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COMPUTER MODELLING OF SMART CONTROL SYSTEMS FOR RESIDENTIAL HOT WATER USAGE

by

Nikos Pontikakis

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Abstract

The design of residential hot-water plumbing supply systems is studied using computer models. The study consists of the following parts:

1. A critical review of the literature was conducted. The objective of this part was to present a document that reviews and evaluates the critical aspects of electrical residential water heating. First, the phenomenon of the *Legionella Pneumophila* bacteria was examined; second, the demand patterns of electrical water heating were reviewed, and finally, currently proposed technological improvements in domestic water heating were summarized.

2. A flow analysis of the hot-water supply was undertaken. When several taps run simultaneously, it creates a problem with the equal distribution of hot water. This results in a reduction of hot water flowing to the open taps. From this study, it was found that, by increasing the pipe diameter from 1/2 in. to 3/4 in. we can greatly improve the flow rates and temperatures at the exit points. Also it was found that, by relocating the hot-water tank closer to a tap, we can improve the flow rates of the hot water at the exit point.

3. Heat losses were confirmed after analysis of the distribution pipes and the hot-water tank. The basic aim of this research was to conserve energy in the hot-water tank by using different designs to optimize the existing systems. From this part, it was found that a low-flow showerhead and the insulation of the pipes can conserve energy , which results in a saving of customers money. A low-flow showerhead gives a 14-17 % savings in the heat losses of the hot-water tank while insulation on the pipes was found to give another 1.5-1.7 % savings.

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Nomenclature

Latin Letters

A_s	surface area, m^2
C_p	specific heat at constant pressure, $\frac{J}{kg \cdot K}$
D	Diameter, m
Gr	Grashof number
H	head, m
h	convection heat-transfer coefficient, $\frac{W}{m^2 \cdot K}$
k	thermal conductivity, $\frac{W}{m \cdot K}$
L	length, m
$\dot{m}$	mass flow rate $\frac{kg}{s}$
Nu	Nusselt number
p	pressure, Pa
Pr	Prandtl number
Q	discharge in the pipe, $\frac{m^2}{s}$
q	heat-transfer rate, W
$\bar{R}$	resistance coefficient, $\frac{s^2}{m^5}$
Ra	Rayleigh number

Re	Reynolds number
r	radius, m
T	temperature, K
t	time, s
V	volume, m^3
W	head loss, m
z	height, m

Greek Letters

α	thermal diffusivity, $\frac{m^2}{s}$
β	volumetric thermal expansion coefficient, K^{-1}
γ	specific weight, $\frac{N}{m^3}$
ΔH	Difference in head loss, m
ΔQ	Difference in the discharge of the pipe, $\frac{m^2}{s}$
ϵ	size of interval
θ	temperature difference, K
ν	kinematic viscosity, $\frac{m^2}{s}$
ρ	mass density, $\frac{k_g}{m^3}$

Subscripts

air	air
b	fluid (used in temperature)

c	hot water
D	diameter
f	fluid (used in convection heat transfer)
h	hot water
hor	horizontal pipe
i	initial conditions
ins	insulation
s	surroundings (used in area)
sur	surroundings
$vert$	vertical pipe
w	wall (used in temperature)
wi	initial temperature of the wall
∞	ambient condition
1	inner
2	outer

Chapter 1

Introduction

1.1 Overview

The design of residential hot-water plumbing supply systems, which are currently being used in countries such as Canada, has long been neglected. These systems tend to be poorly designed from an engineering point of view. Although the systems provide their intended service, so far as the author is aware a design optimization of them has never been performed. The large network of piping that delivers water to a house is a main engineering accomplishment, but the engineering expertise stops at the city water meter, where plumbers' rules of thumb take over.

The reason for this neglect is the abundance of water and electricity in Canada. Where water and electricity are scarce, plumbing and heating design is of great importance. With conservation becoming more and more important in almost every aspect of our lives, the development of improved residential hot water heating is inevitable.

This thesis has three major areas of study. The first area of study is a literature review, the second area of study is a flow analysis of plumbing systems, and the final area of study is the calculation of heat losses in the system. These three areas are closely connected to each other; however, a detailed analysis of each area was essential for the completion of this thesis. Although many of the findings of the literature review have not been used directly in the thesis , these results form a basis for conducting future research.

1.2 Literature Search

At the commencement of the project, a detailed literature search was conducted to assure that previous work in the manufacturing and utilization of domestic hot water heaters would be properly considered. There is currently available a large number of studies related to hot-water heating: however, the reported results are often contradictory and a critical review of this information is essential to the success of future work. Also, recent technological developments related to hot-water residential heating are documented. In addition, usage patterns and peak usage demands in homes are examined and used as the basis for heat loss calculations involving residential hot water plumbing systems.

1.3 Flow Analysis

The plumbing systems that are currently used, although they provide their intended function, do not always adequately supply the daily demand of a common household. Frequently, several taps run simultaneously, creating a problem with the equal distribution of hot water. This results in a reduction of hot water being sent to some open taps. Most people have experienced the discomfort of a sudden drop in water temperature during a shower. This is usually the result of a second tap being opened. With the advance of technology, this type of poor service is becoming unacceptable.

In this study two major areas were considered: firstly, the tap performance due to size of the pipe was examined, and secondly, the tap performance due to the location of the hot-water tank was studied.

1.4 Calculations of Heat Losses

Although heat loss through the distributing plumbing system of a residential home is relatively small, it is a parameter which was considered for the project. As other components of the system (eg. the hot-water tank) are optimized, losses from the plumbing system became more significant. The plumbing system was treated as a pipe network with each segment of the network described separately. The heat losses in each segment were calculated based on the convective and conductive losses resulting from the transport of hot water through the piping system, and cooling of the hot water remaining in the distribution pipes between usages. The losses due to cooling between usage may be important in operating strategies that involve periods in which the heater was not powered. However, these losses were found to be negligible in the present systems, so we have not considered them to be part of our solution. The convective and conductive losses were determined from the predicted temperatures in the distribution pipe arrangement. These losses were relatively independent of the hot water usage pattern. However, the cooling of hot water in the distribution pipes was influenced greatly by the usage pattern and by the time period between usages. Previous patterns of residential hot water usage in Canada were used for the calculation of these losses.

Also, the hot-water-tank losses were calculated. These losses were calculated based on four different cases: first, a comparison was made between insulated and uninsulated pipe; second, the tank was operated at $80°C$ instead of $60°C$ during the peak electrical usage hours; third, a comparison was made between a low-flow showerhead and a regular showerhead; and, finally, a comparison was made between 1/2 in. pipe and 3/4 in. pipe (through this thesis the British units will be used for the measure of the diameter in the pipes).

1.5 The Computer Program

To examine the heat losses from the pipe system and hot-water tank, and calculate the flow rates of the pipe network, two computer codes were developed. The computer programs are executable on IBM PC or compatible computers, and therefore are very transportable. The programming language was FORTRAN77, and the program was written in a concise, logical form, with a generous number of comment statements. The programs rely on entered patterns of residential hot-water usage that were derived from the collection of previous demand patterns in Canada and USA, which were used as examples to show the optimization of the control systems. The programs are simple to use and capable of handling several different operating parameters. For example, the program can determine the effects of low-flow showerheads.

Chapter 2

Review of the Literature

The design of residential water-heating systems which are presently used in countries such as Canada and the United States has long been neglected. Although the systems provide their intended service, a design optimization of them has never been performed. Many studies are currently available that discuss electrical residential water heating. However, these studies are often contradictory; therefore a critical review of this information is essential to the success of future work in the improvement of the design of existing systems.

The main objective of this chapter is to present a document that reviews and evaluates the critical aspects of electrical residential water heating. First, the health problems that may occur from hot water stored in heating and plumbing systems are examined. The most common bacteria found in homes is *Legionella pneumophila.* The cause of the growth of this bacteria is discussed. In addition, proposed design features and operating procedures of hot water systems that will minimize the proliferation of this bacteria are presented. Second, the demand patterns of electrical water heating and factors that contribute to electrical energy consumption are reviewed. Finally, currently proposed technological improvements in domestic water heating are summarized.

2.1 Materials and Methods

For this study a comprehensive review of published papers, articles, research reports and proceedings of technical conferences was conducted. This material was collected over a period of approximately one year. The sources for this information also include technical reports from electrical power utilities and industrial companies. The discussion that follows is based on information collected from the various sources and summarized in a series of tables that appear in the Appendix A. All volumetric quantities are cited using both U.S. gallons in the Inch-Pound (I-P) unit system and litres in the SI system.

2.2 Discussion

2.2.1 Legionella Pneumophila

Research over the past 15 years indicates that bacteria of the family *Legionellaceae* can be found in both natural and human environments. Outbreaks of this disease have been reported in Australia, the USA, Great Britain and France. These reports, from all over the world, clearly suggest that *Legionellaceae* is a worldwide phenomenon. Some of the causes of this bacterial growth are rubber components in water plumbing systems (Colbourne *et al.* 1984; States *et al.* 1990), free-living amoebae and other protozoa in the water plumbing system (Rowbotham 1980, 1983, 1986; Anand *et al.* 1983; Tyndall and Domingue 1982; Skinner *et al.* 1983; Fields *et al.* 1984; Holden *et al.* 1984; Barbaree *et al.* 1986) and temperature stratification at the water tank (Joly 1991, 1992; Dennis *et al.* 1984; Witherell *et al.* 1984; Arnow and Weil 1984). Previous research indicates that the growth of *L. pneumophila* can be reduced by application of ultraviolet (UV) light (Antopol and Ellner 1979; Gilpin 1984, Dutka 1984, Knudson 1985), by adjustment of pH levels (Fliermans *et al.* 1981; and Wadowsky *et al.* 1985; States *et al.* 1987) and by chlorination (Witherell *et al.* 1984; States *et al.* 1990; Kuchta *et al.* 1985).

Recommendations to reduce the growth of *Legionella pneumophila* are as follows:

- The unsafe and safe temperatures for growth and prohibitation of *Legionella pneumophila* are presented in Table A.1. It is clearly indicated through all the results that below $50°C$ ($122°F$) the temperature is unsafe; however five of the seven cases indicate an unsafe temperature between $50°C$ ($122°F$) and $55°C$ ($131°F$). It is therefore recommended that hot water tanks should operate above $55°C$ ($131°F$) so that the growth of *Legionella pneumophila* is prevented.

- Provisions should be made for adjustment of the pH in order to maintain it in the range 6.5 to 8.0 in both hot and cold water (Fliermans *et al.* 1981; Wadowsky *et al.* 1985; States *et al.* 1987).

- Hot-water tanks should be cleaned using chlorination at least once a year (Witherell *et al.* 1984; States *et al.* 1990; Kuchta *et al.* 1985).

- Rubber components should be eliminated from water plumbing systems because they have been linked to the development of *L. pneumophila* (Colbourne *et al.* 1984; States *et al.* 1990).

- Based on experience gained in preparing this report, we recommend that the use of a multi-element water heater should be studied. This hot-water tank would provide upper, middle and bottom electric elements. We suggest that the lower element would have a capacity of 0.8-1.0 kW (2700-3400 Btu/h), and operate only if consumption is heavy and the water at the bottom of the tank drops to a temperature favourable for the proliferation of bacteria.

- Finally we advise the study of a recirculation pump on the hot water tank, so that hot water can recirculate at periods of insignificant demand, hence preventing temperature stratification in the tank.

2.2.2 Electrical Energy Consumption and Demand Patterns

Residential water heating represents the second largest use of energy in North America. With steadily growing demand for energy, the benefits of energy conservation are significant. Therefore, electrical residential water heating represents an area that can yield significant energy savings. To reduce energy consumption, it is important to identify the causes of high electrical energy consumption and present reasons for demand peaks.

The summary that follows considers 150 and 225 L (40 and 60 gal) tanks because most literature refers to those two tank sizes. Information from the studied literature regarding energy consumption is summarized as follows:

- Studies conducted by Lambert and Choy (1986) and Kay and Analyst (1988) resulted in average monthly energy demands for 150 and 225 L (40 and 60 gal) tanks (Tables A.2 and A.3). The results of these studies agree closely with only percentage differences of 2.4% for 150 L (40 gal) tanks and 3.1% for 225 L (60 gal) tanks.

- January through April have the highest average monthly demand for both 150 and 225 L (40 and 60 gal) tanks (Table A.2).

- The daily electrical consumption of hot water is about 26% less in the summer than in the winter for both 150 and 225 L (40 and 60 gal) tanks (Tables A.2).

- August has the lowest average monthly demand for both 150 and 225 L (40 and 60 gal) tanks (Tables A.2).

- The annual energy consumption for a 150 L (40 gal) tank is about 4490 kWh (1.531×10^7 Btu) and for a 225 L (60 gal) tank about 6100 kWh (2.080×10^7 Btu). This indicates that customers with 225 L (60 gal) tanks consume 20-50% more energy than customers with 150 L (40 gal) tanks (Table A.3).

- The average daily hot water use per household is 245 L (65 gal). This is determined from the information provided by Perlman *et al.* (1984) and Ladd and Harrison (1985) (Table A.4).

- The day of the week with the overall largest average consumption of hot water is Monday (Table A.4).

- Studies conducted by Stevenson (1983) and Ladd and Harrison (1985) reported the average daily consumptions of hot water per household in Table A.5. The average percent difference between the results of these two studies is 54%. Obviously, these two studies do not agree. This can be attributed to the fact that the Stevenson (1983) work was conducted using experimental studies, whereas the Ladd and Harrisson study was conducted through a survey.

- Showers consume the largest portion of hot water, approximatly 40%, followed by washing machines which consume 18-24% (Table A.5).

- A family consisting of one person consumes the highest overall daily hot water per person. A family of three people consumes the second highesst average daily hot water usage per person. An interesting outcome from the literature is that the average hot water usage per person declines in households that have more than three people (Table A.6).

- The presence of preschool-age children (less than 6 years old) in a family increases the average hot water consumption (Table A.7).

- The patterns of consumption indicate two major peaks during the day. The first peak is in the morning, (8-10 a.m.) with 8 a.m. having the highest average hourly demand, and the second peak is in the evening (7-10 p.m.) with 7 and 8 p.m. having the highest average hourly demand. (Tables A.8 and A.9).

- Studies that determined the average hourly consumption of hot water per household were conducted by Merrigan (1988), Ladd and Harrison (1985), Perlman *et al.* (1984), and Stevenson (1983) (Tables A.9 and A.10). The results of these studies appear inconsistent, with percent deviations ranging between 10-21%. However, if one considers the level of difficulty in relating the consumption trends of different lifestyles, then the agreement is reasonable.

- The maximum energy consumption for a dishwasher is usually at 8 p.m. on a week day and 10 p.m. on a weekend day (Table A.10).

- The maximum hour for energy consumption for a clothes washer is between 9-10 a.m. on a week day and 10 a.m. on a weekend day (Table A.10).

- The use of dishwashers at 8 p.m. explains the occurrence of night power peaks (Table A.10).

- As hot-water consumption increases, energy consumption (the energy required to raise the temperature of the water used and the energy lost as heat by conduction from storage tanks), unit production (the volume of hot water produced per unit of energy consumed) and efficiency (the energy output divided by the energy input) increase for both 150 and 225 L (40 and 60 gal) tanks (Tables A.11 through A.14).

- Unit production and efficiency improve with increasing hot water consumption because storage tank energy loss becomes a smaller proportion of the total energy consumption (Tables A.11 through A.14).

- Energy is consumed even when no hot water is being used due to storage tank heat loss (Tables A.11 through A.14).

- The storage tank energy loss for a 150 L (40 gal) tank is 3.3 kWh/day (11 000 Btu/day) during the winter compared with 1.4 kWh/day (4700 Btu/day) in the summer. Similarly, for a 225 L (60 gal) tank the storage energy loss is 3.9 kWh/day (13 000 Btu/day) during the winter compared with 1.7 kWh/day (5800 Btu/day) in the summer. This indicates that the storage energy tank loss in the summer is approximately 43% less than the winter for both 150 and 225 L (40 and 60 gal) tanks (Tables A.11 through A.14).

- A slight increase in storage tank energy loss is seen for a 225 L (60 gal) tank compared to a 150 L (40 gal) tank. This causes a slight increase in the energy required by the water heater, which corresponds to a small decrease in unit production and efficiency between 150 and 225 L (60 and 40 gal) tanks (Tables A.11 through A.14).

- The storage-tank temperature, inlet water temperature and ambient air temperature all affect the unit production and efficiency of the system (Tables A.11 through A.14).

- The unit production (L/kWh) is about 50% higher in the summer than the winter for both 150 and 225 L (40 and 60 gal) tanks. Also, the efficiency increases approximately 1.5% between winter and summer for both 150 and 225 L (40 and 60 gal) tanks (Tables A.11 through A.14).

- The average daily hot-water use per person is about 61.5 L (16.2 gal) (Table A.15).

- The average daily consumption of hot water per person (Table A.16) was determined by Kipping (1981), Merrigan (1983) and Perlman *et al.* (1984). The results of these studies agree quite well yielding a percent difference between Kipping (1981) and Merrigan (1988) of 5%, and a percent difference between Kipping (1981) and Perlman *et al.* of only 0.6%.

- Males use 55% more water or 42.4 L (11.2 gal) compared to 27.3 L (7.20 gal) used by a female when they shower without washing their hair (Table A.16).

- Females use 45% more water or 74 L (280 gal) compared to 51 L (193 gal) used by a male when they shower and wash their hair (Table A.16).

- In a hot-water tank most of the heating is done by the bottom element, 100%, 96.8% and 81.5% for 2000 W (6800 Btu/h), 1500 W (5100 Btu/h) and 1000 W (3400 Btu/h) lower elements, respectively. The top element turns on only during major water draws (Table A.17).

- The age group of 25-35 years has the highest hot-water consumption (about 77 L/Day (20 gal/Day)) (Table A.18).

- The age group of people 50 years or greater has the lowest hot-water consumption (approximately 59 L/Day (16 gal/Day)) (Table A.18).

- After 35 years of age, the hot-water consumption of a person declines (Table A.18).

2.2.3 Technological Improvements in Domestic Hot Water Heating

The use of low-flow showerheads and heat traps represent technological improvements in the design and use of residential hot-water systems. The addition of more insulation in a hot-water tank also improves energy consumption. More specifically:

- Foam insulation, such as polyurethane, appears to be superior to fibreglass insulation. The savings for 50 and 25 mm (1.97 and 0.98 in) insulation thickness are about 14-15% (Table A.19).

- Heat losses can be reduced by adding insulation. For example, the addition of 50 mm (1.97 in) of insulation to a 150 L (40 gal) tank gives approximately 360 kWh/yr (1.23×10^6 Btu/yr) of energy savings. Similarly, the addition of 50 mm (1.97 in) of insulation to a 225 L (60 gal) tank gives about 350-460 kWh/yr (1.19×10^6 - 1.57×10^6 Btu/yr) of energy savings (Table A.20).

- A low-flow showerhead is economically functional. This type of showerhead can reduce the flowrate by approximately 5 L/min (13 gal/min) or 38% (Table A.21).

- Heat traps are economically feasible. A typical heat trap is shown in Figure 2.1. A heat trap works by preventing cooler denser water, on the pipe side, from sinking below hotter water on the tank side. Since hot water rises, a simple loop or square made from pipe and installed at the inlet and outlet of the tank will prevent convection currents in the pipe runs. For 12.7 mm (0.5 in) copper tubing,daily energy savings relative to a vertical configuration of approximately 210-230 kJ (199-218 Btu) or 37% can be realized for both inlet and outlet connections (Table A.22).

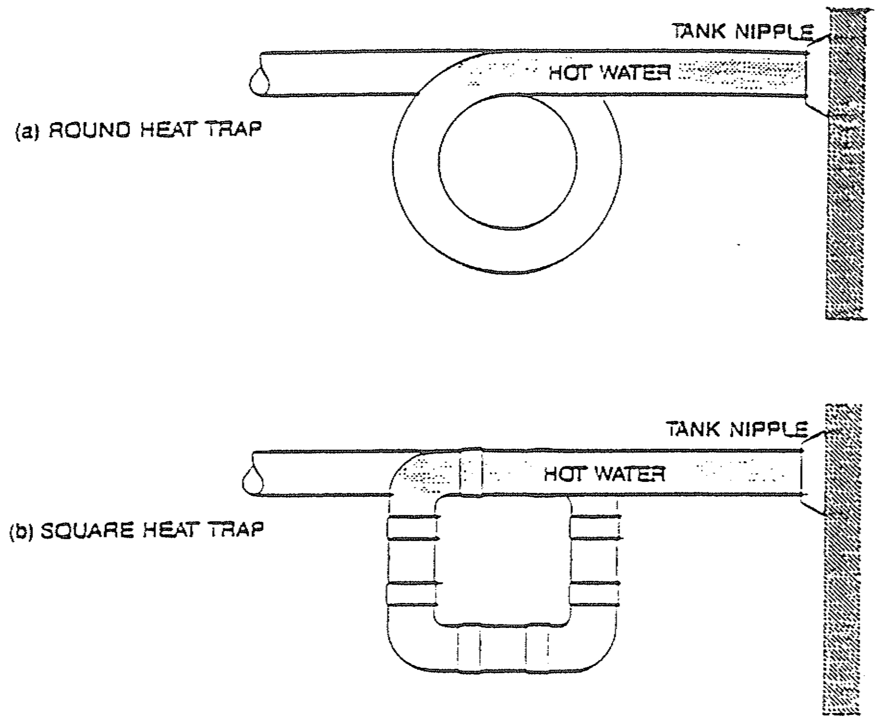

Figure 2.1: Heat Trap - Construction

Other technical improvements cited in the literature that do not relate to energy consumption include the use of powder enamels on the inside surfaces of the tank. Traditionally, water heaters in North America are coated with enamels by spraying with lances. There is, however, a new process called the "electrostatic powder application technique". The powder enamel has a water corrosion resistance 1.4 times superior to that of wet standard enamel (Lapperriere 1990). A second design improvement is the use of an insulation material called Aerogel which contains approximately 5% silica and 95% air. When evacuated it has a thermal resistance 3.5 times higher than rigid polyurethane (Perlman *et al.* 1988). A third technical improvement is a vacuum insulation system which can be made by encasing a vacuum within a metal envelope. Regularly placed glass spacers inside the envelope keep it from collapsing under atmospheric pressure. This insulation system adapts well to a broad range of temperatures, f rom extremely cold to nearly $500°C$ $(932°F)$. Prototypes of a vacuum insulation system already demonstrate an impressive thermal resistance of R-1.74 per centimeter which compares favourably with a typical R-0.49 for 1-centimeter-thick polyurethane foam (Lapperriere 1990).

2.2.4 Summary

In this chapter, a survey of electrical residential hot-water heating was presented. One of the most important elements of electrical residential hot-water heating is the phenomenon of *legionella pneumophila* bacteria. The factors that affect the growth of this bacteria are temperature stratification, rubber plumbing components, and free-living amobae and other protozoa. Previous research indicates that the growth of this bacteria can be reduced by adjusting the pH range and by treating the hot water with chlorine. Another important factor considered in this survey was a review of electrical energy consumption. The number and age of family members, as well as hot water tank size and numbers of hot water appliances, are factors affecting the hot water demand pattern in a residence. A final factor examined in this survey is the energy savings from the use of improved technological devices. Low-flow showerheads and heat traps represent technological improvements that provide significant savings in b oth energy and water consumption. Also, the addition of more insulation in hot water tanks can improve energy consumption.

Chapter 3

Flow Analysis of the Pipe Network

3.1 General

This chapter will give mathematical formulations for the evaluation of the flow analysis in the existing pipe network used in this investigation. For the analysis of the systems considered in this study, the Hardy-Cross method was used.

3.2 The Hardy-Cross Method

This method iteratively determines the flow rates and head losses throughout a piping network, providing the pipes sizes, the lengths, and pipe roughnesses are known. To outline the method, four important terms, "loop", "node", "fixed-grade node" and "pseudoloop" must be defined.

1. A "loop" is a series of pipes forming a closed path, as shown in Fig. 3-1. A sign convention is used to denote the direction of flow and head loss in the system. The flow, Q, and the head loss, H, are positive for flow in the clockwise direction and negative for counterclockwise flow around a loop.

2. A "node" is a point where two or more pipes join. A sign convention also exists for the analysis of nodes. Flow rate into a node is denoted as positive, whereas flow leaving a node is negative.

3. When the hydraulic head is assumed to be known at some point, then this location is referred to as a "fixed-grade node".

4. When a path connects two fixed-grade nodes, then such a path is sometimes termed a "pseudoloop", since an imaginary pipe with infinite resistance, or no flow, can be considered to connect the two reservoirs.

Before explaining the Hardy-Cross equation, it is worthwhile to examine a specific example of a piping network. Figure 3.1a shows a relatively simple network consisting of seven pipes and two reservoirs. The hydraulic heads at A and F are assumed known; these locations are therefore fixed-grade nodes. Outflow demands are presented at nodes C and D. Flow directions, even though not initially known, are assumed to take place as shown. The basic equation for flow between two locations α and β is taken from Mechanics of Fluids by Potter and Wiggert (p 519, 1991).

$$(\frac{p}{\gamma} + z)_{\alpha} - (\frac{p}{\gamma} + z)_{\beta} = \bar{R}Q^2 \tag{3.1}$$

Where the first two terms are the heads at α and β, and the right hand side is the head loss.

This equation may be written as

$$H_\alpha - H_\beta = W \tag{3.2}$$

where

$$H = \frac{p}{\gamma} + z \qquad\qquad W = \bar{R}\,Q^2 \tag{3.3}$$

and R is the resistance coefficient, Q is the discharge in the pipe, W is the head loss, H is the head, p is the pressure, γ is the specific weight, z is the height.

For our example, the energy balance for each pipe we gives:

$$H_A - H_B = W_1 \tag{3.4}$$

$$H_B - H_D = W_2 \tag{3.5}$$

$$H_C - H_D = W_3 \tag{3.6}$$

$$H_B - H_C = W_4 \tag{3.7}$$

$$H_C - H_E = W_5 \tag{3.8}$$

$$H_E - H_D = W_6 \tag{3.9}$$

$$H_F - H_E = W_7 \tag{3.10}$$

A continuity balance for each interior node gives

$$Q_1 - Q_2 - Q_4 = 0 \tag{3.11}$$

$$Q_2 + Q_3 + Q_6 = Q_D \tag{3.12}$$

$$Q_4 - Q_3 - Q_5 = Q_C \tag{3.13}$$

$$Q_5 - Q_6 + Q_7 = 0 \tag{3.14}$$

For the system, two closed paths, or interior loops, can be identified (see Fig 3.1b). Around a loop, the sum of the heads must be zero; therefore,

$$W_4 - W_2 + W_3 = 0 \tag{3.15}$$

and

$$W_5 - W_3 + W_6 = 0 \tag{3.16}$$

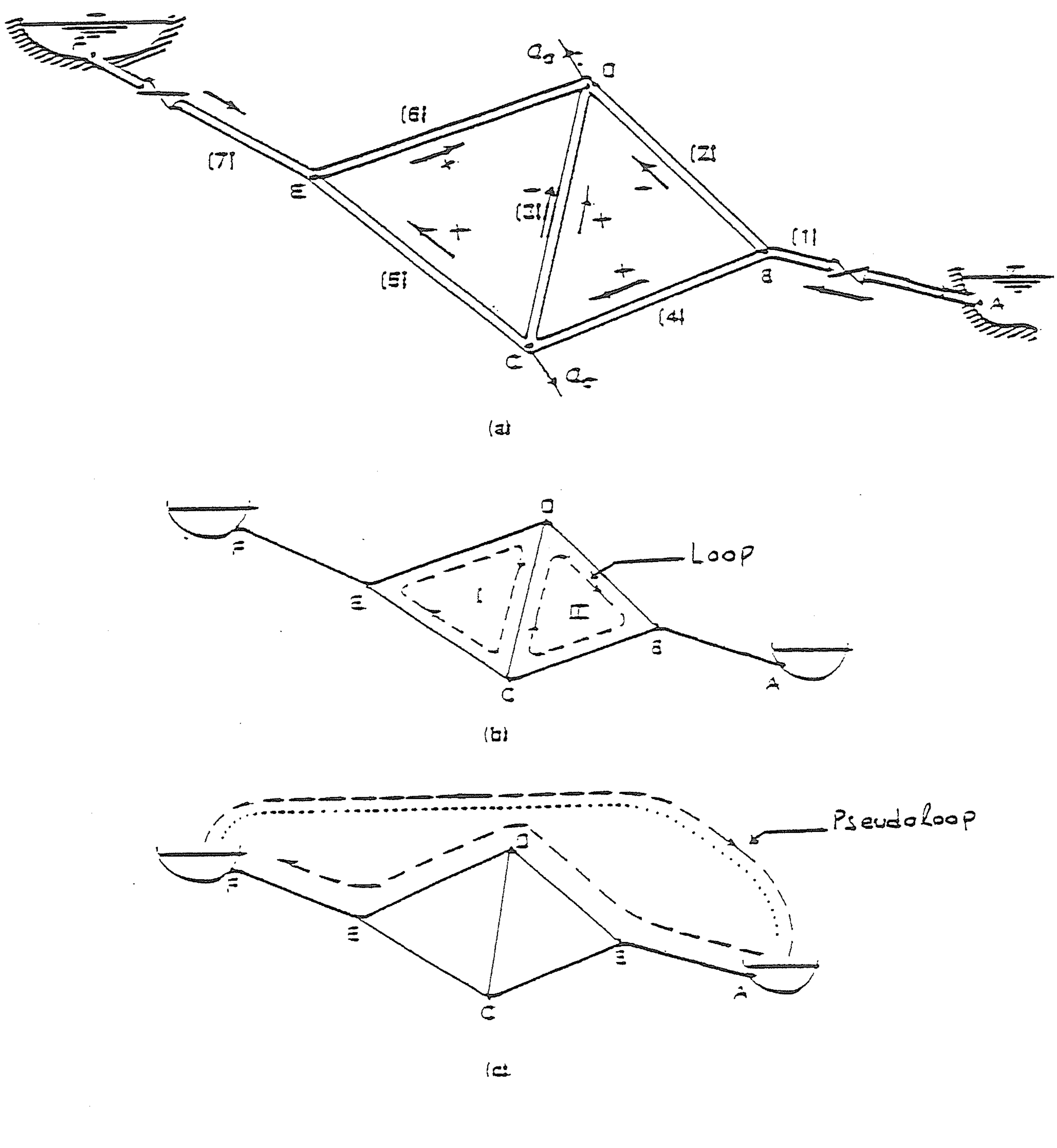

Figure 3.1: Representative Pipe network: (a) assumed flow direction and numbering scheme? (b) designated interior loops? (c) path between two fixed-grade nodes.

Similarly, for the pseudoloop (see Fig 3.1c)

$$H_A - W_1 - W_2 + W_6 + W_7 = H_F \tag{3.17}$$

These set of equations will be solved using the Hardy-Cross method. The Hardy-Cross method is based on two concepts: (1) the law of mass conservation and (2) the total head at any node is single valued. Equations 3.15 to 3.17 are of the form

$$\sum \pm(W_i) + \Delta H = 0 \tag{3.18}$$

In this case ΔH is the difference of two fixed-grade nodes in the path ordered in a clockwise fashion across the imaginary pipe in the pseudoloop. Furthermore, the + applies for clockwise flows and the - applies for counterclockwise flows. It follows from equations 3.2 and 3.3 that

$$\sum_{c}[\bar{R}Q^2] - \sum_{cc}[\bar{R}Q^2] + \Delta H = 0 \tag{3.19}$$

where C denotes clockwise flow and CC denotes counterclockwise flow. Consider the loop I from Figure 3.1b. We want to develop a correction term for a loop that maintains the continuity at each junction. At junction E, continuity requires

$$Q_5 + Q_7 - Q_6 = 0 \tag{3.20}$$

If we develop a flow correction (ΔQ) to apply to the entire loop, then in order for this continuity to be maintained after correction, we would have to add the correction to each of the flows in the specified loop. Therefore

$$(Q_5 + \Delta Q) - (Q_6 + \Delta Q) + Q_7 = 0 \tag{3.21}$$

Obviously, continuity would still result because the ΔQ's in this equation cancel. Now consider the continuity condition at node C

$$Q_4 - Q_3 - Q_5 - Q_c = 0 \tag{3.22}$$

Here, for the correction in loop I, we would have to add the correction to Q_5 but subtract it from Q_3 in order to maintain continuity:

$$Q_4 - (Q_3 - \Delta Q) - (Q_5 + \Delta Q) - Q_c = 0 \tag{3.23}$$

If the sign of Q changes during the iteration, then, for example, Q_4 in the last case would be negative.

$$(Q_3 + \Delta Q) + (-|Q_4| - \Delta Q) - Q_6 = 0 \tag{3.24}$$

Examining the above equations, we see that corrections are added to clockwise flows and subtracted from counterclockwise flows (based on the direction on which our continuity equations were developed). Therefore the corrected form of the governing equation may be written as

$$\sum_{c}[\bar{R}(Q+\Delta Q)^2] - \sum_{cc}[\bar{R}(Q-\Delta Q)^2] + \Delta H = 0 \tag{3.25}$$

Expanding the squared terms

$$\sum_{c}[\bar{R}(Q^2+2Q\Delta Q+(\Delta Q)^2)] - \sum_{cc}[\bar{R}(Q^2-2Q\Delta Q+(\Delta Q)^2)] + \Delta H = 0 \tag{3.26}$$

If ΔQ is small relative to Q, then the (ΔQ^2) terms may be dropped:

$$\sum_{c}[\bar{R}(Q^2+2Q\Delta Q)] - \sum_{cc}[\bar{R}(Q^2-2Q\Delta Q)] + \Delta H = 0 \tag{3.27}$$

Collecting terms in ΔQ

$$\sum_{c}[\bar{R}(Q)^2] - \sum_{cc}[\bar{R}(Q)^2] + \Delta Q(\sum_{c}[2\bar{R}Q] + \sum_{cc}[2\bar{R}Q]) + \Delta H = 0 \tag{3.28}$$

or

$$\Delta Q = \frac{-\sum_{c}[\bar{R}(Q)^2] + \sum_{cc}[\bar{R}(Q)^2] - \Delta H}{\sum_{c}[2\bar{R}Q] + \sum_{cc}[2\bar{R}Q]} \tag{3.29}$$

An outline of how the Hardy-Cross method was implemented in an iterative solution scheme can be found in chapter 5.

Chapter 4

Heat Transfer Formulation of the Pipe Network and Hot Water Tank

4.1 General

This chapter will give mathematical formulations for the evaluation of the heat transfer in the pipe network used in this investigation. This network contains both vertical and horizontal pipes. The heat-transfer correlations for the horizontal and vertical pipes are different mainly because of the gravitational forces that the vertical pipe experiences. Therefore, in this investigation we analyzed vertical and horizontal piping separately.

4.2 Free Convection

In this section, we consider convective transfer in fluid flows that originate when a body force acts on a fluid in which there are density gradients. The net effect is a buoyancy force, which induces free convective currents. In the current situation, the density gradient is due to a temperature difference between the pipe of hot water, normally at $60°C$, and the surroundings with a room temperature of $20°C$.

For the horizontal piping case, we used the correlations for a long horizontal cylinder. We used the Churchill and Chu correlation taken from Fundamentals of Heat and Mass Transfer by Incropera and DeWitt (p 551, 1990) that is good for a wide Rayleigh number range; it is given by

$$Nu_D = \left(0.60 + \frac{0.387\, {Ra_D}^{\frac{1}{6}}}{\left(1 + \left(\frac{0.559}{Pr}\right)^{\frac{9}{16}}\right)^{\frac{8}{27}}} \right)^2 \tag{4.1}$$

and is valid for the Rayleigh number range of $10^{-5} < Ra_D < 10^{12}$. The cases studied fell within the range of application of the above equation.

For a vertical cylinder, normally it is very difficult to obtain correlations. However, in most cases the vertical plate equation is applied to vertical cylinders of height L, if the boundary layer thickness δ is much less than the cylinder diameter D. This condition is known to be satisfied when $\frac{D}{L} \geq \frac{35}{{Gr_L}^{\frac{1}{4}}}$. In the present study, this condition was satisfied because we used pipe diameters of 1/2 in. and 3/4 in. and small lengths. The correlation that is suitable for most engineering calculations and the one that we used in the present study was formulated by Churchill and Chu, was taken from Fundamentals of Heat and Mass Transfer by Incropera and DeWitt (p 543, 1990), and is of the form

$$\overline{Nu}_L = 0.68 + \frac{0.670\, Ra_L^{\frac{1}{4}}}{\left(1 + \left(\frac{0.492}{Pr}\right)^{\frac{9}{16}}\right)^{\frac{4}{9}}} \tag{4.2}$$

In an insulated pipe, the derivation of the heat-transfer coefficients is much more complex. However, we can treat the insulated pipe and the free air stream as one system, and we can find an effective heat-transfer coefficient, h_{eff}, that accounts for both the insulation and the fluid boundary layer. Once the h_{eff} is found, the problem may be solved in the same manner as for the uninsulated case, but with h_{eff} replacing h. Figure 4.1 illustrates the effective heat transfer coefficient.

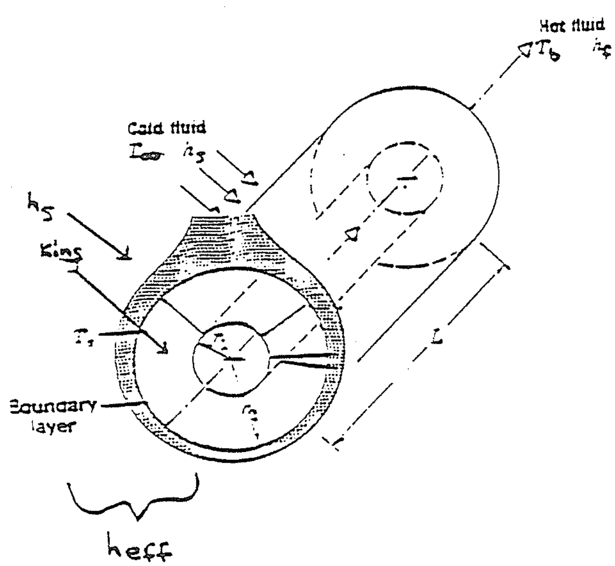

Figure 4.1: The effective heat transfer coefficient (includes effect of both k_{ins} and h_s)

The effective heat transfer coefficient is given by

$$h_{eff} = \frac{1}{ln(\frac{r_2}{r_1})\,\frac{r_1}{k_{ins}} + \frac{r_1}{r_2\,h_s}} \tag{4.3}$$

The above equation is derived in Appendix B.1.1

From the above equation, we can obtain the h_{eff} of a horizontal and vertical pipe if we substitute either the h_s for a horizontal pipe:

$$h_s = \frac{k_{air}}{D}(0.60^2 + 2 \cdot 0.60 \cdot 0.5275 \left(\frac{(T_{ins} - T_\infty)\;{D_{ins}}^3}{(T_{ins} + T_\infty)\;\nu\,\alpha}\right)^{\frac{1}{6}}$$

$$+0.5275^2 \left(\frac{(T_{ins} - T_\infty)\;{D_{ins}}^3}{(T_{ins} + T_\infty)\;\nu\,\alpha}\right)^{\frac{1}{3}}) \tag{4.4}$$

or substitute the h_s for a vertical pipe:

$$h_s = \frac{k_{air}}{L}\left(0.68 + 1.082\left(\frac{(T_{ins} - T_\infty)\;L^3}{(T_{ins} + T_\infty)\;\nu\,\alpha}\right)^{\frac{1}{4}}\right) \tag{4.5}$$

4.3 Transient Conduction

So far we have considered steady, natural-convective flows, in which velocity and temperature fields do not vary with time. The startup and shutdown of systems, such as hot water tanks, leads to transient natural convection. In our present system, the surface temperature of the piping system will drop after the shutdown of the flow. Thus the temperature at each point in the system will also begin to change. The changes will continue to occur until a steady-state temperature distribution is reached.

In the present study, we model the system using the lumped capacitance method. The essence of the lumped-capacitance method is the assumption that the temperature of the water inside of the system is uniform at any instant during the transient process. This assumption implies that temperature gradients within the pipes are negligible. Because the temperature of the pipe surface is very close to the mean temperature of the hot water in the pipe, this assumption is reasonable.

The lumped-capacitance method is preferably used because it is simple and convenient. However, it is important to determine under what condition it may be used with reasonable results. If the Biot number, $Bi = \frac{hL_c}{k}$, is much less than 1, the resistance to conduction within the fluid is much less than the resistance to convection across the fluid boundary layer. Hence, the assumption of a uniform temperature distribution is reasonable. The criterion for using the lumped-capacitance method is

$$Bi = \frac{hL_c}{k} < 0.1 \tag{4.6}$$

In our present study the Biot number is always less than 0.1 so it satisfies the criterion for using the lumped-capacitance method. To find the temperature of the surface of the pipe at any time, t, we use the following equation

$$\frac{\theta}{\theta_i} = exp\left[-\left(\frac{h\,A_s}{\rho\,V\,c}\right)t\right] \tag{4.7}$$

In the above equation $\frac{\theta}{\theta_i} = \frac{T_w - T_\infty}{T_{wi} - T_\infty}$ where T_{wi} is the initial temperature of the wall (where the wall and the bulk are assumed to have the same temperature), T_w is the temperature of the wall, and T_∞ is the temperature of the air. A_s is the surface area of the pipe, ρ is the density of the fluid in the pipe, V is the volume of the pipe, and h is the convective heat transfer coefficient.

The convective heat-transfer coefficient is given for the horizontal pipe by equation B.11 and for the vertical pipe by equation B.16

The derivations of the above convective heat transfer coefficients are given in Appendix B.

For the case of insulation, the insulation material will contribute to the heat-transfer coefficient. The temperature distribution through an insulated pipe is given in Figure 4.2, the heat transfer through the pipe is given by

$$q_f = h_f\,2\,\pi r_1 L(T_b - T_w) \tag{4.8}$$

$$q_{ins} = \frac{k_{ins}\,2\,\pi\,L(T_w - T_{ins})}{ln(\frac{r2}{r1})} \tag{4.9}$$

$$q_{sur} = h_s\,2\,\pi r_2 L(T_{ins} - T_\infty) \tag{4.10}$$

Here T_b is the temperature of the fluid, and T_w is the temperature of the pipe wall, T_{ins} is the temperature of insulation, and T_∞ is the temperature of the air.

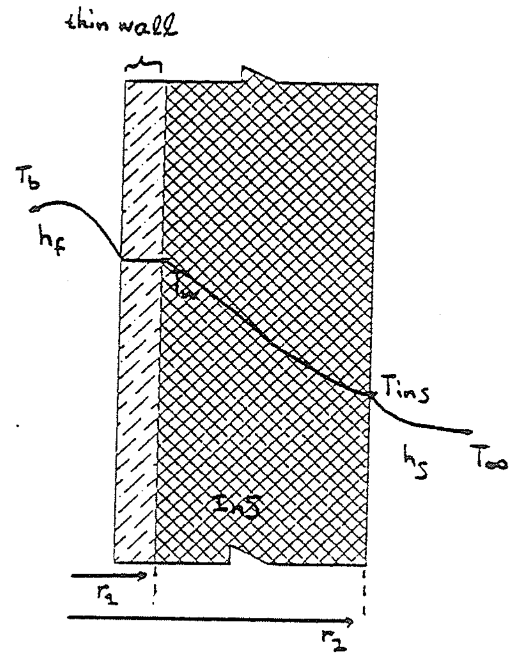

Figure 4.2: Temperature Distribution THrough an Insulated Pipe

The temperature at the surface of the pipe is given by $\dfrac{\theta}{\theta_i} = \dfrac{T_w - T_\infty}{T_{wi} - T_\infty}$. However in this case T_w is given in the form below

$$T_w = \frac{h_s\,2\,\pi\,r_2\,L\,T_b\,h_f\,r_1\,ln(\frac{r_2}{r_1})}{k_{ins}\left(2\,\pi\,r_2\,L\,h_s + \frac{2\,\pi\,r_2\,L\,h_s\,h_f\,r_1\,ln(\frac{r_2}{r_1})}{k_{ins}} + 2\,\pi\,h_f\,r_1\,L\right)}$$
$$+\frac{h_s\,2\,\pi\,r_2\,L\,T_\infty}{k_{ins}\left(2\,\pi\,r_2\,L\,h_s + \frac{2\,\pi\,r_2\,L\,h_s\,h_f\,r_1\,ln(\frac{r_2}{r_1})}{k_{ins}} + 2\,\pi\,h_f\,r_1\,L\right)}$$
$$+\frac{h_f\,2\,\pi\,r_1\,L\,T_b}{k_{ins}\left(2\,\pi\,r_2\,L\,h_s + \frac{2\,\pi\,r_2\,L\,h_s\,h_f\,r_1\,ln(\frac{r_2}{r_1})}{k_{ins}} + 2\,\pi\,h_f\,r_1\,L\right)} \tag{4.11}$$

The above equation is derived in Appendix B.1.

4.4 Heat Transfer Losses from the Hot Water Tank

This section will consider the heat losses from the hot water tank Figure 4.3 indicates the heat transfer modes in a water heater. There are two major losses from the hot water tank: firstly, the losses from the convection and conduction between the temperature of the air in the room and the temperature inside the tank, and secondly, the losses from the withdrawl of the hot water and replacement by cold water.

Convective heat losses describe the energy transfer between a surface and a fluid moving over the surface. The heat transfer due to convection may be expressed as

$$q = h\,A\,(T_b - T_\infty) \tag{4.12}$$

where h is the overall heat transfer coefficient and T_b is the bulk temperature of the water in the tank. In this case the heat transfer coefficient is very difficult to determine through a numerical procedure. Therefore, experimental heat losses from documented sources were taken for a known temperatures in the tank. Then using a curve fitting technique, the value of $h\,A$ was calculated for the hot water tank.

The second loss that occurs in the tank is due to the hot water withdrawal. When a withdrawal occurs, hot water leaves the tank from one end and cold water replaces it from the other. The heat loss due to this process is

$$q = \dot{m}\,c_p\,\delta T \tag{4.13}$$

where $\dot{m}$ is the mass flow rate of the hot water, c_p is the specific heat of the water and δT is the temperature difference between the water leaving the tank and the cold water entering the tank.

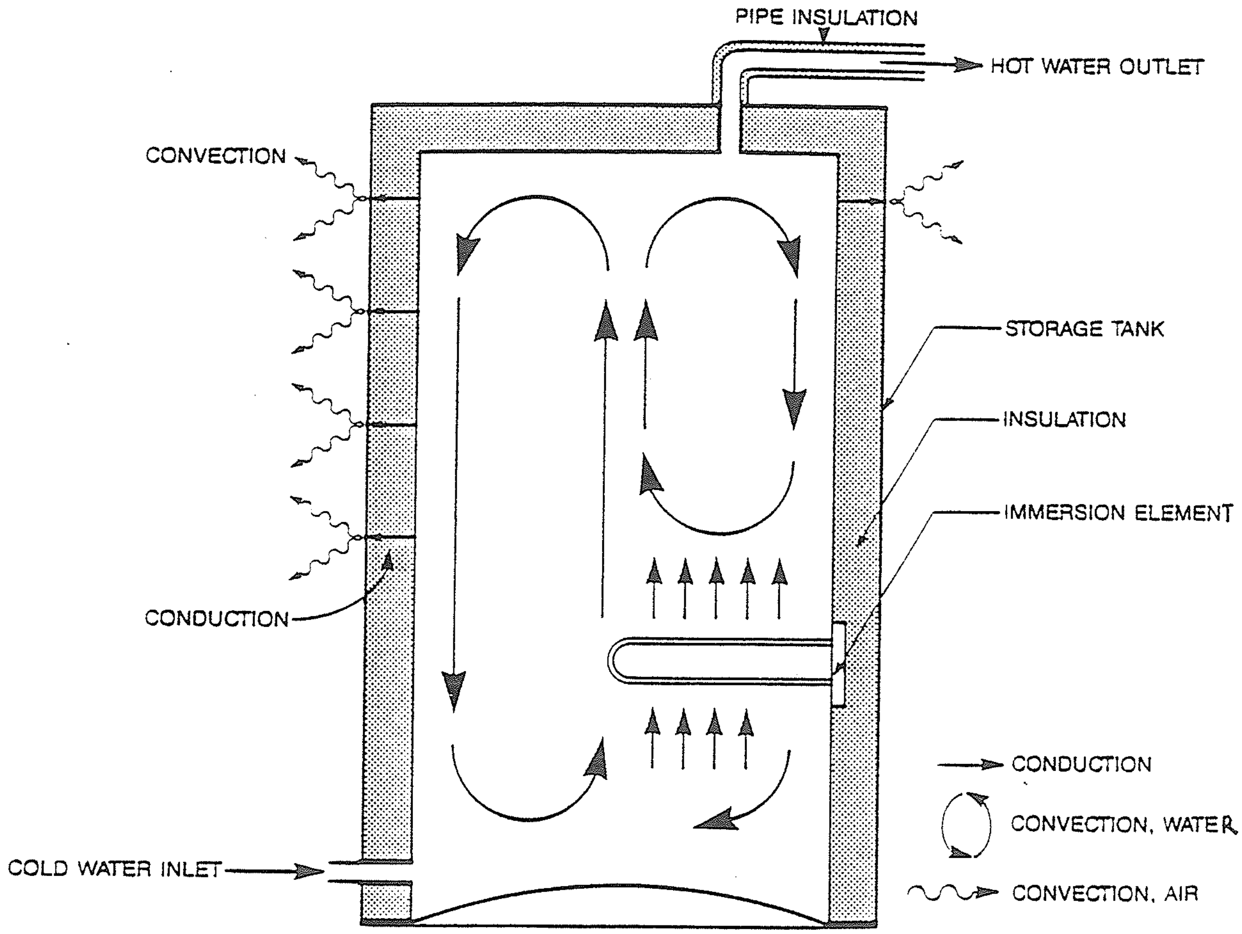

Figure 4.3: Heat Transfer in Water Heaters

Chapter 5

Computer Code

5.1 General

To examine the flow rates in a pipe network and calculate the heat losses from the pipe system and hot water tank, two computer codes were developed. Listings of these programs is given in Appendix D. The first program assumes no insulation exists in the pipe network, whereas the second program assumes insulation is incorporated into the existing system. A detailed analysis of the program and input and output file information is presented in this chapter.

In Section 5.2 the structure of the program is described. Sections 5.3 and 5.4 describe the input and output files. Section 5.5 explains the subroutines and functions that were used in the programs and finally Section 5.6 illustrates the bisection method.

5.2 Structure

The programs are set up to read data from a data file and write relevant data to an output file. Following the read statements, the minor loss coefficients were entered for each different condition. In this particular problem we consider five conditions. First, when the shower is open by itself; second, when the washroom sink tap is open by itself; third, when the laundry is open by itself; fourth, when the kitchen sink is open by itself; and finally, when the dishwasher is open by itself.

The main part of the program consists of the calculation of the flow at the taps. For the calculations of the flow rates at the taps of the network system, the Hardy-Cross method was used. This method has been explained in detail in a previous chapter of this thesis. The Hardy-Cross iterative solution is a simplified version of the iterative linear analysis. We can outline the application of the Hardy-Cross iterative solution by the following steps:

- Assume an initial estimate of the flow distribution in the network that satisfies the continuity equation. The closer the initial estimates is to the correct values, the fewer will be the iteration steps necessary for convergence.
- For each loop or path, evaluate ΔQ in the system.
- Update the flows in each pipe in all loops and paths.
- Repeat steps 2 and 3 until a desired accuracy is attained.

Besides the calculations of the flow rates in the main program, we also determine the demand for hot-water during a certain period of time. We also calculated the mass flow rate at the exit of the hot water tank, and finally the losses in the tank from the withdrawal and convective effects.

The final part of the main program simply outputs the relevant data to an output file.

5.3 Input File

The input file contains all the relevant information describing the plumbing system in question. A sample of an input file is contained in Appendix E.1. The input values are described so that the location of each input can be determined easily.

The first line in the input file is the number of pipe segments in the system. The number of junctions and number of pumps are the next inputs in the data file. The viscosity, the specific gravity and the converge criteria follow the number of inputs.

Next we enter the pipe information. For each pipe in the system, the pipe length, pipe diameter, roughness, and a flow rate guess are given. At this point we select a point in the system to act as a reference point. Then we enter the piezometric head at this location.

The next set of values entered represents the information about the data for the pipes between the joints. First the reference point to the junction, then first to second junction, and so on. For each path we enter the number of pipes between the junctions, then the label number for these pipes. These label numbers are signed to give the direction of flow.

The next set of data shows the information for the loops and pseudoloops. For each loop we enter the piezometric pressure difference between the start and the end of the loop, then the number of pipes in the loop, then the label number for each pipe. These label numbers are signed to give the initially assumed direction of flow.

The following set of values gives the information for the pipes that meet at the junctions. For each junction, we enter the number of tubes entering and the number of each tube. Each tube is signed such that inflow is positive and outflow is negative.

Lastly in this program, one more input file was used. It contains the demand pattern of each day of the week. For every day a different demand pattern was used. Previous patterns of residential hot water usage in Canada and USA, that were collected during the literature search of this thesis, were used. For each day a 24-hour clock schedule was used with periods of demand when a tap was open, and a period of no demand when all taps were closed. During the night between 12 a.m. and 7 a.m. we show very little demand in the schedule of our pattern, while a great demand occurred in the morning between 7 a.m. and 9 a.m. mostly due to showering. Also a second peak was input in our schedule. It occurred in the evening between 7 p.m. and 8 p.m. when the dishwasher was in operation.

5.4 Output File

The output file contains information of interest to the solution of the pipe network and to the solution of the sample problems. All information is labelled in the output file. A sample of an output file is contained in Appendix E.2.

The output file consists of two different sets of information. The first set contains information when a withdrawal occurs in the tank and hot water is circulated through the pipe network. The second set consists of information when no withdrawal is taken from the hot water tank and the flow is zero.

The output of the first case includes the temperature at the wall and heat loss of each pipe. It also contains the length (m), the diameter (cm), the Reynolds number and the flow rate of each pipe $(\frac{m^3}{sec})$.

The next lines consist of the outlet temperature of the taps, followed by the mass flow rate at the output of the hot water tank, the instantaneous demand and the total demand through the day. Finally the instantaneous heat loss from the withdrawal and instantaneous heat loss from the convective effect are presented together with the total withdrawal and total convective heat losses. All heat losses are given in (kJ).

The output, when the water is stationary in the pipe system, includes the temperature of the wall of the pipe and the temperature of the water in the pipe after a period of time t. Finally the heat losses from the convective effect in the hot water tank are presented.

5.5 Subroutines and Functions

The subroutines and functions contain FORTRAN statements which are used repeatedly in the program.

The subroutines for the programs for insulated and uninsulated cases of pipe consist of:

1. A subroutine that calculates the temperature at the wall and the mean temperature of the flow in the pipe (FLOW).
2. A subroutine that calculates the temperature of the wall when the flow is zero in the pipe and a transient is in effect (NOFLOW).

The functions of the program for the insulated pipe case consist of:

1. A function that computes the temperature reached by a horizontal pipe at some time t(TRANS). The equation used is the following:

$$\frac{\theta}{\theta_i} = exp\left(- \left(\frac{\frac{1}{ln(\frac{r_2}{r_1})\frac{r_1}{k_{ins}} + \frac{r_1}{r_2\, h_{hor}}} A_s}{\rho\, V\, c_p} \right) t \right) \tag{5.1}$$

2. A function that computes the temperature reached by a vertical pipe at some time t (TRANS2). The below equation was used:

$$\frac{\theta}{\theta_i} = exp\left(-\left(\frac{\frac{1}{ln(\frac{r_2}{r_1})\frac{r_1}{k_{ins}} + \frac{r_1}{r_2\,h_{vert}}}A_s}{\rho\,V\,c_p}\right)t\right) \tag{5.2}$$

3. A function that determines the fluid heat transfer coefficient in the pipes (F). The equation used is:

$$h_f = \frac{0.023\,Re_D^{\frac{4}{5}}\,Pr^{0.3}\,k}{D} \tag{5.3}$$

   The subroutine also gives an equation for a horizontal pipe with an unknown temperature at the wall. The subroutine FLOW will solve this equation. The equation used is 4.11 with $h_s = h_{hor}$

4. A function that determines the fluid heat-transfer coefficient in the pipes (F1). The equation used is equation 5.3. The subroutine also gives an equation for the a vertical pipe with an unknown temperature at the wall. The subroutine FLOW will solve this equation. The equation used is 4.11 with $h_s = h_{vert}$

5. A function that calculates the heat-transfer coefficient of the air around a horizontal pipe (FHS1). The equation used is B.11.

6. A function that calculates the heat-transfer coefficient of the air around a vertical pipe (FHS2). The equation used is B.16.

The functions of the program for uninsulated pipe case consist of:

1. A function that computes the temperature reached by a horizontal pipe at some time t (TRANS). The equation used is the following:

$$\frac{\theta}{\theta_i} = exp\left(-\left(\frac{h_{hor}A_s}{\rho\, V\, c_p}\right)\, t\right) \tag{5.4}$$

2. A function that computes the temperature reached by a vertical pipe at some time t (TRANS2). The below equation was used:

$$\frac{\theta}{\theta_i} = exp\left(-\left(\frac{h_{vert}A_s}{\rho\, V\, c_p}\right)\, t\right) \tag{5.5}$$

3. A function (F) that gives an equation for a horizontal pipe with an unknown temperature at the wall. The subroutine FLOW will solve (F). The equation given is the following:

$$\frac{0.023\, Re_D^{\frac{4}{5}}\, Pr^{0.3}\, k}{D} (T_b - T_w) -$$

$$\frac{k_{air}}{D} \left(0.60^2 + 2 \cdot 0.60 \cdot 0.5275 \left(\frac{(T_w - T_\infty)\, D^3}{(T_w + T_\infty)\, \nu\, \alpha} \right)^{\frac{1}{6}} + 0.5275^2 \left(\frac{(T_w - T_\infty)\, D^3}{(T_w + T_\infty)\, \nu\, \alpha} \right)^{\frac{1}{3}} \right)$$

$$(T_w - T_\infty) = 0 \qquad (5.6)$$

4. A function (F1) that gives an equation for a vertical pipe with an unknown-temperature at the wall. The subroutine FLOW will solve (F1). The equation given is the following:

$$\frac{0.023\, Re_D^{\frac{4}{5}}\, Pr^{0.3}\, k}{D} (T_b - T_w) -$$

$$\frac{k_{air}}{L} \left(0.68 + 1.082 \left(\frac{(T_w - T_\infty)\, L^3}{(T_w + T_\infty)\, \nu\, \alpha} \right)^{\frac{1}{4}} \right)$$

$$(T_w - T_\infty) = 0 \qquad (5.7)$$

5. A function that calculates the heat-transfer coefficient of the air around a horizontal pipe (FHS1). The equation used is B.11.

6. A function that calculates the heat-transfer coefficient of the air around a vertical pipe (FHS2). The equation used is B.16.

5.6 Bisection Method

The bisection method was used for the root search that found the temperature of the wall of the pipe for both subroutines FLOW and NOFLOW. The description given below is taken from Numerical Recipes in Fortran by Press *et al.* (p 346-347, 1992).

"Once we know that an interval contains a root, several classical procedures are available to refine it. These proceed with varying degrees of speed and sureness toward the answer. Unfortunately, the methods that are guaranteed to converge plod along most slowly, while those that rush to the solution in the best cases can also dash rapidly to infinity without warning if measures are not taken to avoid such behavior.

The bisection method is one that cannot fail. It is thus not to be sneered at as a method for otherwise badly behaved problems. The idea is simple. Over some interval the function is known to pass through zero because it changes sign. We evaluate the function at the interval's midpoint and examine the sign. Use the midpoint to replace whichever limit has the same sign. After each iteration the bound containing the root decrease by a factor of two. If after n iteration the root is known to be within an interval of size ϵ_n , then after the next iteration it will be bracketed within an interval of size

$$\epsilon_{n+1} = \frac{\epsilon_n}{2} \tag{5.8}$$

Neither more or less. Thus we know in advance the number of iterations required to achieve a given tolerance in the solution,

$$n = log_2 \frac{\epsilon_o}{\epsilon} \tag{5.9}$$

where ϵ_o is the size of the initially breaking interval, ϵ is the desired ending tolerance.

It remains to discuss practical criteria for convergence. It is crucial to keep in mind that computers use a fixed number of binary digits to represent floating-point numbers. While the function might analytically pass through zero, it is possible that its computed value is never zero, for any floating point argument. So we had to decide what accuracy on the root is attainable. To be most general, the routine we used requires you to specify an absolute tolerance, such that iterations continue until the interval becomes smaller than this in absolute tolerance".

Chapter 6

Discussion of Results

6.1 Flow Analysis Discussion of Results

For this study, we chose three different types of homes: a small bungalow house of 1400 sq. ft., a large bungalow house of 1700 sq. ft., and a large two story house of 2124 sq. ft. The main objective of this part was to study ways that could prevent the sudden reduction in flow of hot water, and the corresponding drop in temperature, when several taps run simultaneously.

6.1.1 Tap Performance Improvement Due to Increasing the Pipe Diameter

In this section, we analyze the tap performance of hot water in pipes of 1/2 in. and 3/4 in. diameter. The performance of each tap is 100 % when operated autonomously. This performance corresponds to the maximum flow rate at the tap. This study found that increasing the pipe diameter from 1/2 in. to 3/4 in. in a medium two-story house that contains 47.1 m of plumbing, improves the the flow rate of hot water in the taps up to 38.8 % when the showerhead operates by itself. This corresponds to a temperature improvement of $6.6°C$. Also increasing the pipe diameter from 1/2 in. to 3/4 in. in a bungalow house that contains 31.5 m of plumbing, improves the flow rate up to 28.8 % when the showerhead runs by itself. This corresponds to a temperature improvement of $4.6°C$. Finally, increasing the pipe diameter from 1/2 in. to 3/4. in a large house that contains 34 m of plumbing, improves the flow rate of the hot water in the taps up to 29.1 % when the showerhead runs autonomously. This corresponds to a temperature improvement of $4.7°C$. When several taps run simultaneously, a problem is created with the equal distribution of hot water. This results in a reduction of hot water being sent to the open taps. It is useful to mention that for both 1/2 in. and 3/4 in. piping, we experience decreases in the flow rates as soon as a second tap opens. The only time when the pipe will have 100 % output will be as already mentioned, when a tap operates alone. The decrease in flow rate results in a decrease of the temperature at the outlet of the tap. Therefore, in this section when we talk about, for example, a 20.3 % improvement, this number will correspond to the difference of the decreases in the flow rates, between a 1/2 in. and a 3/4 in. pipe. Also, for example, a $3.0°C$ temperature change will correspond to the difference in temperature at the exit of the tap between a 1/2 in. and a 3/4 in. pipe. For the determination of the temperature, two formulas were used. The first one is the mixing formula that states:

$$\dot{m}_h T_h + \dot{m}_c T_c = \dot{m}_t T_t \tag{6.1}$$

and the second formula is the conservation of mass that states:

$$\dot{m}_h + \dot{m}_c = \dot{m}_t \tag{6.2}$$

In these two equations, $\dot{m}_h$ corresponds to the mass flow rate of the hot water, $\dot{m}_c$ to the mass of the cold water, and $\dot{m}_t$ to the total mass flow rate. Also, T_h corresponds to the temperature of the hot water, T_c to the temperature of the cold water, and T_t to the outlet temperature of the tap. In solving these equations, T_h, T_c and $\dot{m}_c$ were held constant, $\dot{m}_h$ was found from the computer model and $\dot{m}_t$ and T_t were found using the equations.

The 1/2 in. pipe diameter is the most common pipe size used in residential plumbing systems. Therefore, comparison of the existing 1/2 in. pipe diameter to a 3/4 in. pipe diameter is performed to determine if any improvements in performance can be gained by using the 3/4 in. pipe. Detailed results of the comparisons may be found in Appendix C.

This study found that increasing the pipe diameter from 1/2 in. to 3/4 in. in a medium two-story house that contains 47.1 m of plumbing, improves the flow rate of the hot water in the taps in a range from 20.3% when the showerhead is opened simultaneously with the washroom sink, to 12.9% when the kitchen sink is opened simultaneously with the dishwasher. This corresponds to a temperature improvement of $3.0°C$ to $1.6°C$. Also increasing the pipe diameter from 1/2 in. to 3/4 in. in a bungalow house that contains 31.5 meters of plumbing, improves the flow rate of the hot water in the taps in a range from 15.1% when the showerhead is opened simultaneously with the washroom sink, to 4.6% when the washroom sink operates simultaneously with the dishwasher. This corresponds to a temperature improvement of $2.0°C$ to $0.21°C$. Finally, increasing the pipe diameter from 1/2 in. to 3/4 in. in a large house that contains 34 m of plumbing, improves the flow rate of the hot water in the taps from 12.9% when the kitchen sink is opened simultaneously with the dishwasher, to 7.5% when the laundry operates simultaneously with the dishwasher. This corresponds to a temperature improvement of $1.6°C$ to $0.9°C$. The expenditure to upgrade the above systems from 1/2 in. plumbing to 3/4 in. is $35 Cdn for a two-story house that contains 47 meter of plumbing, $23.5 Cdn for a large bungalow house that contains 31.8 meter of plumbing and $25 Cdn for a small bungalow house that contains 31.5 meters of plumbing.

For a detailed discussion of the results of this section, a two-story house (Figure 6.1) is used. (For the other two homes, the output data are organized and presented in the form of tables found in Appendix C.) From the two story house results, we will examine two different taps, the showerhead on the second level and the laundry tap. Tables C.3 and C.4 present performance values for all of the taps for 1/2 in. piping. Tables C.5 and C.6 present similar information for 3/4 in. pipe.

The performance of a single tap, such as the showerhead, significantly decreases as other taps are opened simultaneously (Figure 6.2). However, these performance drops can be reduced by increasing the piping diameter. By using 3/4 in. pipe instead of a 1/2 in. pipe, the performance of the showerhead improves by as much as 40% (Figure 6.3). Consequently the water temperature improves by approximately $6.6°C$.

Similarly, the performance of the laundry tap significantly decreases as other taps are opened simultaneously (Figure 6.4). These performance drops can again be reduced by increasing the piping diameter. By using 3/4 in. pipe instead of 1/2 in. pipe, the performance of the laundry tap improves by as much as 20% (Figure 6.5). Consequently, the water temperature improves by approximately $2.0°C$.

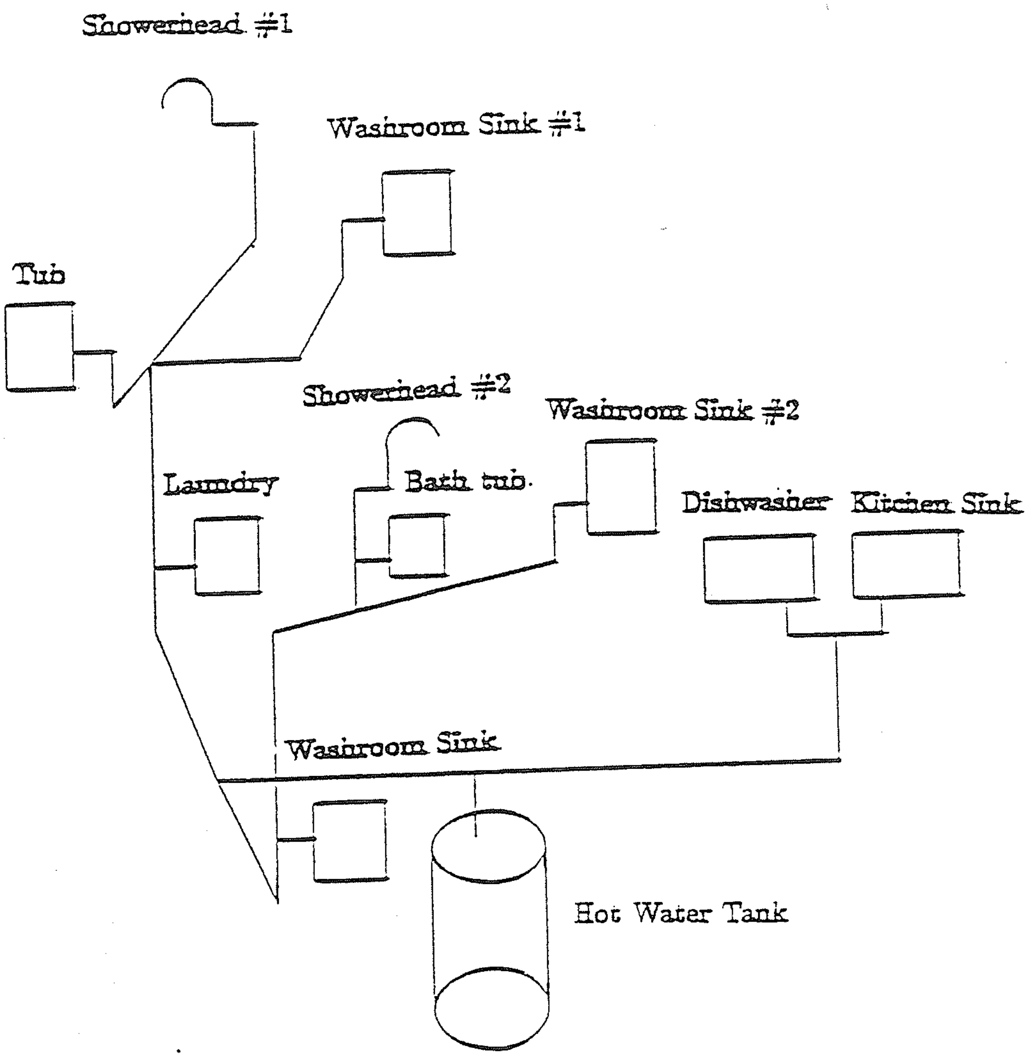

Figure 6.1: Schematic of a Two-Story House Piping System

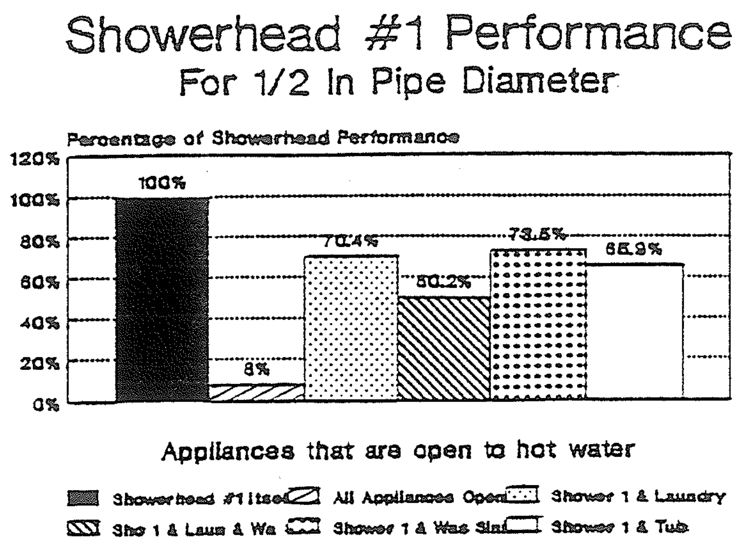

Figure 6.2: Showerhead #1 Performance for 1/2 in. Pipe Diameter

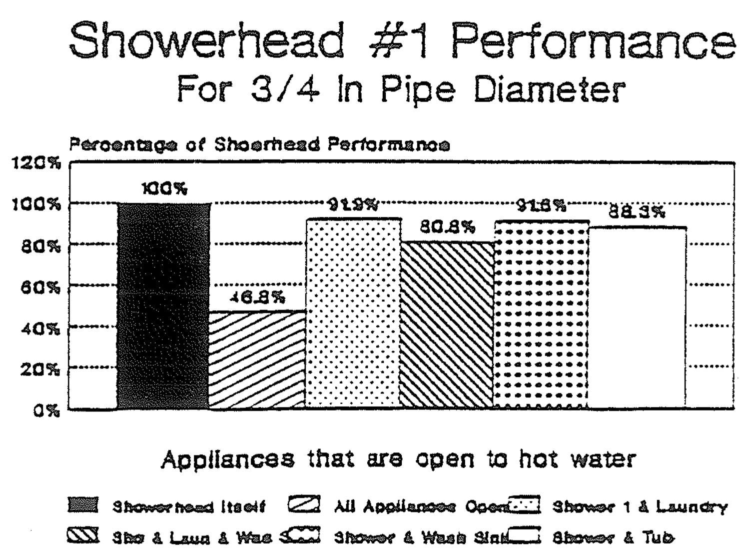

Figure 6.3: Showerhead #1 Performance for 3/4 in. Pipe Diameter

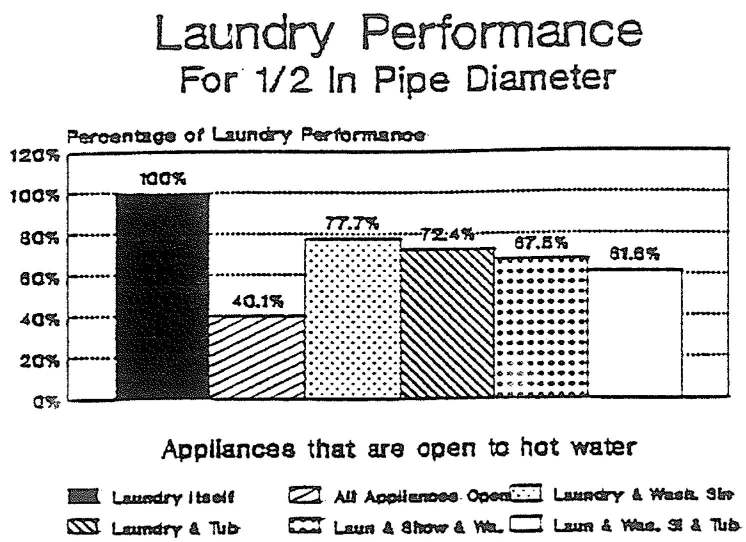

Figure 6.4: Laundry Performance for 1/2 in. Pipe Diameter

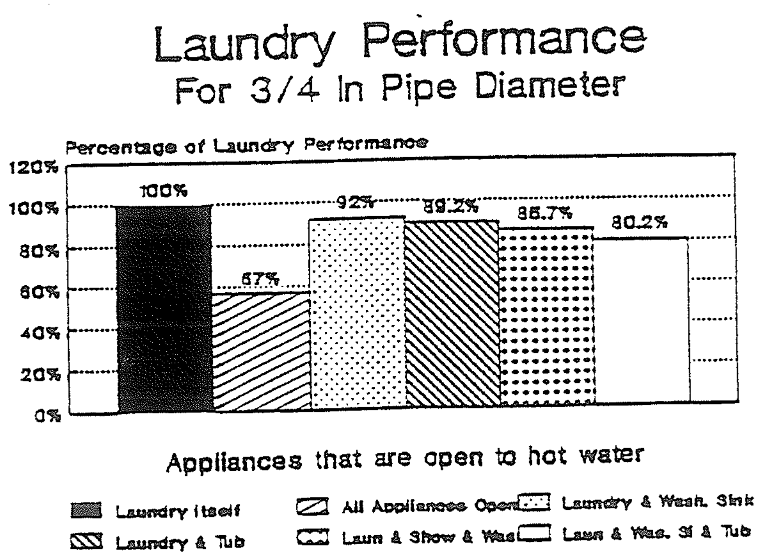

Figure 6.5: Laundry Performance for 3/4 in. Pipe Diameter

6.1.2 Tap Performance Improvement Due to the Location of the Hot Water Tank

The influence of water-tank location on tap performance of a 1/2 in. diameter plumbing system was examined. A medium-sized bungalow was used for this analysis (Figure 6.6). For convenience, the showerhead was used as the reference point because it places the highest demand on the water tank and because a drop in water temperature during a shower is the most irritating problem related to simultaneously opened taps. The water tank was located at distances of 0.3 m, 1.8 m, 4.3 m and 7.3 m from this reference point and the performances of the taps were computed (Tables C.11 - C.16). These distances are the horizontal length of piping connecting the water tank to the showerhead.

The results indicate that when the distance of the water tank from the showerhead increases, the performance of the showerhead decreases (Figures 6.7-6.10). Consequently, as the performance decreases, the water temperature decreases. It seems logical then to locate the hot water tank as close to the showerhead as possible. Relocating the hot water tank from 7.3 m to 0.3 m horizontally from the showerhead showed an improvement in the flow rate of the hot water of the showerhead up to 18.2% which corresponds in a temperature improvement of $2.7°C$.

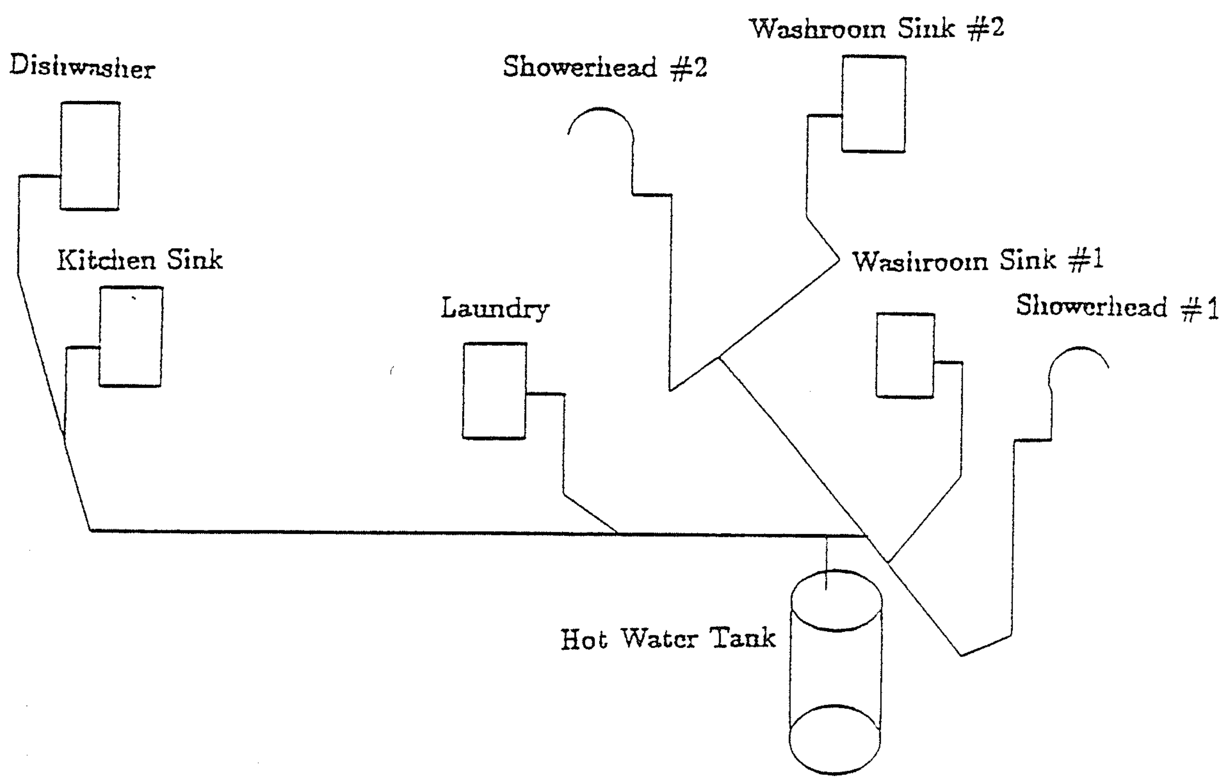

Figure 6.6: Schematic of a Medium-Sized Bungalow Piping System

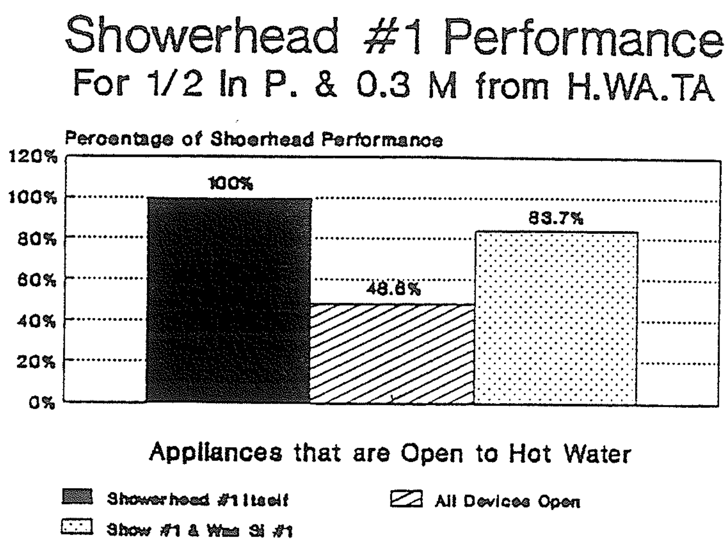

Figure 6.7: Showerhead #1 Performance for 1/2 in Pipe Diameter Located at 0.3 m from Hot Water Tank

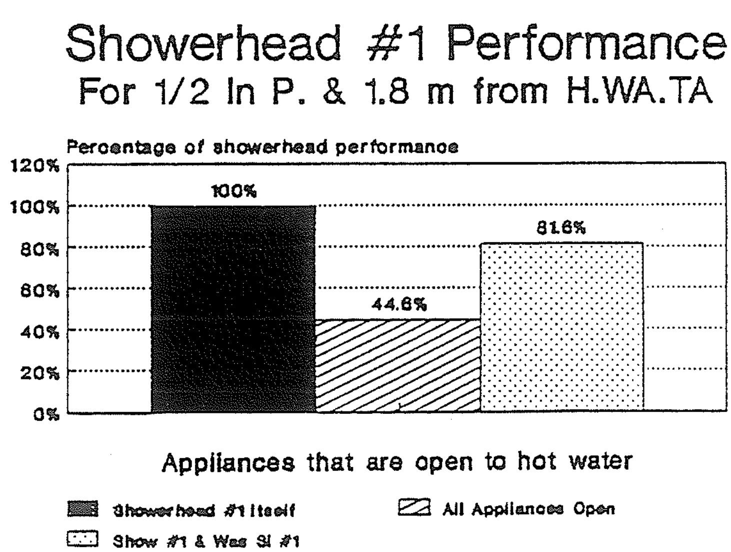

Figure 6.8: Showerhead #1 Performance for 1/2 in Pipe Diameter Located at 1.8 m from Hot Water Tank

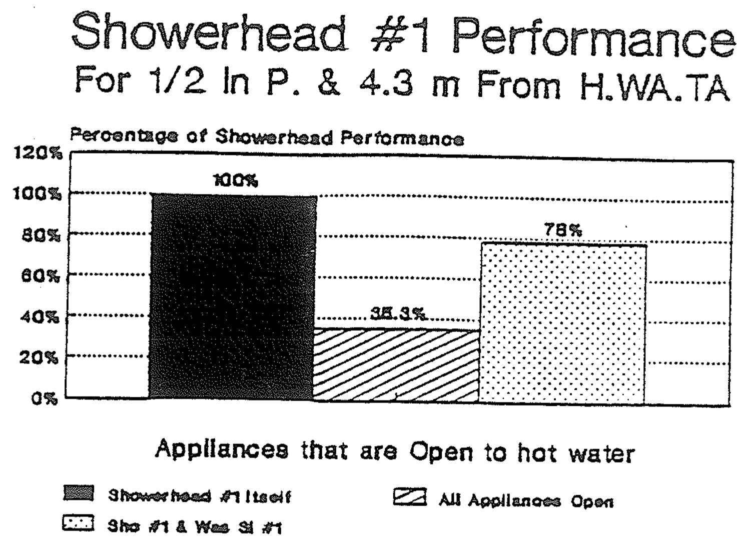

Figure 6.9: Showerhead #1 Performance for 1/2 in Pipe Diameter Located at 4.3 m from Hot Water Tank

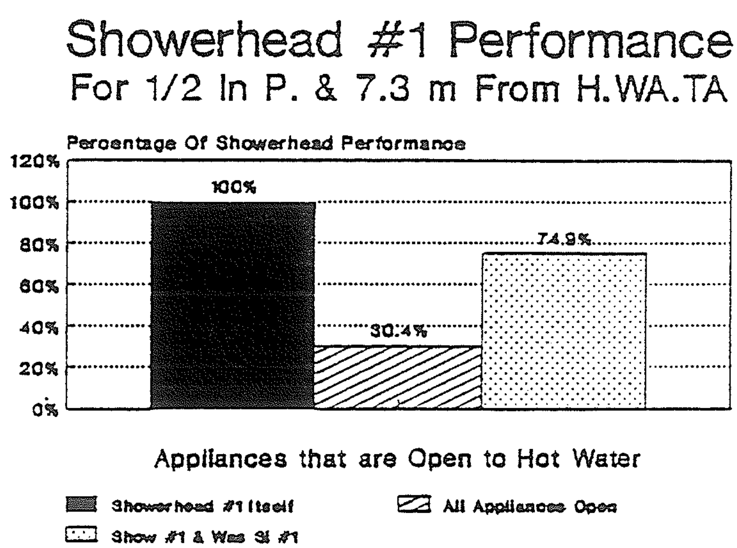

Figure 6.10: Showerhead #1 Performance for 1/2 in Pipe Diameter Located at 7.3 m from Hot Water Tank

6.2 Heat Transfer Discussion of Results

In this section a small bungalow house (1400 sq. ft.) was used for the analysis of the heat losses through the distribution system and the heat losses from the hot water tank. The main objective of this part of the research was to find a way to optimize the existing hot-water plumbing system and hot-water tank.

6.2.1 Distribution Losses

Distribution losses occur from the piping when it delivers hot water to the terminal-usage devices. In this research, these losses were calculated with insulation in the system and when no insulation was present.

Uninsulated Piping System

For a 1/2 in. (1.27 cm) pipe diameter, the losses from the horizontal pipes were approximately 95 W/m and for the vertical pipes 20 W/m. The above results were compared with a diagram from the electric water heating manual written in 1988 by Perlman, M. and N.H. Milligan.The diagram given by Perlman and Milligan estimates a heat loss of about 53 W/m. The reason for comparison was because this was the only information that was found in the literature, and the only source that we could use to validate our current findings. In this manual, a diagram is given for an estimation of heat losses from the pipes if the temperature of the flow and the diameter of the pipe are known. The horizontal pipes yield more heat losses than the vertical. This occurs because the thermal boundary layer has no opportunity to develop and is therefore much thinner in the horizontal pipe than in the vertical. In this case, we see, that the difference in the vertical and horizontal pipes is larger. For a 3/4 in. pipe (1.905 cm) the heat losses from the vertical pipes were 30 W/m and for the horizontal 125

W/m. The diagram estimates a heat loss of 68 W/m which is about the average for the vertical and horizontal piping.

Insulation in the Piping System

In the "insulated" segment of the program, the thermal conductivity of the insulation was $k_{ins} = 0.057(\frac{W}{mK})$. For a 1/2 in. (1.27 cm) pipe diameter, the losses from the horizontal pipes were approximately 13 W/m and for the vertical pipes 11 W/m. The horizontal pipes yield more heat losses than the vertical. In this case, we see that the thermal boundary layer on the outside of the pipe has almost no effect on the heat transfer. For both horizontal and vertical pipes, the heat transfer loss is very close to each other, and the insulation has the major effect in this case for the heat losses. In this case the results of Perlman and Milligan (1988) agree very closely with our findings, as their diagram gives a heat loss of approximately 12.3 W/m. For a 3/4 in. pipe (1.905 cm) the heat losses from the vertical pipes were 8.15 W/m and from the horizontal pipes 9.2 W/m. The diagram estimates a heat loss of 8.5 W/m. From the computer results, we found that the temperature at the wall for a horizontal insulated pipe compared to uninsulated pipe drops about $12°C$, whereas in the vertical pipe, the temperature differential between an insulated and uninsulated pipe is only $4°C$. We already discussed in the previous chapter that free convection occurs due to density gradients that, in this case, are caused by temperature gradients. In the case of the horizontal pipe, we found that the temperature gradient between the insulated and uninsulated pipes is much greater; therefore, a much greater difference in heat loss occurred.

6.2.2 Hot Water Tank Losses

One of the major areas of analysis in this research was to find ways to optimize the hot water tank and, if feasible, to conserve energy. In this analysis, we used four different cases to analyze our system. These four cases were:

1. Compare insulation in the distribution pipes versus uninsulated pipes.
2. Operate the hot water tank at $80°C$ instead of $60°C$ during the peak hours.
3. Compare a regular-flow showerhead versus a low-flow showerhead.
4. Compare 1/2 in. pipe with 3/4 in. pipe.

The most common components found in residential hot-water plumbing systems were 1/2 in. diameter uninsulated pipes with a regular showerhead and the tank operating constantly at $60°C$. Therefore, for the analysis of the existing system, the above factors will provide a base point for comparison.

6.2.3 Insulated Versus Uninsulated Piping Systems

By using insulation in the plumbing system, a energy savings of 1.5 - 1.8 percent can be achieved and a savings in water demand of approximately 2 percent was calculated. (Tables 6.1-6.4).

6.2.4 Low-Flow Showerhead Versus Regular Flow

A low-flow showerhead can significantly reduce the energy of the overall hot-water plumbing supply system. It was found that a low-flow showerhead gives a 14 - 17 percent savings, with 14 - 28 percent savings in the water demand (Tables 6.1-6.4).

6.2.5 60 Versus 80 Degrees in the Peak Hours

When we used $80°C$ instead of $60°C$ degrees in the peak demand hours that usually occur in the mornings between 8-10 a.m. and afternoons between 7-8 p.m., it was found that an increase of about 0.35 percent occurred in the overall energy usage but a reduction of 12 - 16 percent in the hot water demand was achieved (Tables 6.1-6.4).

6.2.6 1/2 in. Pipe Versus 3/4 in. Pipe

A 3/4 in. pipe gives a further 15 - 18 percent energy demand and also gives an additional 16 - 19 percent of water demand. It was found that, while a 3/4 in. pipe showed a better quality of hot water, a higher withdrawal heat loss occurred in the tank (Tables 6.1-6.4).

6.2.7 General Discussion

From this analysis, it was found that the best savings in energy and water demand from the hot water tank can be achieved when the piping system is insulated and a low-flow showerhead is present. The combination of the two previously mentioned components can achieve a 15 - 17 percent savings in heat losses and a 15 - 19 percent reduction in water demand. For a 3/4 in. pipe, the energy losses are too high for the use of this system and the only time that some savings were shown was when a low-flow showerhead was in use. In this case, 0.5 - 5 percent savings in the heat losses was achieved and 0.5 - 17 percent reduction in the water demand. A system like this can be used only if the low-flow showerhead is accepted by the population. In this case, a low-flow showerhead with 3/4 in. pipe may be the best way to satisfy both the customer, and the quality of showering, as well as the utilities because the combination conserves some energy. Finally, the use of $80°C$ at peak hours gave us a

0.3 percent additional heat loss. We do not recommend the use of this strategy in our present system; however, the increase of temperatures does allow the tank to meet the demand over the peak period. Therefore, this strategy could be used for "peak shaving".

Table 6.2: Weekday Results of Heat Losses and Demand of the Hot Water Tank (Continued)

Different Cases studies	Total Heat Loss From the Tank (kJ)	Total Demand of Water (L)	Percent Difference of Heat Loss	Percent Difference of Water Demand
3/4 in. Pipe Diameter with Temperature Rise to 60°C at the Hot Water Tank and Regular Showerhead with Insulation	166,760	777	+14.92	+15.99
3/4 in. Pipe Diameter with Temperature Rise to 60°C at the Hot Water Tank and Regular Showerhead with No Insulation	170,000	793	+17.15	+18.38
3/4 in. Pipe Diameter with Temperature Rise to 80°C at the Hot Water Tank and Regular Showerhead with Insulation	167,017	683	+15.09	+1.97
3/4 in. Pipe Diameter with Temperature Rise to 80°C at the Hot Water Tank and Regular Showerhead with No Insulation	170,525	698	+17.52	+4.19
3/4 in. Pipe Diameter with Temperature Rise to 60°C at the Hot Water Tank and Low-Flow Showerhead with Insulation	141,133	651	-2.70	-2.94
3/4 in. Pipe Diameter with Temperature Rise to 60°C at the Hot Water Tank and Low-Flow showerhead with No Insulation	144,398	667	-0.49	-0.53
3/4 in. Pipe Diameter with Temperature Rise to 80°C at the Hot Water Tank and Low-Flow Showerhead with Insulation	141,389	585	-2.57	-12.67
3/4 in. Pipe Diameter with Temperature Rise to 80°C at the Hot Water Tank and Low-Flow Showerhead with No Insulation	144,920	600	-0.13	-10.43

Table 6.3: Weekend Results of Heat Losses and Demand of the Hot Water Tank

Different Cases studies	Total Heat Loss From the Tank (kJ)	Total Demand of Water (L)	Percent Difference of Heat Loss	Percent Difference of Water Demand
1/2 in. Pipe Diameter with Temperature Rise to 60°C at the Hot Water Tank and Regular Showerhead with No Insulation	126,421	578		
1/2 in. Pipe Diameter with Temperature Rise to 60°C at the Hot Water Tank and Regular Showerhead with Insulation	124,150	566	-1.79	-1.94
1/2 in. Pipe Diameter with Temperature Rise to 80°C at the Hot Water Tank and Regular Showerhead with Insulation	124,414	488	-1.59	-15.60
1/2 in. Pipe Diameter with Temperature Rise to 80°C at the Hot Water Tank and Regular Showerhead with No Insulation	126,867	498	+0.35	-13.82
1/2 in. Pipe Diameter with Temperature Rise to 60°C at the Hot Water Tank and Low-Flow Showerhead with Insulation	104,427	469	-17.40	-18.83
1/2 in. Pipe Diameter with Temperature Rise to 60°C at the Hot Water Tank and Low-Flow Showerhead with No Insulation	106,698	480	-15.60	-16.89
1/2 in. Pipe Diameter with Temperature Rise to 80°C at the Hot Water Tank and Low-Flow Showerhead with Insulation	104,682	412	-17.19	-28.79
1/2 in. Pipe Diameter with Temperature Rise to 80°C at the Hot Water Tank and Low-Flow Showerhead with No Insulation	107,144	422.62	-15.25	-26.88

Table 6.4: Weekend Results of Heat Losses and Demand of the Hot Water Tank (Continued)

Different Cases studies	Total Heat Loss From the Tank (kJ)	Total Demand of Water (L)	Percent Difference of Heat Loss	Percent Difference of Water Demand
3/4 in. Pipe Diameter with Temperature Rise to 60°C at the Hot Water Tank and Regular Showerhead with Insulation	145,632	673.05	+15.2	+16.45
3/4 in. Pipe Diameter with Temperature Rise to 60°C at the Hot Water Tank and Regular Showerhead with No Insulation	148,729	688	+17.64	+19.10
3/4 in. Pipe Diameter with Temperature Rise to 80°C at the Hot Water Tank and Regular Showerhead with Insulation	145,887.7	579	+15.4	+0.2
3/4 in. Pipe Diameter with Temperature Rise to 80°C at the Hot Water Tank and Regular Showerhead with No Insulation	149,249.49	593	+18.06	+2.6
3/4 in. Pipe Diameter with Temperature Rise to 60°C at the Hot Water Tank and Low-Flow Showerhead with Insulation	120,025	546	-5.43	-5.47
3/4 in. Pipe Diameter with Temperature Rise to 60°C at the Hot Water Tank and Low-Flow Showerhead with No Insulation	124,397.9	524.74	-7.67	-7.71
3/4 in. Pipe Diameter with Temperature Rise to 80°C at the Hot Water Tank and Low-Flow Showerhead with Insulation	120,281	481	-4.86	-16.76
3/4 in. Pipe Diameter with Temperature Rise to 80°C at the Hot Water Tank and Low-Flow Showerhead with No Insulation	123,644	495	-2.2	-14.31

Chapter 7

Conclusions and Recommendations

This chapter presents the conclusions of the present study on residential hot water heating systems. Recommendations for future work are also given.

7.1 Conclusions

1. Previous research shows that the factors that affect the growth of *Legionella Pneumophila* bacteria are temperature stratification, rubber components, and free-living amoebae and other Protozoa. Previous research further indicates that the growth of this bacteria can be reduced by adjusting the pH range and by treating the hot water with chlorine.

2. Previous research shows that the major factors affecting the hot-water demand pattern in a residence are: the number and age of family members, the hot-water tank size and number of hot-water appliances.

3. Increasing the pipe diameter from 1/2 in. to 3/4 in. in a bungalow house that contains 31.5 meters of plumbing, improves the flow rate of the hot water in the taps in a range from 28.8% to 4.3%, which corresponds to a temperature improvement of 4.6°C to 0.2°C.

4. Increasing the pipe diameter from 1/2 in. to 3/4 in. in a medium two-story house that contains 47.1 m of plumbing increases the flow rate of the hot water in the taps in a range from 38.8% to 12.1%, which corresponds to a temperature improvement of 6.6°C to 1.6°C.

5. Increasing the pipe diameter from 1/2 in. to 3/4 in. in a large house that contains 34 m of plumbing increases the flow rate of the hot water in the taps in a range from 29.1% to 9%, which corresponds to a temperature improvement of 4.7°C to 1.0°C.

6. Relocating the hot water tank from 7.3 m to 0.3 m horizontally from the showerhead, we can improve the flow rate of the hot water of the showerhead up to 18.2%, which corresponds to a temperature improvement of 2.7°C.

7. Using insulation, it was found that for a 1/2 in. pipe diameter the losses from the horizontal pipes were approximately 13 W/m and for the vertical pipes 11 W/m, while for a 3/4 in. pipe the heat losses from the vertical pipes were 8.15 W/m and from the horizontal pipes 9.2 W/m.

8. Using an uninsulated piping system it was found that for a 1/2 in. pipe diameter the losses from the horizontal pipes were approximately 95 W/m and for the vertical pipes 20 W/m, while for a 3/4 in. pipe the heat losses from the vertical pipes were 30 W/m and from the horizontal pipes 125 W/m

9. Using insulation in the plumbing system, a savings of 1.5-1.7% can be achieved in the heat losses of the hot water tank.

10. A low-flow showerhead gives a 14-17% savings in the heat losses of the hot-water tank.

11. The use of $80°C$ instead of $60°C$ for the peak demand hours show no savings in the heat losses of the hot water tank. However, a reduction of 12-16 percent was achieved in the water demand. Although there was an increase in heat losses using this strategy, the hot water demand for the peak period was satisfied. This strategy is therefore feasible for peak shaving.

12. The use of 3/4 in. pipe instead of 1/2 in. pipe gave an extra 15-18 percent in energy gains.

7.2 Recommendations

1. Based on the findings of the literature review, we recommend that electrical utilities perform research to confirm the statements contained in this part.

2. The hot-water tank should be located as close to the showerhead as possible.

3. Based on the findings of the heat-transfer analysis, we recommend the use of a low-flow showerhead, and the use of insulation in the hot water distribution lines.

4. Experimental analyses should be performed to verify the computer results of the flow analysis section.

5. For the analysis of the heat losses in the hot-water tank, we recommend that more computer runs should be made with more patterns and different house sizes. Also other factors should be examined such as booster heaters and heat traps.

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Appendix A

Tables of the literature review

Table A.1: Unsafe and Safe Temperatures for Growth and Prohibitation of *Legionella Pneumophila*

Author	Sample Size	Unsafe Temperature °C (°F)	Safe Temperature °C (°F)
Wadosky et al. (1982) [1]	Several Hospitals and Institutions	30-54 (86-129)	70 (158)
Plouffe and Coworkers (1983) [1]	6 Buildings	43-45 (109-113)	58-60 (136-140)
Arnow and Weil (1984)	52 Apartments out of 37 Buildings	Below 55 (131)	Above 55 (131)
Witherell et al. (1984) [2]	Medical Center Hospital of Vermont	37-46 (99-115)	77 (171)
Dennis et al. (1984)	148 Water Samples	50 (122)	No Study Has Been Done
Joly (1991) [3]	Two Experimental Electric Water Heaters	50 (122)	60 (140)
Joly (1992) [4]	44 households	55.5 (132)	Above 56 (133)

Remarks:

1. The above information is taken from States *et al.*, Canadian Electrical Association (CEA) Research Report 808 U SOA, *"Legionella Bacteria in Potable Hot Water Systems"* (1990).

2. Some studies show that chlorination can effectively reduce levels of *L.pneumophila,* also mentioned by States *et al.*, (1990); Kuchta *et al.*, (1985).

3. Temperature stratification at the bottom of the tank is the most important factor that accounts for the multiplication of *L.pneumophila* in electric water heaters.

4. *L.pneumophila* is more likely to be present in older heaters.

Table A.2: Average Monthly Energy Demand for 40 and 60 gallon Tank Size

Author	Sample Size [1]	Tank Size L (gal)	Daily (Avg) kWh (Btu) Consumption					
			Jan	Feb	Mar	Apr	May	Jun
Lambert and Choy (1986)	170	150 (40)	13.9 (47 400)	14.2 (48 400)	14.3 (48 800)	14.0 (47 700)	13.1 (44 700)	12.0 (40 900)
Kay and Analyst (1988)	7	150 (40)	14.2 (48 400)	13.7 (46 700)	13.3 (45 300)	13.1 (44 700)	12.2 (41 600)	11.1 (37 800)
Lambert and Choy (1986)	80	225 (60)	19.1 (65 100)	18.8 (64 100)	18.6 (63 400)	19.1 (65 100)	17.4 (59 300)	14.5 (49 400)
Kay and Analyst (1988)	21	225 (60)	21.3 (72 600)	20.1 (68 500)	20.3 (69 200)	21.1 (71 900)	19.2 (65 500)	17.5 (59 700)
Author	Sample Size [1]	Tank Size L (gal)	Daily (Avg) kWh (Btu) Consumption					
			Jul	Aug	Sep	Oct	Nov	Dec
Lambert and Choy (1986)	170	150 (40)	10 (34 100)	9.3 (31 700)	10.4 (35 500)	11 (37 500)	11.8 (40 200)	13.6 (46 400)
Kay and Analyst (1988)	7	150 (40)	10.7 (36 500)	8.5 (29 000)	9.8 (33 400)	11.4 (38 900)	12.2 (41 600)	14.1 (48 100)
Lambert and Choy (1986)	80	225 (60)	12.6 (43 000)	12.3 (41 900)	13.7 (46 700)	15.1 (51 500)	16.1 (54 900)	17.1 (58 300)
Kay and Analyst (1988)	21	225 (60)	16.3 (55 600)	14.1 (48 100)	15.9 (54 200)	17.3 (59 000)	19.1 (65 100)	19.9 (67 800)

Remarks:

1. This entry represents the number of water heaters they used for each test.

Table A.3: Average Annual Energy Demand for 40 and 60 gallon Tank Size

Author	Sample Size	Tank Size L (gal)	Avg Annual Consumption kWh ($10^7\times$Btu)
Lambert and Choy (1986)	170	150 (40)	4 496 (1.533)
Kay and Analyst (1988)	7	150 (40)	4 400 (1.500)
Lambert and Choy (1986)	80	225 (60)	5 961 (2.032)
Kay and Analyst (1988)	21	225 (60)	6 785 (2.313)

Table 6.1: Weekday Results of Heat Losses and Demand of the Hot Water Tank

Different Cases studies	Total Heat Loss from the Tank (kJ)	Total Demand of Water (L)	Percent Difference of Heat Loss	Percent Difference of Water Demand
1/2 in. Pipe Diameter with Temperature Rise to 60°C at the Hot Water Tank and Regular Showerhead with No Insulation	145,108	670		
1/2 in. Pipe Diameter with Temperature Rise to 60°C at the Hot Water Tank and Regular Showerhead with Insulation	142,744	659	-1.63	-1.75
1/2 in. Pipe Diameter with Temperature Rise to 80°C at the Hot Water Tank and Regular Showerhead with Insulation	142,971	579	-1.47	-13.55
1/2 in. Pipe Diameter with Temperature Rise to 80°C at the Hot Water Tank and Regular Showerhead with No Insulation	145,554	590	+0.31	-11.92
1/2 in. Pipe Diameter with Temperature Rise to 60°C at the Hot Water Tank and Low-Flow Showerhead with Insulation	122,994	561	-15.24	-16.33
1/2 in. Pipe Diameter with Temperature Rise to 60°C at the Hot Water Tank and Low-Flow Showerhead with No Insulation	125,385	573	-13.59	-14.56
1/2 in. Pipe Diameter with Temperature Rise to 80°C at the Hot Water Tank and Low-Flow Showerhead with Insulation	123,250	504	-15.06	-24.81
1/2 in. Pipe Diameter with Temperature Rise to 80°C at the Hot Water Tank and Low-Flow Showerhead with No Insulation	125,832	515	-13.28	-23.18

Table A.4: Average Daily Consumption of Hot Water per Household

Author	Sample Size	Overall Avg Daily Hot Water per Household L (gal)	Daily Consumption L (gal)						
			Mon	Tue	Wed	Thu	Fri	Sat	Sun
Stevenson (1983)	600 [1]	159 (42.0)	183 (48.3)	156 (41.2)	150 (39.6)	155 (40.9)	155 (40.9)	170 (44.9)	145 (38.3)
Perlman *et al.* (1984)	55 [2]	236 (62.3)	-	-	-	-	-	-	-
Ladd and Harrison (1985)	110 [3]	249 (65.7)	260 (68.6)	240 (63.3)	237 (62.6)	240.5 (63.5)	230 (60.7)	260.3 (68.7)	247.7 (65.4)

Remarks:

1. Based on 600 single family homes across Canada.
2. Five residences in the Toronto area and fifty more residences located throughout the province of Ontario.
3. Based on 110 single family residances by 11 utilities scattered throughout the continental United States.

Table A.5: Percent of Total Litres Consumed by Each Major Usage

Author	Sample Size	Baths %	Showers %	Washing Machines %	Automatic Dishwashers %	Manual Dishwashers %
Stevenson (1983)	600 [1]	16.5	40.7	24.2	9.7	8.8
Ladd and Harrison (1985)	110 [2]	-	-	18.8	-	-

Remarks:

1. Based on 600 single family homes across Canada.

2. Based on 110 single family residences by 11 utilities scattered throughout the continental United States.

Table A.6: Average Daily Hot-Water Use by Family Size

Author	Sample Size	Daily Consumption L(gal)/person				
		1 Person	2 Persons	3 Persons	4 Persons	$\geq$ 5 Persons
Stevenson (1983)	600 [1]	77.7 (20.5)	48.6 (12.8)	50 (13)	44 (12)	38.6 (10.2)
Perlman *et al.* (1984)	55 [2]	-	68.5 (18.1)	85.7 (22.6)	62.8 (16.6)	46.4 (12.2)

Remarks:

1. Based on 600 single family homes across Canada.
2. Five residences in the Toronto area and fifty more residences located throughout the province of Ontario.

Table A.7: Average Daily Hot-Water Use by Presence and Age of Children

Author	Sample Size	No Children L (gal)	Children L (gal)	Children < 6 yrs old L (gal)
Perlman *et al.* (1984)	55 [1]	65.5 (17.3)	65.3 (17.2)	73.9 (19.5)

Remarks:

1. Five residences in the Toronto area and fifty more residences located throughout the province of Ontario.

Table A.8: Average Hourly Consumption of Hot Water per Household

Author	Sample Size	Hourly Consumption L (gal)								
		6 AM	7	8	9	10	11	12	1 PM	2
Stevenson (1983)	600 [1]	6.0 (1.6)	7.0 (1.8)	15 (3.9)	13.5 (3.56)	13.5 (3.56)	13 (3.4)	8.5 (2.2)	2.0 (0.5)	6.5 (1.7)
Perlman *et al.* (1984)	55 [2]	2.0 (0.5)	7.0 (1.8)	16.5 (4.35)	14 (3.7)	15 (3.9)	14 (3.7)	13.5 (3.56)	13 (3.4)	12 (3.2)
Ladd and Harrison (1985)	110 [3]	5.5 (1.4)	18 (4.7)	19 (5.0)	18.7 (4.93)	16 (4.2)	14.7 (3.88)	12 (3.2)	10 (2.6)	9.0 (2.4)
Merrigan (1988)	18 [4]	2.0 (0.5)	11 (2.9)	17 (4.5)	16 (4.2)	14 (3.7)	10.5 (2.77)	9.0 (2.4)	8.5 (2.2)	7.5 (2.0)

Remarks:

1. Based on 600 single family homes across Canada.
2. Five residences in the Toronto area and fifty more residences located throughout the province of Ontario.
3. Based on 110 single family residences by 11 utilities scattered throughout the continental United States.
4. Based on 18 single family residences located in Florida and North Carolina.

Table A.9: Average Hourly Consumption of Hot Water per Household (Continued)

Author	Sample Size	Hourly Consumtion L (gal)									
		3 PM	4	5	6	7	8	9	10	11	12
Stevenson (1983)	600 [1]	6.0 (1.6)	4.5 (1.2)	6.5 (1.7)	7.5 (2.0)	12.5 (3.30)	13.5 (3.67)	12.5 (3.30)	10.5 (2.77)	9.0 (2.4)	7.0 (1.8)
Perlman *et al.* (1984)	55 [2]	10 (2.6)	9.0 (2.4)	10 (2.6)	11.5 (3.03)	15 (3.9)	16 (4.2)	13.5 (3.56)	12.5 (3.3)	11 (2.9)	9.0 (2.4)
Ladd and Harrison (1985)	110 [3]	8.0 (2.1)	9.0 (2.4)	10.3 (2.7)	13.6 (3.6)	16.6 (4.4)	16 (4.2)	15 (3.9)	11.7 (3.1)	10 (2.6)	5.3 (1.4)
Merrigan (1988)	18 [4]	6.2 (1.6)	6.2 (1.6)	7.0 (1.8)	13 (3.4)	15 (3.9)	14.5 (3.83)	12.5 (3.30)	12 (3.2)	8.0 (2.1)	5.5 (1.5)

Remarks:

1. Based on 600 single family homes across Canada.
2. Five residences in the Toronto area and fifty more residences located throughout the province of Ontario.
3. Based on 110 single family residences by 11 utilities scattered throughout the continental United States.
4. Based on 18 single family residences located in Florida and North Carolina.

Table A.10: Maximum Hour of Energy Consumption for Dishwasher and Clothes Washer

Author	Sample Size	Item	Mon (Time)	Tue (Time)	Wed (Time)	Thu (Time)	Fri (Time)	Sat (Time)	Sun (Time)
Ladd and Harrison (1985)	110 [1]	dishwasher	8 PM	8 PM	8 PM	8 PM	9 PM	10 PM	10 PM
		clothes washer	10 AM	9 AM	9 AM	9 AM	10 AM	10 AM	10 AM

Remarks:

1. Based on 110 single family residances by 11 utilities scattered throughout the continental United States.

Table A.11: Energy Consumption Versus Hot-Water Consumption for a Cascade 40 Electric Water Heater

Author	Hot Water Consumption L (gal)/Day	Energy Consumption kWh/Day (Btu/Day)	Unit Production L/kWh (gal/Btu)	Efficiency %
Kipping (1981)	0 (0)	3.3 (11 000)	0 (0)	0
	50 (13)	6.9 (24 000)	7.2 (0.000 560)	52.0
	100 (26.4)	10.5 (35 800)	9.5 (0.000 730)	68.4
	150 (39.6)	14.0 (47 700)	10.7 (0.000 827)	76.5
	200 (52.8)	17.6 (60 000)	11.4 (0.000 881)	81.3
	250 (66.0)	21.2 (72 300)	11.8 (0.000 912)	84.4
	300 (79.2)	24.8 (84 600)	12.1 (0.000 935)	86.7
	350 (92.4)	28.4 (96 800)	12.3 (0.000 951)	88.4
	400 (106)	31.9 (109 000)	12.5 (0.000 966)	89.7
	450 (119)	35.5 (121 000)	12.7 (0.000 982)	90.7

Remarks:

1. The storage temperature for the tank in the above example is 65.6°C (150.1°F), the inlet temperature is at 4°C (39°F), and the ambient air temperature is at 10°C (50°F).

2. This case illustrates the temperature conditions which result in the most energy required to produce a quantity of hot water and this will occur during the winter.

Table A.12: Energy Consumption Versus Hot-Water Consumption for a Cascade 40 Electric Water Heater

Author	Hot Water Consumption L (gal)/Day	Energy Consumption kWh/Day (Btu/Day)	Unit Production L/kWh (gal/Btu)	Efficiency %
Kipping (1981)	0 (0)	1.4 (4 700)	0 (0)	0
	50 (13)	3.2 (11 000)	15.6 (0.001 210)	55.8
	100 (26.4)	5.0 (17 000)	20.0 (0.001 550)	71.7
	150 (39.6)	6.8 (23 000)	22.1 (0.001 710)	79.1
	200 (52.8)	8.6 (29 000)	23.3 (0.001 800)	83.5
	250 (66.0)	10.4 (35 500)	24.0 (0.001 860)	86.3
	300 (79.2)	12.2 (41 600)	24.6 (0.001 900)	88.4
	350 (92.4)	14.0 (47 700)	25.0 (0.001 930)	89.9
	400 (106)	15.8 (53 900)	25.3 (0.001 960)	91.0
	450 (119)	17.6 (60 000)	25.6 (0.001 980)	91.9

Remarks:

1. The storage temperature for the tank in the above example is $48.9°C$ $(120°F)$, the inlet temperature is at $18°C$ $(64°F)$, and the ambient air temperature is at $25°C$ $(77°F)$.

2. This case illustrates the temperature conditions which result in the least energy required to produce a quantity of hot water and this will occur during the summer.

Table A.13: Energy Consumption Versus Hot-Water Consumption for a Cascade 60 Electric Water Heater

Author	Hot Water Consumption L (gal)/Day	Energy Consumption kWh/Day (Btu/Day)	Unit Production L/kWh (gal/Btu)	Efficiency %
Kipping (1981)	0 (0)	3.9 (13 000)	0 (0)	0
	50 (13)	7.5 (26 000)	6.7 (0.000 520)	47.8
	100 (26.4)	11.1 (37 800)	9.0 (0.000 700)	64.7
	150 (39.6) (39.6)	14.6 (49 800)	10.3 (0.000 796)	73.3
	200 (52.8)	18.2 (62 000)	11.0 (0.000 850)	78.6
	250 (66.0)	21.8 (74 300)	11.5 (0.000 889)	82.1
	300 (79.2)	25.4 (86 600)	11.8 (0.000 912)	84.6
	350 (92.4)	29.0 (98 900)	12.1 (0.000 935)	86.5
	400 (106)	32.5 (111 000)	12.3 (0.000 951)	88.0
	450 (119)	36.1 (123 000)	12.5 (0.000 966)	89.2

Remarks:

1. The storage temperature for the tank in the above example is $65.6°C$ ($150.1°F$), the inlet temperature is at $4°C$ ($39°F$), and the ambient air temperature is at $10°C$ ($50°F$).

2. This case illustrates the temperature conditions which result in the most energy required to produce a quantity of hot water and this will occur during the winter.

Table A.14: Energy Consumption Versus Hot-Water Consumption for a Cascade 60 Electric Water Heater

Author	Hot Water Consumption L (gal)/Day	Energy Consumption kWh/Day (Btu/Day)	Unit Production L/kWh (gal/Btu)	Efficiency %
Kipping (1981)	0 (0)	1.7 (5 800)	0 (0)	0
	50 (13)	3.5 (12 000)	14.3 (0.001 110)	51.7
	100 (26.4)	5.3 (18 000)	18.9 (0.001 460)	68.2
	150 (39.6)	7.1 (24 000)	21.1 (0.001 630)	76.2
	200 (52.8)	8.9 (30 000)	22.5 (0.001 740)	81.1
	250 (66.0)	10.7 (36 500)	23.4 (0.001 810)	84.3
	300 (79.2)	12.5 (42 600)	24.0 (0.001 860)	86.5
	350 (92.4)	14.3 (48 800)	24.5 (0.001 890)	88.2
	400 (106)	16.0 (54 600)	25.0 (0.001 930)	89.5
	450 (119)	17.8 (60 700)	25.3 (0.001 960)	90.6

Remarks:

1. The storage temperature for the tank in the above example is $48.9°C$ ($120°F$), the inlet temperature is at $18°C$ ($64°F$), and the ambient air temperature is at $25°C$ ($77°F$).

2. This case illustrates the temperature conditions which result in the least energy required to produce a quantity of hot water and this will occur during the summer.

Table A.15: Average Daily Consumption of Hot Water per Person

Author	Sample Size	Overall Average Daily Hot Water per Customer L (gal)
Perlman *et al.* (1984)	55 [1]	62.1 (16.4)
Kipping (1981)	16	61.7 [2] (16.3)
Merrigan (1988)	18 [3]	58.6 (15.5)

Remarks:

1. Five residences in the Toronto area and fifty more residences located throughout the province of Ontario.

2. This result is calculated by taking the average of all 16 households given by the author.

3. Based on 18 single family residences located in Florida and North Carolina.

Table A.16: Water Consumption of Males Versus Females

Author	Sample Size	Avg Water Consumption L (gal)			
		Male [1]	Female [1]	Male [2]	Female [2]
Rohles and Konz (1982)	120 people [3]	42.4 (11.2)	27.3 (7.20)	51 (13)	74 (20)

Remarks:

1. This group took a shower without washing their hair.
2. This group took a shower and washed their hair.
3. This group of 120 people includes 60 males and 60 females of age between 18-23 (college students).
4. The people that used a low-flow showerhead set the water temperture at $41.1°C$ ($106.0°F$) , while the people that used a conventional showerheads used a water temperature of $38.9°C$ ($102.0°F$).

Table A.17: Comparison of the Top Versus the Bottom Element for a Daily Energy Usage by Water Heaters with Fixed Water Draw Pattern

Author	Elements Installed [1] W (Btu/h)		Total Time Energized (h)		kWh Used (Btu) Used	
	Top	Bottom	Top	Bottom	Top	Bottom
Colliver *et al.* (1988)	4 500 (15 300)	4 500 (15 300)	0	4.258	0 (0)	15.09 (51 450)
	4 500 (15 300)	2 000 (6 800)	0	9.371	0 (0)	14.76 (50 320)
	4 500 (15 300)	1 500 (5 100)	0.129	11.676	0.46 (1 570)	13.79 (47 020)
	4 500 (15 300)	1 000 (3 400)	0.673	13.730	2.40 (8 180)	10.82 (36 890)

Remarks:

1. These are the listed wattages at 240 V. The corresponding wattages at the measured 213 V are: 3544 for the 4500 W (15 300 Btu/h) element, 1575 for the 2000 W (6800 Btu/h) element, 1181 for the 1500 W (5100 Btu/h) element, and 788 for the 1000 W (3400 Btu/h) element.

Table A.18: Average Daily Hot-Water Use by Average Age of Adults

Author	Sample Size	Average Age of Adults	Average Daily Use L(gal)/Person
Perlman *et al.* (1984)	55 [1]	< 30	55.1 (14.6)
		30-35	77.3 (20.4)
		35-40	72.3 (19.1)
		40-45	66.8 (17.6)
		45-50	64.7 (17.1)
		> 50	59.8 (15.8)
Perlmam *et al.* (1988)	200 [2]	25	88 (23)
	112 [3]	31	77 (20)
	289 [3]	42	67.5 (17.8)
	196 [4]	62	59 (16)

1. Five residences in the Toronto area and fifty more residences located throughout the province of Ontario.
2. Based on 200 rental apartments in the Toronto area.
3. Condos in the Toronto area.
4. Based on 196 senior citizen apartments in the Toronto area.

Table A.19: Standby Losses Compared with Thickness and Type of Insulation

Author	Sample Size	Insulation Type	Insulation Thickness mm (in)	Watts Loss W (Btu)
Sedman *et al.* (1992)	3 [1]	foam	50 (1.97)	104 (355)
	7 [1]	fibreglass	50 (1.97)	121 (412)
	3 [1]	foam	25 (0.98)	138 (470)
	3 [1]	fibreglass	25 (0.98)	163 (556)

Remarks:

1. This number represents the number of water heaters they used for each test.

Table A.20: Energy Savings for Hot-Water Heaters with Added Fiberglass Insulation

Author	Method	Tank Size L (gal)	Original Insulation mm (in)	Added Insulation mm (in)	Original Loss W (Btu/h)	Final Loss W (Btu/h)	Energy Savings kWh/yr ($10^6 \times$Btu/yr)
Johns and Manville [1]	measurement	163 (43)	38 (1.50)	38 (1.50)	170 (580)	120 (410)	440 (1.50)
Hoskins and Hirst [1]	calculation	159 (42)	50 (1.97)	50 (1.97)	107 (365)	64 (218)	380 (1.30)
Critchlow *et al. (1979)*	calculation	150 (40)	50 (1.97)	50 (1.97)	105 (358)	66 (225)	340 (1.16)
McCabe [1]	measurements	225 (60)	50 (1.97)	50 (1.97)	134 (457)	94 (321)	350 (1.19)
Critchlow *et al. (1979)*	calculation	225 (60)	50 (1.97)	50 (1.97)	133 (454)	81 (276)	460 (1.57)

Remarks:

1. These references are taken directly from The Canadian Electrical Association project paper 77-51 with the title "Impoved Energy Efficient Water-Heaters" prepared on February (1979).

Table A.21: Conventional Versus Low-Flow Showerhead Flowrates

Author	Sample Size	Showerhead Type	Flowrate L(gal)/min
Rolles and Konz (1982)	120 people [1]	conventional	11.6 (3.06)
N.R.C of CANADA (1981) [2]		conventional	18.3 (4.83)
Brown and Caldwell (1983) [2]		conventional	12.9 (3.40)
Rolles and Konz (1982)	120 people [1]	low-flow	8.1 (2.1)
N.R.C [3] of CANADA (1981) [2]		low-flow	7.2 (1.9)
Suier and Smith (1975) [2]		low-flow	8-12 (2.0-3.2)

Remarks:

1. This group of 120 people includes 60 males and 60 females of age between 18-23 (college students).
2. The above statistical information is taken from the Energy Conservation Branch, Energy, Mines and Resources of Canada research report with the title *"A Study of Energy Savings Using Low-Flow Showerheads"* published in December 1985.
3. N.R.C. National Research Council.

Table A.22: Daily Heat Loss of Vertical and Horizontal Piping Compared to Heat Traps

Author	Experimental Details	Daily Heat Loss Estimate (Piping Losses) kJ (Btu)	Expected Daily Energy Savings of Heat Trap Relative to Vertical Configuration kJ (Btu)
Schultz et al. (1978) [1]	Vertical Configuration of Nominal 12.7 mm (0.5 in) Copper Tubing; Connected to Electric Water Heater Inlet or Outlet and Uninsulated	600 (569) to 950 (901)	210 (199) to 560 (531)
Johnson et al. (1980)	Vertical Configuration of Nominal 12.7 mm (0.5 in) Copper Tubing; Connected to Gas Water Heater Inlet and Uninsulated	550 (521)	230 (218)
Johnson et al. (1980)	External Heat Trap; Connected to gas Water Heater inlet and Uninsulated Nominal 12.7 mm (0.5 in) Copper Tubing	320 (303)	
Johnson et al. (1980)	Vertical Configuration of Nominal 12.7 mm (0.5 in) Copper Tubing; Connected to Gas Water Heater Outet and Uninsulated	510 (483)	210 (199)
Johnson et al. (1980)	External Heat Trap; Connected to gas Water Heater Outlet and Uninsulated Nominal 12.7 mm (0.5 in) Copper Tubing	300 (284)	

Remarks:

1. Although no heat traps were tested by Schultz, these values do provide an estimate of the maximum savings potential associated with a heat trap for the particular conditions of Schultz's work.

Appendix B

Derivation of Some Heat-Transfer Relations

B.1 Derivation of the Convection Heat-Transfer Coefficient for a Horizontal Pipe

For a turbulent flow in circular tubes, the Dittus-Boelter equation states:

$$Nu_D = 0.023\, Re_D{}^{\frac{4}{5}}\, Pr^n \tag{B.1}$$

where n=0.4 for heating ($T_s > T_m$)and 0.3 for cooling ($T_s < T_m$).

In this case $T_s < T_m$ so n=0.3 and our final equation is then given in the form

$$Nu_D = 0.023\, Re_D{}^{\frac{4}{5}}\, Pr^{0.3} \tag{B.2}$$

The equation have been confirmed experimentally for the range of conditions: $0.7 \leq Pr \leq 160$, $Re_D \geq 10,000$, $\frac{L}{D} \geq 10$

Because $h = \frac{Nu_D k}{D}$ so our final equation is

$$h_f = \frac{0.023\, Re_D{}^{\frac{4}{5}}\, Pr^{0.3}\, k}{D} \tag{B.3}$$

For long horizontal cylinders the Nusselt number that is recommended by Churchill and Chu taken from <u>Fundamentals of Heat and Mass Transfer</u> by Incropera and De-Witt (p 551, 1990) for a wide Reyleigh number range is

$$Nu_D = \left(0.60 + \frac{0.387\, Ra_D{}^{\frac{1}{6}}}{\left(1 + \left(\frac{0.559}{Pr}\right)^{\frac{9}{16}}\right)^{\frac{8}{27}}} \right)^2 \tag{B.4}$$

with a Rayleigh number range of $10^{-5} < Ra_D < 10^{12}$. The Rayleigh number is defined by

$$Ra_D = \frac{\beta\, g\, (T_w - T_\infty)\, D^3}{\nu\, \alpha} \tag{B.5}$$

where β is the volumetric expansion coefficient and g is gravitational acceleration coefficient. But $\beta = \frac{1}{T_f}$, where T_f is the film temperature given by $T_f = \frac{(T_w + T_\infty)}{2}$. Therefore β can be written in the following form

$$\beta = \frac{2}{(T_w + T_\infty)} \tag{B.6}$$

Substituting the beta coefficient, the Rayleigh number is given by

$$Ra_D = \frac{2\,g\,(T_w - T_\infty)\,D^3}{(T_w + T_\infty)\,\nu\,\alpha} \tag{B.7}$$

Substituting the Rayleigh number back into the Nusselt number we get

$$Nu_D = \left(0.60 + \frac{0.387 \left(\frac{2\,g\,(T_w - T_\infty)\,D^3}{(T_w + T_\infty)\,\nu\,\alpha} \right)^{\frac{1}{6}}}{\left(1 + \left(\frac{0.559}{Pr} \right)^{\frac{9}{16}} \right)^{\frac{8}{27}}} \right)^2 \tag{B.8}$$

Substituting $g = 9.81$ and for T= $293°K$ and $Pr = 0.709$ we get a Nusselt number of

$$Nu_D = \left(0.60 + 0.5275 \left(\frac{(T_w - T_\infty)\ D^3}{(T_w + T_\infty)\ \nu\, \alpha}\right)^{\frac{1}{6}}\right)^2 \tag{B.9}$$

Expanding the above equation we get

$$Nu_D = 0.60^2 + 2 \cdot 0.60 \cdot 0.5275 \left(\frac{(T_w - T_\infty)\ D^3}{(T_w + T_\infty)\ \nu\, \alpha}\right)^{\frac{1}{6}} +$$

$$0.5275^2 \left(\frac{(T_w - T_\infty)\ D^3}{(T_w + T_\infty)\ \nu\, \alpha}\right)^{\frac{1}{3}} \tag{B.10}$$

Finally, the heat-transfer coefficient for a long horizontal pipe is given by

$$h = \frac{k_{air}}{D}(0.60^2 + 2 \cdot 0.60 \cdot 0.5275 \left(\frac{(T_w - T_\infty)\ D^3}{(T_w + T_\infty)\ \nu\, \alpha}\right)^{\frac{1}{6}}$$

$$+0.5275^2 \left(\frac{(T_w - T_\infty)\ D^3}{(T_w + T_\infty)\ \nu\, \alpha}\right)^{\frac{1}{3}}) \tag{B.11}$$

B.2 Derivation of the Convection Heat-Transfer Coefficient for a Vertical Pipe

For a vertical cylinder the correlation of a vertical plane may be used, if a cylinder of height L has a boundary layer thickness δ much less than the cylinder diameter D. This condition is satisfied when $\frac{D}{L} \geq \frac{35}{Gr_L^{\frac{1}{4}}}$. Where Gr is the Grashof number

$$G_r = \frac{g\,\beta\,(T_w - T_\infty)\,L^3}{\nu^2} \tag{B.12}$$

In our case this condition is satisfied; therefore, a vertical plate approximation is used in this report for vertical piping. The correlation that Churchill and Chu Fundamentals of Heat and Mass Transfer by Incropera and DeWitt (p 543, 1990) recommended is of the form:

$$\overline{Nu}_L = 0.68 + \frac{0.670\,Ra_L^{\frac{1}{4}}}{\left(1 + \left(\frac{0.492}{Pr}\right)^{\frac{9}{16}}\right)^{\frac{4}{9}}} \tag{B.13}$$

for a Rayleigh number range of $0 < Ra_D < 10^9$

Substituting the Rayleigh number back into the Nusselt number we get

$$\overline{Nu}_L = 0.68 + \frac{0.670 \left(\frac{2\,g\,(T_w - T_\infty)\,L^3}{(T_w + T_\infty)\,\nu\,\alpha} \right)^{\frac{1}{4}}}{\left(1 + \left(\frac{0.492}{Pr} \right)^{\frac{9}{16}} \right)^{\frac{4}{9}}} \tag{B.14}$$

Substituting $g = 9.81$ and for T= $293°K$ a $Pr = 0.709$ we get a Nusselt number of

$$\overline{Nu}_L = 0.68 + 1.082 \left(\frac{(T_w - T_\infty)\,L^3}{(T_w + T_\infty)\,\nu\,\alpha} \right)^{\frac{1}{4}} \tag{B.15}$$

Finally the heat-transfer coefficient for a long vertical pipe is defined by

$$h = \frac{k_{air}}{L} \left(0.68 + 1.082 \left(\frac{(T_w - T_\infty)\,L^3}{(T_w + T_\infty)\,\nu\,\alpha} \right)^{\frac{1}{4}} \right) \tag{B.16}$$

B.3 The Effect of Insulation in the Systems

The derivation of the heat-transfer coefficient will be treated differently when insulation is added to the pipe system. The insulation material will contribute in the heat-transfer coefficient. If we let T_b be the temperature of the fluid, and T_W the temperature of the wall, T_{ins} the temperature of insulation and finally T_∞ the temperature of the air, then the heat transfer through the pipe is given by

$$q_f = h_f\,2\,\pi r_1 L(T_b - T_w) \tag{B.17}$$

$$q_{ins} = \frac{k_{ins}\,2\,\pi\,L(T_w - T_{ins})}{ln(\frac{r2}{r1})} \tag{B.18}$$

$$q_{sur} = h_s\,2\,\pi r_2 L(T_{ins} - T_\infty) \tag{B.19}$$

From equation B.16 and B.17 we get

$$\frac{k_{ins}\,2\,\pi\,L}{ln(\frac{r_2}{r_1})}T_w + h_f\,L\,2\,\pi\,r_1\,T_w = h_f\,2\,\pi\,r_1\,L\,T_b + \frac{k_{ins}\,2\,\pi\,L}{ln(\frac{r_2}{r_1})}T_{ins} \tag{B.20}$$

If we solve the above equation for T_{ins} we get

$$T_{ins} = T_w + \frac{h_f\,r_1\,ln(\frac{r_2}{r_1})T_w}{k_{ins}} - \frac{h_f\,r_1\,ln(\frac{r_2}{r_1})T_b}{k_{ins}} \tag{B.21}$$

Solving simultaneously equations B.17 and B.18 we get

$$\frac{k_{ins}\,2\,\pi\,L}{ln(\frac{r_2}{r_1})}T_w - \frac{k_{ins}\,2\,\pi\,L}{ln(\frac{r_2}{r_1})}T_{ins} = h_s\,L\,2\,\pi\,r_2\,T_{ins} - h_s\,2\,\pi\,r_2\,L\,T_\infty \tag{B.22}$$

Substituting T_{ins} in the above equation it becomes

$$\frac{k_{ins}\,2\,\pi\,L}{ln(\frac{r_2}{r_1})}T_w - \frac{k_{ins}\,2\,\pi\,L}{ln(\frac{r_2}{r_1})}\left(T_w + \frac{h_f\,r_1\,ln(\frac{r_2}{r_1})T_w}{k_{ins}} - \frac{h_f\,r_1\,ln(\frac{r_2}{r_1})T_b}{k_{ins}}\right) =$$

$$h_s\,L\,2\,\pi\,r_2\left(T_w + \frac{h_f\,r_1\,ln(\frac{r_2}{r_1})T_w}{k_{ins}} - \frac{h_f\,r_1\,ln(\frac{r_2}{r_1})T_b}{k_{ins}}\right) - h_s\,2\,\pi\,r_2\,L\,T_\infty \quad \text{(B.23)}$$

Solving for T_w we get

$$T_w = \frac{h_s\,2\,\pi\,r_2\,L\,T_b\,h_f\,r_1\,ln(\frac{r_2}{r_1})}{k_{ins}\left(2\,\pi\,r_2\,L\,h_s + \frac{2\,\pi\,r_2\,L\,h_s\,h_f\,r_1\,ln(\frac{r_2}{r_1})}{k_{ins}} + 2\,\pi\,h_f\,r_1\,L\right)}$$

$$+\frac{h_s\,2\,\pi\,r_2\,L\,T_\infty}{k_{ins}\left(2\,\pi\,r_2\,L\,h_s + \frac{2\,\pi\,r_2\,L\,h_s\,h_f\,r_1\,ln(\frac{r_2}{r_1})}{k_{ins}} + 2\,\pi\,h_f\,r_1\,L\right)}$$

$$+\frac{h_f\,2\,\pi\,r_1\,L\,T_b}{k_{ins}\left(2\,\pi\,r_2\,L\,h_s + \frac{2\,\pi\,r_2\,L\,h_s\,h_f\,r_1\,ln(\frac{r_2}{r_1})}{k_{ins}} + 2\,\pi\,h_f\,r_1\,L\right)} \quad \text{(B.24)}$$

B.3.1 Derivation of an Effective Heat-Transfer Coefficient

For an insulated pipe, the derivation of a heat transfer coefficient is much more complex. The insulation on the pipe causes some complications because we need the heat transfer coefficient between the pipe outlet diameter and the air. However, this problem can be eliminated if we treat the thermal resistance of the insulation and the free stream of air as one system. In this case we calculate an effective heat transfer coefficient for the whole system.

We know that for an insulated pipe that the heat transfer through the pipe is given by

$$q_{ins} = \frac{k_{ins}\, 2\,\pi\, L\,(T_w - T_{ins})}{ln(\frac{r_2}{r_1})} \tag{B.25}$$

and

$$q_{sur} = h_s\, 2\,\pi r_2 L(T_{ins} - T_\infty) \tag{B.26}$$

From B.25 and B.26 we get

$$\frac{k_{ins}\, 2\,\pi\, L\,(T_w - T_{ins})}{ln(\frac{r_2}{r_1})} = h_s\, 2\,\pi r_2 L(T_{ins} - T_\infty) \tag{B.27}$$

or

$$\frac{q_{ins}}{2\pi k_{ins} L}\, ln(\frac{r_2}{r_1}) = T_w - T_{ins} \tag{B.28}$$

From B.26 we get

$$\frac{q_{sur}}{2\,\pi\,r_2\,L\,h_s} = T_{ins} - T_\infty \tag{B.29}$$

If we add B.28 and B.29 we get

$$\frac{q}{2\,\pi\,k_{ins}\,L} ln(\frac{r_2}{r_1}) + \frac{q}{2\,\pi\,r_2\,L\,h_s} = T_w - T_\infty \tag{B.30}$$

or

$$\frac{q}{2\,\pi\,r_1\,L}\,(ln(\frac{r_2}{r_1})\,\frac{r_1}{k_{ins}} + \frac{r_1}{r_2\,h_s}) = T_w - T_\infty \tag{B.31}$$

Finally

$$\frac{q}{A}(ln(\frac{r_2}{r_1})\,\frac{r_1}{k_{ins}} + \frac{r_1}{r_2\,h_s}) = T_w - T_\infty \tag{B.32}$$

Then the effective heat-transfer coefficient, h_{eff} , of the insulation and free stream air is

$$h_{eff} = \frac{1}{ln(\frac{r_2}{r_1})\,\frac{r_1}{k_{ins}} + \frac{r_1}{r_2\,h_s}} \tag{B.33}$$

Appendix C

Tables of improved water heating systems

C.1 Small Bungalow House Size

Table C.1: Taps Percentage Performance (1/2 in. Pipe Diameter; Small Bungalow House)

	Showerhead %	Low-Flow Showerhead %	Laundry %	Washroom Sink %	Dishwasher %	Kitchen Sink %
Tap Itself	100	100	100	100	100	100
All Taps Open	53.2	55.3	63.8	60.4	52.4	56.2
Showerhead	-	-	93.2	77.8	94.9	93.4
Laundry	90.3	92.2	-	89.4	82.5	80.8
Washroom Sink	69.9	72.6	90.0	-	92.7	91.3
Dishwasher	94.7	96.1	88.4	94.2	-	84.0
Kitchen Sink	90.3	93.9	83.4	91.3	78.2	-

Table C.2: Taps Percentage Performance (3/4 in. Pipe Diameter; Small Bungalow House)

	Showerhead %	Low-Flow Showerhead %	Laundry %	Washroom Sink %	Dishwasher %	Kitchen Sink %
Tap Itself	100	100	100	100	100	100
All Taps Open	82.0	84.1	85.5	84.4	82.5	83.7
Showerhead	-	-	98.4	92.9	99.0	98.4
Laundry	98.0	98.4	-	97.5	96.0	95
Washroom Sink	90.7	92.6	97.6	-	98.3	97.5
Dishwasher	98.8	98.9	97.2	98.8	-	95.7
Kitchen Sink	98.3	98.4	95.6	97.9	94.7	-

C.2 Large Two-Story House

Table C.3: Taps Percentage Performance (1/2 in. Pipe Diameter; Large Two-Story House)

	Kitchen Sink Level #1 %	Laundry Level #1 %	Dishwasher Level #1 %	Showerhead 1 Level #2 %	Washroom Sink 1 Level #2 %	Tub Level #2 %
Tap Itself	100	100	100	100	100	100
All Taps Open	63.9	40.1	59.6	8	20.8	23.4
Showerhead #1 Level #2	-	82.6	-	-	79.4	79.4
Washroom Sink #1 Level #2	-	77.7	-	73.5	-	-
Tub Level #2	-	72.4	-	65.9	-	-
Laundry	-	-	-	70.4	70.4	69.9
Dishwasher	82.8	-	-	-	-	-
Kitchen Sink	-	-	77.3	-	-	-
Showerhead and Washroom Sink Level #2	-	67.5	-	-	-	-
Washroom Sink and Tub Level #2	-	61.6	-	-	-	-
Laundry and Washroom Sink Level #2	-	-	-	50.2	-	54.4
Laundry and Showerhead Level #2	-	-	-	-	56.1	-
Laundry and Tub Level #2	-	-	-	-	47.0	-

Table C.4: Taps Percentage Performance (1/2 in. Pipe Diameter; Large Two-Story House) (Continued)

	Washroom Sink Level #1 %	Washroom Sink 2 Level #2 %	Showerhead 2 Level #2 %	Low-Flow Showerhead 1 Level #2 %	Low-Flow Showerhead 2 Level #2 %
Tap Itself	100	100	100	100	100
All Taps Open	44.1	19.2	28.1	9.2	20.7
Shower #2 Level #2	82.8	78.0	-	-	-
Washroom Sink Level #1	-	71.1	71.2	-	74.1
Washroom Sink #2 Level #2	78.2	-	71.2	-	73.6
Washroom Sink #2 Level #2 and Washroom Sink Level #1	-	-	49.0	-	50.6
Shower #2 Level #2 and Washroom Sink Level #1	-	55.3	-	-	-
Shower #2 Level #2 and Washroom Sink #2 Level #2	69.0	-	-	-	-
Washroom Sink #1 Level #2	-	-	-	75.7	-
Tub Level #2	-	-	-	68.2	-
Laundry	-	-	-	73.4	-
Laundry and Washroom Sink #1 Level #2	-	-	-	52.0	-

Table C.5: Taps Percentage Performance (3/4 in. Pipe Diameter; Large Two-Story House)

	Kitchen Sink Level #1 %	Laundry Level #1 %	Dishwasher Level #1 %	Showerhead 1 Level #2 %	Washroom Sink 1 Level #2 %	Tub Level #2 %
Tap Itself	100	100	100	100	100	100
All Taps Open	80.7	57.0	79.4	46.8	50.1	51.3
Showerhead Level #2	-	94.7	-	-	93.7	92.8
Washroom Sink Level #2	-	92.0	-	91.6	-	-
Tub Level #2	-	89.2	-	88.3	-	-
Laundry	-	-	-	91.9	90.9	89.7
Dishwasher	95.7	-	-	-	-	-
Kitchen Sink	-	-	94.1	-	-	-
Showerhead and Washroom Sink Level #2	-	85.7	-	-	-	-
Washroom Sink and Tub Level #2	-	80.2	-	-	-	-
Laundry and Washroom Sink Level #2	-	-	-	80.8	-	78.4
Laundry and Showerhead Level #2	-	-	-	-	83.3	-
Laundry and Tub Level #2	-	-	-	-	76.4	-

Table C.6: Taps Percentage Performance (3/4 in. Pipe Diameter; Large Two-Story House) (Continued)

	Washroom Sink Level #1 %	Washroom Sink 2 Level #2 %	Showerhead 2 Level #2 %	Low-Flow Showerhead 1 Level #2 %	Low-Flow Showerhead 2 Level #2 %
Tap Itself	100	100	100	100	100
All Taps Open	61.9	56.4	53.3	49.7	56.3
Shower #2 Level 2	94.9	93.1	-	-	-
Washroom Sink Level #1	-	91.4	92.2	-	94.0
Washroom Sink 2 Level #2	92.3	-	90.7	-	92.3
Washroom Sink 2 Level #2 and Washroom Sink Level 1	-	-	80.5	-	83.1
Shower #2 Level #2 and Washroom Sink Level #1	-	82.9	-	-	-
Shower #2 Level #2 and Washroom Sink #2 Level #2	86.4	-	-	-	-
Washroom Sink #1 Level #2	-	-	-	93.4	-
Tub Level #2	-	-	-	90.2	-
Laundry	-	-	-	93.4	-
Laundry and Washroom Sink #1 Level #2	-	-	-	83.1	-

C.3 Large Bungalow House Size

Table C.7: Taps Percentage Performance (1/2 in. Pipe Diameter; Large Bungalow House)

	Washroom Sink %	Shower #1 %	Washroom Sink #2 %	Shower #2 %
Tap Itself	100	100	100	100
All Taps Open	52.7	48.6	50.7	46.9
Shower #1	87.8	-	-	-
Washroom Sink #1	-	83.7	-	-
Shower #2	-	-	86.0	-
Washroom Sink #2	-	-	-	82.2

Table C.8: Taps Percentage Performance (1/2 in. Pipe Diameter; Large Bungalow House) (Continued)

	Laundry %	Kitchen Sink %	Dishwasher %
Tap Itself	100	100	100
All Taps Open	56.0	47.8	44.6
Kitchen Sink	86.1	-	76.9
Dishwasher	90.1	82.8	-
Laundry	-	84.1	85.6
Kitchen Sink and Dishwasher	79.1	-	-
Dishwasher and Laundry	-	68.3	
Kitchen Sink and Laundry	-	-	63.7

Table C.9: Taps Percentage Performance (3/4 in. Pipe Diameter; Large Bungalow House)

	Washroom Sink %	Shower #1 %	Washroom Sink #2 %	Shower #2 %
Tap Itself	100	100	100	100
All Taps Open	79.1	77.7	78.7	77.4
Shower #1	96.8	-	-	-
Washroom Sink #1	-	95.7	-	-
Shower #2	-	-	96.3	-
Washroom Sink #2	-	-	-	95.4

Table C.10: Taps Percentage Performance (3/4 in. Pipe Diameter; Large Bungalow House) (Continued)

	Laundry %	Kitchen Sink %	Dishwasher %
Tap Itself	100	100	100
All Taps Open	80.8	78.4	77.1
Kitchen Sink	96.4	-	94.1
Dishwasher	97.6	95.7	-
Laundry	-	95.9	96.4
Kitchen Sink and Dishwasher	93.1	-	-
Dishwasher and Laundry	-	90.4	
Kitchen Sink and Laundry	-	-	89.2

Table C.11: Taps Percentage Performance for 1/2 in. Pipe Diameter and Showerhead Position 1.8 m from Hot Water Tank

	Washroom Sink %	Shower #1 %	Washroom Sink #2 %	Shower #2 %
Tap Itself	100	100	100	100
All Taps Open	49.3	44.6	42.6	46.9
Shower #1	86.1	-	-	-
Washroom Sink #1	-	81.6	-	-
Shower #2	-	-	84.6	-
Washroom Sink #2	-	-	-	80.1

Table C.12: Taps Percentage Performance for 1/2 in. Pipe Diameter and Showerhead Position 1.8 m from Hot Water Tank (Continued)

	Laundry %	Kitchen Sink %	Dishwasher %
Tap Itself	100	100	100
All Taps Open	60.0	51.7	48.6
Kitchen Sink	88.0	-	78.6
Dishwasher	91.5	83.8	-
Laundry	-	86.5	87.9
Kitchen Sink and Dishwasher	81.8	-	-
Dishwasher and Laundry	-	70.8	
Kitchen Sink and Laundry	-	-	66.4

Table C.13: Taps Percentage Performance for 1/2 in. Pipe Diameter and Showerhead Position 4.3 m from Hot Water Tank

	Washroom Sink %	Shower #1 %	Washroom Sink #2 %	Shower #2 %
Tap Itself	100	100	100	100
All Taps Open	41.0	35.3	39.2	33.5
Shower #1	83.5	-	-	-
Washroom Sink #1	-	78.0	-	-
Shower #2	-	-	81.8	-
Washroom Sink #2	-	-	-	76.7

Table C.14: Taps Percentage Performance for 1/2 in. Pipe Diameter and Showerhead Position 4.3 m from Hot Water Tank (Continued)

	Laundry %	Kitchen Sink %	Dishwasher %
Tap Itself	100	100	100
All Taps Open	53.4	63.7	60.6
Kitchen Sink	92.0	-	82.0
Dishwasher	94.4	86.0	-
Laundry	-	91.2	92.6
Kitchen Sink and Dishwasher	87.1	-	-
Dishwasher and Laundry	-	77.3	
Kitchen Sink and Laundry	-	-	73.6

Table C.15: Taps Percentage Performance for 1/2 in. Pipe Diameter and Showerhead Position 7.3 m from Hot Water Tank

	Washroom Sink %	Shower #1 %	Washroom Sink #2 %	Shower #2 %
Tap Itself	100	100	100	100
All Taps Open	37.2	30.4	35.6	28.9
Shower #1	81.4	-	-	-
Washroom Sink #1	-	74.9	-	-
Shower #2	-	-	79.9	-
Washroom Sink #2	-	-	-	74.0

Table C.16: Taps Percentage Performance for 1/2 in. Pipe Diameter and Showerhead Position 7.3 m from Hot Water Tank (Continued)

	Laundry %	Kitchen Sink %	Dishwasher %
Tap Itself	100	100	100
All Taps Open	48.7	69.2	66.4
Kitchen Sink	91.7	-	85.5
Dishwasher	94.4	88.9	-
Laundry	-	91.7	92.7
Kitchen Sink and Dishwasher	86.1	-	-
Dishwasher and Laundry	-	79.9	
Kitchen Sink and Laundry	-	-	76.8

Appendix D

Program listings

D.1 Listing of Program for Insulation Case

```
C      ***** HARDY CROSS PIPE NETWORK ANALYSIS *****
c
       implicit none
c ***********************************************************************
       real*4 diameter,area,length,roughness
       real*4 R_friction,R_minor,R_bar,Q,Q0,Qa,Re
       real*4 delta_H,H_ref
       real*4 HP0,HP1,HP2,Q1,Q2,a0,a1,a2
       real*4 sum_top,sum_G
       real*4 pi,gravity,viscosity,spec_grav,converge,minor_loss
       real*4 test,test1,test2,H,H_drop
       real*4 delta_Q,G,phi0,Q_out,ReK
       real*4 tem,tmenn,ttww,pipelo
       real*4 areal,tmean,qh,t2,tfll,todemand
       real*4 rr2, tme,rho,tcold,tcr,mh,demand
```

```
      real*4 qwith,cp,hl,qloss,troom,toqloss,toqwith
      integer*2 j_tubes,j_tube_number,fjunct_num,junct_num
      integer*2 i,j,n,j_elements,j_element_number,label,iteration
      integer*2 n_pipe,n_junc,n_pump,k,pipeloc,ml,timemax,uct
      dimension diameter(60),area(60),length(60),roughness(60),tcr(60)
      dimension R_friction(60),R_minor(60),R_bar(60),timemax(60)
      dimension delta_H(60),Q(60),Q0(60),H(60),H_drop(60),tfll(60)
      dimension j_elements(60),j_element_number(60,60),ml(60),tme(60)
      dimension j_tubes(60),j_tube_number(60,60),Q_out(60),pipelo(60)
      dimension a0(60),a1(60),a2(60),ReK(60),tem(60),pipeloc(60)
      dimension areal(60),qh(60),fjunct_num(60),tmenn(60),ttww(60)
      dimension junct_num(60),tmean(60),t2(60),rr2(60),minor_loss(60)
c *********************************************************************
c
      pi=3.14159
      gravity=9.806
      rho=985.5
      cp=4184.0
      uct=32
      tcold=284.0
      troom=293.0
      hl=3.1
      open(unit=2,file='hardy.ph2')
      open(unit=3,file='hardy.re1980mo')
      open(unit=4,file='sched.ho12')
      do 11 i=1,uct
      read(4,9) k,ml(k),timemax(k),tme(k),tcr(k)
      write(*,*) ml(k), tme(k), tcr(k)
9     format(14x,3i10,2f10)
```

```
11      continue
        read(2,5) n_pipe,n_junc,n_pump
5       format(12x,i10)
        read(2,6) viscosity,spec_grav,converge
6       format(12x,f10.0)
        read(2,7)
        read(2,7)
7       format(12x)
c
c
        do 10 n=1,n_pipe
        read(2,8) i,length(i),diameter(i),roughness(i),Q(i)
8       format(12x,i10,4f10.0)
        diameter(i)=diameter(i)/100.0
        rr2(i)=(diameter(i)/2.0)+0.001
        area(i)=pi*diameter(i)**2/4.0
        areal(i)=2*pi*(diameter(i)/2)*length(i)
        roughness(i)=roughness(i)/1000.0
        Q0(i)=Q(i)
        a0(i)=0.0
        a1(i)=0.0
        a2(i)=0.0
10      continue
        read(2,7)
        read(2,7)
        read(2,7)
        if(n_pump.ne.0) then
           do 20 i=1,n_pump
           read(2,12) label,HP0,HP1,Q1,HP2,Q2
```

```
12          format(12x,i10,5f10.0)
            a0(label)=HP0
            a2(label)=(HP0+(HP1/HP0-1.0)*Q2-HP2)/(Q1*Q1*Q2/HP0-Q2*Q2)
            a1(label)=(HP1-HP0-a2(label)*Q1*Q1)/HP0
c             a2(label)=((hp1-hp0)*q2-(hp2-hp0)*q1)/(q1**2*q2-q2**2*q1)
c             a1(label)=(hp1-hp0-a2(label)*q1**2)/q1
20          continue
        endif
        read(2,7)
        read(2,7)
        read(2,21) H_ref
21      format(12x,f10.0)
        read(2,7)
        read(2,7)
        read(2,7)
        read(2,7)
        do 30 i=1,n_junc
        read(2,22) j_elements(i),
     &              (j_element_number(i,j),j=1,j_elements(i))
22      format(12x,6i10)
30      continue
        read(2,7)
        read(2,7)
        read(2,7)
        read(2,7)
        do 40 i=n_junc+1,n_pipe
        read(2,31) delta_H(i),j_elements(i),
     &              (j_element_number(i,j),j=1,j_elements(i))
31      format(12x,f10.0,6i10)
```

```
40      continue
        read(2,7)
        read(2,7)
        read(2,7)
        do 240 i=1,n_junc
        read(2,31) Q_out(i),j_tubes(i),
     &              (j_tube_number(i,j),j=1,j_tubes(i))
240     continue
        read(2,7)
        read(2,7)
        do 44 n=1,n_pipe
        read(2,42) i,junct_num(i), fjunct_num(i)
42      format(12x,3i10)
44      continue
        write(3,46)
        write(*,46)
46      format(' ','TRIAL NO.   RELATIVE FLOW CHANGE')
        todemand=0.0
        toqloss=0.0
        toqwith=0.0
        do 102 k=1,uct
         if (ml(k).eq.1) then
          minor_loss(1)= 2.5
          minor_loss(2)= 8.4
          minor_loss(3)= 99999999
          minor_loss(4)= 99999999
          minor_loss(5)= 99999999
          minor_loss(6)= 495.2
          minor_loss(7)= 99999999
```

```
           minor_loss(8)= 99999999
           minor_loss(9)= 99999999
           pipeloc(1)= 1
           pipeloc(2)= 1
           pipeloc(3)= 3
           pipeloc(4)= 3
           pipeloc(5)= 3
           pipeloc(6)= 2
           pipeloc(7)= 3
           pipeloc(8)= 3
           pipeloc(9)= 3
c
          else if (ml(k).eq.2) then
           minor_loss(1)= 2.5
           minor_loss(2)= 8.4
           minor_loss(3)= 99999999
           minor_loss(4)= 99999999
           minor_loss(5)= 99999999
           minor_loss(6)= 99999999
           minor_loss(7)= 246.4
           minor_loss(8)= 99999999
           minor_loss(9)= 99999999
           pipeloc(1)= 1
           pipeloc(2)= 1
           pipeloc(3)= 3
           pipeloc(4)= 3
           pipeloc(5)= 3
           pipeloc(6)= 3
           pipeloc(7)= 1
```

```
      pipeloc(8)= 3
      pipeloc(9)= 3
c
     else if (ml(k).eq.3) then
      minor_loss(1)= 2.5
      minor_loss(2)= 99999999
      minor_loss(3)= 2.4
      minor_loss(4)= 245.9
      minor_loss(5)= 99999999
      minor_loss(6)= 99999999
      minor_loss(7)= 99999999
      minor_loss(8)= 99999999
      minor_loss(9)= 99999999
      pipeloc(1)= 1
      pipeloc(2)= 3
      pipeloc(3)= 1
      pipeloc(4)= 2
      pipeloc(5)= 3
      pipeloc(6)= 3
      pipeloc(7)= 3
      pipeloc(8)= 3
      pipeloc(9)= 3
c
     else if (ml(k).eq.4) then
      minor_loss(1)= 2.5
      minor_loss(2)= 99999999
      minor_loss(3)= 2.4
      minor_loss(4)= 99999999
      minor_loss(5)= 2.9
```

```
        minor_loss(6)= 99999999
        minor_loss(7)= 99999999
        minor_loss(8)= 309.0
        minor_loss(9)= 99999999
        pipeloc(1)= 1
        pipeloc(2)= 3
        pipeloc(3)= 1
        pipeloc(4)= 3
        pipeloc(5)= 1
        pipeloc(6)= 3
        pipeloc(7)= 3
        pipeloc(8)= 2
        pipeloc(9)= 3
c
      else if (ml(k).eq.5) then
       minor_loss(1)= 2.5
       minor_loss(2)= 99999999
       minor_loss(3)= 2.4
       minor_loss(4)= 99999999
       minor_loss(5)= 2.9
       minor_loss(6)= 99999999
       minor_loss(7)= 99999999
       minor_loss(8)= 99999999
       minor_loss(9)= 665.5
       pipeloc(1)= 1
       pipeloc(2)= 3
       pipeloc(3)= 1
       pipeloc(4)= 3
       pipeloc(5)= 1
```

```
          pipeloc(6)= 3
          pipeloc(7)= 3
          pipeloc(8)= 3
          pipeloc(9)= 1
          end if
        if (ml(k).eq.6) go to 120
          do 75 i=1,n_pipe
            R_minor(i)=(minor_loss(i))/(2.0*gravity*area(i)**2)
75        continue

c
        do 100 iteration=1,100
        test1=0.0
        test2=0.0
        do 80 i=n_junc+1,n_pipe
        sum_top=-delta_H(i)
        sum_G=0.0
        do 60 j=1,j_elements(i)
        n=IABS(j_element_number(i,j))
        Qa=ABS(Q(n))
        Re=Qa/area(n)*diameter(n)/viscosity
        R_friction(n)=1.07*length(n)/(gravity*diameter(n)**5)
     &  *(LOG(.27*roughness(n)/diameter(n)+5.74*(1.0/Re)**.9))**(-2)
c
c
        R_bar(n)=R_friction(n)+R_minor(n)
        G=2*R_bar(n)*Qa-(a1(n)+2*a2(n)*Qa)
        phi0=R_bar(n)*Qa**2
     &      -(a0(n)+a1(n)*Qa+a2(n)*Qa**2)
```

```
         sum_G=sum_G+G
         sum_top=sum_top-phi0*j_element_number(i,j)*Q(n)/(Qa*n)
60       continue
         delta_Q=sum_top/sum_G
         do 70 j=1,j_elements(i)
         n=IABS(j_element_number(i,j))
         Q(n)=Q(n)+delta_Q*j_element_number(i,j)/n
70       continue
80       continue
         do 90 i=1,n_pipe
         test1=test1+ABS(ABS(Q(i))-ABS(Q0(i)))
         test2=test2+ABS(Q(i))
         Q0(i)=Q(i)
90       continue
         test=test1/test2
         write(3,91)  iteration,test
         write(*,91)  iteration,test
91       format(' ',i9,f23.6)
         IF (test.lt.converge) GO TO 105
100      continue
105      do 112 i=1,n_pipe
         Qa=ABS(Q(i))
         Re=Qa/area(i)*diameter(i)/viscosity
         R_friction(i)=1.07*length(i)/(gravity*diameter(i)**5)
     &      *(LOG(.27*roughness(i)/diameter(i)
     &      +5.74*(1.0/Re)**.9))**(-2)

c
c
```

```
      R_bar(i)=R_friction(i)+R_minor(i)
      H_drop(i)=R_bar(i)*Qa**2-(a0(i)+a1(i)*Qa+a2(i)*Qa**2)
      ReK(i)=Re
c
112   continue
      H(1)=H_ref
      do 120 i=1,n_junc
      if(i.ne.1) H(i)=H(i-1)
      do 120 j=1,j_elements(i)
      n=IABS(j_element_number(i,j))
      H(i)=H(i)-H_drop(n)*n/j_element_number(i,j)
120   continue
      if (ml(k).eq.1) then
      H(2)=H(1)
      H(3)=H(1)
      else if (ml(k).eq.2) then
      H(2)=H(1)
      H(3)=H(1)
      else if (ml(k).eq.3) then
      H(4)=H(1)
      else if (ml(k).eq.4) then
      H(4)=H(1)
      else if (ml(k).eq.5) then
      H(4)=H(1)
      end if
      do 125 i=1,n_pipe
        if(ml(k).eq.1.or.ml(k).eq.2.or.ml(k).eq.3
     &         .or.ml(k).eq.4.or.ml(k).eq.5) then
        write(*,*) ml(k)
```

```
      if (i.eq.1) then
      tfll(1)=tme(k)
      tmean(1)=tme(k)
      end if
      if (i.gt.1) then
      tfll(i)=t2(fjunct_num(i))
      end if
       call flow (i,n_pipe,pipeloc(i),length(i),diameter(i),
     &              Re,rr2(i),Rek(i),Q(i),
     &                tem(i),qh(i),t2(junct_num(i)),tmean(i),tfll(i))
     pipelo(i)=pipeloc(i)
      if (ml(k).eq.1) then
      mh=((Q(1)*rho*tcr(k))-(Q(1)*rho*tcold))/
     &        (t2(9)-tcold)
      demand=((mh/rho)*1000)*timemax(k)
      else if (ml(k).eq.2) then
      mh=((Q(1)*rho*tcr(k))-(Q(1)*rho*tcold))/
     &        (t2(10)-tcold)
      demand=((mh/rho)*1000)*timemax(k)
      else if (ml(k).eq.3) then
      mh=((Q(1)*rho*tcr(k))-(Q(1)*rho*tcold))/
     &        (t2(6)-tcold)
      demand=((mh/rho)*1000)*timemax(k)
      else if (ml(k).eq.4) then
      mh=((Q(1)*rho*tcr(k))-(Q(1)*rho*tcold))/
     &        (t2(7)-tcold)
      demand=((mh/rho)*1000)*timemax(k)
      else if (ml(k).eq.5) then
      mh=((Q(1)*rho*tcr(k))-(Q(1)*rho*tcold))/
```

```
     &          (t2(8)-tcold)
          demand=((mh/rho)*1000)*timemax(k)
          end if
          qwith=(cp*mh*(tme(k)-tcold)*timemax(k))/1000
          qloss=(hl*(tme(k)-troom)*timemax(k))/1000
         else if (ml(k).eq.6) then
          write(*,*) ml(k)
           call noflow (i,pipelo(i),tmean(i),diameter(i),length(i),
     &          tmenn(i),ttww(i),timemax(k),k)
          qloss=(hl*(tme(k)-troom)*timemax(k))/1000
         end if
125     continue
c


c
        if(ml(k).eq.1.or.ml(k).eq.2.or.ml(k).eq.3
     &         .or.ml(k).eq.4.or.ml(k).eq.5) then
        todemand=todemand+demand
        toqwith=toqwith+qwith
        toqloss=toqloss+qloss
        write(3,128)
        write(*,128)
128     format(/', ','PIPE NO.          FLOW RATE        TEMPERATURE')
        do 130 i=1,n_pipe
         if (q(i).gt.0.000001) then
           write(3,129) i,Q(i), tem(i), qh(i)
           write(*,129) i,Q(i), tem(i), qh(i)
129        format(' ',i8,2f19.6,2f19.6,2f19.6)
         end if
```

```
130     continue
        write(3,131)
        write(*,131)
131     format(/' ','NODE NO.    HYD. GRADE LINE           Flow Sum')
        do 140 i=1,n_junc
        test=-Q_out(i)
        do 1140 j=1,j_tubes(i)
        n=IABS(j_tube_number(i,j))
        test=test+Q(n)*j_tube_number(i,j)/n
1140    continue
        write(3,129) i,H(i),test
        write(*,129) i,H(i),test
140     continue
        write(3,141)
        write(*,141)
141     format(/' ','Pipe    Length  Diameter     Rough',
     &          '         Re      R_bar          Q')
        write(3,142) (i,length(i),diameter(i)*100.0,roughness(i)*1000.0,
     &      Rek(i),R_bar(i),Q(i),i=1,n_pipe)
        write(*,142) (i,length(i),diameter(i)*100.0,roughness(i)*1000.0,
     &      ReK(i),R_bar(i),Q(i),i=1,n_pipe)
142     format(' ',i4,f10.1,f10.3,f10.4,e10.3,e10.3,f10.5)
        write(3,144)
        write(*,144)
144     format(/' ','pipe      outlet temperature')
        do 150 i=1,n_pipe+1
          write(3,145) i, t2(i)
          write(*,145) i, t2(i)
145       format(' ',i4,f10.4)
```

```
150    continue
       write(3,151)
       write(*,151)
151    format(/' ','mass fl. rate    demand (litres)   total demand')
       write(3,152) mh, demand, todemand
       write(*,152) mh, demand, todemand
152    format(' ',f10.5,f20.2,f20.2)
       write(3,154)
       write(*,154)
154    format(/' ','heat withdraw loss (KJ), heat loss (KJ)')
       write(3,156) qwith, qloss
       write(*,156) qwith, qloss
156    format(' ',f14.4,f14.4)
       write(3,158)
       write(*,158)
158    format(/' ','Total heat withd loss (KJ), Tot heat loss (KJ)')
       write(3,159) toqwith, toqloss
       write(*,159) toqwith, toqloss
159    format(' ',f14.4,f14.4)

c
c
       else if (ml(k).eq.6) then
       toqloss=toqloss+qloss
       write(3,228)
       write(*,228)
228    format(/' ','PIPE NO.          FLOW RATE         TEMPERATURE')
       do 230 i=1,n_pipe
        if (q(i).gt.0.000001) then
```

```
         write(3,229) i,Q(i), tmenn(i)
         write(*,229) i,Q(i), tmenn(i)
229      format(' ',i8,2f19.6,2f19.6,2f19.6)
        end if
230    continue
       write(3,231)
       write(*,231)
231    format(/' ','NODE NO.    HYD. GRADE LINE            Flow Sum')
       do 239 i=1,n_junc
       test=-Q_out(i)
       do 2140 j=1,j_tubes(i)
       n=IABS(j_tube_number(i,j))
       test=test+Q(n)*j_tube_number(i,j)/n
2140   continue
       write(3,229) i,H(i),test
       write(*,229) i,H(i),test
239    continue
       write(3,241)
       write(*,241)
241    format(/' ','Pipe    Length  Diameter     Rough',
     &         '         Re      R_bar          Q')
       write(3,242) (i,length(i),diameter(i)*100.0,roughness(i)*1000.0,
     &      Rek(i),R_bar(i),Q(i),i=1,n_pipe)
       write(*,242) (i,length(i),diameter(i)*100.0,roughness(i)*1000.0,
     &      ReK(i),R_bar(i),Q(i),i=1,n_pipe)
242    format(' ',i4,f10.1,f10.3,f10.4,e10.3,e10.3,f10.5)
       write(3,244)
       write(*,244)
244    format(/' ','pipe      pipe temperature')
```

```
        do 250 i=1,n_pipe
         if (minor_loss(i).lt.99999) then
          write(3,245) i, ttww(i)
          write(*,245) i, ttww(i)
245       format(' ',i4,f10.4)
         end if
250     continue
        write(3,254)
        write(*,254)
254     format(/' ','heat loss from isulat (KJ) Total heat loss (KJ)')
        write(3,256) qloss, toqloss
        write(*,256) qloss, toqloss
256     format(' ',f14.4,f14.4)
        end if
102     continue
c
c
        close(2)
        close(3)
        close(4)
        stop
        end
c
c
c *******************************************************************
      subroutine flow (i,n_pipe,pipeloc,length,diameter,Re,
     &                 rr2,Rek,Q,tem,qh,t2,tmean,tfll)
       implicit none
       real*4 diameter,length
```

```
      real*4 Q,Re
      real*4 pi,gravity
      real*4 ReK
      real*4 f,f1,left,right,mid,size,root,tem,alpha
      real*4 kw,pr,tfll,tmean,qh,t2,rho,cp,testt,tlower
      real*4 tair,vair,aair,kair,rr2,kins
      integer*2 i,j
      integer*2 n_pipe,count,a,pipeloc
      logical done
      external f,f1
c ***********************************************************************
c
      pi=3.14159
      gravity=9.806
      kw=0.6536
      pr=3.02
      rho=985.5
      cp=4184.0
      alpha=0.201
      tair=293.0
      vair=0.0000153
      aair=0.0000216
      kair=0.02574
      kins=0.057
c
      write(*,*) i,n_pipe,pipeloc,length,diameter,
     &           Re,
     &                rr2,Rek,Q
      tlower=303.0
```

```
        tmean=tfll
        t2=tfll
        if (pipeloc.eq.3) go to 124
         do 124 j=1,40
           if (pipeloc.eq.1) then
            count= 0
            left= 298.0
            do 106 a=1,300
               left= 298.0 +real(a-1)*0.25
               right=left+0.25
C
               if (abs(f(left,Re,length,diameter,
     &            tmean)).lt.0.001) then

                 print 107, left, f(left,Re,length,diameter,
     &            tmean)
107               format (1x,'root = ',f7.3)

                 count=count+1
               else if (f(left,Re,length,diameter,tmean)*
     &            f(right,Re,length,diameter,
     &            tmean).lt.0.0) then
                 done= .false.
                 size = right - left

108              if (size.gt.0.01.and..not.done) then
                   mid= (left+right)/2.0
                   if (abs(f(mid,Re,length,diameter,
     &                tmean)).lt.0.001) then
```

```
                    done= .true.
                 else if (f(mid,Re,length,diameter,
     &                     tmean)*
     &                    f(left,Re,length,diameter,
     &                    tmean).lt.0.0) then
                    right=mid
                 else
                    left=mid
                 end if
                 size= right - left
                 go to 108
              end if

              if (size.gt.0.01) then
                 root = mid
              else
                 root = (left+right)/ 2.0
              end if

              print 107, root, f(root,Re,length,diameter,
     &                          tmean)
              count = count + 1
           endif
106     continue
        left=333.0
        if (abs(f(left,Re,length,diameter,
     &      tmean)).lt.0.001) then
         print 107, left, f(left,Re,length,diameter,
     &                 tmean)
```

```
            count = count +1
           end if
           if (count.eq.0) then
             print*, 'no roots in interval [25,60]'
           end if
          else if (pipeloc.eq.2) then
           count= 0
           left= 298.0
           do 109 a=1,300
             left= 298.0 +real(a-1)*0.25
             right=left+0.25
C
             if (abs(f1(left,Re,length,diameter,tmean))
     &           .lt.0.001) then
c
                 print 110, left,
     &               f1(left,Re,length,diameter,tmean)
110               format (1x,'root = ',f7.3)
c
                 count=count+1
             else if (f1(left,Re,length,diameter,tmean)*
     &                f1(right,Re,length,diameter,tmean)
     &                  .lt.0.0) then
                 done= .false.
                 size = right - left

111               if (size.gt.0.01.and..not.done) then
                    mid= (left+right)/2.0
                    if (abs(f1(mid,Re,length,diameter,
```

```
     &                tmean)).lt.0.001) then
                        done= .true.
                     else if (f1(mid,Re,length,diameter,
     &                  tmean)*f1(left,Re,length,diameter,
     &                  tmean)
     &                           .lt. 0.0) then
                        right=mid
                     else
                        left=mid
                     end if
                     size= right - left
                     go to 111
                  end if
c
                  if (size.gt.0.01) then
                     root = mid
                  else
                     root = (left+right)/ 2.0
                  end if
c
                  print 110, root, f1(root,Re,length,diameter,
     &                          tmean)
                  count = count + 1
               endif
109         continue
            left=333.0
            if (abs(f1(left,Re,length,diameter,tmean))
     &               .lt.0.001) then
             print 110, left, f1(left,Re,length,diameter,
```

```
     &                 tmean)
          count = count +1
         end if
         if (count.eq.0) then
          print*, 'no roots in interval [25,60]'
         end if
        end if
       tem=root
      if(pipeloc.eq.1) then
       qh=(tmean-tair)/((1/(((0.023*(Rek)**(0.8)*(pr)**
     &  (0.3)*kw)/(diameter))*2.0*pi*diameter/2.0*
     &   length))+((exp(rr2/diameter/2.0))/(kins*2.0*pi*
     &     length))+(1/(2.0*pi*rr2
     &    *length*((kair/diameter)*(0.36*((tmean+tair)**
     &    (0.3333))+((0.633)*(((tmean-tair)**(0.16666)*
     &    (diameter)**(0.5)*(tmean+tair)**(0.1666))/
     &    ((vair*aair)**(0.16666)))+((0.2783)*(((tmean-tair)**
     &    (0.3333)*diameter)/((vair*aair)**(0.3333))))))))
c
c
      else if (pipeloc.eq.2) then
       qh=(tmean-tair)/((1/(((0.023*(Rek)**(0.8)*(pr)**
     &  (0.3)*kw)/(diameter))*2.0*pi*diameter/2.0*
     &  length))+((exp(rr2/diameter/2.0))/(kins*2.0*pi*
     &   length))+(1/(2.0*pi*rr2
     &    *length*((kair/length)*(0.68*((tmean+tair)**
     &    (0.25))+((1.082)*((tmean-tair)**(0.25)*(length)**
     &    (0.75))/((vair*aair)**(0.25))))))))
      end if
```

```
        testt=tfll-qh/(rho*Q*cp)
        if(testt.gt.tfll) then
        testt=(t2+tfll)/2.0
        else if (testt.lt.tlower) then
        testt=(t2+tlower)/2.0
        end if
        t2=t2+alpha*(testt-
     &                    t2)
        tmean=(tfll+t2)/2.0
        write(*,*) qh,tem,tmean,tfll
c
c
c
124     continue
       write(*,*) Rek, diameter,Q,tem,tmean
c
c
      return
      end
c
c
c *******************************************************************
      subroutine noflow (i,pipeloc,tmean,diameter,length,tmenn,ttww,
     &                    timemax,k)
        implicit none
        real*4 tmen,diameter,length,time,pipeloc
        real*4 ttw,trans,tmean,deltat,ttww,trans2
        real*4 left,right,mid,size,root,tmenn
        dimension ttw(3900),tmen(3900)
```

```
      integer*2 j,count,a,timemax,i,k
      logical done
      external trans,trans2
c ******************************************************************
c
c
        time=0.0
        deltat=35.0
        tmen(1)=tmean
c
c
       write(*,*) i,pipeloc,tmean,diameter,length,
     &        tmenn,ttww,timemax,k
       if (pipeloc.eq.3) go to 20
       if (pipeloc.eq.1) then
        do 10 j=1,timemax/35
        time=time+deltat

         count= 0
         left= 293.0
         do 209 a=1,400
           left= 293.0 +real(a-1)*0.20
           right=left+0.20
C
           if (abs(trans(left,tmen(j),diameter,length,time))
     &           .lt.0.0001) then
c
               print 210, left,
     &             trans(left,tmen(j),diameter,length,time)
```

```
210               format (1x,'root = ',f7.3)
c
                  count=count+1
              else if (trans(left,tmen(j),diameter,length,time)*
     &                 trans(right,tmen(j),diameter,length,time)
     &                   .lt.0.0) then
                  done= .false.
                  size = right - left

211               if (size.gt.0.0001.and..not.done) then
                    mid= (left+right)/2.0
                    if (abs(trans(mid,tmen(j),diameter,length,time
     &                   )).lt.0.0001) then
                       done= .true.
                    else if (trans(mid,tmen(j),diameter,length,time
     &                   )*trans(left,tmen(j),diameter,length,time)
     &                         .lt. 0.0) then
                       right=mid
                    else
                       left=mid
                    end if
                    size= right - left
                    go to 211
                  end if
c
                  if (size.gt.0.0001) then
                     root = mid
                  else
                     root = (left+right)/ 2.0
```

```
                end if
c
                print 210, root, trans(root,tmen(j),diameter,
     &                           length,time)
                count = count + 1
              endif
209         continue
            left=333.0
            if (abs(trans(left,tmen(j),diameter,length,time))
     &              .lt.0.0001) then
             print 210, left, trans(left,tmen(j),diameter,
     &                  length,time)
             count = count +1
            end if
            if (count.eq.0) then
             print*, 'no roots in interval [25,61]'
            end if
           ttw(j)=root
c
c
           tmen(j+1)=ttw(j)
           write(*,*) tmen(j), ttw(j), time
10         continue
           tmenn=tmen(timemax/35)
           ttww=ttw(timemax/35)
c
c
          else if (pipeloc.eq.2) then
           do 20 j=1,timemax/35
```

```
      time=time+deltat


       count= 0
       left= 293.0
       do 219 a=1,400
         left= 293.0 +real(a-1)*0.20
         right=left+0.20
C
         if (abs(trans2(left,tmen(j),diameter,length,time))
     &        .lt.0.0001) then
c
             print 210, left,
     &            trans2(left,tmen(j),diameter,length,time)
220           format (1x,'root = ',f7.3)
c
             count=count+1
         else if (trans2(left,tmen(j),diameter,length,time)*
     &              trans2(right,tmen(j),diameter,length,time)
     &                .lt.0.0) then
             done= .false.
             size = right - left

221           if (size.gt.0.0001.and..not.done) then
               mid= (left+right)/2.0
               if (abs(trans2(mid,tmen(j),diameter,length,time
     &              )).lt.0.0001) then
                  done= .true.
               else if (trans2(mid,tmen(j),diameter,length,time
     &              )*trans2(left,tmen(j),diameter,length,time)
```

```
     &                               .lt. 0.0) then
                          right=mid
                       else
                          left=mid
                       end if
                       size= right - left
                       go to 221
                    end if
c
                    if (size.gt.0.0001) then
                       root = mid
                    else
                       root = (left+right)/ 2.0
                    end if
c
                    print 220, root, trans2(root,tmen(j),diameter,
     &                                 length,time)
                    count = count + 1
                 endif
219           continue
               left=333.0
               if (abs(trans2(left,tmen(j),diameter,length,time))
     &                   .lt.0.0001) then
                print 220, left, trans2(left,tmen(j),diameter,
     &                     length,time)
                count = count +1
               end if
               if (count.eq.0) then
                print*, 'no roots in interval [25,61]'
```

```
            end if
c
           ttw(j)=root
c
c
           tmen(j+1)=ttw(j)
20        continue
          tmenn=tmen(timemax/35)
          ttww=ttw(timemax/35)
         end if

c
      return
      end
c
c
c ********************************************************************
        real function trans(ttw,tmen,diameter,length,time)
        implicit none
        real*4 ttw,tair,diameter,pi,length,rho,cp,time
        real*4 tmen,fhs1,deltat,r1,r2,kins
        external fhs1
c ********************************************************************
c
c
        rho=985.5
        cp=4184.0
        deltat=35.0
        pi=3.14159
```

```
        tair=293.0
        r1=(diameter/2.0)
        r2=(diameter/2.0)+0.001
        kins=0.057
c
c
          trans=(exp(-((1/(exp(r2/r1)*(r1/kins)+(r1/
     &         (r2*fhs1(ttw,diameter))))*2*pi*(diameter/2)*
     &      length)/(rho*cp*pi*((diameter/2)**2)*length)*deltat)))
     &        -((ttw-tair)/(tmen-tair))
c
        return
        end
c
c
c ********************************************************************
        real function trans2(ttw,tmen,diameter,length,time)
        implicit none
        real*4 ttw,tair,diameter,pi,length,rho,cp,time
        real*4 tmen,fhs2,deltat,r1,r2,kins
        external fhs2
c ********************************************************************
c
        rho=985.5
        cp=4184.0
        deltat=35.0
        pi=3.14159
        tair=293.0
        r1=(diameter/2.0)
```

```
        r2=(diameter/2.0)+0.001
        kins=0.057
c
c
          trans2=(exp(-((1/(exp(r2/r1)*(r1/kins)+(r1/
     &          (r2*fhs2(ttw,length,diameter))))*2*pi*(diameter/2)*
     &      length)/(rho*cp*pi*((diameter/2)**2)*length)*deltat)))
     &        -((ttw-tair)/(tmen-tair))
c
        return
        end

c
c
c *********************************************************************
         real function f(tw,Re,length,diameter,tfl)
         real*4 tw,diameter,kair,vair,aair,tout,Re,pr,tfl,kw
         real*4 pi,r2,r1,a1,a2,kins,length,a3,hf,hs,fhs1
c *********************************************************************
c
c
         external fhs1
c
c
         kair=0.02574
         vair=0.0000153
         aair=0.0000216
         kw=0.6536
         kins=0.057
```

```
      r1=(diameter/2.0)
      r2=(diameter/2.0)+0.001
      pr=3.02
      pi=3.14159
      tout=293.0
c
      hf=(0.023*(Re)**(0.8)*(pr)**(0.3)*kw)/(diameter)
c
c
      hs=fhs1(tw,diameter)
c
c
      a1=2.0*pi*r2*length
      a2=r1*exp(r2/r1)
      a3=2.0*pi*hf*length*r1
c
      f=(hf*a2*a1*hs*tfl)/
     &  (kins*(a1*hs+(a1*hs*hf*a2)
     &    /kins+a3))+(a1*hs*tout)/
     &  (a1*hs+(a1*hs*hf*a2)/kins+a3)
     &   +(2.0*pi*hf*r1*length*tfl)/(a1*hs+
     &   (a1*hs*hf*a2)/kins+a3)-tw
c
      return
      end
c
c
c ********************************************************************
      real function f1(tw,Re,length,diameter,tfl)
```

```
      real*4 tw,length,kair,vair,aair,tout,Re,pr,tfl,kw
      real*4 pi,r2,r1,a1,a2,kins,a3,hf,hs,fhs2
      real*4 diameter
c ********************************************************************
c
c
      external fhs2
c
c
      kair=0.02574
      vair=0.0000153
      aair=0.0000216
      kw=0.6536
      kins=0.057
      r1=(diameter/2.0)
      r2=(diameter/2.0)+0.001
      pr=3.02
      pi=3.14159
      tout=293.0
c
      hf=(0.023*(Re)**(0.8)*(pr)**(0.3)*kw)/(diameter)
c
c
      hs=fhs2(tw,length,diameter)
c
      a1=2.0*pi*r2*length
      a2=r1*exp(r2/r1)
      a3=2.0*pi*hf*length*r1
c
```

```
c
        f1=(hf*a2*a1*hs*tfl)/
     &        (kins*(a1*hs+(a1*hs*hf*a2)/
     &       kins+a3))+(a1*hs*tout)/(a1*hs+
     &      (a1*hs*hf*a2)/kins+a3)+
     &      (2.0*pi*hf*r1*length*tfl)/(a1*hs+
     &      (a1*hs*hf*a2)/kins+a3)-tw
c
        return
        end
c
c
c ************************************************************************
        real function fhs1(tw,diameter)
        real*4 tw,kair,vair,aair,tout
        real*4 diameter
c ************************************************************************
c
c
        kair=0.02574
        vair=0.0000153
        aair=0.0000216
        tout=293.0


         fhs1= ((kair/diameter)*(0.36*((tw+tout)**
     &   (0.3333))+((0.633)*(((tw-tout)**(0.16666)*(diameter)**
     &   (0.5)*(tw+tout)**(0.1666))/((vair*aair)**(0.16666))))+
     &    ((0.2783)*(((tw-tout)**(0.3333)*diameter)/
```

```
     &     ((vair*aair)**(0.3333)))))

        return
        end
c
c
c ***********************************************************************
        real function fhs2(tw,length,diameter)
        real*4 tw,kair,vair,aair,tout,length
        real*4 diameter
c ***********************************************************************
c
c
        kair=0.02574
        vair=0.0000153
        aair=0.0000216
        tout=293.0
c
         fhs2=((kair/length)*(0.68*((tw+tout)**
     &   (0.25))+((1.082)*((tw-tout)**(0.25)*(length)**
     &   (0.75))/((vair*aair)**(0.25)))))

        return
        end
c
```

D.2 Listing of Program for Uninsulated Case

```
C       ***** HARDY CROSS PIPE NETWORK ANALYSIS *****
```

```
c
      implicit none
c ***********************************************************************
      real*4 diameter,area,length,roughness
      real*4 R_friction,R_minor,R_bar,Q,Q0,Qa,Re
      real*4 delta_H,H_ref
      real*4 HP0,HP1,HP2,Q1,Q2,a0,a1,a2
      real*4 sum_top,sum_G
      real*4 pi,gravity,viscosity,spec_grav,converge,minor_loss
      real*4 test,test1,test2,H,H_drop
      real*4 delta_Q,G,phi0,Q_out,ReK
      real*4 tem,tmenn,ttww,pipelo
      real*4 areal,tmean,qh,t2,tfll,todemand
      real*4 rr2, tme,rho,tcold,tcr,mh,demand
      real*4 qwith,cp,hl,qloss,troom,toqloss,toqwith
      integer*2 j_tubes,j_tube_number,fjunct_num,junct_num
      integer*2 i,j,n,j_elements,j_element_number,label,iteration
      integer*2 n_pipe,n_junc,n_pump,k,pipeloc,ml,timemax,uct
      dimension diameter(60),area(60),length(60),roughness(60),tcr(60)
      dimension R_friction(60),R_minor(60),R_bar(60),timemax(60)
      dimension delta_H(60),Q(60),Q0(60),H(60),H_drop(60),tfll(60)
      dimension j_elements(60),j_element_number(60,60),ml(60),tme(60)
      dimension j_tubes(60),j_tube_number(60,60),Q_out(60),pipelo(60)
      dimension a0(60),a1(60),a2(60),ReK(60),tem(60),pipeloc(60)
      dimension areal(60),qh(60),fjunct_num(60),tmenn(60),ttww(60)
      dimension junct_num(60),tmean(60),t2(60),rr2(60),minor_loss(60)
c *********************************************************************
c
      pi=3.14159
```

```
      gravity=9.806
      rho=985.5
      cp=4184.0
      uct=28
      tcold=284.0
      troom=293.0
      hl=3.1
      open(unit=2,file='hardy.ph2')
      open(unit=3,file='hardy.nire1960sa')
      open(unit=4,file='shed.ho15')
      do 11 i=1,uct
      read(4,9) k,ml(k),timemax(k),tme(k),tcr(k)
      write(*,*) ml(k), tme(k), tcr(k)
9     format(14x,3i10,2f10)
11    continue
      read(2,5) n_pipe,n_junc,n_pump
5     format(12x,i10)
      read(2,6) viscosity,spec_grav,converge
6     format(12x,f10.0)
      read(2,7)
      read(2,7)
7     format(12x)
c
c
      do 10 n=1,n_pipe
      read(2,8) i,length(i),diameter(i),roughness(i),Q(i)
8     format(12x,i10,4f10.0)
      diameter(i)=diameter(i)/100.0
      rr2(i)=(diameter(i)/2.0)+0.005
```

```
        area(i)=pi*diameter(i)**2/4.0
        areal(i)=2*pi*(diameter(i)/2)*length(i)
        roughness(i)=roughness(i)/1000.0
        Q0(i)=Q(i)
        a0(i)=0.0
        a1(i)=0.0
        a2(i)=0.0
10      continue
        read(2,7)
        read(2,7)
        read(2,7)
        if(n_pump.ne.0) then
           do 20 i=1,n_pump
           read(2,12) label,HP0,HP1,Q1,HP2,Q2
12         format(12x,i10,5f10.0)
           a0(label)=HP0
           a2(label)=(HP0+(HP1/HP0-1.0)*Q2-HP2)/(Q1*Q1*Q2/HP0-Q2*Q2)
           a1(label)=(HP1-HP0-a2(label)*Q1*Q1)/HP0
C             a2(label)=((hp1-hp0)*q2-(hp2-hp0)*q1)/(q1**2*q2-q2**2*q1)
C             a1(label)=(hp1-hp0-a2(label)*q1**2)/q1
20         continue
        endif
        read(2,7)
        read(2,7)
        read(2,21) H_ref
21      format(12x,f10.0)
        read(2,7)
        read(2,7)
        read(2,7)
```

```
      read(2,7)
      do 30 i=1,n_junc
      read(2,22) j_elements(i),
     &           (j_element_number(i,j),j=1,j_elements(i))
22    format(12x,6i10)
30    continue
      read(2,7)
      read(2,7)
      read(2,7)
      read(2,7)
      do 40 i=n_junc+1,n_pipe
      read(2,31) delta_H(i),j_elements(i),
     &           (j_element_number(i,j),j=1,j_elements(i))
31    format(12x,f10.0,6i10)
40    continue
      read(2,7)
      read(2,7)
      read(2,7)
      do 240 i=1,n_junc
      read(2,31) Q_out(i),j_tubes(i),
     &           (j_tube_number(i,j),j=1,j_tubes(i))
240   continue
      read(2,7)
      read(2,7)
      do 44 n=1,n_pipe
      read(2,42) i,junct_num(i), fjunct_num(i)
42    format(12x,3i10)
44    continue
      write(3,46)
```

```
      write(*,46)
46    format(' ','TRIAL NO.   RELATIVE FLOW CHANGE')
      todemand=0.0
      toqloss=0.0
      toqwith=0.0
      do 102 k=1,uct
       if (ml(k).eq.1) then
        minor_loss(1)= 2.5
        minor_loss(2)= 8.4
        minor_loss(3)= 99999999
        minor_loss(4)= 99999999
        minor_loss(5)= 99999999
        minor_loss(6)= 495.2
        minor_loss(7)= 99999999
        minor_loss(8)= 99999999
        minor_loss(9)= 99999999
        pipeloc(1)= 1
        pipeloc(2)= 1
        pipeloc(3)= 3
        pipeloc(4)= 3
        pipeloc(5)= 3
        pipeloc(6)= 2
        pipeloc(7)= 3
        pipeloc(8)= 3
        pipeloc(9)= 3
c
       else if (ml(k).eq.2) then
        minor_loss(1)= 2.5
        minor_loss(2)= 8.4
```

```
      minor_loss(3)= 99999999
      minor_loss(4)= 99999999
      minor_loss(5)= 99999999
      minor_loss(6)= 99999999
      minor_loss(7)= 246.4
      minor_loss(8)= 99999999
      minor_loss(9)= 99999999
      pipeloc(1)= 1
      pipeloc(2)= 1
      pipeloc(3)= 3
      pipeloc(4)= 3
      pipeloc(5)= 3
      pipeloc(6)= 3
      pipeloc(7)= 1
      pipeloc(8)= 3
      pipeloc(9)= 3
c
     else if (ml(k).eq.3) then
      minor_loss(1)= 2.5
      minor_loss(2)= 99999999
      minor_loss(3)= 2.4
      minor_loss(4)= 245.9
      minor_loss(5)= 99999999
      minor_loss(6)= 99999999
      minor_loss(7)= 99999999
      minor_loss(8)= 99999999
      minor_loss(9)= 99999999
      pipeloc(1)= 1
      pipeloc(2)= 3
```

```
         pipeloc(3)= 1
         pipeloc(4)= 2
         pipeloc(5)= 3
         pipeloc(6)= 3
         pipeloc(7)= 3
         pipeloc(8)= 3
         pipeloc(9)= 3
c
        else if (ml(k).eq.4) then
         minor_loss(1)= 2.5
         minor_loss(2)= 99999999
         minor_loss(3)= 2.4
         minor_loss(4)= 99999999
         minor_loss(5)= 2.9
         minor_loss(6)= 99999999
         minor_loss(7)= 99999999
         minor_loss(8)= 309.0
         minor_loss(9)= 99999999
         pipeloc(1)= 1
         pipeloc(2)= 3
         pipeloc(3)= 1
         pipeloc(4)= 3
         pipeloc(5)= 1
         pipeloc(6)= 3
         pipeloc(7)= 3
         pipeloc(8)= 2
         pipeloc(9)= 3
c
        else if (ml(k).eq.5) then
```

```
        minor_loss(1)= 2.5
        minor_loss(2)= 99999999
        minor_loss(3)= 2.4
        minor_loss(4)= 99999999
        minor_loss(5)= 2.9
        minor_loss(6)= 99999999
        minor_loss(7)= 99999999
        minor_loss(8)= 99999999
        minor_loss(9)= 665.5
        pipeloc(1)= 1
        pipeloc(2)= 3
        pipeloc(3)= 1
        pipeloc(4)= 3
        pipeloc(5)= 1
        pipeloc(6)= 3
        pipeloc(7)= 3
        pipeloc(8)= 3
        pipeloc(9)= 1
        end if
      if (ml(k).eq.6) go to 120
        do 75 i=1,n_pipe
          R_minor(i)=(minor_loss(i))/(2.0*gravity*area(i)**2)
75      continue

c
      do 100 iteration=1,100
      test1=0.0
      test2=0.0
      do 80 i=n_junc+1,n_pipe
```

```
          sum_top=-delta_H(i)
          sum_G=0.0
          do 60 j=1,j_elements(i)
          n=IABS(j_element_number(i,j))
          Qa=ABS(Q(n))
          Re=Qa/area(n)*diameter(n)/viscosity
          R_friction(n)=1.07*length(n)/(gravity*diameter(n)**5)
     &  *(LOG(.27*roughness(n)/diameter(n)+5.74*(1.0/Re)**.9))**(-2)
c
c
          R_bar(n)=R_friction(n)+R_minor(n)
          G=2*R_bar(n)*Qa-(a1(n)+2*a2(n)*Qa)
          phi0=R_bar(n)*Qa**2
     &      -(a0(n)+a1(n)*Qa+a2(n)*Qa**2)
          sum_G=sum_G+G
          sum_top=sum_top-phi0*j_element_number(i,j)*Q(n)/(Qa*n)
60        continue
          delta_Q=sum_top/sum_G
          do 70 j=1,j_elements(i)
          n=IABS(j_element_number(i,j))
          Q(n)=Q(n)+delta_Q*j_element_number(i,j)/n
70        continue
80        continue
          do 90 i=1,n_pipe
          test1=test1+ABS(ABS(Q(i))-ABS(Q0(i)))
          test2=test2+ABS(Q(i))
          Q0(i)=Q(i)
90        continue
          test=test1/test2
```

```
      write(3,91)  iteration,test
      write(*,91)  iteration,test
91    format(' ',i9,f23.6)
      IF (test.lt.converge) GO TO 105
100   continue
105   do 112 i=1,n_pipe
      Qa=ABS(Q(i))
      Re=Qa/area(i)*diameter(i)/viscosity
      R_friction(i)=1.07*length(i)/(gravity*diameter(i)**5)
     &     *(LOG(.27*roughness(i)/diameter(i)
     &     +5.74*(1.0/Re)**.9))**(-2)

c
c
      R_bar(i)=R_friction(i)+R_minor(i)
      H_drop(i)=R_bar(i)*Qa**2-(a0(i)+a1(i)*Qa+a2(i)*Qa**2)
      ReK(i)=Re
c
112   continue
      H(1)=H_ref
      do 120 i=1,n_junc
      if(i.ne.1) H(i)=H(i-1)
      do 120 j=1,j_elements(i)
      n=IABS(j_element_number(i,j))
      H(i)=H(i)-H_drop(n)*n/j_element_number(i,j)
120   continue
      if (ml(k).eq.1) then
      H(2)=H(1)
      H(3)=H(1)
```

```
      else if (ml(k).eq.2) then
      H(2)=H(1)
      H(3)=H(1)
      else if (ml(k).eq.3) then
      H(4)=H(1)
      else if (ml(k).eq.4) then
      H(4)=H(1)
      else if (ml(k).eq.5) then
      H(4)=H(1)
      end if
      do 125 i=1,n_pipe
        if(ml(k).eq.1.or.ml(k).eq.2.or.ml(k).eq.3
     &        .or.ml(k).eq.4.or.ml(k).eq.5) then
         write(*,*) ml(k)
         if (i.eq.1) then
         tfll(1)=tme(k)
         tmean(1)=tme(k)
         end if
         if (i.gt.1) then
         tfll(i)=t2(fjunct_num(i))
         end if
          call flow (i,n_pipe,pipeloc(i),length(i),diameter(i),
     &               Re,Rek(i),Q(i),areal(i),
     &                 tem(i),qh(i),t2(junct_num(i)),tmean(i),tfll(i))
        pipelo(i)=pipeloc(i)
         if (ml(k).eq.1) then
         mh=((Q(1)*rho*tcr(k))-(Q(1)*rho*tcold))/
     &        (t2(9)-tcold)
         demand=((mh/rho)*1000)*timemax(k)
```

```
          else if (ml(k).eq.2) then
          mh=((Q(1)*rho*tcr(k))-(Q(1)*rho*tcold))/
     &         (t2(10)-tcold)
          demand=((mh/rho)*1000)*timemax(k)
          else if (ml(k).eq.3) then
          mh=((Q(1)*rho*tcr(k))-(Q(1)*rho*tcold))/
     &         (t2(6)-tcold)
          demand=((mh/rho)*1000)*timemax(k)
          else if (ml(k).eq.4) then
          mh=((Q(1)*rho*tcr(k))-(Q(1)*rho*tcold))/
     &         (t2(7)-tcold)
          demand=((mh/rho)*1000)*timemax(k)
          else if (ml(k).eq.5) then
          mh=((Q(1)*rho*tcr(k))-(Q(1)*rho*tcold))/
     &         (t2(8)-tcold)
          demand=((mh/rho)*1000)*timemax(k)
          end if
          qwith=(cp*mh*(tme(k)-tcold)*timemax(k))/1000
          qloss=(hl*(tme(k)-troom)*timemax(k))/1000
         else if (ml(k).eq.6) then
          write(*,*) ml(k)
           call noflow (i,pipelo(i),tmean(i),diameter(i),length(i),
     &         tmenn(i),ttww(i),timemax(k),k)
          qloss=(hl*(tme(k)-troom)*timemax(k))/1000
         end if
125    continue
c


c
```

```
      if(ml(k).eq.1.or.ml(k).eq.2.or.ml(k).eq.3
     &        .or.ml(k).eq.4.or.ml(k).eq.5) then
      todemand=todemand+demand
      toqwith=toqwith+qwith
      toqloss=toqloss+qloss
      write(3,128)
      write(*,128)
128   format(/', ',’PIPE NO.          FLOW RATE       TEMPERATURE’)
      do 130 i=1,n_pipe
       if (q(i).gt.0.000001) then
         write(3,129) i,Q(i), tem(i), qh(i)
         write(*,129) i,Q(i), tem(i), qh(i)
129      format(' ',i8,2f19.6,2f19.6,2f19.6)
       end if
130   continue
      write(3,131)
      write(*,131)
131   format(/' ','NODE NO.    HYD. GRADE LINE            Flow Sum')
      do 140 i=1,n_junc
      test=-Q_out(i)
      do 1140 j=1,j_tubes(i)
      n=IABS(j_tube_number(i,j))
      test=test+Q(n)*j_tube_number(i,j)/n
1140  continue
      write(3,129) i,H(i),test
      write(*,129) i,H(i),test
140   continue
      write(3,141)
      write(*,141)
```

```
141    format(/' ','Pipe    Length  Diameter     Rough',
     &         '          Re      R_bar          Q')
       write(3,142) (i,length(i),diameter(i)*100.0,roughness(i)*1000.0,
     &      Rek(i),R_bar(i),Q(i),i=1,n_pipe)
       write(*,142) (i,length(i),diameter(i)*100.0,roughness(i)*1000.0,
     &      ReK(i),R_bar(i),Q(i),i=1,n_pipe)
142    format(' ',i4,f10.1,f10.3,f10.4,e10.3,e10.3,f10.5)
       write(3,144)
       write(*,144)
144    format(/' ','pipe      outlet temperature')
       do 150 i=1,n_pipe+1
         write(3,145) i, t2(i)
         write(*,145) i, t2(i)
145      format(' ',i4,f10.4)
150    continue
       write(3,151)
       write(*,151)
151    format(/' ','mass fl. rate    demand (litres)   total demand')
       write(3,152) mh, demand, todemand
       write(*,152) mh, demand, todemand
152    format(' ',f10.5,f20.2,f20.2)
       write(3,154)
       write(*,154)
154    format(/' ','heat withdraw loss (KJ), heat loss (KJ)')
       write(3,156) qwith, qloss
       write(*,156) qwith, qloss
156    format(' ',f14.4,f14.4)
       write(3,158)
       write(*,158)
```

```
158    format(/' ','Total heat withd loss (KJ), Tot heat loss (KJ)')
       write(3,159) toqwith, toqloss
       write(*,159) toqwith, toqloss
159    format(' ',f14.4,f14.4)

c
c
       else if (ml(k).eq.6) then
       toqloss=toqloss+qloss
       write(3,228)
       write(*,228)
228    format(/' ','PIPE NO.          FLOW RATE          TEMPERATURE')
       do 230 i=1,n_pipe
        if (q(i).gt.0.000001) then
         write(3,229) i,Q(i), tmenn(i)
         write(*,229) i,Q(i), tmenn(i)
229      format(' ',i8,2f19.6,2f19.6,2f19.6)
        end if
230    continue
       write(3,231)
       write(*,231)
231    format(/' ','NODE NO.    HYD. GRADE LINE           Flow Sum')
       do 239 i=1,n_junc
       test=-Q_out(i)
       do 2140 j=1,j_tubes(i)
       n=IABS(j_tube_number(i,j))
       test=test+Q(n)*j_tube_number(i,j)/n
2140   continue
       write(3,229) i,H(i),test
```

```
      write(*,229) i,H(i),test
239   continue
      write(3,241)
      write(*,241)
241   format(/' ','Pipe    Length  Diameter    Rough',
     &        '         Re      R_bar         Q')
      write(3,242) (i,length(i),diameter(i)*100.0,roughness(i)*1000.0,
     &     Rek(i),R_bar(i),Q(i),i=1,n_pipe)
      write(*,242) (i,length(i),diameter(i)*100.0,roughness(i)*1000.0,
     &     ReK(i),R_bar(i),Q(i),i=1,n_pipe)
242   format(' ',i4,f10.1,f10.3,f10.4,e10.3,e10.3,f10.5)
      write(3,244)
      write(*,244)
244   format(/' ','pipe      pipe temperature')
      do 250 i=1,n_pipe
       if (minor_loss(i).lt.99999) then
        write(3,245) i, ttww(i)
        write(*,245) i, ttww(i)
245     format(' ',i4,f10.4)
       end if
250   continue
      write(3,254)
      write(*,254)
254   format(/' ','heat loss from isulat (KJ) Total heat loss (KJ)')
      write(3,256) qloss, toqloss
      write(*,256) qloss, toqloss
256   format(' ',f14.4,f14.4)
      end if
102   continue
```

```
c
c
        close(2)
        close(3)
        close(4)
        stop
        end
c
c
c **********************************************************************
      subroutine flow (i,n_pipe,pipeloc,length,diameter,Re,
     &                 Rek,Q,areal,tem,qh,t2,tmean,tfll)
       implicit none
       real*4 diameter,length
       real*4 Q,Re
       real*4 pi,gravity
       real*4 ReK
       real*4 f,f1,left,right,mid,size,root,tem,alpha
       real*4 kw,pr,tfll,tmean,qh,t2,rho,cp,testt,tlower
       real*4 tair,vair,aair,kair,areal
       integer*2 i,j
       integer*2 n_pipe,count,a,pipeloc
       logical done
       external f,f1
c ************************************************************************
c
       pi=3.14159
       gravity=9.806
       kw=0.6536
```

```
      pr=3.02
      rho=985.5
      cp=4184.0
      alpha=0.201
      tair=293.0
      vair=0.0000153
      aair=0.0000216
      kair=0.02574
c
      write(*,*) i,n_pipe,pipeloc,length,diameter,
     &           Re,
     &                Rek,Q
      tlower=303.0
      tmean=tfll
      t2=tfll
      if (pipeloc.eq.3) go to 124
       do 124 j=1,40
         if (pipeloc.eq.1) then
          count= 0
          left= 298.0
          do 106 a=1,300
             left= 298.0 +real(a-1)*0.25
             right=left+0.25
C
             if (abs(f(left,Re,diameter,
     &           tmean)).lt.0.001) then

                print 107, left, f(left,Re,diameter,
     &            tmean)
```

```
107         format (1x,'root = ',f7.3)

           count=count+1
        else if (f(left,Re,diameter,tmean)*
     &      f(right,Re,diameter,
     &      tmean).lt.0.0) then
           done= .false.
           size = right - left

108        if (size.gt.0.01.and..not.done) then
             mid= (left+right)/2.0
             if (abs(f(mid,Re,diameter,
     &          tmean)).lt.0.001) then
                done= .true.
             else if (f(mid,Re,diameter,
     &           tmean)*
     &          f(left,Re,diameter,
     &          tmean).lt.0.0) then
                right=mid
             else
                left=mid
             end if
             size= right - left
             go to 108
          end if

          if (size.gt.0.01) then
             root = mid
          else
```

```
                    root = (left+right)/ 2.0
                  end if

                  print 107, root, f(root,Re,diameter,
     &                         tmean)
                  count = count + 1
                endif
106           continue
              left=333.0
              if (abs(f(left,Re,diameter,
     &            tmean)).lt.0.001) then
               print 107, left, f(left,Re,diameter,
     &                      tmean)
               count = count +1
              end if
              if (count.eq.0) then
                print*, 'no roots in interval [25,60]'
              end if
             else if (pipeloc.eq.2) then
              count= 0
              left= 298.0
              do 109 a=1,300
                left= 298.0 +real(a-1)*0.25
                right=left+0.25
C
                if (abs(f1(left,Re,length,diameter,tmean))
     &              .lt.0.001) then
c
                    print 110, left,
```

```
     &                f1(left,Re,length,diameter,tmean)
110                format (1x,'root = ',f7.3)
c
                    count=count+1
                else if (f1(left,Re,length,diameter,tmean)*
     &                f1(right,Re,length,diameter,tmean)
     &                  .lt.0.0) then
                    done= .false.
                    size = right - left

111                 if (size.gt.0.01.and..not.done) then
                      mid= (left+right)/2.0
                      if (abs(f1(mid,Re,length,diameter,
     &                  tmean)).lt.0.001) then
                        done= .true.
                      else if (f1(mid,Re,length,diameter,
     &                  tmean)*f1(left,Re,length,diameter,
     &                  tmean)
     &                           .lt. 0.0) then
                        right=mid
                      else
                        left=mid
                      end if
                      size= right - left
                      go to 111
                    end if
c
                    if (size.gt.0.01) then
                      root = mid
```

```
                else
                   root = (left+right)/ 2.0
                end if
c
                print 110, root, f1(root,Re,length,diameter,
     &                         tmean)
                count = count + 1
              endif
109         continue
            left=333.0
            if (abs(f1(left,Re,length,diameter,tmean))
     &               .lt.0.001) then
             print 110, left, f1(left,Re,length,diameter,
     &                  tmean)
             count = count +1
            end if
            if (count.eq.0) then
             print*, 'no roots in interval [25,60]'
            end if
           end if
          tem=root
         if(pipeloc.eq.1) then
          qh=((tmean-tair)/((1/((0.023*(ReK)**(0.8)*(pr)**(0.3)
     &     *kw)/(diameter))+(1/((kair/diameter)*
     &     (0.36*((tem+tair)**(0.3333))+((0.633)*(((tem-tair)**
     &     (0.16666)*(diameter)**(0.5)*(tem+tair)**(0.1666))/
     &     ((vair*aair)**(0.16666))))+((0.2783)*(((tem-tair)**
     &     (0.3333)*diameter)/((vair*aair)**(0.3333))))))))*areal
         else if (pipeloc.eq.2) then
```

```
       qh=((tmean-tair)/((1/((0.023*(ReK)**(0.8)*(pr)**(0.3)
     &    *kw)/(diameter))+(1/((kair/length)*(0.68*
     &    ((tem+tair)**(0.25))+((1.082)*((tem-tair)**(0.25)*
     &    (length)**(0.75))/((vair*aair)**(0.25))))))))*areal
      end if
c
c
      testt=tfll-qh/(rho*Q*cp)
      if(testt.gt.tfll) then
      testt=(t2+tfll)/2.0
      else if (testt.lt.tlower) then
      testt=(t2+tlower)/2.0
      end if
      t2=t2+alpha*(testt-
     &                   t2)
      tmean=(tfll+t2)/2.0
      write(*,*) qh,tem,tmean,tfll
c
c
c
124   continue
     write(*,*) Rek, diameter,Q,tem,tmean
c
c
    return
    end
c
c
c *********************************************************************
```

```
      subroutine noflow (i,pipeloc,tmean,diameter,length,tmenn,ttww,
     &                   timemax,k)
        implicit none
        real*4 tmen,diameter,length,time,pipeloc
        real*4 ttw,trans,tmean,deltat,ttww,trans2
        real*4 left,right,mid,size,root,tmenn
        dimension ttw(3900),tmen(3900)
        integer*2 j,count,a,timemax,i,k
        logical done
        external trans,trans2
c *******************************************************************
c
c
          time=0.0
          deltat=20.0
          tmen(1)=tmean
c
c
         write(*,*) i,pipeloc,tmean,diameter,length,
     &        tmenn,ttww,timemax,k
         if (pipeloc.eq.3) go to 20
         if (pipeloc.eq.1) then
          do 10 j=1,timemax/20
          time=time+deltat

           count= 0
           left= 293.0
           do 209 a=1,400
             left= 293.0 +real(a-1)*0.20
```

```
                right=left+0.20
C
                if (abs(trans(left,tmen(j),diameter,length,time))
     &              .lt.0.0001) then
c
                    print 210, left,
     &                  trans(left,tmen(j),diameter,length,time)
210                  format (1x,'root = ',f7.3)
c
                    count=count+1
                else if (trans(left,tmen(j),diameter,length,time)*
     &                   trans(right,tmen(j),diameter,length,time)
     &                     .lt.0.0) then
                    done= .false.
                    size = right - left

211                  if (size.gt.0.0001.and..not.done) then
                       mid= (left+right)/2.0
                       if (abs(trans(mid,tmen(j),diameter,length,time
     &                     )).lt.0.0001) then
                          done= .true.
                       else if (trans(mid,tmen(j),diameter,length,time
     &                      )*trans(left,tmen(j),diameter,length,time)
     &                            .lt. 0.0) then
                          right=mid
                       else
                          left=mid
                       end if
                       size= right - left
```

```
                  go to 211
               end if
c
               if (size.gt.0.0001) then
                  root = mid
               else
                  root = (left+right)/ 2.0
               end if
c
               print 210, root, trans(root,tmen(j),diameter,
     &                                 length,time)
               count = count + 1
            endif
209      continue
         left=333.0
         if (abs(trans(left,tmen(j),diameter,length,time))
     &            .lt.0.0001) then
          print 210, left, trans(left,tmen(j),diameter,
     &                  length,time)
          count = count +1
         end if
         if (count.eq.0) then
          print*, 'no roots in interval [25,61]'
         end if
        ttw(j)=root
c
c
        tmen(j+1)=ttw(j)
        write(*,*) tmen(j), ttw(j), time
```

```
10        continue
          tmenn=tmen(timemax/20)
          ttww=ttw(timemax/20)
c
c
        else if (pipeloc.eq.2) then
         do 20 j=1,timemax/20
         time=time+deltat

          count= 0
          left= 293.0
          do 219 a=1,400
            left= 293.0 +real(a-1)*0.20
            right=left+0.20
C
            if (abs(trans2(left,tmen(j),diameter,length,time))
     &          .lt.0.0001) then
c
                print 210, left,
     &              trans2(left,tmen(j),diameter,length,time)
220              format (1x,'root = ',f7.3)
c
                count=count+1
            else if (trans2(left,tmen(j),diameter,length,time)*
     &               trans2(right,tmen(j),diameter,length,time)
     &                 .lt.0.0) then
                done= .false.
                size = right - left
```

```
221           if (size.gt.0.0001.and..not.done) then
                mid= (left+right)/2.0
                if (abs(trans2(mid,tmen(j),diameter,length,time
     &                )).lt.0.0001) then
                   done= .true.
                else if (trans2(mid,tmen(j),diameter,length,time
     &                 )*trans2(left,tmen(j),diameter,length,time)
     &                       .lt. 0.0) then
                   right=mid
                else
                   left=mid
                end if
                size= right - left
                go to 221
             end if
c
             if (size.gt.0.0001) then
                root = mid
             else
                root = (left+right)/ 2.0
             end if
c
             print 220, root, trans2(root,tmen(j),diameter,
     &                      length,time)
             count = count + 1
          endif
219    continue
        left=333.0
        if (abs(trans2(left,tmen(j),diameter,length,time))
```

```
     &              .lt.0.0001) then
             print 220, left, trans2(left,tmen(j),diameter,
     &                 length,time)
             count = count +1
            end if
            if (count.eq.0) then
             print*, 'no roots in interval [25,61]'
            end if
c
           ttw(j)=root
c
c
           tmen(j+1)=ttw(j)
20        continue
          tmenn=tmen(timemax/20)
          ttww=ttw(timemax/20)
         end if

c
      return
      end
c
c
c *********************************************************************
        real function trans(ttw,tmen,diameter,length,time)
        implicit none
        real*4 ttw,tair,diameter,pi,length,rho,cp,time
        real*4 tmen,fhs1,deltat
        external fhs1
```

```
c ********************************************************************
c
c
       rho=985.5
       cp=4184.0
       deltat=20.0
       pi=3.14159
       tair=293.0
c
c
         trans=(exp(-((fhs1(ttw,diameter)*2*pi*(diameter/2)*
     &      length)/(rho*cp*pi*((diameter/2)**2)*length)*deltat)))
     &       -((ttw-tair)/(tmen-tair))
c
c
       return
       end
c
c
c ********************************************************************
       real function trans2(ttw,tmen,diameter,length,time)
       implicit none
       real*4 ttw,tair,diameter,pi,length,rho,cp,time
       real*4 tmen,fhs2,deltat
       external fhs2
c ********************************************************************
c
       rho=985.5
       cp=4184.0
```

```
      deltat=20.0
      pi=3.14159
      tair=293.0
c
       trans2=(exp(-((fhs2(ttw,diameter)*2*pi*(diameter/2)*
     &        length)/(rho*cp*pi*((diameter/2)**2)*length)*deltat)))
     &         -((ttw-tair)/(tmen-tair))

      return
      end

c
c
c     ************************************************************
      real function f(tw,Re,diameter,tfl)
      real*4 tw,diameter,kair,vair,aair,tout,Re,pr,tfl,kw
c     ************************************************************
      kair=0.02574
      vair=0.0000153
      aair=0.0000216
      kw=0.6536
      pr=3.02
      tout=293.0
      f=(((0.023*(Re)**(0.8)*(pr)**(0.3)*kw)/diameter)*(tfl-tw))*
     &  ((tw+tout)**(0.3333))-((kair/diameter)*(0.36*((tw+tout)**
     &  (0.3333))+((0.633)*(((tw-tout)**(0.16666)*(diameter)**
     &  (0.5)*(tw+tout)**(0.1666))/((vair*aair)**(0.16666)))+
     &   ((0.2783)*(((tw-tout)**(0.3333)*diameter)/
     &   ((vair*aair)**(0.3333))))))*(tw-tout)
```

```
      return
      end
c
c
c     *************************************************************
      real function f1(tw,Re,length,diameter,tfl)
      real*4 tw,length,kair,vair,aair,tout,Re,pr,tfl,kw
      real*4 diameter
c     *************************************************************
      kair=0.02574
      vair=0.0000153
      aair=0.0000216
      kw=0.6536
      pr=3.02
      tout=293.0
      f1=(((0.023*(Re)**(0.8)*(pr)**(0.3)*kw)/diameter)*(tfl-tw))*
    & ((tw+tout)**(0.25))-((kair/length)*(0.68*((tw+tout)**
    &  (0.25))+((1.082)*((tw-tout)**(0.25)*(length)**
    &  (0.75))/((vair*aair)**(0.25)))))*(tw-tout)

      return
      end

c
c
c ***************************************************************************
      real function fhs1(tw,diameter)
      real*4 tw,kair,vair,aair,tout
```

```
      real*4 diameter
c ***************************************************************************
c
c
      kair=0.02574
      vair=0.0000153
      aair=0.0000216
      tout=293.0


       fhs1= ((kair/diameter)*(0.36*((tw+tout)**
     &  (0.3333))+((0.633)*(((tw-tout)**(0.16666)*(diameter)**
     &  (0.5)*(tw+tout)**(0.1666))/((vair*aair)**(0.16666)))+
     &   ((0.2783)*(((tw-tout)**(0.3333)*diameter)/
     &   ((vair*aair)**(0.3333)))))

      return
      end
c
c
c ***************************************************************************
      real function fhs2(tw,length,diameter)
      real*4 tw,kair,vair,aair,tout,length
      real*4 diameter
c ***************************************************************************
c
c
      kair=0.02574
      vair=0.0000153
```

```
      aair=0.0000216
      tout=293.0
c
       fhs2=((kair/length)*(0.68*((tw+tout)**
     &  (0.25))+((1.082)*((tw-tout)**(0.25)*(length)**
     &  (0.75))/((vair*aair)**(0.25)))))

      return
      end
c
```

Appendix E

Input and Output Listings

E.1 Listing of an Input File

```
n_pipes              9
n_junc               4
n_pumps              0
viscosity    0.0000006
spec_gravity       1.0
converge      .0000001
Now enter the pipe data: Number(#), length(L:m), diameter(d:cm),
roughness(e:mm), minor loss coefficient(K:-), initial flow rate guess(Q:m^3/s)
#,L,d,e,K,Q          1       2.3      1.905     0.0015     0.0400
#,L,d,e,K,Q          2      10.4      1.905     0.0015     0.0200
#,L,d,e,K,Q          3       2.8      1.905     0.0015     0.0200
#,L,d,e,K,Q          4       1.0      1.905     0.0015     0.0100
#,L,d,e,K,Q          5       3.6      1.905     0.0015     0.0100
#,L,d,e,K,Q          6       2.0      1.905     0.0015     0.0100
#,L,d,e,K,Q          7       3.2      1.905     0.0015     0.0100
```

```
#,L,d,e,K,Q          8       1.0     1.905    0.0015    0.0050
#,L,d,e,K,Q          9       5.5     1.905    0.0015    0.0050
```

Next would enter the data for the pumps. First enter the pipe label Enter Hp at Q=0, Hp and Q at an intermediate point, and Hp and Q at a high point. Hp:m; Q:m^3/s.

You must select a point in your system to act as a reference point. Then enter the piezometric head at this location. H:m.

```
Reference        52.46
```

Next enter the data for the pipes between the joints. First the reference point to the first junction, then first to second junction, and so on. For each path enter the number of pipes between the junctions, then the label number for these pipes. These label numbers are signed to give the direction of flow.

```
Path to 1            1         1
Path 1 to 2          1         3
Path 2 to 3          1         5
Path 3 to 4          3        -5        -3        2
```

Next enter the data for the loops and pseudoloops. For each loop enter the piezometric pressure difference between the start and end of the loop (dH:m), then the number of pipes in the loop, then the label number for each pipe. These label numbers are signed to give the direction of flow.

```
dH,# p,#'s       -39.9      3       1       3       4
dH,# p,#'s       -39.9      4       1       3       5       8
dH,# p,#'s       -38.9      3       1       2       6
dH,# p,#'s       -39.9      3       1       2       7
dH,# p,#'s       -39.9      4       1       3       5       9
```

Finally enter the data for the tubes that meet at the junctions. For each junction enter the number of tubes entering and the number of the tube. Each tube is signed such that inflow is positive and outflow is negative. Q:m^3/s.

```
Q,# p,#'s          0.0      3       1      -2      -3
```

```
Q,# p,#'s          0.0        3        3        -4        -5
Q,# p,#'s          0.0        3        2        -6        -7
Q,# p,#'s          0.0        3        5        -8        -9
Finally enter tha data for specification of pipe location. If pipe is 1 then
Pipe is in horizontal position, if pipe is 2 then pipe is in vertical
#,P                1          2        1
#,P                2          5        2
#,P                3          3        2
#,P                4          6        3
#,P                5          4        3
#,P                6          9        5
#,P                7         10        5
#,P                8          7        4
#,P                9          8        4
```

E.2 Listing of an Output File

```
 1          0.987199
 2          0.995911
 3          0.981743
 4          0.928088
 5          0.756710
 6          0.403692
 7          0.091670
 8          0.005746
 9          0.000439
10          0.000068
11          0.000013
```

12	0.000009
13	0.000006
14	0.000004
15	0.000003
16	0.000002
17	0.000002
18	0.000001
19	0.000001
20	0.000001
21	0.000000
22	0.000000
23	0.000000
24	0.000000
25	0.000000
26	0.000000
27	0.000000

, PIPE NO.	FLOW RATE	TEMPERATURE	
1	0.000483	328.906250	21.582298
2	0.000482	328.878906	97.515739
7	0.000481	328.847656	29.980518

NODE NO.	HYD. GRADE LINE	Flow Sum
1	51.729813	0.000000
2	51.729813	0.000000
3	51.729813	0.000000
4	48.860428	0.000000

Pipe	Length	Diameter	Rough	Re	R_bar	Q

1	2.3	1.905	0.0015	0.538E+05	0.314E+07	0.00048
2	10.4	1.905	0.0015	0.537E+05	0.124E+08	0.00048
3	2.8	1.905	0.0015	0.778E+02	0.628E+14	0.00000
4	1.0	1.905	0.0015	0.411E+02	0.628E+14	0.00000
5	3.6	1.905	0.0015	0.367E+02	0.628E+14	0.00000
6	2.0	1.905	0.0015	0.835E+02	0.628E+14	0.00000
7	3.2	1.905	0.0015	0.536E+05	0.157E+09	0.00048
8	1.0	1.905	0.0015	0.184E+02	0.628E+14	0.00000
9	5.5	1.905	0.0015	0.184E+02	0.628E+14	0.00000

pipe	outlet temperature
1	0.0000
2	332.9892
3	0.0000
4	0.0000
5	0.0000
6	0.0000
7	0.0000
8	0.0000
9	332.9402
10	0.0000

mass fl. rate	demand (litres)	total demand
0.28188	51.48	225.11

heat withdraw loss (KJ), heat loss (KJ)

10402.1748 22.3200

Total heat withd loss (KJ), Tot heat loss (KJ)

```
45482.1641      989.5200
```