.m.s. deviations for the whole set of data (1806 points in total) were +3.75% and 25.8%, respectively.

Table 7.1

Summary of the Comparison Between the Two-Phase
Local-Heat-Transfer Data and Eq. (5.11)

Range of Deviation (%)	Number of data points (% of total N) lying in the specified range of deviations		
	Water-Air	Glyc. & Water-Air	Silicone-Air
N	329	511	966
± 20	82.1	33.9	37.2
± 30	97.0	83.5	63.4
± 40	98.8	98.4	86.0
± 50	99.1	99.2	93.4
> 50	0.9	0.8	6.6
$\bar{e}$	-4.1	-17.3	+17.6
$\bar{e}_r$ (%)	15.8	23.8	29.3

Similar results were obtained in the earlier work of (1,93,107) with an extensive set of data that covered a wide range of fluid properties and mass flow rates of the liquid and gas phases.

In order to establish the generality of the modified theory and for the sake of completeness, the results obtained by the above three authors are presented in Table 7.2 with the present comparisons. This combined set of data, to the best of the present author's knowledge, covers the widest range of variables studied to this point. This range of variables is:

Re_{SL}	1.8 to 1.26×10^5
Re_{SG}	14.0 to 1.5×10^5
Pr_L	5.6 to 7000
ρ_G/ρ_L	2×10^{-4} to 0.01
σ	19.7×10^{-3} to 72×10^{-3} N/m

Even with such an extremely wide range, the overall algebraic and r.m.s. for the whole set of data (4263 data points in total) were 7.4% and 27.5%, respectively.

It should be noted that the water-air data of Vijay (93) and Aggour (1) have been excluded from the comparison since the combination of the present water-air data and those of Zaidi (107) covers almost the entire range studied by them, and moreover, they were in good agreement when compared with those of (1,93).

From the material presented in this section, it can be concluded that the modified Spalding theory is indeed a successful means of correlating the two-phase local heat-transfer coefficients for a very wide range of variables, provided its range of applicability is observed.

Table 7.2

Summary of the Comparison Between the Local Heat-Transfer
Data of Vijay, Aggour, Zaidi and Present Study; and Eq. (5.11)

Range of Deviation	Percent of Total N Lying in the Specified Range of Deviation										
	Present Data				Data of Vijay		Data of Aggour		Data of Zaidi		OVERALL
	Water- air	Gly. & water-air (58%-42%)	Silicone- air	Complete set	Gly. & water- air (75%-25%)	Gly.-air	Water-helium	Water- Freon-12	Water- air	Surfactant -air	
± 20%	82.1	33.9	37.2	43.77	42.67	45.57	64.88	93.23	65.79	83.67	55.0
± 30%	97.0	83.5	63.4	75.2	61.14	70.20	88.39	100.00	89.29	98.47	79.5
± 40%	98.8	98.4	86.0	91.84	73.71	79.56	100.00	100.00	96.40	99.23	90.8
± 50%	99.1	99.2	93.4	96.08	81.71	85.96	100.00	100.00	98.31	100.00	94.5
$\bar{e}(\%)$	-4.1	-17.3	+17.6	+3.75	30.27	29.11	-12.04	4.45	-7.59	-4.46	7.4
$\bar{e}_r(\%)$	15.8	23.8	29.3	25.8	42.85	38.67	18.56	11.27	20.71	14.35	27.5
N	329	511	966	1806	525	406	336	266	532	392	4263

7.4 MEAN HEAT-TRANSFER COEFFICIENTS

The two-phase mean heat-transfer coefficients were evaluated from the local values by applying a length-mean integration to the local values. Details of the calculation procedure are given in Appendix D.

Experiments with water-air mixtures were performed first, prior to obtaining heat-transfer data for the other liquids, mainly to check the performance of the experimental apparatus and to ensure that the data repeated well when compared with previous water-air results. Comparison of the present water-air data with the previous data of (1,93,107) is shown in Fig. 7.8, which reveals excellent agreement with them. The data of Vijay (93) and Zaidi (107) at $V_{SL} = 0.185$ ft/s (0.056 m/s) are those obtained after applying a small heat balance correction to the original data. The continued satisfactory performance of the rig was therefore established and it was believed that any data obtained further would be accurate and reliable. Repeatability tests were also performed during and at the end of the present investigation. The overall algebraic and r.m.s. deviations were -4.9% and 6.6%, respectively. (Details are given in Appendix E.)

The mean heat-transfer coefficients taken during the present work are plotted as a function of V_{SG} with V_{SL} as a parameter; these plots are shown in Figs. 7.9 to 7.11 B for

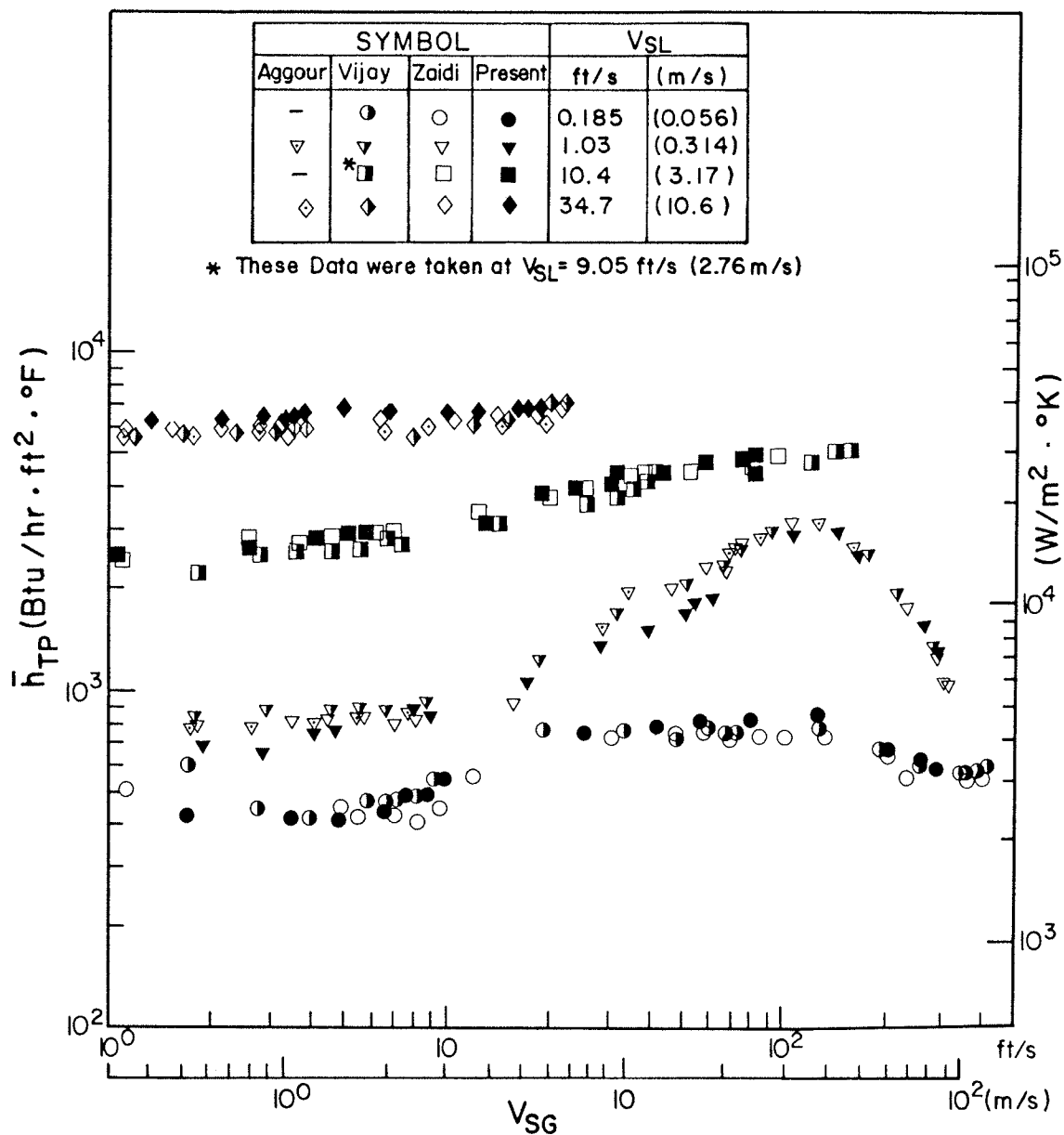


Fig. 7.8 Comparison of Present Water-Air $\bar{h}_{TP}$ Data with the Previous Data of Vijay, Aggour and Zaidi

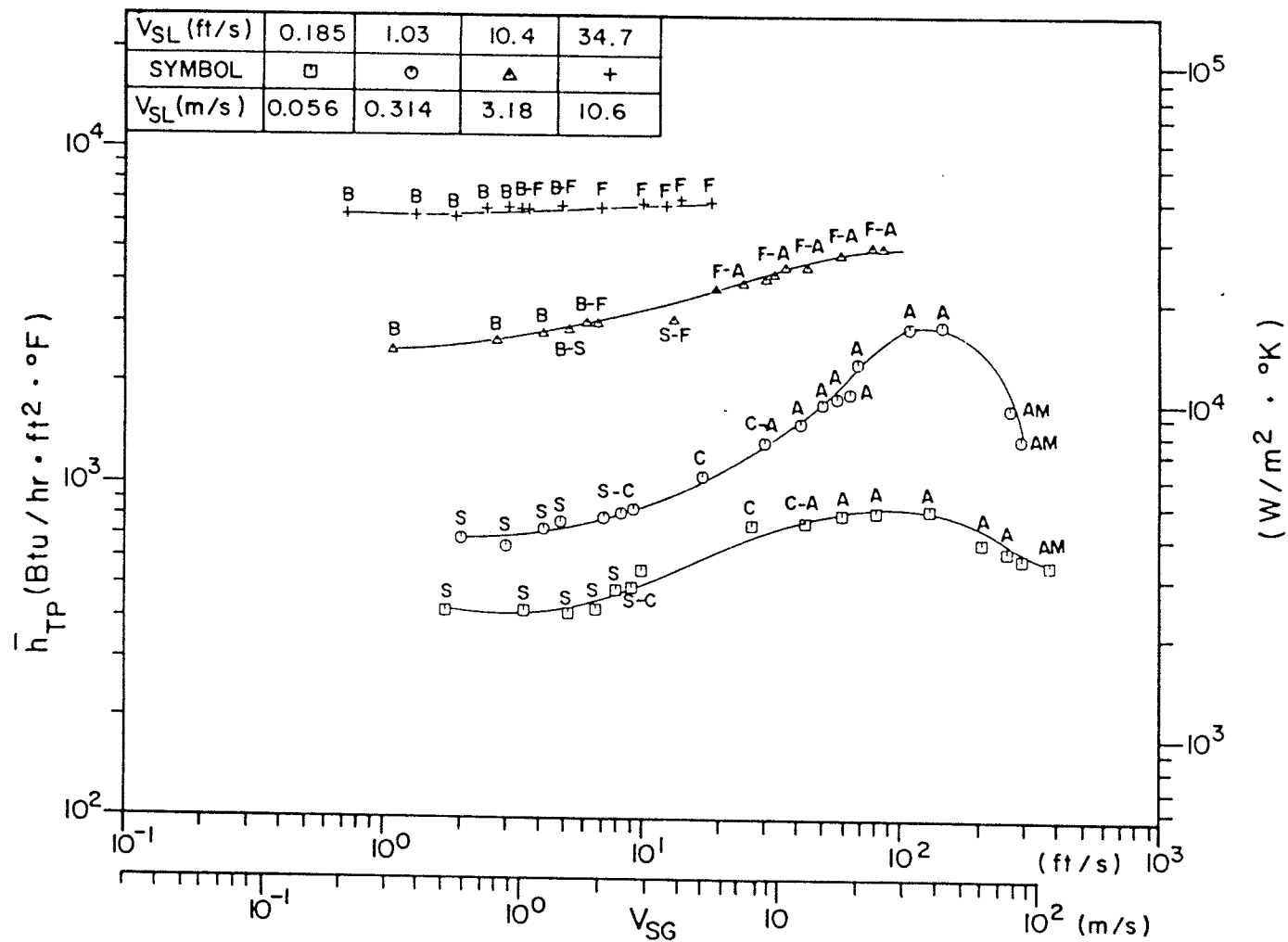


Fig. 7.9 Water-Air Mean Heat-Transfer Coefficient Results

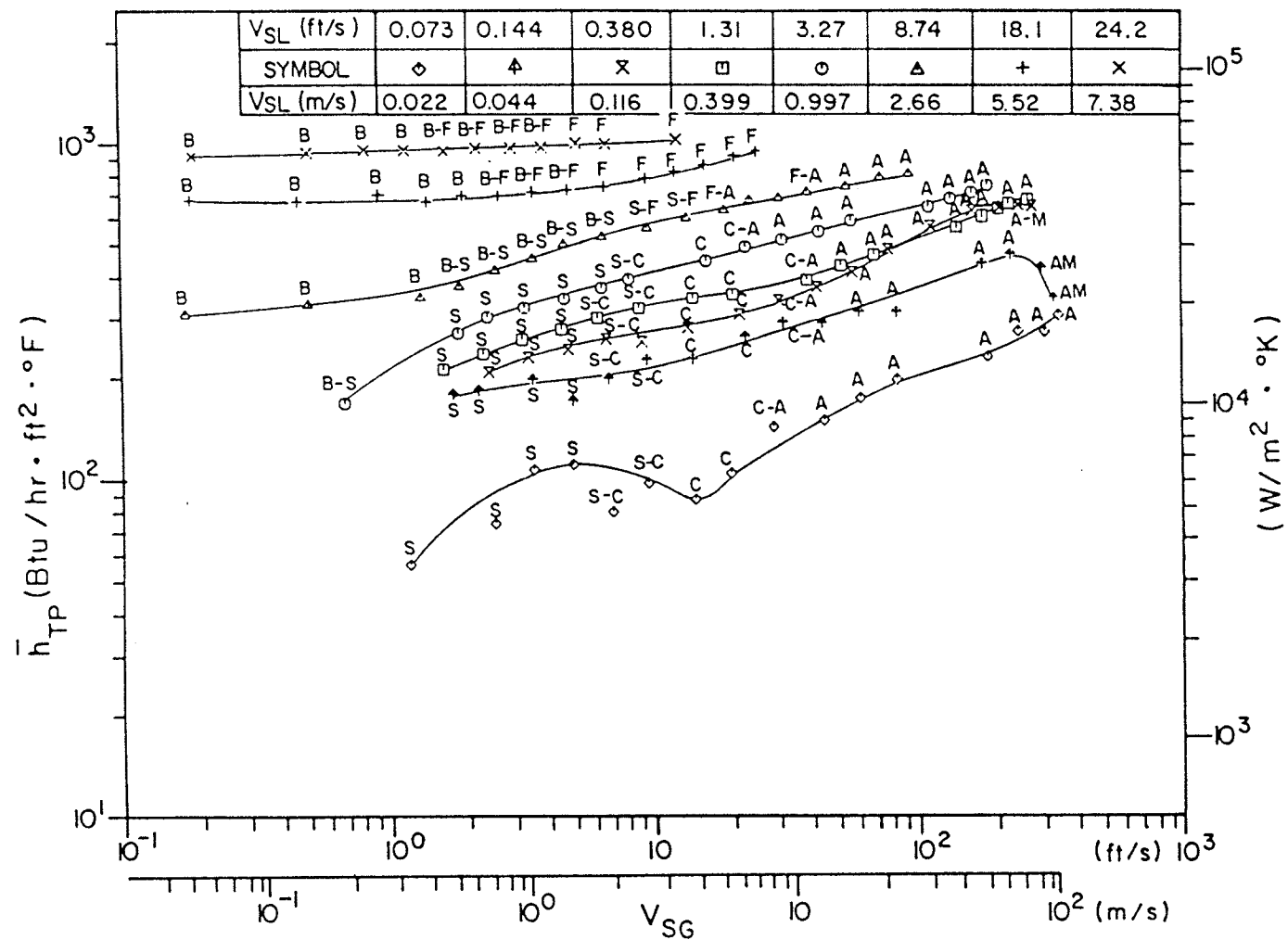


Fig. 7.10 Glycerine & Water-Air Mean-Heat-Transfer-Coefficient Results

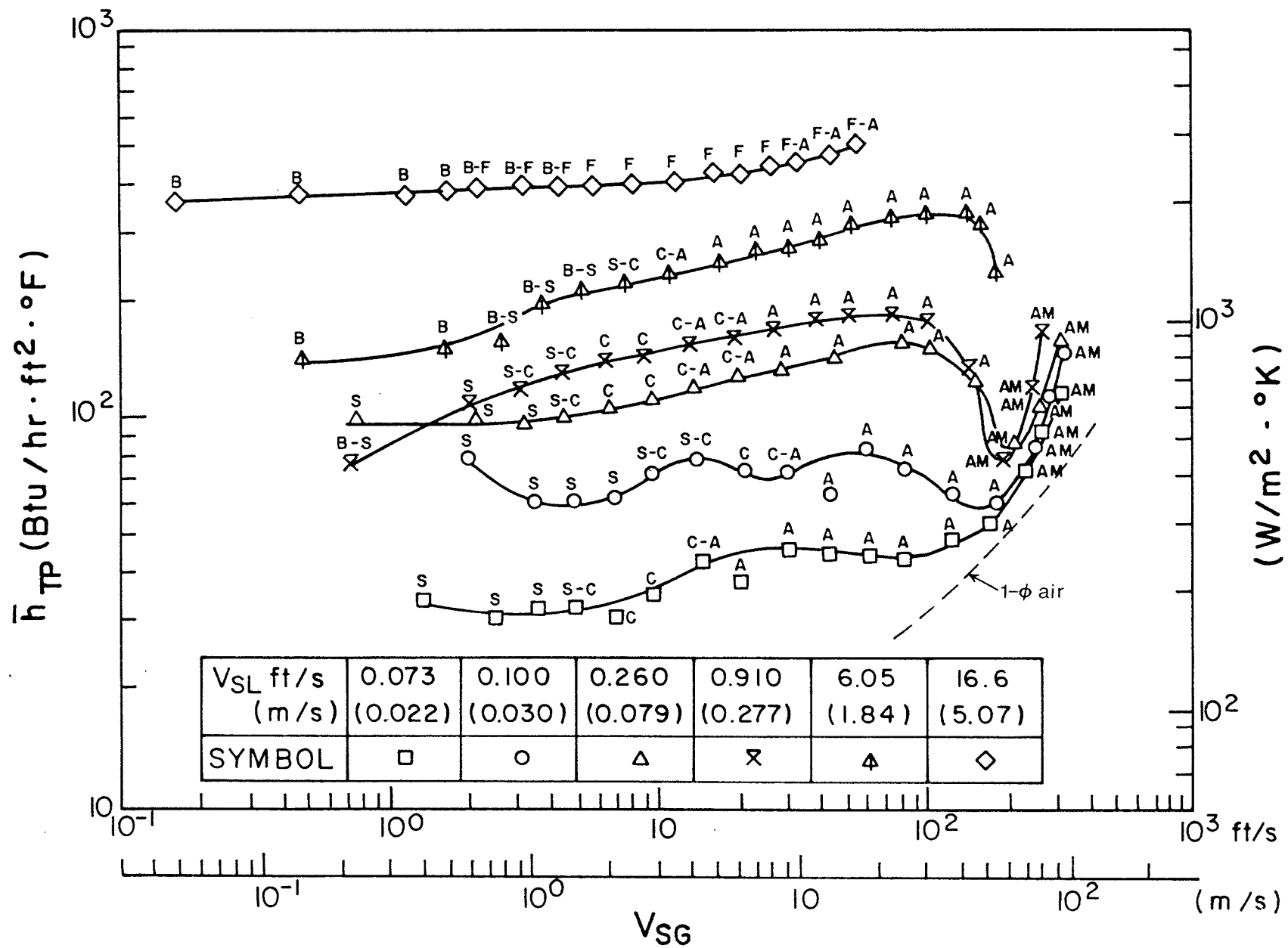


Fig. 7.11A Silicone-Air Mean-Heat-Transfer Coefficient Results

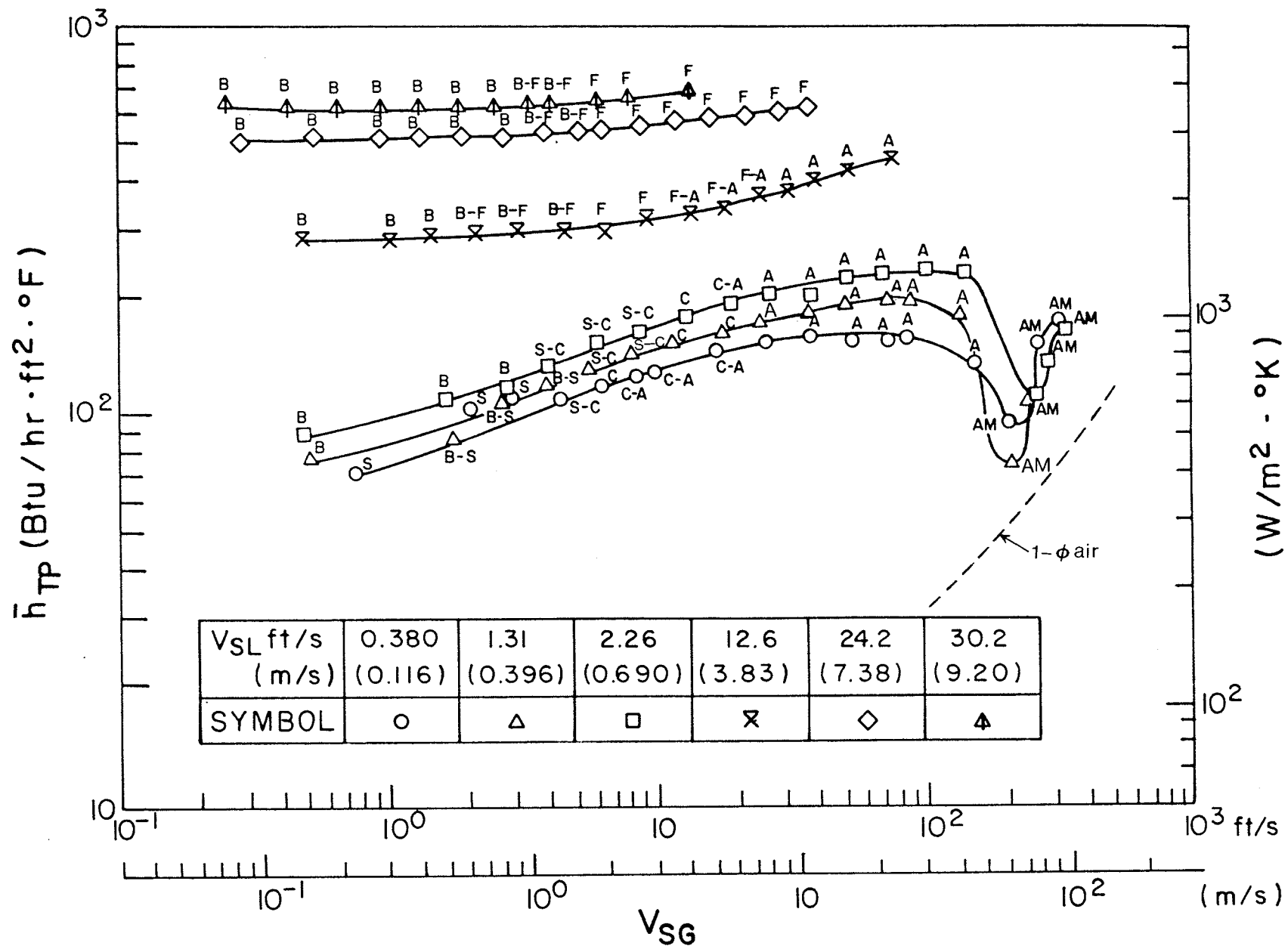


Fig. 7.11B Silicone-Air Mean-Heat-Transfer Coefficient Results (cont.)

water-air, glycerine & water-air, and silicone-air, respectively. The flow pattern observed for each data point is indicated beside it, using the appropriate code (as given in Table 6.1).

The following points can be made from a careful study of Figs. 7.9 to 7.11 B:

1. For a given V_{SL} , $\bar{h}_{TP}$ generally increases with increasing V_{SG} ; the rate of increase of $\bar{h}_{TP}$ depends, however, on the value of V_{SL} . For lower values of V_{SL} , the contribution of the gas phase in increasing $\bar{h}_{TP}$ is more pronounced than at high liquid flow rates.
2. For the lower liquid velocities, typically between 0.100 and 2.25 ft/s (0.030 and 0.690 m/s), an unmistakable maximum in $\bar{h}_{TP}$ is observed. This generally appears as the flow pattern changes from annular to annular-mist. However, this was not the case with the silicone-air data where the flow pattern was still annular at and after the maximum was reached (Figs. 7.11 A & B).
3. For the silicone-air data, at low-to-medium V_{SL} ($0.260 \leq V_{SL} \leq 2.26$ ft/s or $0.080 \leq V_{SL} \leq 0.690$ m/s) the behaviour of $\bar{h}_{TP}$ at high gas flow rates differs from that seen with other liquids. Initially, as with other liquids, for any liquid velocity within this range, $\bar{h}_{TP}$ increases with an increase of the

gas flow rate until it reaches a maximum of about 5.1 to 9.3 of the single-phase value (the ratio decreases as V_{SL} increases). This maximum occurs at a superficial gas velocity of 70.0 to 110.0 ft/s (21.3 to 33.5 m/s) in the annular flow regime. At yet higher gas velocities, $\bar{h}_{TP}$ starts to decrease, reaching a minimum of about 1.6 to 5.3 the value of $\bar{h}_{SP}$ after which $\bar{h}_{TP}$ increases again.

From extensive visual observations of the flow pattern in those regions of substantial drop of $\bar{h}_{TP}$, it was found that these minima in $\bar{h}_{TP}$ occurred just as the flow was getting to the annular-mist transition at gas superficial velocity of about 200.0 ft/s (61.0 m/s). A further increase in the gas flow rate resulted in a monotonic increase of $\bar{h}_{TP}$ analogous to that for single-phase air flow (though it was less steep for the latter).

It is believed, therefore, that the behaviour of $\bar{h}_{TP}$ in the annular-mist flow transition could be basically attributed to the possibility that at the very high gas flow rates ($V_{SG} \geq 200$ ft/s), the annular-mist flow behaves in a manner analagous to that of a single-phase gas flow. In order to explain this further, consider Fig. 7.12, taken from Ref. (47).

This plot of the ratio Nu_x/Nu_∞ against the distance from the entrance shows the strong influence of Prandtl number on the local heat-transfer coefficients in circular tubes with a constant heat rate. From the same figure, it can be seen that at $x/D = 25$ (half way through the test section of the present investigation), the local Nusselt number of the fluid with $Pr = 0.7$ (like air) is still decreasing and that the ratio Nu_x/Nu_∞ is higher than that for fluids with higher Pr .

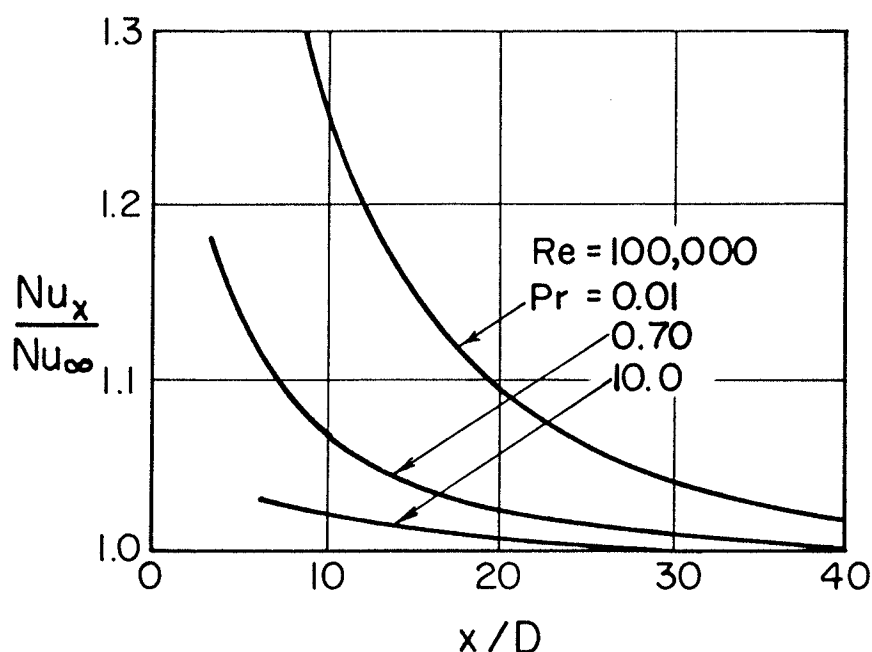


Fig.7.12 Nusselt Numbers in the Thermal Entry Length of a Circular Tube, Constant Heat Rate, Taken from Ref. (47)

The local-heat-transfer data, presented earlier in this chapter, showed a similar trend of h_{TP} against Z at high gas flow rates. Identification of these points, where h_{TP} decreased along Z , would indicate that this trend occurred after the maximum in $\bar{h}_{TP}$ was reached; this was consistent for all three liquids used in the study. For water-air and glycerine & water-air, this trend took place as the mixture was getting into the annular-mist transition. However, for the silicone-air data, the flow pattern was still annular after the maximum in $\bar{h}_{TP}$ was reached (the procedure of identifying a particular flow pattern and the latter's definition remained unchanged in this case).

Figures 7.13 and 7.14 show the glycerine & water-air and silicone-air data plotted in terms of the two-phase mean Nusselt number $\bar{Nu}_{TP}$ vs V_{SG}/V_{SL} for a Reynolds numbers range of 84 to 13,025. The silicone-air data (with the exception of the lowest two liquid velocities) appears to lie above the glycerine & water-air data up to the maximum in $\bar{Nu}_{TP}$ after which the silicone-air data drop significantly, as discussed earlier. Table 7.3 gives the ratio of the Nusselt numbers for the two liquid-air combinations, for the same Pr and Re .

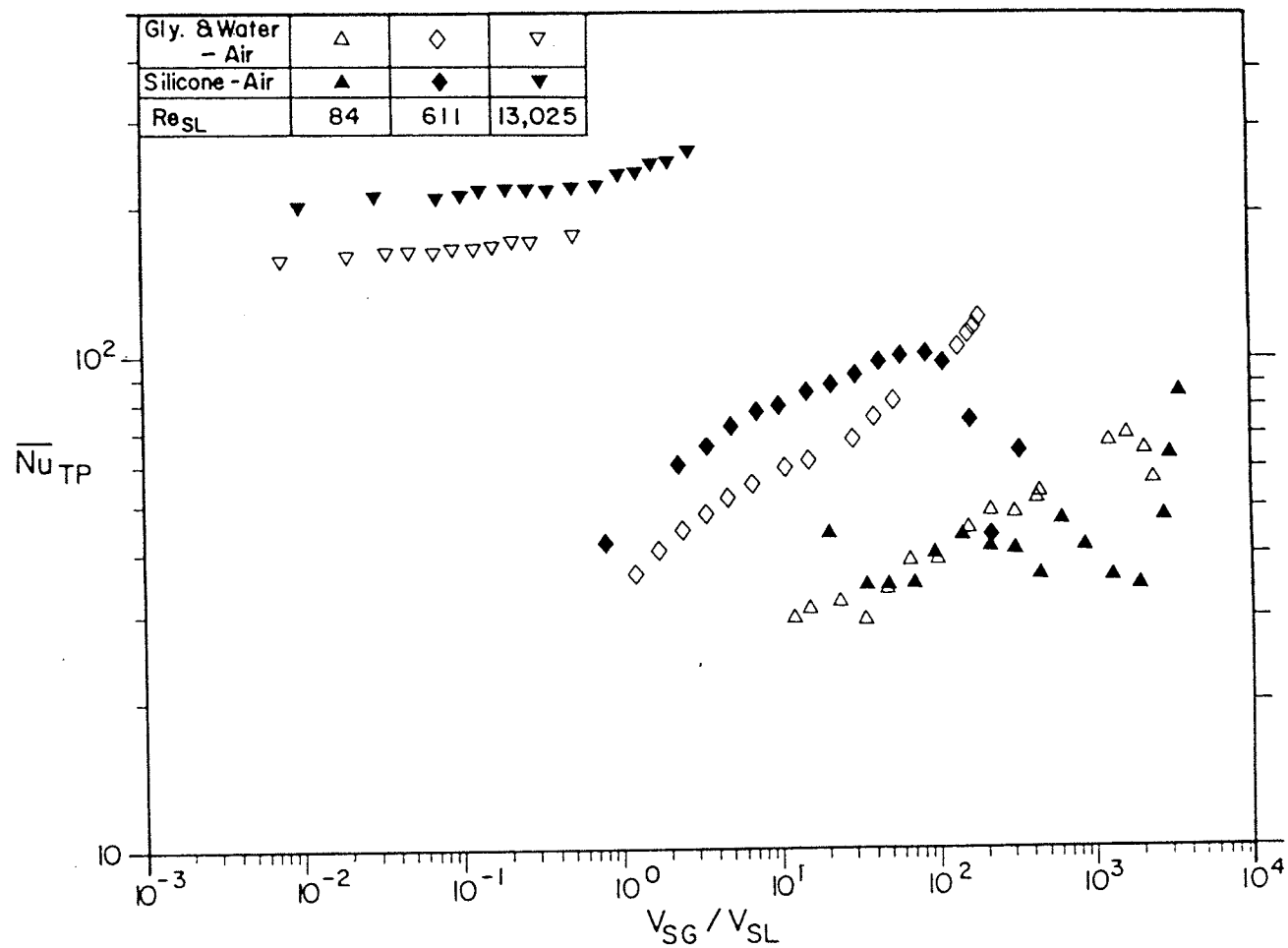


Fig. 7.13 Mean Nu_{TP} vs V_{SG}/V_{SL} for Glycerine & Water-Air and Silicone-Air Data, Same Re_{SL}

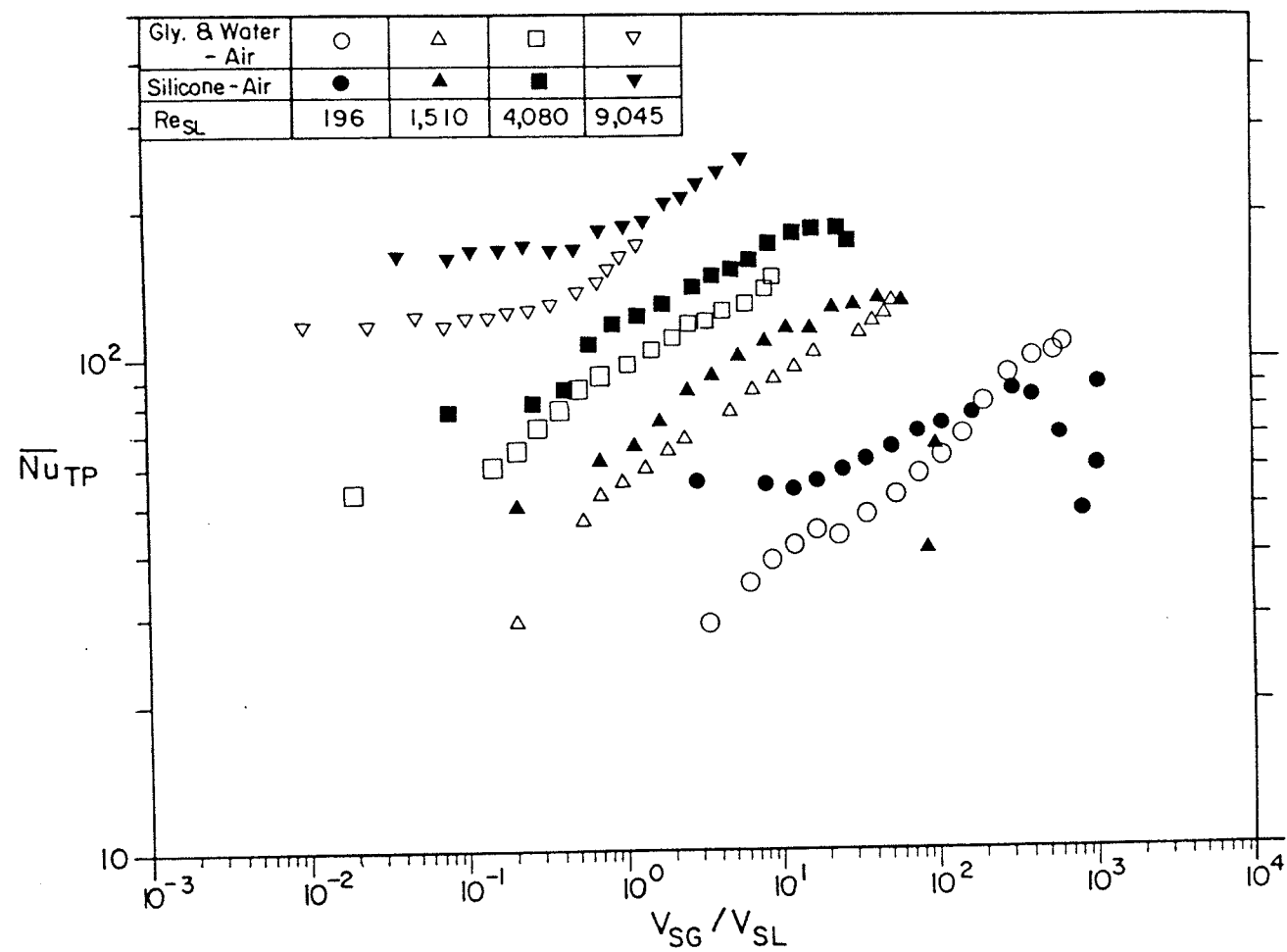


Fig. 7.14 Mean Nu_{TP} vs V_{SG}/V_{SL} for Glycerine & Water-Air and Silicone-Air, Same Re_{SL} (cont.)

Table 7.3

Tabulated Values of the Ratio
 $\bar{Nu}_{TP}$ (Silicone-Air)/ $\bar{Nu}_{TP}$ (Glyc. & Water-Air)

Re_{SL}	Ratio
196	1.9-1* [<1 for $V_{SG} > 200$ ft/s (67.0 m/s)]
611	1.4-1* [<1 for $V_{SG} > 100$ ft/s (30.5 m/s)]
1,510	1.6-1* [<1 for $V_{SG} > 60.0$ ft/s (18.3 m/s)]
4,080	1.4-1.2
9,045	1.4-1.11
13,025	1.3

* at approximately the maximum in $\bar{Nu}_{TP}$ for the silicone-air data

Another attempt was made to compare both sets of data by plotting the ratio $\bar{h}_{TP}/\bar{h}_{SP}$, where $\bar{h}_{SP}$ is the measured single-phase heat-transfer coefficient, against V_{SG}/V_{SL} ; this is shown in Figs. 7.15 to 7.17. Examination of these figures shows that the corresponding data of both liquids have slightly collapsed, with the silicone-air data being higher up to the maximum in $\bar{h}_{TP}$ (this applies to all Reynolds numbers except the lowest Re_{SL}).

Also, for the highest glycerine & water-air liquid velocities, the two-phase heat-transfer coefficient fell slightly below the single-phase value (see Fig. 7.17). The same results were obtained with the water-air data for the present study and also with the water-air, glycerine & water solution (75% - 25% by weight)-air and glycerine-air data of Vijay (93) and water-helium data of Aggour (1). For all cases, this occurred mainly in the bubble and froth regions at high liquid superficial velocities with a minimum ratio

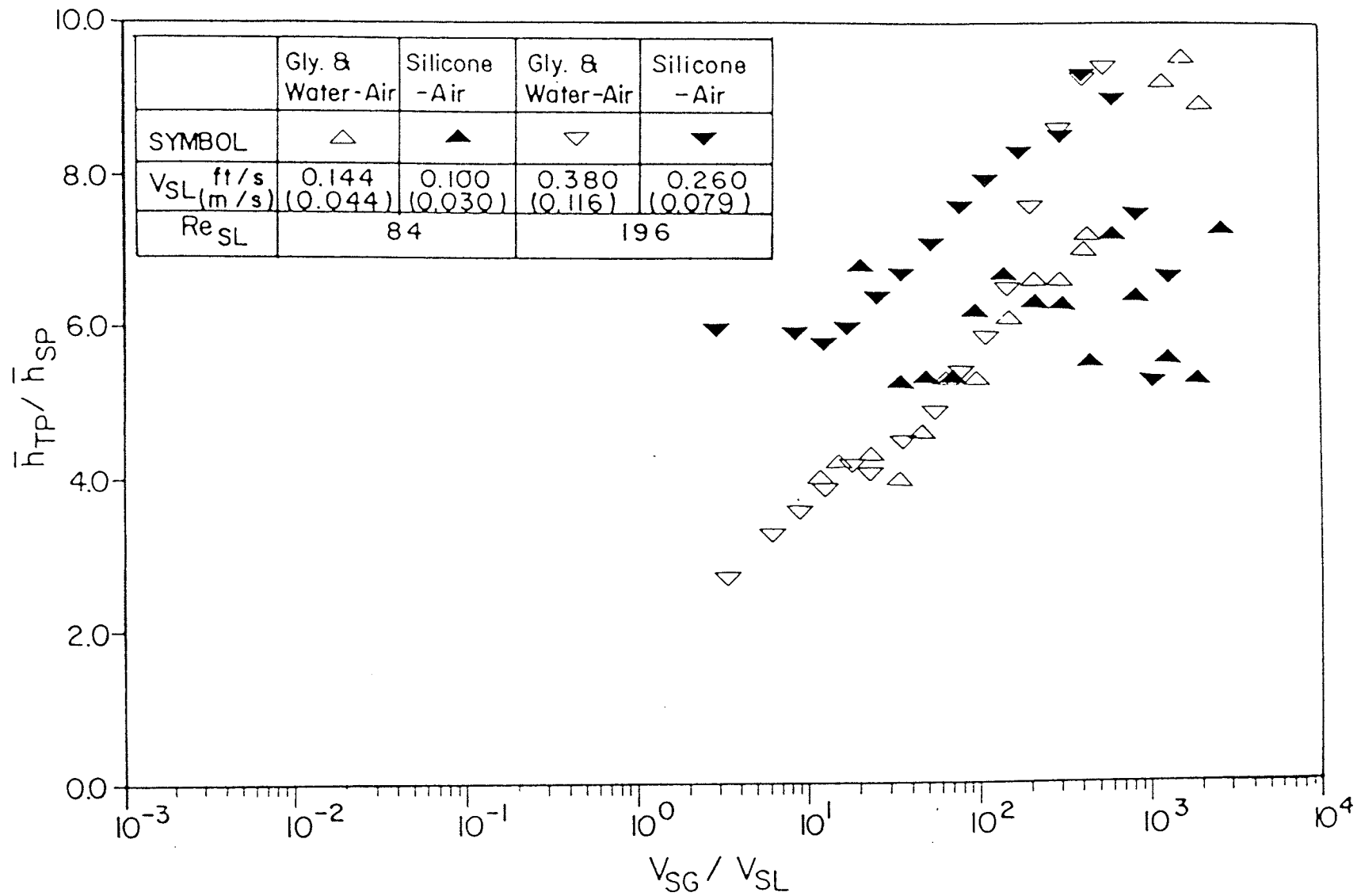


Fig. 7.15 Comparison of the Mean Heat-Transfer Coefficients Between Glycerine & Water-Air and Silicone-Air Data, Laminar Flow

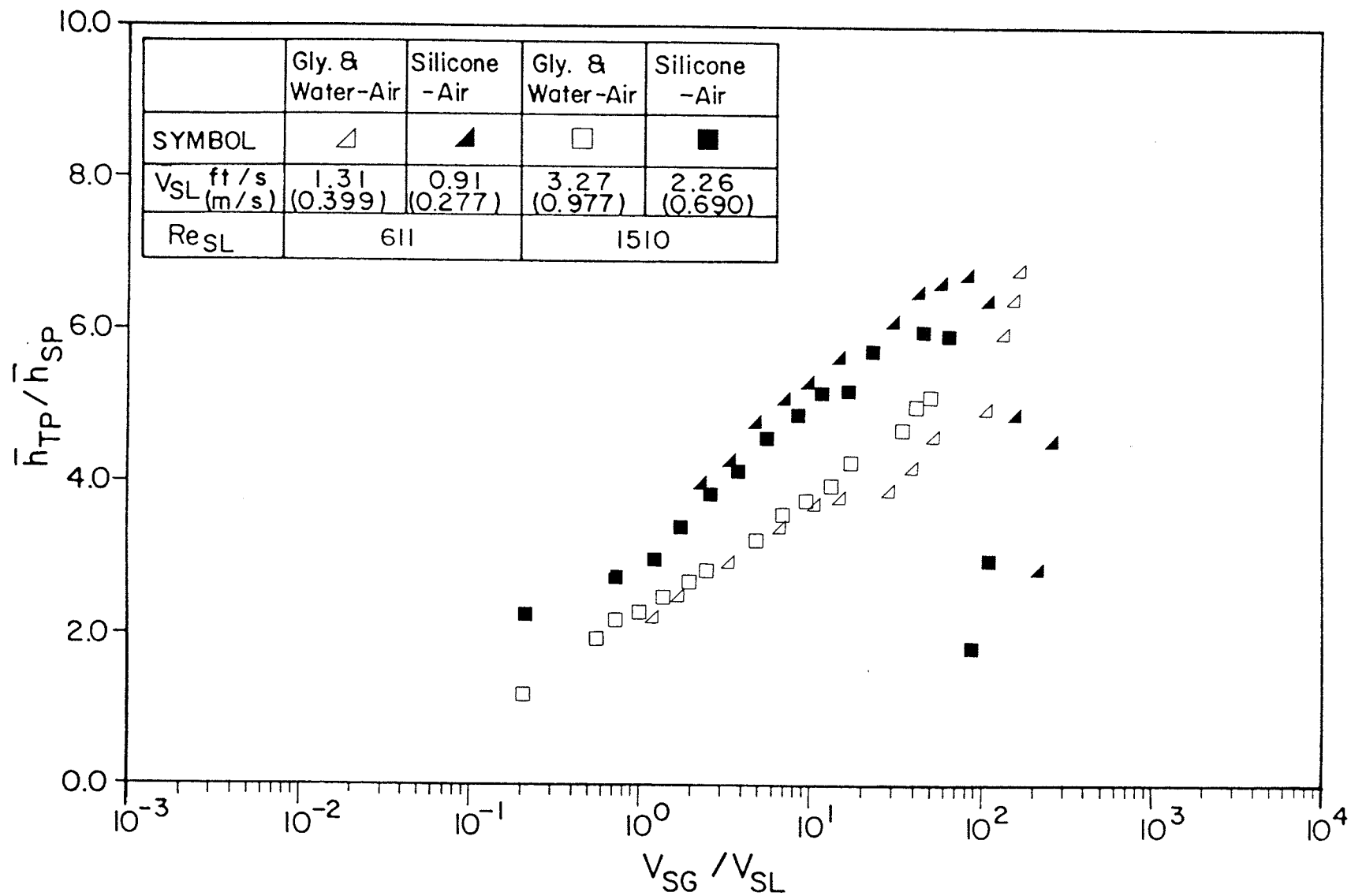


Fig. 7.16 Comparison of the Mean Heat-Transfer Coefficients Between Glycerine & Water-Air and Silicone-Air Data, Laminar Flow (cont.)

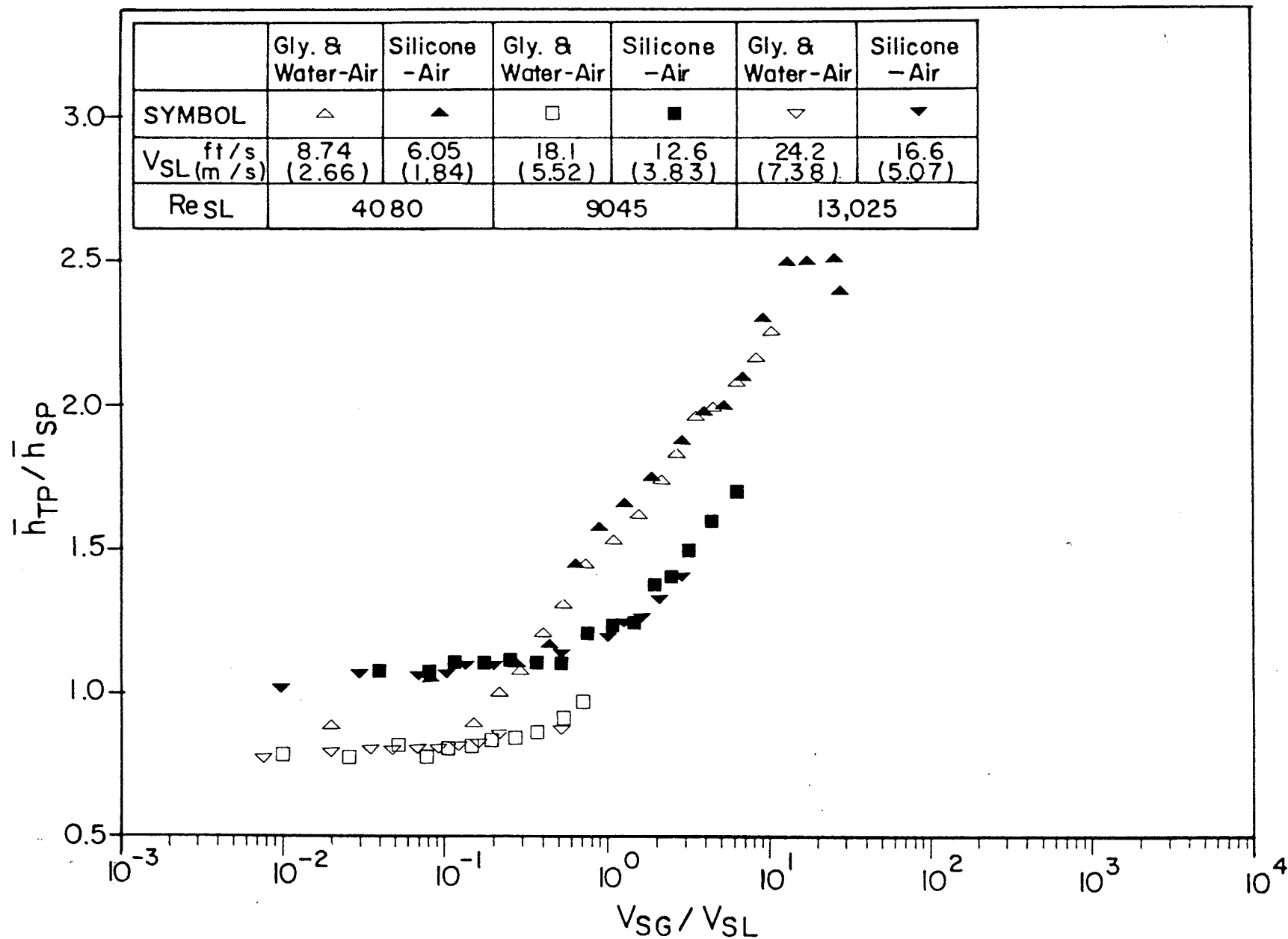


Fig. 7.17 Comparison of the Mean Heat-Transfer Coefficients Between Glycerine & Water-Air and Silicone-Air, Turbulent Flow

of approximately 0.8. Other authors, like Knott et al. (53), have reported similar results. In their paper, the authors presented their data on similar co-ordinates ($\bar{h}_{TP}/\bar{h}_{SP}$ against V_{SG}/V_{SL}). From that plot it can be seen that some of the oil-nitrogen heat-transfer data fell below the single-phase values (the lowest ratio being 0.88). No other attempt was made in the present study to explain this trend of the two-phase heat-transfer coefficient in the bubble and froth regions.

Zaidi (107), in his study using surfactant solution-air and water-air, reported that when the surface tension of water was reduced by adding a surfactant, it produced very little effect on $\bar{h}_{TP}$ and that the tendency was for $\bar{h}_{TP}$ to be lower for the surfactant solution than for water. The differences were believed to be significant where changes in the flow patterns were observed (mainly in the bubble and slug regions). Figure 7.18, taken from Ref. (108), shows the two velocities where the author (107) believed significant differences were observed.

Other investigations done using liquids with lower surface tension than that of water are those by Domanskii et al. (23), Ueda and Hanaoka (90) and Perroud and de laHapre (70). For the first two, the results were not adequately given in the original papers, and the third investigation was carried out with substantial evaporation. Also, Ravipudi (75) conducted a heat-transfer test using a toluene-air mixture. His results showed essentially no

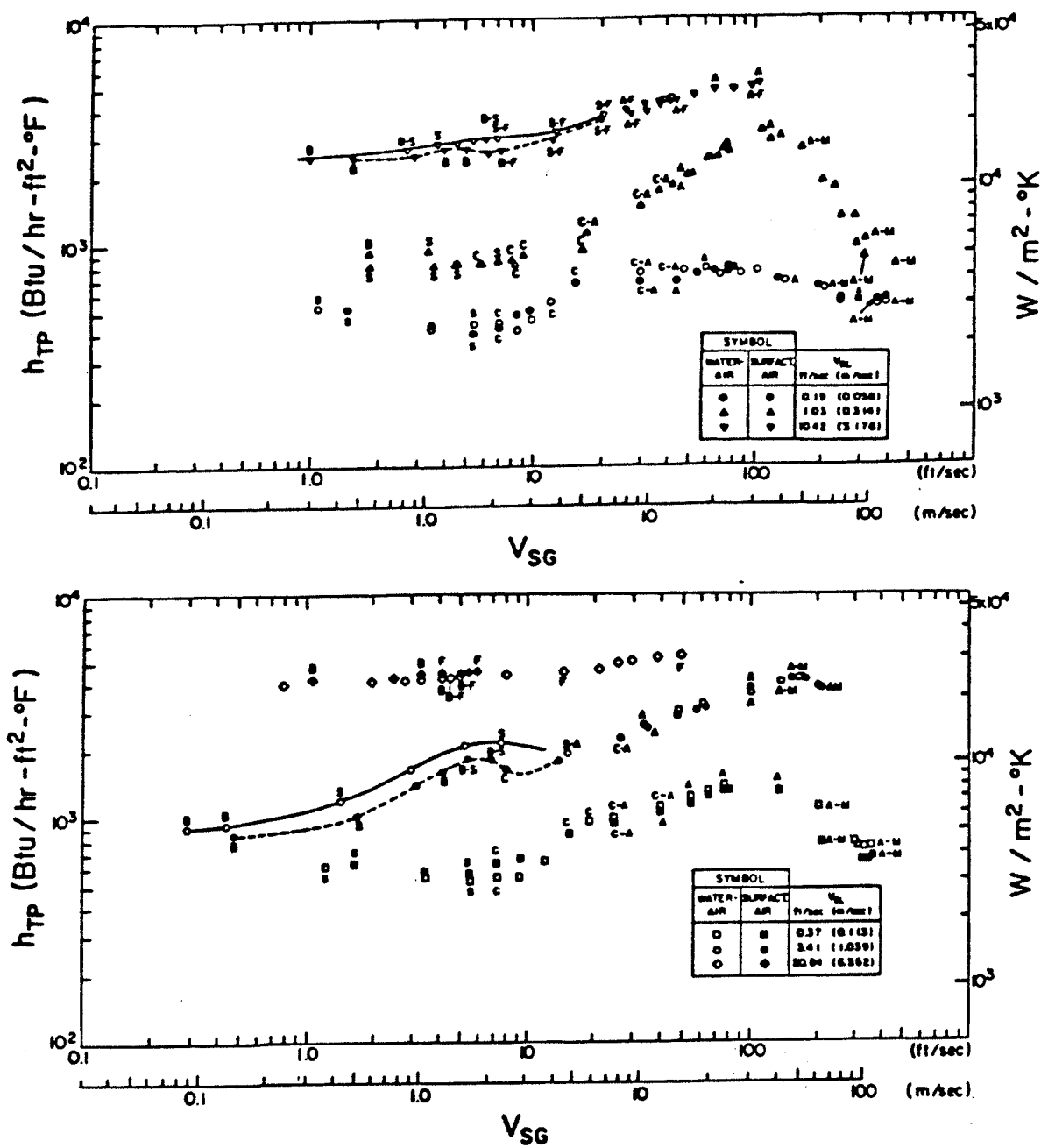


Fig. 7.18 Mean-Heat-Transfer Data of Zaidi, Taken from Ref. (108)

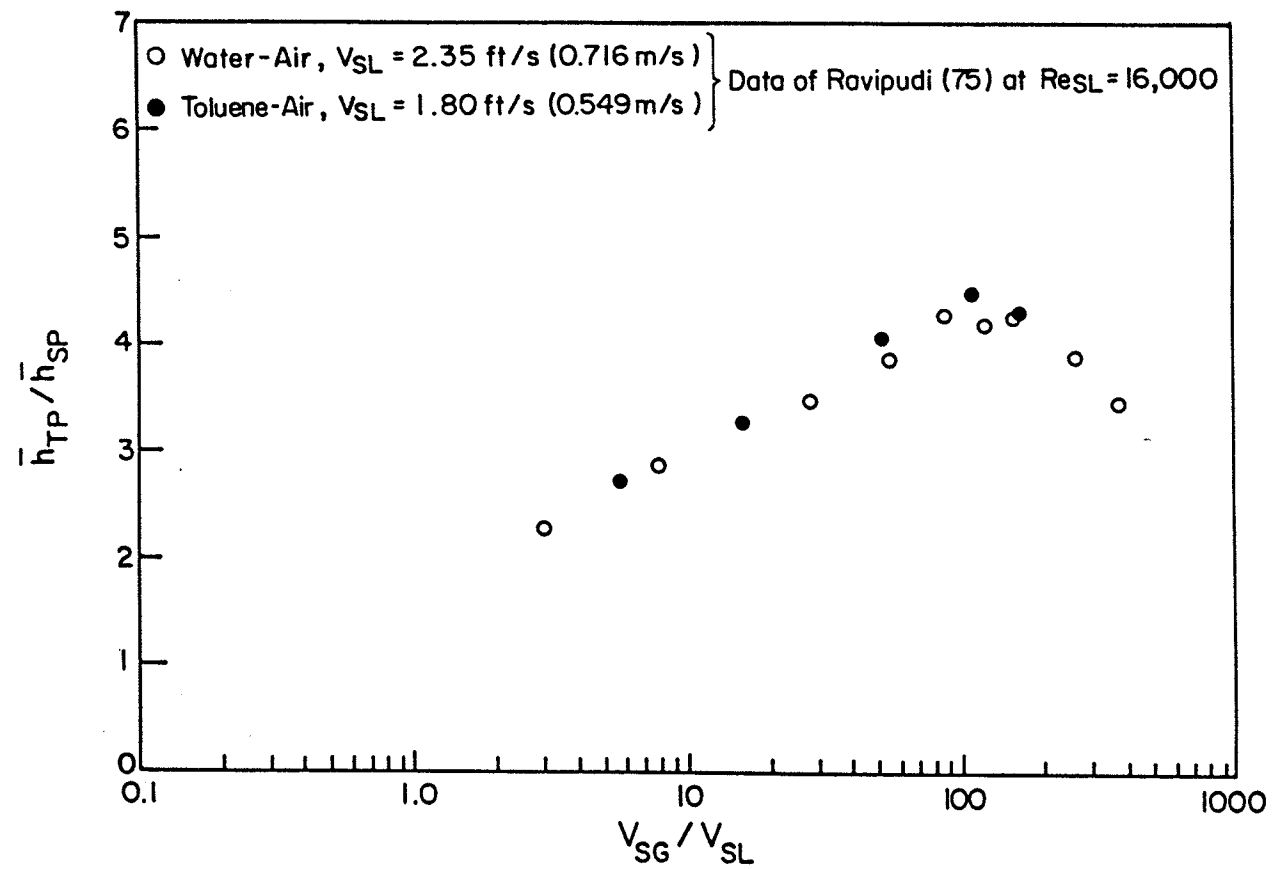


Fig. 7.19 Water-Air and Toluene-Air Mean-Heat-Transfer Data of Ravipudi (75)

effect of surface tension on the mean heat-transfer coefficient (see Fig.7.19) for the same liquid Reynolds number.

From the material presented in this section, the following conclusions could be drawn:

1. The behaviour of the two-phase silicone-air mean heat-transfer coefficients in the annular-mist transition with a sudden drop (after the maximum in $\bar{h}_{TP}$ was reached) followed by a monotonic rise with further introduction of air could be basically attributed to the very thin film on the tube wall. This in turn attends a condition where the gas phase becomes more important in the heat-transfer process than at lower gas mass flow rates.
2. When comparison was made between the glycerine & water-air and silicone-air data at the same Re_{SL} (in the range of $Re_{SL} < 2000$) and V_{SG}/V_{SL} , the two-phase mean Nusselt numbers were higher for the silicone-air data up to the maximum in Nu_{TP} , after which the data cross. At $Re_{SL} > 2000$, the silicone-air data were 10 to 40% higher than those for the glycerine & water-air for the entire range of gas flow rates.

7.5 COMPARISON OF THE MEAN HEAT-TRANSFER COEFFICIENTS

In this section, the mean-heat-transfer data, taken during the present investigation, were first compared with some experimental results of $\bar{h}_{TP}$ in the literature. Then they were compared with some of the existing correlations used to predict the mean heat-transfer coefficients in two-phase flow.

7.5.1 Comparison of the Present Mean-Heat-Transfer Data with Other Data in the Literature

As mentioned earlier in this chapter, the present water-air data showed good agreement when compared with the previous water-air data taken on the same rig by (1,93,107). A search was done to locate other pertinent data in the literature for comparison. Some water-air data were found to be comparable with those of the present investigation. In some cases there were differences in the method of heating, wall temperature, and the tube size, etc. To accommodate these differences, the comparison was done in terms of $\bar{h}_{TP}/\bar{h}_{SP}$ against V_{SG}/V_{SL} ; these coordinates are likely to be less sensitive to such differences.

The present water-air data taken at a liquid velocity of $V_{SL} = 1.03 \text{ ft/s}$ (0.314 m/s) were compared with the water-air data of Groothuis & Hendal (35), Kudirka (55), Ravipudi (75), and Chu (15) at approximately the same V_{SL} . This comparison is shown in Fig. 7.20, from which it can be seen that the agreement between the present data and that of

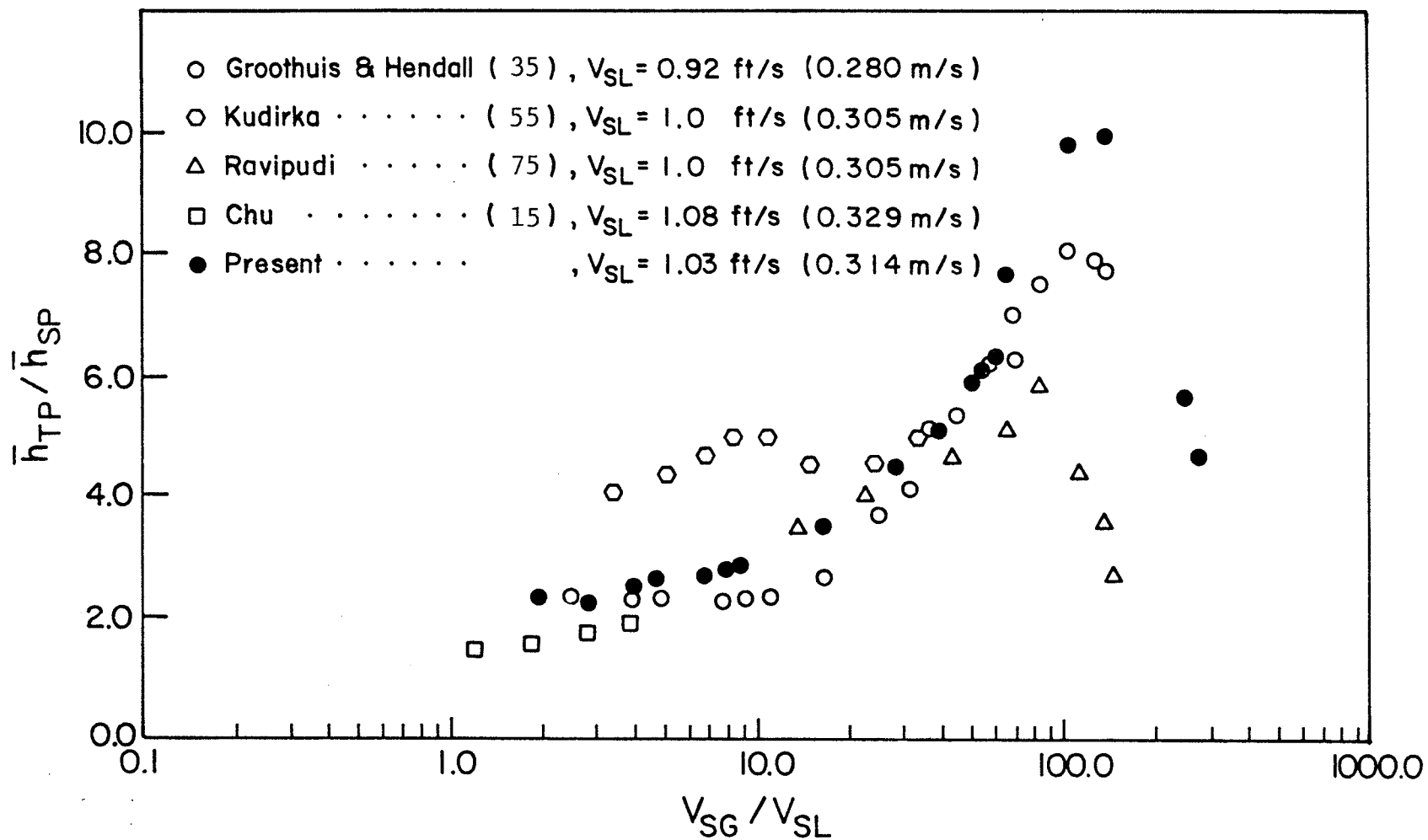


Fig. 7.20 Comparison of Present $\bar{h}_{TP}$ for Water-Air with Some Existing Data in the Literature

Groothuis & Hendal (35) at $V_{SL} = 0.920$ ft/s (0.280 m/s) is quite good up to just before the maximum $\bar{h}_{TP}$, after which the present data lie above them with the $\bar{h}_{TP}$ values decreasing in both cases. The same could be said with the data of Ravipudi (75). Also, the data of Chu (15) compared quite well in its range of V_{SG}/V_{SL} .

For the present water-air data at $V_{SL} = 10.4$ ft/s (3.17 m/s), the comparison was done with those reported by Kudirka (55) and Ravipudi (75) at slightly lower liquid velocities. As shown in Fig. 7.21, the agreement was excellent between the present data and those of Kudirka (55) over the total range of V_{SG} of the latter. For $V_{SG}/V_{SL} > 1.0$, the present data compared well with those of Ravipudi(75) taken at $V_{SL} = 8.0$ ft/s (2.44m/s).

From the comparisons mentioned above, it could be concluded that the present water-air data are in good agreement with those reported in the literature.

7.5.2 Comparison with Some Correlations of the Mean Heat-Transfer Coefficients

In this section, the present data are compared with the correlations of (46, 35, 53, 56, 90, 75, 16, 80, 94, 26, and the Liquid Acceleration Model). The statements of these correlations and their ranges of applicability are given in Table 2.2. A thorough discussion and examination of the eleven correlations is presented in the following chapter;

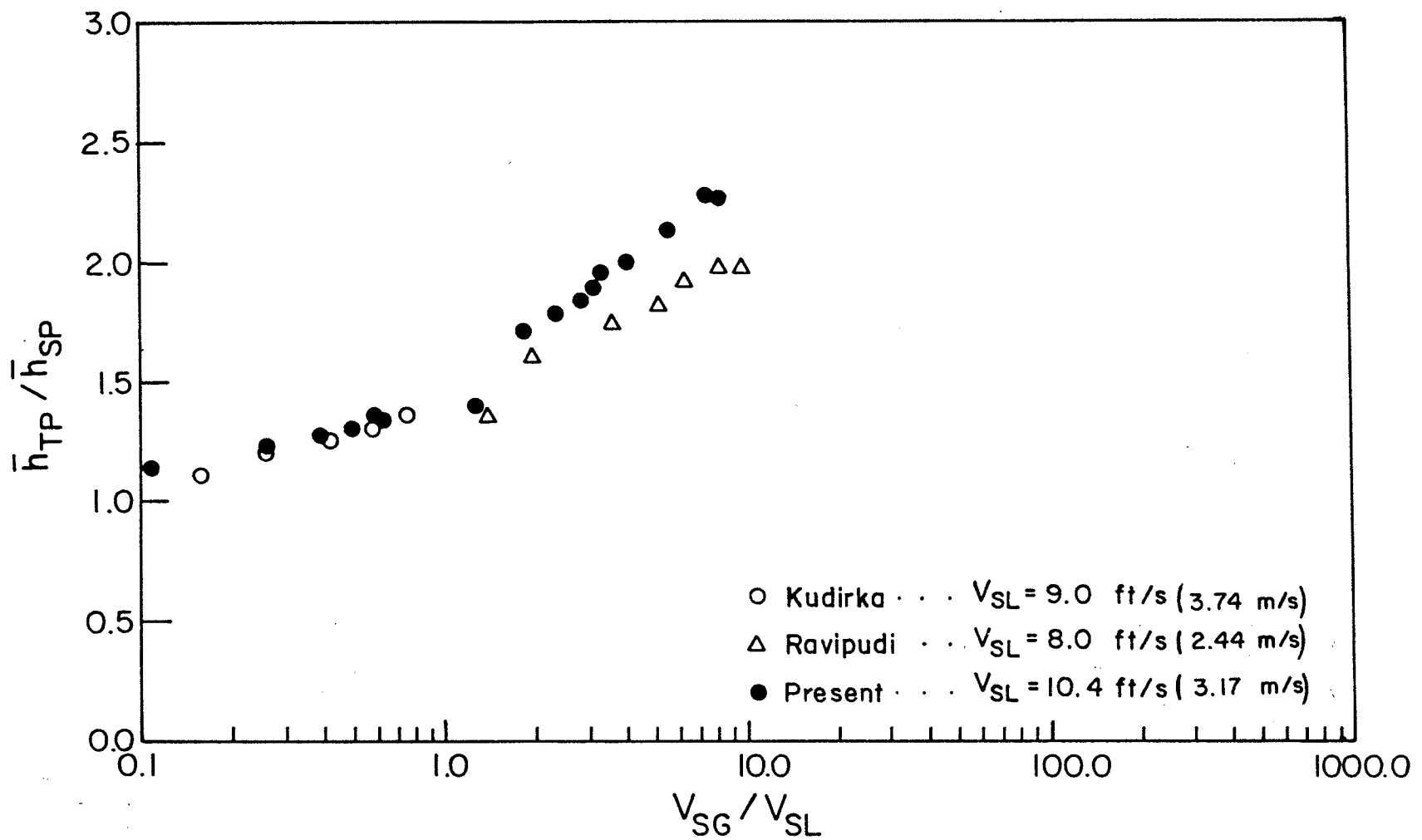


Fig. 7.21 Comparison of Present $\bar{h}_{TP}$ for Water-Air with the Data of Kudirka (55) and Ravipudi (75)

therefore, only a brief discussion of the results is presented in this section. Most of these correlations are given in an algebraic form, except the correlation of Shah (80) for $Re_{SL} > 170$ is given in graphical form. Only the data that fell within the original authors' restrictions were used here in the comparisons. Some of the correlations included dependent variables, e.g. α , $\bar{h}_{SP}$, ΔP_{TPF} . The void fraction was estimated using the correlation of Chisholm (14), while $\bar{h}_{SP}$ and ΔP_{TPF} were the actual measured values. No annular-mist data were used in these comparisons.

The results of the comparisons with most of the correlations are shown in Figs. 7.22 to 7.27 for as much of the present data as the restrictions, proposed by the original authors, allowed. The algebraic mean and r.m.s. deviations between the present data and the eleven correlations are given in Table 7.4, in which N is the number of data points that fell within the range of applicability of each correlation, $\bar{e}$ is the mean algebraic deviation, and $\bar{e}_r$ is the r.m.s. deviation.

A careful examination of the above-mentioned figures and Table 7.4 shows that the best agreement was obtained with the correlations of Vijay et al. (94), Ravipudi and Godbold (76) and the Liquid Acceleration Model (with $n = 0.8$). The comparison with the first was done using the exponent $n = 0.451$ for all the data points. This is presented in Fig. 7.26, which shows the data evenly spread above and below the

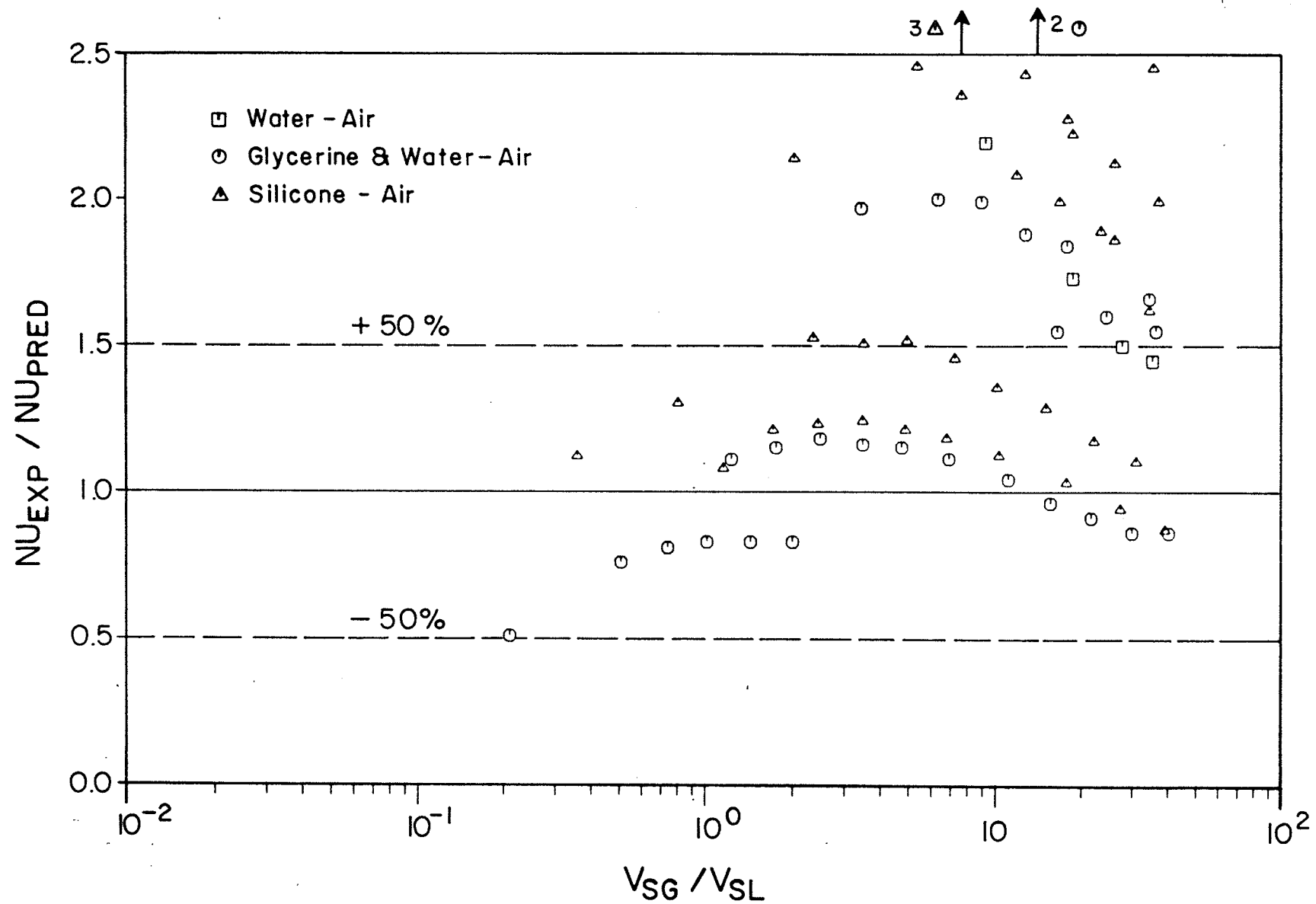


Fig. 7.22 Comparison of Present $\bar{h}_{TP}$ Data with the Correlation of Knott et al.(53)

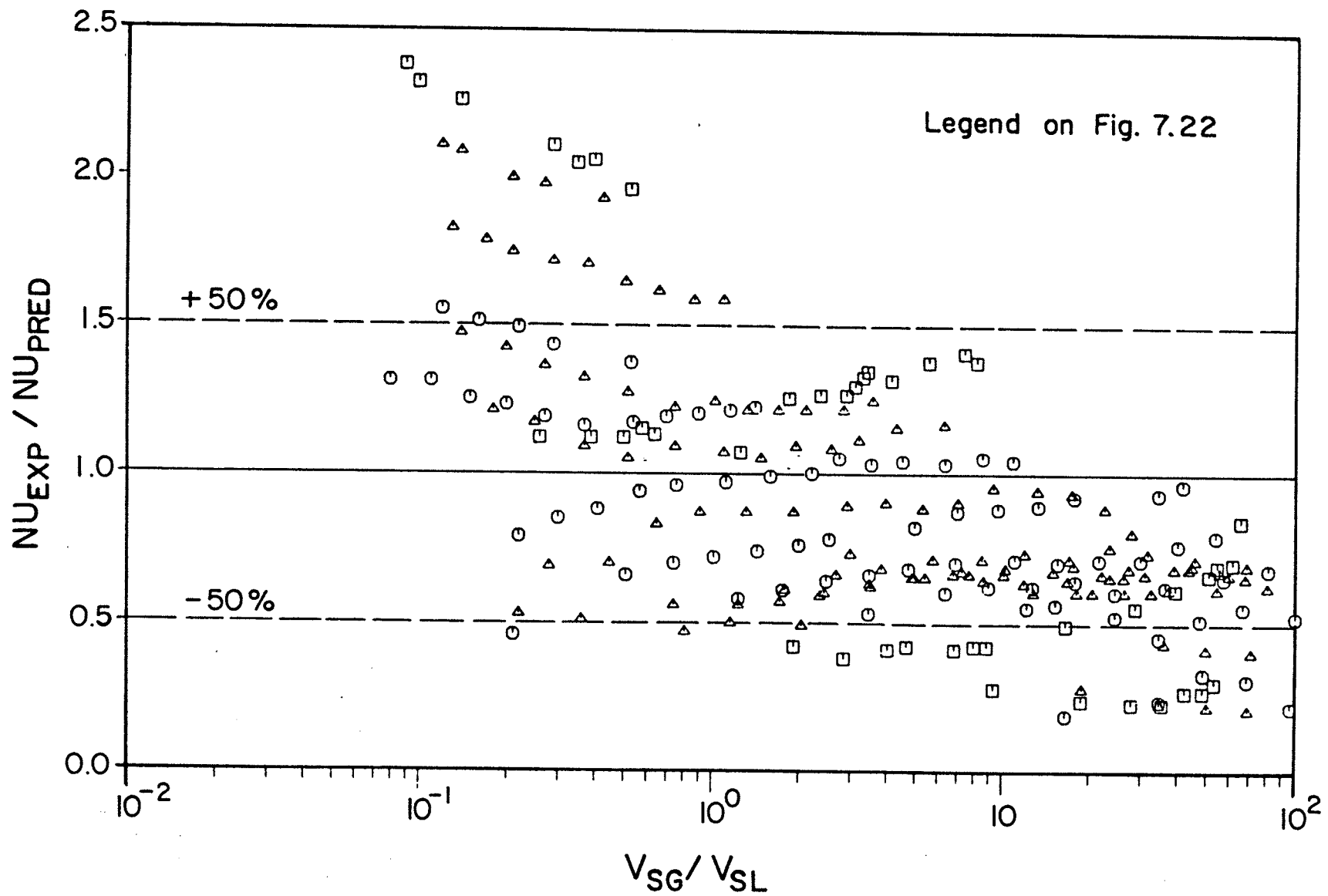


Fig. 7.23 Comparison of Present $\bar{h}_{TP}$ Data with the Correlation of Kudirka et al. (56)

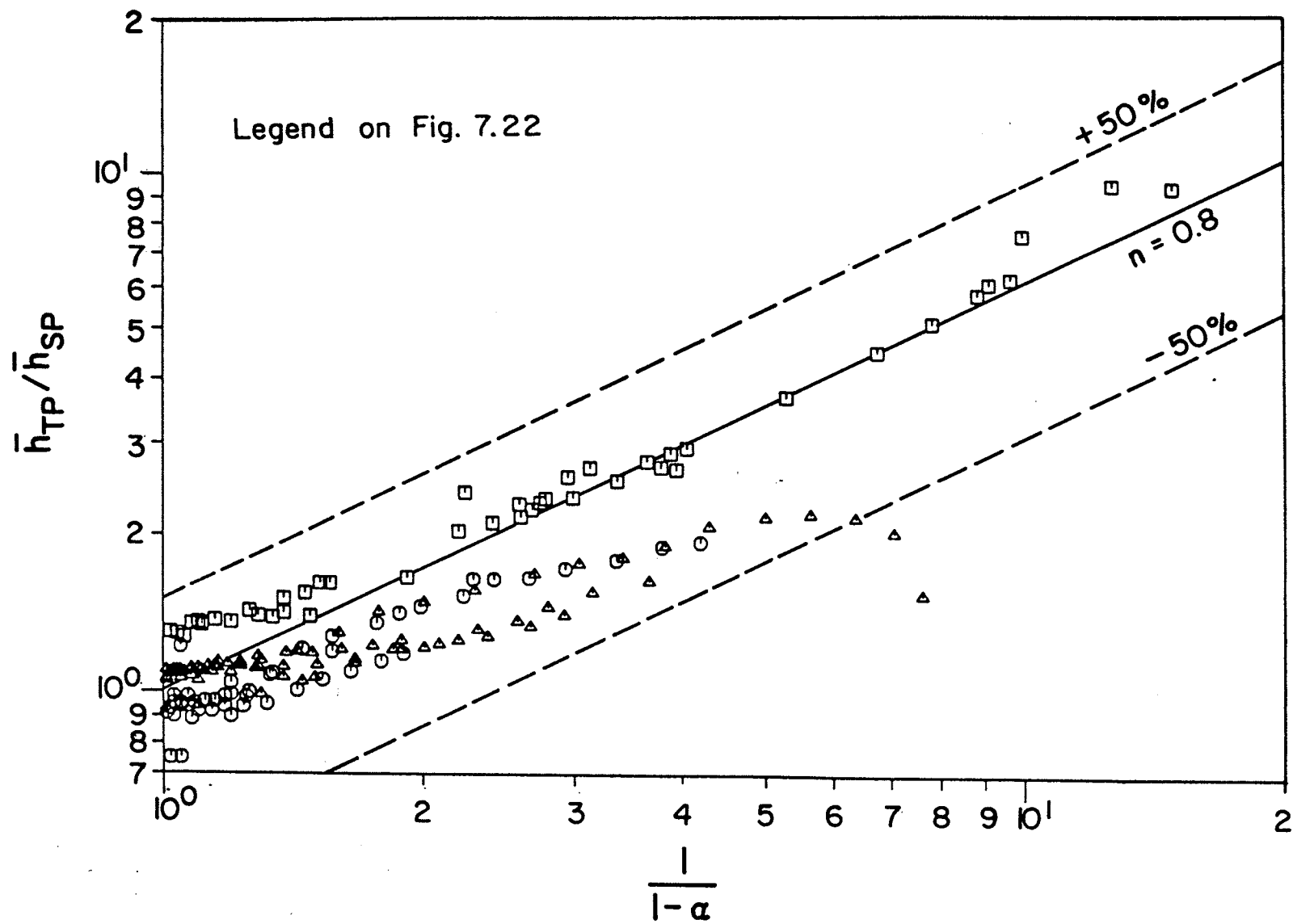


Fig. 7.24 Comparison of Present $\bar{h}_{TP}$ with the Liquid Acceleration Model

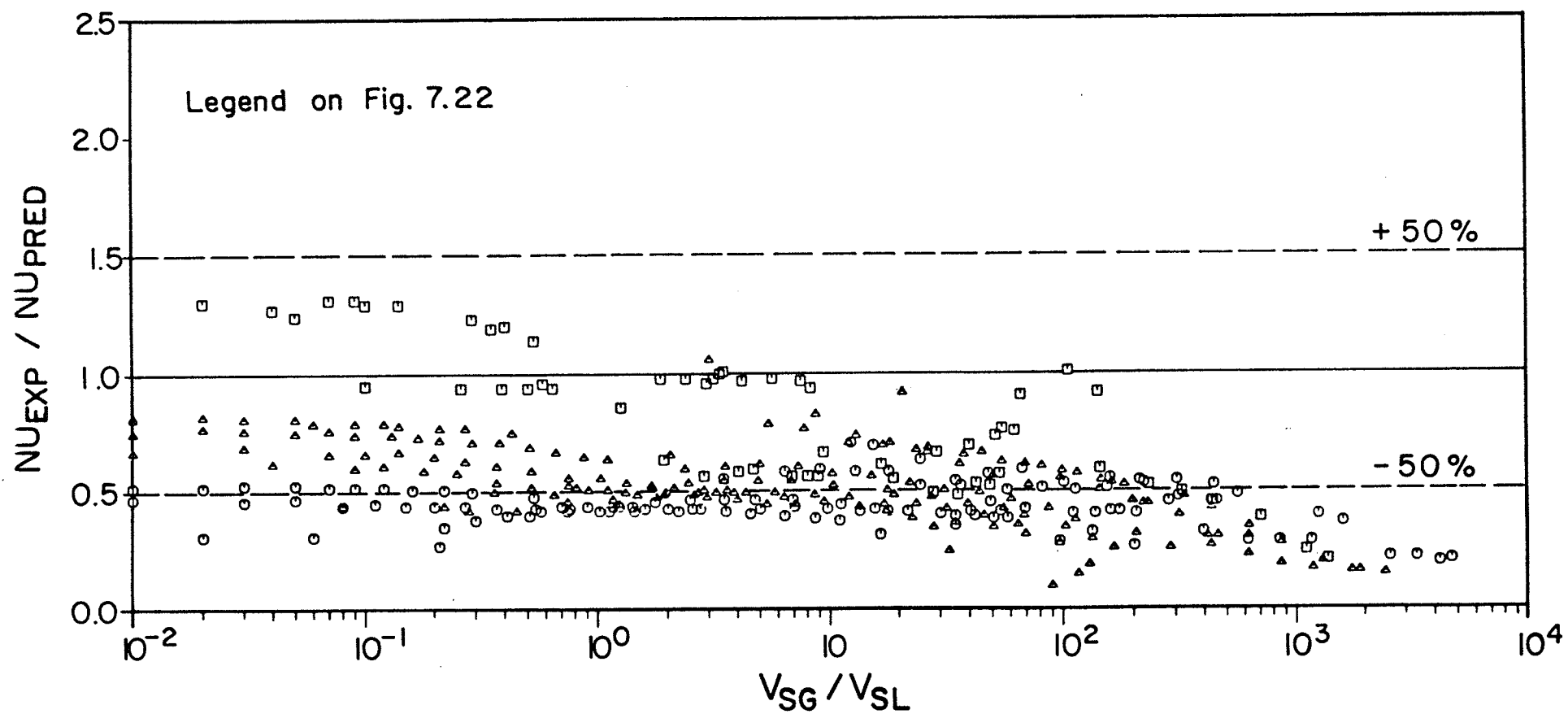


Fig. 7.25 Comparison of Present $\bar{h}_{TP}$ Data with the Correlation of Chu & Jones (16)

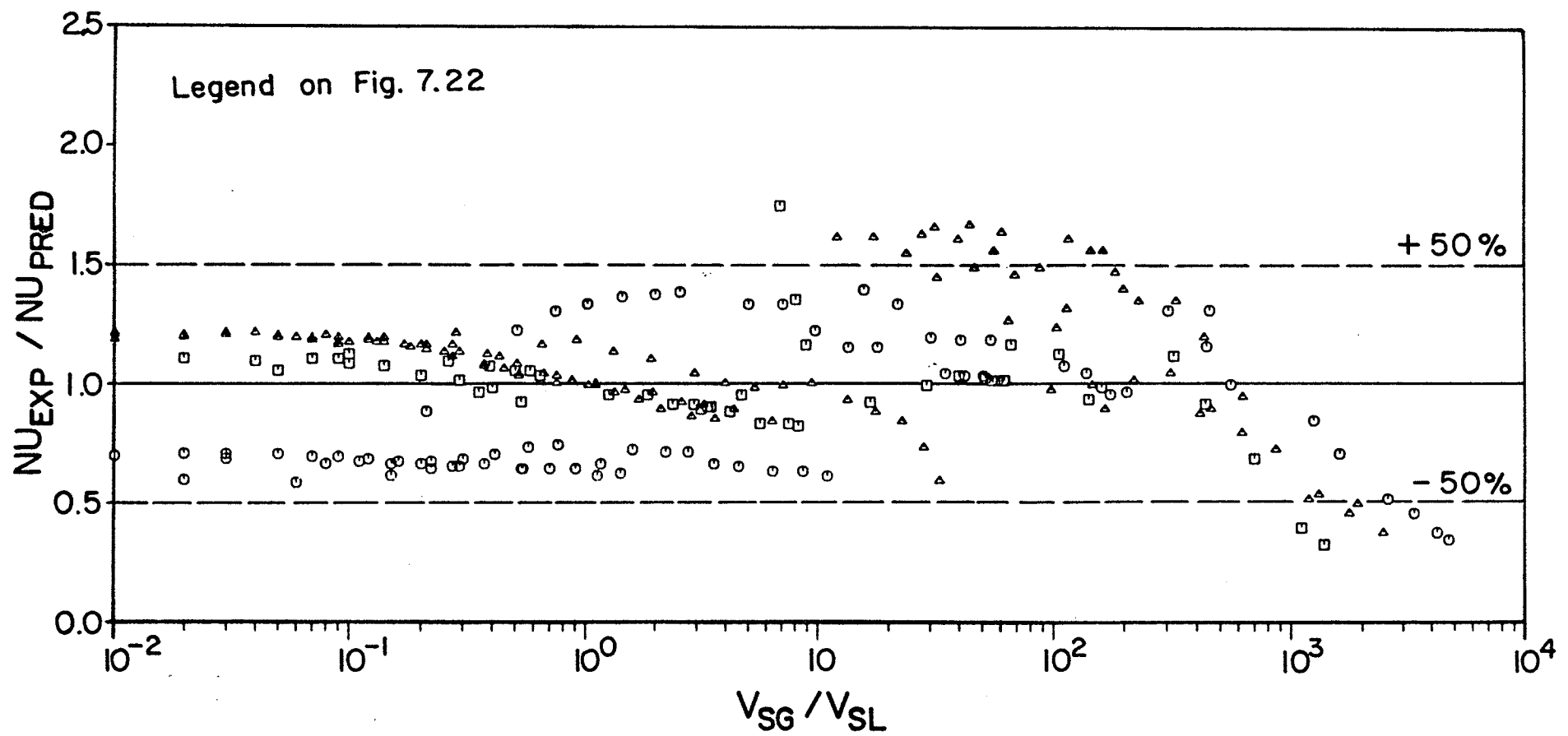


Fig. 7.26 Comparison of Present $\bar{h}_{TP}$ Data with the Correlation of Vijay et al. (94)

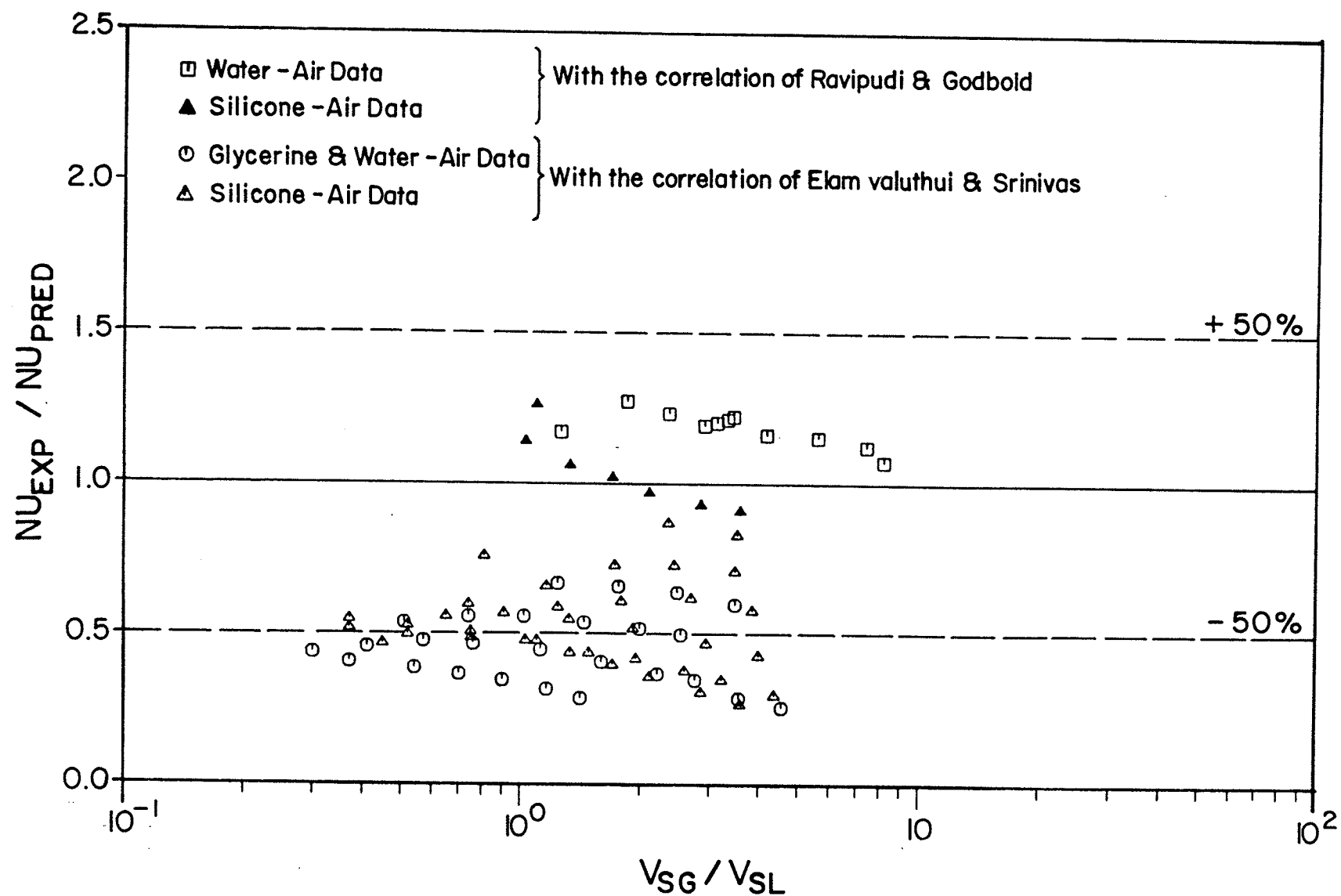


Fig. 7.27 Comparison of Present $\bar{h}_{TP}$ Data with the Correlations of (a) Ravipudi & Godbold (76) and (b) $\bar{h}_{TP}$ Elamvaluthi & Srinivas (26)

Table 7.4 Summary of Comparisons of the Present Mean-Heat-Transfer Data with Correlations.

Correlation of	Water-Air Data			Glycerine & Water-Air			Silicone-Air Data			Overall		
	N	$\bar{e}(\%)$	$\bar{e}_r(\%)$	N	$\bar{e}(\%)$	$\bar{e}_r(\%)$	N	$\bar{e}(\%)$	$\bar{e}_r(\%)$	N	$\bar{e}(\%)$	$\bar{e}_r(\%)$
Katsuhara & Kazama (46)	16	+11.2	34.5	51	-78.6	79.3	46	-66.7	67.6	113	-61.0	70.0
Groothuis & Hendal (35)	11	-39.1	39.7	-	-	-	13	+59.0	59.1	24	+14.0	51.1
Knott et al. (53)	4	+70.6	76.4	28	+34.6	68.3	37	+73.8	101.2	69	+57.7	87.8
Kudirka et al. (56)	45	+3.4	65.8	77	-16.6	35.2	116	-9.7	43.5	238	-9.4	46.3
Ueda & Hanaoka (90)	22	-42.6	43.8	107	-75.4	75.9	103	76.3	77.1	232	-72.7	74.0
Ravipudi & Godbold (76)	11	+18.1	18.8	-	-	-	7	+4.1	12.1	18	+2.8	20.6
Liquid Acc. Model	46	9.9	14.6	41	-18.2	19.9	75	-15.2	23.4	162	-8.8	20.4
Chu & Jones (16)	59	-16.3	33.2	119	-55.6	56.4	175	-46.7	49.7	353	-44.6	49.8
Shah, $Re_{SL} < 170$	-	-	-	31	+14.1	40.5	32	-0.87	40.1	63	-6.5	40.3
(80) $Re_{SL} > 170$	18	-4.4	22.2	46	+21.4	42.0	79	+20.2	40.9	143	+17.5	39.4
Vijay et al. (94)	48	+0.13	20.2	78	+9.6	31.3	116	+12.6	30.9	242	+9.2	29.3
Elamvaluthi & Srinivas (26)	-	-	-	26	-54.3	55.5	37	-47.1	49.2	63	-50.1	51.9

correlation line. When the comparisons were done for each flow pattern using the appropriate exponent given by the authors in (94), results were improved significantly (see Table 7.5). The exponent n was 0.427, 0.489, 0.269, and 0.455 for bubble, slug, froth, and annular flow respectively. It can be seen from this table that the best agreement occurred with the froth data, while the data in the slug region gave higher deviations. This is due to the high fluctuations associated with the slug flow which results in unsteadiness in the temperature and pressure measurements. The annular flow data, except a few points of the silicone-air data, correlated well with the theoretical line.

Table 7.5

Comparison of the Present Data with
the Correlation of Vijay et al. (94)

Flow Pattern	Water-Air			Gly.&Water-Air			Silicone-Air			Total Set		
	N	$\bar{e}$	$\bar{e}_r$	N	$\bar{e}$	$\bar{e}_r$	N	$\bar{e}$	$\bar{e}_r$	N	$\bar{e}$	$\bar{e}_r$
Bubble	8	-10.3	10.5	12	-14.3	16.4	25	20.3	31.7	45	5.6	25.5
Slug	1	10.7	10.5	5	18.5	20.7	3	12.6	25.2	9	15.7	21.5
Froth	5	-6.4	6.9	9	-6.7	7.6	18	7.6	8.6	32	1.4	8.0
Annular	10	-0.2	13.0	30	2.5	33.3	51	6.24	36.3	91	4.3	33.5
							Overall			117	4.7	25.0

The comparison with the Liquid Acceleration Model in the turbulent flow regime gave an r.m.s. deviation as low as 20.4% for all the three liquids used. This correlation, however, overpredicted the mean heat-transfer coefficient for the glycerine & water-air and silicone-air data over almost the total range of V_{SG}/V_{SL} .

The correlation of Ravipudi and Godbold (76) correlated well the very few data points that fell within its limited range of Re_{SL} . A total of only 18 data points were used with this correlation. On the other hand, the Chu & Jones (16) correlation covered the whole range of Re_{SL} and V_{SG}/V_{SL} and included the largest number of data points (353 in total). The authors did not give any restriction or range of applicability in their work (15,16). However, the correlation was developed using water-air data that covered a total range of Re_{SL} and Re_{SG} of 16,000 to 123,430 and 690 to 3260, respectively. It is believed, therefore, that introducing appropriate limits on the liquid Reynolds number or Prandtl number or even both could improve significantly the agreement with the data. The largest deviations associated with this correlation were for the lowest liquid velocities [0.185 ft/s (0.056 m/s) for water-air, 0.073 ft/s (0.022 m/s) for glycerine & water-air, and 0.074 ft/s (0.022 m/s) and 0.100 ft/s (0.030 m/s) for silicone-air]. The overall r.m.s. deviation was 49.8% and the mean algebraic deviation was -44.6% (over prediction).

The simple schemes proposed by Knott et al. (53) and Shah (80) for predicting the heat-transfer coefficient in the laminar flow region were not very successful in predicting the present data that fell in this region. As for the Shah (80) graphical correlation for $Re_{SL} > 170$, the results were better, especially with the water-air data. This graphical correlation is given as continuous lines on dimensionless co-ordinates, $\bar{h}_{TP} / \bar{h}_{SP}$ vs v_{SG} / v_{SL} , with the liquid phase Froude number as a parameter. In the original paper (80), the author recommended that the correlation should be used with $Fr_L > 0.1$. For the data points that fell within $0.1 < Fr_L < 50$ and had Fr_L that was not given on the plot of the correlation, linear interpolation was done between any two successive given lines to obtain the desired Fr_L values. The total r.m.s. deviation with all three liquids was 39.4%.

The largest deviations occurred with the correlations of (53, 46, 90) especially with liquids other than water. The correlations of Groothuis and Hendal (35) and Kudirka (56) and that of Elamvaluthi & Srinivas(26) gave an overall r.m.s. deviation of about 50% when used with the data that fell within their ranges. The latter (26) is the most restrictive among the whole set in terms of Re_{SL} and v_{SG} / v_{SL} ranges.

From the results presented in this section, the following can be concluded:

1. In general, the present data are in good agreement with a number of the correlations for predicting the mean heat-transfer coefficients.
2. In particular, the agreement with the correlations of Vijay et al.(94) and the Liquid Acceleration Model were good indeed, especially when the comparison was done for each flow pattern in the first case.
3. The correlation of Chu & Jones(16) could be improved by introducing some restrictions on Re_{SL} or Pr_L or both.

Chapter 8

COMPARISON OF CORRELATIONS OF HEAT-TRANSFER COEFFICIENTS IN TWO-PHASE TWO-COMPONENT GAS- LIQUID FLOW IN VERTICAL TUBES

8.1 INTRODUCTORY REMARKS

A number of correlations exist in the literature for predicting the mean heat-transfer coefficients in two-phase, two-component, gas-liquid upward flow in vertical tubes. While some of the correlations are purely empirical, others are based on theoretical or semi-theoretical models. In any case, the correlations have been tested against only a limited range of data and their general validity has not been established. In this chapter, eleven correlations were first tested using the extensive set of data taken to date on the present experimental facility, which includes those of Vijay(93), Aggour(1), Zaidi(107) and present. These comparisons will show how well the tested correlations predicted the mean heat-transfer coefficients when fluid properties changed while keeping the pipe size unchanged and using the same method of temperature and pressure measurements. The tested correlations are those by:

Katsuhara & Kazama(46)	Groothuis & Hendal(35)
Knott et al.(53)	Kudirka et al.(56)
Ueda and Hanaoka(90)	Ravipudi & Godbold(76)
Chu & Jones(16)	Shah(80)
Vijay et al.(94)	Elamvaluthi & Srinivas(26)

and the "Liquid Acceleration Model".

Secondly, a comprehensive examination of the correlations was done using other data which appear in the literature in an analyzable form. These data are those of:

Verschoor & Stemerding(92)	Groothuis & Hendal(35)
Knott et al.(53)	Kudirka(55)
Dorresteiijn(24)	Ravipudi(75)
Chu(15)	

This set of data, together with the present data and those of Vijay(93), Aggour(1) and Zaidi(107), cover a very wide range of variables and form the largest set of data so far used (it is believed) in assessing the correlations that predict the mean heat-transfer coefficients in two-phase, two-component, vertical flow.

The theoretical and empirical correlating expressions appearing in this chapter were presented in Table 2.2 with their range(s) of applicability as proposed by the original author(s) and the definition of the terms and dimensionless groups which do not appear in the Nomenclature. Therefore, only the name(s) of the author(s) will be stated here in referring to their correlation(s).

In addition to the eleven correlations tested here, there are others which appear in the literature, for example, the correlation of Domanskii et al.(23) which includes variables that were not able to be determined. Others, like Fedotkin & Zarudnev (27) and Kapinos et al.(45), included variables and constants which were not clearly defined in the original work. Perroud and de la Harpe(70) conducted their experiments with substantial evaporation. Also, most recently, Dobran(21, 22) used a physical model for annular flow as a basis to derive a theoretical correlation for that specific flow pattern; it requires a knowledge of film thickness which was not measured for all the data used in the comparisons.

8.2 COMPARISON OF CORRELATIONS USING ALL DATA TAKEN TO DATE ON THE PRESENT EXPERIMENTAL FACILITY

Most of the material presented in this section was reported by Rezkallah et al.(77) where comparisons of this sort were done using all the data taken to date (mentioned below) on the present rig with the exception of the present data.

The data used in the following comparisons are those of Vijay(93), Aggour(1), Zaidi(107), and the present author. The gas-liquid combinations used in the four investigations were: glycerine and air ($1.8 < Re_{SL} < 21$); glycerine & water solution of 75% glycerine by weight ($\mu = 27.2$ CP @ 25°C) and air ($8 < Re_{SL} < 4500$); water and air ($260 < Re_{SL} < 1.3 \times$

10^5); water and helium ($3800 < Re_{SL} < 1.3 \times 10^5$); water and Freon 12 vapour ($4200 < Re_{SL} < 5.5 \times 10^4$); surfactant solution and air ($818 < Re_{SL} < 8.2 \times 10^4$); glycerine & water solution of 58% glycerine by weight ($\mu = 8.2$ CP @ 25°C) and air ($42 < Re_{SL} < 13,000$); and silicone-air ($51 < Re_{SL} < 20,700$). In total, the range of variables was:

Re_{SL}	2 to 1.3×10^5
Pr_L	5.6 to 7000
V_{SG}/V_{SL}	0.01 to 7900
ρ_G/ρ_L	2×10^{-4} to 0.01
Static σ	19.7×10^{-3} to 72×10^{-3} N/m

Aggour (1) and Zaidi (107) repeated most of Vijay's (93) water-air data with a maximum deviation of less than 10%; the same results were obtained with the present water-air data. Therefore, only the original Vijay (93) water-air data are used here in the comparisons.

A careful examination of the correlations (see Table 2.2 for statements and definitions of variables) shows that among them there is a vast array of dimensionless groups, e.g. Nu , Re , Pr , μ_G/μ_L , μ_B/μ_W , V_{SG}/V_{SL} , Pa/P , h_{TP}/h_L , Fr , and $\Delta P_{TPF}/\Delta P_L$. These groups involve in their determination some combination of flow rates of both phases, liquid and gas properties, single and two-phase frictional pressure drop, tube diameter, gravitational acceleration, and single-phase heat-transfer coefficient. Sometimes

dependent variables such as wall shear stress and void fraction are included; sometimes mixture properties are used, combining liquid and gas properties in some special way [e.g. Katsuhara and Kazama(46)]. The void fraction appears in some of them (46, 90, 16 and the L.A.M.⁴), in which cases it was predicted here using the correlation of Chisholm(14). Somewhat different results would be expected if other methods were used to predict α . The single-phase heat-transfer coefficient appears in some of them (53, 80, 94, and the L.A.M.) and was predicted using the appropriate single-phase correlations.

The restrictions on the correlations have been stated by the original authors in terms of some combinations of independent variables, dependent variables, or flow pattern. No annular-mist data have been used in these comparisons. All the liquid properties were calculated at the mean bulk temperature.

The comparisons between the experimental data and the tested correlations are given in Figs. 8.1 to 8.8 in terms of the dimensionless groups (Nu_{EXP}/Nu_{PRED}) and (V_{SG}/V_{SL}) where Nu_{EXP} and Nu_{PRED} are the experimental and predicted Nusselt numbers, respectively. The present data are not shown on those figures as they have been already presented on the same co-ordinates in the previous chapter

⁴ L.A.M. stands for "Liquid Acceleration Model" and will be used only in this chapter.

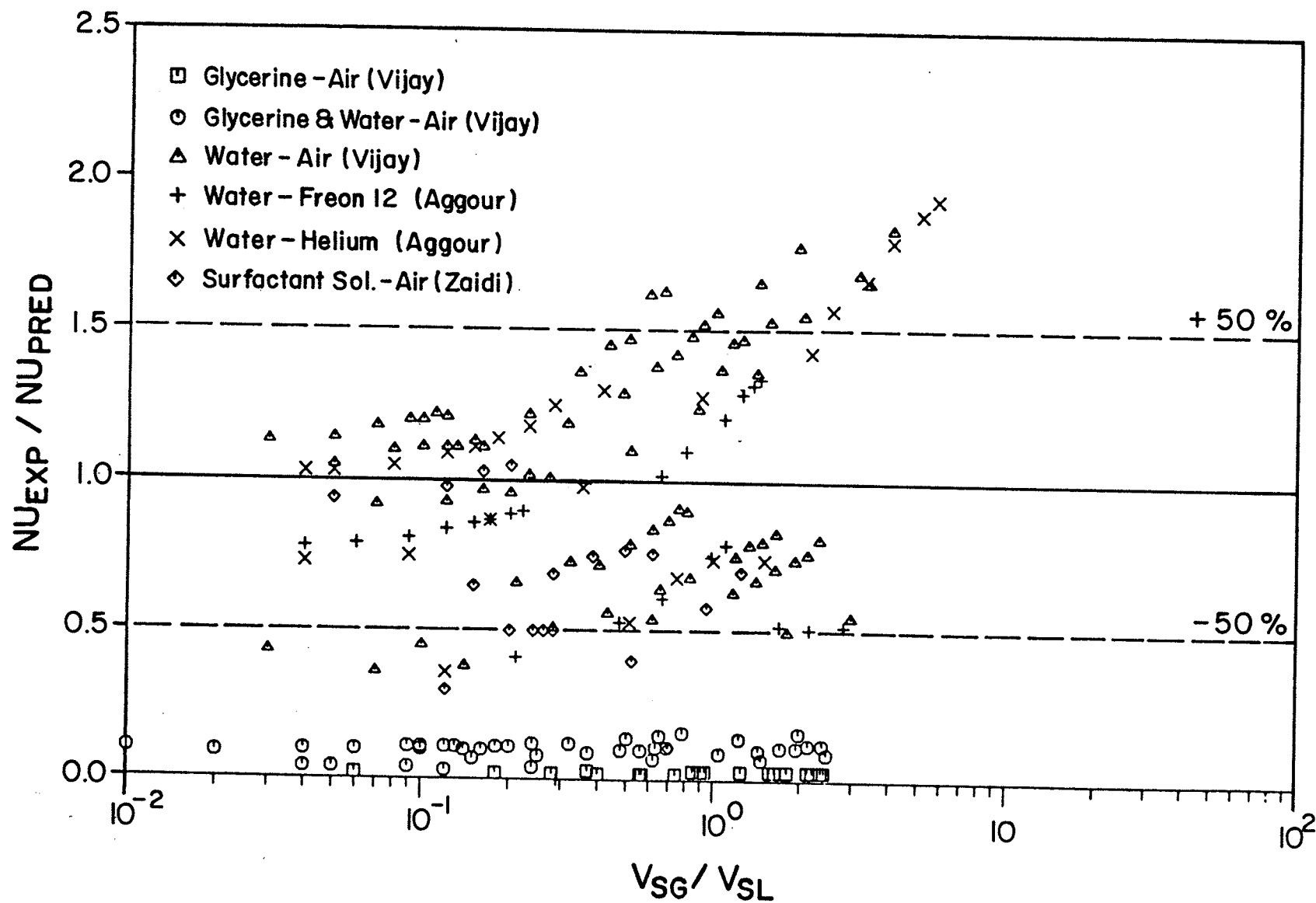


Fig. 8.1 Comparison of the Experimental Data of Vijay, Aggour, and Zaidi with the Correlation of Katsuhara & Kazama (46)

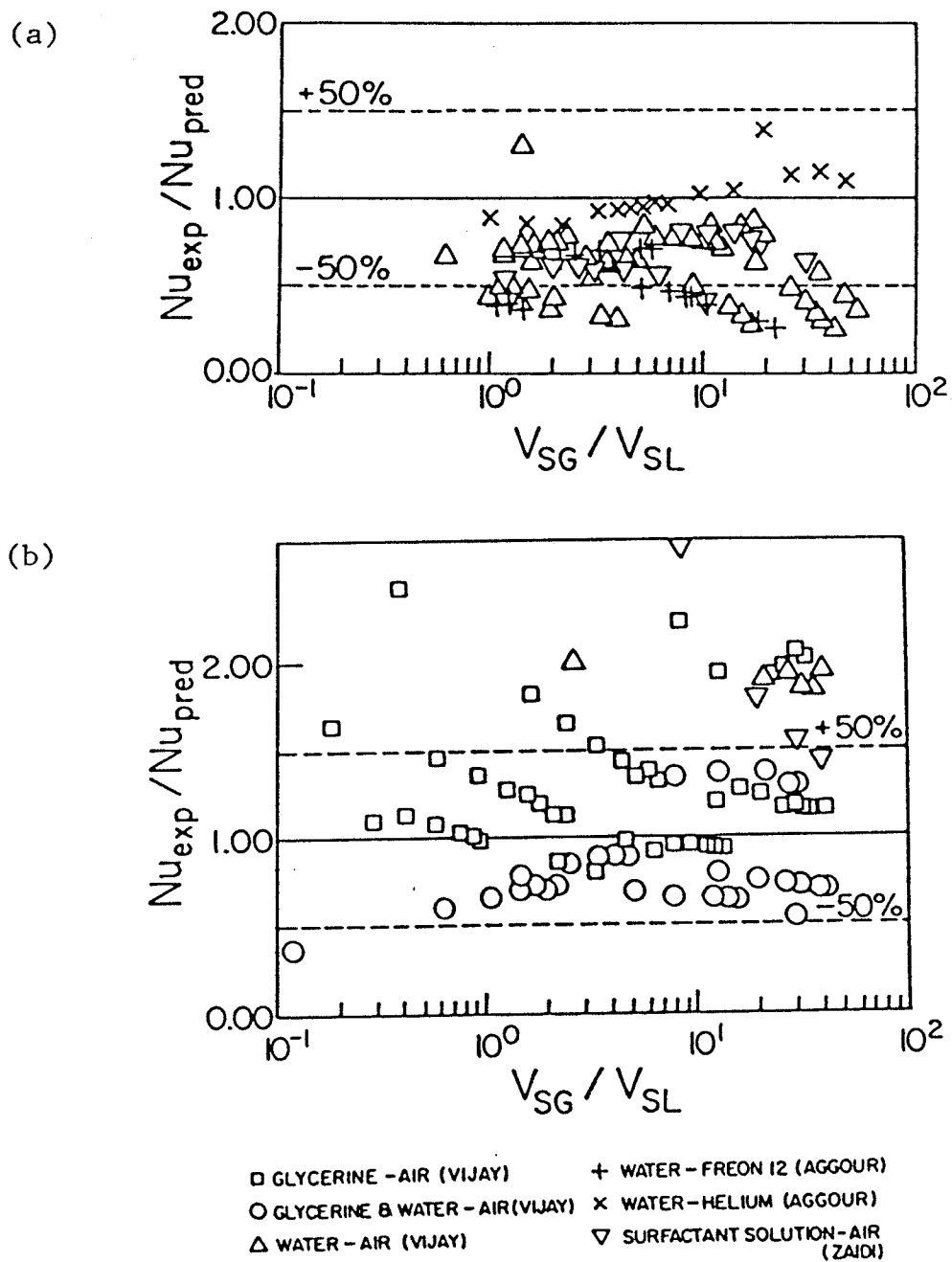


Fig. 8.2 Comparison of the Experimental Data of Vijay, Aggour, and Zaidi with the Correlations of (a) Groothuis & Hendal(35) and (b) Knott et al. (53). (Present data are shown in Fig. 7.22.)

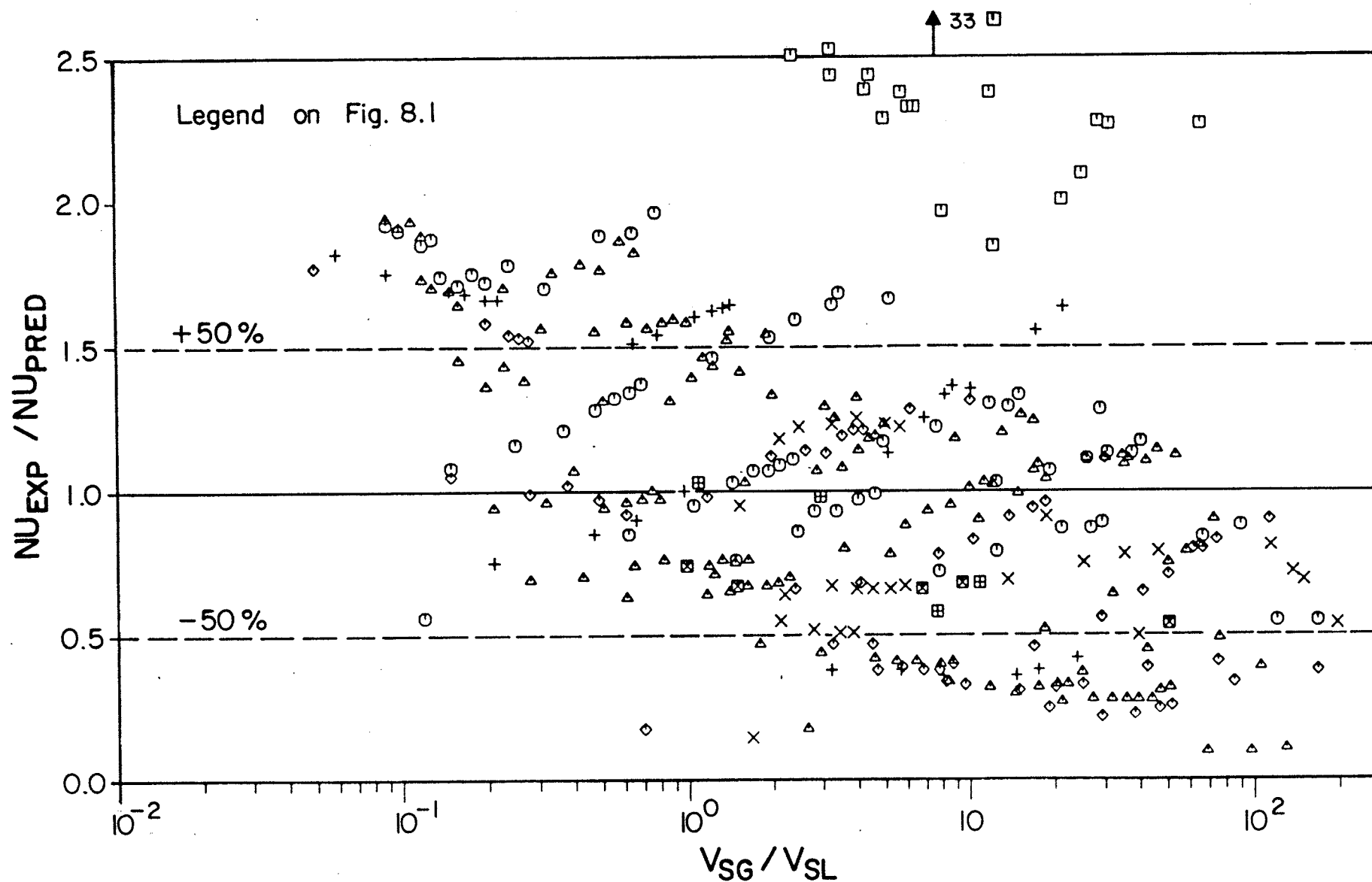


Fig. 8.3 Comparison of the Experimental Data of Vijay, Aggour, and Zaidi with the Correlation of Kudirka et al. (56). (Present data are shown in Fig. 7.23.)

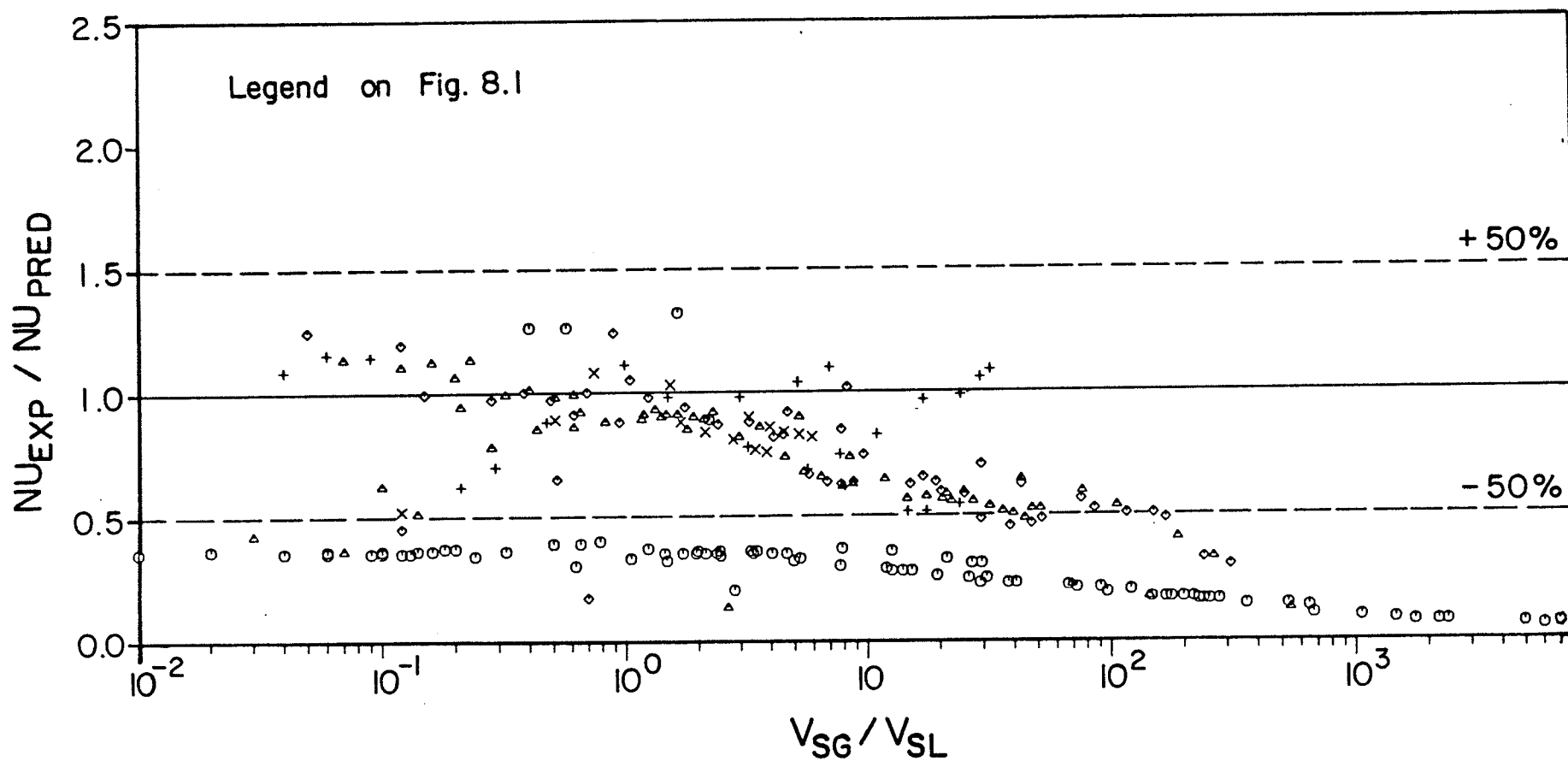


Fig. 8.4 Comparison of the Experimental Data of Vijay, Aggour, and Zaidi with the Correlation of Ueda & Hanaoka (90)

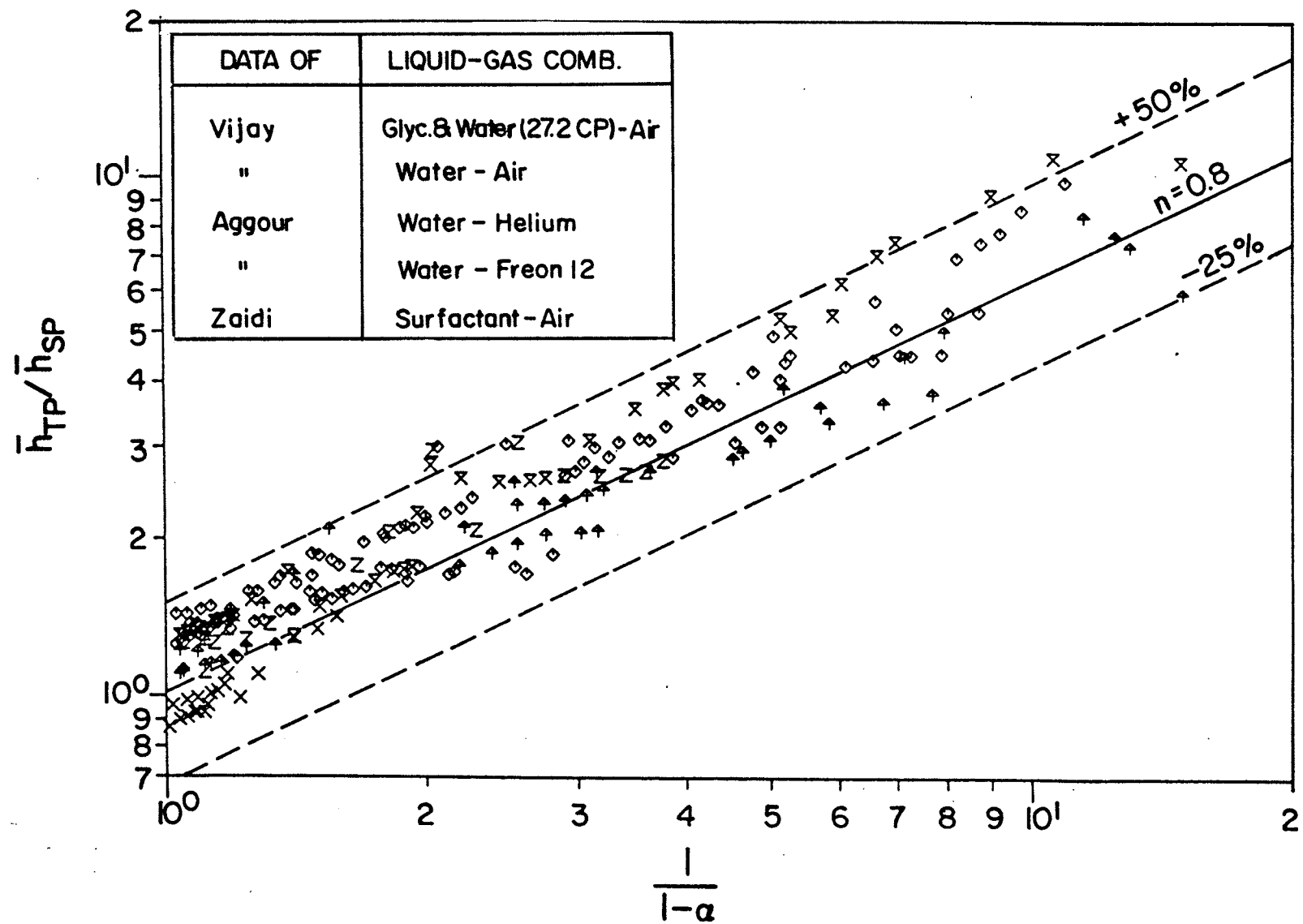


Fig. 8.5 Comparison of the Experimental Data of Vijay, Aggour and Zaidi with the Liquid Acceleration Model. (Present data are shown in Fig. 7.24.)

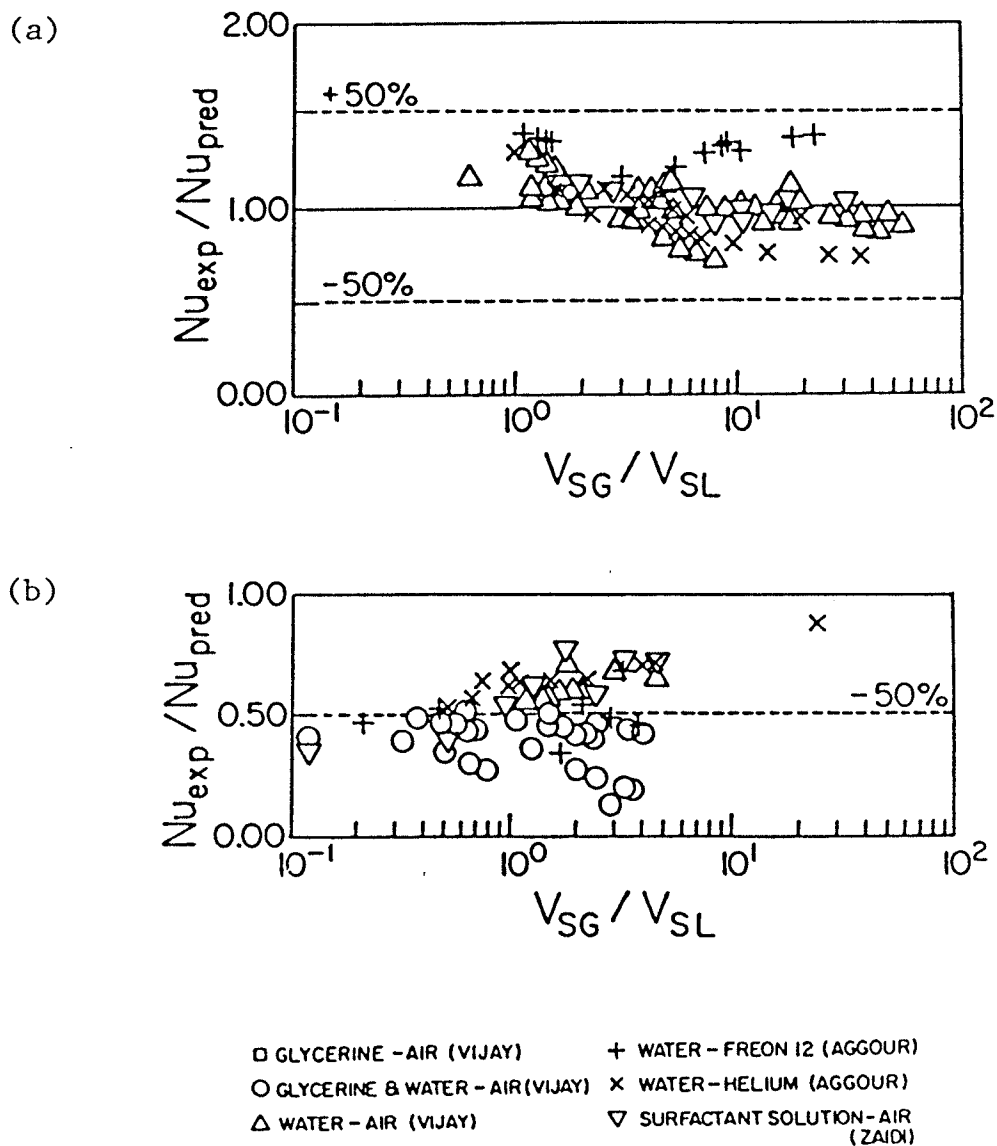


Fig. 8.6 Comparison of the Experimental Data of Vijay, Aggour, and Zaidi with the Correlations of (a) Ravipudi & Godbold (76) (b) Elamvaluthi & Srinivas (26). (Present data are shown in Fig. 7.27.)

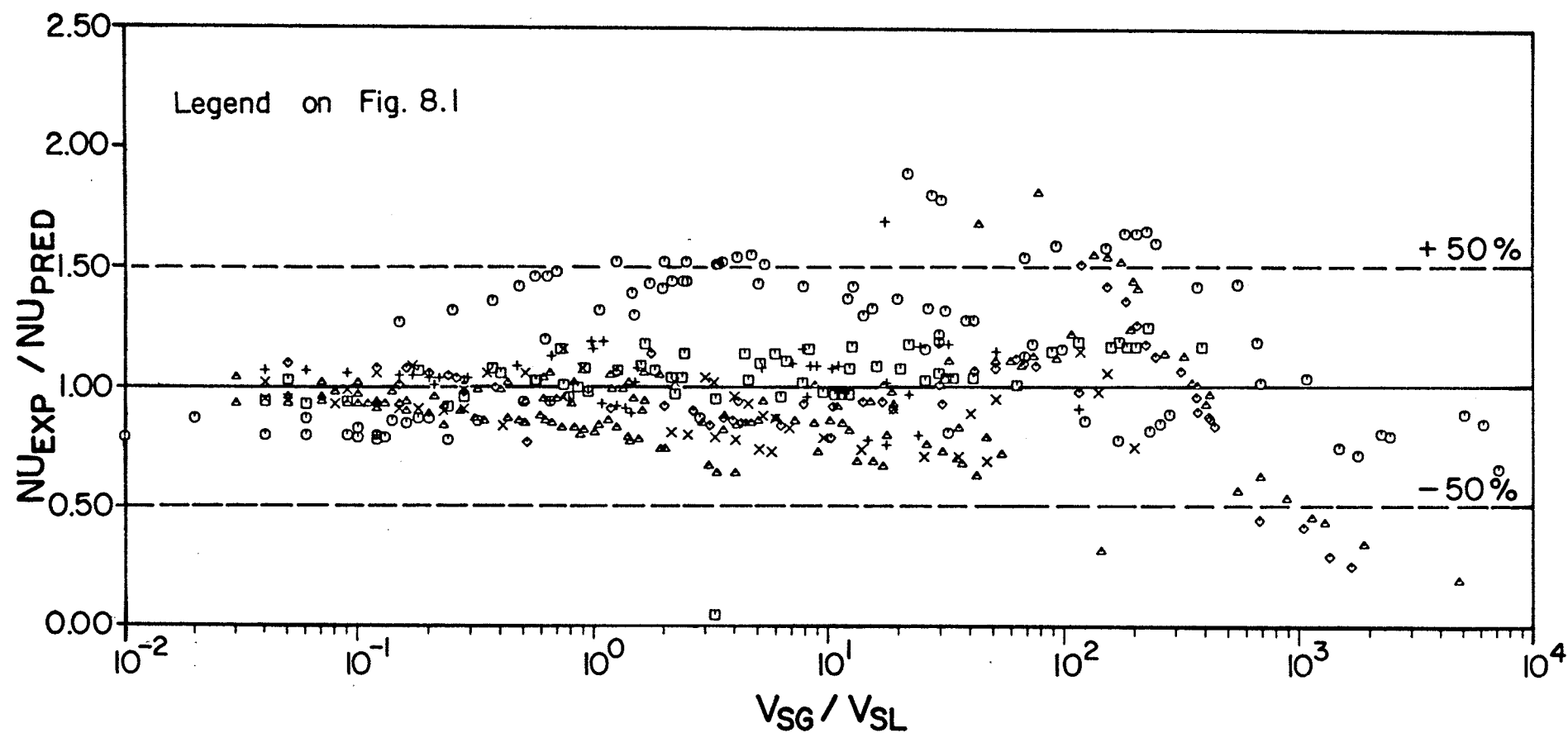


Fig. 8.7 Comparison of Experimental Data of Vijay, Aggour, and Zaidi with the Correlation of Vijay et al. (94). (Present data are shown in Fig. 7.26.)

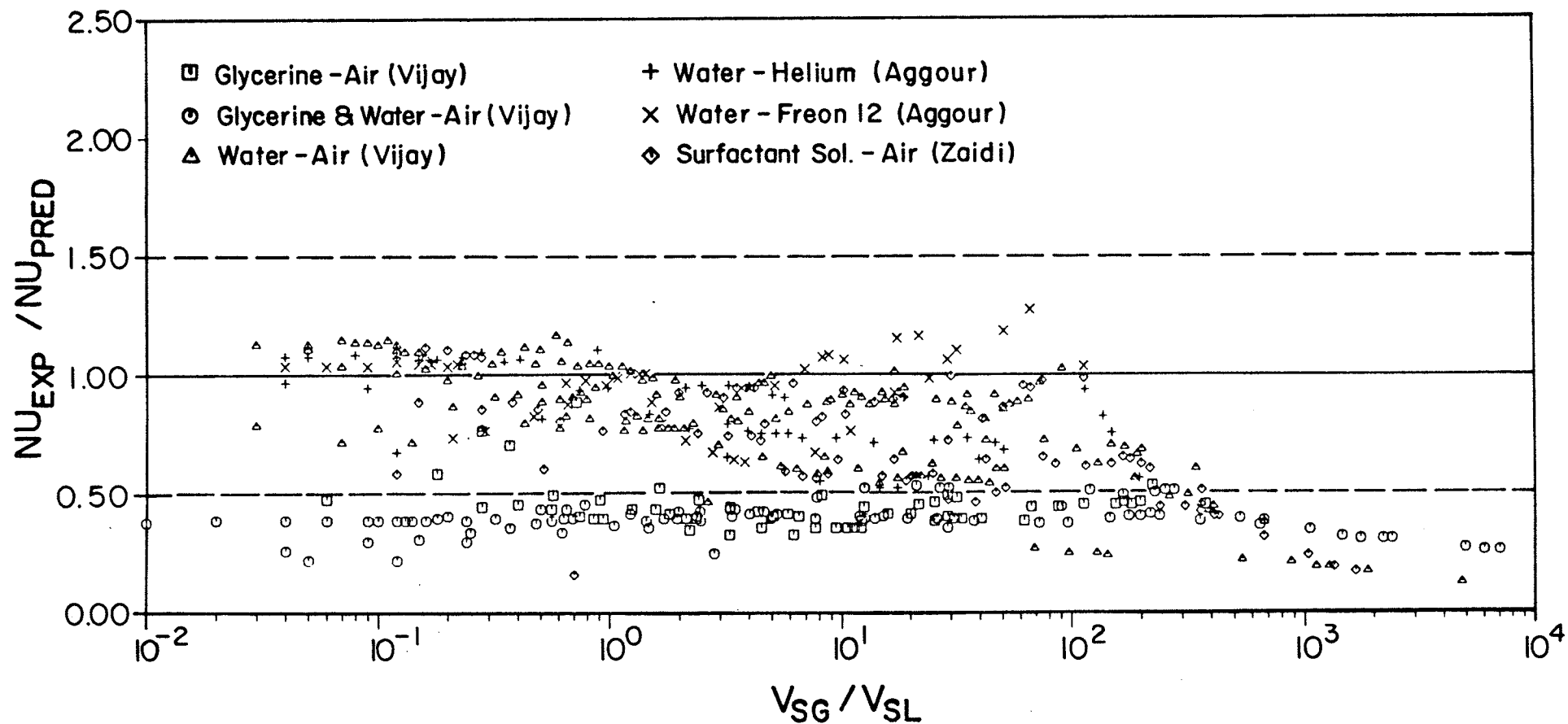


Fig. 8.8 Comparison of the Experimental Data of Vijay, Aggour, and Zaidi with the Correlation of Chu & Jones (16). (Present data are shown in Fig. 7.25.)

(Figs. 7.22 to 7.27) for most of the correlations. This was done to avoid graphs with so much data on them that, in some cases, identification of a specific liquid-gas combination would be extremely difficult. For all the tested correlations, Table 8.1 gives the liquid-gas combinations used, the range of Re_{SL} and V_{SG}/V_{SL} of the data points that fell within the restrictions, the mean algebraic deviation $\bar{e}$ [defined as $\Sigma (Nu_{EXP} - Nu_{PRED}) / Nu_{PRED}$ divided by the number of data points used] and the r.m.s. deviation ($\bar{e}_r$) for each tested correlation. The maximum number of data points which was used with one correlation, as the restrictions allowed, was 781 [with Chu & Jones(16)]. The total number of comparisons, in terms of data points, was 3757 for the eleven correlations.

Table 8.1 shows the overall algebraic mean and r.m.s. deviations. In order to examine how well each correlation predicted $\bar{h}_{TP}$ when fluid properties changed, a table introduced later (Table 8.2) gives the deviations associated with each liquid-gas combination.

A careful study of Figs. 8.1 to 8.8 shows that most of the tested correlations gave reasonably good agreement with the water-air data; this is expected due to the fact that the majority of the correlations are empirical or semi-empirical equations derived, in many cases, using data which always included water-air. The liquids which gave large deviations (so making for large deviations for the whole

Chu & Jones (16)	Glycerine-air	2-21	0.06-377.	-37.8	45.6
	Glycerine & water-air (93)	9-4,500	0.01-7,900.		
	Water-air	290-128,000	0.03-5,200.		
	Water-helium	4,000-125,800	0.04-196.		
	Water-Freon 12	4,200-55,200	0.04-114.		
	Surfactant-air	835-82,200	0.05-1,700.		
	Glyc. & water-air (present)	42-13,000	0.01-4,716.		
	Silicone-air	51-20,700	0.01-2,444.		
Shah (80)	Glycerine-air	2-21	0.06-377.	+22.0	65.9
	Glycerine & water-air (93)	9-78	7.80-7,925.		
	Glyc. & water-air (present)	42-84	12.2-4,716		
	Silicone-air	51-66	18.8-4,981.		
Vijay et al. (94)	Glycerine-air	2-21	0.06-377.	+5.3	27.3
	Glycerine & water-air (93)	9-4,500	0.01-7,900.		
	Water-air	330-128,000	0.03-5,200.		
	Water-helium	4,000-125,800	0.04-196.		
	Water-Freon 12	4,400-55,200	0.04-114.		
	Surfactant-air	835-82,200	0.05-1,700.		
	Glyc. & water-air (present)	42-13,000	0.01-4,716.		
	Silicone-air	51-20,700	0.01-2,444.		
Elamvaluthi & Srinivas (26)	Glycerine & water-air (93)	300-3,600	0.37-4.0	-49.6	51.9
	Water-air	4,200-14,300	0.6-4.6		
	Water-helium	4,000-13,700	0.51-4.5		
	Water-Freon 12	4,200-13,500	0.30-3.8		
	Surfactant-air	4,100-13,500	0.52-4.5		
	Glyc. & water-air (present)	611-9,050	0.3-4.54		
	Silicone-air	630-11,500	0.37-4.35		
Liquid Acc. Model	Glycerine & water-air (93)	3,500-4,500	0.12-91.	+3.5	22.3
	Water-air	4,000-128,000	0.03-91.		
	Water-helium	4,000-125,800	0.04-196.		
	Water-Freon 12	4,200-55,200	0.04-114.		
	Surfactant-air	4,150-82,200	0.05-114.		
	Glyc. & water-air (present)	4,080-13,000	0.01-11.0		
	Silicone-air	2,735-20,700	0.01-32.7		

Table 8.1 Tabulated Results of the Comparison using
all Data Taken on the Present Rig.

Correlation	Present Data Within the Restrictions			Algebraic Mean Dev. (%)	R.M.S. Dev. (%)
	Liquid-Gas Combination	Re _{SL} Range	V _{SG} /V _{SL} Range		
Katsuhara & Kazama (46)	Glycerine-air	6.6-21	0.06-2.4	-42.8	64.9
	Glycerine & water-air (93)	298-4,500	0.01-2.5		
	Water-air	2,800-128,000	0.03-4.0		
	Water-helium	13,300-125,800	0.04-5.7		
	Water-Freon 12	4,200-55,100	0.04-2.8		
	Surfactant-air	4,100-82,200	0.05-0.94		
	Glyc. & water-air (present)	611-13,000	0.01-57.9		
	Silicone-air	260-20,700	0.09-2.4		
Groothuis & Hendal (35)	Water-air	13,000-103,300	1.16-53.7	-21.2	48.2
	Water-helium	13,500-56,000	1.0-46.6		
	Water-Freon 12	13,500-55,100	5.20-22.0		
	Surfactant-air	13,500-41,600	1.20-30.0		
	Silicone-air	8,350-11,500	1.03-6.3		
Knott et al. (53)	Glycerine-air	2-21	0.20-40.0	+38.0	78.3
	Glycerine & water-air (93)	12-664	0.12-40.0		
	Water-air	836-843	3.0-38.5		
	Surfactant-air	818-844	8.0-38.0		
	Glyc. & water-air (present)	42-1,500	0.21-40.0		
	Silicone-air	66-820	0.36-39.0		
Kudirka et al. (56)	Glycerine-air	2-21	0.20-62.	+8.7	42.1
	Glycerine & water-air (93)	11-4,500	0.10-185.		
	Water-air	290-128,000	0.03-137.		
	Water-helium	4,000-125,800	2.10-196.		
	Water-Freon 12	4,200-55,200	0.06-90.		
	Surfactant-air	818-81,800	0.15-167.		
	Glyc. & water-air (present)	42-13,000	0.08-100.		
	Silicone-air	51-20,700	0.12-81.0		
Ueda & Hanaoka (90)	Glycerine & water-air (93)	9-4,500	0.01-7,900	-56.4	73.8
	Water-air	289-78,000	0.03-580		
	Water-helium	4,000-13,800	0.04-32.		
	Water-Freon 12	4,200-54,400	0.04-166.		
	Surfactant-air	818-40,300	0.12-311.		
	Glyc. & water-air (present)	42-13,000	0.01-4,716		
	Silicone-air	51-3,750	0.65-2,444		
Ravipudi & Gobold (76)	Water-air	13,700-79,000	1.16-54.0	+5.1	15.5
	Water-helium	13,400-56,000	1.00-46.6		
	Water-Freon 12	13,500-55,200	1.10-22.0		
	Surfactant-air	13,500-41,600	1.20-30.0		
	Silicone-air	11,500-16,900	1.03-3.6		

data set) were glycerine and glycerine-water solutions where Pr_L range was typically from 63 to 7000. These Prandtl numbers were generally higher than those used by the original authors in obtaining their correlations.

The following section, as mentioned before, gives the results of a thorough examination of the correlations using other data in the literature. Also, a discussion is made in that section on how well each correlation predicted the total set of data, including those taken to date on the present rig. To avoid repetition, the discussion based on the comparisons made in this section will be included when the total data set is considered.

8.3 GENERAL COMPARISON OF CORRELATIONS USING THE TOTAL DATA SET

In order to establish the general validity of the previous correlations in predicting the heat-transfer coefficients, it was desirable to compare them with other data that exist in the literature for two-phase, two-component gas-liquid flow in vertical tubes. A thorough search was carried out in order to locate pertinent experimental data and compare them with these correlations. In some publications the data were not given in an analyzable form, e.g. Refs. (23, 27, 45). Nine sources of analyzable data for vertical tube were found, though in some of them the presentation of data was such that certain

assumptions and approximations had to be made to use them. With all the data taken on the present rig to date, a total of seventeen sources of data were used in the comparisons here.

It should be noted here that the single-phase heat-transfer coefficients were calculated using the Sieder-Tate equation in all cases where reported values of $\bar{h}_L$ were not given.

The results of the comparisons are given in Table 8.2 for each data set used in the study. The overall results obtained from all data sets used with a single correlation are given in Table 8.3. In order to draw the most possible conclusions from these comparisons, the results obtained with each correlation will be discussed separately; general conclusions are given at the end of this section.

The correlation of Katsuhara & Kazama (46) predicted fairly well the water-air data; poor results were obtained with other liquids. This correlation is one of the earliest to appear in the literature for predicting $\bar{h}_{TP}$ in two-phase, two-component flow. No annular data were used with it due to the restriction on the void fraction ($\alpha < 0.6$).

The correlation of Groothuis & Hendal (35) for water-air predicted well the water-air data that fell within its range of Re_{SL} ; the overall r.m.s. deviation was 34.5%. The general application of the second correlation, for gas-

Table 8.2 Comparisons of the Two-Phase, Two Component Mean Heat-Transfer Data with the Correlations

Correlation of	Data of	Data Within the Restrictions			No of Data Points	Alg. Dev. (%)	R.M.S. Dev.	Overall	
		Liquid-Gas Combinations	Re_{SL} Range	V_{SG}/V_{SL} range				Alg. Mean Dev. (%)	R.M.S. Dev. (%)
Katsuhara & Kazama (46)	Kudirka (55)	Water-air	23,000-45,600	0.27-0.76	8	+3.6	17.4	-21.1	43.3
		Ethylene-glycol/air	380-1,700	0.25-2.90	4	-70.5	70.9		
	Chu (15)	Water-air	16,000-123,430	0.13-2.12	30	+16.8	25.9	+16.8	25.9
	Groothuis & Hendal (35)	Water-air	5,940-16,550	1.01-3.1	13	-11.6	16.8	-17.7	21.7
		Gas-oil/air	1,850-3,640	0.7-2.0	10	-25.7	26.8		
	Ravipudi (75)	Water-air	33,800-52,500	1.30-2.69	5	+36.8	39.3	+36.8	39.3
	Vijay (93)	Glycerine-air	6.6-21	0.06-2.4	19	-97.4	97.4		
		Glyc. & water-air (27.2 CP)	298-4,500	0.01-2.5	42	-90.2	90.2	-38.1	68.0
		Water-air	2,800-128,000	0.03-4.0	75	+6.1	37.8		
	Aggour (1)	Water-helium	13,300-125,800	0.04-5.7	25	+9.3	42.3	-2.0	39.6
		Water-Freon 12	4,200-55,160	0.04-2.8	23	-14.3	35.6		
	Zaidi (107)	Surfactant-air	4,100-82,200	0.05-0.94	18	-25.2	37.4	-25.2	37.4
	Verschoor & Stermerding (92)	Water-air	2,960-9,460	0.1-225.	51	+4.5	75.1	+4.5	75.1
	Domreesteijn (24)	Gas-oil/air	300-66,000	0.01-3.13	35	-11.8	41.8	-11.8	41.8
	Present	Glycerine & water (8.2 CP) -air	610-13,000	0.01-57.9	51	-78.6	79.3		
		Silicone-air	260-20,700	0.09-2.4	46	-66.7	67.6	-72.9	74.0
Groothuis & Hendal (35)	Groothuis & Hendal (35)	Water-air	5,940-16,550	1.01-140.	84	+0.3	14.2	+0.3	14.2
	Kudirka (55)	Water-air	5,190-22,350	3.4-71.0	15	+36.5	65.8	+36.5	65.8
	Chu (15)	Water-air	16,000-56,400	1.19-2.1	6	-5.5	21.9	-5.5	21.9
	Ravipudi (75)	Water-air	9,500-53,000	1.3-144.8	61	-28.0	38.0	-25.5	36.6
		Toluene-air	19,900-20,400	7.7-40.4	5	+5.9	10.9		
	Vijay (93)	Water-air	13,000-103,300	1.16-53.7	54	-34.9	43.3	-34.9	43.3
	Aggour (1)	Water-helium	13,500-56,000	1.0-46.6	21	-8.5	20.5	-23.9	37.3
		Water-Freon 12	13,500-55,100	5.2-22.0	11	-54.3	57.0		
	Zaidi (107)	Surfactant-air	13,500-41,600	1.2-30.0	16	-34.9	36.2	-34.9	36.2
	Verschoor & Stermerding (92)	Water-air	5,660-9,460	1.0-112.0	21	-15.2	22.5	-15.2	22.5
	Present	Silicone-air	8,350-11,500	1.03-6.3	13	59.0	59.1	59.0	59.1
Knott et al. (53)	Knott et al. (53)	Oil-nitrogen	34.7-162	0.25-2.2	30	-8.0	10.5	-8.0	10.5
	Kudirka (55)	Ethylene-glycol/air	380	2.9-65.0	11	+69	81.0	+69	81.0
	Vijay (93)	Glycerine-air	2-21	0.2-40.0	47	46.4	87.8		
		Glycerine & water/air (27.2 CP)	12-664	0.12-40.0	29	-13.9	31.7	+23.4	70.5
		Water-air	836-843	3.0-38.5	6	+42.5	77.3		
	Zaidi (107)	Surfactant-air	818-844	8.0-38.0	4	+85.7	97.9	+85.7	97.9
	Domreesteijn (24)	Gas-oil/air	300	0.5-4,727	7	-25.1	58.7	-25.1	58.7
	Present	Glycerine & water (8.2 CP)	42-1,500	0.21-40.0	28	+34.6	68.3		
		Silicone-air	66-817	0.36-39.0	37	+73.8	101.2	+56.9	88.5

Correlation of	Data of	Liquid-Gas Combinations	Data Within the Restrictions		No of Data Points	Alg. Dev. (%)	R.M.S. Dev.	Overall	
			Re _{SL} Range	V _{SG} /V _{SL} range				Alg. Mean Dev. (%)	R.M.S. Dev. (%)
Kudirka (56) et al.	Groothuis & Hendal (35)	Water-air	3,180-16,550	1.01-209.6	88	-16.1	33.2	-9.7	29.3
		Gas-oil/air	1,850-3,640	0.7-70.1	31	+8.5	12.8		
	Knott et al. (53)	Oil-nitrogen	34.7-162.0	0.25-2.2	30	-8.5	15.9	-8.5	15.9
	Kudirka (55)	Water-air	5,190-45,600	0.16-71.0	23	-6.3	11.4	-5.8	11.0
		Ethylene-glyc./air	380-1,700	0.25-65.0	19	-5.2	10.4		
	Chu (15)	Water-air	16,000-123,400	0.24-2.1	27	+9.8	13.5	9.8	13.5
	Ravipudi (75)	Water-air	10,400-53,000	1.3-65.9	53	+5.9	16.1	+3.8	16.5
		Toluene-air	19,900-20,400	7.7-40.4	5	-18.9	20.3		
	Vijay (93)	Glycerine-air	2-21	0.2-62.0	49	+163.8	167.6		
		Glyc. & water-air (27.2 CP)	11-4,550	0.1-185.0	61	+25.1	46.1	+37.5	87.0
		Water-air	290-128,000	0.03-137.0	137	-3.7	49.6		
	Aggour (1)	Water-helium	4,000-125,800	2.10-196.0	35	-28.4	38.9		
		Water-Freon 12	4,200-55,200	0.06-90.0	33	19.3	50.1	-5.2	44.7
	Zaidi (107)	Surfactant-air	818-81,760	0.15-167.0	59	-25.9	46.3	-25.9	46.3
	Verschoor & Stemerding (92)	Water-air	2,960-9,460	0.2-75.	40	-54.7	54.5	-54.7	54.5
	Dorresteiijn (24)	Gas-oil/air	300-66,000	0.15-62.7	27	166.	187	166	187
	Present	Glycerine & water (8.2 CP) -air	42-13,000	0.08-100.3	77	-16.6	35.2		
		Silicone-air	51-20,700	0.12-80.9	116	-9.7	43.5	-12.4	40.4
Ueda & Hanaoka (90)	Groothuis & Hendal (35)	Water-air	3,180-16,550	1.01-76.0	41	+9.3	19.7	-4.9	23.9
		Gas-oil/air	1,850-3,640	0.7-70.1	31	-23.7	28.1		
	Kudirka (55)	Water-air	5,400-24,500	0.27-34.0	11	+53.9	63.4	-17.2	62.4
		Ethylene-glyc./air	380-1,700	0.25-65.0	18	-60.7	61.8		
	Vijay (93)	Glyc. & water-air (27.2 CP)	9-5,000	0.01-7,925	93	-72.3	73.0		
		Water-air	289-78,000	0.03-580	64	-29.4	39.5	-54.8	61.5
	Aggour (1)	Water-helium	4,000-13,800	0.04-32.0	21	-22.1	28.2	-12.3	22.5
		Water-Freon 12	4,200-54,400	0.04-166.0	23	-3.4	15.5		
	Zaidi (107)	Surfactant-air	818-40,260	0.12-311.0	38	-27.7	33.0	-27.7	33.0
	Verschoor & Stemerding (92)	Water-air	2,960	2.0-50.0	5	-22.3	28.0	-22.3	28.0
	Dorresteiijn (24)	Gas-oil/air	300-47,000	0.27-547.	14	-32.1	40.1	-32.1	40.1
	Present	Glyc. & water (8.2 CP)-air	42-13,000	0.01-4,716.0	107	-75.4	75.9		
								-75.8	76.5
		Silicone-air	51-3,735	0.65-2,444.0	103	-76.3	77.1		
Ravipudi & Godbold (76)	Groothuis & Hendal (35)	Water-air	12,730-16,550	1.17-90.0	51	+10.7	13.6	+10.7	13.6
	Kudirka (55)	Water-air	21,700-23,000	2.6-12.8	6	+10.1	11.2	+10.1	11.2
	Chu (15)	Water-air	16,000-56,400	1.19-2.1	6	+44.6	46.0	+44.6	46.0
	Ravipudi (75)	Water-air	10,300-53,000	1.3-88.0	57	-1.7	12.9	-1.8	12.4
		Toluene-air	19,900-20,400	7.7-40.4	5	-3.1	4.5		
	Vijay (93)	Water-air	13,700-79,000	1.16-54.0	57	+4.8	12.2	+4.8	12.2

Correlation of	Data of	Liquid-Gas Combinations	Data Within the Restrictions		No of Data Points	Alg. Dev. (%)	R.M.S. Dev.	Overall	
			Re _{SL} Range	V _{SG} /V _{SL} range				Alg. Mean Dev. (%)	R.M.S. Dev. (%)
Ravipudi & Godbold (cont'd.)	Aggour (1)	Water-helium	13,400-56,000	1.00-46.6	19	-7.5	16.7	+7.2	24.1
		Water-Freon 12	13,500-55,200	1.10-22.0	13	+28.5	32.1		
	Zaidi (107)	Surfactant-air	13,500-41,600	1.20-30.0	16	+2.3	7.5	+2.3	7.5
	Verschoor & Stemerding (92)	Water-air	9,460	1.0-1.38	7	-21.3	23.2	-21.3	23.2
	Present	Silicone-air	11,500-16,900	1.03-3.6	7	4.1	12.1	4.1	12.1
Liquid Acc. Model	Groothuis & Hendaal (35)	Water-air	3,180-16,550	1.0-210.0	104	23.4	26.9	29.3	43.0
		Gas-oil/air	2,600-3,600	0.7-40.0	9	+97.2	122.0		
	Kudirka (55)	Water-air	5,190-45,600	0.16-71.0	23	+48.6	67.2	+48.6	67.2
	Chu (15)	Water-air	16,000-123,430	0.13-2.10	30	4.3	24.2	4.3	24.2
	Ravipudi (75)	Water-air	9,500-53,000	1.3-145.0	59	-2.5	16.6	-1.6	16.2
		Toluene-air	19,900-20,400	7.7-40.4	5	9.0	11.2		
	Vijay (93)	Glyc. & water-air (27.2 CP)	3,520-4,500	0.12-91.0	19	-8.6	9.8		
		Water-air	4,100-128,000	0.03-91.0	105	+16.9	22.5	13.0	21.1
	Aggour (1)	Water-helium	4,000-125,800	0.04-196.0	45	0.99	15.2	12.9	18.5
		Water-Freon 12	4,200-55,200	0.04-114.0	36	27.7	31.9		
	Zaidi (107)	Surfactant-air	4,150-82,200	0.05-114.0	19	14.2	21.8	14.2	21.8
	Verschoor & Stemerding (92)	Water-air	2,960-9,460	0.02-225.0	43	+15.7	31.8	+15.7	31.8
	Dornesteijn (24)	Gas-oil/air	4,600-66,000	0.01-265.0	45	15.0	61.4	+15.0	61.4
	Present	Glyc. & water (8.2 CP)-air	4,080-13,000	0.01-11.0	41	-18.2	19.9	-16.3	22.2
		Silicone-air	2,700-20,700	0.01-32.7	75	-15.2	23.4		
Chu & Jones (16)	Groothuis & Hendaal (35)	Water-air	3,180-16,550	0.11-209.6	104	+0.7	16.8	+5.7	19.8
		Gas & oil/air	1,850-3,640	0.7-70.1	31	+22.3	27.78		
	Kudirka (55)	Water-air	5,190-45,600	0.16-71.0	23	+11.7	21.8	-10.4	31.8
		Ethylene-glycol/air	380-1,700	0.25-65.0	19	-37.1	40.7		
	Chu (15)	Water-air	16,000-123,400	0.13-2.1	30	-1.9	8.5	-1.9	8.5
	Ravipudi (75)	Water-air	9,500-53,000	1.3-144.8	61	-5.1	18.0	-4.2	17.4
		Toluene-air	19,900-20,400	7.7-40.4	5	+6.7	9.1		
	Vijay (93)	Glycerine-air	2-21	0.06-377.	58	-55.0	55.8		
		Glyc. & water-air (27.2 CP)	9-5,000	0.01-7,925	93	-60.6	61.0	-37.9	46.5
		Water-air	290-128,000	0.03-5,217	161	-18.7	30.3		
	Aggour (1)	Water-helium	4,000-125,800	0.04-196.	52	-15.5	23.3	-4.8	21.8
		Water-Freon 12	4,230-55,200	0.04-114.	43	-3.7	15.6		
	Zaidi (107)	Surfactant-air	818-82,200	0.05-1,682	80	-24.5	35.7	-24.5	35.7
	Verschoor & Stemerding (92)	Water-air	2,960-9,460	0.02-225.	61	-27.5	30.2	-27.5	30.2
	Dornesteijn (24)	Gas-oil-air	300-66,000	0.004-4,727.	58	14.1	45.0	+14.1	45.0
	Present	Glyc. & water (8.2 CP)-air	42-13,000	0.01-4,716.0	119	-55.6	56.4	-50.3	52.5
		Silicone-air	51-20,700	0.01-2,444.0	175	-46.7	49.7		

Correlation of	Data of	Liquid-Gas Combinations	Data Within the Restrictions		No of Data Points	Alg. Dev. (%)	R.M.S. Dev.	Overall		
			Re _{SL} Range	V _{SG} /V _{SL} range				Alg. Mean Dev. (%)	R.M.S. Dev. (%)	
Elamvaluthi & Srinivas (26)	Groothuis & Hendal (35)	Water-air	5,940-16,500	1.01-4.5	19	-31.4	32.0	-5.4	37.3	
		Gas-oil/air	1,850-3,640	0.7-2.0	10	+44	45.8			
	Vijay (93)	Glyc. & water-air (27.2 CP)	300-3,560	0.37-4.0	27	-61.8	62.5	-54.7	56.3	
		Water-air	4,200-14,260	0.6-4.6	12	-38.8	39.0			
	Aggour (1)	Water-helium	4,000-13,700	0.51-4.5	9	-43.2	39.5	-42.8	46.5	
		Water-Freon 12	4,200-13,500	0.30-3.8	13	-42.6	50.2			
	Zaidi (107)	Surfactant-air	4,100-13,500	0.52-4.5	8	-41.0	43.5	-41.0	43.5	
	Verschoor & Stemending (92)	Water-air	2,960-9,460	0.5-3.4	15	-34.1	36.6	-34.1	36.6	
	Dorrestieijn (24)	Gas-oil/air	300-14,880	0.3-4.1	10	+97.3	133.5	+97.3	133.5	
	Present	Glyc. & water (8.2 CP)-air	611-9,050	0.3-4.5	26	-54.3	55.5	-50.1	51.9	
		Silicone-air	630-11,500	0.37-4.4	37	-47.1	49.2			
Vijay et al. (94)	Vijay (93)	Glycerine-air	9-21	0.06-377.	58	+8.1	24.8			
		Glyc. & water-air (27.2 CP)	9-5,000	0.01-7,925.	90	+19.6	37.4	+5.5	27.8	
		Water-air	330-128,000	0.03-5,217	129	-5.5	20.3			
	Aggour (1)	Water-helium	4,000-125,800	0.04-196.	50	-8.9	15.3	-1.9	15.3	
		Water-Freon 12	4,400-55,200	0.04-114.	38	+7.7	15.3			
	Zaidi (107)	Surfactant-air	835-82,160	0.05-1,682	59	-4.6	25.5	-4.6	25.5	
	Present	Glyc. & water (8.2 CP)-air	42-13,000	0.01-4,716.0	78	9.6	31.3	11.4	31.1	
		Silicone-air	51-20,700	0.01-2,444.0	116	12.6	30.9			
	Shah (80)	Knott et al. (53)	Oil-Nitrogen	34.7-162.0	0.25-2.2	30	-3.8	7.4	-3.8	7.4
	Re _{SL} < 170	Vijay (93)	Glycerine-air	2-21	0.06-377.	49	+47.5	87.2	+45.3	81.1
			Glyc. & water-air (27.2 CP)	9-78	7.80-7,925.	28	+41.4	69.		
Present		Glyc. & water (8.22 CP)-air	42-84	12.2-4,716.	31	+14.1	40.5	-6.5	40.3	
		Silicone-air	51-66	18.8-4,981.	32	-0.87	40.1			
Re _{SL} > 170		Verschoor & Stemending (92)	Water-air	2,960-9,460	0.02-225.	61	-17.7	18.5	-17.7	18.5
	Groothuis & Hendal (35)	Water-air	3,180-16,550	0.11-209.6	104	+22.1	31.3	+28.0	37.4	
		Gas-oil/air	1,850-3,640	0.7-70.1	31	+47.8	53.1			
	Kudirka (55)	Water-air	5,440-44,800	0.16-71.0	24	+32.5	40.	+27.4	36.4	
		Ethylene-glycol/air	380-1,700	0.25-65.0	19	+21.3	31.5			
	Chu (15)	Water-air	16,000-123,400	0.12-2.14	30	-5.7	11.2	-5.7	11.2	
	Dorresteiijn (24)	Gas-oil/air	290-67,300	0.004-4,500.	44	-2.2	17.0	-2.2	17.0	
	Vijay (93)	Glyc. & water-air (27.2 CP)	300-620	0.09-95.8	30	+13.8	29.3	+23.4	38.3	
		Water-air	1,460-17,780	0.03-344.4	54	+28.7	42.4			

Correlation of	Data of	Liquid-Gas Combinations	Data Within the Restrictions		No of Data Points	Alg. Dev. (%)	R.M.S. Dev.	Overall	
			Re_{SL} Range	V_{SG}/V_{SL} range				Alg. Mean Dev. (%)	R.M.S. Dev. (%)
$Re_{SL} > 170$ (Cont'd)	Shah (80)	Water-helium	4,190-13,500	0.12-196.0	28	+4.4	21.0	+20.1	34.7
	Aggoun (1)	Water-Freon 12	4,200-13,500	0.21-113.6	24	+38.4	45.9		
	Zaidi (107)	Surfactant-air	1,540-13,700	0.12-365.5	25	+34.4	49.1	+34.4	49.1
	Ravipudi (75)	Water-air	9,500-53,000	1.3-144.8	61	+7.2	15.6	+7.2	15.2
		Toluene-air	19,900-20,400	7.7-40.4	5	+7.7	8.7		
	Present	Glyc. & water (8.2 CP)-air	196-1,500	0.21-740.7	46	21.4	42.0	20.6	41.3
		Silicone-air	260-3,700	0.08-322.6	79	20.2	40.9		

Table 8.3 Overall Results of Comparisons with the Correlations
using the Total Data Set

Correlation of	Overall Range Re_{SL}	Overall Range V_{SG}/V_{SL}	Total N	Overall Alg. Dev. (%)	Overall R.M.S. Dev. (%)
Katsuhara & Kazama (46)	6.6-128,000	0.01-225	455	-37.6	61.6
Groothuis & Hendal (35)	5,190-56,000	1.0-145	337	-11.3	34.5
Knott et al. (53)	2-1,500	0.12-4727	169	+38.7	78.9
Kudirka et al. (56)	2-128,000	0.03-210	875	+7.1	64.1
Ueda & Hanaoka (90)	9-78,000	0.01-2444	569	-48.4	60.3
Ravipudi & Godbold (76)	9,460-79,000	1.0-90	244	+4.8	16.3
Liquid Acc. Model	2,600-128,000	0.01-265	658	10.4	32.8
Chu & Jones (16)	2-128,000	0.01-7,900	1173	-25.6	40.5
Vijay et al. (94)	9-128,000	0.01-7,900	618	+5.3	27.3
Shah (80)					
$Re_{SL} < 170$	2-84	0.06-7,900	140	+22.0	65.9
$Re_{SL} > 170$	196-123,400	0.004-4,500	665	+15.8	33.8
Elamvaluthi & Srinivas (26)	300-16,500	0.3-4.6	186	-33.6	56.5

oil/air, was not defined as the equation was derived to correlate those very data and it was not used in the comparisons here.

The correlation of Knott et al.(53), being the most restrictive, was used with few data points. Large deviations were obtained with most of the liquid-gas combinations for the data within its range of applicability.

The correlation of Kudirka et al.(56) included most of the data points and covered the total range of fluid properties. Good predictions were obtained with water-air data, while it gave very large deviations with the glycerine-air data of Vijay(93) and the gas-oil/air data of Dorresteijs (24).

The correlation of Ueda & Hanaoka (90) predicted well most of the data points that fell within its range of the mixture Reynolds numbers except those of Kudirka(55), glycerine-air data of Vijay(93) and the present data.

The correlation of Ravipudi & Godbold (76), which is similar to that by Kudirka et al.(56), correlated very well indeed the data that fell within its range of Re_{SL} (85.5% of these data were for water-air). The overall r.m.s. deviation was 16.3%. However, no conclusion can be drawn on its usefulness if fluid properties changed due to the restriction on Re_{SL} which did not allow for using data with a wide range of variables.

The correlation of Chu & Jones (16), with no explicit restrictions given by the original authors, covered all the data points used in this comparison (a total of 1173 data points) and the total range of fluid properties. The equation gave very good predictions with the water-air data and fair predictions with liquids having high Prandtl numbers. With such a very wide range of fluid properties and variables ($2 \leq Re_{SL} \leq 128,000$ and $0.01 \leq V_{SG}/V_{SL} \leq 7900$), the correlation gave an overall r.m.s. deviation of 40.5%. The results could be improved if some restrictions on Pr_L or Re_{SL} (or both) were introduced.

The correlation of Elamvaluthi & Srinivas (26) is very restrictive in terms of both Re_{SL} and V_{SG}/V_{SL} . It was not successful in predicting the few data points that fell within its limited range.

The correlation of Vijay et al. (94) includes mostly independent variables and was used with all data where the frictional pressure drops were given (the data taken on the present rig). All data points with $\Delta P_{TPF}/\Delta P_L < 1000$ Pa/m were excluded from the comparisons, as proposed by the authors (94). The equation was used with the exponent $n = 0.451$ with all flow patterns including transitions (except the annular-mist data, as proposed by the original authors). Very good predictions with all the data points included were obtained with an overall r.m.s. deviation of 27.3%. Better results could be obtained if the equation is used with each exponent according to the flow pattern.

The correlation of Shah(80) for laminar flow ($Re_{SL} < 170$), being very similar to that of Knott et al.(53), was also unsuccessful in predicting $\bar{h}_{TP}$ in that range of Re_{SL} . However, the graphical correlation for turbulent flow ($Re_{SL} > 170$) gave good results when used to correlate the data points that fell within its range of applicability. This graphical correlation was given in the form of continuous lines with the liquid Froude number (Fr_L) being a parameter. The author (80) recommended that the correlation should be used for $Fr_L > 0.1$. The correlation was also given in a tabulated form for Fr_L up to 50. For other values of Fr_L , linear interpolation was applied between any two successive lines to obtain the desired value. This procedure makes the correlation difficult to use and also some errors result from the use of interpolation. Otherwise, good predictions were obtained with a total r.m.s. deviation of 33.8%.

The Liquid Acceleration Model, which requires a knowledge of the void fraction α , covered a very wide range of variables and was used in the turbulent region with most of the data points (63% of the total N). Except for some of the water-air data of Kudirka(55) and the gas-oil/air data of Dorresteijs(24), the model gave very good results with an overall r.m.s. deviation of 32.8%. The exponent 'n' (which appears in the equation) was taken equal to 0.8, being the most common exponent used with the single-phase equations.

From this study, the following general conclusions can be drawn :

1. The most restrictive correlations are those of Knott et al.(53), Shah(80) (for laminar flow) and Elamvaluthi & Srinivas(26).
2. The least restrictive correlations are those of Kudirka et al.(56), Chu & Jones(16), Vijay et al.(94) and the Liquid Acceleration Model.
3. The correlations of Groothuis & HENDAL (35), Kudirka et al.(56), Ravipudi & Godbold (76) and Elamvaluthi & Srinivas (26), including only independent variables, are the easiest to use. However, they do not predict well the data of liquids other than water-air (i.e. liquids with higher Pr or lower surface tension than those for water).
4. The correlations of Katsuhara and Kazama (46), Chu & Jones (16) and the Liquid Acceleration Model, though easy to use, require appropriate prediction of the void fraction α .
5. The correlation of Ravipudi & Godbold (76) correlated very well indeed the water-air data that fell in its range of applicability giving a total r.m.s. deviation of 16.3%.
6. The graphical correlation of Shah(80) for turbulent flow ($Re_{SL} > 170$), though difficult to use, predicted well the data used with it.

7. The correlation of Vijay et al.(94) and the Liquid Acceleration Model covered a wide range of data and gave very good results with r.m.s. deviations of 27.3% and 32.8%, respectively. However, a knowledge of ΔP_{TPF} (for the first correlation) and void fraction α (for the second) is required.
8. The correlation of Chu & Jones (16) covered the whole range of data and gave very good results indeed with an r.m.s. deviation of 40.5%.

8.4 PRESENTATION OF TWO CORRELATIONS FOR PREDICTING THE MEAN HEAT-TRANSFER COEFFICIENT

8.4.1 Introductory Remarks

In this section, two correlations are presented for the prediction of the mean heat-transfer data in laminar ($Re_{SL} \leq 2000$) and turbulent ($Re_{SL} > 2000$) flows.

The correlation for laminar flow ($Re_{SL} \leq 2000$) was developed empirically using a large set of data that cover a very wide range of fluid properties, liquid and gas flow rates, and flow patterns. The second correlation, in the turbulent flow region, is similar to the Liquid Acceleration Model with the void fraction term α predicted from the Chisholm (14) correlation. This correlation was also compared with a large set of data and the results are given in detail in this section.

These two correlations gave the best agreement when used with the total set of the mean-heat-transfer data of both present and other investigators with the least restrictions on the range of applicability. They can be considered as a method of obtaining a very good estimate of the mean heat-transfer coefficient in two-phase, two-component co-current vertical flow for any liquid-gas combination while applying the least restrictions on the range of variables involved, i.e. flow rates, fluid properties, tube size, and flow patterns.

8.4.2 Laminar Flow Correlation ($Re_{SL} \leq 2000$)

The proposed correlation is given in terms of independent variables and $\bar{h}_L$ (which can be calculated from equations that involve in them independent variables only) as follows:

$$\frac{\bar{h}_{TP}}{\bar{h}_L} = 1 + 4.0 \left(\frac{V_{SG}}{V_{SL}} \right)^{0.25} (Pr_L)^{-0.23} \quad (8.1)$$

in which $\bar{h}_L$ is the best estimate of the single-phase heat-transfer coefficient, Pr_L is the Prandtl number of the liquid phase, and V_{SG} and V_{SL} are the superficial gas and liquid velocities respectively.

The data which were used in developing the correlation are those of Verschoor & Stemerding(92), Groothuis & Hendal(35), Knott et al.(53), Kudirka(55), Dorresteijs(24), Vijay(93), Aggour(1), Zaidi(107) and present. The range of variables covered by these data is given below.

Re_{SL}	1.8	to	1960
Pr_L	4.2	to	7000
v_{SG}/v_{SL}	0.06	to	7030
Pipe size	12.8	to	70 mm
Static σ	19.7×10^{-3}	to	72×10^{-3} N/m

The dependency on the Prandlt number was found to be systematic with all the data used except with the gas-oil/air data of Groothuis & Hendal (35) and Dorresteiijn (24) at Reynolds numbers higher than 1000 (these data represent 3% of the total data set) and also with the data of Vijay(93) for water-air at $v_{SL} = 0.066$ ft/s (0.020 m/s) and glycerine & water (75%-25% by weight)-air at $v_{SL} = 0.044$ ft/s (0.013 m/s) where errors in the measured variables involved in the calculations of the single-phase and two-phase heat-transfer coefficients were the largest for these cases of very low liquid flow rates.

Therefore, the proposed correlation [Eq. (8.1)] was developed with all data points (except those mentioned above) and included all flow patterns and their transitions except those data at the annular-mist transition where gas properties become significantly important while Eq.(8.1) does not account for such cases.

The single-phase heat-transfer coefficient, which was used to compare the experimental results with Eq. (8.1), was the measured $\bar{h}_L$ in most cases wherever the values were

given in a tabulated form or could be extracted from a given figure. In some cases (35, 53, 24), the ratio $\bar{h}_{TP}/\bar{h}_L$ was obtained directly from the given plots of $\bar{h}_{TP}/\bar{h}_L \sim v_{SG}/v_{SL}$.

The results of the comparisons between the total set of experimental data [excluding only the lowest two liquid velocities of Vijay(93)] and Eq. (8.1) are shown in Fig. 8.9 and are summarized in Table 8.4. The annular-mist data fell considerably below the correlation line and gave the largest deviations. Being small in number (10% of the total set), they changed slightly the overall r.m.s. deviation. However, in terms of the total collapse of the data, much better results were obtained when they were excluded from the comparisons. The collapse of the data when the annular-mist data points were excluded is given in Fig. 8.10 from which it can be seen that, except for the gas-oil/air data of (24, 35), the data collapsed within $\pm 50\%$ of the correlation line with an overall algebraic and r.m.s. deviations of -6.3% and 30.7% , respectively.

8.4.3 Turbulent Flow Correlation ($Re_{SL} > 2000$)

From the comprehensive comparisons done earlier in this chapter, it was found that an excellent method of correlating $\bar{h}_{TP}$ was that which utilized in it the concept of the Liquid-Acceleration Model. This model basically attributes the increase of $\bar{h}_{TP}$ over $\bar{h}_L$ to the increase of the liquid velocity (or the acceleration of the liquid

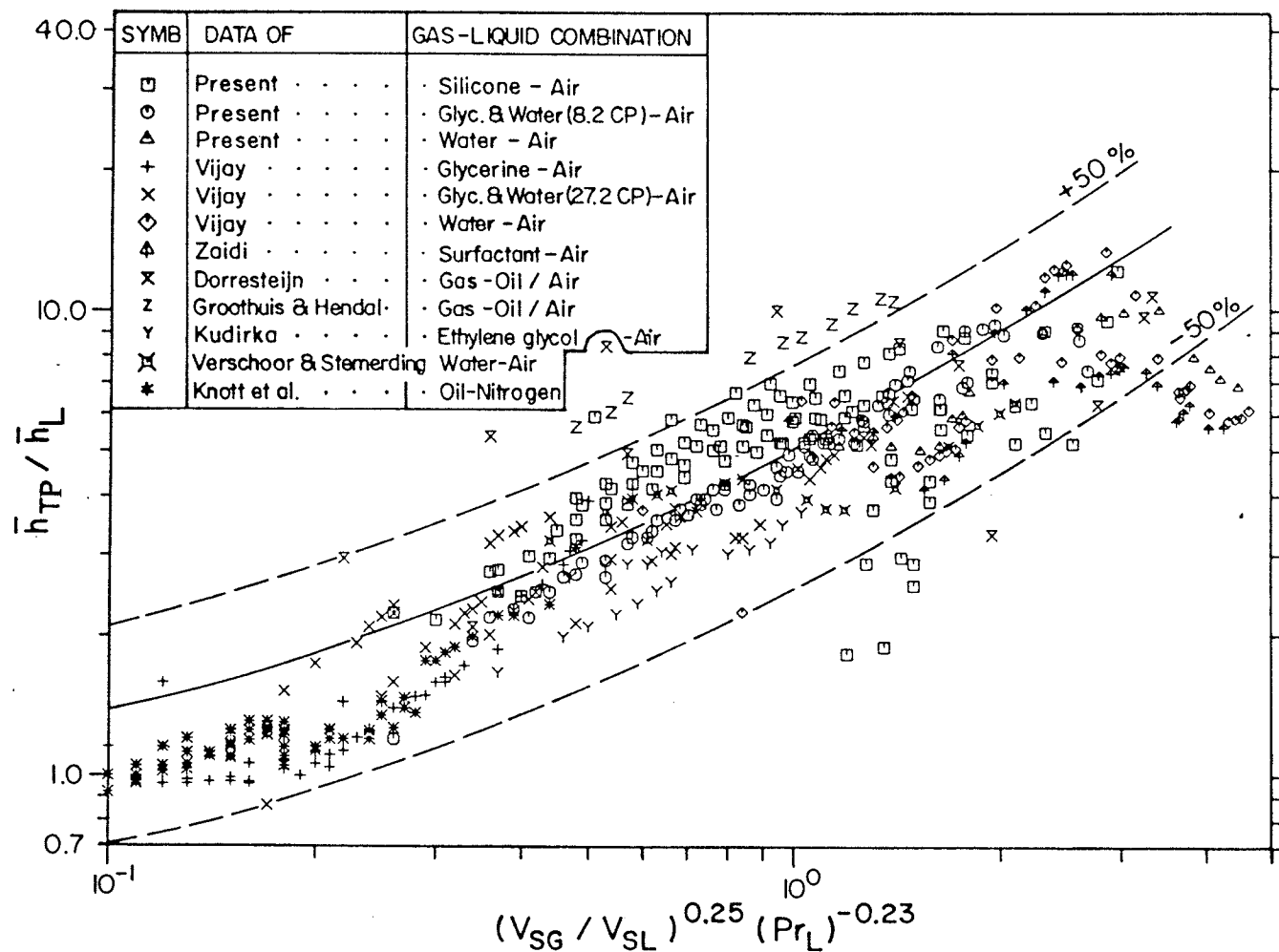


Fig. 8.9 Comparison Between Experimental Data and the Proposed Correlation for Laminar Flow, $Re_{SL} \leq 2000$

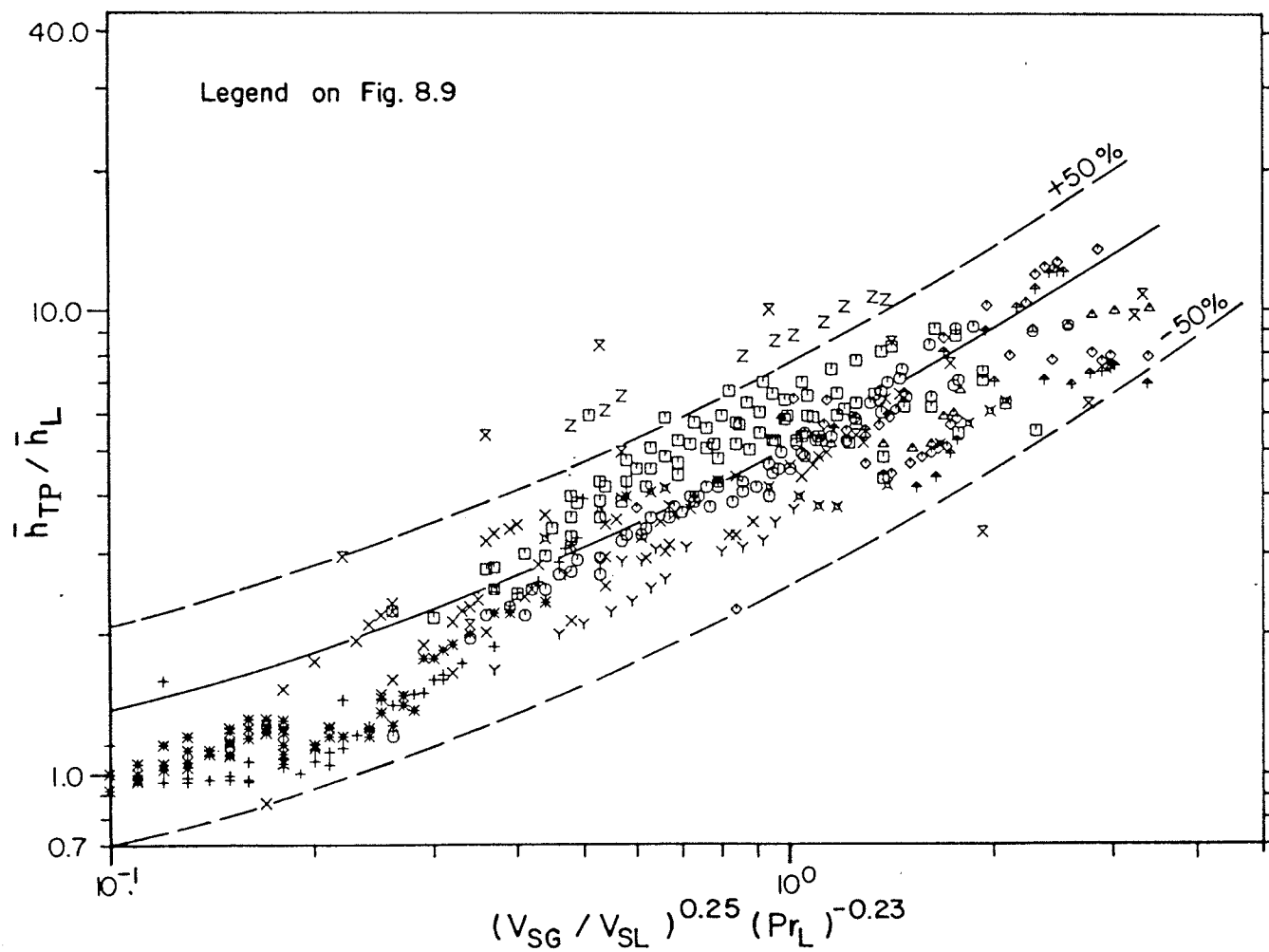


Fig. 8.10 Comparison Between Experimental Data (Excluding A-M) and the Proposed Correlation for Laminar Flow, $Re_{SL} \leq 2000$

Table 8.4 Summary of Comparisons Between the Experimental Data and Eq. (8.1) for $Re_{SL} \leq 2000$.

Data of	Liquid-gas Combination	V_{SG}/V_{SL} range	Re_{SL} range	No. of Data pts.	Mean Alg. Dev. (%)	R.M.S. Dev. (%)
Verschoor & Stemerding (92)	Water-air	0.1-100.0	1960	16	-9.6	23.5
Groothuis & Hendal (35)	Gas-oil/air	1.0-70.1	1440	10	74.5	78.8
Knott et al. (53)	Oil-Nitrogen	0.1-39.0	6.7-162	67	-27.3	28.3
Kudirka (55)	Ethylene glycol-air	0.25-65.0	380-1700	19	-22.7	24.5
Dorresteijs (24)	Gas-oil/air	0.1-4750	300-1500	13	26.0	72.
Vijay (93)	Glycerine- air	0.06-377.4	1.8-21.0	48.	-25.5	31.6
	Glycerine & water (27.2CP)-air	0.12- 6993.2	8.2-1620	52	-2.8	16.7
	Water-air	0.7-7030	260-1500	47	-22.4	36.0
Zaidi (107)	Surfactant- air	4.7-2040	800-1500	35	-24.7	36.4
Present	Water-air	9.4-2010	800	16	-27.5	32.7
	Glycerine & water (7.2CP)-air	0.2-2300	84-1500	66	-4.2	10.4
	Silicone-air	0.22-3450	66-1555	100	7.7	32.6
Overall		0.06-7030	1.8-1960	489	-9.4	32.6

phase) with the introduction of the gas-phase. The equation description of this model is:

$$\frac{\bar{h}_{TP}}{\bar{h}_L} = \left(\frac{1}{1-\alpha} \right)^n \quad (8.2)$$

Equation(8.2) has been used in single-component and two-component, two-phase flow in different cases where the exponent n was taken in the range from 0.8 to 0.9 [$n = 0.9$ was the single-phase exponent used by Dorresteijs(24)]. In all those cases, the equation was tested against a limited set of data [one point only with Dorresteijs(24)] for a very small range of variables and flow patterns. Also, the void fraction α was taken in some cases as the measured value and in others as a calculated value.

In this analysis, the void fraction was predicted from the correlation of Chisholm(14) which includes independent variables only and has been extensively used with the data taken on the present rig. This void fraction correlation, when used in the comparisons presented earlier, gave good results with most of the fluids involved in the comparisons, including those of other investigators (though an extensive study could be done in order to examine other expressions for predicting α).

When Eq.(8.2) was used with the large set of data (of present and other studies), the best fit of the data set in the turbulent flow region ($Re_{SL} > 2000$) was obtained with $n = 0.89$ (when the total set was used) and with $n = 0.91$ [when

the gas-oil/air data of Groothuis & Hendal(35) and Dorresteijs(24) were excluded]. For simplicity without significant change in the overall results of the comparisons, an exponent $n = 0.9$ was chosen to be used; therefore, the proposed correlating expression in the turbulent flow is

$$\frac{\bar{h}_{TP}}{\bar{h}_L} = \left(\frac{1}{1-\alpha}\right)^{0.9} \quad (8.3)$$

where

$\bar{h}_L$ is the best estimate of the single-phase heat-transfer and α is the void fraction predicted by the correlation of Chisholm(14) given by

$$R_L = 1-\alpha = \frac{S(1-x)/\rho_L}{x/\rho_G + S(1-x)/\rho_L} \quad (8.4)$$

in which S is the slip ratio (which is the ratio of the mean velocities of the two phases = V_G/V_L) and can be approximated (14) by:

$$S \approx (\rho_L/\rho_{MIX})^{1/2} \quad (8.5)$$

where

$$\frac{1}{\rho_{MIX}} = \frac{(1-x)}{\rho_L} + \frac{x}{\rho_G} \quad (8.6)$$

and x is the quality, given by

$$x = \dot{m}_G / (\dot{m}_L + \dot{m}_G) \quad (8.7)$$

Notice that with no introduction of the gas flow, Eq.(8.7) gives $x = 0$ and Eq.(8.4) yields the void fraction $\alpha = 0$.

Consequently, $\bar{h}_{TP}$ in Eq.(8.3) asymptotes to the single-phase heat-transfer coefficient.

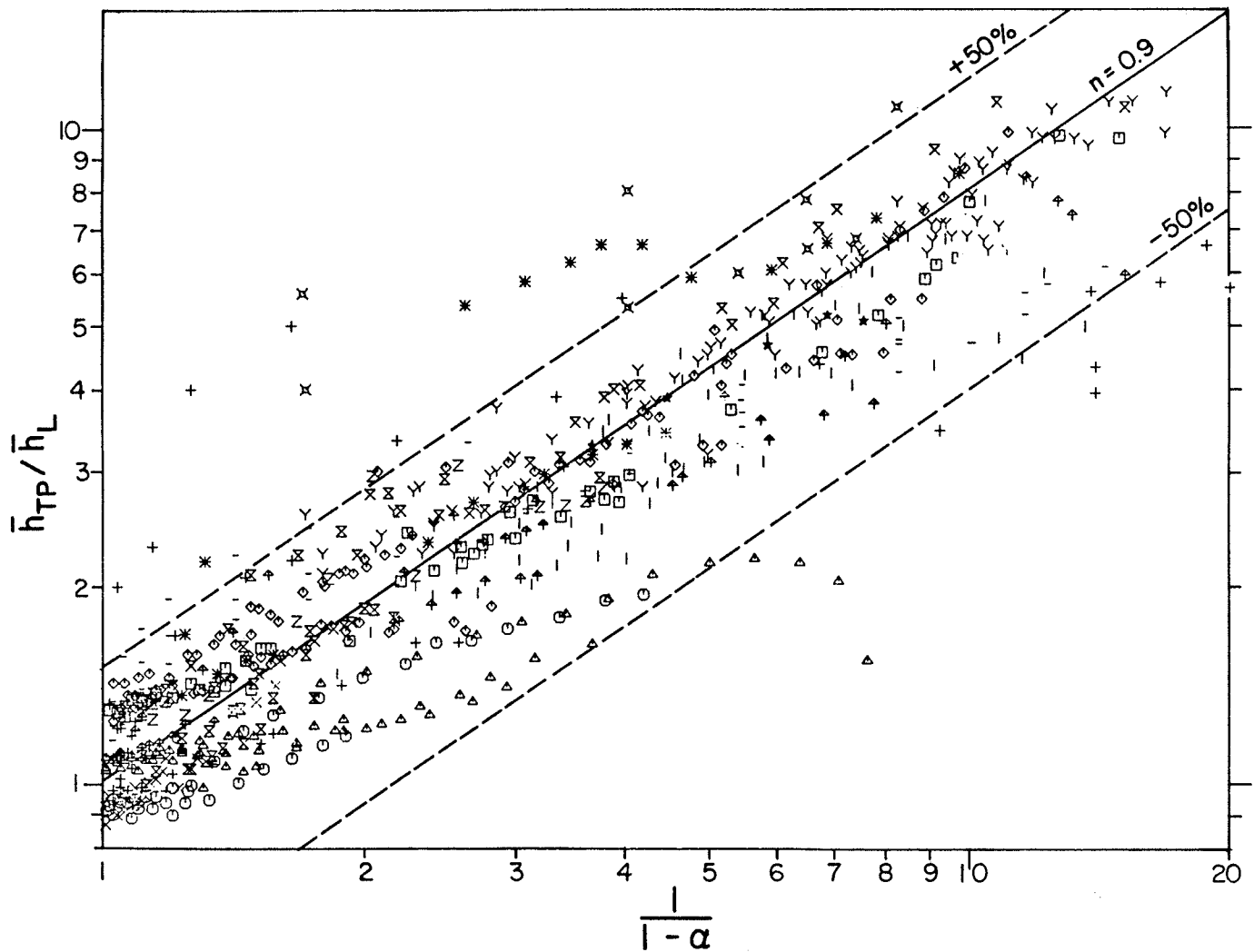
It should be mentioned here that the exponent $n = 0.9$ was used earlier by Dorresteijs (24) to correlate his single-phase data.

Equation (8.4) applies to any liquid-gas combination with no restriction on fluid properties or flow patterns except the annular-mist transition. This reservation seems logical since in this transition $\bar{h}_{TP}$ decreases with the further increase of $\dot{m}_G$ (except with some silicone-air data), contrary to the theory on which Eq.(8.3) is based.

The results of the comparisons between the experimental data and Eq.(8.3) are given in Fig. 8.11 and Table 8.5 for each of the liquid-gas combinations used. In general, the range of variables included in the data was:

Re_{SL}	2,400 to 1.3×10^5
Pr_L	4.2 to 7,000
v_{SG}/v_{SL}	0.01 to 265.0
ρ_G/ρ_L	2×10^{-4} to 0.01
Static σ	19.7×10^{-3} to 72×10^{-3} N/m

From Fig. 8.11 it can be seen that the largest deviations occurred with the gas-oil/air data of (35, 24). When these data (total of 54 data points or 7.6% of the total data set) were excluded from the comparison, the overall algebraic and r.m.s. deviations were reduced to -1.1% and 23.3%, respectively.



SYMB.	DATA OF	LIQUID-GAS COMB.	SYMB.	DATA OF	LIQUID-GAS COMB.
-	Verschoor & Stermerding	Water - Air	x	Vijay	Glyc.& Water (27.2 CP)-Air
Y	Groothuis & Hendal	Water - Air	◇	"	Water - Air
⊗	" "	Gas - Oil / Air	⋈	Aggour	Water - Helium
*	Kudirka	Water - Air	⊗	"	Water - Freon 12
+	Dorresteyn	Gas - Oil / Air	z	Zaidi	Surfactant - Air
!	Ravipudi	Water - Air	⊠	Present	Water - Air
★	"	Toluene - Air	⊙	"	Glyc.& Water (8.2 CP)-Air
⊠	Chu	Water - Air	Δ	"	Silicone - Air

Fig.8.11 Comparison Between the Experimental Data and
Eq.(8.3) for Turbulent Flow ($Re_{SL} > 2000$)

Table 8.5 Summary of Comparisons Between the Experimental Data and Eq. (8.3) for $Re_{SL} > 2000$.

Data of	Liquid-gas Combination	V_{SG}/V_{SL} range	Re_{SL} range	N	Mean Alg. Dev. (%)	R.M.S. Dev. (%)
Verschoor & Stemerding (92)	Water-air	0.02-225.0	2,960-9460	43	6.5	33.1
Groothuis & Hendal (35)	Water-air Gas-oil/air	1.11-210.0 0.7-50.0	3,180-16,550 2,400-3,400	104 9	3.9 74.1	14.5 104.3
Kudirka (55)	Water-air	0.16-71.0	5,190-45,600	23	33.6	52.7
Dorresteyjn (24)	Gas-oil/air	0.01-265.0	4,600-66,000	45	8.4	59.7
Ravipudi (75)	Water-air Toluene-air	1.3-144.8 7.7-40.4	9,500-53,600 19,900-20,400	59 5	-16.4 -5.2	21.9 8.6
Chu (15)	Water-air	0.13-2.1	16,000-123,400	30	-0.8	22.0
Vijay (93)	Glyc. & water (27.2 CP)-air Water-air	0.12-91.0 0.03-91.0	3,520-4,500 4,100-128,000	19 105	-9.9 8.1	10.8 18.9
Aggour (1)	Water-helium Water-Freon 12	0.04-196.0 0.04-114.0	4,000-125,800 4,230-55,200	45 36	-7.7 16.1	20.2 19.8
Zaidi (107)	Surfactant-air	0.05-2.4	4,150-81,000	19	8.1	18.3
Present	Water-air Glyc. & water (8.2 CP)-air Silicone-air	0.02-140.0 0.01-11.0 0.01-32.7	3,745-126,900 4,080-13,000 3,735-20,700	46 41 75	0.9 -20.9 -18.6	15.1 23.1 27.4
Overall		0.01-265.0	2,400-128,000	704	0.55	29.7

This section is concluded with the following remarks:

1. The two correlating equations presented are simple, easy to use and rely on well-known and well-established single-phase heat-transfer correlations.
2. For the case of no gas introduction into the liquid phase, both equations asymptote to the single-phase heat-transfer coefficient.
3. When the range of variables covered in the comparisons is considered, these two equations correlated the data of present and others, taken by different authors, better than any other existing correlation in the literature.
4. They can be used to obtain a very good estimate of $\bar{h}_{TP}$ in laminar and turbulent flow regions while applying the least restrictions on fluid properties, liquid and gas flow rates, tube sizes, or flow patterns.

Chapter 9

SUMMARY AND CONCLUSIONS

During this study, the effects of changing the surface tension (and hence the Weber number) on the heat-transfer coefficient and some hydrodynamic aspects of two-phase, two-component, co-current flow in a vertical tube were investigated. These effects were assumed to prevail as long as the tube wall was wetted with a layer which was thick enough to contain the thermal resistance to heat transfer, in which case the gas properties were considered unimportant. Three liquids, namely water, glycerine & water (58% - 42% by weight) and silicone liquid were used with air as the gas phase. In addition, the study included a comprehensive examination of the correlations that exist in the literature for predicting the mean heat-transfer coefficient for the conditions described above.

The following are the main findings in the present investigation:

1. The single-phase local-heat-transfer results were reported and compared with the theories of Worsøe-Schmidt (106) and Siegel et al.(81) in the laminar region and with the theory of Spalding (83) in the turbulent region. In both cases, the data correlated

well with the predictions. Also, there was excellent agreement when the mean heat-transfer coefficients were compared with the Sieder and Tate(79) correlation for the entire range of the liquid Reynolds numbers.

2. Two-phase flow patterns and their transitions for all three liquids at every liquid-gas combination were observed and photographed in the present study. The effect of surface tension was most profound on the bubble-slug boundary, which changed in such a way that much of the region previously occupied with slug flow has been replaced by bubble flow. The slug-churn, annular-mist and froth-annular transitions were slightly affected by changing σ . The churn-annular boundary moved such that annular flow was observed at lower superficial gas velocities with the lower surface tension liquid.
3. The two-phase frictional-pressure-drop results showed a weak dependence on the surface tension with the silicone-air data lying slightly beneath those for glycerine & water-air in terms of the ratio ϕ^2 vs V_{SG}/V_{SL} at the same Re_{SL} in the range of $Re_{SL} > 1500$).
4. Local heat-transfer coefficients, measured along the heated test section, showed internal consistency for all three liquids with trends that varied according to the combination of the liquid and gas flow rates. The surface tension appeared to have no effect on the shapes or the trends of h_{TP} along Z .

5. The behaviour of the mean heat-transfer coefficients for silicone-air in the range of liquid superficial velocities of 0.260 ft/s (0.079 m/s) to 2.26 ft/s (0.690 m/s) was as follows: $\bar{h}_{TP}$ increased with the introduction of air in the silicone liquid until it reached a maximum in the annular region (at lower V_{SG} than with other liquids at the same V_{SL}) which was followed by a steep drop to a minimum at $V_{SG} \sim 200.0$ ft/s (61.0 m/s) as the mixture was approaching the annular-mist transition. A further increase in the air flow rate was followed by a monotonic rise in $\bar{h}_{TP}$. The reason for this sudden drop in $\bar{h}_{TP}$ in the annular-mist transition followed by a monotonic rise was believed to be due to the very thin film on the wall with the attendant condition of the gas phase becoming more important in the heat-transfer process. Also, at the same liquid Reynolds numbers and V_{SG}/V_{SL} when the data were plotted in terms of $\bar{Nu}_{TP}$ vs V_{SG}/V_{SL} , the silicone-air data fell above those for glycerine & water-air during the early rising stage of $\bar{Nu}_{TP}$ (before the maximum in $\bar{Nu}_{TP}$ was reached), after which the data cross.
6. A comprehensive examination of most of the correlations that exist in the literature for predicting the mean heat-transfer coefficients in two-phase, two-component flow in vertical tubes led to conclusions on their success, or otherwise, in

predicting a very large set of data points. This set of data included those taken to date on the present experimental facility plus those taken by other investigators. Among the correlations that covered most of the range of variables involved in this data set and gave good results were those by Chu and Jones(16), Vijay et al.(94) and the Liquid-Acceleration Model.

7. Two simple correlations for predicting $\bar{h}_{TP}$ in the laminar ($Re_{SL} \leq 2000$) and turbulent ($Re_{SL} > 2000$) flow regions were developed in the present investigation. Those correlations, which include mostly independent variables, gave very good results indeed when used with the total data set while applying minimum restrictions on their ranges of applicability (mainly no annular-mist data).

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