CONSTRUCTION AND PERFORMANCE TESTING OF A UNIFORM HEAT FLUX TWO-PHASE GAS-LIQUID EXPERIMENTAL SETUP USING A HORIZONTAL CIRCULAR TUBE

By

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NOMENCLATUE

A	cross-sectional area, ft^2 or m^2
A_m	eigenvalue, dimensionless; see Table 5.2
$\widetilde{A}_G$	gas flow cross-sectional area, dimensionless $(= 0.25[\cos^{-1}(2\widetilde{H}_L - 1) - (2\widetilde{H}_L - 1)\sqrt{1-(2\widetilde{H}_L - 1)^2}\,])$
$\widetilde{A}_L$	liquid flow cross-sectional area, dimensionless $(= 0.25[\pi - \cos^{-1}(2\widetilde{H}_L - 1) + (2\widetilde{H}_L - 1)\sqrt{1-(2\widetilde{H}_L - 1)^2}\,])$
B	dispersed bubble flow dimensionless parameter; see Eq. (5-27)
C_p, C_{PL}, c	specific heat at constant pressure, Btu/(lb_m-°F) or J/kg-K
c_f	local friction coefficient, dimensionless
$\bar{c}_{f_{app}}$	apparent mean friction coefficient, dimensionless; see Eq. (5-3)
c_g	air percentage, %
D_i, d	inside diameter of a circular tube, ft or m
D_o	outside diameter of a circular tube, ft or m
DP	pressure difference, in H_2O
$\widetilde{D}_L$	liquid flow hydraulic diameter in two-phase flow, dimensionless $(= 4\widetilde{A}_L / (\pi - \cos^{-1}(2\widetilde{H}_L - 1)))$
$Error_{HB}$	heat balance error, %; see Eq. (5-12)
F	modified Froude number; see Eq. (5-29)
F_a	vapor shear axial gradient ($= 2f_v G_v^2 / D_i \rho_v$), lb_f/ft^3 or Pa/m

F_r	gravity radial gradient (= $g(\rho_l - \rho_v)$), lb_f/ft^3 or Pa/m
f	Fanning friction factor, dimensionless
f_{app}	apparent Fanning friction factor ($=2\Delta p_{0\text{-}x}D_i/x\rho V^2$), dimensionless
G	mass flux or mass velocity (= ρV), $lb_m/(ft^2\text{-}s)$ or $kg/(m^2\text{-}s)$
GP	gas pressure, lb_f/in^2 or Pa
Gr	Grashof number (= $d^3\rho^2\beta\Delta Tg/\mu^2$), dimensionless
g	acceleration due to gravity, ft/s^2 or m/s^2
H_L	liquid level or gas gap for two-phase flow in a circular tube, ft or m
$\widetilde{H}_L$	liquid level or gas gap in two-phase flow, dimensionless (= H_L/D_i)
$Heat_{in}$	power input through the test section, Btu/hr or W
$Heat_{taken}$	power taken by the test fluid, Btu/hr or W
h	heat transfer coefficient, $Btu/(hr\text{-}ft^2\text{-}°F)$ or $W/(m^2\text{-}K)$
h_i	local peripheral heat transfer coefficient, $Btu/(hr\text{-}ft^2\text{-}°F)$ or $W/(m^2\text{-}K)$
I	current, A
j^*_g	gas velocity, dimensionless parameter; see Eq. (5-34)
K	wavy flow, dimensionless parameter; see Eq. (5-30)
K_U	velocity ratio (= V_G/V_L), dimensionless parameter
k	thermal conductivity, $Btu/(hr\text{-}ft\text{-}°F)$ or $W/(m\text{-}K)$
L	length of test section, ft or m
l	length of the element(= Δz), ft or m
$\dot{m}$	mass flow rate, lb_m/s or kg/s
Nu	Nusselt number (= hD_i/k), dimensionless

N_{TH}	number of finite-difference sections in the θ-direction (peripheral) which is equal to the number of thermocouples at each station.
Pe	Péclet number (= RePr), dimensionless
Pr	Prandtl number, dimensionless
p	pressure, lb_f/in^2 or Pa
Δp	pressure difference, lb_f/in^2 or Pa
Q	volumetric flow rate, ft^3/min or m^3/s
$\dot{q}$	rate of heat transfer, Btu/hr or W
$\dot{q}_g$	generated heat, Btu/hr or W; see Eqs. (4-7) and (4-8)
$\dot{q}''$	heat flux, Btu/(hr-ft^2) or W/m^2
R	resistance ($= \gamma l/A$), Ω
R^2	regression coefficient
Ra	Rayleigh number ($= g\beta\Delta T D^3 c_p \mu/\nu^2 k$), dimensionless
Re	Reynolds number ($= D_i G/\mu$), dimensionless
r	tube inside radius, ft or m
Δr	incremental radius, ft or m
St	Stanton number ($= h/Gc$ or $h/V\rho c$), dimensionless
$\widetilde{S}_i$	perimeter of gas-liquid interface over which the stress act in two-phase flow, dimensionless ($= \sqrt{1-(2\widetilde{H}_L-1)^2}$)
$\widetilde{S}_G$	perimeter of gas-phase over which the stress act in two-phase flow, dimensionless ($= \cos^{-1}(2\widetilde{H}_L-1)$)
$\widetilde{S}_L$	perimeter of liquid-phase over which the stress act in two-phase flow, dimensionless ($= \pi - \cos^{-1}(2\widetilde{H}_L-1)$)

s	Jeffrey's sheltering coefficient, dimensionless
T	temperature, °F or °C
T_X	temperature, °F or °C; refer to Appendix D
T_Y	temperature, °F or °C; refer to Appendix D
u	velocity in the x direction, ft/s or m/s
$\widetilde{u}_G$	gas velocity in two-phase flow, dimensionless ($= A/(D_i^2 \widetilde{A}_G)$)
$\widetilde{u}_L$	liquid velocity in two-phase flow, dimensionless ($= A/(D_i^2 \widetilde{A}_L)$)
V	mean velocity, ft/s or m/s
V_D	voltage drop through the test section, V
v_m	mixture velocity, ft/s or m/s
w	uncertainty interval, dimensionless
X	Martinelli parameter, dimensionless; see Eqs. (5-26) and (5-35)
x	local distance along the test section from the inlet, ft or m
x^+	axial distance inside a tube ($= (x/r)/(\mathrm{RePr})$), dimensionless
x_m	flow quality ($= \dot{m}_G / \dot{m}_t$), dimensionless
Y	dimensionless inclination parameter; see Eq. (5-28)
y	local weight fraction vapor, dimensionless
Δz	length of element, ft or m

Greek Symbols

α_p	angle between the pipe axis and the horizontal, positive for downward flow, rad
α	void fraction ($= A_G/(A_G+A_L)$), dimensionless

β	volumetric coefficient of thermal expansion, $°F^{-1}$ or $°C^{-1}$
γ	electric resistivity of the element, $\mu\Omega$-in or Ω-m; see Eq. (4-11)
γ^2_m	eigenvalue, dimensionless; see Table 5.2
ζ	friction parameter ($=(x/D_i)/\mathrm{Re_D}$), dimensionless
λ	Baker correction ($= (\rho_G\rho_L/\rho_a\rho_{wt})^{0.5}$), dimensionless
μ	dynamic viscosity coefficient, $\mathrm{lb_m/(hr\text{-}ft)}$ or $\mathrm{N\text{-}s/m^2}$
ν	kinematic viscosity ($= \mu/\rho$), $\mathrm{ft^2/s}$ or $\mathrm{m^2/s}$
ρ	density of the test fluid, $\mathrm{lb_m/ft^3}$ or $\mathrm{kg/m^3}$
σ	surface tension, $\mathrm{lb_f/in^2}$ or $\mathrm{N/m^2}$
τ_w	shear stress at the inside wall, $\mathrm{lb_f/in^2}$ or $\mathrm{N/m^2}$
ψ	Baker correction ($= (\sigma_{wt}/\sigma_L)[(\mu_L/\mu_{wt})(\rho_{wt}/\rho_L)^2]^{0.33}$), dimensionless

Abbreviations

ABSL	annular/bubbly slug
ABW	annular/wavy bubble
AD	annular with dispersed or annular
AW	annular/wavy
BSL	bubbly slug
DB	dispersed bubble or bubble
I	intermittent
PL	plug
PT	pressure tap
SL	slug

SS	smooth stratified
St	station
SW	wavy stratified
T	transition
TC	thermocouple
W	wavy
WSL	wavy/slug

Subscripts

0	denotes onset of significant free convection effects
a	denotes air
b, bulk	denotes bulk or mixed-mean fluid condition
cal, predict	evaluated based on calculation or correlation
D	evaluated based on diameter
exp	evaluated based on experimental data
FR	denotes flow rate
f	denotes fluid
G, g	denotes gas
HOM	evaluated based on homogeneous mixture
i	index of the finite-difference grid points along the radial direction starting from the outside surface of the tube
in	evaluated based on inlet condition
j	index of the finite-difference grid points along the peripheral direction starting from top of the tube and increasing clockwise as you look downstream

L, l	denotes liquid
m	denotes mean
out	evaluated based on outlet condition
PT	denotes pressure tap
SG	denotes superficial gas, and evaluated based on the assumption that only the gas-phase flows through the total cross section of the tube.
SL	denotes superficial liquid, and evaluated based on the assumption that only the liquid-phase flows through the total cross section of the tube.
T, t	denotes total
v	denotes vapor
w, wall	denotes condition at inside wall of tube
wt	denotes water
wi	evaluated based on the inside wall
wo	evaluated based on the outside wall
x	evaluated at a particular point along the surface
∞	evaluated at free stream condition

CHAPTER I

INTRODUCTION

1.1 Background

The expression 'two-phase flow' is used to describe the simultaneous flow, usually in a closed channel, pipe or conduit, of a gas and a liquid, a gas and a solid, or a liquid and a solid. All three of these types of two-phase flow occur in practical engineering systems. Many engineering applications also involve two-phase flow with or without heat addition. Examples are the flow with boiling in nuclear reactor channels and the flow of natural gas and oil in long pipelines.

The two-phase system that is the subject of this present study is of the gas-liquid type, formed with air-water. Whether laminar or turbulent, two-phase gas-liquid flow hydrodynamic and thermal conditions are dependent upon the flow patterns present. The ability to predict flow regimes is required for the proper flow modeling, as well as for the successful development of a correlation for the heat transfer coefficient. A number of investigators, for example Bergeline and Gazley (1949), Kosterin (1949), Abou-Sabe (1951), Alves (1954), Baker (1954), White and Huntington (1955), Krasiakova (1952), Hoogendoorn (1959), Schicht (1969), Mandhane *et al.* (1974), Taitel and Dukler (1976), Weisman *et al.* (1979), Breber *et al.* (1980), Troniewski and Ulbrich (1984), Lin and Hanratty (1987), Spedding and Spence (1993), and Ewing *et al.* (1999) have dealt with two-phase flow patterns coupled with void fraction measurement or prediction. However, as many generalized flow pattern maps exist as the number of investigators in this field. In addition, there has been less investigation of forced convection heat transfer for two-phase gas-water flow in horizontal pipes, and the accessible two-phase heat transfer data in the literature is rare (refer to Kim *et al.* (1999))

Therefore, in order to investigate and to understand the heat transfer for two-phase gas-liquid flow with various flow patterns, it was necessary to build a test loop which was capable of generating various two-phase flow patterns, of adding heat with uniform heat flux, and of measuring all required properties accurately.

1.2 Objectives of the Study

The primary objectives of this study are to:

(1) design and to build an experimental setup for two-phase gas-liquid flow heat transfer measurement;

(2) verify the performance of the experimental setup by the measurement and analysis of single-phase heat transfer and pressure drop data before the two-phase flow heat transfer experiments are performed;

(3) confirm the validity of a chosen void fraction correlation by measuring experimental void fractions and comparing the acquired data with the results from the chosen void fraction correlation for future use in the two-phase flow heat transfer measurement and analysis; and

(4) plots of develop a two-phase air-water flow regime map for the experimental setup before measuring the heat transfer with various two-phase flow patterns.

1.3 Scope and Limitations

The results reported in this thesis are the:

(1) description of the experimental setup for two-phase gas-liquid flow heat transfer measurement;

(2) comparison of the experimental single-phase heat transfer coefficients with the calculated single-phase heat transfer coefficients from selected published correlations;

(3) comparison of the experimental single-phase friction factors with the calculated single-phase friction factors from selected published correlations;

(4) two-phase gas-liquid flow pattern data on the selected published two-phase regime maps in horizontal pipes; and

(5) comparison of the experimental void fractions with the calculated void fractions from selected published correlations.

The present study is largely divided into two main areas. One is the verification of progress for the two-phase gas-liquid flow heat transfer experimental setup by means of the measurement and analysis of the single-phase flow heat transfer. This progress is limited to single-phase heat transfer in a horizontal circular tube with distilled water. Another area is providing data collection and information for the future study of two-phase gas-liquid flow heat transfer with various flow patterns. The data collection and information are limited to the present experimental setup, which has been built for two-phase gas-liquid flow heat transfer measurements having various flow patterns in a horizontal circular tube.

[illegible] coefficients very well and
[illegible] 48 as shown in Fig. 2.1

CHAPTER II

LITERATURE SURVEY

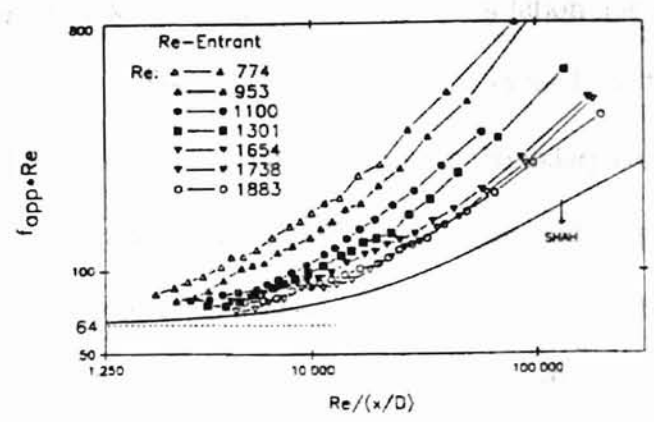
The primary study objective, as mentioned in the previous chapter, is constructing and testing a uniform heat flux two-phase gas-liquid flow experimental setup using a horizontal circular tube. Therefore, the collected literature for this study was focused on single-phase flow heat transfer and pressure drop, and two-phase flow pattern prediction and void fraction measurement.

2.1 Single-Phase Flow in a Horizontal Pipe

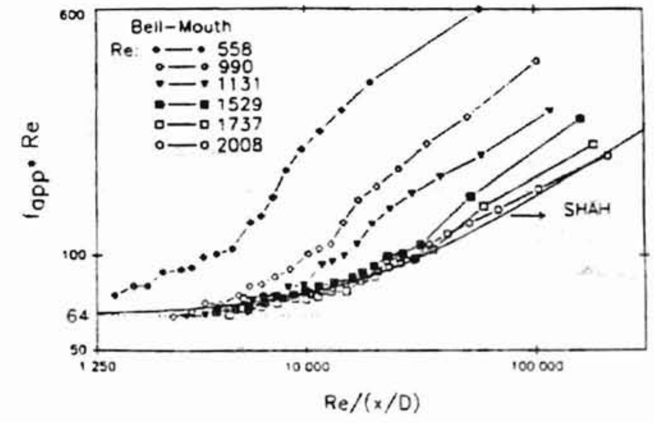
2.1.1 Single-Phase Flow Pressure Drop

Shah (1978) has suggested a correlation for laminar hydrodynamic entry length for circular tubes, parallel plates, rectangular ducts, equilateral triangular ducts, and concentric annular ducts. The predicted apparent friction factors by the correlation agree within ± 2.4 % of the data taken. The influence of form drag was not included in the correlation.

Ghajar and Madon (1992) investigated the validity of Shah's (1978) correlation with the experimental pressure drop data for laminar flow obtained from a circular tube with three different inlet condition (reentrant, square-edged, and bell-mouth inlets). Their results indicated that only for Reynolds numbers greater than 1,500, Shah's (1978) correlation predicted the bell-mouth laminar apparent friction coefficients very well and the accuracy of the correlation improved considerably for x/D > 48 as shown in Fig. 2.1.



(a) Reentrant Inlet Condition



(b) Bell-Mouth Inlet Condition

Figure 2.1 Comparison between Experimental Laminar Flow Apparent Friction Factor and Correlation of Shah (1978) [Adapted from Ghajar and Tam (1992)]

2.1.2 Single-Phase Flow Heat Transfer

In the case of single-phase flow heat transfer, analysis is also well researched and a great amount of information is available in the literature. Therefore, considering the vast information in the literature, the selected single-phase heat transfer correlations for both the laminar and turbulent cases, which were used to compare with the heat transfer data acquired from this study, are introduced in this section.

Seigel *et al.* (1958) proposed an analytical solution for laminar heat transfer without natural convection. They developed an equation for local Nusselt number with a fully developed velocity profile and uniform heat flux boundary condition. Petukhov and Polyakov (1967), Bergles and Simonds (1971), and Hong and Bergles (1976) applied the Seigel *et al.* (1958) correlation as a basic solution for larminar forced convection heat transfer. However, their predictions for heat transfer coefficients were lower than the experimental values. For example, Petukhov and Polyakov (1967) observed that, with increased heat flux, higher deviations from the predictions occurred as shown in Fig. 2.2.

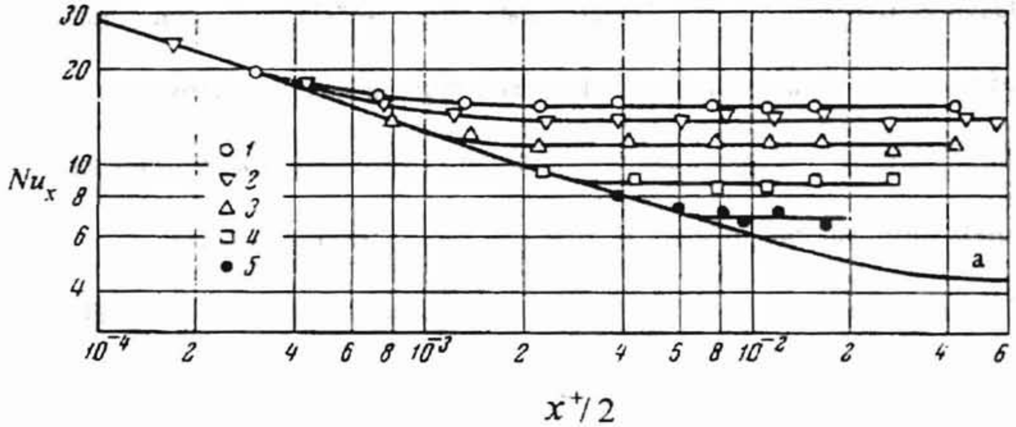


Figure 2.2 Average Nusselt Number over the Pipe Perimeter as a Function of the Reduced Length (Re = 300 – 800), 1) Ra = 2.5×10^7; 2) 1.2×10^7; 3) 6.0×10^6; 4) 1.4×10^6; 5) 3.5×10^6; a) Viscous Flow[Seigel *et al.*'s (1958) solution] (Adapted from Petukhov and Polyakov (1967))

Colburn (1933) proposed a general method for the correlation of forced convection heat transfer data chosen from the literature. Among the correlations suggested by him, the correlation proposed for turbulent forced convection in circular ducts for liquids was

$$St\,\mathrm{Pr}^{2/3} = 0.023\,\mathrm{Re}^{-0.2} \tag{2-1}$$

with limitations of $L/d > 60$, $\mathrm{Pr} > 0.6$, $\mathrm{Re} > 10{,}000$. Equation (2-1) is inadequate for large $T_w - T_b$. Later, Sieder and Tate (1936) introduced the ratio μ_b/μ_w into Colburn's (1933) correlation for moderate $T_w - T_b$ as follows:

$$Nu = 0.023\,\mathrm{Re}^{0.8}\,\mathrm{Pr}^{1/3}\left(\frac{\mu_b}{\mu_w}\right)^{0.14} \tag{2-2}$$

Kakac *et al.* (1987) have examined a great many correlations for fully developed turbulent flow in a circular tube, and concluded that Gnielinski (1976) correlated the available data somewhat better than any other researcher over the range of Prandtl number from 0.5 to 2000, and Reynolds number from 2300 to 5×10^6.

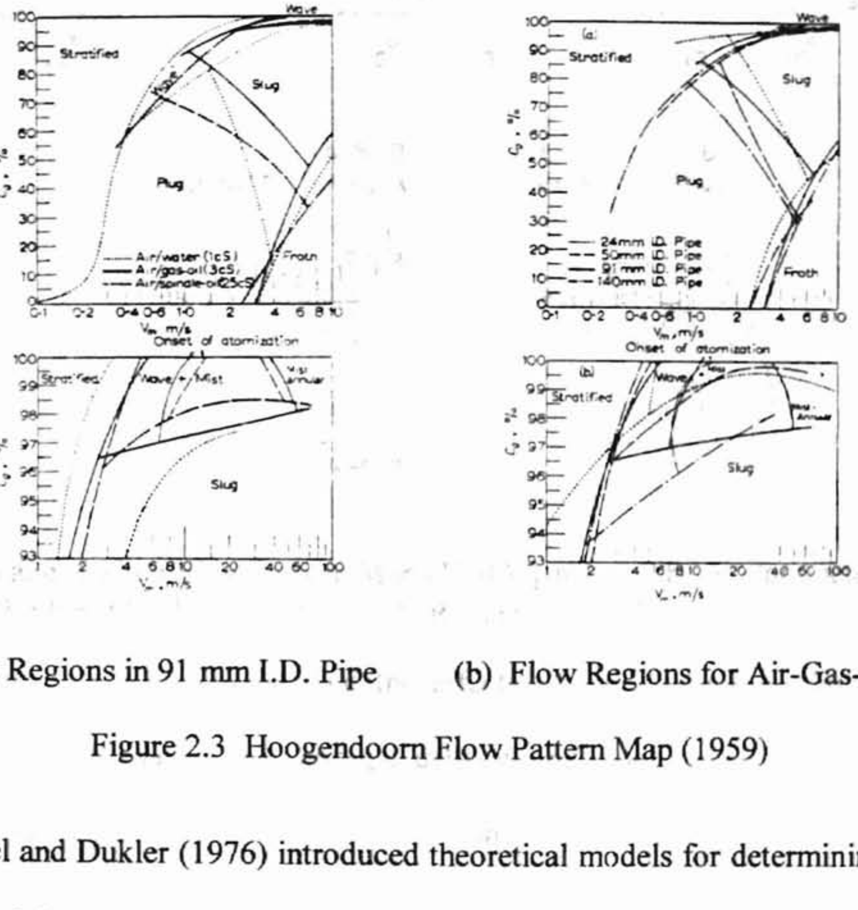
Ghajar and Tam (1994) researched local forced and mixed convective heat transfer in a horizontal circular straight tube with reentrant, square-edged, and bell-mouth inlets under uniform wall heat flux conditions over the range of Reynolds numbers from 280 to 49,000, Prandtl numbers from 4 to 158, and Grashof number from about 1000 to 2.5×10^5. They proposed correlations for prediction of the developing and fully developed forced and mixed convection heat transfer coefficients in the laminar, transition and turbulent regions for the three different inlet conditions.

2.2 Two-Phase Flow in a Horizontal Pipe

2.2.1 Two-Phase Flow Regime Map

In order to move on to the two-phase flow heat transfer measurements, the knowledge of the flow regime (or flow pattern) for the present experimental setup was required. The flow pattern data acquired through this study's experiments will be compared with published maps to confirm the response of the experimental setup. A number of researchers have investigated two-phase flow patterns in horizontal pipes and proposed their own two-phase flow regime maps.

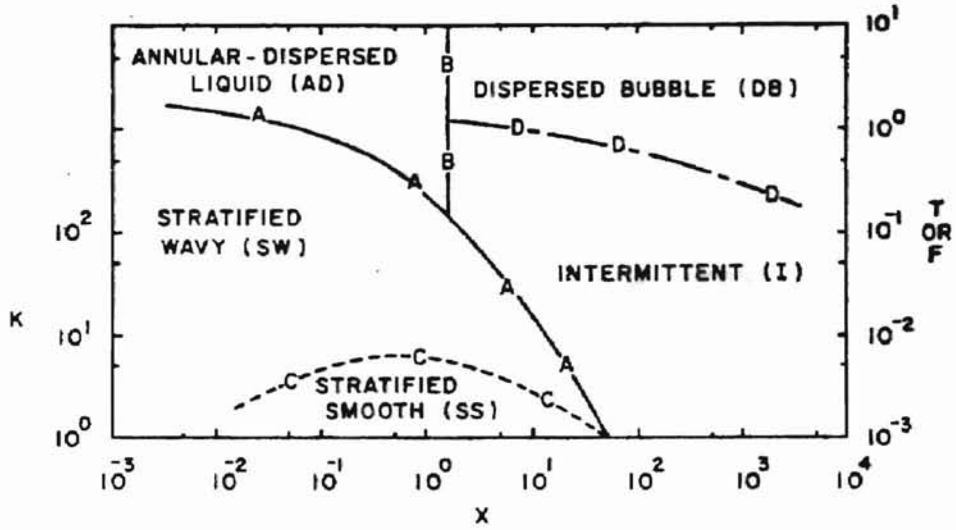
Hoogendoorn (1959) provided two-phase flow region maps (see Fig. 2.3) and experimental correlations for flow regions by investigating air-water and air-oil flow in horizontal smooth pipes with inner diameters ranging from 1 inch (24 mm) to 5.5 inches (139.7 mm), and rough pipes with an inner diameter of 2 inches (50 mm).



(a) Flow Regions in 91 mm I.D. Pipe (b) Flow Regions for Air-Gas-Oil Flow

Figure 2.3 Hoogendoorn Flow Pattern Map (1959)

Taitel and Dukler (1976) introduced theoretical models for determining transition boundaries of five flow regimes in horizontal and near horizontal two-phase gas-liquid flow. The theory was developed in dimensionless form, and the flow regime boundaries were introduced as a function of five dimensionless parameters. The theoretically located transition boundaries between adjacent regimes for horizontal tubes were shown as a generalized two-dimensional map (see Fig. 2.4).



CURVE:	A & B	C	D
COORDINATE:	F vs X	K vs X	T vs X

$$X = \left[\frac{(dP/dx)_L^S}{(dP/dx)_G^S} \right]^{1/2} \qquad F = \sqrt{\frac{\rho_G}{(\rho_L - \rho_G)}} \frac{U_G^S}{\sqrt{Dg \cos \alpha}}$$

$$T = \left[\frac{\left| (dP/dx)_L^S \right|}{(\rho_L - \rho_G) g \cos \alpha} \right]^{1/2} \qquad K = \left[\frac{\rho_G U_G^{S^2} U_L^S}{(\rho_L - \rho_G) g \nu_L \cos \alpha} \right]^{1/2}$$

Figure 2.4 Taitel-Dukler Flow Pattern Map (1976) [In This Thesis, Parameter 'T' Is Replaced by 'B' and Angle 'α' Is Replaced by 'α_p']

Weisman *et al.* (1979) studied the effects of fluid properties (liquid viscosity, liquid density, interfacial tension, and gas density) and pipe diameter (inner diameter of 0.5 inch (1.2 cm) to 2 inches (5.1 cm)) on two-phase flow patterns in horizontal pipes. In this research, the flow pattern data resulted in an overall flow pattern map (see Fig. 2.5) in terms of V_{SG} and V_{SL}, and they introduced revised dimensionless correlations to predict the transition boundaries.

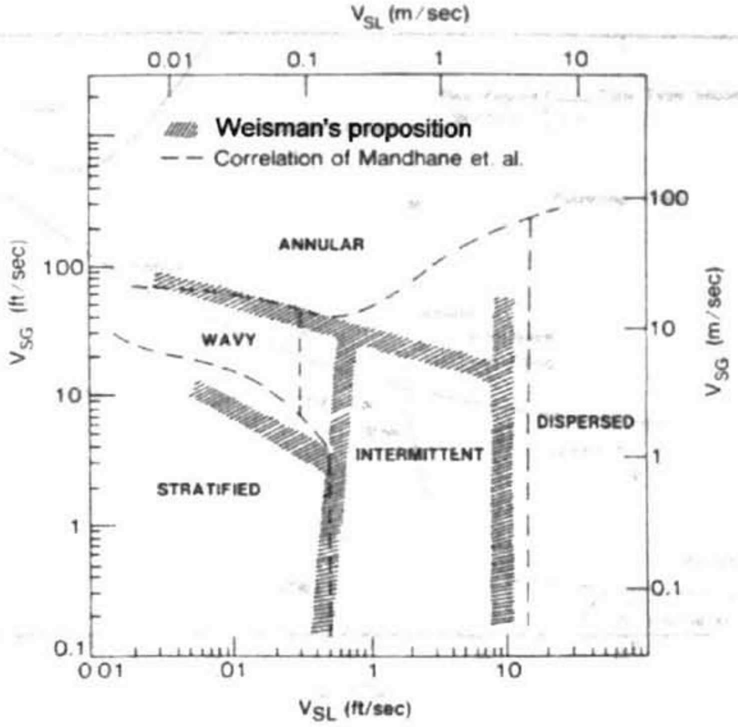


Figure 2.5 Weisman Flow Pattern Map (1979); Air-Water, 1 in. I.D.

Spedding and Nguyen (1980) provided two-phase gas-liquid flow regime maps for conditions from vertically downward to vertically upward flow based on air-water flow data. Among 11 flow pattern maps provided, the flow regime map for horizontal flow shows four main flow patterns (stratified flow, bubble and slug flow, droplet flow and mixed flow) and further 13 flow pattern subdivisions of the main flow patterns (see Fig. 2.6).

Breber *et al.* (1980) confirmed that the theoretically derived flow regime parameters by Taitel and Dukler (1976) were significant for condensation, both by an alternative derivation and by comparison with experimental data. They also provided a flow pattern map (see Fig. 2.7) of simplified criteria for horizontal tubeside condensation flow regimes.

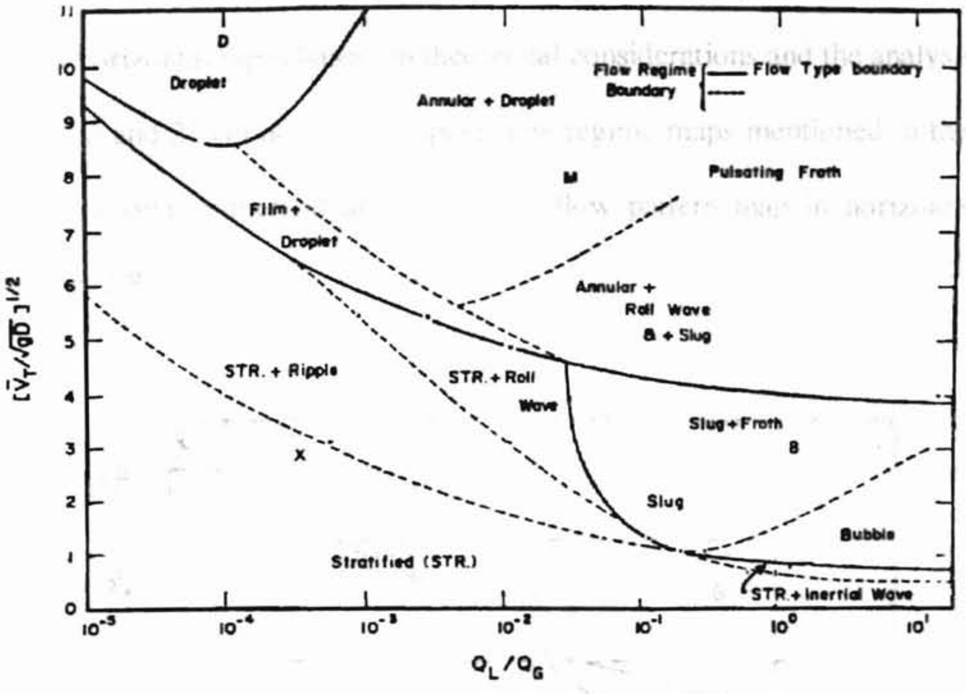


Figure 2.6 Spedding and Nguyen Flow Pattern Map (1980)
(D: Droplet; X: Stratification; M: Mixed; B: Bubble)

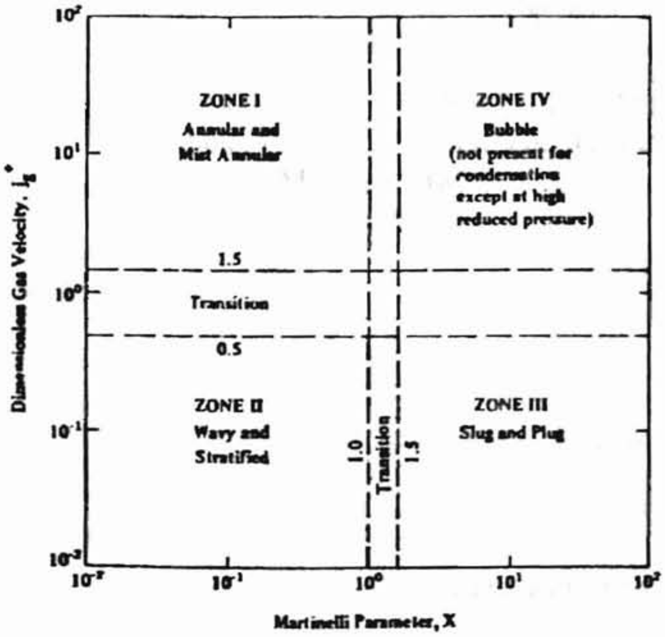


Figure 2.7 Breber *et al.* Flow Pattern Map (1980)

Troniewski and Ulbrich (1984) suggested general two-phase flow regime maps in vertical and horizontal pipes based on theoretical considerations and the analysis of 31 (in vertical pipes) and 21 (in horizontal pipes) flow regime maps mentioned in the literature based on their own numerical analysis. The flow pattern map in horizontal pipes is shown in Fig. 2.8.

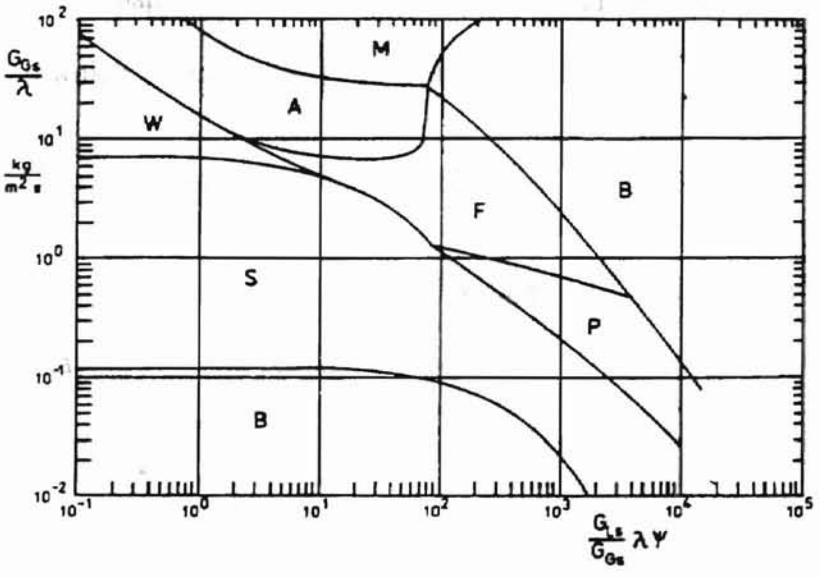


Figure 2.8 Troniewski and Ulbrich Flow Pattern Map (1984)
(B: bubble; P: plug; S: stratified; W: wavy; F: slug;
A: annular; M: mist flow)

Spedding and Spence (1993) provided a comparison of their experimental data to theoretical and empirical models developed for the prediction of flow pattern transitions, which were published in the literature. The experimental data were determined for air-water two-phase flow in horizontal pipes with inner diameters of 3.68 inches (0.0953 m) and 1.78 inches (4.54 cm), and the flow patterns were identified by a combination of visual/video observation. They concluded that the theoretical and empirical models were deficient for handling changes in physical properties and geometry.

Ewing *et al.* (1999) investigated horizontal two-phase flow patterns in a transparent circular pipe with an inner diameter of 0.75 inch (1.90 cm) using adiabatic mixtures of air and water. The experimental flow pattern data, which was supplemented with photographs, was plotted on the Breber *et al.* (1980) flow regime map for condensation applications. The results indicated reliability between the observed data and the predictions of the map, and supported the general applicability of the Breber *et al.* (1980) flow regime map by providing data for fluids and conditions that were different from those with which the map was developed.

2.2.2 Pressure Drop and Liquid Holdup (Void Fraction)

Chisholm (1973) developed a convenient analytical equation for the ratio of the gas velocity to that of the liquid during two-phase flow as follows:

$$K_U = \left(\frac{\rho_L}{\rho_{HOM}} \right)^{1/2} \tag{2-3}$$

where $$\frac{1}{\rho_{HOM}} = \frac{1 - x_m}{\rho_L} + \frac{x_m}{\rho_G}$$

The void fraction can be calculated from velocity ratio, which is calculated from his equation, with experimental information such as densities and ratios of gas-mass flow rate to that of the mixture in two-phase flow.

Hetsroni (1982) first unified the approaches to multiphase systems developed in various traditional disciplines in a handbook. In the handbook, Hewitt (one of contributors in the handbook) explained a selection method of techniques and provided a selection chart for techniques for void fraction measurement as shown in Fig. 2.9. He also described various techniques for void fraction measurement in detail.

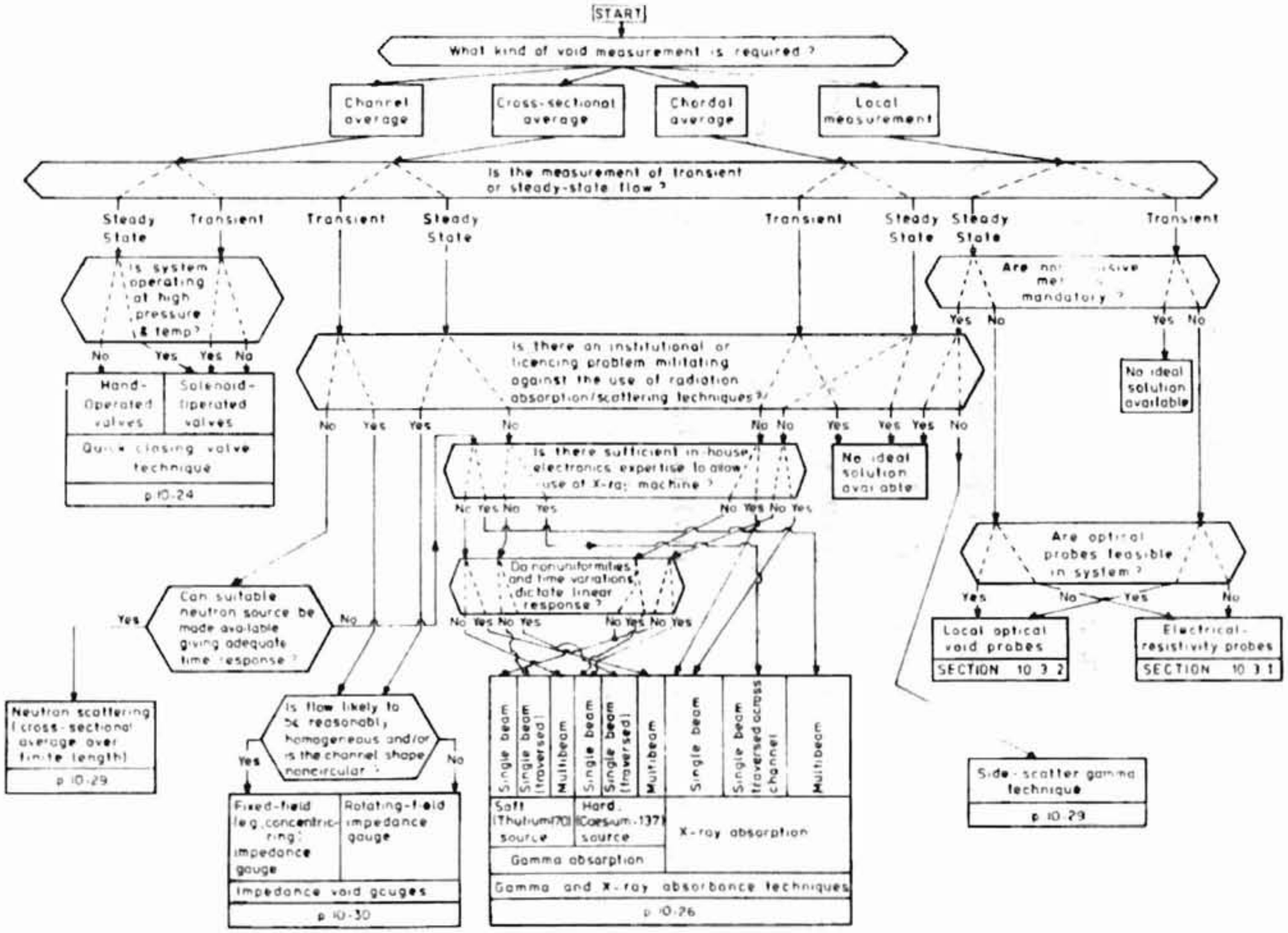


Figure 2.9 Selection Chart for Techniques for Void Fraction Measurement (Adapted from Hetsroni (1982))

CHAPTER III

EXPERIMENTAL SETUP AND CALIBRATION

3.1 Description of the Experimental Setup and Instrumentation

In this Section, the experimental apparatus to measure two-phase pressure drop, void fraction, and heat transfer is described. The experimental setup for the two-phase heat transfer measurement is schematically shown in Fig. 3.1. The design, construction, and instrumentation of the experimental setup was performed by a Ph.D. candidate, Dongwoo Kim, a Masters student, Venkata Ryali (1999), and the present author. More details are provided in the following sections. The specifications for instrumentation and materials are described in Appendix A.

3.1.1 Water Supply Line

Distilled water was supplied from a 35 gallon cylindrical polyethylene tank. A float type control switch (OMEGA LV62-P with LV600-CW counterweight, which turned on and off a centrifugal type 1/3 HP pump, Pump 3 in Fig. 3.1) automatically controlled the water level in the water storage tank. For experiments using the higher water flow rate (more than 3 gpm), a centrifugal type 1 HP pump (Pump 1 in Fig. 3.1) was operated; and for the lower water flow rate (less than 3 gpm), a centrifugal type 1/3 HP pump (Pump 2 in Fig. 3.1) was operated. After the pumps, two liquid turbine

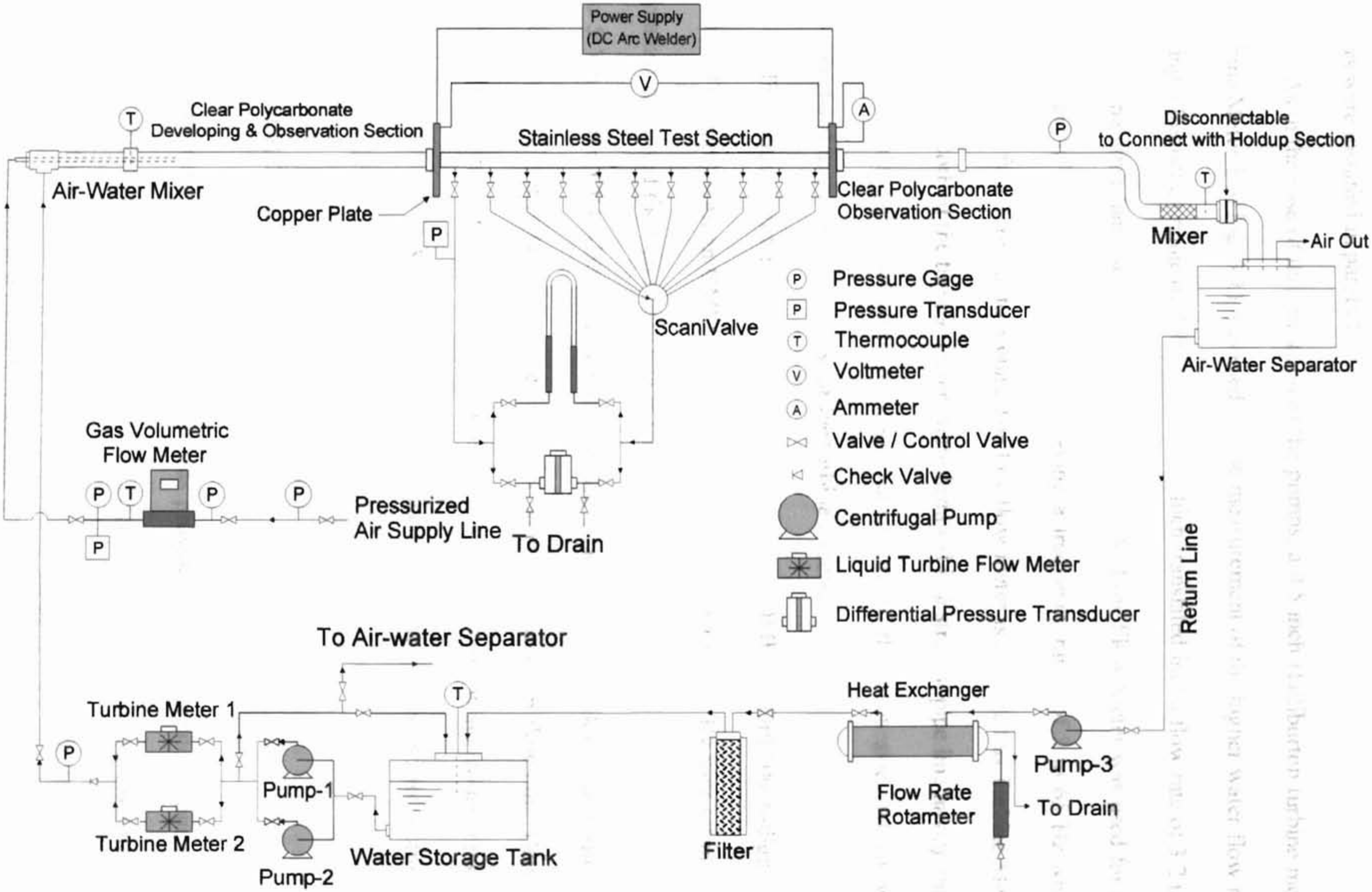


Figure 3.1 Schematic Diagram of the Experimental Setup

meters were installed in parallel.

As in the case of the operation of the pumps, a 0.5 inch Halliburton turbine meter (Turbine Meter 1 in Fig. 3.1) was used for the measurement of the higher water flow rate yielding a frequency range of 700 to 2000 Hz which translated into a flow rate of 3.2 to 9 gpm. On the other hand, a SeaMetrics S-Series (SPX) Low Flow Meter was used for the measurement of lower water flow rates having a frequency range of 3 to 65 Hz which translated into flow rates up to 3 gpm. The low flow meter is indicated as Turbine Meter 2 in Fig. 3.1. Both of the turbine meters were installed in a straight pipe line having more than five inside pipe diameters of length upstream of the inlet side, which was recommended in the user's manuals for the turbine meters.

Each liquid turbine meter was connected to an OMEGA DPF700 6-digit rate meter (Totalizer) with an OMEGA DPF700-A analog output board. By user setting, the totalizer displayed the water flow rate in terms of frequency and sent voltage signals of 0 to 5 Vdc to the CIO-AD08 A/D board installed inside of a PC. Before and after the turbine meters, ½ inch ball valves were installed to control the water flow rate. Between the pumps and the turbine meters, there was a feedback line to the water storage tank and the air-water separator, which was used to reduce the pumping load and to control the water flow rate.

3.1.2 Air Supply Line

Compressed air for this experiment was provided by the laboratory compressed-air supply. After the three ball valves which acted as regulators, the air flow rate was measured by a Cole-Parmer P-32915-15 0.25 inch NPT flowmeter. This gas flow meter measures up to 100 lpm at a maximum pressure of 100 psig and displays the flow rate in units of lpm through a 3-digit LCD panel. The air flow rate was acquired by the CIO-AD08 A/D board installed inside of a PC in the form of the voltage signals of 0.010 Vdc for zero flow rate to 5.0 Vdc for full scale flow. The air flow rate was controlled by a 3/8 inch ball valve that was installed before the gas flow meter.

To convert the volumetric flow rate measured by the gas flow meter into the mass flow rate of the supplied air and to calculate gas density, the absolute pressure of the supplied air was required. For this calculation using ideal gas laws, a thermocouple with a temperature indicator and an OMEGA PX137 pressure transducer was installed after the gas flow meter in order to provide knowledge of gas density change. The absolute gas pressure transducer had a silicone pressure sensor in conjunction with a stress free packing technique and was connected to the CIO-AD08 A/D board in order to acquire the pressure data in the form of the voltage signal of 0 to 4.5 Vdc.

3.1.3 Air-Water Mixing Section

The detailed setup for the air-water mixer is shown in Fig. 3.2. This type of mixer was successfully used by Ewing *et al.* (1998) in their two-phase experiment to generate various two-phase flow patterns, such as stratified, wavy, slug, plug, bubbly, and annular flow as defined in Section 5.2.2. The compressed air was passed through a perforated copper tube (1/4 in O.D) inserted into the water stream by means of a compression fitting. The end of the copper tube was silver soldered and four 1/16 in (1.6 mm) holes, located at 90 degree intervals around the perimeter of the tube, were placed at eight equally spaced axial locations.

At the connection between the #40 PVC pipe, having a 1 inch (2.54 cm) I.D., and the developing/observation section, an OMEGA TT-T-30 copper-constantan insulated T-

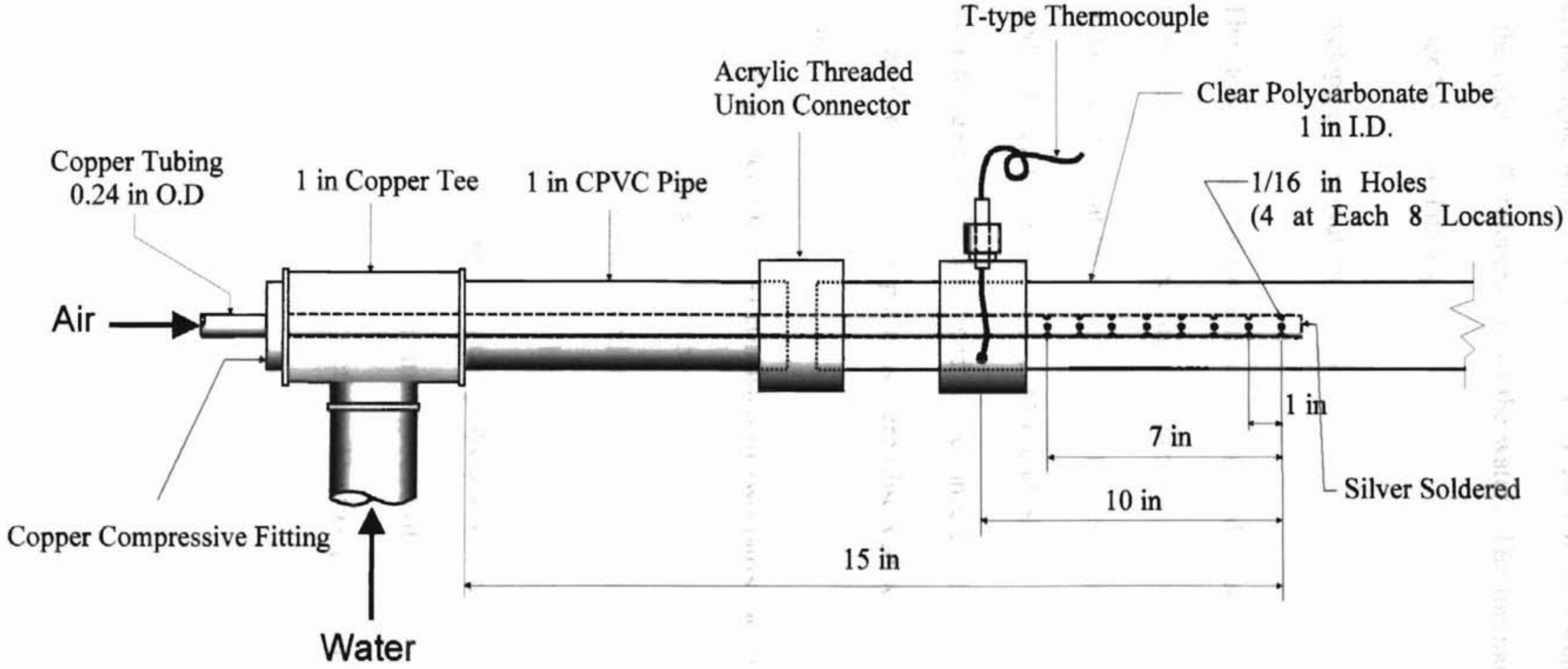


Figure 3.2 Schematic Diagram of the Air-Water Mixing Section

type thermocouple with OMEGA EXPP-T-20-TWSH extension wire was inserted to measure the inlet bulk temperature of the water. The thermocouple was connected to a Cole-Parmer MAC-14 data logger.

3.1.4 Developing/Observation Section

The developing/observation section served these purposes: a flow straighter, a flow pattern developing device, and a two-phase flow observation location. This clear polycarbonate section was 96 inches (2.44 m) in length (an L/D of 88), had a 1 inch (2.54 m) I.D. and 1/8 inch (3.18 mm) O.D. One end of this section was connected to the test section by a flange and the other end was connected to the air-water mixer as shown in Fig. 3.3. The two-phase flow patterns were observed within this section and in the post test section.

The flange (see Fig. 3.4) consisted of two parts (acrylic and nylon 101 part) and installed as a connection between the clear polycarbonate tube as the developing/observation section, and the stainless steel tube, as the test section. The acrylic part was ½ inch (1.27 cm) thick by 5 inches (12.7 cm) in diameter using a 1.25 inch (3.175 cm) I.D. hole for the clear polycarbonate tube glued into it with Weld-On3 cement. The nylon 101 part had a small groove of 1/10-inch depth in order to place an O-ring and was screwed to the test section. The two parts bolted together kept the heated test section from touching the clear polycarbonate tube in order to avoid damaging the polycarbonate tube by heat.

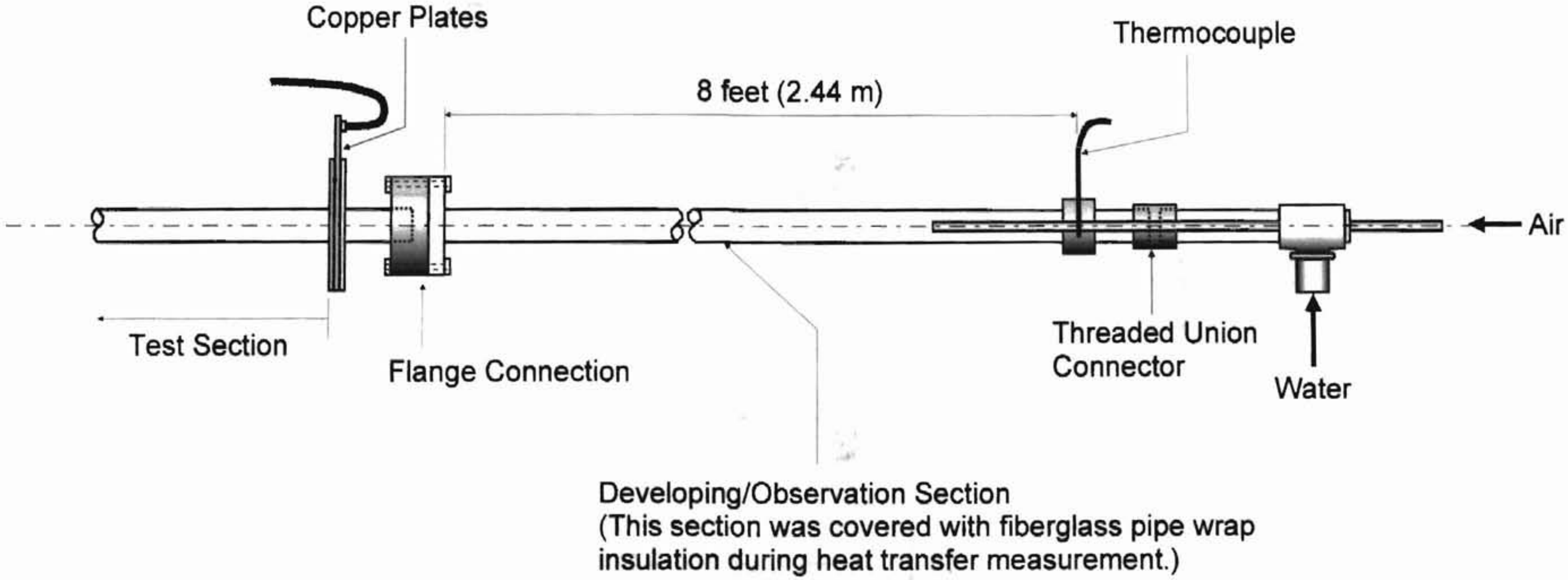


Figure 3.3 Mixer, Developing/Observation Section, and Flange Connection to Stainless Steel Test Section

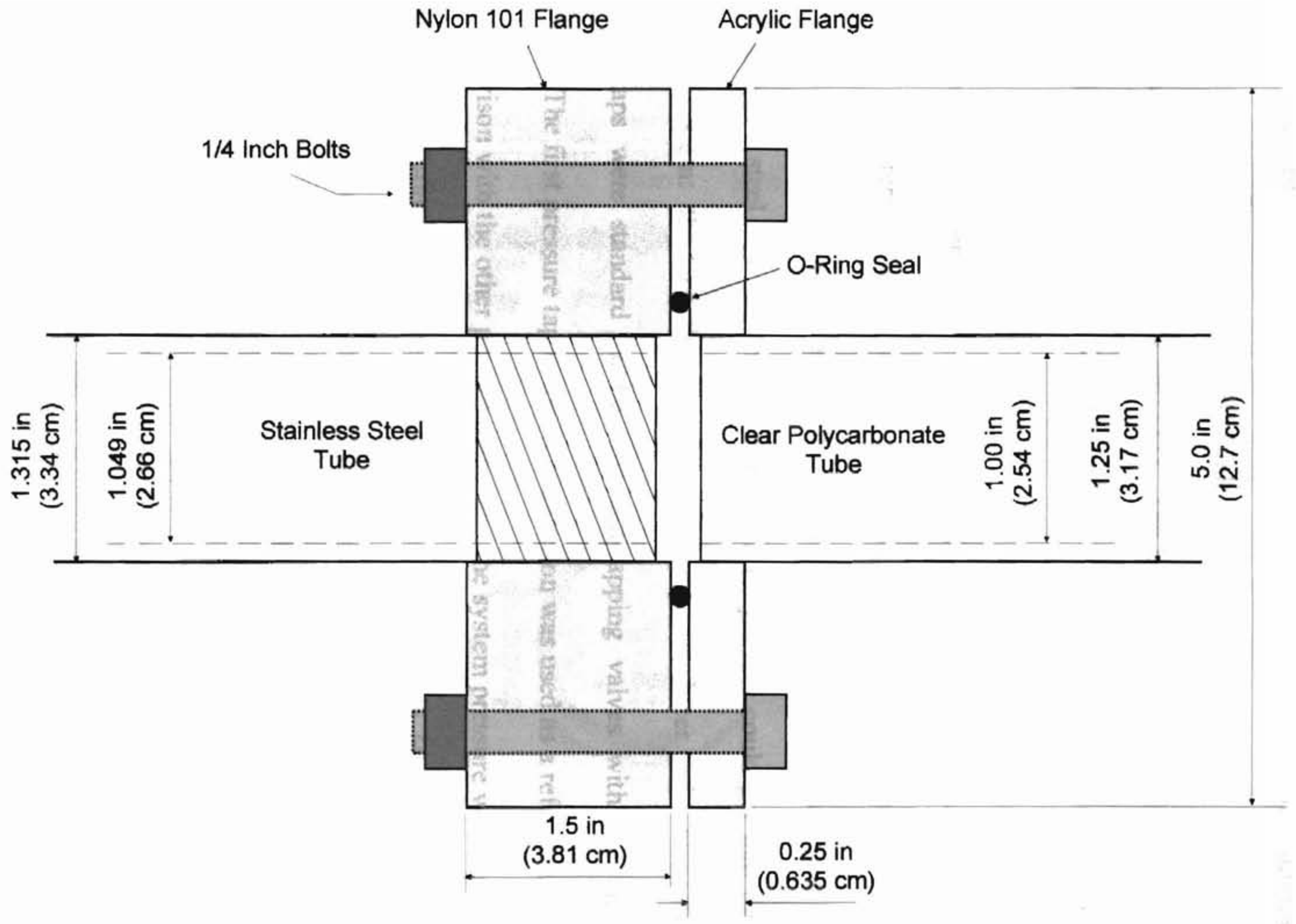


Figure 3.4 Flange Connection between Stainless Steel Tube and Clear Polycarbonate Tube

3.1.5 Test Section

The test section for the heat transfer and the pressure drop measurement was a horizontal seamless schedule 40 316 stainless steel circular tube with a 1.097 inch (2.79 cm) I.D. and a 1.315 inch (3.34 cm) O.D. The length of the test section was 110 inches (2.79 m), providing a length to diameter ratio (L/D) of 100. The details of the test section are shown in Fig. 3.5.

Holes for eleven pressure taps were drilled along the test section (refer to Fig. 3.5). The diameters of the holes were 0.068 inch (1.73 mm), and were equally spaced at 10 inch (25.4 cm) intervals along the test section. The holes were located at the bottom of the stainless steel tube in order to ensure that only water could get into the pressure measuring system: the taps, the differential pressure transducer and a manometer. The pressure taps were standard saddle type self-tapping valves with the tapping core removed. The first pressure tap in the flow direction was used as a reference pressure tap for comparison with the other pressure taps; and the system pressure was measured by an OMEGA PX242-060G pressure transducer which had a 0 to 60 psig operation range. The reference pressure tap was directly connected to a VALIDYNE DP15 wet-wet differential pressure transducer (equipped with a replaceable sensing DP15 No. 20 diaphragm having a differential pressure range up to 5.5 inches of water) with CD15 carrier demodulator. The other pressure taps were connected to a Scanivalve W0601/1P-12T that allowed each pressure tap to sequentially connect to the differential pressure transducer. The CD15 carrier demodulator providing DC voltage signals was connected to the CIO-AD08 A/D board.

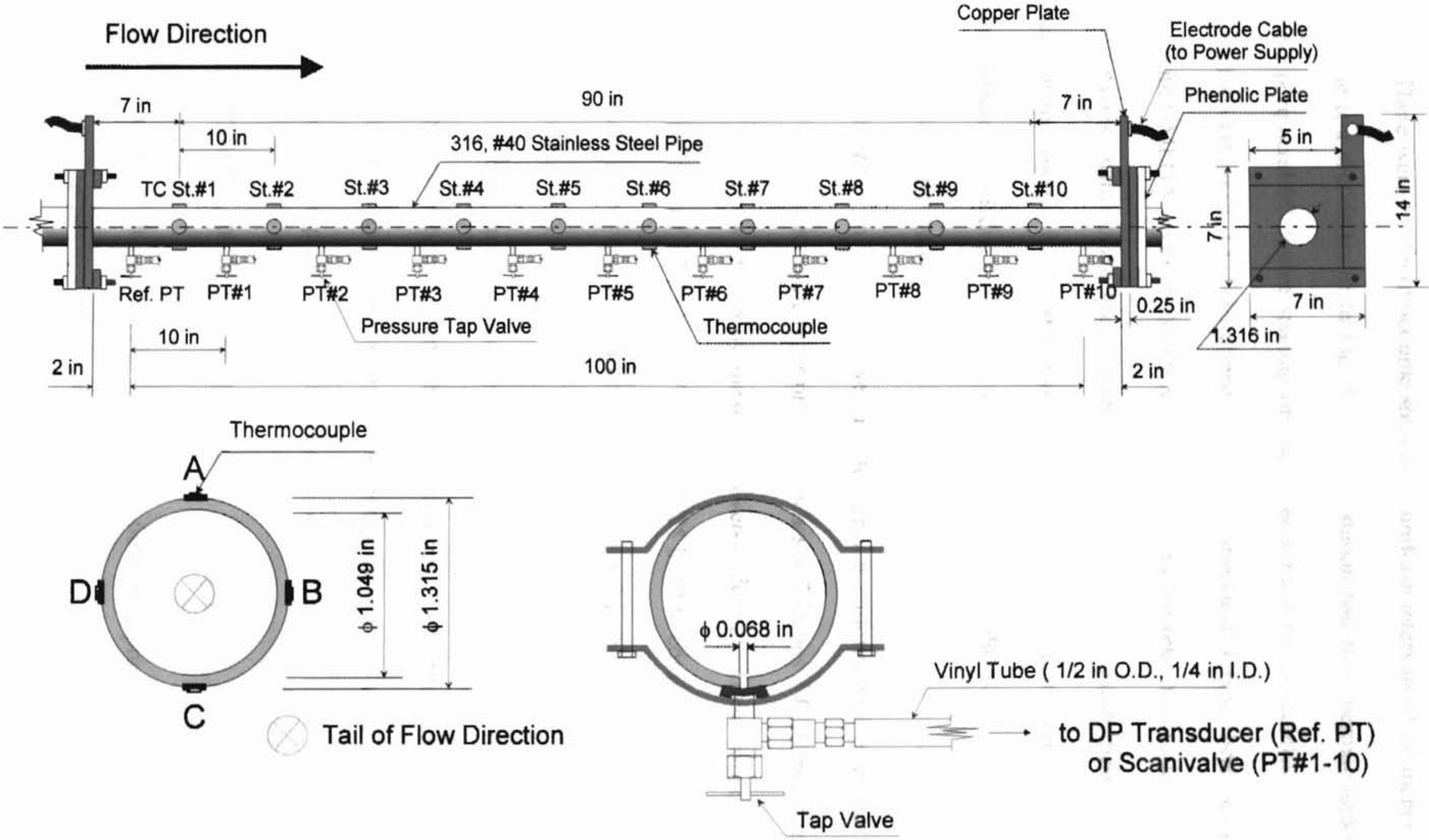


Figure 3.5 Test Section and Copper Plates

There were ten thermocouple stations at uniform intervals of 10 inches (25.4 cm) along the test section (refer to Fig. 3.5). Each station had four thermocouples attached with a peripheral 90 degree spacing on the outer surface of the stainless steel tube. A total of 40 OMEGA TT-T-30 copper-constantan insulated T-type thermocouples were used with OMEGA EXPP-T-20-TWSH extension wire for relay to a Cole-Palmer MAC-14 ninety-six channel data logger interfaced with a PC. To attach these thermocouple beads on the outside of the stainless steel tube, Omegabond 101 epoxy adhesive was used, which provided high thermal conductivity (0.6 Btu/hr-ft-°F) and high electrical resistivity (3.28×10^{15} ohm-ft).

In order to provide the power and to apply a uniform wall heat flux boundary condition to the test section, copper plates (5 inches × 7 inches × 0.25 inch) were placed at each end of the test section by means of silver-soldering. These copper plates were combined with bus bars (2 inches × 7 inches × 0.25 inch) to connect to an electrical cable from the power supply and a phenolic plate (5 inches × 7 inches × 0.5 inch) for insulation purposes (see Fig. 3.5).

For the heat transfer measurements, the entire length of the mixing section, the developing/observation section and the test section, and the post test section was wrapped with fiberglass pipe insulation having a thickness of about 0.5 inch, followed by a thin polymer vapor seal to prevent moisture penetration.

3.1.6 Power Supply and Power Measurement

A variable voltage Lincoln Idealarc DC-600 three-phase rectified type electric welder was used to produce DC current as a heating source in the test section. The DC welder had a maximum output of 26.4 kW and was rated for 100% duty cycle at 600 amperes and 44 volts for either 60 or 50 Hertz. To minimize room heating caused by the DC welder, it was placed in a plywood box having an exhaust duct leading outside of the laboratory and a suction steel net gate to bring in cooler air from outside of the laboratory. To avoid the vibration from the DC welder through the floor to the experimental apparatus, the DC welder was placed on rubber damping pads. The current was delivered to the test section through Radaflex AWG 4/0 welding cable attached to the copper plates located at the beginning and the end of the test section. Heat was generated internally in the stainless steel tube due to its electrical resistivity powered by the DC welder.

In order to measure the actual voltage drop in the test section, a Hewlett-Packard 3468B digital multimeter, having a range up to 300 volts and a resolution of 10 microvolts, was connected to the copper plates in parallel with the test section. In addition, the current passing through the test section was measured with a Weston Instruments Division ammeter, having a full scale of 750 amperes, placed in parallel with a 50 millivolt shunt.

3.1.7 Post Test Section

There was a clear polycarbonate observation section (refer to Fig. 3.1) just after the test section, which was used to confirm and compare the flow pattern with that observed in the developing/observation section. The length of the post observation section was 20 inches (50.8 cm). An OMEGA PGC-20L-60 pressure gage as shown in Fig. 3.1, having a range of 0 to 60 psig, was installed at a location 3 ft (0.915 m) from the end of the test section in order to monitor the pressure in the post test section. In order to measure the outlet bulk temperature, an OMEGA TJ36-CPSS-14U-12 thermocouple probe was used and this thermocouple probe was connected to the Cole-Parmer MAC-14 data logger.

After the pressure gage and before the thermocouple probe, an alternating polypropylene baffle type OMEGA FMX7109-P static mixer, having a length of 5.3 inches (13.46 cm) and a diameter of 0.9 inch (2.30 cm), was placed inside of schedule 40 PVC pipe having a 1 inch I.D as shown in Fig. 3.1. The mixer was included in order to ensure measurement of a uniform bulk temperature of the flow existing the test section.

3.1.8 Liquid Holdup Section

In order to make accurate void fraction measurements, two quick-closing solenoid valves and a quick-opening solenoid valve were included in the liquid holdup section (refer to Fig. 3.6). The entire liquid holdup section was detachable from the test loop in order to reduce the pressure load on the test loop. Therefore, in this study, the liquid holdup section was included in the test loop only when the void fraction measurements were being made. This also means that void fraction tests were not made for all possible test conditions occurring without the liquid holdup section installed. Between the two quick closing valves, a clear polycarbonate tube having a length of 24 inches (60.96 cm) and a 1 inch (2.54 cm) I.D. was connected as the main two-phase flow holdup section. Two manually operated OMEGA Teflon-PFA type ¼ inch (0.635 cm) valves were equipped with a ¼ inch (0.635 cm) clear tube on the bottom of the clear polycarbonate tube to allow draining of the water trapped between the two quick closing solenoid valves.

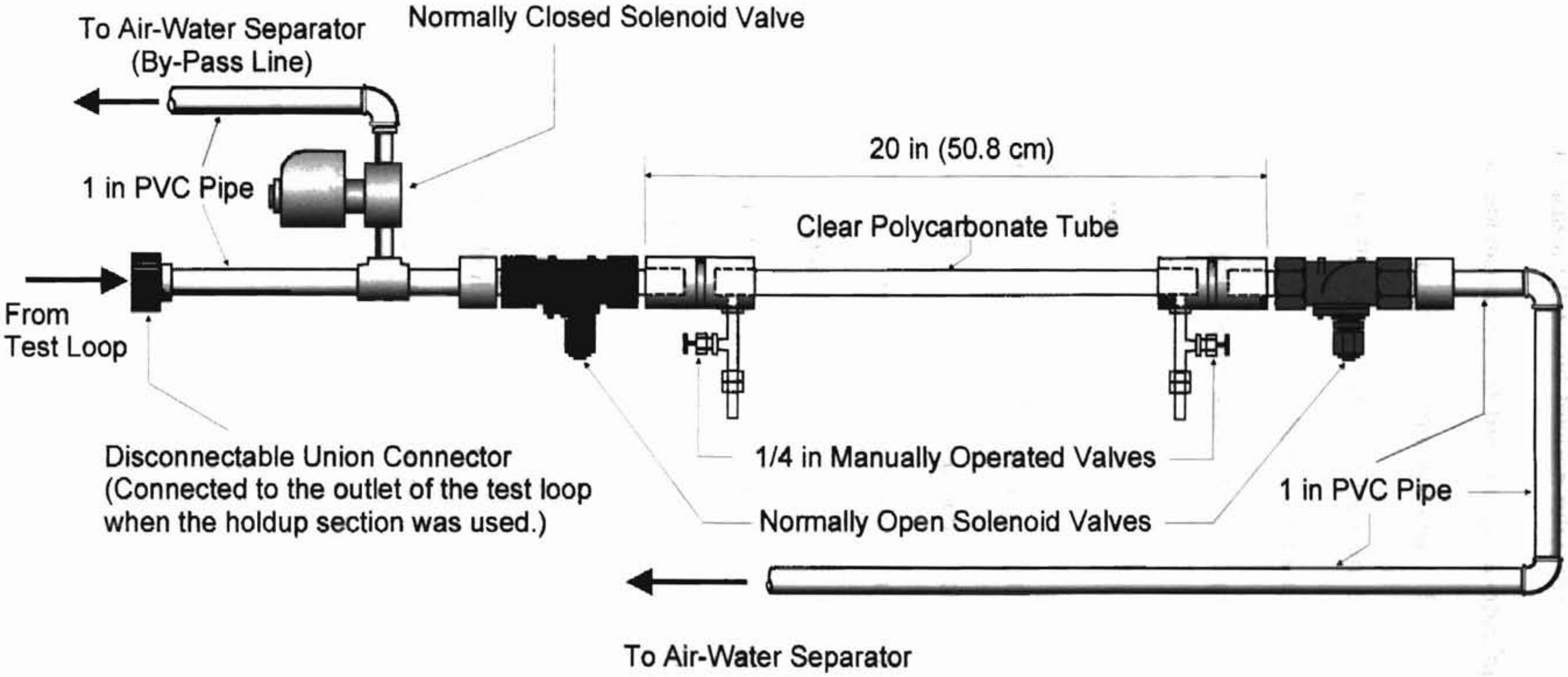


Figure 3.6 Liquid Holdup Section

In order to measure the void fraction ratio, the two quick-closing solenoid valves could be closed instantaneously, and the one quick-opening solenoid valve, which was included in the by-pass line, opened simultaneously. Then, the trapped water was drained through the two Teflon-PFA type valves to measure the volume of water. Knowing the total volume of the holdup section of the tube between the two quick-closing valves and also the volume of the trapped water allowed the computation of the void fraction.

3.1.9 Water Return Line

A 65 gallon cylindrical polyethylene plastic tank was used to separate the air and the water. After separation, the water was sent back to the storage tank by a 1/3 HP centrifugal pump (Pump 3 in Fig. 3.1) that was controlled by the float switch (refer to Section 3.1.1) installed in the storage tank.

Two filter cartridges (model AP110 H/C) were mounted in an Aqua-Pure Filter Housing (model AP12) in order to remove dirt and dust particles from the water in the flow line.

In order to cool the water heated after passing the test section, an ITT Standard model BCF 4063 one shell and two tube pass heat exchanger was used. The heat exchanger was placed on a wooden saw horse for stability. Tap water was used as the cooling water through an Omega FL-9028 rotameter indicating the flow rate in lpm and having a range up to 10 lpm.

3.1.10 Data Acquisition System

An IBM compatible personal computer with 80386 CPU and an 80387 coprocessor was connected to a Cole-Parmer MAC-14 data logger in order to log temperature data from thermocouples and to store the temperature data. The accepted voltage range by the data logger was 0.3 microvolt to 10 volts with an accuracy of ± 0.02 % of full-scale range and 16-bit resolution. Connection between the printer port of the computer and the RS232 port of the data logger was through a shielded cable.

A CIO-AD08 A/D board was installed in another IBM compatible personal computer with an AMD Pentium 233 MHz processor for the measurement of gas and liquid flow rates, gas absolute pressure, system pressure, and the pressure drops from various locations along the test section. The A/D board had a maximum 50 kHz sampling rate, 8 single ended input channels, 12-bit A/D resolution and 7 digital input/output bits.

3.2 Experimental Calibration

In the experimental facility, there were many sensing elements and measuring instruments. To establish the accuracy of the experimental measurements and consequently the results of the heat transfer, every instrument was carefully calibrated. In the experimental facility, the equipment was categorized in six key groups: thermocouples, liquid flow meter, gas flow meter, system pressure transducer, liquid differential pressure transducer, and gas pressure transducer. The procedure adopted for calibration and the results are explained in the following sections.

3.2.1 Thermocouples

The calibration of Thermocouples was performed by Ryali (1999). The detailed information of the progress and results was published in his MS thesis. The description of the calibration of thermocouples in this section is based on his MS thesis.

Before being installed in the facility, the thermocouples, which were used in the experimental setup, were calibrated by means of an FTP System RC-00180-A constant temperature bath with HT-30 fluid. All 56 thermocouples were made for this experiment, and calibrated in the constant temperature bath to check that they worked properly. Among 56 thermocouples, 44 thermocouples were used in the experiments.

In order to read temperatures from those thermocouples, a Model 5100 data logger was used. The thermocouples were divided in two groups (32 and 24 thermocouples) due to the capacity of the data logger, and then tested in the constant temperature bath over a range of 10 °C to 65°C at 5°C intervals. The temperature data read by the data logger and the temperature set by the constant temperature bath were compared. Even though there were slight deviations (± 0.1 °C) in the constant temperature bath, it was assumed to be accurate.

A sample calibration curve for thermocouple (TC) 1 is shown in Fig. 3.7. The calibration curves for all of the other thermocouples used in this setup were almost identical to these in Fig. 3.7 within ± 0.4 °C temperature reading difference. Similarly, the thermocouple probes measuring outlet temperature and gas temperature were also calibrated similarly using the constant temperature bath. The calibration curves for those thermocouple probes were almost identical with Fig. 3.7. In order to examine the behavior of the thermocouples as a function of the temperature of the constant temperature bath, Fig. 3.8 was plotted. From this plot, it is evident that the thermocouples were working well enough to carry out the experiment. Similar plots as to Fig. 3.8 for all of the other 46 thermocouples were also obtained (refer to Appendix D for all of the other thermocouples).

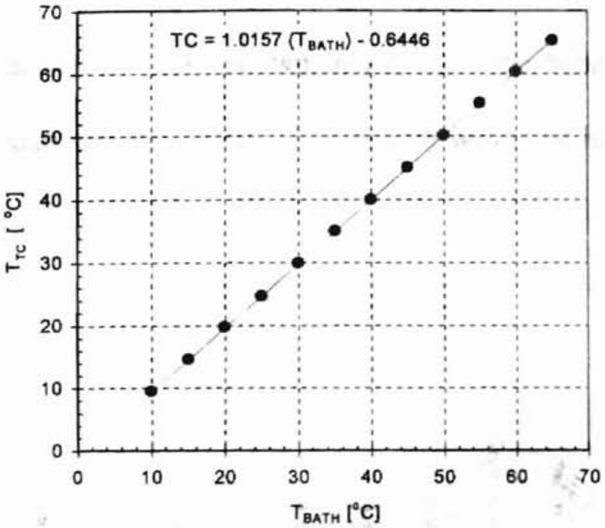


Figure 3.7 Calibration Curve for Thermocouple No. 1

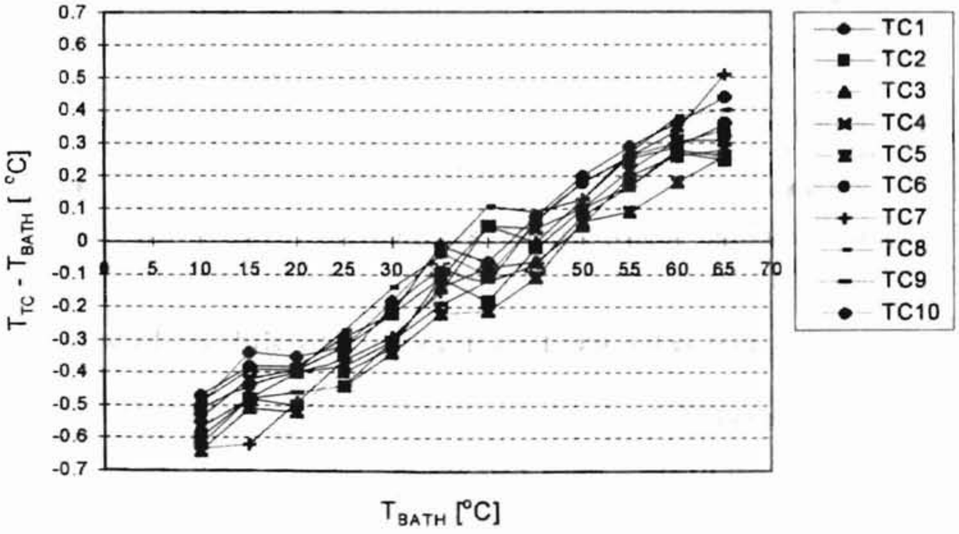


Figure 3.8 Trends of Temperature Difference between Thermocouples (TC) 1 to 10 and the Bath

Figure 3.9 shows the thermocouple behavior after being placed on the test section. The cases shown in Fig. 3.9 were from running under isothermal conditions, and the temperature of each thermocouple station is the average value of four thermocouples spaced circumferentially around the pipe at that station. Station numbers 0 and 11 indicate the inlet and outlet bulk temperature measurement, and the legend indicates Reynolds number of each case. As shown in Fig. 3.9, the behavior of the inlet bulk temperature and thermocouple station nos. 2, 9, and 10 was to be higher or lower than the other stations.

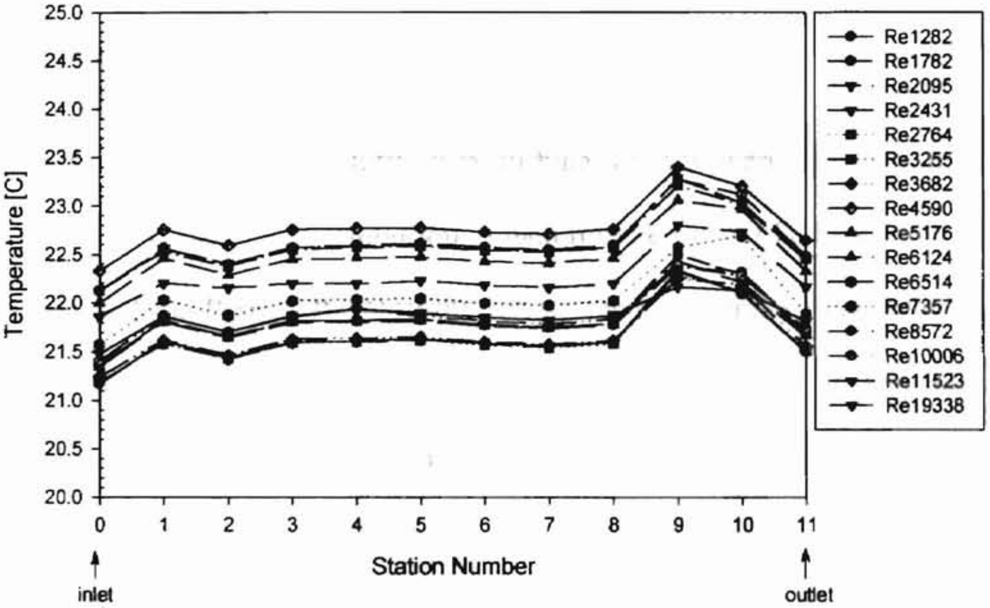


Figure 3.9 Average Wall Temperatures vs. Thermocouple Stations; Isothermal Runs

In the case of the difference between inlet and outlet bulk temperature, this may be explained the effect of the frictional heating or by the different response time between the thermocouple for the inlet and the thermocouple probe for the outlet. It was determined that the probe's response was much slower than that of the thermocouples, so this seemed to be the major source of error. However, the difference between inlet and outlet bulk temperatures was within a range of ± 0.5 °C for all isothermal cases, which was the acceptable reading error of the thermocouple. As shown in Fig. 3.9, the readings of the inlet bulk temperature were always about 0.3 °C higher than those of the outlet bulk temperature in the isothermal cases. The higher inlet temperature may explain that the heat balance errors of the test runs tended to have minus errors as described in Section 5.1.2.2.

In the case of the thermocouple station nos. 2, 9 and 10, the problems with them might have been caused by improper installation of those thermocouples on the test section. Therefore, the information from those stations was excluded from this study.

3.2.2 Liquid Turbine Flow Meters

In the experimental facility, two turbine meters were used to measure the volumetric water flow rate: a Halliburton ½ inch turbine meter (Turbine Flow Meter 1 in Fig. 3.1) and a Cole-Parmer P-33110-00 turbine meter (Turbine Flow Meter 2 in Fig. 3.1). The detailed specifications for those turbine meters are listed in Appendix A. The turbine meters were calibrated using the OMEGA DPF700 rate-meter/totalizer, the CIO-AD08 A/D board with a simple computer code (program CAL-TUB2, see Appendix C), and a five gallon container.

For this calibration, only water was run through the system. The voltage signal converted from the frequency measured in the turbine meters was recorded in a file during the time that the five gallon container was being filled with water. When five gallons of water had been collected, the program recorded the time elapsed and the average frequency determined by using the voltage data and Eq. (3-1).

$$\text{Avg. Frequency} = \frac{\sum \text{Voltage} \times \text{Factor}}{1000} \qquad (3\text{-}1)$$

where Avg. Frequency is an average of the frequency readings over the fill time,

Voltage is a value of the voltage signal acquired by the A/D board,

Factor is a constant to convert from voltage to frequency:

Turbine Flow Meter 1: Factor = 400

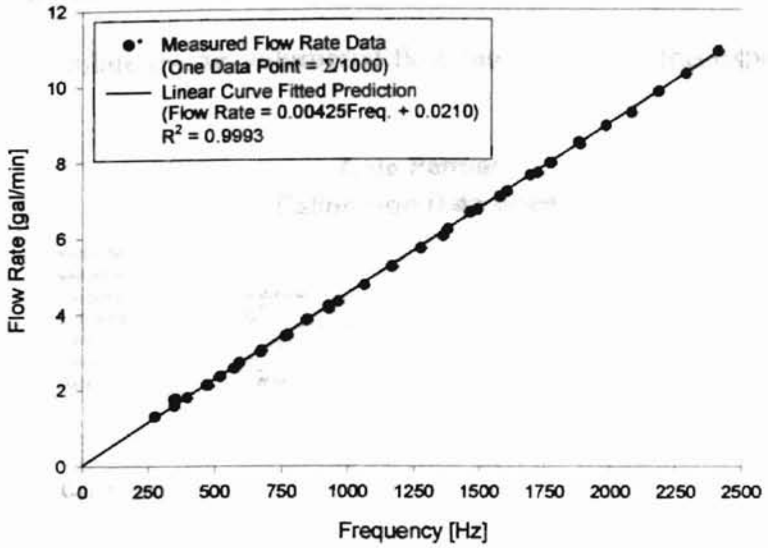
Turbine Flow Meter 2: Factor = 20

Each frequency data point taken for filling the five gallon container was actually the average of one thousand frequency signals acquired using the A/D board and the computer code. The volumetric flow rate was calculated by dividing the five gallon volume by the time required to fill up the container. This procedure was repeated over the useful frequency range (Turbine Flow Meter 1: 300 – 2400 Hz, Turbine Flow Meter 2: 3-100 Hz). The data for volumetric flow rate versus the average frequency was fitted to a linear equation for each turbine meter. Figure 3.10 shows the collected data and the correlated linear fits. The resulting equations were used to calculate the flow rate in gpm.

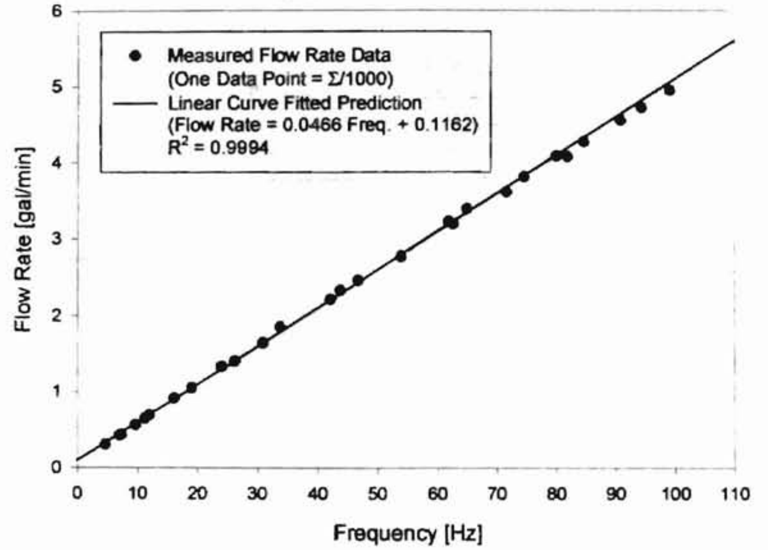
3.2.3 Gas Volumetric Flow Meter

The Cole-Parmer Model 32915 differential pressure flow meter was calibrated by the manufacturer using air in the flow rate range of 0 to 100 lpm as shown in Fig. 3.11. However, the data for the calibration consisted of only four points. Therefore, in order to obtain greater accuracy and produce an equation to calculate air flow rate, more data was required.

The compressed air supplied by the laboratory was used as a source. The voltage signal from the gas flow meter was calibrated against the gas flow rate in lpm displayed on the LCD of the gas flow meter. Using a simple computer code (program GAS-PV2, see Appendix C) and the CIO-AD08 A/D board, the voltage signals and the measured air



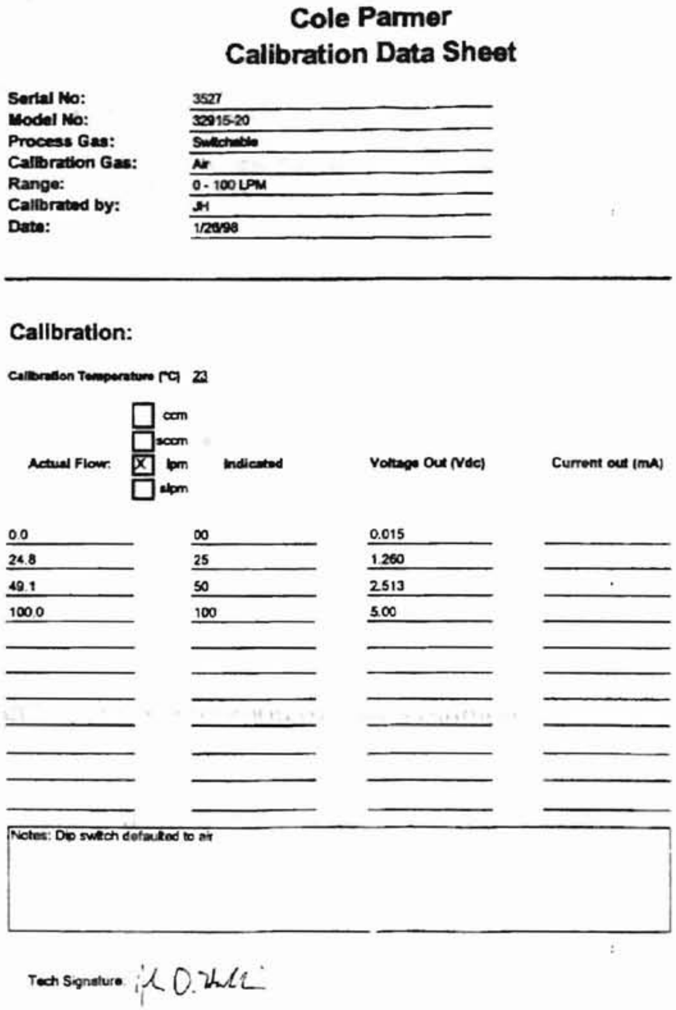
(a) Liquid Turbine Meter 1



(b) Liquid Turbine Meter 2

Figure 3.10 Calibration of Liquid Turbine Meters

flow rates were recorded. After repeating the procedure over the available air flow range up to 100 lpm, the voltage data versus the LCD display of air flow rates were fitted to a linear equation. Figure 3.12 shows the collected data as compared to the equation. In the figure, one data point represents the average value of one thousand acquired voltage values using the program GAS_PV2 and the A/D board. The equation shown on Fig. 3.12 was used to calculate the air volumetric flow rate in lpm for this experiment.



Cole Parmer
Calibration Data Sheet

Serial No: 3527
Model No: 32915-20
Process Gas: Switchable
Calibration Gas: Air
Range: 0 - 100 LPM
Calibrated by: JH
Date: 1/26/98

Calibration:

Calibration Temperature (°C) 23

Actual Flow: ☐ ccm ☐ sccm ☒ lpm ☐ slpm	**Indicated**	**Voltage Out (Vdc)**	**Current out (mA)**
0.0	00	0.015	
24.8	25	1.260	
49.1	50	2.513	
100.0	100	5.00	

Notes: Dip switch defaulted to air

Tech Signature:

Figure 3.11 Factory Calibration Sheet for Gas Volumetric Flow Meter

3.2.4 Absolute Gas Pressure Transducer

To convert volumetric air flow rate into mass flow rate, the air pressure was required, and this information was acquired using an OMEGA PX137-100AV absolute gas pressure transducer. To calibrate this pressure transducer, the laboratory compressed air supply and a U-tube mercury manometer were used. The atmospheric pressure read from a barometer was required to convert the gage pressure acquired by the U-tube mercury manometer to absolute pressure, since the gas pressure transducer was designed to measure absolute pressure.

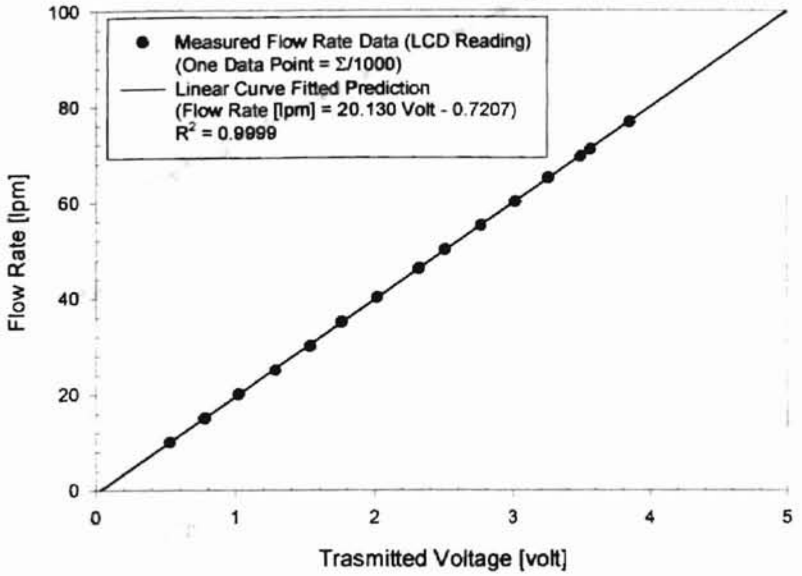


Figure 3.12 Calibration of Gas Volumetric Flow Meter

The voltage signals from the transducer and the measured gage pressure from a U-tube mercury manometer were recorded using the CIO-AD08 A/D board and a program GAS-PV2 (see Appendix C). Then, the program GAS-PV2 converted the gage pressure to absolute pressure using that day's atmospheric pressure. This procedure was repeated over the available pressure range (up to 35 psia) of the U-tube mercury manometer. Figure 3.13 shows the voltage data from the absolute pressure transducer versus the measured absolute pressure using the mercury manometer, as well as the resulting linear curve-fit. In the figure, each voltage data point represents the average value of one thousand data samples collected by the A/D board and the program GAS-PV2. The resulting equation was used to calculate the absolute gas pressure in psia.

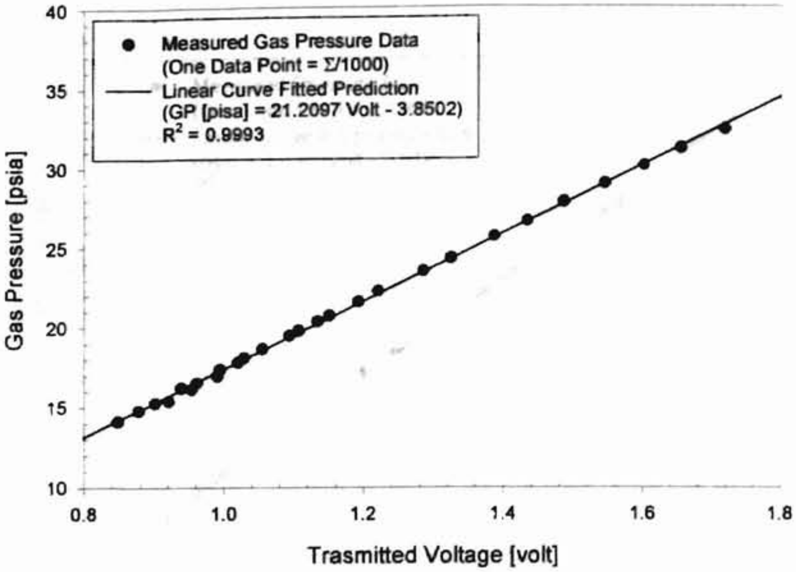


Figure 3.13 Calibration of Absolute Gas Pressure Transducer

3.2.5 System Pressure Transducer

In order to measure the system pressure of the test section, an OMEGA PX242-060G pressure transducer was used. The calibration procedure for the system pressure transducer was same as that of the absolute gas pressure transducer, except for conversion of the measured pressure to absolute pressure. According to the specifications of the system pressure transducer, it was capable of handling both air and water. Therefore, for convenience in the calibration procedure, laboratory compressed air was used as a pressure source.

Figure 3.14 shows the measured pressure data using a U-tube mercury manometer versus the voltage data (one thousand sample acquisitions per data point) using a simple computer code (program LIQ_PSI, see Appendix C) and the A/D board. The resulting linear curve-fit is also shown in Fig. 3.14. This linear equation was used to calculate the system pressure in psig.

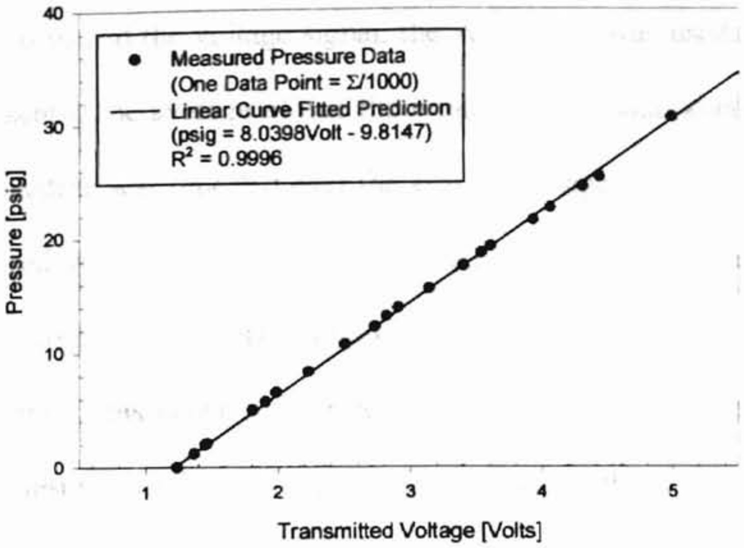


Figure 3.14 Calibration of System Pressure Transducer

3.2.6 Differential Pressure Transducer

A Validyne DP15 differential pressure transducer was calibrated using an inverted U-tube manometer for comparison with the voltage signal from the differential pressure transducer. To produce a pressure drop, water was run through the test section, and the lines from the reference pressure tap and pressure tap No. 10 (refer to Fig. 3.5) were directly connected to the differential pressure transducer and to the manometer. In order to prevent air from getting into these pressure taps and tubing lines, the pressure taps were located at the bottom of the test section as mentioned in the experimental setup in Chapter II. Moreover, only water was run in the experimental setup during a calibration. To get an appropriate gain from the differential pressure transducer, a DP15 No. 20 diaphragm (range up to 5.5 inches of water) was used.

After the single-phase flow system reached steady-state, the voltage signal from the differential pressure transducer and the measured differential pressure from the manometer were recorded using a simple computer code (program CA_PV_LQ, see Appendix C). To record the voltage signal, the A/D board was used, and one recorded data point represented the average of one thousand sampled data points through the A/D board. This procedure was repeated over the available range of 0 to 1.6 inches of water. Using the acquired voltage data and the measured pressure differences, a linear curve-fitted equation relating the two was developed. Figure 3.15 shows the collected data and the curve-fitted line. This linear curve-fitted equation was used to calculate the pressure drop through the test section for single-phase and two-phase flows.

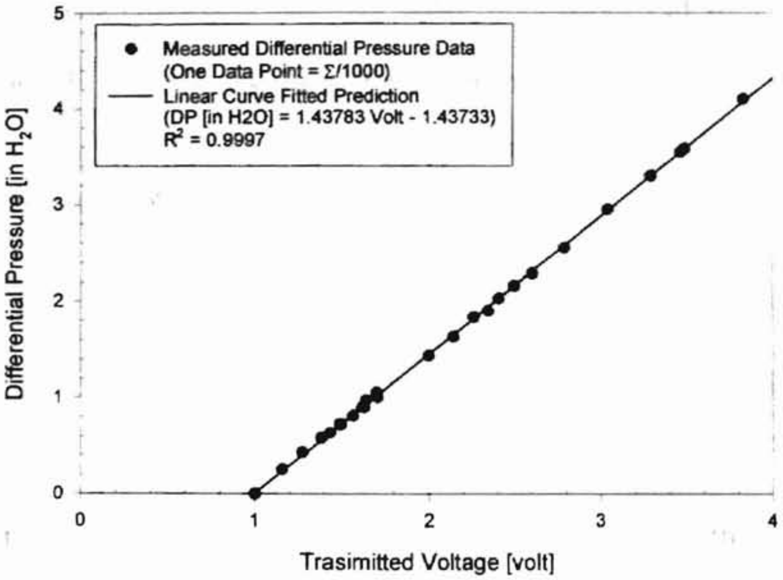


Figure 3.15 Calibration of Differential Pressure Transducer

CHAPTER IV

EXPERIMENTAL PROCEDURE AND DATA REDUCTION

4.1 Experimental Procedure

This chapter explains the procedure used in collecting the experimental data. The system warm up, data collection, and shut down were conceived with consideration for accuracy, repeatability, safety, and ease of performance.

4.1.1 Observation of Flow Patterns

In this study, even though the two-phase flow heat transfer measurements were not performed, the observation of two-phase flow patterns was needed in preparation for future testing.

These procedures had to be performed independently for the acquisition of the two-phase heat transfer data. This was due to the fact that, during actual heat transfer runs, the clear tubing was covered with the insulation. Therefore, a procedure was needed in order to build a flow pattern map so that the map could be used to predict the two-phase flow patterns since it would not be possible to simultaneously observe the flow pattern while taking two-phase flow heat transfer data (refer to Fig. 3.1 for location of components mentioned in this procedure).

(1) The atmospheric pressure of the day was measured and recorded.

(2) All necessary instruments were turned on and a 10 minute stabilization period was allowed for all instruments; then the initial conditions for all of them were confirmed.

(3) The cooling water from the city tap to the heat exchanger was turned on and adjusted to a rate of 10 lpm.

(4) Pump 1 or 2 (depending on the desired water flow rate) was started with the by-pass valve fully open.

(5) The air supply valve was opened and adjusted to 5 gpm in order to avoid sudden pressure loads on the test loop.

(6) The desired water flow rate was set by adjusting the control valve and the by-pass valve, based on the frequency displayed on the totalizer.

(7) The desired air flow rate was set by adjusting the control valve based on the flow rate displayed on the LCD of the gas flow rate meter.

(8) The liquid flow rate was adjusted again.

(9) Program RTG (bundle software for monitoring the MAC-14 data logger output) was started and the inlet and the outlet bulk temperatures were monitored.

(10) The system was then allowed to stabilize and reach steady-state.

(11) Program Bptt17 (for measuring flow properties; refer to Appendix C for the code) was then ready to acquire data.

(12) The two-phase flow pattern was carefully observed by eye and recorded while program Bptt17 took the necessary data.

(13) Programs Bptt17 and RTG were shut down, and then the acquired data was saved in a file with an appropriate name.

(14) The by-pass valve in the liquid line was fully opened in order to prevent the hammer effect.

(15) The liquid pump was turned off. The check valve in the liquid supply line prevented any air from entering the liquid supply line.

(16) After all of the liquid was removed in the test line, the air supply valve was closed.

(17) The cooling water to the heat exchanger was turned off.

4.1.2 Void Fraction Measurements

These procedures were also performed independently from the acquisition of the two-phase heat transfer data. These void fraction measurements for two-phase flow were used in order to verify that one or more of the correlations could predict void fraction ratio for use in the calculation for two-phase flow heat transfer (refer to Fig. 3.1 for location of components mentioned in this procedure).

(1) The void fraction measurement section (refer to Fig. 3.6) was connected to the experimental setup.

(2) The atmospheric pressure of the day was recorded.

(3) The cooling water from the tap to the heat exchanger was turned on.

(4) All necessary instruments were turned on and about 10 minutes was allowed for stabilization of all instruments. Then the initial conditions of these instruments were confirmed.

(5) The cooling water from the city tap to the heat exchanger was turned on and adjusted at 10 lpm.

(6) Pump 1 or 2 (depending on the desired water flow rate) was started with the by-pass valve fully open.

(7) The air supply valve was opened and adjusted to 5 gpm in order to avoid sudden pressure loads on the test loop.

(8) The desired water flow rate was set by adjusting the control valve and the by-pass valve, based on the frequency displayed on the totalizer.

(9) The desired air flow rate was set by adjusting the control valve, based on the flow rate displayed on the LCD of the gas flow rate meter.

(10) The liquid flow rate was adjusted again.

(11) Program RTG (bundle software for monitoring the MAC-14 data logger output) was started and the inlet and the outlet bulk temperatures were monitored.

(12) The system was allowed to stabilize and reach steady-state.

(13) The data were acquired and saved in files using program Bptt17 (refer to Appendix C for the code).

(14) The holdup solenoid-valves were closed and the by-pass solenoid-valve was opened electronically and simultaneously (refer to Fig. 3.6).

(15) All water in the holdup section was withdrawn (drained using valves on the bottom of the section) and the volume of the withdrawn water was measured and recorded.

(16) Then all solenoid-valves were reset to their original positions.

(17) The system was allowed to stabilize and reach steady-state.

(18) Steps 13 to 17 of this procedure were repeated four times and the four volumes of withdrawn water were averaged later.

(19) RTG was stopped, and then the acquired data was saved in a file with an appropriate name.

(20) The by-pass valve in the liquid line was fully opened in order to prevent the hammer effect.

(21) The liquid pump was turned off. The check valve in the liquid supply line prevented any air from entering the liquid supply line.

(22) After all liquid was removed from the test line, the air supply valve was closed.

(23) The cooling water to the heat exchanger was turned off.

4.1.3 Pressure Drop and Heat Transfer Measurements

The procedure to start up the experimental setup and to prepare for the experiment was simple and is listed as follows transfer (refer to Fig. 3.1 for location of components mentioned in this procedure):

(1) The atmospheric pressure of the day was measured and recorded.

(2) All necessary instruments were turned on and about 10 minutes was allowed for stabilization of all instruments. Then the initial conditions of these instruments were confirmed.

(3) The cooling water from the tap to the heat exchanger was turned on and adjusted to 10 lpm.

(4) Pump 1 or 2 (depending on the desired water flow rate) was started with the by-pass valve fully open.

(5) All pressure taps and lines were checked for the presence of any air bubbles and purged if necessary.

(6) The desired liquid flow rate was set by adjusting the control valve, based on the frequency displayed on the flow rate monitor.

(7) Program RTG (bundle software for monitoring the MAC-14 data logger output) was brought up on the computer and the inlet and outlet bulk temperatures were monitored.

(8) The inlet, outlet, and tank temperatures were allowed to stabilize.

(9) The power supply to heat the test section was turned on and adjusted to the desired power.

(10) The system was allowed to come to steady-state conditions.

These steps were sufficient for the single-phase flow study. For two-phase experiments, the following additional procedures were required.

(10-1) The air supply valve was opened.

(10-2) The desired air flow rate was set by adjusting the control valve, based on the flow rate displayed on the LCD of the gas volumetric flow rate meter.

(10-3) The liquid flow rate was adjusted again to get the desired value.

The steps to acquire the data for pressure drop and heat transfer were as follows:

(1) The temperature data was displayed on a monitor and saved in a file by program RTG, which monitored the outputs from the MAC-14 data logger.

(2) When the first and the last thermocouple station temperatures and the inlet and outlet bulk temperatures all indicated less than 0.3 °F deviation over a five minute period, steady-state conditions were assumed to exist.

(3) The flow properties, such as the flow rate, pressure of air and water, and pressure drops along the test section were read and recorded in files by program Bptt17. (It took about 20 minutes to acquire one set of pressure drop data; refer to Appendix C for the code.)

(4) The frequency displayed on the totalizer, the air flow rate displayed on the LCD of the gas flow meter, the water inlet temperature, the gas inlet temperature, the data file name, and the flow pattern observed (for two-phase flow) were recorded on the data log sheet.

(5) The voltage read from the digital voltmeter and the amperage read from the ammeter were recorded every 2 minutes.

(6) After program Bptt17 finished, the temperature data acquired by program RTG was also saved in a file by run number.

(7) All data were saved with the proper name.

The steps to shut down the experimental setup were as follows:

(1) The electrical power to the test section was turned off.

(2) The by-pass valve in the liquid line was fully opened in order to prevent the hammer effect.

(3) The liquid pump was turned off. The check valve in the liquid supply line prevented any air from entering the liquid supply line.

(4) After all liquid was removed from the test line, the air supply valve was closed.

(5) The cooling water to the heat exchanger was turned off.

(6) All instruments were turned off.

(7) The test section apparatus was inspected in order to insure that no leaks had become evident.

4.2 Data Reduction and Heat Transfer Calculation

The experimental procedure for a uniform wall heat flux boundary condition consists of measuring the tube outside wall surface temperature at discrete locations and the inlet and outlet bulk temperatures in addition to other measurements, such as gas flow rate (for two-phase flows), liquid flow rates, room temperature, voltage drop and current in the test section. The local peripheral heat transfer coefficient and the local Nusselt number thereafter were calculated based on the prediction of the pipe inside wall surface temperature. Since measurement of the inside wall temperature was difficult, it was calculated from the measurement of the outside wall temperature, the heat generation within the pipe wall, and the thermophysical properties of the pipe material, such as electrical resistivity and thermal conductivity.

Ghajar and Zurigat (1991) developed an interactive computer program, RHt98F (see Appendix C for the program code), to calculate the local inside wall temperatures and local peripheral heat transfer coefficients from local outside wall temperatures measured at different axial locations along an electrically heated horizontal circular tube. The test fluids used were water and mixtures of ethylene glycol and water. The main ideas of Ghajar and Zurigat's (1991) program were adapted to this study and will be introduced in the following sections.

Program RHt98F consisted of four segments: the input data, the finite-difference formulations, the physical properties and the output.

4.2.1 Input Data

The inputs for program RHt98F included the type of test fluid, the voltage drop, the current, the volumetric flow rate, the bulk fluid temperature at the inlet and outlet, and the outside wall temperature data for all thermocouple locations. These input data were obtained in a specified format by another computer program, Datared98F (see Appendix C for the program code) which directly took all of the necessary information from the experimental measurements.

4.2.2 Finite Difference Formulation

The numerical solution of the conduction equation with internal heat generation and variable thermal conductivity and electrical resistivity was based on the following assumptions:

(1) Steady-state conditions exist.

(2) Peripheral and radial wall conduction exist.

(3) Axial conduction is negligible.

(4) The electrical resistivity and thermal conductivity of the tube wall are functions of temperature.

Based on the above assumptions, the expressions for calculation of the local inside wall temperatures, heat flux, and local and average peripheral heat transfer coefficients are presented next.

4.2.2.1 Calculation of the Local Inside Wall Temperature and the Local Inside Wall Heat Flux

The heat balance on a segment of the tube wall at any particular station is given by (see Fig. 4.1)

$$\dot{q}_g = \dot{q}_1 + \dot{q}_2 + \dot{q}_3 + \dot{q}_4 \tag{4-1}$$

From Fourier's law of heat conduction in a given direction *n*, we know that

$$\dot{q} = -kA\frac{dT}{dn} \tag{4-2}$$

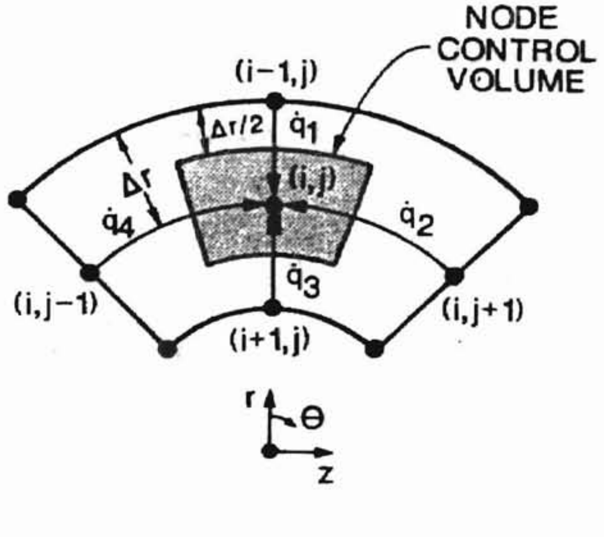


Figure 4.1 Finite-Difference Grid Arrangement (Ghajar and Zurigat, 1991)

Now substituting Fourier's law and applying the finite-difference formulation for the radial (i) and peripheral (j) directions in Eq. (4-1), we obtain:

$$\dot{q}_1 = \frac{(k_{i,j} + k_{i-1,j})}{2} \frac{2\pi(r_i + \Delta r/2)\Delta z}{N_{TH}} \frac{(T_{i,j} - T_{i-1,j})}{\Delta r} \tag{4-3}$$

$$\dot{q}_2 = \frac{(k_{i,j} + k_{i,j+1})}{2} (\Delta r \Delta z) \frac{(T_{i,j} - T_{i,j+1})}{2\pi r_i / N_{TH}} \tag{4-4}$$

$$\dot{q}_3 = \frac{(k_{i,j} + k_{i+1,j})}{2} \frac{2\pi(r_i - \Delta r/2)\Delta z}{N_{TH}} \frac{(T_{i,j} - T_{i+1,j})}{\Delta r} \tag{4-5}$$

$$\dot{q}_4 = \frac{(k_{i,j} + k_{i,j-1})}{2} (\Delta r \Delta z) \frac{(T_{i,j} - T_{i,j-1})}{2\pi r_i / N_{TH}} \tag{4-6}$$

Heat generated in the i, j elemental volume is given by:

$$\dot{q}_g = I^2 R \tag{4-7}$$

Substituting $R = \gamma l / A$ and $A = (2\pi r_i / N_{TH})\Delta r$ into Eq. (4-7) gives:

$$\dot{q}_g = I^2 \frac{\gamma \Delta z}{(2\pi r_i / N_{TH})\Delta r} \tag{4-8}$$

Substituting Eqs. (4-3) to (4-6) and (4-8) into Eq. (4-1) and solving for $T_{i+1,j}$ gives:

$$T_{i+1,j} = T_{i,j} - \left\{ \begin{array}{l} \dfrac{I^2 \gamma N_{TH}}{2\pi r_i \Delta r} - (k_{i,j} + k_{i-1,j}) \dfrac{\pi(r_i + \Delta r/2)}{\Delta r N_{TH}} (T_{i,j} - T_{i-1,j}) \\ - (k_{i,j} + k_{i+1,j}) \dfrac{\Delta r N_{TH}}{4\pi r_i} (T_{i,j} - T_{i,j+1}) \\ - (k_{i,j} + k_{i,j-1}) \dfrac{\Delta r N_{TH}}{4\pi r_i} (T_{i,j} - T_{i,j-1}) \end{array} \right] \left\{ (k_{i,j} + k_{i+1,j}) \frac{\pi(r_i - \Delta r/2)}{\Delta r N_{TH}} \right\} \tag{4-9}$$

Equation (4-9) was used to calculate the temperature of the interior nodes. In this equation, the thermal conductivity and electrical resistivity of each node's control volume were determined as a function of temperature from following equations for 316 stainless steel (Ghajar and Zurigat, 1991).

$$k = 7.27 + 0.0038T \tag{4-10}$$

$$\gamma = 27.67 + 0.0213T \tag{4-11}$$

where T is in °F, k is in Btu/hr-ft-°F, and γ is in μΩ-in. Once the local inside wall temperatures were calculated from Eq. (4-9), the local peripheral inside wall heat flux could be calculated from the heat balance equation (see Eq. (4-1)).

4.2.2.2 Calculation of the Local Peripheral and Local Average Heat Transfer Coefficients

From the local inside wall temperature, the local peripheral inside wall heat flux and the local bulk fluid temperature, the local peripheral heat transfer coefficient could be calculated as follows:

$$h_i = \dot{q}_i''/(T_{wi} - T_b) \tag{4-12}$$

Note that, in this analysis, it was assumed that the bulk temperature increases linearly from the inlet to the outlet according to the following equation:

$$T_b = T_{in} + (T_{out} - T_{in})x/L \tag{4-13}$$

The local average heat transfer coefficient at each station could be calculated by the following equation:

$$\bar{h}_i = \overline{\dot{q}_i''}/(\bar{T}_{wi} - T_b) \tag{4-14}$$

4.2.3 Physical Properties of the Fluids

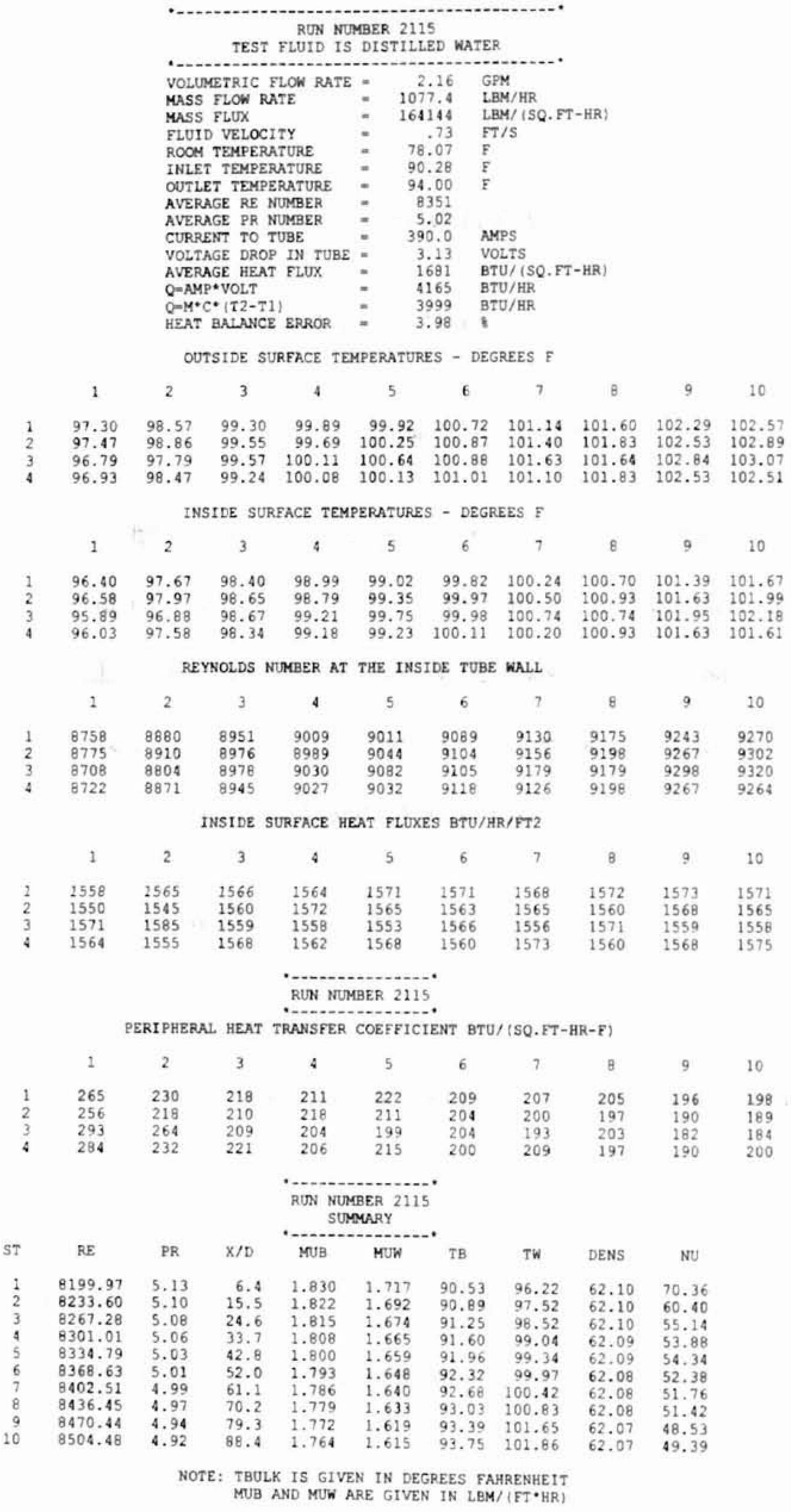
The correlation equations for the test fluids are based on the information given in Table 4.1.

4.2.4 Output

Figure 4.2 shows a sample output data file using program RHt98F. The output data files starts with a summary of information of the experiment, such as the experimental run number, mass flow rate, fluid velocity, room temperature, average Reynolds number, average Prandtl number, current, voltage drop, average heat flux, and heat balance error. Then, the program output lists results of an experiment use, for example, the calculated inside wall temperatures, Reynolds numbers, the inside surface peripheral heat fluxes and heat transfer coefficients, and so on.

Table 4.1 Physical Properties of the Test Fluids

Fluid	Equation for the Physical Property (T = Temperature in °F except where noted)	Range of Validity & Accuracy	Source
Air	ρ (lb_m/ft^3) = p/RT	p ≤150 psi	Vijay (1978)
	where p is in lb_f/ft^2, T is in °R, and R = 53.34 ft-lb_f/lb_m-°R		
	C_p (Btu/lb_m-°F) = $7.540\times10^{-6}T + 0.2401$	$-10 \le T \le 242$, 0.2 %	
	μ (lb_m/ft-hr) = $-2.637\times10^{-8}T^2 + 6.819\times10^{-5}T + 0.03936$	$-10 \le T \le 242$, 0.1 %	
	k (Btu/hr-ft-°F) = $-6.154\times10^{-9}T^2 + 2.591\times10^{5}T + 0.01313$	$-10 \le T \le 242$, 0.2 %	
Water	ρ (lb_m/ft^3) = $(2.101\times10^{-8}T^2 - 1.303\times10^{-6}T + 0.01602)^{-1}$	$32 \le T \le 212$, 0.1 %	Vijay (1978)
	C_p (Btu/lb_m-°F) = $1.337\times10^{-6}T^2 - 3.374\times10^{-4}T + 1.018$	$32 \le T \le 212$, 0.3 %	
	μ (lb_m/ft-hr) = $(1.207\times10^{-5}T^2 + 3.863\times10^{-3}T + 0.0946)^{-1}$	$32 \le T \le 212$, 1.0 %	
	k (Btu/hr-ft-°F) = $4.722\times10^{-4}T + 0.3149$	$32 \le T \le 212$, 0.2 %	



```
                    *----------------------------------------*
                               RUN NUMBER 2115
                         TEST FLUID IS DISTILLED WATER
                    *----------------------------------------*
                    VOLUMETRIC FLOW RATE =      2.16   GPM
                    MASS FLOW RATE       =    1077.4   LBM/HR
                    MASS FLUX            =    164144   LBM/(SQ.FT-HR)
                    FLUID VELOCITY       =       .73   FT/S
                    ROOM TEMPERATURE     =     78.07   F
                    INLET TEMPERATURE    =     90.28   F
                    OUTLET TEMPERATURE   =     94.00   F
                    AVERAGE RE NUMBER    =      8351
                    AVERAGE PR NUMBER    =      5.02
                    CURRENT TO TUBE      =     390.0   AMPS
                    VOLTAGE DROP IN TUBE =      3.13   VOLTS
                    AVERAGE HEAT FLUX    =      1681   BTU/(SQ.FT-HR)
                    Q=AMP*VOLT           =      4165   BTU/HR
                    Q=M*C*(T2-T1)        =      3999   BTU/HR
                    HEAT BALANCE ERROR   =      3.98   %

                     OUTSIDE SURFACE TEMPERATURES - DEGREES F

         1       2       3       4       5       6       7       8       9      10

1    97.30   98.57   99.30   99.89   99.92  100.72  101.14  101.60  102.29  102.57
2    97.47   98.86   99.55   99.69  100.25  100.87  101.40  101.83  102.53  102.89
3    96.79   97.79   99.57  100.11  100.64  100.88  101.63  101.64  102.84  103.07
4    96.93   98.47   99.24  100.08  100.13  101.01  101.10  101.83  102.53  102.51

                     INSIDE SURFACE TEMPERATURES - DEGREES F

         1       2       3       4       5       6       7       8       9      10

1    96.40   97.67   98.40   98.99   99.02   99.82  100.24  100.70  101.39  101.67
2    96.58   97.97   98.65   98.79   99.35   99.97  100.50  100.93  101.63  101.99
3    95.89   96.88   98.67   99.21   99.75   99.98  100.74  100.74  101.95  102.18
4    96.03   97.58   98.34   99.18   99.23  100.11  100.20  100.93  101.63  101.61

                     REYNOLDS NUMBER AT THE INSIDE TUBE WALL

         1       2       3       4       5       6       7       8       9      10

1     8758    8880    8951    9009    9011    9089    9130    9175    9243    9270
2     8775    8910    8976    8989    9044    9104    9156    9198    9267    9302
3     8708    8804    8978    9030    9082    9105    9179    9179    9298    9320
4     8722    8871    8945    9027    9032    9118    9126    9198    9267    9264

                      INSIDE SURFACE HEAT FLUXES BTU/HR/FT2

         1       2       3       4       5       6       7       8       9      10

1     1558    1565    1566    1564    1571    1571    1568    1572    1573    1571
2     1550    1545    1560    1572    1565    1563    1565    1560    1568    1565
3     1571    1585    1559    1558    1553    1566    1556    1571    1559    1558
4     1564    1555    1568    1562    1568    1560    1573    1560    1568    1575

                               *---------------*
                                RUN NUMBER 2115
                               *---------------*
                PERIPHERAL HEAT TRANSFER COEFFICIENT BTU/(SQ.FT-HR-F)

         1       2       3       4       5       6       7       8       9      10

1      265     230     218     211     222     209     207     205     196     198
2      256     218     210     218     211     204     200     197     190     189
3      293     264     209     204     199     204     193     203     182     184
4      284     232     221     206     215     200     209     197     190     200

                               *---------------*
                                RUN NUMBER 2115
                                    SUMMARY
                               *---------------*
ST      RE        PR     X/D     MUB     MUW      TB      TW    DENS      NU

 1   8199.97    5.13     6.4   1.830   1.717   90.53   96.22   62.10   70.36
 2   8233.60    5.10    15.5   1.822   1.692   90.89   97.52   62.10   60.40
 3   8267.28    5.08    24.6   1.815   1.674   91.25   98.52   62.10   55.14
 4   8301.01    5.06    33.7   1.808   1.665   91.60   99.04   62.09   53.88
 5   8334.79    5.03    42.8   1.800   1.659   91.96   99.34   62.09   54.34
 6   8368.63    5.01    52.0   1.793   1.648   92.32   99.97   62.08   52.38
 7   8402.51    4.99    61.1   1.786   1.640   92.68  100.42   62.08   51.76
 8   8436.45    4.97    70.2   1.779   1.633   93.03  100.83   62.08   51.42
 9   8470.44    4.94    79.3   1.772   1.619   93.39  101.65   62.07   48.53
10   8504.48    4.92    88.4   1.764   1.615   93.75  101.86   62.07   49.39

                     NOTE: TBULK IS GIVEN IN DEGREES FAHRENHEIT
                           MUB AND MUW ARE GIVEN IN LBM/(FT*HR)
```

Figure 4.2 A Sample Output Data File from Program RHt98F

CHAPTER V

RESULTS AND DISCUSSION

5.1 Single-Phase Flow

To verify the quality of the experimental setup for future two-phase heat transfer measurement, all classical single-phase heat transfer and pressure drop measurements were performed. The data from the single-phase heat transfer and pressure drop measurements were compared with well-known correlations, and the performance of the experimental setup was verified based on these results.

5.1.1 Single-Phase Flow Pressure Drop Measurement

Figure 5.1 shows the acquired pressure difference data from each pressure tap compared to the reference pressure tap along the test section for some turbulent cases. As shown in Fig. 5.1, the slopes of the pressure differences from pressure tap numbers 3 to 10 were relatively constant, which helped to estimate the pressure drop and the friction factor. Therefore, to determine pressure drop and hence fiction factor, only the information acquired from pressure tap numbers 3 to 8 were used, and the other taps were ignored.

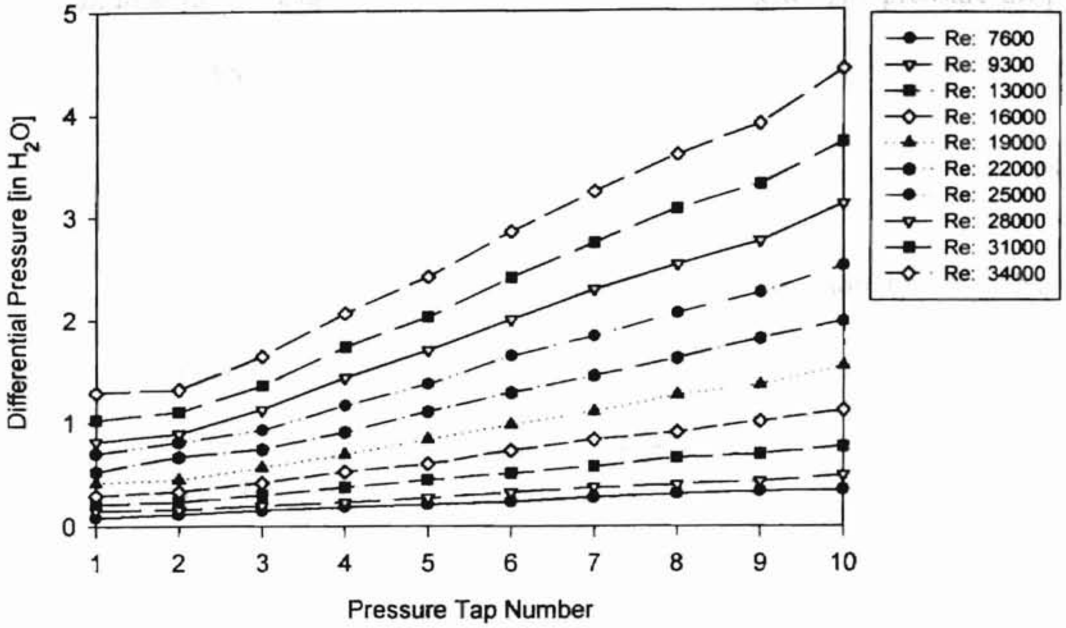


Figure 5.1 Profiles of Differential Pressure along the Test Section

The measurement of pressure drop covered all of the range of the capacity of the experimental setup. They were divided to two categories; the laminar flow case and the turbulent flow case. In the laminar flow case, the range of Reynolds number was up to about 3,500 (including some transitional cases) and the case of turbulent flow was from about 3,500 to 35,000.

5.1.1.1 Laminar Flow Cases

The fully developed entry length for the laminar flow case was calculated using a simple equation introduced by Kays and Crawford (1993);

$$(x / D_i)_{entry} = 0.05\,\mathrm{Re} \tag{5-1}$$

According to Eq. (5-1), the required $(x/D_i)_{entry}$ for laminar flow with a Reynolds number of 2300 is 115. This indicates that the test section for the experimental setup (L/D_i =

94.1) has an insufficient length for fully developed laminar flow. The pressure drop from 0 to x can be calculated from

$$\Delta p_{cal} = 4\bar{c}_{f_{app}} \frac{\rho V^2}{2} \frac{x}{D_i} \tag{5-2}$$

where $\bar{c}_{f_{app}}$ is the apparent friction factor, and a curve-fit equation for $\bar{c}_{f_{app}}$ has been suggested by Shah (1978):

$$\bar{c}_{f_{app}} \mathrm{Re}_D = \frac{3.44}{\zeta^{0.5}} + \frac{0.31/\zeta + 16 - 3.44/\zeta^{0.5}}{1 + 0.00021/\zeta^2} \tag{5-3}$$

where ζ is the friction parameter, $(x/D_i)/\mathrm{Re}_D$.

A total of 12 data sets (5 laminar cases and 7 transition cases) were analyzed for pressure drop, and 5 laminar cases were investigated for apparent friction coefficient. As shown in Figs. 5.2 and 5.3, the predictions of Δp and $c_{f_{app}}$ using Shah's (1978) correlation did not demonstrate good agreement with the experimental data. The experimental pressure drop data for laminar flow ranged from 0.0840 in H_2O to 0.1725 in H_2O (refer to Appendix B for the detailed data). Based on the instrument accuracy of the differential pressure transducer (refer to Appendix A), a probable error range of 8 % to 16.4 % may be applicable to the pressure drop data. Even if this probable error range was attributed to the experimental data, the results shown in Figs. 5.2 and 5.3 indicate that the predictions of Δp and $c_{f_{app}}$, using Shah's (1978) correlation, deviated too much from the experimental values to be acceptable.

Ghajar and Madon (1992) investigated the validity of Shah's (1978) correlation with two extreme inlets (reentrant and bell-mouth) and concluded that Shah's (1978) correlation well predicted the apparent friction coefficients only for the bell-mouth inlet condition with Reynolds numbers greater than 1,500. The results shown in this study also indicated that Shah's (1978) correlation did not predict the apparent friction coefficient accurately.

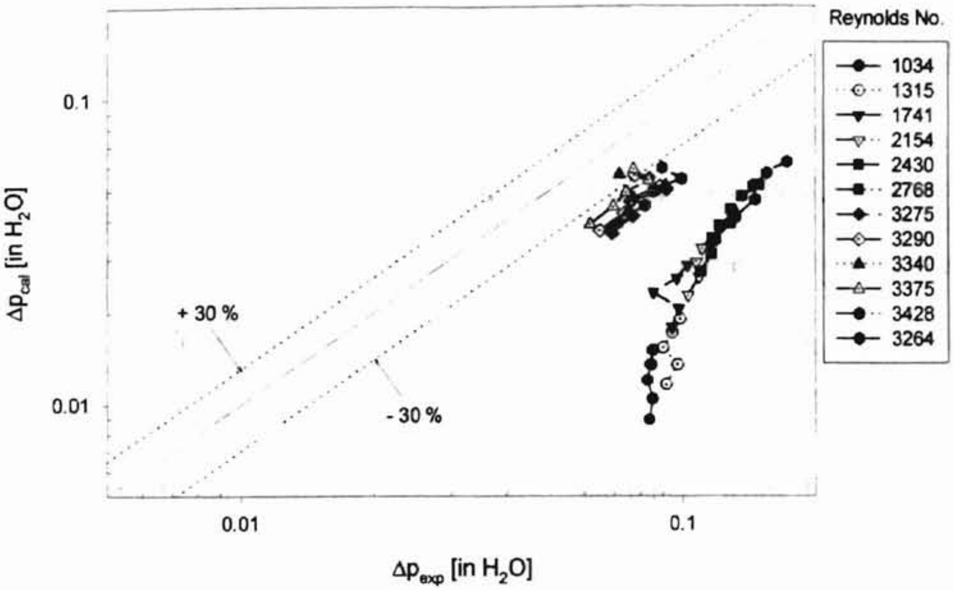


Figure 5.2 Comparison of Δp_{exp} with Δp_{cal} for Laminar Flow Cases

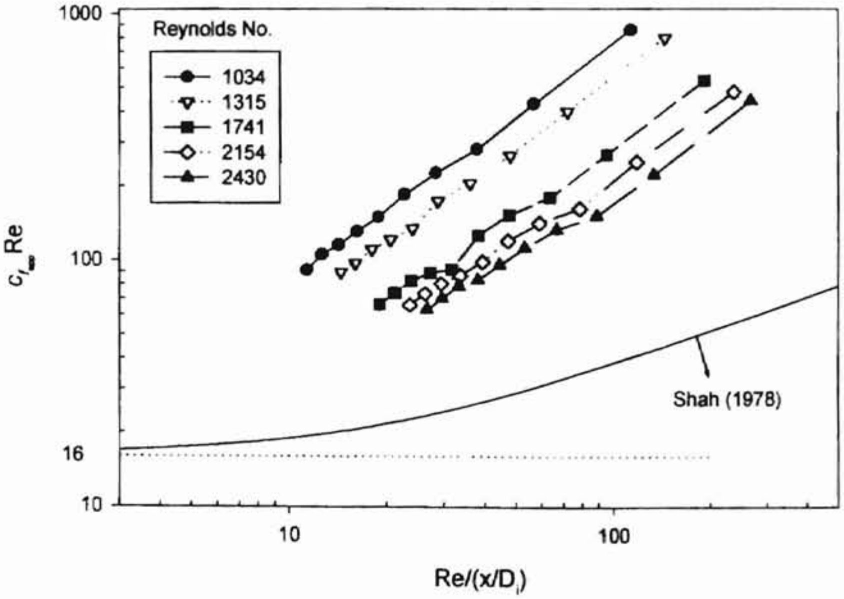


Figure 5.3 Comparison of Experimental Apparent Friction Coefficient with the Prediction using Shah (1978) Correlation

5.1.1.2 Turbulent Flow Cases

The entry length for the fully developed turbulent flow was calculated using a simple equation introduced by Kays and Crawford (1993);

$$(x/D_i)_{entry} = 0.623\,\mathrm{Re}^{0.25} \tag{5-4}$$

When Reynolds number is 40,000, the required $(x/D_i)_{entry}$ will be 8.81. This indicates that all pressure taps along the test section were located sufficiently beyond the entry length for the fully developed flow in the case of turbulent flow [$(x/D_i)_{\mathrm{tap}\ 1} = 9.12$; the detailed dimensions of the pressure taps were described in the experimental setup, Chapter III].

The predicted pressure drops were calculated from the following equation proposed by White (1994):

$$\Delta p_{cal} \approx 0.158 L \rho^{3/4} \mu^{1/4} D_i^{-5/4} V^{7/4} \tag{5-5}$$

The predicted friction factors were calculated from the following equations recommended by Kays (1966):

for $\mathrm{Re} < 30{,}000$

$$c_{f_{cal}} = 0.0791\,\mathrm{Re}^{-0.25} \tag{5-6}$$

for $\mathrm{Re} > 30{,}000$

$$c_{f_{cal}} = 0.046\,\mathrm{Re}^{-0.2} \tag{5-7}$$

For the pressure drop measurement in the turbulent flow case, the range of Reynolds number was 3,500 (including some transition cases) to 34,000, and a total of 22 cases was examined. The procedure to measure the pressure drop was followed according to the experimental details laid out in Section 4.1.3. In order to calculate experimental pressure drop and friction factor, two procedures to confirm the calc

were applied as follows:

(1) Calculate Δp/Δx and friction factor between each pressure tap and

the values from pressure taps 3 to 8.

(2) Pick up a nice constant slope from pressure taps 4 to 8, and calculat

and friction factor for that section.

After calculation, the results from the above two procedures were compared with

5), (5-6) and (5-7).

The experimental pressure gradient, Δp/Δx was calculated from the fo

equation:

$$\left(\frac{\Delta p}{\Delta x}\right)_{\exp} = \frac{DP_{PT2} - DP_{PT1}}{\Delta L}$$

The experimental friction factor, c_f was calculated from the following equation:

$$\frac{c_{f_{\exp}}}{2} = \frac{\tau_{w_{\exp}}}{\rho V^2}$$

where $\tau_{w_{\exp}}$ is experimental shear stress at the wall, $\Delta p D_i / 4\Delta L$

The gradients from pressure taps 3 to 8 were relatively constant as compar the other gradients as shown in Fig. 5.1, so the experimental pressure gradien pressure taps 3 to 8 was compared with the predicted pressure gradient by using E after averaging (procedure 1 above) each experimental pressure gradient from p taps 3 to 8 or simply calculating (procedure 2 above) an experimental pressure g using the pressure difference between pressure taps 4 and 8.

Figure 5.4 shows the results of the pressure gradients computed using procedures 1 and 2 along the test section. The results from procedures 1 and 2 were almost identical to each other. As shown in the figure, the experimental pressure gradients fall in the ± 5 % error band when they are compared with the calculated pressure gradients from Eq. (5-5). There was a mean error of -0.16 % and an rms error of 3.88 %, with a maximum error of 7.98 % and a minimum error of -6.26 %.

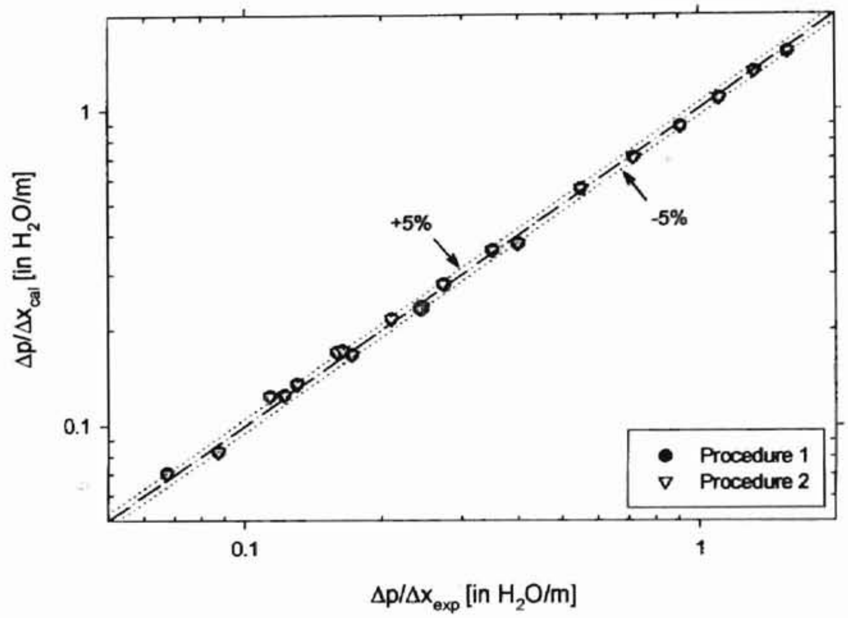


Figure 5.4 Comparison of $\Delta p/\Delta x_{exp}$ with $\Delta p/\Delta x_{cal}$ for Turbulent Flow Cases

Figure 5.5 shows the results of the friction factors computed from procedures 1 and 2 along the test section. As shown in the figure, the experimental friction factors compared with the calculated friction factors from Eqs. (5-6) and (5-7) mostly fall in the ±5 % error band; and there was a mean error of -0.10 % and an rms error of 3.84 %, with a maximum error of 7.86 % and a minimum error of -6.39 %. This figure demonstrates nearly identical results with those of the pressure gradient comparison (Fig. 5.4). These results show that the setup for the pressure drop measurement was verified to use for the turbulent two-phase flow case.

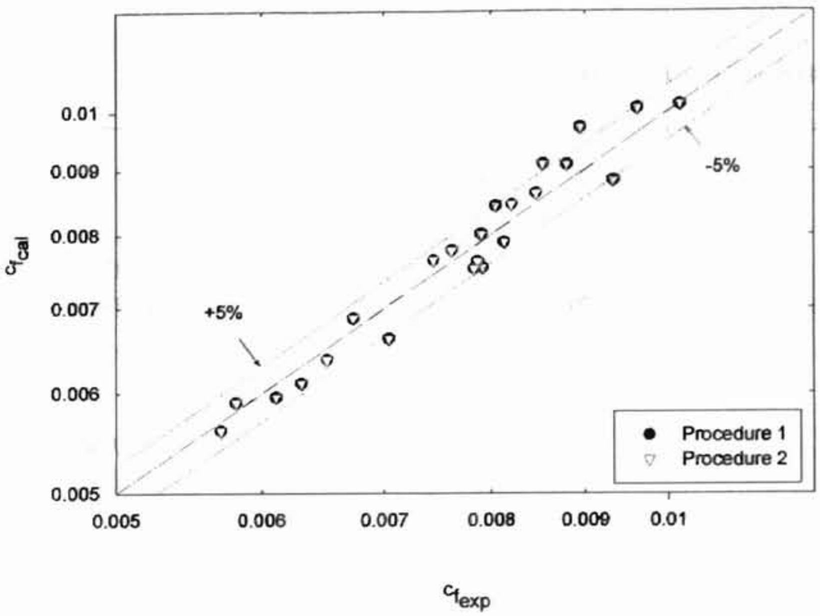


Figure 5.5 Comparison of $c_{f\text{exp}}$ with $c_{f\text{cal}}$ for Turbulent Flow Cases

5.1.2 Single-Phase Flow Heat Transfer Measurement

The purpose of the single-phase flow heat transfer measurement was, as mentioned at the beginning of this chapter, to verify the accuracy of the experimental setup which will be used in the future to carry out the two-phase flow experiments. In addition, the results from the single-phase flow heat transfer measurements would assist in determining the capacity of the test setup for the two-phase flow heat transfer experiment.

The single-phase test runs were classified as shown in Table 5.1 according to the flow rate of water and the power input (Ryali, 1999). This classification covered pure laminar flow down to a Reynolds number of 2,000 and fully turbulent flow up to a

Reynolds number of 30,000. According to this classification, the results of the single-phase flow heat transfer measurements were checked as to how the experimental setup responded to different levels of heat input and flow rate.

Table 5.1 Classification Matrix of the Single-Phase Test Runs

	Low Flow Rate [Laminar] (0 – 0.7 gpm) $0 < Re < 2{,}300$	Medium-Low Flow Rate [Transition] (1 – 3 gpm) $3{,}000 < Re < 10^4$	Medium-High Flow Rate [Turbulent] (3 – 5 gpm) $10^4 < Re < 2\times10^4$	High Flow Rate [Turbulent] (6 – 10 gpm) $2\times10^4 < Re < 3\times10^4$
Low Power Supply (0 – 500 W)	Test #1 $5.78 < Pr < 6.16$ $1.15 < \Delta T_b < 3.80$	Test #3 $5.91 < Pr < 6.19$ $0.71 < \Delta T_b < 1.61$	-	-
Medium Power Supply (500 –1,500 W)	Test #2 $5.35 < Pr < 5.70$ $5.49 < \Delta T_b < 13.55$	Test #4 $5.02 < Pr < 6.64$ $1.02 < \Delta T_b < 5.61$	Test #6 $5.97 < Pr < 6.50$ $1.01 < \Delta T_b < 2.85$	Test #8 $Pr = 6.37$ $\Delta T_b = 1.76$
High Power Supply (1,500 – 2,500 W)	-	Test #5 $5.59 < Pr < 6.50$ $4.23 < \Delta T_b < 6.33$	Test #7 $5.39 < Pr < 6.64$ $1.52 < \Delta T_b < 4.98$	Test #9 $5.03 < Pr < 6.57$ $1.52 < \Delta T_b < 3.19$

The experimental Nusselt numbers were calculated by using program Datared98F and RHt98F, and then these Nusselt numbers were compared with predictions by using published correlations for single-phase flow heat transfer. Power input (that is, heat addition) was provided in the form of a uniform wall heat flux using a DC welder (see Fig. 3.1). Whenever data was acquired, it was necessary to establish thermal steady-state conditions. When the inlet bulk temperature and the outlet bulk temperature were checked, the temperature deviations were required to be no more than 0.5 °C for a 5 minute time period, and the deviation in the difference between the inlet and outlet bulk temperatures during that 5 minutes was to be less than 0.1 °C: Then it was assumed that thermal steady-state conditions had been achieved. Figrue 5.6 shows an example of establishing thermal steady-state conditions.

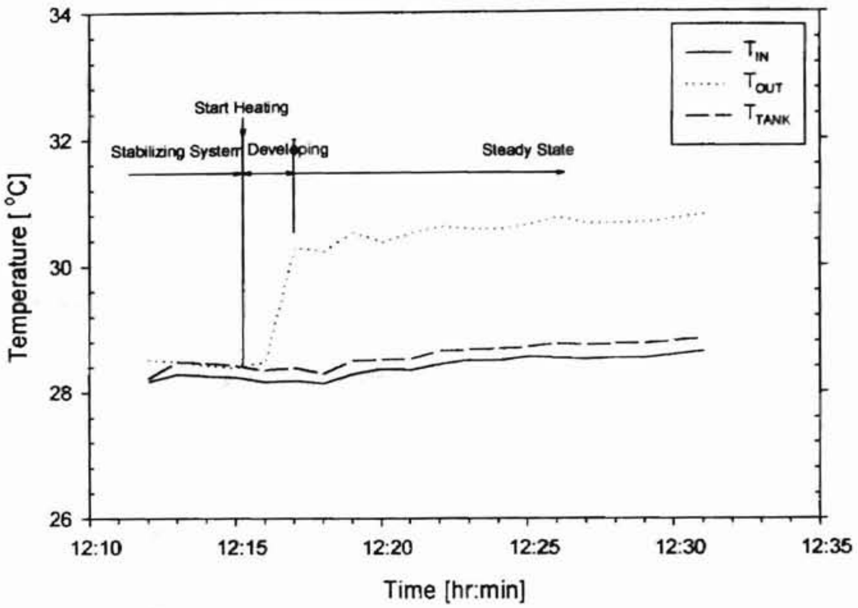


Figure 5.6 An Example of Establishing Thermal Steady-State Conditions (Run No. RN5107; Re = 14,000; Heat Flux: 2795 Btu/ft^2-hr)

Checking heat balance error was used as a method to verify the quality of the single-phase experimental data. The heat balance error shows the difference between the heat input by the power supply and the energy absorbed by the liquid. The procedure to check heat balance error was as follows: the heat input was calculated from

$$Heat_{in} = I \times V_D \tag{5-10}$$

and the heat absorbed by the water was calculated from

$$Heat_{taken} = \dot{m} C_p \Delta T_{bulk} \tag{5-11}$$

Then, the heat balance error was finally calculated from

$$Error_{HB}(\%) = \frac{Heat_{in} - Heat_{taken}}{Heat_{in}} \times 100 \tag{5-12}$$

The bulk temperature difference between the inlet and the outlet directly affects the heat transfer coefficient and the heat balance error. Therefore, by checking the heat balance error, the proper heat transfer from the heat source to the water can be confirmed. The probability of obtaining good heat transfer measurement data will be increased by obtaining good heat balance errors.

5.1.2.1 Single-Phase Laminar Flow Heat Transfer Measurement

In order to determine whether the flow was thermally fully developed or not for laminar flow in the test section, the thermal entry length was calculated using a simple equation introduced by Kays and Crawford (1993);

$$(x/D_i)_{fully\_dev} \approx 0.05\,\mathrm{Re}\,\mathrm{Pr} \tag{5-13}$$

Based on Eq. (5-13), the required thermal entry length for laminar water flow with a Reynolds number of 2000 and a Prandtl number of 6.99 (at 20 °C) is 699; and hence the present test section (x/D_i = 88.4 at thermocouple station no. 10) is insufficient. Therefore, to find the local Nusselt number for the thermal entry problem in laminar flow, Seigel et al.'s (1958) solution was used:

$$Nu_x = \left[\frac{1}{Nu_\infty} - \frac{1}{2}\sum_{m=1}^{\infty}\frac{\exp(-\gamma_m^2 x^+)}{A_m \gamma_m^4}\right]^{-1} \tag{5-14}$$

where $$Nu_\infty = \frac{48}{11} \qquad x^+ = \frac{2x/D_i}{\mathrm{Re}\,\mathrm{Pr}}$$

A_m, γ_m = eigenvalues listed in Table 5.2

Table 5.2 Values of A_m and γ^2_m

m	γ^2_m	A_m
1	25.86	7.630×10^{-3}
2	83.86	7.630×10^{-3}
3	174.20	7.630×10^{-3}
4	296.50	7.630×10^{-3}
5	450.90	7.630×10^{-3}

For larger m, $\gamma_m = 4m + 4/3$; $A_m = 0.428\gamma_m^{-7/3}$

The solution in the thermal entry region for laminar flow using Eq. (5-14) is shown in Table 5.3 along thermocouple stations for the present experimental setup. It should be noted that the solution in the thermal entry region applies rigorously only when the velocity profile is fully developed before heat transfer starts. However, such solutions are excellent approximations for fluids whose Prandtl numbers are high relative to unity. Based on this fact, the solution shown in Table 5.3 is sufficient for this study in the case of forced convective heat transfer with laminar flow, even though the velocity profile is still developing (refer to Section 5.1.1.1 and Eq. (5-1)).

Table 5.3 Predicted Local Nusselt Numbers for Laminar Flow in Thermal Entry Length for the Present Experimental Setup (Solution for Re = 2,000, Pr = 5.83)

Thermocouple Station No.	x/D_i	x^+	Nu_x
1	6.4	1.0978e-3	14.9600
2	15.5	2.6587e-3	11.2750
3	24.6	4.2196e-3	9.7281
4	33.7	5.7804e-3	8.8090
5	42.8	7.3413e-3	8.1798
6	52.0	8.9194e-3	7.7089
7	61.1	0.0105	7.3461
8	70.2	0.0120	7.0528
9	79.3	0.0136	6.8093
10	88.4	0.0152	6.6031
	...	...	...
	∞	∞	4.364

In order to investigate the response of the system for laminar flow, 7 cases were run with a Reynolds number of about 2,000 and varied power inputs whose range was 330 Btu/hr (97 W) to 3920 Btu/hr (1148 W). Figure 5.7 shows the variation of the average inside wall temperature at each thermocouple station, with bulk temperatures that assumed a linear variation from the inlet to the outlet bulk temperatures (station no. 0 and 11 in Fig. 5.7). As mentioned in Chapter III, the temperatures at station nos. 2, 9 and 10 were not considered to be sufficiently accurate, so they were neglected. The temperatures at station nos. 1, 3, 4 and 5 clearly show the typical trend (increasing temperature vs. length) of the thermal entry length for the uniform wall heat flux condition. However, the experimental Nusselt number as a function of thermocouple station was quite different from the predictions, as shown in Fig. 5.8. The experimental Nusselt numbers were always higher than the predictions, with more than an error of -30 % in most cases. Note that the difference was bigger with increasing power provided to the system.

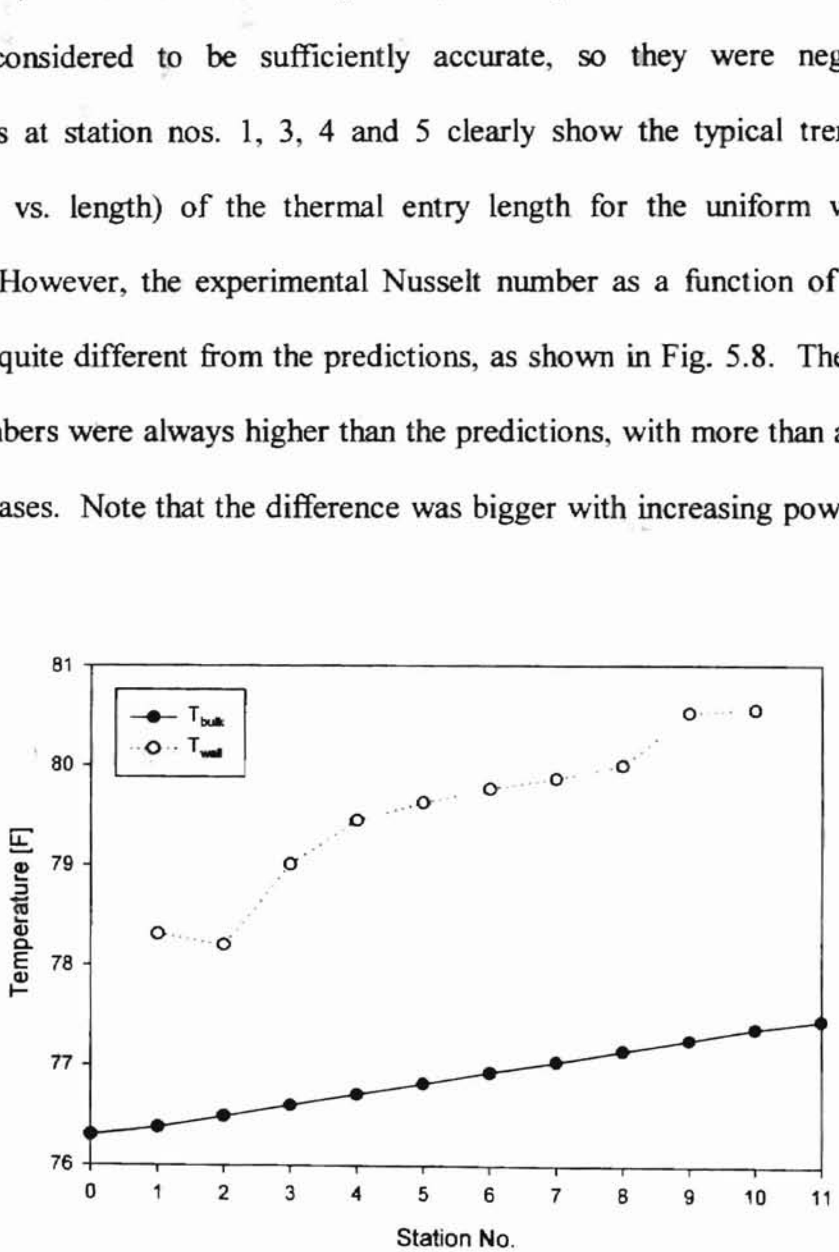


Figure 5.7 Trends of T_{bulk} and Average T_{wall} along Thermocouple Stations (Run No. RN 1130; Re = 1933; Pr = 6.16; $Power_{in}$ = 330 Btu/hr)

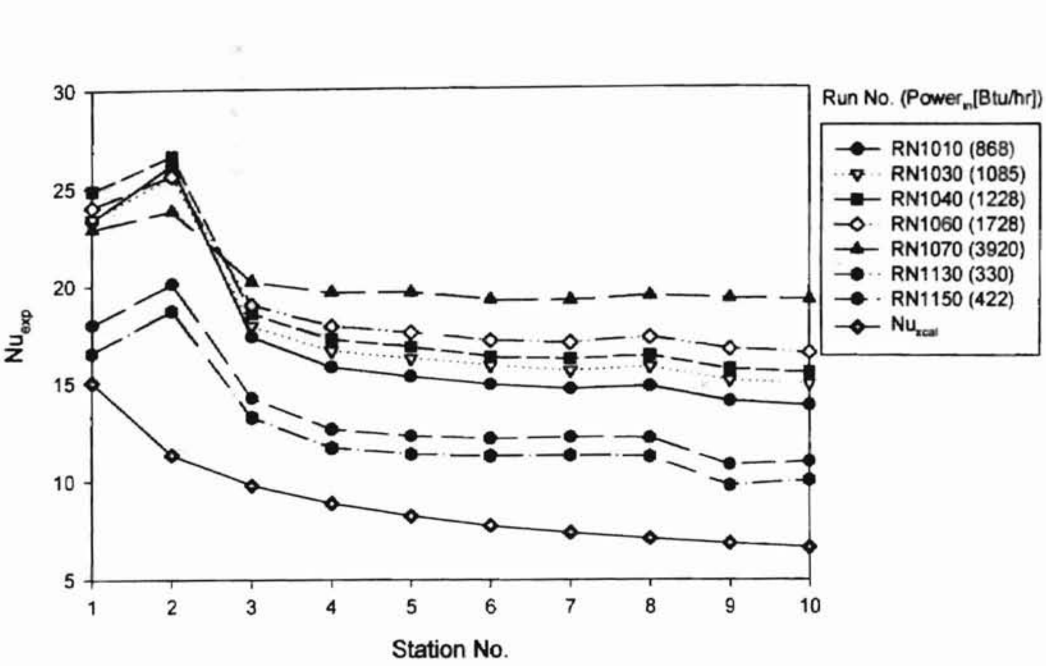


Figure 5.8 Trends of Local Nu_{exp} along Thermocouple Stations for Laminar Flow in Thermal Entrance Region (Mean Re = 2,000)

Petukhov and Polyakov's (1967) observed that, with increased heat flux, higher deviations from the prediction by Seigel *et al.* (1958) were observed. These phenomena were also found in the studies performed by Bergles and Simonds (1971), and Hong and Bergles (1976). In fact, the Seigel *et al.* (1958) solution was developed for laminar forced convection heat transfer. Therefore, another approach was necessary to understand laminar flow heat transfer for the present experimental setup.

As shown in Fig. 5.9, the wall temperatures at the top were much higher than the other wall temperatures, and the bottom wall temperatures were shown to be the lowest temperatures along the stations. This is showing a typical mixed convection temperature distribution. These phenomena were observed for all laminar flow cases.

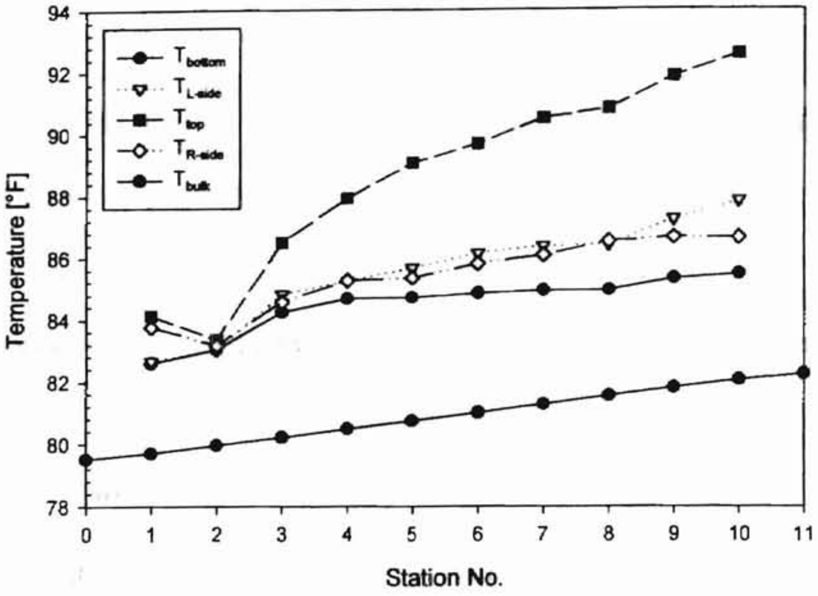


Figure 5.9 Peripheral Inside Wall Temperature Distributions along Thermocouple Stations for Laminar Flow in Thermal Entrance Region with Uniform Heat Flux (Run No. RN1010; Re = 2,000; Power$_{in}$ = 868 Btu/hr)

In literature, two correlations are available for mixed convection in the thermal entry region for laminar flow. One was suggested by Petukhov and Polyakov (1967) and the other was developed by Ghajar and Tam (1994). The two correlations are as follows:

Petukhov and Polyakov (1967) correlation

$$Nu_x = Nu_l \left[1 + \left(\frac{\mathrm{Ra}}{\mathrm{Ra}_0} \right)^4 \right]^{0.045} \tag{5-15}$$

where Nu$_l$ is the Seigel *et al.* (1958) solution at a given x^+

$\mathrm{Ra}_0 = 5\times10^3(x^+/2)^{-1}$ for $x^+/2 < 1.7\times10\text{-}3$

$\mathrm{Ra}_0 = 1.8\times10^4 + 55(x^+/2)^{-1.7}$ for $x^+/2 > 1.7\times10\text{-}3$

Ghajar and Tam (1994) correlation

$$Nu_x = 1.24[(\mathrm{Re}\,\mathrm{Pr}\,D_i/x) + 0.025(\mathrm{Gr}\,\mathrm{Pr})^{0.75}]^{1/3}(\mu_b/\mu_w)^{0.14} \tag{5-16}$$

where $3 \leq x/D_i \leq 192$, $280 \leq \mathrm{Re} \leq 3{,}800$, $40 \leq \mathrm{Pr} \leq 160$,

$1{,}000 \leq \mathrm{Gr} \leq 2.8\times10^4$, $1.2 \leq \mu_b/\mu_w \leq 3.8$

The comparison of the experimental Nusselt numbers with the predictions using Eqs. (5-15) and (5-16) is shown in Fig. 5.10. As shown in Fig. 5.10, the predictions using the Petukhov and Polyakov (1967) correlation did not agree with the experimental Nusselt numbers, which needs more investigation for validity. However, Ghajar and Tam's (1994) correlation predicted Nusselt numbers very well with a mean error of 7.70 % and an rms deviation of 9.98 %. Among a total of 48 data points, about 48 % of the data (23 data points) fell into a ± 10 % error band, and all 48 data points fell into a ± 20 % error band as shown in Fig. 5.10.

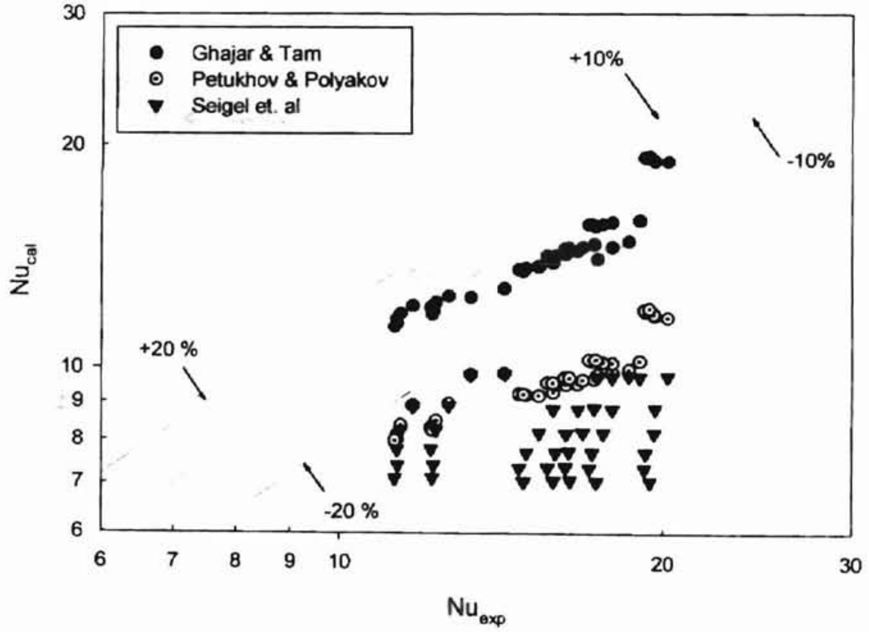


Figure 5.10 Comparison between Experimental Nusselt Numbers and Those Predicted by the Available Correlations in the Thermal Entry Region for Laminar Flow (Re = about 2,000)

5.1.2.2 Single-Phase Transitional/Turbulent Flow Heat Transfer Measurement

Data were collected according to the experimental procedure as described in Chapter IV, and the experimental Nusselt numbers were compared with the predictions by using the chosen single-phase correlations. The fully turbulent forced convection uniform heat flux correlations proposed by Colburn (1933), Sieder and Tate (1936). Gnielinski (1976), and Ghajar and Tam (1994) were chosen to predict Nusselt numbers from the experimental data. The following items were examined to check the quality of the acquired data: the temperature profile along the test section, the ratio of the top and the bottom temperatures at each thermocouple station, heat balance error, and the trend of Nusselt number along the test section.

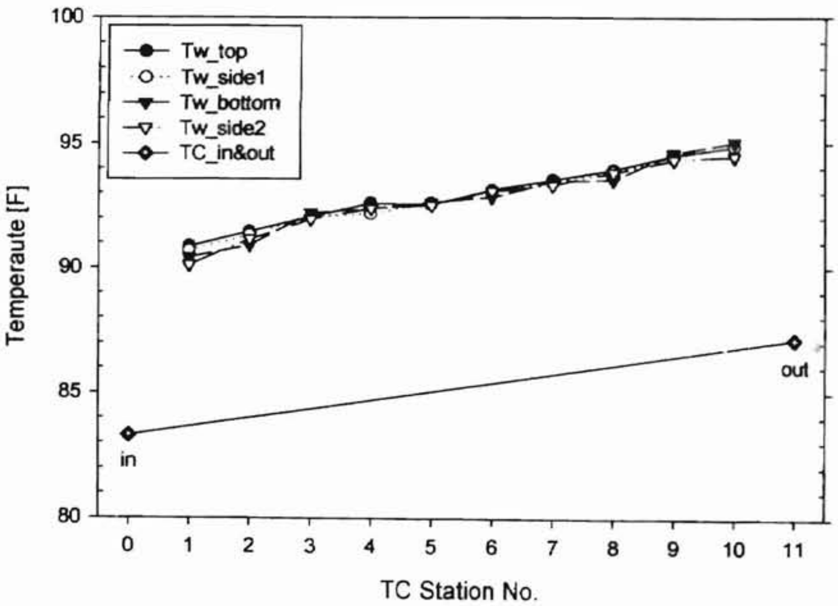


Figure 5.11 Temperature at the Inside Wall of Top, Sides and Bottom and Inlet to Outlet Bulk Temperature at Each Station – Turbulent Case [Run No. RN5107; Re = 14,000]

Figure 5.11 shows one set of the inside wall temperature profiles along the test section. As shown in the figure, the temperatures linearly increased along the test section. The relation between the wall temperature and the bulk temperature along the test section also indicated that there was a constant difference between the bulk and the inside wall temperatures, which is the ideal relation for fully turbulent flow. Most cases showed this phenomenon except the transitional cases. In the transitional flow cases, the earlier thermocouple stations showed a typical thermal entrance profile as shown in Fig. 5.12. However, the temperature profile for the transitional flow along the test section approached linear behavior and had a constant difference from the bulk temperature. Wall temperatures at thermocouple stations 2, 9 and 10 should be ignored as mentioned in Section 3.2.

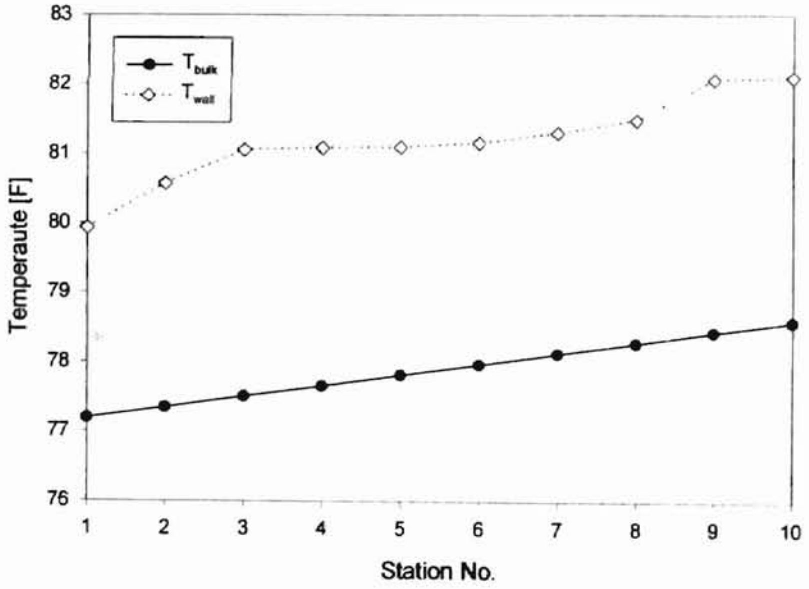


Figure 5.12 Temperature at the Wall and the Bulk Temperature at Each Station after Steady-State Conditions Are Reached – Transition Case [Run No. RN2065, Re = 3,300]

The ratios of the top and the outlet temperatures at thermocouple station no. 6 were plotted versus Reynolds number on Fig. 5.13. These ratios showed whether mixed convection existed or not, and whether mixed convection strongly affected the heat transfer measurement or not. The reason for checking for the existence of mixed convection was, if there was mixed convection and it was strong enough to affect the heat transfer, then the experiment should be analyzed as a mixed convection problem, and it was not favorable to compare with the forced convection correlations.

Figure 5.13 shows that the temperature ratios for the transitional and the turbulent flow cases were within ± 0.5 %, which suggests perfect harmony between the top and the bottom inside wall temperatures. This means that the heat transfer measurement data for the transitional and the turbulent flow cases are the fully forced convection heat transfer cases, and it was reasonable to compare with the forced convection correlations.

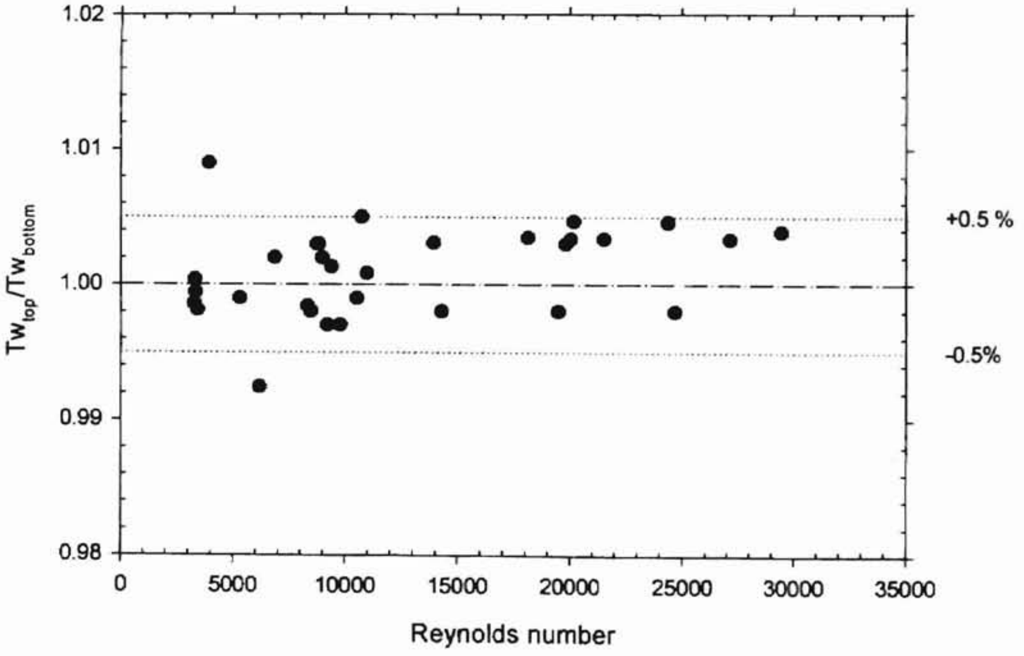


Figure 5.13 The Ratio of the Top and Bottom Inside Wall Temperatures Compared with the Local Reynolds Number at Thermocouple Station No. 6

Figure 5.14 shows the heat balance errors from the transitional and turbulence cases. As shown in the figure, the errors were compared with the bulk temperature differences between the inlet and the outlet. Acceptable heat balance errors (within ± 15 %) could be achieved when the bulk temperature difference between the inlet and outlet was more than 1.2 °F. If the bulk temperature difference was less than 1.2 °F, then the heat balance error increased to a significant negative error.

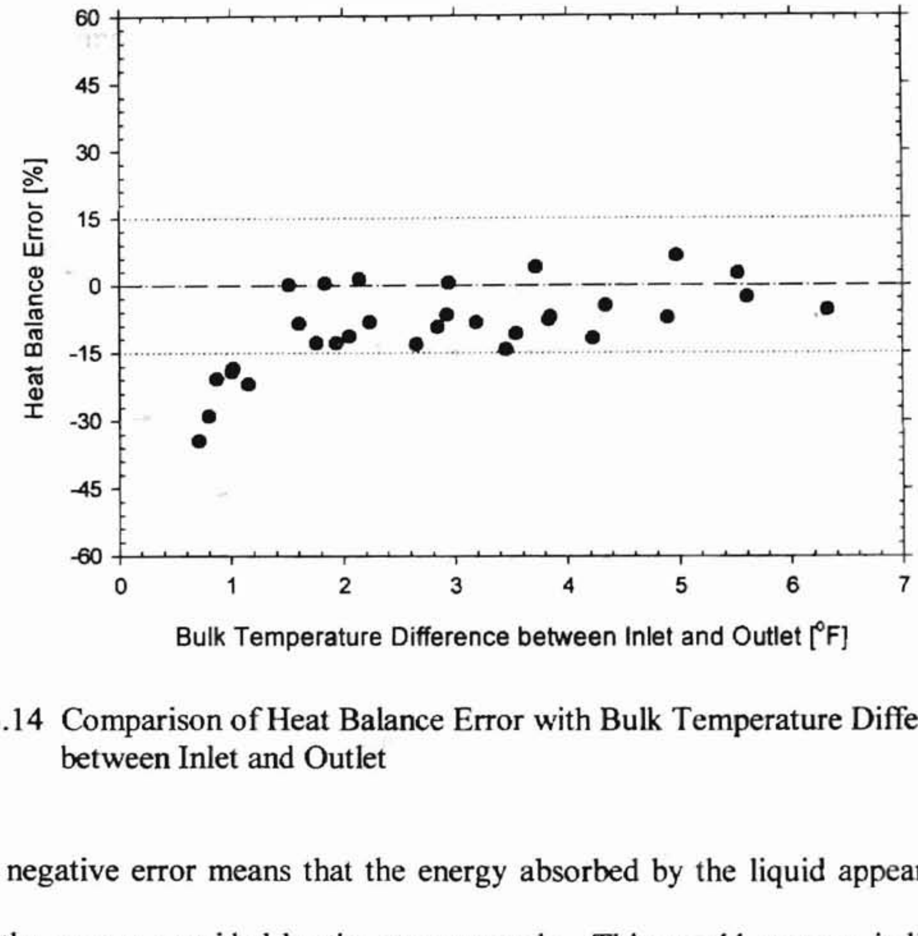


Figure 5.14 Comparison of Heat Balance Error with Bulk Temperature Difference between Inlet and Outlet

The negative error means that the energy absorbed by the liquid appeared to be larger than the energy provided by the power supply. This would seem to indicate that somehow extra energy was input to the system, or there was some error in one of the energy measurements. The extra energy case is obviously impossible, and so the error in measurement would be the deduced reason for those negative errors. In the cases of smaller bulk temperature difference (less than 1.2 °F), the power supplied was usually a small value. Therefore, an incorrect reading for the power or for the bulk temperature would have a greater impact on the heat balance error, because of the small magnitude of the bulk temperature difference. Alternatively, in the cases of the larger bulk temperature difference (more than 1.2 °F), an incorrect reading of power or temperature would have less impact on the heat balance error. However, the heat balance error didn't appear to have a significant impact on the Nusselt number comparison in this study, as shown in the summary of single-phase flow heat transfer measurement data (see Section B.1.2 in Appendix B).

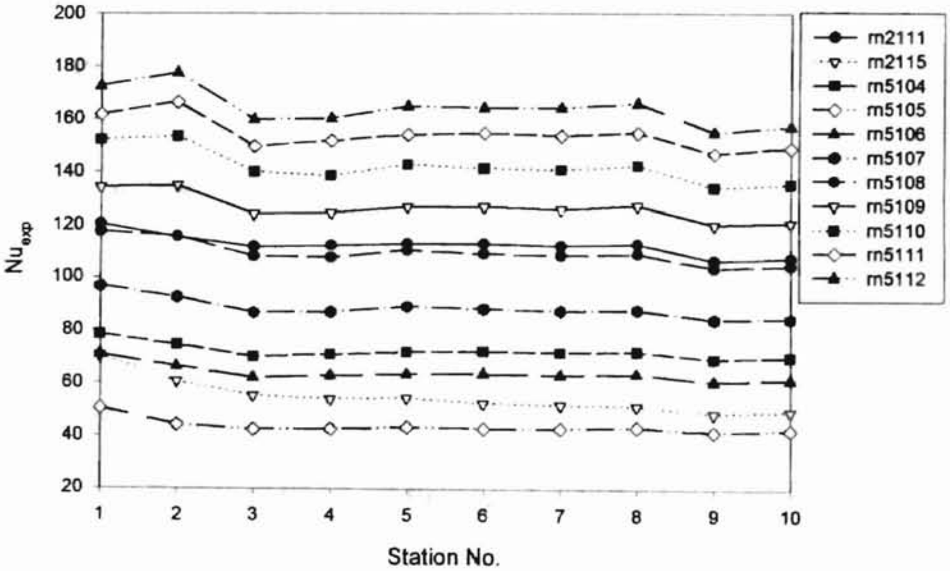


Figure 5.15 Nusselt Number as a Function of Thermocouple Station Number

The experimental Nusselt number was calculated by using programs Datared98 and RHt98. If the flow was fully developed, then Nusselt number should theoretically become a constant value beyond the thermal entrance length. As shown in Fig. 5.15, the Nusselt number trend along the test section indicated that the experimental Nusselt number had a constant value in the section from thermocouple station nos. 5 to 8. Among those stations would be a good location to obtain a representative Nusselt number for the test run. Hence, thermocouple station no. 6 ($x/D_i = 52$) was considered to be an ideal position to compare with the predicted Nusselt number by using the chosen turbulent forced convection correlations.

One of the goals of this study was providing confidence in the performance of the experimental setup for the two-phase flow heat transfer measurement. In order to achieve that goal, the single-phase flow heat transfer measurements were done and compared with well-known correlations that have been checked by many researchers. As mentioned at the beginning of this section, five correlations were chosen to compare with the experimental Nusselt numbers. Those correlations are as follows:

<u>Colburn (1933) correlation:</u>

$$Nu = 0.023\,\mathrm{Re}^{0.8}\,\mathrm{Pr}^{1/3} \tag{5-17}$$

where $\mathrm{Re} \geq 10{,}000,\ 0.6 \leq \mathrm{Pr} \leq 160$

<u>Sieder and Tate (1936) correlation:</u>

$$Nu = 0.023\,\mathrm{Re}^{0.8}\,\mathrm{Pr}^{1/3}(\mu_b/\mu_w)^{0.14} \tag{5-18}$$

where $\mathrm{Re} \geq 10{,}000,\ 0.7 \leq \mathrm{Pr} \leq 16{,}700$

<u>Gnielinski [1] (1976) correlation:</u>

$$Nu = \frac{(c_f/2)(\mathrm{Re}-1000)\,\mathrm{Pr}}{1+12.7(c_f/2)^{1/2}(\mathrm{Pr}^{2/3}-1)} \tag{5-19}$$

where $\dfrac{1}{\sqrt{c_f}} = 1.58\ln\mathrm{Re} - 3.28$; Filonenko Correlation

$0.5 \leq \mathrm{Pr} \leq 2{,}000,\ 2{,}300 \leq \mathrm{Re} \leq 5\times10^6$

Gnielinski [3] (1976) correlation:

$$Nu = 0.012(\mathrm{Re}^{0.87} - 280)\,\mathrm{Pr}^{0.4} \qquad (5\text{-}20)$$

where $1.5 \le \mathrm{Pr} \le 500,\ 3{,}000 \le \mathrm{Re} \le 1\times10^{6}$

Ghajar and Tam (1994) correlation:

$$Nu = 0.023\,\mathrm{Re}^{0.8}\,\mathrm{Pr}^{0.385}(x/D_i)^{-0.0054}(\mu_b/\mu_w)^{0.14} \qquad (5\text{-}21)$$

where $3 \le x/D_i \le 192,\ 7000 \le \mathrm{Re} \le 49000$

$4 \le \mathrm{Pr} \le 34,\ 1.1 \le \mu_b/\mu_w \le 1.7$

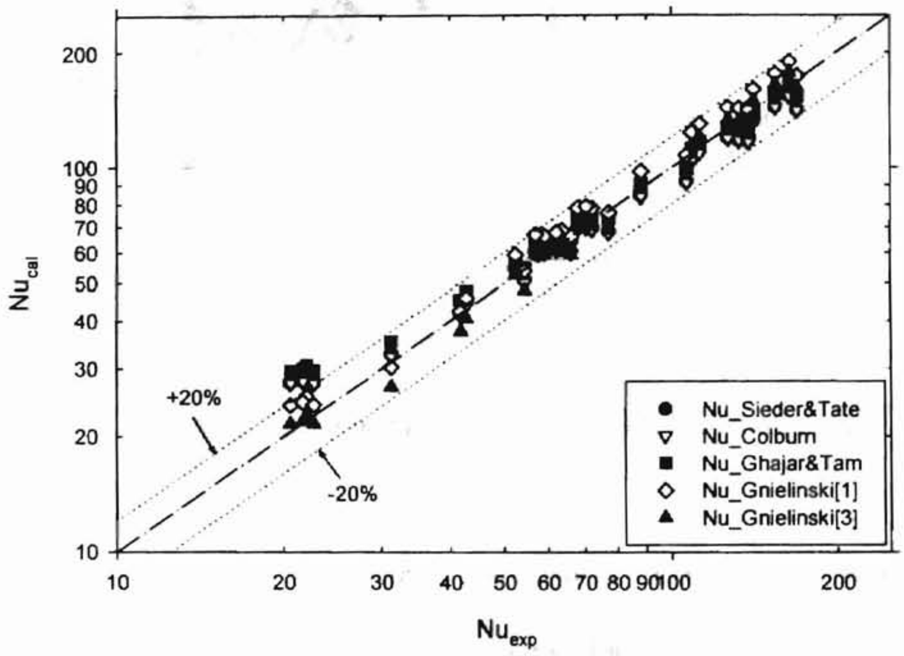


Figure 5.16 Comparison of $\mathrm{Nu}_{\mathrm{exp}}$ vs. $\mathrm{Nu}_{\mathrm{cal}}$ from Selected Correlations at Thermocouple Station No. 6 (3,000 < Re < 30,000)

The predicted Nusselt numbers using the above correlations were compared with the experimental Nusselt numbers. The results of the comparison (without concern for the recommended parameter ranges) for each of the five correlations are shown in Figs. 5.16 and 5.17. As shown in those figures, the experimental Nusselt numbers were in good agreement with the calculated Nusselt numbers, and all of them were within a ± 20 % error band except for Colburn, Sieder and Tate, and Ghajar and Tam correlations in the low Reynolds number (Re < 5,000) regime. A detailed comparison for each correlation follows.

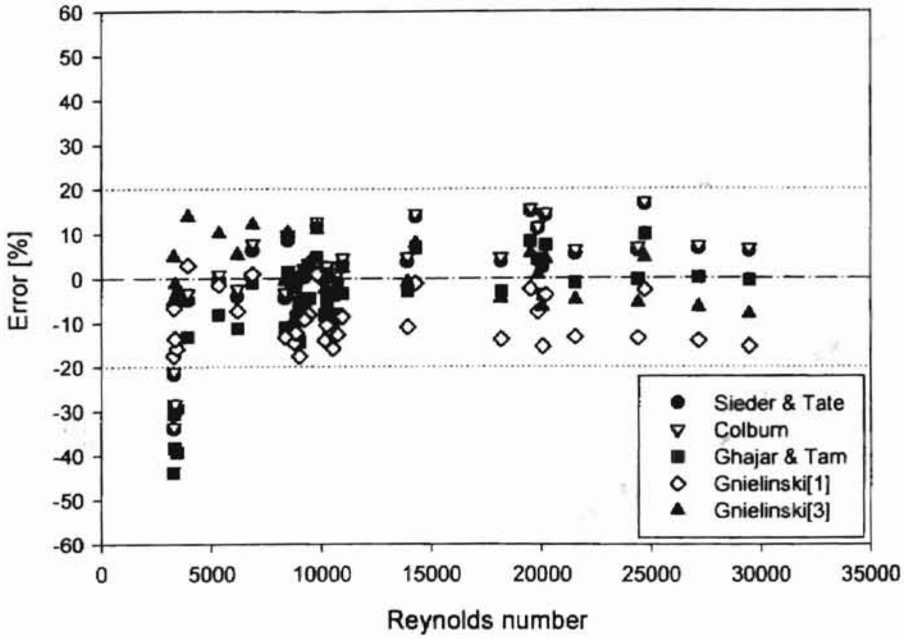


Figure 5.17 Errors of Nu_{cal} Referenced to Nu_{exp} vs. Reynolds Number at Thermocouple Station No. 6 (3,000 < Re < 30,000)

Colburn: Figure 5.18 shows the comparison of experimental Nusselt numbers with the calculated Nusselt numbers by using the Colburn correlation. As shown in Eq. (5-17), the lower recommended Reynolds number range of the Colburn correlation is 10,000. According to this recommendation, our results show the experimental Nusselt numbers followed the Colburn correlation very well. Among all 31 transitional/turbulent data points, 23 data were within or near (Re > 8,000) the recommended Reynolds number range, and there was a maximum error of 16.99 % and a minimum error of -5.49 %, with a mean error of 4.81 % and an rms deviation of 8.55 %. Most of the 23 data points fall within a ± 10 % error band, which showed a very good Nusselt number comparison (Fig. 5.18 and Table 5.4).

Table 5.4 Comparison of Experimental Results with the Colburn Correlation

	Avg. Re	Avg. Pr	Nu_{exp}	Nu_{cal}	Error [%] $(1-Nu_{cal}/Nu_{exp})\times 100$
Minimum	8351	5.02	52.38	54.09	-0.86
Maximum	29443	6.64	164.12	153.25	16.99
Mean Error	18987	-	-	-	5.76

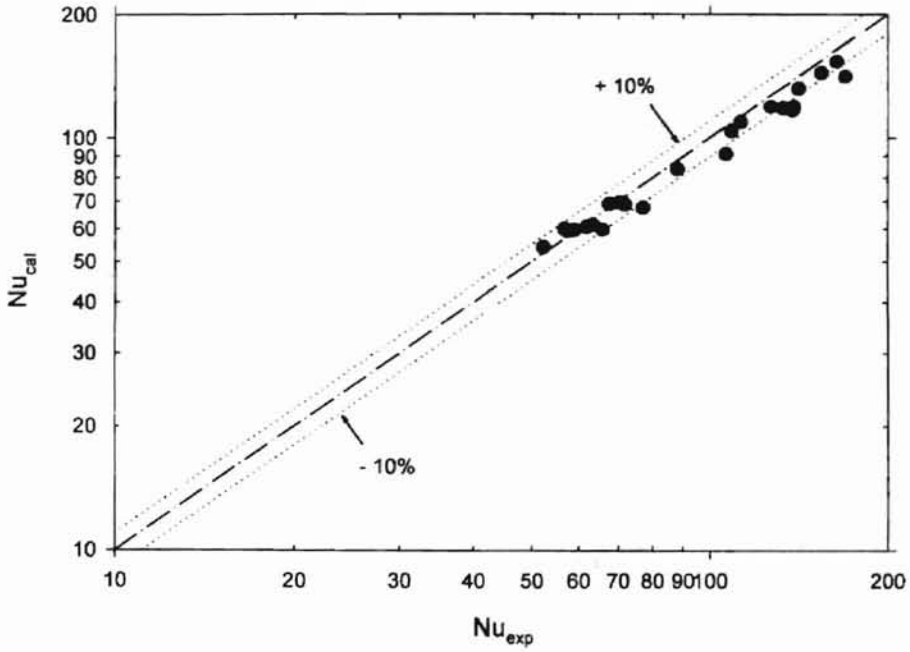


Figure 5.18 Nu_{exp} vs. Nu_{cal} – Colburn Correlation

Sieder and Tate: The experimental Nusselt numbers of 23 data points were compared with the Sieder and Tate turbulent correlation. As for the Colburn correlation, the lower recommended Reynolds number range was 10,000. Therefore, only the data for which Reynolds numbers were greater than 8,000 were analyzed by using the Sieder and Tate correlation. Figure 5.19 shows the results of the comparison. As shown in the figure, the results were very similar to those produced by the Colburn correlation due to the fact the Sieder and Tate correlation adds a viscosity ratio to the Colburn correlation. There were a maximum error of 16.45 % and a minimum error of -6.75 %, with a mean error of 4.81 % and an rms deviation of 8.08 %. Most of data points fell into a ± 10 % error band, which showed a very good Nusselt number comparison (Fig. 5.19 and Table 5.5).

Table 5.5 Comparison of Experimental Results with the Sieder and Tate Correlation

	Avg. Re	Avg. Pr	Nu_{exp}	Nu_{cal}	Error [%] $(1-Nu_{cal}/Nu_{exp})\times 100$
Minimum	8351	5.02	52.38	54.73	0.24
Maximum	29443	6.64	164.12	154.31	16.45
Mean Error	-	-	-	-	4.81

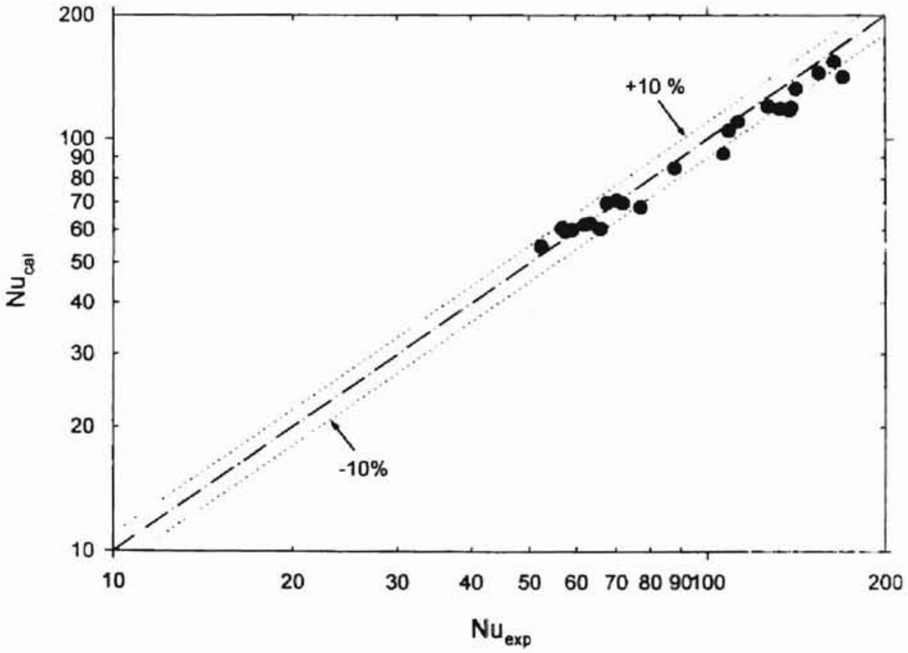


Figure 5.19 Nu_{exp} vs. Nu_{cal} - Sieder and Tate Correlation

Ghajar and Tam: The Ghajar and Tam correlation applies several limitations as shown in Eq. (5-21). Among those limitations, two of them were of concern (the rest of the recommendations were sufficiently satisfied): Reynolds number and viscosity ratio. Taking account of these concerns, a total of 16 data points ($1.06 \le \mu_b/\mu_w \le 1.151$, $Re \ge 6{,}000$) were predicted with the Ghajar and Tam correlation. The results shown in Table 5.6 and Fig. 5.20 indicate that the experimental Nusselt numbers agreed well with the predictions of the Ghajar and Tam correlation. Most of data fell into the ± 10 % error band, having a maximum error of 6.91 % and a minimum error of -14.36 %, with a mean error of -4.28 % and an rms deviation of 6.90 %.

Table 5.6 Comparison of Experimental Results with the Ghajar and Tam Correlation

	Avg. Re	Avg. Pr	μ_b/μ_w	Nu_{exp}	Nu_{cal}	Error [%] $(1-Nu_{cal}/Nu_{exp})\times 100$
Minimum	6176	5.02	1.06	42.83	47.65	-0.95
Maximum	21522	6.64	1.151	126.92	128.29	-14.36
Mean Error	-	-	-	-	-	-4.28

Gnielinski (1976) proposed three correlations for different parameter ranges. The Gnielinski [1] correlation employed the friction factor and was developed for transitional and turbulent flows. The Gnielinski [2] correlation covered the low Prandtl number region ($0.5 \le Pr \le 1.5$) and fully turbulent flow ($10^4 \le Re \le 5\times10^6$). Finally, the Gnielinski [3] correlation was designed for transitional and turbulent flow regions without using the friction factor. In this study, Gnielinski [1] and [3] were used to compare the experimental Nusselt numbers with the calculated Nusselt numbers.

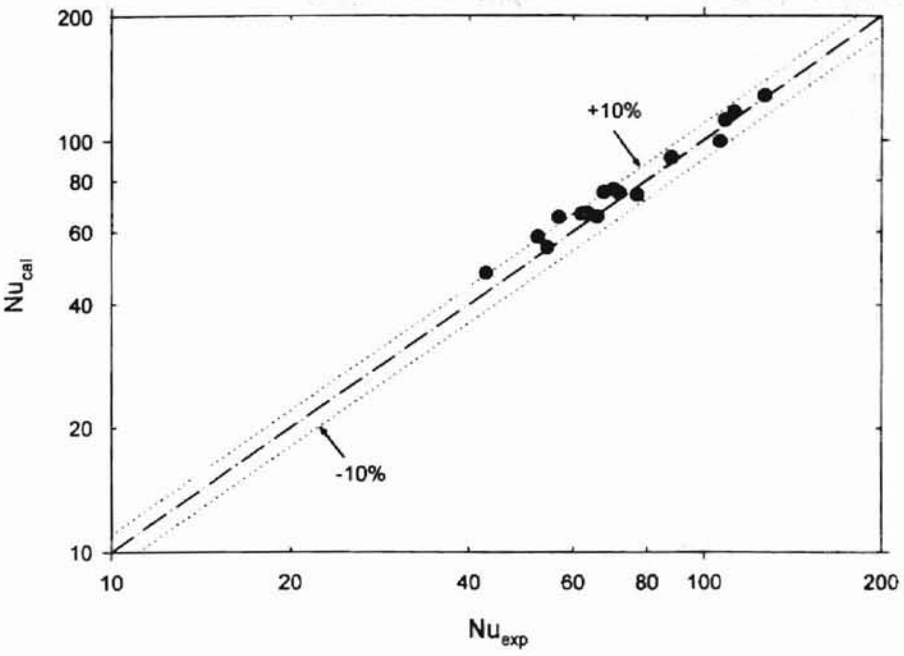


Figure 5.20 Nu_{exp} vs. Nu_{cal} - Ghajar and Tam Correlation

Gnielinski [1]: The lower limit of recommended Reynolds number is 2300, so 13 transitional (3,000 < Re < 9,000) and 18 fully turbulent (Re ≥ 9,000) flow heat transfer measurement data points were predicted with the Gnielinski [1] correlation. The calculation of friction coefficients for these cases employed the Filonenko correlation which was used by Gnielinski (1976) himself to develop the correlation. As shown in Fig. 5.21 and Table 5.7, the results of the comparison using the Gnielinski [1] were sufficiently acceptable. The calculated Nusselt numbers by using the Gnielinski [1] correlation had a maximum error of 2.97 % and a minimum error of -17.60 %, with a mean error of -9.16 % and an rms deviation of 11.02 %. All 33 data points fell into a ± 20 % error band as shown in Fig. 5.21.

Table 5.7 Comparison of Experimental Results with the Gnielinski [1] Correlation

	Avg. Re	Avg. Pr	Nu_{exp}	Nu_{cal}	Error [%] $(1-Nu_{cal}/Nu_{exp})\times100$
Minimum	3286	5.02	20.57	24.17	-0.38
Maximum	29443	6.64	164.12	189.35	-17.60
Mean Error	-	-	-	-	-9.16

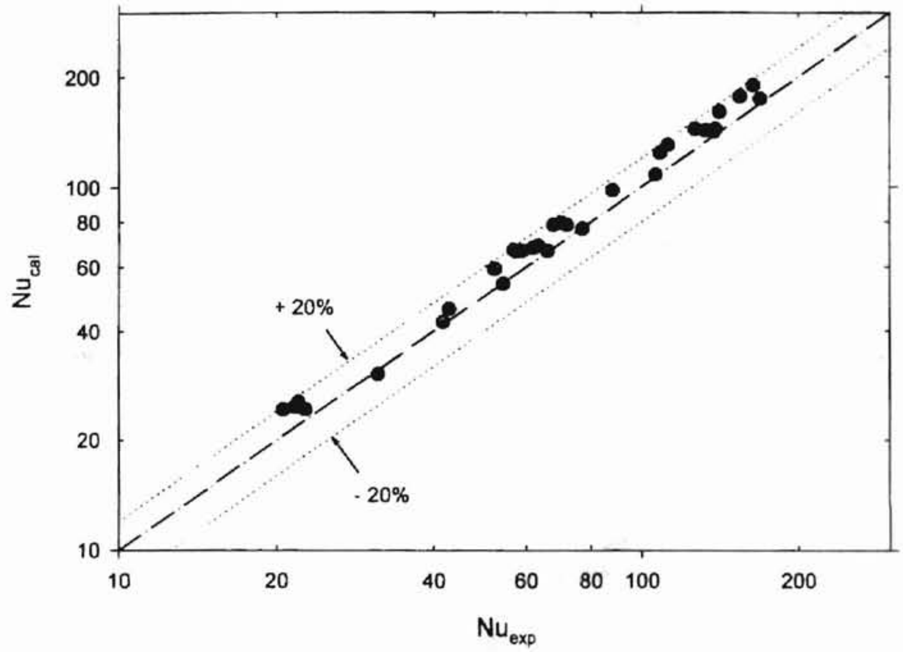


Figure 5.21 Nu_{exp} vs. Nu_{cal} - Gnielinski [1] Correlation

Gnielinski [3]: As with the Gnielinski [1] correlation, the Gnielinski [3] correlation covered transitional and fully turbulent ($3,000 \leq Re \leq 10^6$) flows. Therefore, the 13 transitional and 18 fully turbulent flow heat transfer data points were again examined. Unlike the Gnielinski [1] correlation, the Gnielinski [3] does not employ the friction coefficient and predicts using only Reynolds number and Prandtl number. As shown in Fig. 5.22 and Table 5.8, the comparison of the experimental Nusselt numbers with the calculated ones using the Gnielinski [3] correlation showed very good agreement between the experimental and the predicted values. The results with the Gnielinski [3] correlation had a maximum error of 13.82 % and a minimum error of -8.18 %, with a mean error of 1.20 % and an rms error of 6.49 %. Most of the data fell into a ± 10 % error band as shown in Fig. 5.22.

Table 5.8 Comparison of Experimental Results with the Gnielinski [3] Correlation

	Avg. Re	Avg. Pr	Nu_{exp}	Nu_{cal}	Error [%] $(1-Nu_{cal}/Nu_{exp})\times 100$
Minimum	3286	5.02	20.57	24.17	-0.31
Maximum	29443	6.64	164.12	189.35	13.82
Mean Error	-	-	-	-	1.20

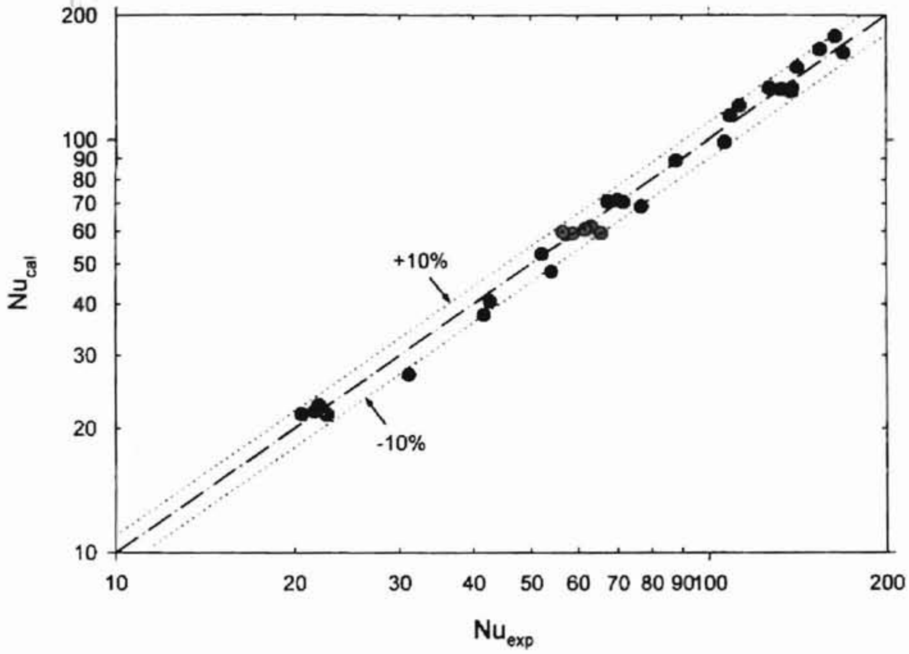


Figure 5.22 Nu_{exp} vs. Nu_{cal} - Gnielinski [3] Correlation

5.2 Two-Phase Flow

5.2.1 Void Fraction Measurement

A knowledge of void fraction was required to calculate the hydraulic pressure gradient and hence the fractional pressure drop. The void fraction was also required to correlate the two-phase heat-transfer coefficients. Void fraction is defined as either of:

(1) the fraction of the channel volume that is occupied by the gas phase

(2) the fraction of the channel cross-sectional area that is occupied by the gas phase

For this study, it is assumed that these two quantities are identical and designated as α. According to the above definition (1), to obtain the volume of air, that is, the void fraction, the volume of water held in the liquid holdup section was measured and subtracted from the whole volume of the liquid holdup section.

The measurement data of void fraction was used for comparison with one of the available correlations in order to determine the void fraction and verify the test setup as to whether the chosen correlation was suitable to use for future study. For this purpose, Chisholm's (1973) equation was chosen to predict the calculated void fraction.

The equation suggested by Chisholm (1973) is

$$K_U = \left(\frac{\rho_L}{\rho_{HOM}} \right)^{1/2} \tag{5-22}$$

where

$$\frac{1}{\rho_{HOM}} = \frac{1-x_m}{\rho_L} + \frac{x_m}{\rho_G} \tag{5-23}$$

From the definition of the flow quality and the void fraction, the liquid fraction is expressed as follows:

$$\frac{1}{1-\alpha}=\frac{x_m/\rho_G+K_U(1-x_m)/\rho_L}{K_U(1-x)/\rho_L} \tag{5-24}$$

Therefore, substituting Eq. (5-22) into Eq. (5-24) and rearranging, then the void fraction becomes

$$\frac{1}{\alpha}=1+K_U\left(\frac{1-x_m}{x_m}\right)\frac{\rho_G}{\rho_L} \tag{5-25}$$

Since x_m, ρ_G, and ρ_L are known from measurement, then K_U can be evaluated from Eq. (5-22). Finally, the void fraction can be calculated from Eq. (5-25).

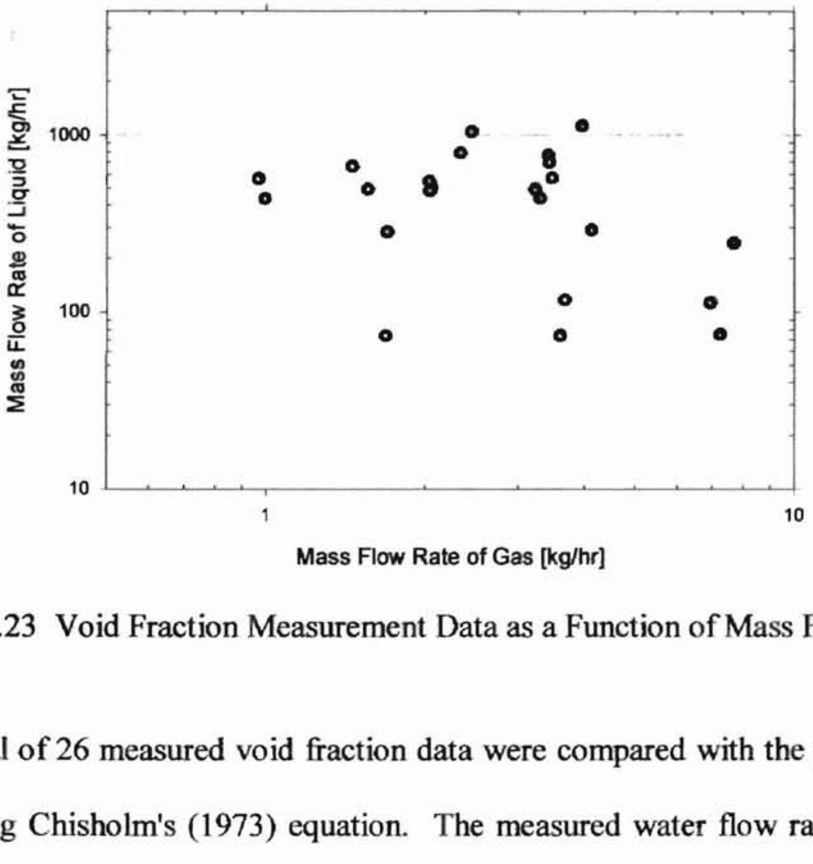


Figure 5.23 Void Fraction Measurement Data as a Function of Mass Flow Rate

A total of 26 measured void fraction data were compared with the predicted void fractions using Chisholm's (1973) equation. The measured water flow rate data was in the range of 73.42 kg/hr to 1118.12 kg/hr, and the air flow rate was from 0.48 to 7.70 as shown in Fig. 5.23. The comparison yielded a mean error of -9.05 % and an rms deviation of 16.53 % with a maximum error of 15.02% and a minimum error of -36.53 % as listed in Table 5.9. As shown in Fig. 5.24, most of the data fell within a ± 30 % error band, which means that Chisholm's (1973) equation appears to be capable of predicting the void fraction for the two-phase measurement cases using the present experimental setup.

Table 5.9 Summary of Void Fraction Measurement Data

	V_{SL} (m/s)	V_{SG} (m/s)	K_U (V_G/V_L)	$\alpha_{Measured}$	$\alpha_{Chisholm}$	Error (%)	Flow Pattern
Maximum α	0.034	1.676	6.75	0.8545	0.8788	-2.84	Stratified
Minimum α	0.309	0.130	5.58	0.2965	0.2608	12.03	Slug
Maximum Mean Error	0.359	0.603	1.63	0.5962	0.5067	15.02	Slug
Minimum Mean Error	0.475	0.578	3.09	0.3298	0.4503	-36.53	Slug

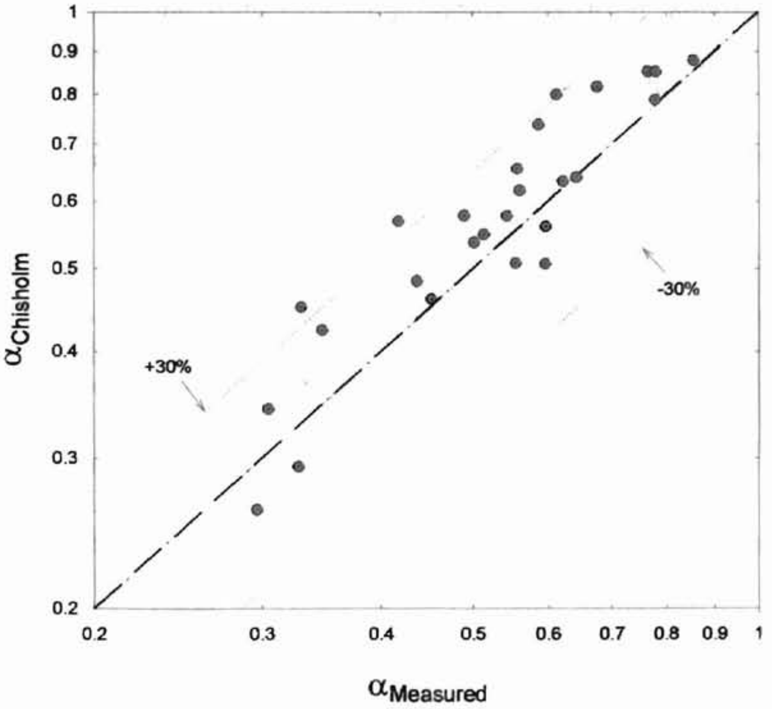


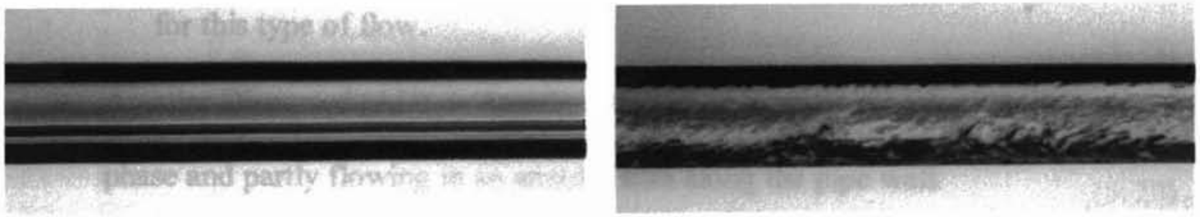
Figure 5.24 Comparison of Measured Void Fractions with the Predictions

5.2.2 Flow Pattern Map Construction for the Present Experimental Setup

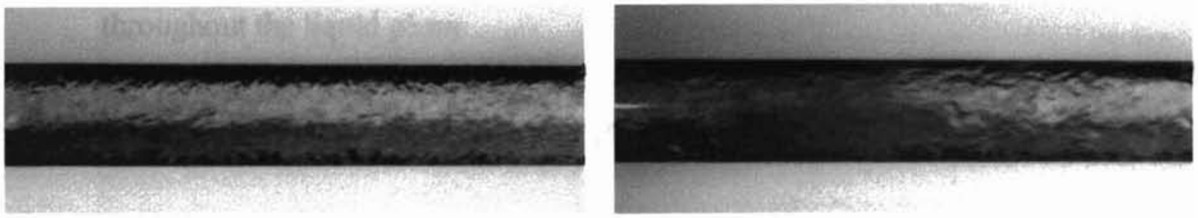
5.2.2.1 Description of Flow Patterns in Horizontal Pipe Flow

In this work, Taitel and Dukler's (1976) regimes and Breber *et al.*'s (1980) regimes have been adapted to distinguish among the two-phase flow patterns in horizontal pipe flow. According to Taitel and Dukler (1976), there are five basic flow regimes: smooth stratified (SS), stratified wavy (SW), intermittent (I) (slug and plug), annular dispersed (AD), and dispersed bubble (DB). In the case of the two-phase flow regimes of Breber *et al.*, there are four flow regimes: annular and mist-annular (Zone I), wavy and stratified (Zone II), intermittent (Zone III), and bubble (Zone IV). Furthermore, among the above flow patterns, transitional patterns were observed in this study, such as stratified/slug transition, slug/bubbly transition, annular/wavy transition, and annular/bubbly transition. The various flow patterns are shown in Fig. 5.25 and the descriptions of flow patterns by Hoogendoorn (1959) can be divided into five basic flow regimes as follows:

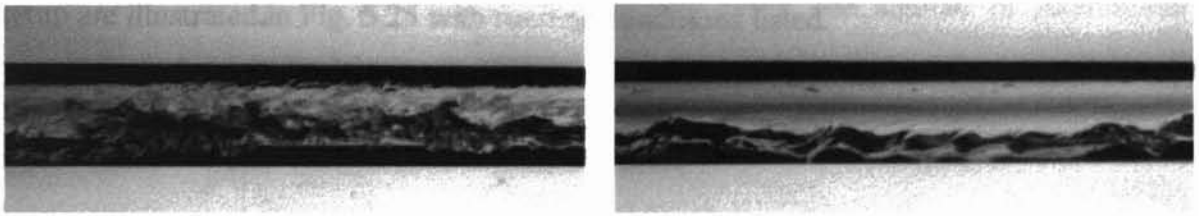
- Smooth Stratified (SS): the liquid flows in the lower part of the pipe and the gas flows over it with a smooth interface between the two phases.
- Stratified Wavy(SW) or Wavy (W): similar to smooth stratified flow, except for a wavy interface, due to a velocity difference between the two phases.
- Intermittent (I):
  - Plug (PL): the gas moves in bubbles or plugs along the upper side of the pipe.



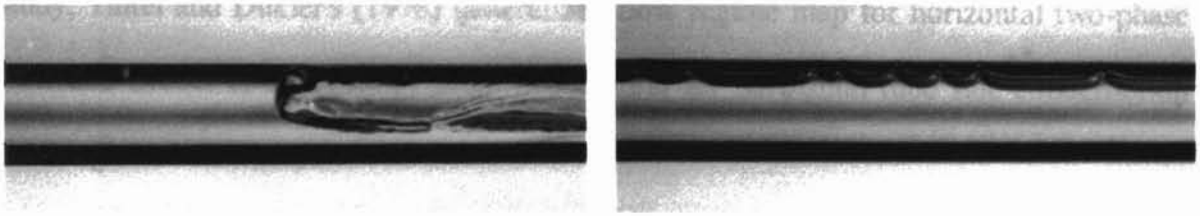
(a) Smooth Stratified (b) Annular/Wavy Transition



(c) Annular/Bubbly Transition (d) Annular/Bubbly Slug Transition



(e) Wavy/Slug Transition (f) Wavy



(g) Slug (h) Plug

Figure 5.25 Photographs of Representative Flow Patterns:
(a) $\dot{m}_L = 63.2$ kg/hr, $\dot{m}_G = 0.33$ kg/hr; (b) $\dot{m}_L = 187.3$ kg/hr, $\dot{m}_G = 30.9$ kg/hr;
(c) $\dot{m}_L = 1824$ kg/hr, $\dot{m}_G = 33.6$ kg/hr; (d) $\dot{m}_L = 1048.7$ kg/hr, $\dot{m}_G = 33.6$ kg/hr;
(e) $\dot{m}_L = 272.2$ kg/hr, $\dot{m}_G = 7.5$ kg/hr; (f) $\dot{m}_L = 61.3$ kg/hr, $\dot{m}_G = 12.4$ kg/hr;
(g) $\dot{m}_L = 489.9$ kg/hr, $\dot{m}_G = 1.3$ kg/hr; (h) $\dot{m}_L = 484.8$ kg/hr, $\dot{m}_G = 0.06$ kg/hr
(f = 8 @ 1/2000 sec)

  - Slug (SL): splashes or slugs of liquid occasionally pass through the pipe with a higher velocity than the bulk of the liquid. Pressure fluctuations are typical for this type of flow.

- Annular Dispersed (AD) or Annular: the liquid is partly atomized in the gas phase and partly flowing in an annular film along the pipe wall.
- Dispersed Bubble (DB) or Bubble: the gas is dispersed in fine bubbles throughout the liquid phase.

5.2.2.2 Presentation of Flow Pattern Photographs

The represented flow patterns achieved and repeatable in the present experimental setup are illustrated in Fig. 5.25 with running conditions listed.

5.2.2.3 Flow Pattern Maps

In order to determine the flow regimes for the present experimental setup for this study, Taitel and Dukler's (1976) generalized flow regime map for horizontal two-phase flow and Breber *et al.*'s (1980) simplified criteria for horizontal tube side condensation flow regimes were used.

A theoretical model developed by Taitel and Dukler (1976) was designed to determine transition boundaries between the adjacent flow regimes in two-phase gas-liquid flow by calculating the following dimensionless groups and by establishing the relation between the flow patterns and the dimensionless parameters:

$$X = \left[\frac{\left| (dp/dx)_{SL} \right|}{\left| (dp/dx)_{SG} \right|} \right]^{1/2} = \left[\frac{\left(\tilde{u}_G / \tilde{D}_G \right)^{-0.2} \tilde{u}_G^2 \left(\tilde{S}_G / \tilde{A}_G + \tilde{S}_i / \tilde{A}_L + \tilde{S}_i / \tilde{A}_G \right)}{\left(\tilde{u}_L / \tilde{D}_L \right)^{-0.2} \tilde{u}_L^2 \left(\tilde{S}_L / \tilde{A}_L \right)} \right]^{1/2} \qquad (5\text{-}26)$$

$$B = \left[\frac{\left|(dp/dx)_{SL}\right|}{(\rho_L - \rho_G) g \cos\alpha_p} \right]^{1/2} \tag{5-27}$$

$$Y = \frac{(\rho_L - \rho_G) g \sin\alpha_p}{\left|(dp/dx)_{SG}\right|} \tag{5-28}$$

$$F = \sqrt{\frac{\rho_G}{(\rho_L - \rho_G)}} \frac{V_{SG}}{\sqrt{D g \cos\alpha_p}} \tag{5-29}$$

$$K = F\left[\frac{D_i V_{SL}}{\nu_L}\right]^{1/2} = F\left[\mathrm{Re}_{SL}\right]^{1/2} \tag{5-30}$$

Based on their theory and the dimensionless parameters of Eqs. (5-26) to (5-30), the transitions between adjacent flow patterns were summarized as follows:

(1) Transition boundary between stratified wavy and annular or intermittent regimes is given as a function of F below and X in Eq. (5-26).

$$F^2\left[\frac{1}{2}\frac{\widetilde{u}_G\, d\widetilde{A}_L / d\widetilde{H}_L}{\widetilde{A}_G}\right] = 1 \tag{5-31}$$

The graphical illustration of the numerical determination of this boundary is Curve 'A' in Fig. 5.26. The transition takes place either to the intermittent (slug or plug flow), stratified or annular pattern.

(2) Transition boundary between intermittent and annular regimes is distinguished by a single X value of 1.6 as Curve 'B' in Fig. 5.26.

(3) Transition boundary between intermittent and dispersed bubble regimes is determined by solving the following function of B below and X in Eq. (5-26).

$$B^2 = \left[\frac{8\widetilde{A}_G}{\widetilde{S}_i \widetilde{u}_L^2 (\widetilde{u}_L \widetilde{D}_L)^{-0.2}}\right] \tag{5-32}$$

The graphical illustration of this boundary is plotted as Curve 'D' in Fig. 5.26.

(4) Transition boundary between stratified smooth and stratified wavy regimes is determined by solving the following function of K below and X in Eq. (5-26).

$$K = \frac{2}{\sqrt{\tilde{u}_L}\tilde{u}_G\sqrt{s}} \tag{5-33}$$

In Eq. (5-33), Taitel and Dukler (1976) set s = 0.01 in their work. The graphical illustration of this boundary is illustrated as Curve 'C' in Fig. 5.26.

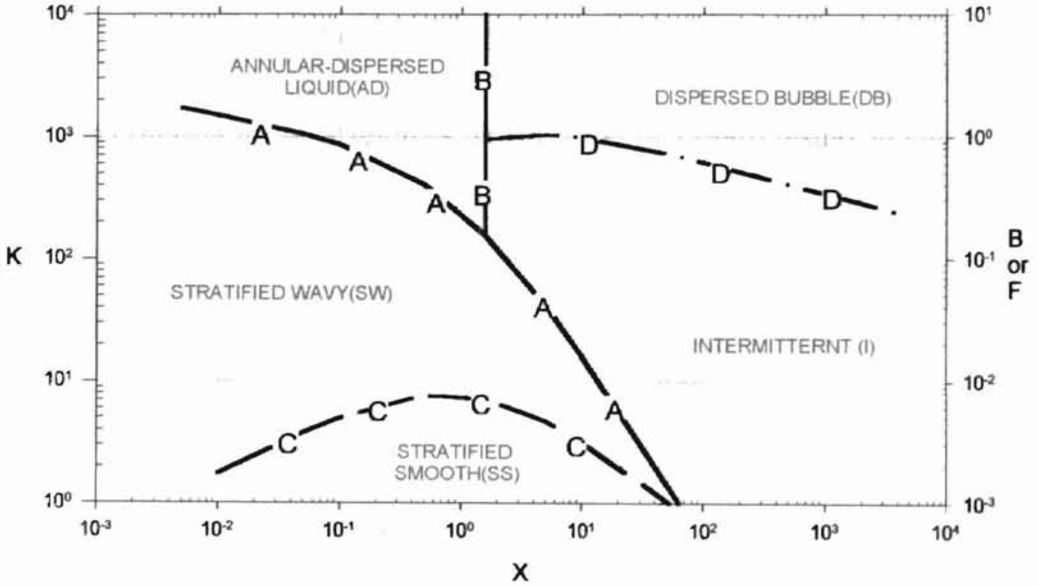


Figure 5.26 Taitel-Dukler Flow Regime Map for Horizontal Tubes, Taitel and Dukler (1976)

Another flow pattern map to confirm the flow regime applied to the Taitel-Dukler flow regime map was Breber *et al.*'s (1980) simplified criteria for horizontal tube side condensation flow regimes. In the case of Breber *et al.*'s (1980) map, the flow regimes are divided into four zones and criteria determined by dimensionless gas velocity, j_g^* (Eq. (5-30)), and the Martinelli parameter, X (Eqs. (5-26) and (5-35) are identical to each other), are as follows:

(1) Zone I $j_g^* > 1.5, X < 1.0$ Annular Flow

(2) Zone II $j_g^* < 0.5, X > 1.0$ Wavy and Stratified Flow

(3) Zone III $j_g^* < 1.5, X > 1.5$ Slug (Intermittent) Flow

(4) Zone IV $j_g^* > 1.5, X > 10$ Bubble Flow

where

$$j_g^* = \frac{G_t y}{\sqrt{D_t g \rho_v (\rho_l - \rho_v)}} = \left[\left(\frac{F_a}{F_r}\right)\left(\frac{1}{2f_v}\right)\right]^{0.5} \tag{5-34}$$

$$X = \sqrt{\Delta p_l / \Delta p_v} \cong \left(\frac{1-y}{y}\right)^{0.9}\left(\frac{\rho_v}{\rho_l}\right)^{0.5}\left(\frac{\mu_l}{\mu_v}\right)^{0.1} \tag{5-35}$$

The simplified criterion for flow regimes by Breber *et al.* (1980) results in Fig. 5.27.

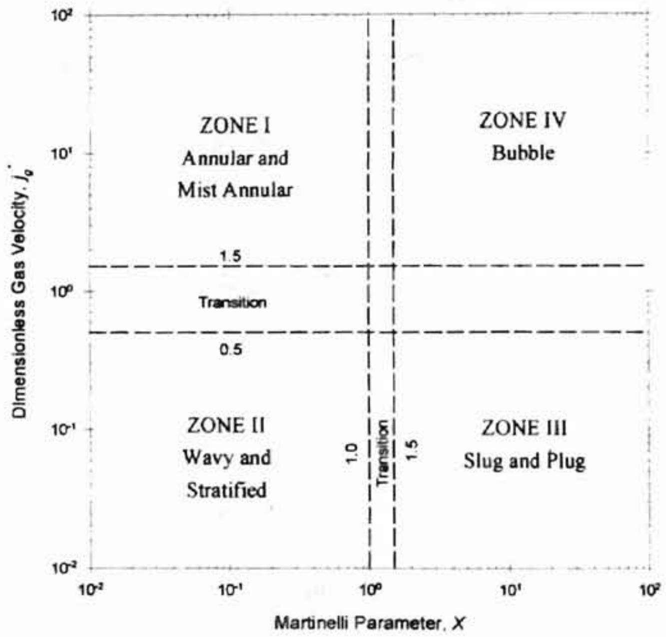


Figure 5.27 Simplified Criteria for Horizontal Tube Side Condensation Flow Regime, Breber *et al.* (1980)

A total of 111 flow pattern data points were collected. The collected data were classified by flow patterns: smooth stratified (SS), slug (SL), plug (PL), wavy (SW or

W), wavy/slug (WSL), annular/wavy (AW), annular/bubbly wavy (ABW), bubbly slug (BSL) and annular/bubbly slug (ABSL). The flow patterns of bubble (DB) and annular (AD) were not observed in the present experimental setup due to the limitation of the pressure and flow rate of compressed air provided by the laboratory. The maximum pressure and flow rate of compressed air obtained in this study were 100 psig (6.9×10^5 Pa) and 100 lpm (0.1 m^3/min). The necessary air/water supply conditions to obtain all expected flow patterns for two-phase gas-liquid flow based on Breber *et al.*'s (1980) map are explained in Appendix E.

First, the flow pattern data were plotted on the two general two-phase gas-liquid flow regime maps introduced in Figs. 5.26 and 5.27. Figures 5.28, 5.29 and 5.30 show the flow pattern data on the Taitel-Dukler map and the Breber *et al.* map.

The data points and the transition boundary curves shown in Figs. 5.28 and 5.29 were grouped by color: gray, dark gray or black. These colors help match the data points to the corresponding transition boundaries.

The gray data points (the values of K vs. X) match with the gray curve (curve 'C', refer to Fig. 5.26), and if the gray data point is plotted under curve 'C', then it's flow pattern is SS. If the gray data doesn't satisfy this SS condition, then the dark gray data point is checked to determine whether it's flow pattern is SW (or W) or I (PL or SL).

The dark gray data points (the values of F vs. X) match with the dark gray curve (curve 'A', refer to Fig. 5.26), and if the dark gray data point is plotted under curve 'A', then it's flow pattern is SW (or W). If the dark gray data point doesn't satisfy the SW (or W) condition, then the black data point will be checked to determine whether it's flow pattern is AD, I (PL or SL) or DB.

The black data points (the values of B vs. X) match with the black curve (curve 'D', refer to Fig. 5.26) and the dash-dot curve (curve 'B', refer Fig. 5.26), and if the black data point is plotted under curve 'D' and on the left side of curve 'B', then it's flow pattern is I (PL or SL).

As shown in Fig. 5.28, the transitional flow patterns were tracked according to Taitel and Dukler's (1976) theory on their map. Among the whole data set, 42 data points (ABSL-11; ABW-2; AW-12; WSL-6; BSL-10) were transitional flow patterns. Wavy (9 data), slug (46 data), plug (1 data) and smooth stratified (13 data) flow pattern data points are shown in Fig. 5.29.

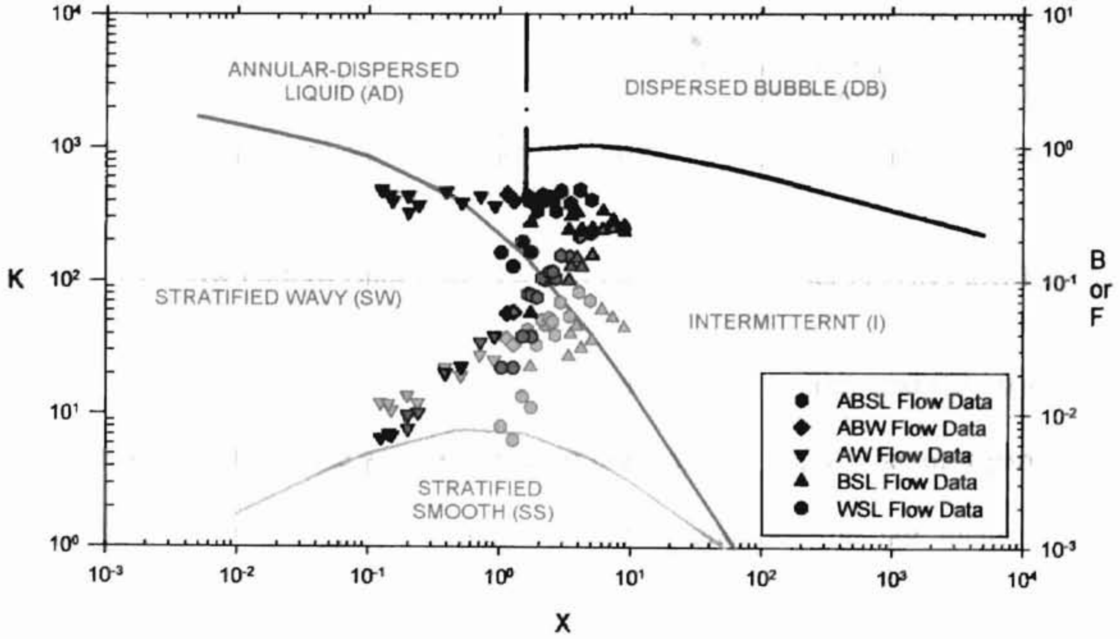


Figure 5.28 Transition Flow Pattern Data on Taitel-Dukler (1976) Flow Regime Map

The general trends of flow patterns were correctly predicted. However, the widths of each transition boundary were not clear on the Taitel-Dukler map due to the theoretical decision for the transition boundaries; so it was difficult to judge whether the data were in transitional flow or not without observed flow pattern information, even though the data were located on or around the boundaries on the map. Also, the predictions for slug flow did not show great accuracy (10/47 mis-prediction) as displayed in Fig. 5.29.

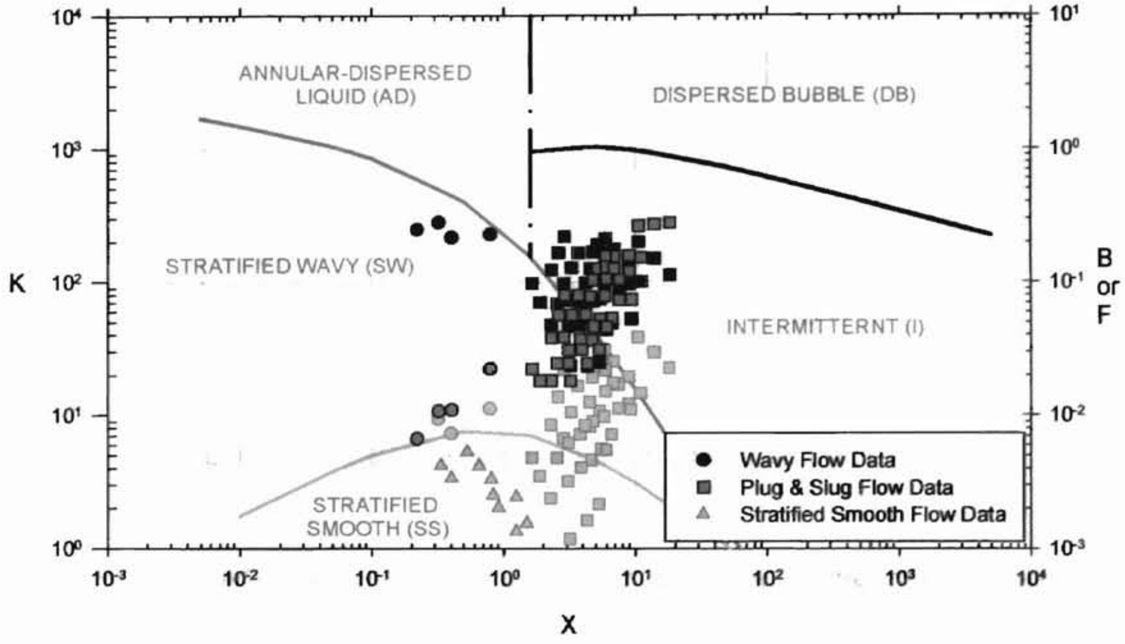


Figure 5.29 Flow Pattern Data - SS, SW and I on Taitel-Dukler (1976) Flow Regime Map

Breber *et al.*'s (1980) map was very convenient for plotting and data was easy to read on the map; and also the general trends of prediction were, for the most part, correct. However, as shown in Fig. 5.30, the transition boundaries did not match with the observed transitional flow pattern data ('T' in Fig. 5.30) in Zones I-II and III-IV (refer to Fig. 5.27 for Zones). Limitations of the present experimental setup precluded testing Zones I and IV, but most of the wavy, smooth stratified and slug flow patterns were accurately predicted in Zones II and III.

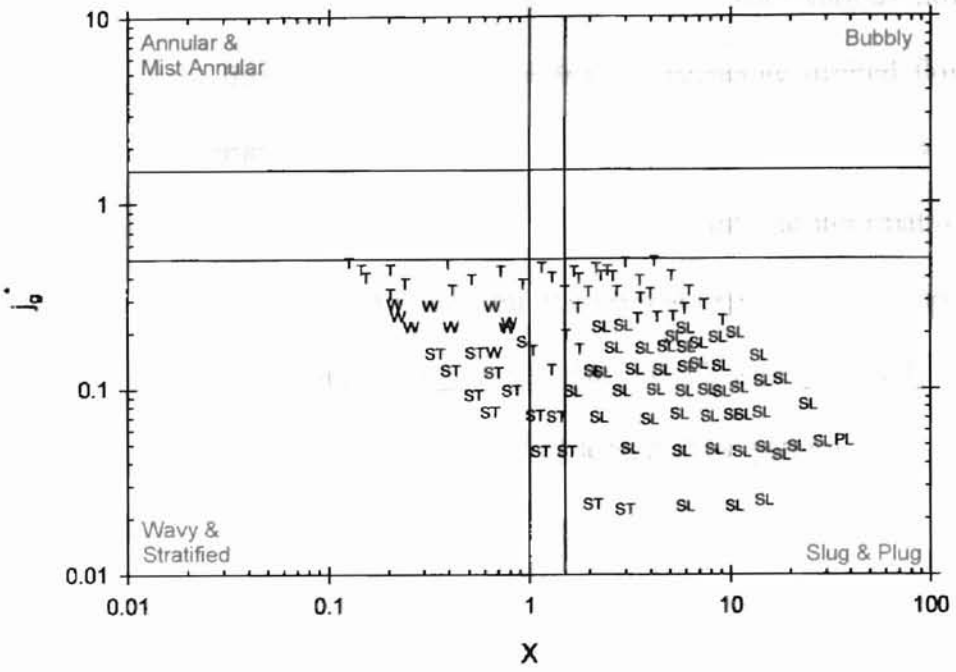


Figure 5.30 Flow Pattern Data on Breber *et al.* (1980) Map

Secondly and for the two-phase gas-liquid flow heat transfer measurement, a flow regime map was constructed, based on gas/liquid mass flow rate as shown in Fig. 5.31. The figure shows that the flow patterns are divided into five regimes: I-smooth stratified, II-slug, III-wavy, IV-annular/wavy, and V-bubbly slug or annular/bubbly slug. The other flow patterns observed were shown in the figure, but not included in the five regimes because of the difficulty to establish the relations between the flow pattern and the gas/liquid mass flow rate or because the area in the figure is too small to define as a flow regime.

The purpose of constructing the flow regime map, such as in Fig. 5.31, is to make it easy to regenerate the desired flow patterns using gas and liquid mass flow rate information for the specific experimental setup. Detailed mass flow rate information is tabulated in Table 5.10. The present experimental setup will finally be used to measure two-phase gas-liquid flow heat transfer in a horizontal tube with various flow patterns and uniform wall heat flux. Therefore, the ability to regenerate desired flow patterns without visual confirmation is very important because most of the test loop will be wrapped with insulation during actual testing. For this reason, the information in Table 5.10 will be very useful for future studies using the present experimental setup. The area of the five regimes was determined using certain data, which were positively in the zone of each particular flow pattern. The detailed observed flow pattern data are given in Appendix B.

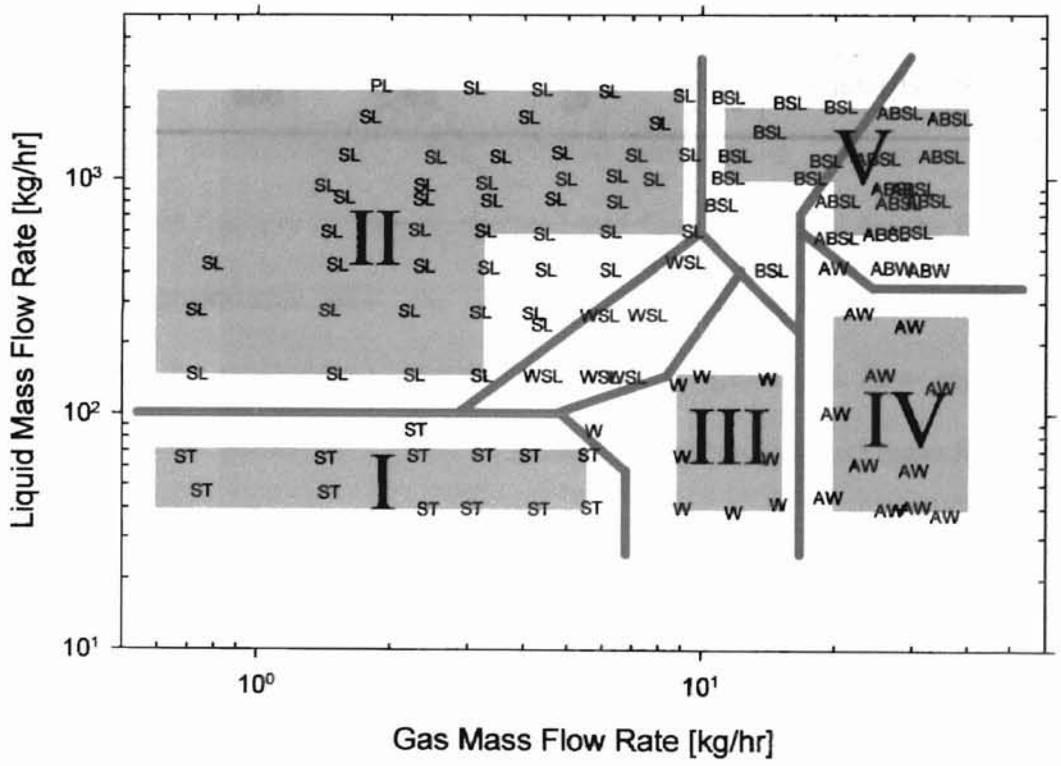


Figure 5.31 Flow Pattern Map Coordinated by Gas/Liquid Mass Flow Rates with Flow Pattern Data

Table 5.10 Regeneration Criterion of Flow Pattern Based on Mass Flow Rate

Region	$\dot{m}_L$ [kg/hr]		$\dot{m}_G$ [kg/hr]		Expected Flow Pattern
	Minimum	Maximum	Minimum	Maximum	
I	0	66.5	0	4.5	Smooth Stratified
II	270	2500	0	2.2	Slug
	600	2500	2.2	9.0	
III	40	140	9	15	Wavy
IV	40	260	20	35	Annular/Wavy
V	1000	2500	11	20	Bubbly Slug or Annular/Bubbly Slug
	600	2500	20	35	

CHAPTER VI

CONCLUSIONS AND RECOMMENDATIONS

6.1 Conclusions

The experimental setup for two-phase gas-liquid flow heat transfer measurements in a horizontal pipe has been built, and its performance also was verified by means of experimenting with single-phase flow heat transfer and comparing the experimental results with the predictions by using selected correlations. Moreover, a chosen correlation of void fraction for two-phase gas-liquid flow was tested for the future use by comparing its predictions with the experimental values. Based on the verified performance of the experimental setup, the two-phase gas-liquid flow regimes for a horizontal pipe were plotted on a graph coordinated by gas and liquid mass flux and also on the chosen published maps.

Therefore, the research for two-phase gas-liquid flow heat transfer in a horizontal pipe with various flow patterns can be performed with the present experimental setup with sufficient confidence.

6.1.1 Experimental Apparatus

With the completion of the experimental setup and the prepared instrumentation, planned experiments were executed. The setup was designed to be capable of measuring the single/two-phase flow pressure drops and heat transfers with uniform wall heat flux, and various two-phase gas-liquid flow patterns were achieved. In order to verify the performance of the test loop, the single-phase flow cases of pressure drop and heat transfer, which have been well investigated by a great number of researchers, were tested.

6.1.2 Tests of Single-Phase Flow

As mentioned in the previous section, the single-phase flow tests were run to confirm the performance of the experimental setup. The test runs covered laminar, transitional, and turbulent flow. For all types of test runs, carefully selected correlations for single-phase flow were used for the process of verification.

In the case of the experiment for measurement of pressure drop, hence friction coefficient, the experimental results (refer to Section 5.1.1) showed very good agreement with the predictions for turbulent flow. However, for laminar and some transitional flows, the experimental data failed to fit the predictions using Shah's (1978) correlation. Ghajar and Madon (1992) discussed the invalidity of the Shah's (1978) correlation. There were also probable errors caused by the range of small differential pressures found in this research (refer to Appendix A for the specification of the differential pressure transducer).

In addition, the results of heat transfer measurements (refer to Section 5.1.2) showed that the experimental system responded reasonably accurately to the expectations for transitional and turbulent flow. For laminar flow, the experimental heat transfer coefficients were higher than the predictions from Seigel *et al.*'s (1958) analytical solution for laminar forced convection heat transfer. These experimental results were similar to those of Petukhov and Polyakov (1967), showing that higher deviation from predictions occurred with increased heat flux. However, comparing the experimental laminar flow heat transfer data with the Ghajar and Tam's (1994) correlation for mixed convection showed good agreement. Therefore, the present experimental setup has a reasonable response for heat transfer in the laminar flow regime, and a very good response for turbulent flow heat transfer.

6.1.3 Comparison of Experimental and Predicted Void Fraction

In order to predict void fraction for two-phase gas-liquid flow, Chisholm's (1973) equation was used. Based on the comparison with the experimental data, Chisholm's (1973) equation is capable of predicting void fraction within an error of about ± 30 % for the present experimental apparatus.

6.1.4 Two-Phase Gas-Liquid Flow Regime Map

With the present experimental setup, the achieved and repeatable representative flow patterns are annular/wavy transition, annular/bubbly transition, bubbly/slug transition, slug, plug, wavy/slug transition, wavy, wavy/smooth stratified transition, and smooth stratified. A two-phase gas-liquid flow regime map coordinated by gas and liquid mass flow rate for the present experimental setup was built for convenience to regenerate the desired flow patterns for future study of two-phase flow heat transfer. The experimental flow pattern data were also plotted on the chosen published flow pattern maps.

6.2 Recommendations

In order to accurately measure the wall temperature along the test section for the two-phase flow heat transfer measurement, as discussed in Section 3.2.1, thermocouple station nos. 2, 9 and 10 need to be carefully examined, and some of the thermocouples at those stations should be replaced if required. In addition, the thermocouple probe to measure the outlet bulk temperature should also be replaced with the same type of thermocouple used for measuring the inlet bulk temperature in order to eliminate the different response time between the thermocouple and the thermocouple probe, which may cause inaccurate differential temperature results between the inlet and outlet.

It was not possible to generate annular flow and bubbly flow using the present experimental setup due to the lack of capacity for air and water flow rates. In order to achieve those two missing flow patterns, greater air and water flow rates and pressures should be supplied to the experimental setup. Based on the criterion of Breber *et al.*'s (1980) map, the air and water operating conditions required to produce the annular and bubbly flow are shown in Table 6.1, and the resulting operating conditions given in Table 6.1 are plotted on Breber *et al.*'s (1980) map in Fig. 6.1. The results shown in Table 6.1 and Fig. 6.1 will be helpful to determine the required operating conditions of air and water for upgrading the experimental setup for future study.

Table 6.1 The Air and Water Operating Conditions ($T_{L,in}$ = 30 °C, $T_{G,in}$ = 30 °C)

Q_L [gpm]	Q_G [lpm]	P_G [psi]	V_{SL} [m/s]	V_{SG} [m/s]	$\dot{m}_L$ [kg/hr]	$\dot{m}_G$ [kg/hr]	Re_{SL}	Re_{SG}
0.1	30	1	0.0124	0.9868	22.6	2.24	399	1671
0.2	40	2	0.0249	1.3157	45.2	3.18	797	2370
0.5	50	5	0.0622	1.6446	113.1	4.68	1993	3494
1	60	10	0.1245	1.9735	226.1	7.04	3985	5258
2	70	30	0.2490	2.3024	452.3	14.87	7971	11101
3	80	60	0.3735	2.6314	678.4	28.41	11956	21203
4	90	80	0.4980	2.9603	904.5	40.52	15942	30240
5	100	90	0.6225	3.2892	1130.7	49.77	19927	37148
10	150	100	1.2451	4.9338	2261.4	81.79	39855	61044
20	200	100	2.4902	6.5784	4522.7	109.06	79710	81392
30	250	150	3.7353	8.2230	6784.1	195.75	119564	146093
40	300	150	4.9804	9.8676	9045.4	234.90	159419	175311

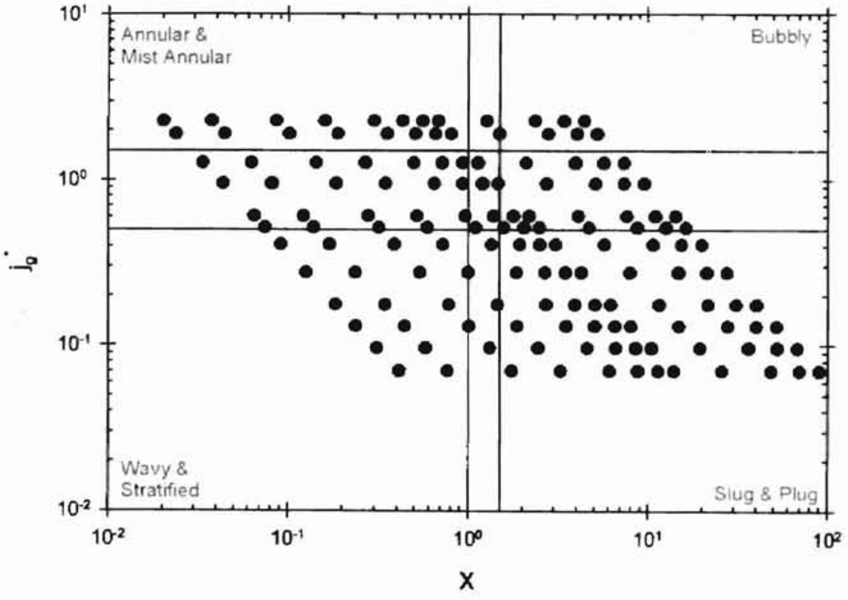


Figure 6.1 Combination Results of Operating Conditions Given in Table 6.1 on Breber *et al.* (1980) Map

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APPENDIX A

EQUIPMENT SPECIFICATIONS

In this appendix, a list of the all equipment (and their specifications) used in this study is given as follows:

1. Test Section (stainless tube)
   - Material: A 316 schedule 40 stainless steel circular pipe
   - Ordered from Stillwater Steel and Supply, Stillwater, OK
   - Size: I.D. = 1.097 ± 0.001 inches (2.7863 ± 0.00254 cm)

     O.D. = 1.316 ± 0.001 inches (3.3426 ± 0.00254 cm)
2. Power Supply (DC Welder)

   (1) Power Supply (replaced with Lincolnweld SA-750)
   - Model: Lincoln Idealarc DC-600 3-phase rectified electric welder
   - 100 % duty cycle at 600 amps and 44 volts at 50/60 Hz
   - Maximum power: 26.4 kW

   (2) Power Supply
   - Model: Lincolnweld SA-750
   - 100 % duty cycle: 750 amps at 40 volts, continuous duty
   - Maximum power: 30 kW
3. Developing/Observation Section
   - Material: Clear Polycarbonate Tube

- Producer: Cope Plastic Inc., Oklahoma City, OK
- Part number: Lextube 1.00×1.25
- Size: I.D. = 1.0 inch (2.54 cm)
  O.D. = 1.25 inch (3.175 cm)

4. Thermocouple, Wire, and Related Materials.
   - Thermocouple: OMEGA TT-T-30 copper-constantan insulated T-type insulated thermocouple having a max. temperature of 300 °F (150 °C)
   - Extension wire: OMEGA EXPP-T-20-TWSH-UL extension wire
   - Thermocouple Probes: OMEGA TJ36-CPSS-14U-12
   - Thermocouple Welder: Tigtech 116SRL thermocouple welder
   - Thermocouple Glue:
     - Model: OMEGA Omegabond 101 epoxy adhesive
     - Conductivity: 0.6 Btu/hr-ft-°F
     - Resistivity: 1×10^5 ohm-m
5. Temperature Bath
   - Model: FTS RC-00180-A
6. Data Logger
   - Model: Cole-Parmer 96 channel MAC-14 data logger
   - Input voltage: 0.3 μV – 10 V
   - Accuracy: ± 0.02 % of range
   - Resolution: 16 bits
7. Data Logger for Calibration of Thermocouples
   - Model: ECD 5100 digital data logger

- Resolution: 0.1 °F over a temperature range of 158 to 752 °F
- Conformity error: ± 0.1 °F over the range of −105 to 400 °F

8. Voltmeter/Ammeter
   - Digital Voltmeter
     - Model: Hewlett-Packard 3468B
     - Measurement range: 1 μV – 300 V
     - Accuracy: 1 % of reading
     - Resolution: 10 μV
   - D.C. Ammeter (replaced with Clamp Power Meter/Data logger)
     - Model: Weston Instruments Division 931 mounted with a 50 mV shunt
     - Range: up to 750 amp
     - Accuracy: 1 % of full scale
   - Clamp Power Meter/Data logger with RS-232 interface
     - Model: Cole-Parmer EW-26847-00
     - Power range/accuracy: 1000 kW / ± 2 % of reading + 5 digits
     - DC current range/accuracy: 1000 A / ± 2 % of reading + 5 digits
     - DC voltage range/accuracy: 1000 V / ± 0.75 % of reading + 2 digits
9. Heat Exchanger
   - Model: ITT Standard BFC 4036
   - Type: one shell and two tube pass heat exchanger
   - Effective surface area of shell: 21.2 ft^2 (1.97 m^2)
   - Max. duty: 67190 Btu/hr (19.7 kW)
10. Flow Rate Rotameter

- Model: OMEGA FL-9028
- Measurement range: 4 – 28 gpm
- Accuracy: ± 5 % of full scale
- Repeatability: ± 1 % of full scale

11. Valves

- Quick-Closing Valves: W&W International RD 222DVYD
- Quick-Opening Valve: ASCO 826820
- Manually Operated Valves
  - Model: OMEGA Teflon-PFA type E-06373-25 (M)
  - Size: ¼ inch
  - Maximum pressure: 40 psi
  - Maximum temperature: 300 °F
- Tab Valves: Ace self-piercing tap valve for 3/8 inch to 1 inch O.D. copper tube with ¼ inch O.D tube outlet

12. Water storage tank and air-water separate tank

(1) Water storage tank

- Type: Cylindrical polyethylene tank
- Capacity: 35 gallons

(2) Air-water separate tank

- Type: Cylindrical polyethylene tank
- Capacity: 55 gallons

13. Pumps

- Pump 1 and Pump 3 (refer to Fig. 3.1)

    - Model: Oberdorfer Pump SKH35FN193T
    - Flow rate: 11 gpm at 3450 rpm
    - Moter: General Electric 1/3 HP motor
  - Pump 2 (refer to Fig. 3.1)
    - Model: Armstrong 4270 1 HP
    - Flow rate: 30 gpm at 3500 rpm for 68 ft head

14. Gas Volumetric Flow Meter
    - Model: Cole-Parmer P-32915-15 gas flowmeter
    - Measurement range: 0 to 100 LPM
    - Output span: 5 Vdc (0.010 Vdc for zero flow and 5.0 Vdc for full scale flow)
    - Accuracy: ± 2 % of full scale
    - Repeatability: ± 1 % of full scale
    - Operating temperature: 0 to 50 °C
    - Max. pressure: 100 psig
    - Connection: ¼ female NPT

15. Liquid Turbine Flow Meters
    - Liquid Turbine Flow Meter 1
      - Model: Halliburton 0.5 inch turbine meter
      - Measurement Range: up to 10.5 gpm
      - Accuracy: ± 1 % of reading
      - Repeatability: ± 0.05 % of reading
      - Operating temperature: - 67 to 250 °F (- 55 to 121 °C)
      - Max. pressure: 200 psi

- Liquid Turbine Flow Meter 2
  - Model: Cole-Parmer P-33110-00 turbine meter
  - Measurement flow rate: 0.07 – 5 gpm
  - Output: 6 – 24 VDC pulse
  - Max. temperature: 160 °F
  - Max. pressure: 150 psi
  - Accuracy: ± 1 % of full scale
  - Linearity: ± 1 % of full scale
  - Repeatability: 0.5 % of full scale
  - Connections: 3/8 inch female NPT standard

16. Rate Meter/Totalizer

- Model: OMEGA DPF701 6-digit rate meter/totalizer with OMEGA DPF700-A analog output board
- Functions: rate and totalize selected by menu
- Display: 6-digit, 7-segment red LED display
- Inputs
  - types: single input, TTL, CMOS, NPN open collector, contact closure and magnetic pickup compatible; selected by dip switch. Non-isolated.
  - Level: max. 60 V; min 25 mV rms
  - Frequency: 30 kHz max.
  - Accuracy: ± ½ LSD of total; 0.01 % of the rate ± 1 ½ LSD
- Communication: RS-232, analog output, optional
- Rate measurement technique: 1/x

- Gate time: 0.30 sec
- Analog output: Scalable, 4 to 20 mA, 0 to 20 mA, 0 to 10 V (optional)

17. Pressure Transducer
    - Differential Pressure Transducer
        - Model: Validyne DP15 Laboratory Pressure Transducer
        - Measurement range: ± 0.08 to ± 3200 psid
        - Accuracy: ± 0.25 % of full scale
        - Output: ± 34 mV/V, nominal
        - Excitation: 5 Vrms, 3 kHz to 5kHz
        - Pressure media: liquids and gases compatible with 410 SST
        - Temperature range: 0 to 165 °F
        - Over pressure: 200 % of full scale
        - Pressure connection: 1/8 inch female NPT
    - System Pressure Transducer
        - Model: OMEGA PX240-060G
        - Measurement pressure range: 0 to 60 psi
        - Full scale output: 5.00 ± 2.5 V
        - Linearity: ± 1.5 % of full scale
        - Hysteresis and repeatability: ± 0.25 % of full scale
        - Operable over pressure: two times of full scale
        - Operating temperature: - 18 to + 63 °C (-40 to + 185 °F)
18. Static Mixer
    - Model: OMEGA FMX71009-P

- Type: Alternating polypropylene baffle
- Dimension: a diameter of 0.9 inch and a length of 5.3 inches
- Max. service temperature: 200 °F

19. Scanivalve

- Model: Scanivalve W0601/1P-12T
- 24 channels with one reference channel connector
- Max. pressure: 50 psi

20. A/D board

- Model: Computer Board CIO-AD08
- Max. sampling rate: 50 kHz
- 8 single ended input channels
- 12-bit A/D resolution
- 7 digital input/output bits

APPENDIX B

EXPERIMENTAL DATA

B.1 Summary of Test Runs

In this appendix, the results from all of the test runs discussed in Chapter V are summarized in tables. For the single-phase flow measurements, the following data are tabulated:

- Single-phase flow pressure drop measurements
- Single-phase flow heat transfer measurements

For the two-phase flow measurements, the following data are tabulated:

- Two-phase flow void fraction measurements
- Two-phase flow pattern measurements

All of the summary tables are arranged by the main measured and calculated parameters.

B.1.1 Single-Phase Flow Pressure Drop Measurement

Table B.1 Summary of Pressure Drop Measurement for Laminar/Transition Cases (Re < 3,500)

Run No.	Q_L [lpm]	T_L [°C]	V_L [m/s]	Re	$DP_{exp}04$ [in H_2O]	$DP_{exp}05$ [in H_2O]	$DP_{exp}06$ [in H_2O]	$DP_{exp}07$ [in H_2O]	$DP_{exp}08$ [in H_2O]	Error [%]	RMS [%]
1	0.350	21.13	0.0362	1034	0.0840	0.0856	0.0832	0.0848	0.0855	89.46	84.98
2	0.434	22.20	0.0449	1316	0.0919	0.0974	0.0903	0.0950	0.0989	87.45	80.08
3	0.589	21.19	0.0609	1742	0.0948	0.0983	0.0858	0.0972	0.1028	81.26	74.87
4	0.708	22.30	0.0733	2155	0.1032	0.1092	0.1077	0.1109	0.1172	78.11	72.57
5	0.803	22.10	0.0831	2430	0.1105	0.1165	0.1194	0.1211	0.1305	75.56	69.54
6	0.934	21.26	0.0967	2769	0.1172	0.1286	0.1288	0.1364	0.1492	71.12	56.82
7	1.012	24.86	0.1047	3276	0.0693	0.0772	0.0764	0.0920	0.0840	48.09	41.58
8	1.024	24.55	0.1060	3290	0.0650	0.0737	0.0767	0.0890	0.0779	43.48	39.81
9	1.033	24.86	0.1068	3341	0.0684	0.0750	0.0773	0.0917	0.0721	45.91	37.13
10	1.057	24.30	0.1094	3376	0.0617	0.0697	0.0745	0.0837	0.0774	37.49	38.77
11	1.068	24.53	0.1105	3428	0.0714	0.0821	0.0861	0.0995	0.0899	45.40	55.62
12	1.075	22.25	0.1112	3265	0.1317	0.1461	0.1445	0.1553	0.1725	69.12	65.91

Table B.1 Summary of Pressure Drop Measurement for Laminar/Transition Cases (Re < 3,500) (Continued)

Run No.	$DP_{predict}01$ [in H_2O]	$DP_{predict}02$ [in H_2O]	$DP_{predict}03$ [in H_2O]	$DP_{predict}04$ [in H_2O]	$DP_{predict}05$ [in H_2O]	$DP_{predict}06$ [in H_2O]	$DP_{predict}07$ [in H_2O]	$DP_{predict}08$ [in H_2O]	$DP_{predict}09$ [in H_2O]	$DP_{predict}10$ [in H_2O]
1	0.0038	0.0057	0.0073	0.0089	0.0104	0.0119	0.0134	0.0149	0.0164	0.0179
2	0.0050	0.0075	0.0096	0.0115	0.0134	0.0153	0.0171	0.0189	0.0207	0.0226
3	0.0079	0.0118	0.0149	0.0178	0.0205	0.0231	0.0257	0.0283	0.0308	0.0334
4	0.0102	0.0150	0.0190	0.0226	0.0259	0.0291	0.0322	0.0352	0.0382	0.0412
5	0.0122	0.0180	0.0228	0.0270	0.0309	0.0346	0.0382	0.0417	0.0452	0.0486
6	0.0154	0.0227	0.0286	0.0338	0.0386	0.0432	0.0475	0.0518	0.0560	0.0601
7	0.0165	0.0242	0.0305	0.0360	0.0410	0.0457	0.0502	0.0546	0.0588	0.0630
8	0.0169	0.0247	0.0311	0.0368	0.0419	0.0467	0.0513	0.0557	0.0601	0.0643
9	0.0170	0.0249	0.0313	0.0370	0.0422	0.0470	0.0516	0.0561	0.0604	0.0647
10	0.0177	0.0259	0.0327	0.0386	0.0440	0.0490	0.0538	0.0584	0.0629	0.0674
11	0.0179	0.0262	0.0330	0.0390	0.0444	0.0495	0.0543	0.0590	0.0636	0.0680
12	0.0186	0.0273	0.0344	0.0407	0.0464	0.0517	0.0568	0.0617	0.0665	0.0712

Table B.2 Summary of Pressure Drop Measurement for Transition/Turbulent Cases ($3,500 < Re < 35,000$)

Run No.	Q_L [gpm]	T_L [°C]	Re_L	DP4 [in H_2O]	DP5 [in H_2O]	DP6 [in H_2O]	DP7 [in H_2O]	DP8 [in H_2O]
1	1.24	21.33	3691	0.138291	0.152268	0.151958	0.161425	0.187287
2	1.51	22.20	4575	0.165618	0.188675	0.198554	0.218506	0.237175
3	1.74	21.26	5165	0.184463	0.207799	0.206251	0.225312	0.268353
4	2.03	21.95	6117	0.221504	0.255889	0.239393	0.296053	0.346547
5	2.19	21.52	6539	0.215674	0.259833	0.253513	0.281718	0.352248
6	2.46	21.54	7351	0.271272	0.318396	0.319586	0.389703	0.443777
7	2.16	28.50	7612	0.186938	0.212234	0.236359	0.278526	0.313121
8	2.88	21.45	8591	0.296442	0.366747	0.355590	0.432371	0.516354
9	2.62	26.99	8915	0.200630	0.245645	0.272093	0.312979	0.370202
10	2.58	29.85	9327	0.228153	0.272748	0.325652	0.372095	0.402766
11	3.18	23.50	9948	0.295436	0.364007	0.412354	0.486381	0.533190
12	3.36	21.50	10029	0.359524	0.445292	0.442098	0.540819	0.642990
13	3.18	24.26	10147	0.295720	0.364721	0.415908	0.488187	0.536241
14	3.18	24.62	10227	0.295694	0.370755	0.419185	0.480957	0.536505
15	3.18	25.39	10402	0.298391	0.370804	0.416775	0.480554	0.535396
16	3.87	21.80	11616	0.428544	0.537398	0.542391	0.677496	0.792308
17	3.45	30.70	12726	0.374916	0.445387	0.509504	0.572919	0.658801
18	4.29	30.90	15902	0.525787	0.600060	0.730635	0.834316	0.907012
19	5.15	30.80	19044	0.691509	0.835549	0.978754	1.104205	1.261473
20	5.99	30.00	21757	0.907450	1.106163	1.287934	1.450648	1.621373
21	6.85	29.70	24730	1.164189	1.374079	1.644507	1.836463	2.059403
22	7.69	30.20	28048	1.432696	1.701099	1.999362	2.292796	2.531775
23	8.53	30.20	31111	1.735564	2.025847	2.409304	2.746395	3.074658
24	9.39	30.20	34253	2.062449	2.418464	2.858054	3.242326	3.603600

Table B.2 Summary of Pressure Drop Measurement for Transition/Turbulent Cases ($3,500 < Re < 35,000$) (Continued)

Run No.	$dp/dx_{4\text{-}5exp}$ [in H_2O/m]	$dp/dx_{5\text{-}6exp}$ [in H_2O/m]	$dp/dx_{6\text{-}7exp}$ [in H_2O/m]	$dp/dx_{7\text{-}8exp}$ [in H_2O/m]	avg. $dp/dx_{4\text{-}8exp}$ [in H_2O/m]	$dp/dx_{4\text{-}8exp}$ [in H_2O/m]	$dp/dx_{predict}$ [in H_2O/m]	Error [%]
1	0.055028	-0.001220	0.037272	0.101819	0.048224	0.048224	0.048255	-0.06
2	0.090776	0.038894	0.078551	0.073500	0.070430	0.070430	0.067292	4.46
3	0.091874	-0.006094	0.075043	0.169453	0.082569	0.082569	0.087203	-5.61
4	0.135374	-0.064945	0.223071	0.198795	0.123074	0.123074	0.113258	7.98
5	0.173854	-0.024882	0.111043	0.277677	0.134423	0.134423	0.130041	3.26
6	0.185528	0.004685	0.276051	0.212890	0.169788	0.169788	0.159438	6.10
7	0.099591	0.094980	0.166012	0.136201	0.124196	0.124196	0.121909	1.84
8	0.276791	-0.043925	0.302287	0.330642	0.216449	0.216449	0.210389	2.80
9	0.177224	0.104126	0.160969	0.225287	0.166902	0.166902	0.172051	-3.09
10	0.175571	0.208283	0.182846	0.120752	0.171863	0.171863	0.163936	4.61
11	0.269965	0.190343	0.291445	0.184287	0.234010	0.234010	0.245773	-5.03
12	0.337669	-0.012575	0.388665	0.402248	0.279002	0.279002	0.275188	1.37
13	0.271657	0.201524	0.284563	0.189189	0.236733	0.236733	0.245276	-3.61
14	0.295516	0.190669	0.243197	0.218693	0.237019	0.237019	0.244396	-3.11
15	0.285091	0.180988	0.251098	0.215913	0.233273	0.233273	0.242748	-4.06
16	0.428559	0.019657	0.531909	0.452016	0.358035	0.358035	0.350519	2.10
17	0.277445	0.252429	0.249665	0.338118	0.279414	0.279414	0.272249	2.56
18	0.292413	0.514075	0.408193	0.286205	0.375221	0.375221	0.398696	-6.26
19	0.567087	0.563799	0.493902	0.619165	0.560988	0.560988	0.548902	2.15
20	0.782335	0.715634	0.640606	0.672146	0.702680	0.702680	0.717167	-2.06
21	0.826339	1.064677	0.755732	0.877717	0.881116	0.881116	0.909125	-3.18
22	1.056705	1.174264	1.155252	0.940862	1.081771	1.081771	1.108961	-2.51
23	1.142846	1.509673	1.327130	1.292374	1.318006	1.318006	1.329490	-0.87
24	1.401634	1.730669	1.512882	1.422339	1.516881	1.516881	1.573263	-3.72

Table B.2 Summary of Pressure Drop Measurement for Transition/Turbulent Cases (3,500 < Re < 35,000) (Continued)

Run No.	$cf_{4\text{-}5exp}$	$cf_{5\text{-}6exp}$	$cf_{6\text{-}7exp}$	$cf_{7\text{-}8exp}$	$cf_{4\text{-}8exp}$	avg. $cf_{4\text{-}8exp}$	$cf_{predict}$	Error [%]
1	1.1558E-02	-2.5635E-04	7.8286E-03	2.1386E-02	1.0129E-02	1.0129E-02	1.0148E-02	-0.19
2	1.2958E-02	5.5518E-03	1.1213E-02	1.0492E-02	1.0053E-02	1.0053E-02	9.6177E-03	4.33
3	9.8179E-03	-6.5127E-04	8.0193E-03	1.8108E-02	8.8235E-03	8.8235E-03	9.3305E-03	-5.75
4	1.0677E-02	-5.1223E-03	1.7594E-02	1.5679E-02	9.7071E-03	9.7071E-03	8.9442E-03	7.86
5	1.1745E-02	-1.6810E-03	7.5018E-03	1.8759E-02	9.0813E-03	9.0813E-03	8.7963E-03	3.14
6	9.9280E-03	2.5071E-04	1.4772E-02	1.1392E-02	9.0857E-03	9.0857E-03	8.5427E-03	5.98
7	6.9093E-03	6.5895E-03	1.1517E-02	9.4492E-03	8.6163E-03	8.6163E-03	8.4684E-03	1.72
8	1.0796E-02	-1.7132E-03	1.1790E-02	1.2896E-02	8.4422E-03	8.4422E-03	8.2162E-03	2.68
9	8.3747E-03	4.9204E-03	7.6065E-03	1.0646E-02	7.8869E-03	7.8869E-03	8.1405E-03	-3.22
10	8.6094E-03	1.0214E-02	8.9662E-03	5.9213E-03	8.4276E-03	8.4276E-03	8.0491E-03	4.49
11	8.6889E-03	6.1262E-03	9.3802E-03	5.9313E-03	7.5317E-03	7.5317E-03	7.9203E-03	-5.16
12	9.6865E-03	-3.6073E-04	1.1149E-02	1.1539E-02	8.0036E-03	8.0036E-03	7.9042E-03	1.24
13	8.7178E-03	6.4671E-03	9.1319E-03	6.0713E-03	7.5970E-03	7.5970E-03	7.8811E-03	-3.74
14	9.4990E-03	6.1289E-03	7.8173E-03	7.0297E-03	7.6187E-03	7.6187E-03	7.8658E-03	-3.24
15	9.1871E-03	5.8324E-03	8.0917E-03	6.9578E-03	7.5172E-03	7.5172E-03	7.8325E-03	-4.19
16	9.3039E-03	4.2676E-04	1.1548E-02	9.8131E-03	7.7728E-03	7.7728E-03	7.6193E-03	1.98
17	7.5800E-03	6.8965E-03	6.8210E-03	9.2376E-03	7.6338E-03	7.6338E-03	7.4474E-03	2.44
18	5.1596E-03	9.0708E-03	7.2025E-03	5.0501E-03	6.6207E-03	6.6207E-03	7.0439E-03	-6.39
19	6.9477E-03	6.9075E-03	6.0511E-03	7.5858E-03	6.8730E-03	6.8730E-03	6.7335E-03	2.03
20	7.0958E-03	6.4908E-03	5.8103E-03	6.0964E-03	6.3733E-03	6.3733E-03	6.5130E-03	-2.19
21	5.7261E-03	7.3776E-03	5.2368E-03	6.0821E-03	6.1056E-03	6.1056E-03	6.3077E-03	-3.31
22	5.8169E-03	6.4640E-03	6.3593E-03	5.1792E-03	5.9549E-03	5.9549E-03	6.1123E-03	-2.64
23	5.1133E-03	6.7546E-03	5.9378E-03	5.7823E-03	5.8970E-03	5.8970E-03	5.8100E-03	1.48
24	5.1735E-03	6.3880E-03	5.5842E-03	5.2500E-03	5.5989E-03	5.5989E-03	5.6993E-03	-1.79

B.1.2 Single-Phase Flow Heat Transfer Measurement

In this section, a total of 38 test sets (7 test runs for laminar flow and 31 test runs for turbulent flow) were tabulated.

In the laminar flow cases, the main experimental and the calculated parameters are presented in Table B.3 with the comparison results of experimental Nusselt numbers with predictions using Siegel et al. (1958), Petukhov and Polyakov (1967), and Ghajar and Tam (1994) correlations.

In the turbulent flow cases, the test runs were grouped according to Table 5.1. The main experimental and calculated parameters are presented in Tables B.4 and B.5 with the comparison results of the experimental Nusselt numbers at thermocouple station no. 6 with the predictions using Colburn (1933), Sieder and Tate (1936), Gnielinski [1] (1976), Gnielinski [3] (1976), and Ghajar and Tam (1994) correlations.

Table B.3 Summary of Laminar Flow Heat Transfer Experimental Data

Run & St. No.	x/D_i	x^+	Re	Pr	Gr	μ_b/μ_w	h_{top}/h_{bottom}	Ra_0	Ra	Nu_{exp}	Nu_{Seigel}	$Nu_{Ghajar\&Tam}$	$Nu_{Petuhkov\&Polyakov}$	$Error_S$[%]	$Error_{GT}$[%]	$Error_{PP}$[%]
RN1010 St. 3	24.61	0.004199	1984	5.88	213191	1.060	1.871	1965131	1253565	17.39	9.73	14.02	9.80	44.05	19.37	43.66
St. 4	33.73	0.005761	1991	5.86	237000	1.066	2.323	1157065	1388819	15.83	8.81	13.85	9.27	44.34	12.49	41.46
St. 5	42.84	0.007331	1997	5.84	247185	1.068	3.016	776429	1443562	15.35	8.18	13.71	9.18	46.70	10.71	40.19
St. 6	51.96	0.008912	2004	5.81	256990	1.070	3.385	562525	1493110	14.93	7.71	13.63	9.19	48.39	8.68	38.42
St. 7	61.08	0.010503	2010	5.79	263965	1.071	4.078	431500	1528356	14.70	7.34	13.58	9.22	50.05	7.59	37.26
St. 8	70.19	0.012086	2017	5.77	264272	1.070	4.484	344341	1524851	14.84	7.05	13.49	9.21	52.50	9.12	37.90
RN1030 St. 3	24.61	0.004199	1977	5.86	263205	1.074	2.074	1941398	1542384	17.94	9.73	14.54	9.88	45.77	18.95	44.95
St. 4	33.73	0.005761	1985	5.84	287395	1.079	2.510	1144784	1678387	16.67	8.81	14.38	9.52	47.16	13.75	42.89
St. 5	42.84	0.007331	1993	5.81	298910	1.081	3.105	767119	1736668	16.26	8.18	14.24	9.49	49.69	12.41	41.63
St. 6	51.96	0.008912	2001	5.78	309858	1.083	3.576	556582	1790980	15.90	7.71	14.18	9.52	51.52	10.81	40.14
St. 7	61.08	0.010503	2010	5.76	319617	1.084	4.314	427559	1840994	15.63	7.35	14.16	9.56	53.00	9.41	38.87
St 8	70.19	0.012086	2018	5.73	320243	1.083	4.764	340719	1834990	15.82	7.05	14.06	9.55	55.42	11.10	39.63
RN1040 St. 3	24.61	0.004199	2019	5.85	290218	1.081	1.985	2005284	1697776	18.59	9.77	14.83	9.95	47.46	20.23	46.47
St. 4	33.73	0.005761	2028	5.82	317558	1.087	2.419	1179564	1848188	17.26	8.84	14.68	9.65	48.77	14.93	44.07
St. 5	42.84	0.007331	2037	5.79	330263	1.089	3.214	790724	1912225	16.85	8.21	14.56	9.64	51.28	13.61	42.82
St. 6	51.96	0.008912	2046	5.76	345722	1.091	3.572	573896	1991358	16.35	7.73	14.53	9.68	52.70	11.11	40.81
St. 7	61.08	0.010503	2055	5.73	353672	1.092	4.279	439737	2026538	16.23	7.37	14.48	9.70	54.60	10.76	40.23
St. 8	70.19	0.012086	2064	5.71	355455	1.091	4.737	351506	2029647	16.39	7.08	14.41	9.70	56.83	12.10	40.81
RN1060 St. 3	24.61	0.004199	2029	5.80	407929	1.111	2.213	1994010	2365986	19.04	9.73	15.82	10.22	48.90	16.92	46.32
St. 4	33.73	0.005761	2042	5.76	442668	1.117	2.685	1173342	2549769	17.94	8.81	15.72	10.15	50.89	12.39	43.41
St. 5	42.84	0.007331	2056	5.72	461339	1.119	3.472	786780	2638859	17.59	8.18	15.63	10.18	53.49	11.13	42.15
St. 6	51.96	0.008912	2069	5.68	482747	1.122	3.937	571167	2742003	17.18	7.71	15.64	10.22	55.15	8.99	40.51
St. 7	61.08	0.010503	2082	5.64	496482	1.122	4.857	437725	2800159	17.07	7.34	15.62	10.25	56.99	8.51	39.92
St. 8	70.19	0.012086	2095	5.60	499574	1.120	5.336	348952	2797616	17.33	7.05	15.54	10.25	59.33	10.33	40.84
RN1070 St. 3	24.61	0.004199	2092	5.60	965459	1.237	2.861	1978922	5406570	20.22	9.74	18.98	11.68	51.81	6.14	42.21
St. 4	33.73	0.005761	2127	5.50	1048276	1.241	3.437	1162508	5765518	19.67	8.82	19.00	11.77	55.17	3.38	40.19
St. 5	42.84	0.007331	2162	5.40	1107811	1.238	4.692	777681	5982179	19.64	8.18	19.02	11.81	58.33	3.18	39.84
St. 6	51.96	0.008912	2198	5.31	1190079	1.240	5.394	564619	6319319	19.27	7.71	19.17	11.91	59.99	0.52	38.20
St. 7	61.08	0.010503	2233	5.21	1256368	1.238	6.723	431135	6545677	19.22	7.34	19.26	11.98	61.80	-0.21	37.68
St. 8	70.19	0.012086	2269	5.12	1306149	1.233	7.199	343320	6687483	19.45	7.05	19.30	12.02	63.78	0.77	38.19
RN1130 St. 3	24.61	0.004199	1927	6.18	90761	1.031	1.258	2034160	560901	13.27	9.79	12.44	9.80	26.20	6.27	26.18
St. 4	33.73	0.005761	1930	6.18	103475	1.035	1.517	1200553	639477	11.71	8.87	12.11	8.90	24.24	-3.45	23.98
St. 5	42.84	0.007331	1933	6.17	106828	1.036	2.147	805308	659130	11.40	8.24	11.84	8.37	27.75	-3.82	26.54
St. 6	51.96	0.008912	1935	6.16	108208	1.036	2.280	584876	666561	11.31	7.76	11.63	8.11	31.38	-2.82	28.26
St. 7	61.08	0.010503	1938	6.15	108542	1.036	2.897	448458	667535	11.33	7.39	11.47	8.01	34.74	-1.20	29.31
St. 8	70.19	0.012086	1941	6.14	109743	1.036	2.919	357723	673824	11.26	7.10	11.36	7.98	36.97	-0.90	29.11
RN1150 St. 3	24.61	0.004199	1950	6.16	110499	1.037	1.349	2063093	680676	14.25	9.82	12.79	9.83	31.09	10.25	31.05
St. 4	33.73	0.005761	1953	6.15	125291	1.042	1.664	1214734	770537	12.65	8.89	12.50	8.95	29.71	1.21	29.24
St. 5	42.84	0.007331	1956	6.14	129572	1.043	2.235	815083	795571	12.31	8.25	12.25	8.50	32.94	0.52	30.97
St. 6	51.96	0.008912	1959	6.13	131671	1.043	2.471	592149	807140	12.18	7.78	12.06	8.32	36.14	0.96	31.70
St. 7	61.08	0.010503	1963	6.12	131843	1.043	3.031	454163	806882	12.24	7.41	11.91	8.25	39.45	2.73	32.56
St. 8	70.19	0.012086	1966	6.11	132891	1.043	3.171	362365	811963	12.21	7.11	11.80	8.24	41.74	3.33	32.51
Mimimum:	24.61	0.004199	1927	5.12	90761	1.031	1.258	340719	560901	11.26	7.05	11.36	7.98	24.24	-3.82	23.98
Maximum:	70.19	0.012086	2269	6.18	1306149	1.241	7.199	2063093	6687483	20.22	9.82	19.30	12.02	63.78	20.23	46.47
Mean Error:														46.73	7.70	37.58
rms dev.:														47.98	9.98	38.14

Table B.4 Summary of Transition/Turbulent Flow Heat Transfer Measurement Data

Run No.	Q_L [gpm]	ΔT_b [°F]	Avg. Re	Avg. Pr	Power [W]	Heat Balance Error [%]	At Thermocouple Station No. 6 ($x/D_i = 52$)						
							Re	Pr	μ_b/μ_w	T_{top}/T_{bottom}	T_b [°F]	T_w [°F]	Nu_{exp}
TEST #3													
RN2010	1.02	0.71	3286	6.19	79.00	-34.54	3291	6.18	1.016	0.999	76.61	77.89	20.57
RN2030	1.07	0.80	3434	6.18	96.80	-28.97	3440	6.17	1.018	0.998	76.82	78.27	22.01
RN2050	1.03	1.16	3344	6.13	143.38	-22.05	3352	6.11	1.028	0.999	77.45	79.64	21.67
RN2065	1.01	1.61	3304	6.07	219.45	-8.51	3314	6.05	1.041	1.000	78.12	81.3	22.68
RN0604	2.62	0.87	8770	5.91	367.65	-20.83	8776	5.90	1.027	1.003	79.91	82.03	57.59
MIN:	1.01	0.71	3286	5.91	79.00	-34.54	3291	5.90	1.016	0.998	76.61	77.89	20.57
MAX:	2.62	1.61	8770	6.19	367.65	-8.51	8776	6.18	1.041	1.003	79.91	82.03	57.59
MEAN:		1.03				-22.98							
RMS:						24.60							
TEST #4													
RN5168	1.28	4.90	3914	6.54	854.25	-7.40	3927	6.52	1.122	1.009	72.98	82.14	31.22
RN5169	1.76	3.46	5326	6.63	780.86	-14.27	5339	6.61	1.084	0.999	72.01	78.29	41.75
RN5105	1.73	5.61	6176	5.5	1381.95	-2.65	6197	5.48	1.130	0.992	85.4	96.07	42.83
RN2115	2.16	3.72	8351	5.02	1220.70	3.98	8369	5.01	1.088	0.998	92.32	99.97	52.38
RN0606	2.62	1.02	8850	5.85	559.15	-18.47	8860	5.84	1.039	1.003	80.68	83.82	59.08
RN0607	2.62	3.55	8993	5.74	1226.96	-10.77	9012	5.73	1.089	1.002	82.08	89.23	56.90
RN5106	2.65	3.85	9396	5.53	1390.28	-7.11	9417	5.52	1.088	1.001	84.86	92.12	63.56
RN5175	3.24	2.95	9784	6.64	1407.78	0.57	9803	6.63	1.084	0.997	71.84	78.12	77.25
MIN:	1.28	1.02	3914	5.02	559.15	-18.47	3927	5.01	1.039	0.992	71.84	78.12	31.22
MAX:	3.24	5.61	9784	6.64	1407.78	3.98	9803	6.63	1.130	1.009	92.32	99.97	77.25
MEAN:		3.63				-7.02							
RMS:						9.93							
TEST #5													
RN5172	2.20	5.53	6861	6.39	1609.21	2.57	6882	6.36	1.131	1.002	74.60	84.53	54.37
RN5170	2.75	4.23	8464	6.50	1523.20	-11.87	8492	6.48	1.103	0.998	73.38	81.12	66.04
RN0608	2.62	6.33	9213	5.59	2295.15	-5.57	9247	5.57	1.151	0.997	84.21	96.47	62.05
MIN:	2.20	4.23	6861	5.59	1523.20	-11.87	6882	5.57	1.103	0.997	73.38	81.12	54.37
MAX:	2.75	6.33	9213	6.50	2295.15	2.57	9247	6.48	1.151	1.002	84.21	96.47	66.04
MEAN:		5.36				-4.96							
RMS:						7.71							

Table B.4 Summary of Transition/Turbulent Flow Heat Transfer Measurement Data (Continued)

Run No.	Q_L [gpm]	ΔT_b [°F]	Avg. Re	Avg. Pr	Power [W]	Heat Balance Error [%]	At Thermocouple Station No. 6 ($x/D_i = 52$)						
							Re	Pr	μ_b/μ_w	T_{top}/T_{bottom}	T_b [°F]	T_w [°F]	Nu_{exp}
TEST #6													
RN6570	3.17	2.85	10526	5.97	1209.00	-9.33	10544	5.96	1.075	0.999	79.27	85.23	67.77
RN1503	6.45	1.01	19833	6.50	798.93	-19.30	19847	6.50	1.027	1.003	73.19	75.22	132.97
MIN:	3.17	1.01	10526	5.97	798.93	-19.30	10544	5.96	1.027	0.999	73.19	75.22	67.77
MAX:	6.45	2.85	19833	6.50	1209.00	-9.33	19847	6.50	1.075	1.003	79.27	85.23	132.97
MEAN:		1.93				-14.32							
RMS:						15.16							
TEST #7													
RN6580	3.17	4.98	10722	5.85	2469.75	6.50	10754	5.83	1.147	1.005	80.87	92.53	70.34
RN5104	3.02	4.34	10954	5.39	1827.87	-4.51	10981	5.37	1.101	1.001	86.91	95.32	72.05
RN5107	3.90	3.84	13916	5.49	2029.11	-7.70	13947	5.48	1.092	1.003	85.40	93.01	88.17
RN5176	4.74	2.15	14288	6.64	1511.64	1.40	14308	6.63	1.065	0.998	71.78	76.66	106.7
RN5108	5.10	2.93	18136	5.52	2045.25	-6.67	18167	5.51	1.075	1.003	85.04	91.23	108.9
RN5177	6.42	1.84	19482	6.59	1733.71	0.37	19506	6.58	1.057	0.998	72.28	76.58	138.28
MIN:	3.02	1.84	10722	5.39	1511.64	-7.70	10754	5.37	1.057	0.998	71.78	76.58	70.34
MAX:	6.42	4.98	19482	6.64	2469.75	6.50	19506	6.63	1.147	1.005	86.91	95.32	138.28
MEAN:		3.35				-1.77							
RMS:						5.30							
TEST #8													
RN1504	6.45	1.76	20192	6.37	1469.71	-12.89	20214	6.36	1.046	1.005	74.67	78.23	138.91
TEST #9													
RN2111	5.20	3.19	20040	5.03	2229.21	-8.39	20075	5.02	1.075	1.003	92.13	98.61	112.83
RN5109	6.05	2.66	21522	5.51	2075.70	-13.13	21555	5.50	1.066	1.003	85.1	90.51	126.92
RN5110	6.87	2.24	24367	5.53	2075.70	-8.14	24399	5.52	1.058	1.005	84.86	89.72	141.29
RN5178	8.10	1.52	24685	6.57	1803.80	0.10	24710	6.56	1.048	0.998	72.51	76.17	169.52
RN5111	7.69	2.06	27134	5.56	2075.70	-11.35	27167	5.55	1.054	1.003	84.40	88.84	154.67
RN5112	8.34	1.94	29443	5.56	2091.00	-12.84	29476	5.55	1.050	1.004	84.47	88.66	164.12
MIN:	5.20	1.52	20040	5.03	1803.80	-13.13	20075	5.02	1.054	0.998	72.51	76.17	112.83
MAX:	8.34	3.19	29443	6.57	2229.21	0.10	29476	6.56	1.075	1.005	92.13	98.61	169.52
MEAN:		2.27				-8.96							
RMS:						10.02							

Table B.5 Summary of Nusselt Number Comparison for Transition/Turbulent Cases at Thermocouple Station No. 6

Run No.	Experiment	Sieder & Tate		Colburn		Ghajar & Tam		Gnielinski[1]		Gnielinski[3]	
	Nu	Nu	Error [%]	Nu	Error [%]	Nu	Error [%]	Nu	Error [%]	Nu	Error [%]
TEST #3											
RN2010	20.57	-	-	-	-	-	-	24.17	-17.49	21.59	-4.96
RN2030	22.01	-	-	-	-	-	-	25.48	-15.75	22.69	-3.11
RN2050	21.67	-	-	-	-	-	-	24.62	-13.60	21.95	-1.30
RN2065	22.68	-	-	-	-	-	-	24.20	-6.70	21.58	4.84
RN0604	57.59	59.55	-3.41	59.34	-3.03	-	-	66.00	-14.61	58.96	-2.38
MIN:	20.57	59.55	-3.41	59.34	-3.03	-	-	24.17	-17.49	21.58	-4.96
MAX:	57.59	59.55	-3.41	59.34	-3.03	-	-	66.00	-6.70	58.96	4.84
MEAN:			-3.41		-3.03				-13.63		-1.38
RMS:			3.41		3.03				14.12		3.60
TEST #4											
RN5168	31.22	-	-	-	-	-	-	30.29	2.97	26.91	13.82
RN5169	41.75	-	-	-	-			42.36	-1.46	37.53	10.10
RN5105	42.83	-	-	-	-	47.65	-11.25	45.98	-7.35	40.56	5.31
RN2115	52.38	54.73	-4.49	54.09	-3.27	58.23	-11.17	59.33	-13.28	52.73	-0.67
RN0606	59.08	59.91	-1.40	59.59	-0.86	-	-	66.33	-12.28	59.27	-0.31
RN0607	56.9	60.74	-6.75	60.02	-5.49	65.07	-14.36	66.91	-17.60	59.79	-5.09
RN5106	63.56	62.13	2.25	61.40	3.40	66.43	-4.52	68.72	-8.12	61.47	3.30
RN5175	77.25	68.17	11.76	67.40	12.75	73.58	4.75	76.46	1.02	68.74	11.01
MIN:	31.22	54.73	-6.75	54.09	-5.49	47.65	-14.36	30.29	-17.60	26.91	-5.09
MAX:	77.25	68.17	11.76	67.40	12.75	73.58	4.75	76.46	2.97	68.74	13.82
MEAN:			0.27		1.31		-7.31		-7.01		4.68
RMS:			6.50		6.57		10.00		9.80		7.74
TEST #5											
RN5172	54.37	-	-	-	-	54.89	-0.95	53.83	0.99	47.83	12.02
RN5170	66.04	60.45	8.46	59.63	9.71	65.17	1.31	66.29	-0.38	59.29	10.23
RN0608	62.05	61.90	0.24	60.69	2.19	66.22	-6.72	67.80	-9.26	60.61	2.32
MIN:	54.37	60.45	0.24	59.63	2.19	54.89	-6.72	53.83	-9.26	47.83	2.32
MAX:	66.04	61.90	8.46	60.69	9.71	66.22	1.31	67.80	0.99	60.61	12.02
MEAN:			4.35		5.95		-2.12		-2.88		8.19
RMS:			5.99		7.04		3.99		5.38		9.21

Table B.5 Summary of Nusselt Number Comparison for Transition/Turbulent Cases at Thermocouple Station No. 6 (Continued)

Run No.	Experiment	Sieder & Tate		Colburn		Ghajar & Tam		Gnielinski[1]		Gnielinski[3]	
	Nu	Nu	Error [%]	Nu	Error [%]	Nu	Error [%]	Nu	Error [%]	Nu	Error [%]
TEST #6											
RN6570	67.77	69.65	-2.78	68.95	-1.74	74.77	-10.33	78.52	-15.86	70.64	-4.23
RN1503	132.97	118.16	11.14	117.72	11.47			143.06	-7.59	132.00	0.73
MIN:	67.77	69.65	-2.78	68.95	-1.74	74.77	-10.33	78.52	-15.86	70.64	-4.23
MAX:	132.97	118.16	11.14	117.72	11.47	74.77	-10.33	143.06	-7.59	132.00	0.73
MEAN:			4.18		4.86		-10.33		-11.73		-1.75
RMS:			8.12		8.20		10.33		12.43		3.04
TEST #7											
RN6580	70.34	70.88	-0.77	69.54	1.14	76.00	-8.05	79.28	-12.70	71.35	-1.43
RN5104	72.05	69.73	3.22	68.80	4.51	74.45	-3.33	78.28	-8.65	70.43	2.25
RN5107	88.17	84.90	3.70	83.86	4.89	90.75	-2.92	97.84	-10.97	88.95	-0.88
RN5176	106.7	92.02	13.76	91.21	14.52	99.32	6.91	107.86	-1.08	98.31	7.86
RN5108	108.9	104.86	3.71	103.80	4.68	112.11	-2.94	123.89	-13.77	113.92	-4.61
RN5177	138.28	117.49	15.04	116.57	15.70			141.59	-2.39	130.56	5.59
MIN:	70.34	69.73	-0.77	68.80	1.14	74.45	-8.05	78.28	-13.77	70.43	-4.61
MAX:	138.28	117.49	15.04	116.57	15.70	112.11	6.91	141.59	-1.08	130.56	7.86
MEAN:			6.44		7.57		-2.07		-8.26		1.46
RMS:			8.70		9.35		4.83		9.60		4.51
TEST #8											
RN1504	138.91	119.35	14.08	118.60	14.62			144.13	-3.76	133.07	4.20
TEST #9											
RN2111	112.83	110.10	2.42	109.00	3.40	117.15	-3.83	130.19	-15.39	120.29	-6.61
RN5109	126.92	120.01	5.44	118.95	6.28	128.29	-1.08	143.78	-13.29	133.16	-4.91
RN5110	141.29	132.55	6.18	131.50	6.93			160.39	-13.52	149.29	-5.66
RN5178	169.52	141.64	16.45	140.71	16.99			173.99	-2.63	161.81	4.55
RN5111	154.67	144.62	6.50	143.57	7.18			176.45	-14.08	164.93	-6.63
RN5112	164.12	154.31	5.98	153.25	6.62			189.35	-15.38	177.55	-8.18
MIN:	112.83	110.10	2.42	109.00	3.40	117.15	-3.83	130.19	-15.39	120.29	-8.18
MAX:	169.52	154.31	16.45	153.25	16.99	128.29	-1.08	189.35	-2.63	177.55	4.55
MEAN:			7.16		7.90		-2.46		-12.38		-4.58
RMS:			8.39		8.97		2.71		13.15		6.21

B.1.3 Two-Phase Flow Void Fraction Measurement

In this section, a total of 26 void fraction measurement data were tabulated with the main experimental and the calculated parameters. The comparison results of the experimental void fractions with the predictions using Chisholm's (1973) equation were also tabulated with the flow patterns of the void fraction measurement data.

Table B.6 Summary of Two-Phase Flow Void Fraction Measurement Data

Run No.	Q_L [lpm]	Q_G [gpm]	P_G [psig]	T_L [°C]	T_G [°C]	$\dot{m}_L$ [kg/s]	$\dot{m}_G$ [kg/s]	V_{SL} [m/s]	V_{SG} [m/s]	Re_{SL}	Re_{SG}	K_U	$Vol_{L,avg}$ [ml]	α_{exp}	$\alpha_{predict}$	Error [%]	Flow Pattern
1	0.32	20.47	2.49	24.6	24	73.42	1.68	0.034	0.560	1043	1162	4.1574	137.7	0.6122	0.8005	-30.75	Stratified
2	0.33	40.07	4.11	25.3	24	73.73	3.61	0.034	1.095	1065	2491	5.6518	83.5	0.7648	0.8519	-11.39	Stratified
3	0.33	61.31	9.96	26.1	24	74.94	7.26	0.034	1.676	1103	5013	6.7466	51.7	0.8545	0.8788	-2.85	Stratified
4	0.51	39.61	4.72	26.6	24	116.38	3.68	0.053	1.083	1732	2543	4.5493	115.0	0.6761	0.8173	-20.89	Slug
5	0.49	59.99	9.44	27.3	24	111.88	6.95	0.051	1.640	1692	4802	5.5788	78.3	0.7793	0.8518	-9.29	Slug
6	1.25	18.57	4.35	26.8	24	281.90	1.69	0.129	0.508	4215	1169	2.2157	126.7	0.6432	0.6400	0.50	Slug
7	1.27	41.84	5.93	27.2	24	288.04	4.14	0.132	1.143	4347	2857	3.0897	146.7	0.5869	0.7376	-25.68	Slug
8	1.07	58.41	12.75	27.2	24	243.18	7.70	0.111	1.596	3670	5321	3.8584	78.7	0.7784	0.7882	-1.26	Slug
9	2.21	20.43	6.23	24.2	23	501.10	2.06	0.229	0.558	7047	1424	1.8507	206.7	0.4178	0.5686	-36.07	Slug
10	2.16	30.54	7.36	25.1	24	488.84	3.23	0.223	0.835	7025	2232	2.1693	134.2	0.6221	0.6327	-1.71	Slug
11	3.47	22.08	7.33	26.2	24	786.50	2.33	0.359	0.603	11598	1611	1.6342	143.3	0.5962	0.5067	15.02	Slug
12	3.37	29.61	9.37	26.4	24	763.63	3.42	0.349	0.809	11314	2363	1.8177	142.9	0.5974	0.5606	6.17	Slug
13	4.59	21.16	9.38	27.2	24	1038.10	2.45	0.475	0.578	15667	1690	1.4878	237.9	0.3298	0.4503	-36.53	Slug
14	4.94	31.45	11.62	27.5	25	1118.12	3.96	0.511	0.860	16991	2731	1.6347	158.1	0.5548	0.5071	8.60	Slug
15	2.07	5.27	4.56	21.6	21	469.49	0.49	0.214	0.144	6193	343	1.2926	246.9	0.3046	0.3422	-12.36	Slug
16	1.91	10.61	4.63	22.2	21	433.03	0.99	0.198	0.290	5798	692	1.5688	200.0	0.4366	0.4832	-10.67	Slug
17	2.52	4.85	5.59	23	21	571.47	0.48	0.261	0.133	7805	332	1.2276	238.8	0.3275	0.2928	10.60	Slug
18	2.47	9.83	5.58	22.7	21	560.46	0.97	0.256	0.269	7598	673	1.4303	231.9	0.3468	0.4232	-22.01	Slug
19	2.99	4.75	5.78	23.5	21	676.22	0.47	0.309	0.130	9350	329	1.1914	249.8	0.2965	0.2608	12.04	Slug
20	2.16	16.41	4.84	20.6	20	490.70	1.56	0.224	0.449	6310	1087	1.7300	177.0	0.5014	0.5365	-7.00	Slug
21	2.13	20.63	5.68	21	20	482.95	2.04	0.220	0.564	6274	1426	1.8822	162.0	0.5437	0.5761	-5.96	Slug
22	1.93	31.87	6.63	21.5	20	436.30	3.30	0.199	0.871	5740	2306	2.3092	157.3	0.5570	0.6544	-17.48	Slug
23	2.41	19.65	6.60	22	20	545.62	2.03	0.249	0.537	7269	1421	1.7733	172.5	0.5141	0.5487	-6.74	Slug
24	2.51	31.88	7.74	22.5	20	569.45	3.48	0.260	0.871	7682	2429	2.0796	156.0	0.5606	0.6171	-10.08	Slug
25	2.91	14.19	6.39	22.7	20	659.13	1.45	0.301	0.388	8936	1015	1.5112	194.5	0.4521	0.4603	-1.81	Slug
26	3.08	29.91	8.92	22.6	20	696.89	3.44	0.318	0.818	9425	2400	1.8846	181.0	0.4901	0.5769	-17.69	Slug

B.1.4 Two-Phase Flow Pattern Measurement

A total of 111 two-phase flow pattern measurement data were tabulated with the main experimental and the calculated parameters, and grouped by those flow patterns. For the abbreviations of the flow patterns in Table B.7, refer to the NOMENCLATUE.

Table B.7 Summary of Two-Phase Flow Pattern Experimental Data

Run No.	Q_L [gpm]	Q_G [lpm]	P_G [psig]	T_L [°C]	T_G [°C]	$\dot{m}_L$ [kg/s]	$\dot{m}_G$ [kg/s]	V_{SL} [m/s]	V_{SG} [m/s]	Re_{SL}	Re_{SG}	X	F	K	B	j^*_R	Pattern
1	2.49	76.00	40.72	28.8	30.0	563.28	20.12	0.310	2.500	9669	15017	1.947	0.334	32.853	0.075	0.334	ABSL
2	2.58	80.80	53.71	28.8	34.0	583.86	26.04	0.321	2.658	10022	19240	1.758	0.392	39.252	0.078	0.392	ABSL
3	2.64	85.74	56.88	27.9	29.0	596.80	29.38	0.328	2.820	10039	21986	1.663	0.429	42.994	0.080	0.429	ABSL
4	3.58	84.11	65.57	26.2	28.0	810.37	32.42	0.446	2.766	13110	24316	2.135	0.446	51.116	0.105	0.446	ABSL
5	3.49	80.59	57.37	28.2	29.0	789.57	27.81	0.435	2.651	13372	20806	2.255	0.405	46.802	0.102	0.405	ABSL
6	3.58	75.66	41.22	28.2	29.0	809.74	20.28	0.446	2.488	13714	15171	2.701	0.335	39.187	0.105	0.335	ABSL
7	4.01	84.60	59.05	27.1	28.0	908.36	29.97	0.500	2.783	15004	22480	2.429	0.430	52.724	0.116	0.430	ABSL
8	4.03	82.09	55.08	27.3	33.0	912.23	27.07	0.502	2.700	15137	20053	2.574	0.403	49.573	0.117	0.403	ABSL
9	5.53	88.99	66.67	27.8	29.0	1251.26	34.65	0.689	2.927	21001	25929	2.976	0.475	68.822	0.155	0.475	ABSL
10	8.00	88.26	70.75	25.9	29.0	1810.55	36.09	0.996	2.903	29085	27001	4.118	0.483	82.306	0.217	0.483	ABSL
11	8.47	80.94	57.26	25.8	29.0	1918.03	27.88	1.055	2.662	30740	20863	5.022	0.406	71.184	0.229	0.406	ABSL
12	5.38	80.46	49.87	27.0	29.0	1216.97	24.88	0.669	2.647	20055	18619	3.491	0.382	54.152	0.151	0.382	ABSL
13	1.81	84.73	65.54	27.0	29.0	410.44	32.53	0.226	2.787	6764	24341	1.149	0.449	36.922	0.057	0.449	ABW
14	1.85	80.57	54.86	27.0	29.0	419.47	26.83	0.231	2.650	6913	20074	1.298	0.397	33.039	0.058	0.397	ABW
15	0.16	88.16	69.82	28.0	29.0	37.31	35.55	0.021	2.900	629	26603	0.125	0.479	12.010	0.007	0.479	AW
16	0.17	81.25	54.56	31.0	31.0	39.36	26.68	0.022	2.673	709	19860	0.153	0.398	10.600	0.007	0.398	AW
17	0.18	86.74	59.92	30.0	32.0	40.59	30.58	0.022	2.853	715	22708	0.144	0.440	11.780	0.007	0.440	AW
18	0.20	75.33	39.44	31.5	31.0	44.59	19.33	0.025	2.478	812	14394	0.202	0.326	9.292	0.008	0.326	AW
19	0.26	87.04	57.82	28.0	29.0	58.18	30.12	0.032	2.863	981	22535	0.201	0.438	13.709	0.010	0.438	AW
20	0.27	80.65	46.03	29.0	30.0	60.99	23.30	0.034	2.653	1052	17386	0.241	0.370	12.013	0.010	0.370	AW
21	0.45	78.99	37.44	26.0	24.0	101.26	20.11	0.056	2.598	1631	15240	0.411	0.340	13.745	0.016	0.340	AW
22	0.58	87.82	68.67	28.2	33.0	130.22	34.58	0.072	2.889	2205	25614	0.391	0.471	22.134	0.020	0.471	AW
23	0.65	81.47	50.50	28.2	31.0	147.27	25.27	0.081	2.680	2494	18815	0.514	0.388	19.368	0.023	0.388	AW
24	1.05	86.52	56.65	29.2	30.0	236.42	29.45	0.130	2.846	4094	21981	0.717	0.432	27.618	0.035	0.432	AW
25	1.19	80.92	45.10	31.2	36.0	268.62	22.65	0.148	2.662	4858	16657	0.918	0.366	25.510	0.039	0.366	AW
26	1.85	78.16	37.34	26.0	24.0	418.88	19.86	0.230	2.571	6745	15050	1.490	0.336	27.633	0.058	0.336	AW
27	0.63	65.10	6.57	26.0	24.0	143.66	6.82	0.079	2.141	2313	5172	0.955	0.180	8.647	0.022	0.180	WSL
28	0.63	60.53	5.47	28.2	28.0	143.66	5.92	0.079	1.991	2433	4442	1.042	0.162	7.967	0.022	0.162	WSL
29	0.64	50.62	3.15	28.2	27.0	143.90	4.40	0.079	1.665	2437	3312	1.286	0.127	6.288	0.022	0.127	WSL
30	1.16	61.44	5.37	30.2	31.0	262.52	5.92	0.145	2.021	4647	4406	1.772	0.163	11.093	0.038	0.163	WSL
31	1.17	68.99	8.51	30.7	34.0	264.58	7.59	0.146	2.269	4734	5611	1.521	0.195	13.442	0.038	0.195	WSL
32	1.96	69.23	12.32	26.0	24.0	442.62	9.19	0.243	2.277	7127	6964	2.264	0.215	18.165	0.061	0.215	WSL

Table B.7 Summary of Two-Phase Flow Pattern Experimental Data (Continued)

Run No.	Q_L [gpm]	Q_G [lpm]	P_G [psig]	T_L [°C]	T_G [°C]	$\dot{m}_L$ [kg/s]	$\dot{m}_G$ [kg/s]	V_{SL} [m/s]	V_{SG} [m/s]	Re_{SL}	Re_{SG}	X	F	K	B	j^*_g	Pattern
33	1.81	71.16	27.07	27.4	28.0	410.34	14.31	0.226	2.341	6825	10735	1.740	0.272	22.509	0.057	0.272	BSL
34	4.46	74.33	35.10	26.6	33.0	1009.72	17.52	0.555	2.445	16487	12978	3.533	0.308	39.570	0.128	0.308	BSL
35	4.44	70.47	19.20	26.8	31.0	1005.95	11.41	0.553	2.318	16502	8496	4.293	0.242	31.092	0.128	0.242	BSL
36	5.28	75.97	37.36	27.3	28.0	1195.11	19.03	0.658	2.499	19831	14271	3.934	0.325	45.729	0.149	0.325	BSL
37	5.53	70.38	19.85	27.5	26.0	1252.32	11.81	0.689	2.315	20876	8904	5.159	0.246	35.556	0.155	0.246	BSL
38	6.98	70.84	26.24	29.5	24.0	1578.47	14.19	0.869	2.330	27517	10751	5.864	0.271	44.912	0.190	0.271	BSL
39	8.94	75.35	42.38	26.0	30.0	2023.01	20.55	1.113	2.479	32574	15334	6.166	0.336	60.658	0.240	0.336	BSL
40	9.33	70.48	31.94	26.0	29.0	2112.63	15.77	1.162	2.318	34017	11798	7.371	0.285	52.497	0.249	0.285	BSL
41	3.40	70.78	17.58	27.3	28.0	769.96	11.03	0.424	2.328	12776	8270	3.413	0.238	26.950	0.100	0.238	BSL
42	9.78	65.61	21.66	26.4	30.0	2213.96	11.42	1.218	2.158	35983	8526	9.055	0.234	44.326	0.260	0.234	BSL
43	0.18	71.19	11.24	26.0	24.0	39.75	9.08	0.022	2.342	640	6879	0.256	0.217	5.487	0.007	0.217	W
44	0.18	75.20	25.77	26.0	24.0	41.45	14.89	0.023	2.474	667	11283	0.213	0.286	7.379	0.007	0.286	W
45	0.17	71.19	20.14	31.5	30.0	38.30	11.80	0.021	2.342	697	8807	0.220	0.248	6.535	0.007	0.248	W
46	0.29	75.09	25.22	29.0	29.0	64.72	14.31	0.036	2.470	1116	10705	0.320	0.280	9.350	0.011	0.280	W
47	0.29	70.59	12.26	28.8	29.0	66.07	9.09	0.036	2.322	1134	6798	0.404	0.216	7.279	0.011	0.216	W
48	0.37	60.00	4.71	26.0	24.0	84.60	5.75	0.047	1.973	1362	4356	0.662	0.158	5.846	0.014	0.158	W
49	0.59	70.69	10.91	26.0	24.0	132.78	8.90	0.073	2.325	2138	6743	0.768	0.214	9.893	0.021	0.214	W
50	0.62	76.09	23.14	26.0	24.0	140.94	14.09	0.078	2.503	2269	10679	0.650	0.279	13.314	0.022	0.279	W
51	0.64	70.69	14.52	28.2	27.0	144.58	10.01	0.080	2.325	2449	7527	0.787	0.227	11.234	0.022	0.227	W
52	0.64	40.30	1.64	28.2	27.0	144.64	3.21	0.080	1.326	2450	2418	1.641	0.097	4.806	0.022	0.097	SL
53	0.64	29.91	0.80	28.5	27.0	145.38	2.26	0.080	0.984	2479	1703	2.201	0.070	3.495	0.022	0.070	SL
54	0.64	20.60	0.36	28.5	27.0	145.92	1.52	0.080	0.677	2488	1140	3.125	0.048	2.377	0.022	0.048	SL
55	0.65	10.24	0.00	29.2	27.0	145.99	0.74	0.080	0.337	2528	553	5.910	0.023	1.177	0.022	0.023	SL
56	1.05	49.37	3.24	26.0	24.0	237.58	4.38	0.131	1.624	3826	3319	2.060	0.125	7.756	0.035	0.125	SL
57	1.18	49.85	2.71	30.3	30.0	266.64	4.18	0.147	1.640	4730	3123	2.292	0.123	8.476	0.038	0.123	SL
58	1.19	40.66	1.53	30.5	30.0	269.72	3.19	0.149	1.337	4805	2377	2.858	0.097	6.731	0.039	0.097	SL
59	1.21	29.53	0.73	30.2	30.0	272.99	2.20	0.150	0.971	4832	1644	3.932	0.069	4.783	0.039	0.069	SL
60	1.21	20.07	0.31	30.2	30.0	273.31	1.46	0.150	0.660	4838	1087	5.634	0.046	3.208	0.039	0.046	SL
61	1.21	10.23	0.07	30.3	30.0	274.65	0.73	0.151	0.337	4872	545	10.440	0.023	1.628	0.039	0.023	SL
62	1.81	50.17	3.67	27.8	29.0	409.54	4.46	0.225	1.650	6874	3334	3.296	0.128	10.574	0.057	0.128	SL
63	1.81	60.55	6.65	28.0	29.0	408.48	6.24	0.225	1.992	6887	4669	2.614	0.166	13.763	0.057	0.166	SL
64	1.84	40.56	2.15	28.8	29.0	417.18	3.31	0.230	1.334	7161	2476	4.188	0.099	8.365	0.057	0.099	SL

Table B.7 Summary of Two-Phase Flow Pattern Experimental Data (Continued)

Run No.	Q_L [gpm]	Q_G [lpm]	P_G [psig]	T_L [°C]	T_G [°C]	$\dot{m}_L$ [kg/s]	$\dot{m}_G$ [kg/s]	V_{SL} [m/s]	V_{SG} [m/s]	Re_{SL}	Re_{SG}	X	F	K	B	j^{*}_{g}	Pattern
65	1.86	30.87	1.22	29.2	30.0	421.61	2.37	0.232	1.015	7301	1771	5.531	0.073	6.239	0.058	0.073	SL
66	1.89	20.44	0.57	29.0	30.0	426.94	1.51	0.235	0.672	7361	1126	8.245	0.047	4.063	0.059	0.047	SL
67	1.90	10.92	0.24	29.0	30.0	430.09	0.79	0.237	0.359	7415	589	14.713	0.025	2.156	0.059	0.025	SL
68	2.57	49.62	3.77	28.5	30.0	581.88	4.42	0.320	1.632	9921	3300	4.552	0.126	12.587	0.078	0.126	SL
69	2.61	19.75	0.63	28.5	30.0	590.97	1.46	0.325	0.650	10076	1093	11.383	0.046	4.605	0.079	0.046	SL
70	2.63	60.26	6.81	28.3	30.0	595.97	6.24	0.328	1.982	10116	4657	3.679	0.165	16.640	0.079	0.165	SL
71	2.63	39.86	2.22	28.6	30.0	594.57	3.26	0.327	1.311	10160	2431	5.850	0.097	9.798	0.079	0.097	SL
72	2.64	69.14	14.13	28.5	31.0	597.78	9.53	0.329	2.274	10192	7098	2.905	0.219	22.123	0.080	0.219	SL
73	2.66	29.95	1.26	28.5	30.0	602.77	2.31	0.332	0.985	10277	1725	7.840	0.071	7.195	0.080	0.071	SL
74	3.54	40.20	2.46	26.5	28.0	801.77	3.35	0.441	1.322	13061	2515	7.575	0.099	11.315	0.104	0.099	SL
75	3.53	60.22	7.48	26.8	28.0	799.97	6.47	0.440	1.981	13123	4852	4.746	0.168	19.286	0.104	0.168	SL
76	3.58	30.01	1.53	26.5	28.0	810.34	2.37	0.446	0.987	13201	1777	10.170	0.072	8.262	0.105	0.072	SL
77	3.60	50.76	4.34	26.6	28.0	815.26	4.69	0.448	1.670	13312	3518	5.981	0.132	15.184	0.106	0.132	SL
78	3.66	20.60	0.90	26.0	28.0	827.58	1.56	0.455	0.678	13326	1174	14.782	0.048	5.590	0.107	0.048	SL
79	4.12	29.99	1.63	27.7	29.0	931.71	2.38	0.513	0.987	15602	1777	11.489	0.072	8.993	0.119	0.072	SL
80	4.11	18.76	0.87	27.9	30.0	930.04	1.41	0.512	0.617	15645	1055	17.839	0.044	5.494	0.118	0.044	SL
81	4.20	39.12	2.60	27.6	29.0	949.30	3.28	0.522	1.287	15860	2454	8.995	0.097	12.167	0.121	0.097	SL
82	4.41	64.47	10.34	26.9	29.0	997.36	7.79	0.549	2.121	16399	5825	5.191	0.191	24.477	0.126	0.191	SL
83	4.39	52.05	4.99	27.4	30.0	993.64	4.94	0.547	1.712	16526	3688	6.897	0.137	17.587	0.126	0.137	SL
84	4.54	59.84	7.65	27.1	30.0	1028.14	6.44	0.566	1.968	16983	4803	5.972	0.167	21.818	0.130	0.167	SL
85	5.47	39.92	3.49	27.9	29.0	1236.92	3.52	0.681	1.313	20807	2630	10.982	0.101	14.577	0.153	0.101	SL
86	5.56	59.81	9.92	27.6	29.0	1257.36	7.10	0.692	1.967	21007	5314	6.877	0.176	25.489	0.156	0.176	SL
87	5.43	30.52	2.27	28.8	29.0	1229.44	2.51	0.677	1.004	21103	1878	14.266	0.075	10.847	0.152	0.075	SL
88	5.61	65.79	14.43	27.6	25.0	1269.79	9.35	0.699	2.164	21215	7069	5.932	0.212	30.832	0.157	0.212	SL
89	5.65	49.73	5.44	27.8	29.0	1279.01	4.84	0.704	1.636	21466	3622	8.924	0.132	19.394	0.158	0.132	SL
90	5.54	20.50	1.45	28.8	30.0	1253.58	1.60	0.690	0.674	21518	1194	21.203	0.049	7.168	0.155	0.049	SL
91	8.04	20.61	2.73	25.6	23.0	1820.42	1.78	1.001	0.678	29038	1355	28.572	0.052	8.812	0.218	0.052	SL
92	7.61	60.77	12.08	30.4	23.0	1719.76	8.02	0.947	1.999	30574	6096	8.576	0.189	32.961	0.205	0.189	SL
93	8.04	40.82	5.42	29.9	23.0	1817.58	4.06	1.001	1.343	31964	3088	14.453	0.110	19.651	0.216	0.110	SL
94	9.98	60.50	16.54	26.6	30.0	2259.67	9.06	1.243	1.990	36897	6764	10.532	0.200	38.382	0.264	0.200	SL
95	10.34	50.62	10.66	27.0	30.0	2340.34	6.17	1.288	1.665	38569	4603	13.850	0.151	29.605	0.272	0.151	SL
96	10.55	40.24	7.84	27.6	30.0	2387.70	4.36	1.314	1.324	39893	3257	18.138	0.113	22.584	0.277	0.113	SL

Table B.7 Summary of Two-Phase Flow Pattern Experimental Data (Continued)

Run No.	Q_l [gpm]	Q_G [lpm]	P_G [psig]	T_L [°C]	T_G [°C]	$\dot{m}_L$ [kg/s]	$\dot{m}_G$ [kg/s]	V_{SL} [m/s]	V_{SG} [m/s]	Re_{SL}	Re_{SG}	X	F	K	B	j^*_g	Pattern
97	10.74	30.39	6.24	30.0	30.0	2428.57	3.06	1.337	1.000	42802	2287	24.295	0.082	17.036	0.280	0.082	SL
98	10.94	20.22	4.64	30.0	30.0	2473.59	1.89	1.362	0.665	43595	1407	36.772	0.053	11.001	0.285	0.053	PL
99	0.17	50.22	3.28	31.6	28.0	39.43	4.33	0.022	1.652	719	3246	0.402	0.126	3.374	0.007	0.126	ST
100	0.17	31.98	1.12	31.9	27.0	39.27	2.43	0.022	1.052	721	1831	0.632	0.075	2.022	0.007	0.075	ST
101	0.17	38.81	1.71	31.8	27.5	39.49	3.06	0.022	1.276	723	2296	0.527	0.093	2.500	0.007	0.093	ST
102	0.18	58.18	5.67	31.8	28.0	39.82	5.68	0.022	1.914	729	4261	0.338	0.155	4.191	0.007	0.155	ST
103	0.20	19.92	0.54	32.2	27.0	46.00	1.46	0.025	0.655	850	1098	1.133	0.046	1.342	0.008	0.046	ST
104	0.21	10.44	0.27	32.2	27.0	46.47	0.75	0.026	0.343	858	566	2.058	0.024	0.701	0.008	0.024	ST
105	0.28	20.32	0.01	29.5	28.0	64.24	1.43	0.035	0.668	1120	1075	1.534	0.046	1.541	0.011	0.046	ST
106	0.29	10.00	-0.25	29.6	28.0	64.88	0.69	0.036	0.329	1134	520	2.950	0.022	0.756	0.011	0.022	ST
107	0.29	50.17	2.47	29.0	27.0	66.51	4.14	0.037	1.650	1147	3115	0.660	0.123	4.165	0.011	0.123	ST
108	0.29	40.79	1.88	29.0	28.0	66.59	3.24	0.037	1.342	1148	2432	0.807	0.098	3.325	0.011	0.098	ST
109	0.29	60.14	4.80	29.0	28.0	66.69	5.62	0.037	1.978	1150	4216	0.534	0.157	5.319	0.011	0.157	ST
110	0.29	30.60	1.10	29.5	28.0	66.26	2.32	0.036	1.006	1155	1738	1.061	0.072	2.441	0.011	0.072	ST
111	0.38	30.38	0.47	26.0	24.0	85.05	2.29	0.047	0.999	1369	1732	1.351	0.071	2.629	0.014	0.071	ST

B.2 Test Run Outputs of Single-Phase Flow Heat Transfer

This section presents the output files from program RHt98F of the all of the 38 single-phase flow heat transfer test runs which are summarized in Tables B.3, B.4 and B.5. Each output file was compressed to fit on a single page.

```
                  *-----------------------------------------*
                                 RUN NUMBER 1130
                          TEST FLUID IS DISTILLED WATER
                  *-----------------------------------------*
                  VOLUMETRIC FLOW RATE =      .60   GPM
                  MASS FLOW RATE       =    299.5   LBM/HR
                  MASS FLUX            =    45635   LBM/(SQ.FT-HR)
                  FLUID VELOCITY       =      .20   FT/S
                  ROOM TEMPERATURE     =    70.55   F
                  INLET TEMPERATURE    =    76.30   F
                  OUTLET TEMPERATURE   =    77.45   F
                  AVERAGE RE NUMBER    =     1933
                  AVERAGE PR NUMBER    =     6.16
                  CURRENT TO TUBE      =    110.0   AMPS
                  VOLTAGE DROP IN TUBE =      .88   VOLTS
                  AVERAGE HEAT FLUX    =      133   BTU/(SQ.FT-HR)
                  Q=AMP*VOLT           =      330   BTU/HR
                  Q=M*C*(T2-T1)        =      344   BTU/HR
                  HEAT BALANCE ERROR   =    -4.16   %

                    OUTSIDE SURFACE TEMPERATURES - DEGREES F

          1        2        3        4        5        6        7        8        9       10

 1      78.22    78.31    78.93    79.22    79.21    79.27    79.24    79.24    79.74    79.72
 2      78.21    78.21    79.09    79.42    79.57    79.70    79.75    79.75    80.41    80.60
 3      78.47    78.18    79.30    79.95    80.57    80.74    81.12    81.13    82.08    82.37
 4      78.62    78.38    79.02    79.49    79.47    79.64    79.66    80.16    80.19    79.83

                    INSIDE SURFACE TEMPERATURES - DEGREES F

          1        2        3        4        5        6        7        8        9       10

 1      78.15    78.24    78.86    79.15    79.13    79.19    79.16    79.16    79.66    79.64
 2      78.14    78.14    79.02    79.35    79.49    79.62    79.67    79.67    80.33    80.52
 3      78.40    78.11    79.23    79.89    80.51    80.68    81.07    81.07    82.03    82.33
 4      78.55    78.31    78.95    79.42    79.39    79.56    79.58    80.09    80.11    79.74

                    REYNOLDS NUMBER AT THE INSIDE TUBE WALL

          1        2        3        4        5        6        7        8        9       10

 1       1965     1967     1982     1989     1989     1991     1990     1990     2002     2002
 2       1964     1965     1986     1994     1998     2001     2003     2003     2019     2024
 3       1971     1964     1992     2008     2023     2028     2037     2037     2061     2069
 4       1975     1969     1985     1996     1996     2000     2000     2013     2013     2004

                      INSIDE SURFACE HEAT FLUXES BTU/HR/FT2

          1        2        3        4        5        6        7        8        9       10

 1        127      122      125      128      130      132      134      140      136      134
 2        125      123      123      126      130      130      133      133      135      133
 3        121      125      116      110       96       96       87       93       78       69
 4        115      119      124      125      132      131      135      123      140      152

                                *---------------*
                                 RUN NUMBER 1130
                                *---------------*

               PERIPHERAL HEAT TRANSFER COEFFICIENT BTU/(SQ.FT-HR-F)

          1        2        3        4        5        6        7        8        9       10

 1         71       69       55       52       56       58       63       69       56       59
 2         71       74       50       48       48       48       50       52       43       42
 3         59       77       44       34       26       25       21       23       16       14
 4         53       65       53       46       51       49       53       41       49       64

                                *---------------*
                                 RUN NUMBER 1130
                                     SUMMARY
                                *---------------*

ST       RE       PR     X/D     MUB      MUW       TB       TW      DENS      NU

 1    1921.78    6.20     6.4   2.171    2.119    76.38    78.31    62.25    16.59
 2    1924.48    6.19    15.5   2.168    2.121    76.49    78.20    62.25    18.73
 3    1927.19    6.18    24.6   2.165    2.100    76.60    79.01    62.24    13.27
 4    1929.89    6.18    33.7   2.162    2.089    76.71    79.45    62.24    11.71
 5    1932.60    6.17    42.8   2.159    2.084    76.82    79.63    62.24    11.40
 6    1935.31    6.16    52.0   2.156    2.080    76.93    79.77    62.24    11.31
 7    1938.02    6.15    61.1   2.153    2.078    77.04    79.87    62.24    11.33
 8    1940.74    6.14    70.2   2.150    2.074    77.15    80.00    62.24    11.26
 9    1943.45    6.13    79.3   2.147    2.061    77.26    80.53    62.24     9.80
10    1946.17    6.12    88.4   2.144    2.060    77.37    80.56    62.24    10.06

                      NOTE: TBULK IS GIVEN IN DEGREES FAHRENHEIT
                            MUB AND MUW ARE GIVEN IN LBM/(FT*HR)
```

```
              *----------------------------------------*
                          RUN NUMBER 1150
                    TEST FLUID IS DISTILLED WATER
              *----------------------------------------*
              VOLUMETRIC FLOW RATE =        .61   GPM
              MASS FLOW RATE       =      302.0   LBM/HR
              MASS FLUX            =      46014   LBM/(SQ.FT-HR)
              FLUID VELOCITY       =        .20   FT/S
              ROOM TEMPERATURE     =      70.64   F
              INLET TEMPERATURE    =      76.51   F
              OUTLET TEMPERATURE   =      77.87   F
              AVERAGE RE NUMBER    =       1957
              AVERAGE PR NUMBER    =       6.13
              CURRENT TO TUBE      =      125.0   AMPS
              VOLTAGE DROP IN TUBE =        .99   VOLTS
              AVERAGE HEAT FLUX    =        170   BTU/(SQ.FT-HR)
              Q=AMP*VOLT           =        422   BTU/HR
              Q=M*C*(T2-T1)        =        410   BTU/HR
              HEAT BALANCE ERROR   =       2.85   %

                 OUTSIDE SURFACE TEMPERATURES - DEGREES F

        1       2       3       4       5       6       7       8       9      10

 1    78.75   78.90   79.63   79.94   79.97   79.99   79.97   79.96   80.47   80.46
 2    78.79   78.81   79.84   80.21   80.37   80.58   80.61   80.61   81.31   81.58
 3    79.20   78.83   80.23   81.04   81.74   81.98   82.39   82.46   83.41   83.83
 4    79.22   78.99   79.74   80.25   80.25   80.44   80.48   80.97   81.07   80.68

                 INSIDE SURFACE TEMPERATURES - DEGREES F

        1       2       3       4       5       6       7       8       9      10

 1    78.65   78.81   79.54   79.84   79.87   79.89   79.87   79.86   80.37   80.36
 2    78.70   78.72   79.75   80.11   80.27   80.48   80.51   80.51   81.21   81.48
 3    79.11   78.74   80.14   80.96   81.67   81.91   82.32   82.39   83.35   83.77
 4    79.13   78.90   79.65   80.15   80.15   80.34   80.38   80.87   80.97   80.57

                 REYNOLDS NUMBER AT THE INSIDE TUBE WALL

        1       2       3       4       5       6       7       8       9      10

 1     1994    1998    2016    2023    2024    2025    2024    2024    2037    2036
 2     1995    1995    2021    2030    2034    2039    2040    2040    2058    2065
 3     2005    1996    2031    2051    2069    2075    2086    2088    2112    2123
 4     2006    2000    2018    2031    2031    2036    2037    2049    2052    2042

                   INSIDE SURFACE HEAT FLUXES BTU/HR/FT2

        1       2       3       4       5       6       7       8       9      10

 1      164     158     162     165     166     171     172     178     176     175
 2      162     159     160     165     170     168     172     173     174     172
 3      153     160     147     138     123     122     113     117     103      92
 4      152     155     163     164     173     171     175     164     180     194

                          *----------------*
                           RUN NUMBER 1150
                          *----------------*

            PERIPHERAL HEAT TRANSFER COEFFICIENT BTU/(SQ.FT-HR-F)

        1       2       3       4       5       6       7       8       9      10

 1       80      76      60      58      60      65      69      76      64      67
 2       77      80      55      52      54      52      55      57      48      46
 3       61      79      44      34      27      26      22      24      18      15
 4       60      71      58      52      57      55      58      48      54      69

                          *----------------*
                           RUN NUMBER 1150
                              SUMMARY
                          *----------------*

ST      RE      PR     X/D     MUB     MUW      TB      TW     DENS      NU

 1   1943.26   6.18    6.4   2.165   2.103   76.60   78.90   62.24    18.02
 2   1946.49   6.17   15.5   2.161   2.106   76.73   78.79   62.24    20.11
 3   1949.72   6.16   24.6   2.157   2.080   76.86   79.77   62.24    14.25
 4   1952.95   6.15   33.7   2.154   2.068   76.99   80.27   62.24    12.65
 5   1956.19   6.14   42.8   2.150   2.062   77.12   80.49   62.24    12.31
 6   1959.42   6.13   52.0   2.147   2.058   77.26   80.66   62.24    12.18
 7   1962.66   6.12   61.1   2.143   2.055   77.39   80.77   62.24    12.24
 8   1965.90   6.11   70.2   2.140   2.051   77.52   80.91   62.24    12.21
 9   1969.15   6.09   79.3   2.136   2.037   77.65   81.47   62.24    10.83
10   1972.39   6.08   88.4   2.133   2.035   77.78   81.55   62.23    11.00

                NOTE: TBULK IS GIVEN IN DEGREES FAHRENHEIT
                      MUB AND MUW ARE GIVEN IN LBM/(FT*HR)
```

```
                    *----------------------------------------*
                              RUN NUMBER 1010
                         TEST FLUID IS DISTILLED WATER
                    *----------------------------------------*
                    VOLUMETRIC FLOW RATE =       .59   GPM
                    MASS FLOW RATE       =     294.7   LBM/HR
                    MASS FLUX            =     44899   LBM/(SQ.FT-HR)
                    FLUID VELOCITY       =       .20   FT/S
                    ROOM TEMPERATURE     =     71.91   F
                    INLET TEMPERATURE    =     79.52   F
                    OUTLET TEMPERATURE   =     82.27   F
                    AVERAGE RE NUMBER    =      2000
                    AVERAGE PR NUMBER    =      5.82
                    CURRENT TO TUBE      =     178.0   AMPS
                    VOLTAGE DROP IN TUBE =      1.43   VOLTS
                    AVERAGE HEAT FLUX    =       350   BTU/(SQ.FT-HR)
                    Q=AMP*VOLT           =       868   BTU/HR
                    Q=M*C*(T2-T1)        =       809   BTU/HR
                    HEAT BALANCE ERROR   =      6.83   %

                      OUTSIDE SURFACE TEMPERATURES - DEGREES F

        1        2        3        4        5        6        7        8        9       10

 1    82.79    83.25    84.45    84.89    84.95    85.08    85.17    85.19    85.56    85.70
 2    82.87    83.25    85.04    85.47    85.90    86.38    86.60    86.67    87.46    88.05
 3    84.30    83.56    86.68    88.10    89.22    89.83    90.66    90.96    91.97    92.69
 4    83.95    83.38    84.81    85.49    85.60    86.05    86.32    86.76    86.89    86.88

                      INSIDE SURFACE TEMPERATURES - DEGREES F

        1        2        3        4        5        6        7        8        9       10

 1    82.60    83.06    84.26    84.70    84.75    84.88    84.97    84.98    85.35    85.49
 2    82.67    83.06    84.85    85.27    85.70    86.18    86.40    86.46    87.26    87.85
 3    84.13    83.38    86.52    87.95    89.08    89.69    90.53    90.83    91.85    92.57
 4    83.77    83.19    84.61    85.29    85.39    85.84    86.11    86.56    86.68    86.66

                      REYNOLDS NUMBER AT THE INSIDE TUBE WALL

        1        2        3        4        5        6        7        8        9       10

 1    2042     2054     2083     2094     2096     2099     2101     2102     2111     2114
 2    2044     2054     2098     2109     2120     2132     2137     2139     2159     2174
 3    2080     2062     2140     2177     2205     2221     2242     2250     2276     2295
 4    2071     2057     2092     2109     2112     2123     2130     2141     2144     2144

                        INSIDE SURFACE HEAT FLUXES BTU/HR/FT2

        1        2        3        4        5        6        7        8        9       10

 1     337      323      334      337      342      350      354      360      363      367
 2     338      325      335      348      352      349      355      357      355      351
 3     300      316      279      257      236      233      218      217      204      193
 4     312      322      341      347      359      357      362      355      369      380

                                 *---------------*
                                 RUN NUMBER 1010
                                 *---------------*

                  PERIPHERAL HEAT TRANSFER COEFFICIENT BTU/(SQ.FT-HR-F)

        1        2        3        4        5        6        7        8        9       10

 1     116      104       83       80       85       91       96      105      102      107
 2     114      105       72       72       71       67       69       72       65       61
 3      67       92       44       34       28       26       23       23       20       18
 4      76      100       77       72       77       74       75       71       76       83

                                 *---------------*
                                 RUN NUMBER 1010
                                     SUMMARY
                                 *---------------*

ST      RE       PR      X/D      MUB      MUW       TB       TW      DENS       NU

 1    1971.48   5.92      6.4    2.082    1.993    79.71    83.29    62.22     23.39
 2    1977.95   5.90     15.5    2.075    1.995    79.97    83.17    62.21     26.17
 3    1984.43   5.88     24.6    2.068    1.951    80.23    85.06    62.21     17.39
 4    1990.91   5.86     33.7    2.062    1.934    80.50    85.80    62.21     15.83
 5    1997.41   5.84     42.8    2.055    1.924    80.76    86.23    62.21     15.35
 6    2003.91   5.81     52.0    2.048    1.914    81.03    86.65    62.20     14.93
 7    2010.42   5.79     61.1    2.042    1.906    81.29    87.00    62.20     14.70
 8    2016.94   5.77     70.2    2.035    1.902    81.56    87.21    62.20     14.84
 9    2023.46   5.75     79.3    2.028    1.889    81.82    87.78    62.20     14.07
10    2030.00   5.73     88.4    2.022    1.881    82.08    88.14    62.19     13.85

                     NOTE: TBULK IS GIVEN IN DEGREES FAHRENHEIT
                           MUB AND MUW ARE GIVEN IN LBM/(FT*HR)
```

```
                  *-----------------------------------------*
                              RUN NUMBER 1030
                        TEST FLUID IS DISTILLED WATER
                  *-----------------------------------------*
                  VOLUMETRIC FLOW RATE =       .59   GPM
                  MASS FLOW RATE       =     292.9   LBM/HR
                  MASS FLUX            =     44625   LBM/(SQ.FT-HR)
                  FLUID VELOCITY       =       .20   FT/S
                  ROOM TEMPERATURE     =     72.22   F
                  INLET TEMPERATURE    =     79.52   F
                  OUTLET TEMPERATURE   =     82.99   F
                  AVERAGE RE NUMBER    =      1997
                  AVERAGE PR NUMBER    =      5.80
                  CURRENT TO TUBE      =     200.0   AMPS
                  VOLTAGE DROP IN TUBE =      1.59   VOLTS
                  AVERAGE HEAT FLUX    =       438   BTU/(SQ.FT-HR)
                  Q=AMP*VOLT           =      1085   BTU/HR
                  Q=M*C*(T2-T1)        =      1014   BTU/HR
                  HEAT BALANCE ERROR   =      6.48   %

                    OUTSIDE SURFACE TEMPERATURES - DEGREES F

          1       2       3       4       5       6       7       8       9      10

 1      83.54   84.14   85.45   85.88   86.05   86.13   86.25   86.29   86.71   86.85
 2      83.69   84.28   86.23   86.69   87.15   87.70   88.01   88.08   89.00   89.72
 3      85.82   85.04   88.67   90.15   91.39   92.14   93.17   93.55   94.70   95.28
 4      84.96   84.38   85.91   86.68   86.79   87.32   87.65   88.17   88.27   88.48

                    INSIDE SURFACE TEMPERATURES - DEGREES F

          1       2       3       4       5       6       7       8       9      10

 1      83.29   83.90   85.21   85.63   85.80   85.88   85.99   86.03   86.45   86.58
 2      83.44   84.04   85.98   86.44   86.89   87.45   87.75   87.82   88.74   89.47
 3      85.60   84.81   88.47   89.96   91.21   91.97   93.01   93.39   94.55   95.13
 4      84.73   84.14   85.66   86.43   86.53   87.06   87.39   87.91   88.00   88.21

                    REYNOLDS NUMBER AT THE INSIDE TUBE WALL

          1       2       3       4       5       6       7       8       9      10

 1      2047    2062    2094    2105    2109    2111    2114    2115    2125    2129
 2      2051    2065    2114    2125    2137    2151    2158    2160    2183    2202
 3      2104    2085    2176    2214    2246    2266    2292    2302    2332    2347
 4      2083    2068    2106    2125    2127    2141    2149    2162    2165    2170

                      INSIDE SURFACE HEAT FLUXES BTU/HR/FT2

          1       2       3       4       5       6       7       8       9      10

 1       426     411     423     427     430     442     447     454     456     464
 2       431     414     428     440     446     443     450     454     450     442
 3       370    '389     343     321     298     292     275     273     257     254
 4       399     412     436     440     455     453     459     451     469     472

                              *----------------*
                               RUN NUMBER 1030
                              *----------------*

               PERIPHERAL HEAT TRANSFER COEFFICIENT BTU/(SQ.FT-HR-F)

          1       2       3       4       5       6       7       8       9      10

 1       120     107      88      87      91      99     105     115     113     121
 2       116     104      76      77      76      73      75      79      71      65
 3        63      82      42      34      29      27      24      24      21      20
 4        80     101      83      77      83      80      81      77      84      86

                              *----------------*
                               RUN NUMBER 1030
                                   SUMMARY
                              *----------------*

ST      RE       PR     X/D     MUB     MUW      TB      TW     DENS     NU

 1    1960.64   5.92    6.4   2.081   1.969   79.75   84.27   62.22   23.47
 2    1968.76   5.89   15.5   2.072   1.970   80.09   84.22   62.21   25.59
 3    1976.89   5.86   24.6   2.064   1.922   80.42   86.33   62.21   17.94
 4    1985.03   5.84   33.7   2.055   1.904   80.75   87.11   62.21   16.67
 5    1993.19   5.81   42.8   2.047   1.893   81.09   87.61   62.20   16.26
 6    2001.35   5.78   52.0   2.038   1.882   81.42   88.09   62.20   15.90
 7    2009.54   5.76   61.1   2.030   1.873   81.76   88.53   62.20   15.63
 8    2017.73   5.73   70.2   2.022   1.867   82.09   88.79   62.19   15.82
 9    2025.94   5.70   79.3   2.014   1.853   82.42   89.43   62.19   15.11
10    2034.16   5.68   88.4   2.006   1.844   82.76   89.85   62.19   14.94

                     NOTE: TBULK IS GIVEN IN DEGREES FAHRENHEIT
                           MUB AND MUW ARE GIVEN IN LBM/(FT*HR)
```

```
                  *----------------------------------------*
                              RUN NUMBER 1040
                       TEST FLUID IS DISTILLED WATER
                  *----------------------------------------*
                  VOLUMETRIC FLOW RATE =       .60   GPM
                  MASS FLOW RATE       =     298.5   LBM/HR
                  MASS FLUX            =     45476   LBM/(SQ.FT-HR)
                  FLUID VELOCITY       =       .20   FT/S
                  ROOM TEMPERATURE     =     72.42   F
                  INLET TEMPERATURE    =     79.60   F
                  OUTLET TEMPERATURE   =     83.40   F
                  AVERAGE RE NUMBER    =      2041
                  AVERAGE PR NUMBER    =      5.78
                  CURRENT TO TUBE      =     213.0   AMPS
                  VOLTAGE DROP IN TUBE =      1.69   VOLTS
                  AVERAGE HEAT FLUX    =       495   BTU/(SQ.FT-HR)
                  Q=AMP*VOLT           =      1228   BTU/HR
                  Q=M*C*(T2-T1)        =      1132   BTU/HR
                  HEAT BALANCE ERROR   =      7.80   %

                   OUTSIDE SURFACE TEMPERATURES - DEGREES F

       1      2      3      4      5      6      7      8      9     10

1    83.95  84.75  86.18  86.65  86.64  86.85  86.95  87.00  87.39  87.61
2    84.04  84.88  86.94  87.46  87.98  88.66  88.89  89.00  89.99  90.79
3    86.42  85.40  89.53  91.20  92.72  93.53  94.57  95.02  96.23  96.94
4    85.40  84.98  86.64  87.44  87.54  88.18  88.49  89.04  89.20  89.26

                   INSIDE SURFACE TEMPERATURES - DEGREES F

       1      2      3      4      5      6      7      8      9     10

1    83.67  84.48  85.90  86.37  86.36  86.56  86.66  86.70  87.09  87.31
2    83.76  84.61  86.66  87.17  87.69  88.37  88.60  88.71  89.70  90.50
3    86.18  85.14  89.30  90.98  92.52  93.33  94.38  94.83  96.05  96.77
4    85.14  84.71  86.36  87.15  87.24  87.89  88.19  88.75  88.90  88.95

                   REYNOLDS NUMBER AT THE INSIDE TUBE WALL

       1      2      3      4      5      6      7      8      9     10

1    2096   2116   2152   2164   2164   2169   2171   2173   2183   2188
2    2098   2119   2171   2185   2198   2215   2221   2224   2250   2271
3    2159   2133   2239   2283   2323   2345   2372   2384   2417   2436
4    2133   2122   2164   2184   2186   2203   2211   2225   2229   2230

                      INSIDE SURFACE HEAT FLUXES BTU/HR/FT2

       1      2      3      4      5      6      7      8      9     10

1     480    466    477    482    490    502    506    513    518    524
2     490    466    485    499    505    501    509    513    508    500
3     419    450    394    369    339    335    316    313    298    291
4     456    463    492    499    516    513    519    512    528    538

                                *---------------*
                                 RUN NUMBER 1040
                                *---------------*

               PERIPHERAL HEAT TRANSFER COEFFICIENT BTU/(SQ.FT-HR-F)

       1      2      3      4      5      6      7      8      9     10

1     125    109     89     89     97    102    109    119    120    125
2     125    106     79     80     79     74     77     81     73     68
3      66     91     45     36     30     28     25     25     22     21
4      86    103     85     80     87     82     84     80     86     92

                                *---------------*
                                 RUN NUMBER 1040
                                     SUMMARY
                                *---------------*

ST      RE       PR     X/D     MUB     MUW      TB      TW     DENS      NU

 1    2000.56   5.91     6.4   2.078   1.959   79.86   84.69   62.21    24.88
 2    2009.62   5.88    15.5   2.069   1.958   80.22   84.74   62.21    26.61
 3    2018.70   5.85    24.6   2.059   1.905   80.59   87.06   62.21    18.59
 4    2027.79   5.82    33.7   2.050   1.886   80.95   87.92   62.20    17.26
 5    2036.91   5.79    42.8   2.041   1.874   81.32   88.45   62.20    16.85
 6    2046.03   5.76    52.0   2.032   1.862   81.68   89.04   62.20    16.35
 7    2055.18   5.73    61.1   2.023   1.853   82.05   89.46   62.19    16.23
 8    2064.34   5.71    70.2   2.014   1.846   82.41   89.75   62.19    16.39
 9    2073.51   5.68    79.3   2.005   1.832   82.78   90.44   62.19    15.70
10    2082.70   5.65    88.4   1.996   1.823   83.14   90.88   62.18    15.53

                    NOTE: TBULK IS GIVEN IN DEGREES FAHRENHEIT
                          MUB AND MUW ARE GIVEN IN LBM/(FT*HR)
```

```
                 *-----------------------------------------*
                             RUN NUMBER 1060
                       TEST FLUID IS DISTILLED WATER
                 *-----------------------------------------*
                 VOLUMETRIC FLOW RATE =       .60   GPM
                 MASS FLOW RATE       =     297.8   LBM/HR
                 MASS FLUX            =     45368   LBM/(SQ.FT-HR)
                 FLUID VELOCITY       =       .20   FT/S
                 ROOM TEMPERATURE     =     72.57   F
                 INLET TEMPERATURE    =     79.78   F
                 OUTLET TEMPERATURE   =     85.27   F
                 AVERAGE RE NUMBER    =      2062
                 AVERAGE PR NUMBER    =      5.70
                 CURRENT TO TUBE      =     252.0   AMPS
                 VOLTAGE DROP IN TUBE =      2.01   VOLTS
                 AVERAGE HEAT FLUX    =       697   BTU/(SQ.FT-HR)
                 Q=AMP*VOLT           =      1728   BTU/HR
                 Q=M*C*(T2-T1)        =      1632   BTU/HR
                 HEAT BALANCE ERROR   =      5.57   %

                   OUTSIDE SURFACE TEMPERATURES - DEGREES F

         1       2       3       4       5       6       7       8       9      10

  1  85.86   87.06   88.65   89.16   89.24   89.43   89.52   89.63   90.15   90.45
  2  86.25   87.38   89.71   90.38   91.12   91.96   92.30   92.49   93.78   94.85
  3  90.24   88.66   94.01   96.09   98.05   99.14  100.67  101.21  102.79  103.57
  4  87.77   87.40   89.37   90.39   90.45   91.35   91.75   92.42   92.53   92.94

                   INSIDE SURFACE TEMPERATURES - DEGREES F

         1       2       3       4       5       6       7       8       9      10

  1  85.47   86.68   88.26   88.77   88.84   89.02   89.11   89.22   89.73   90.03
  2  85.85   87.00   89.31   89.98   90.71   91.55   91.89   92.08   93.37   94.45
  3  89.91   88.30   93.70   95.79   97.78   98.87  100.41  100.96  102.55  103.33
  4  87.39   87.02   88.97   89.99   90.03   90.94   91.33   92.00   92.10   92.51

                   REYNOLDS NUMBER AT THE INSIDE TUBE WALL

         1       2       3       4       5       6       7       8       9      10

  1   2136    2167    2207    2220    2222    2227    2229    2232    2245    2253
  2   2146    2175    2234    2252    2271    2293    2301    2306    2340    2368
  3   2250    2208    2349    2404    2457    2486    2528    2543    2586    2607
  4   2185    2175    2226    2252    2253    2276    2287    2304    2307    2318

                     INSIDE SURFACE HEAT FLUXES BTU/HR/FT2

         1       2       3       4       5       6       7       8       9      10

  1    676     655     671     680     688     705     713     721     726     737
  2    692     659     689     705     712     708     720     723     718     705
  3    566     615     536     506     467     462     433     430     408     408
  4    654     659     697     705     729     723     733     725     749     753

                               *---------------*
                                RUN NUMBER 1060
                               *---------------*

             PERIPHERAL HEAT TRANSFER COEFFICIENT BTU/(SQ.FT-HR-F)

         1       2       3       4       5       6       7       8       9      10

  1    127     109      95      96     104     113     123     134     135     143
  2    121     104      85      85      84      80      84      87      79      73
  3     58      80      42      36      30      28      25      25      22      22
  4     90     103      89      85      93      88      91      88      96      98

                               *---------------*
                                RUN NUMBER 1060
                                    SUMMARY
                               *---------------*

 ST      RE      PR     X/D     MUB     MUW      TB      TW    DENS       NU

  1  2003.09   5.88     6.4   2.071   1.903   80.15   87.16   62.21    24.04
  2  2016.18   5.84    15.5   2.057   1.901   80.68   87.25   62.21    25.61
  3  2029.30   5.80    24.6   2.044   1.840   81.21   90.06   62.20    19.04
  4  2042.45   5.76    33.7   2.031   1.817   81.73   91.13   62.20    17.94
  5  2055.64   5.72    42.8   2.018   1.803   82.26   91.84   62.19    17.59
  6  2068.85   5.68    52.0   2.005   1.787   82.79   92.60   62.19    17.18
  7  2082.11   5.64    61.1   1.992   1.776   83.32   93.19   62.18    17.07
  8  2095.39   5.60    70.2   1.979   1.768   83.84   93.56   62.18    17.33
  9  2108.71   5.56    79.3   1.967   1.751   84.37   94.44   62.17    16.73
 10  2122.06   5.52    88.4   1.954   1.739   84.90   95.08   62.16    16.54

                   NOTE: TBULK IS GIVEN IN DEGREES FAHRENHEIT
                         MUB AND MUW ARE GIVEN IN LBM/(FT*HR)
```

```
                  *----------------------------------------*
                              RUN NUMBER 1070
                       TEST FLUID IS DISTILLED WATER
                  *----------------------------------------*
                  VOLUMETRIC FLOW RATE =       .60   GPM
                  MASS FLOW RATE       =     297.8   LBM/HR
                  MASS FLUX            =     45367   LBM/(SQ.FT-HR)
                  FLUID VELOCITY       =       .20   FT/S
                  ROOM TEMPERATURE     =     72.91   F
                  INLET TEMPERATURE    =     80.00   F
                  OUTLET TEMPERATURE   =     94.35   F
                  AVERAGE RE NUMBER    =      2179
                  AVERAGE PR NUMBER    =      5.35
                  CURRENT TO TUBE      =     378.0   AMPS
                  VOLTAGE DROP IN TUBE =      3.04   VOLTS
                  AVERAGE HEAT FLUX    =      1582   BTU/(SQ.FT-HR)
                  Q=AMP*VOLT           =      3920   BTU/HR
                  Q=M*C*(T2-T1)        =      4264   BTU/HR
                  HEAT BALANCE ERROR   =     -8.77   %

                    OUTSIDE SURFACE TEMPERATURES - DEGREES F

          1       2       3       4       5       6       7       8       9      10

 1    94.11   96.38   98.56   99.28   99.17   99.70  100.17  101.02  101.43  101.57
 2    95.14   98.12  100.97  102.27  103.80  105.58  106.45  107.15  109.69  112.12
 3   107.20  104.80  113.94  117.53  121.81  124.20  127.63  129.05  132.09  133.69
 4    97.34   97.47  100.30  102.25  102.13  104.38  105.28  106.85  106.86  108.39

                    INSIDE SURFACE TEMPERATURES - DEGREES F

          1       2       3       4       5       6       7       8       9      10

 1    93.23   95.51   97.68   98.39   98.27   98.78   99.24  100.08  100.48  100.60
 2    94.22   97.24  100.05  101.34  102.86  104.65  105.50  106.19  108.75  111.20
 3   106.51  104.06  113.28  116.90  121.23  123.63  127.09  128.52  131.58  133.17
 4    96.45   96.58   99.37  101.32  101.17  103.43  104.31  105.89  105.87  107.41

                    REYNOLDS NUMBER AT THE INSIDE TUBE WALL

          1       2       3       4       5       6       7       8       9      10

 1     2336    2397    2454    2473    2470    2484    2496    2519    2530    2533
 2     2362    2443    2518    2553    2594    2643    2667    2686    2757    2825
 3     2695    2627    2884    2988    3113    3183    3285    3327    3419    3467
 4     2422    2425    2500    2552    2548    2610    2634    2677    2677    2720

                      INSIDE SURFACE HEAT FLUXES BTU/HR/FT2

          1       2       3       4       5       6       7       8       9      10

 1     1524    1506    1529    1554    1577    1617    1630    1638    1662    1711
 2     1608    1531    1607    1631    1647    1641    1670    1683    1663    1625
 3     1187    1289    1131    1082     991     982     918     911     867     877
 4     1551    1548    1624    1632    1690    1672    1700    1690    1737    1722

                              *---------------*
                               RUN NUMBER 1070
                              *---------------*

               PERIPHERAL HEAT TRANSFER COEFFICIENT BTU/(SQ.FT-HR-F)

          1       2       3       4       5       6       7       8       9      10

 1      124     114     109     117     133     148     163     173     196     237
 2      121     102      98     100     100      97     102     108      99      91
 3       46      59      38      34      28      27      24      24      21      22
 4      100     108     103     100     115     107     112     110     125     122

                              *---------------*
                               RUN NUMBER 1070
                                   SUMMARY
                              *---------------*

ST       RE      PR     X/D     MUB     MUW      TB      TW    DENS       NU

 1  2023.27    5.82     6.4   2.050   1.691   80.97   97.60   62.20    22.93
 2  2057.68    5.71    15.5   2.016   1.677   82.35   98.35   62.19    23.81
 3  2092.32    5.60    24.6   1.982   1.603   83.73  102.60   62.18    20.22
 4  2127.18    5.50    33.7   1.950   1.571   85.11  104.49   62.16    19.67
 5  2162.26    5.40    42.8   1.918   1.549   86.49  105.88   62.15    19.64
 6  2197.56    5.31    52.0   1.887   1.521   87.86  107.62   62.13    19.27
 7  2233.07    5.21    61.1   1.857   1.500   89.24  109.04   62.12    19.22
 8  2268.81    5.12    70.2   1.828   1.483   90.62  110.17   62.10    19.45
 9  2304.75    5.03    79.3   1.799   1.461   92.00  111.67   62.09    19.31
10  2340.91    4.94    88.4   1.772   1.440   93.38  113.10   62.07    19.25

                    NOTE: TBULK IS GIVEN IN DEGREES FAHRENHEIT
                          MUB AND MUW ARE GIVEN IN LBM/(FT*HR)
```

```
                 *-----------------------------------------*
                            RUN NUMBER 2010
                      TEST FLUID IS DISTILLED WATER
                 *-----------------------------------------*
                 VOLUMETRIC FLOW RATE =     1.02   GPM
                 MASS FLOW RATE       =    511.4   LBM/HR
                 MASS FLUX            =    77916   LBM/(SQ.FT-HR)
                 FLUID VELOCITY       =      .35   FT/S
                 ROOM TEMPERATURE     =    69.93   F
                 INLET TEMPERATURE    =    76.15   F
                 OUTLET TEMPERATURE   =    76.86   F
                 AVERAGE RE NUMBER    =     3286
                 AVERAGE PR NUMBER    =     6.19
                 CURRENT TO TUBE      =    100.0   AMPS
                 VOLTAGE DROP IN TUBE =      .79   VOLTS
                 AVERAGE HEAT FLUX    =      108   BTU/(SQ.FT-HR)
                 Q=AMP*VOLT           =      269   BTU/HR
                 Q=M*C*(T2-T1)        =      362   BTU/HR
                 HEAT BALANCE ERROR   =   -34.54   %


                   OUTSIDE SURFACE TEMPERATURES - DEGREES F

         1       2       3       4       5       6       7       8       9      10

 1    77.71   77.85   77.97   77.99   77.93   77.96   77.93   77.96   78.47   78.47
 2    77.67   77.75   77.99   77.91   77.94   77.96   77.98   77.94   78.45   78.51
 3    77.57   77.65   77.98   77.82   77.91   77.85   77.95   77.83   78.56   78.76
 4    77.61   77.86   77.96   78.04   77.96   77.97   77.95   78.31   78.43   78.00


                   INSIDE SURFACE TEMPERATURES - DEGREES F

         1       2       3       4       5       6       7       8       9      10

 1    77.65   77.79   77.91   77.93   77.87   77.90   77.87   77.90   78.41   78.41
 2    77.61   77.69   77.93   77.85   77.88   77.90   77.92   77.88   78.39   78.45
 3    77.51   77.59   77.92   77.76   77.85   77.79   77.89   77.77   78.50   78.71
 4    77.55   77.80   77.90   77.98   77.90   77.91   77.89   78.26   78.37   77.93


                   REYNOLDS NUMBER AT THE INSIDE TUBE WALL

         1       2       3       4       5       6       7       8       9      10

 1     3334    3340    3345    3346    3343    3345    3343    3344    3366    3366
 2     3332    3336    3346    3342    3344    3345    3345    3344    3365    3368
 3     3328    3331    3345    3339    3342    3340    3344    3339    3370    3379
 4     3330    3340    3345    3348    3345    3345    3344    3359    3364    3346


                     INSIDE SURFACE HEAT FLUXES BTU/HR/FT2

         1       2       3       4       5       6       7       8       9      10

 1       99     100     101     100     101     101     102     105     100      95
 2      100     101     100     101     100      99     100     100     102     103
 3      102     105     101     105     102     104     101     108      98      88
 4      101      98     101      97     100      99     100      91     103     116


                               *---------------*
                                RUN NUMBER 2010
                               *---------------*

              PERIPHERAL HEAT TRANSFER COEFFICIENT BTU/(SQ.FT-HR-F)

         1       2       3       4       5       6       7       8       9      10

 1       68      65      64      66      72      74      80      85      60      59
 2       71      71      63      69      71      73      76      83      62      63
 3       78      79      63      77      74      83      79      99      55      46
 4       75      64      64      61      70      72      78      57      63     103


                               *---------------*
                                RUN NUMBER 2010
                                    SUMMARY
                               *---------------*

ST      RE       PR     X/D     MUB     MUW      TB      TW     DENS      NU

 1    3273.69   6.22     6.4   2.176   2.138   76.20   77.58   62.25    19.14
 2    3276.54   6.21    15.5   2.174   2.134   76.27   77.72   62.25    18.24
 3    3279.39   6.21    24.6   2.172   2.129   76.33   77.92   62.25    16.74
 4    3282.24   6.20    33.7   2.170   2.130   76.40   77.88   62.25    17.92
 5    3285.09   6.20    42.8   2.168   2.130   76.47   77.88   62.25    18.84
 6    3287.94   6.19    52.0   2.166   2.130   76.54   77.88   62.25    19.80
 7    3290.79   6.18    61.1   2.164   2.130   76.61   77.89   62.24    20.57
 8    3293.64   6.18    70.2   2.163   2.128   76.68   77.95   62.24    20.76
 9    3296.50   6.17    79.3   2.161   2.116   76.74   78.42   62.24    15.82
10    3299.35   6.17    88.4   2.159   2.117   76.81   78.38   62.24    16.93

                   NOTE: TBULK IS GIVEN IN DEGREES FAHRENHEIT
                         MUB AND MUW ARE GIVEN IN LBM/(FT*HR)
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```
            *-----------------------------------------*
                        RUN NUMBER 2065
                  TEST FLUID IS DISTILLED WATER
            *-----------------------------------------*
            VOLUMETRIC FLOW RATE =      1.01   GPM
            MASS FLOW RATE       =     505.4   LBM/HR
            MASS FLUX            =     76993   LBM/(SQ.FT-HR)
            FLUID VELOCITY       =       .34   FT/S
            ROOM TEMPERATURE     =     71.42   F
            INLET TEMPERATURE    =     77.08   F
            OUTLET TEMPERATURE   =     78.69   F
            AVERAGE RE NUMBER    =      3304
            AVERAGE PR NUMBER    =      6.07
            CURRENT TO TUBE      =     165.0   AMPS
            VOLTAGE DROP IN TUBE =      1.33   VOLTS
            AVERAGE HEAT FLUX    =       302   BTU/(SQ.FT-HR)
            Q=AMP*VOLT           =       748   BTU/HR
            Q=M*C*(T2-T1)        =       812   BTU/HR
            HEAT BALANCE ERROR   =     -8.51   %

              OUTSIDE SURFACE TEMPERATURES - DEGREES F

         1       2       3       4       5       6       7       8       9      10

 1     80.13   80.70   81.08   81.18   81.17   81.26   81.34   81.46   82.10   82.21
 2     80.11   80.69   81.21   81.22   81.26   81.36   81.50   81.58   82.21   82.36
 3     80.06   80.73   81.39   81.24   81.34   81.29   81.55   81.56   82.43   82.73
 4     80.05   80.81   81.16   81.32   81.25   81.34   81.44   81.97   82.18   81.74

              INSIDE SURFACE TEMPERATURES - DEGREES F

         1       2       3       4       5       6       7       8       9      10

 1     79.97   80.54   80.92   81.02   81.01   81.10   81.18   81.30   81.94   82.05
 2     79.95   80.53   81.05   81.06   81.10   81.20   81.34   81.42   82.05   82.20
 3     79.90   80.57   81.23   81.08   81.18   81.13   81.39   81.40   82.27   82.58
 4     79.89   80.65   81.00   81.16   81.09   81.18   81.28   81.82   82.02   81.57

              REYNOLDS NUMBER AT THE INSIDE TUBE WALL

         1       2       3       4       5       6       7       8       9      10

 1      3391    3415    3431    3435    3435    3439    3442    3447    3474    3479
 2      3390    3415    3437    3437    3439    3443    3449    3452    3479    3485
 3      3388    3417    3444    3438    3442    3440    3451    3451    3489    3502
 4      3388    3420    3435    3441    3438    3442    3446    3469    3478    3459

                INSIDE SURFACE HEAT FLUXES BTU/HR/FT2

         1       2       3       4       5       6       7       8       9      10

 1       274     277     278     278     278     278     279     284     278     272
 2       275     276     276     276     276     274     274     274     277     279
 3       276     276     271     277     274     277     274     281     270     259
 4       277     273     278     273     276     274     276     264     278     294

                          *---------------*
                          RUN NUMBER 2065
                          *---------------*

         PERIPHERAL HEAT TRANSFER COEFFICIENT BTU/(SQ.FT-HR-F)

         1       2       3       4       5       6       7       8       9      10

 1        98      86      81      82      86      88      91      93      79      78
 2        99      86      77      81      83      84      85      87      76      77
 3       102      85      72      80      81      87      83      90      70      64
 4       102      82      79      77      84      85      87      74      77      98

                          *---------------*
                          RUN NUMBER 2065
                              SUMMARY
                          *---------------*

ST     RE       PR     X/D    MUB     MUW      TB      TW     DENS     NU

 1   3275.83   6.13    6.4   2.149   2.076   77.19   79.93   62.24   26.34
 2   3282.25   6.12   15.5   2.144   2.060   77.34   80.57   62.24   22.35
 3   3288.66   6.11   24.6   2.140   2.048   77.50   81.05   62.24   20.32
 4   3295.09   6.09   33.7   2.136   2.047   77.65   81.08   62.24   21.05
 5   3301.52   6.08   42.8   2.132   2.047   77.81   81.09   62.23   21.94
 6   3307.95   6.07   52.0   2.128   2.045   77.96   81.15   62.23   22.61
 7   3314.39   6.05   61.1   2.124   2.041   78.12   81.30   62.23   22.68
 8   3320.83   6.04   70.2   2.120   2.037   78.27   81.48   62.23   22.46
 9   3327.28   6.03   79.3   2.115   2.022   78.43   82.07   62.23   19.80
10   3333.73   6.01   88.4   2.111   2.022   78.58   82.10   62.23   20.50

              NOTE: TBULK IS GIVEN IN DEGREES FAHRENHEIT
                    MUB AND MUW ARE GIVEN IN LBM/(FT*HR)
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               *-----------------------------------------*
                           RUN NUMBER 2050
                     TEST FLUID IS DISTILLED WATER
               *-----------------------------------------*
               VOLUMETRIC FLOW RATE =     1.03    GPM
               MASS FLOW RATE       =    515.4    LBM/HR
               MASS FLUX            =    78526    LBM/(SQ.FT-HR)
               FLUID VELOCITY       =      .35    FT/S
               ROOM TEMPERATURE     =    70.94    F
               INLET TEMPERATURE    =    76.70    F
               OUTLET TEMPERATURE   =    77.86    F
               AVERAGE RE NUMBER    =     3344
               AVERAGE PR NUMBER    =     6.13
               CURRENT TO TUBE      =    134.0    AMPS
               VOLTAGE DROP IN TUBE =     1.07    VOLTS
               AVERAGE HEAT FLUX    =      197    BTU/(SQ.FT-HR)
               Q=AMP*VOLT           =      489    BTU/HR
               Q=M*C*(T2-T1)        =      597    BTU/HR
               HEAT BALANCE ERROR   =   -22.05    %


                 OUTSIDE SURFACE TEMPERATURES - DEGREES F

       1      2      3      4      5      6      7      8      9      10

 1   78.96  79.32  79.57  79.64  79.64  79.66  79.70  79.76  80.36  80.39
 2   78.93  79.25  79.62  79.63  79.62  79.71  79.78  79.78  80.37  80.50
 3   78.86  79.21  79.68  79.54  79.66  79.61  79.78  79.73  80.54  80.81
 4   78.87  79.38  79.61  79.71  79.66  79.71  79.73  80.17  80.38  79.90

                 INSIDE SURFACE TEMPERATURES - DEGREES F

       1      2      3      4      5      6      7      8      9      10

 1   78.86  79.21  79.46  79.53  79.53  79.55  79.59  79.65  80.25  80.29
 2   78.82  79.14  79.51  79.52  79.51  79.61  79.67  79.67  80.26  80.39
 3   78.75  79.10  79.58  79.43  79.55  79.50  79.67  79.62  80.44  80.71
 4   78.76  79.28  79.50  79.61  79.55  79.61  79.62  80.07  80.27  79.79

                 REYNOLDS NUMBER AT THE INSIDE TUBE WALL

       1      2      3      4      5      6      7      8      9      10

 1   3411   3427   3437   3440   3440   3441   3443   3445   3471   3472
 2   3410   3424   3439   3440   3439   3443   3446   3446   3471   3477
 3   3407   3422   3442   3436   3441   3439   3446   3444   3479   3491
 4   3407   3429   3439   3443   3441   3443   3444   3463   3472   3451

                   INSIDE SURFACE HEAT FLUXES BTU/HR/FT2

       1      2      3      4      5      6      7      8      9      10

 1    180    181    183    182    182    183    183    187    182    177
 2    181    182    182    180    182    180    181    181    184    184
 3    182    184    180    185    181    184    181    188    178    167
 4    182    179    182    179    181    180    182    171    183    199

                              *---------------*
                               RUN NUMBER 2050
                              *---------------*

             PERIPHERAL HEAT TRANSFER COEFFICIENT BTU/(SQ.FT-HR-F)

       1      2      3      4      5      6      7      8      9      10

 1     86     78     74     75     78     82     85     89     70     70
 2     88     80     72     75     79     79     81     85     70     70
 3     92     83     70     79     77     85     81     91     64     57
 4     92     75     72     71     78     79     83     68     70     99

                              *---------------*
                               RUN NUMBER 2050
                                   SUMMARY
                              *---------------*

ST     RE       PR    X/D     MUB     MUW      TB      TW     DENS      NU

 1   3323.74   6.17    6.4   2.160   2.106   76.78   78.80   62.24    23.53
 2   3328.45   6.16   15.5   2.157   2.095   76.89   79.18   62.24    20.73
 3   3333.15   6.15   24.6   2.154   2.087   77.00   79.51   62.24    18.93
 4   3337.86   6.14   33.7   2.151   2.087   77.11   79.52   62.24    19.72
 5   3342.57   6.13   42.8   2.148   2.086   77.22   79.54   62.24    20.54
 6   3347.28   6.12   52.0   2.145   2.086   77.34   79.57   62.24    21.32
 7   3352.00   6.11   61.1   2.142   2.084   77.45   79.64   62.24    21.67
 8   3356.72   6.10   70.2   2.139   2.081   77.56   79.75   62.24    21.65
 9   3361.44   6.09   79.3   2.136   2.067   77.67   80.31   62.23    18.04
10   3366.16   6.08   88.4   2.133   2.067   77.78   80.29   62.23    18.93

                 NOTE: TBULK IS GIVEN IN DEGREES FAHRENHEIT
                       MUB AND MUW ARE GIVEN IN LBM/(FT*HR)
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                  *----------------------------------------*
                             RUN NUMBER 2030
                       TEST FLUID IS DISTILLED WATER
                  *----------------------------------------*
                  VOLUMETRIC FLOW RATE =     1.07   GPM
                  MASS FLOW RATE       =    533.1   LBM/HR
                  MASS FLUX            =    81223   LBM/(SQ.FT-HR)
                  FLUID VELOCITY       =      .36   FT/S
                  ROOM TEMPERATURE     =    70.41   F
                  INLET TEMPERATURE    =    76.30   F
                  OUTLET TEMPERATURE   =    77.10   F
                  AVERAGE RE NUMBER    =     3434
                  AVERAGE PR NUMBER    =     6.18
                  CURRENT TO TUBE      =    110.0   AMPS
                  VOLTAGE DROP IN TUBE =      .88   VOLTS
                  AVERAGE HEAT FLUX    =      133   BTU/(SQ.FT-HR)
                  Q=AMP*VOLT           =      330   BTU/HR
                  Q=M*C*(T2-T1)        =      425   BTU/HR
                  HEAT BALANCE ERROR   =   -28.97   %

                    OUTSIDE SURFACE TEMPERATURES - DEGREES F

        1       2       3       4       5       6       7       8       9      10

  1   77.99   78.17   78.30   78.32   78.29   78.34   78.32   78.35   78.87   78.89
  2   77.95   78.05   78.31   78.23   78.28   78.33   78.37   78.34   78.84   78.90
  3   77.84   77.91   78.27   78.11   78.25   78.19   78.33   78.20   78.93   79.13
  4   77.89   78.16   78.28   78.36   78.31   78.34   78.35   78.69   78.84   78.40

                    INSIDE SURFACE TEMPERATURES - DEGREES F

        1       2       3       4       5       6       7       8       9      10

  1   77.92   78.10   78.23   78.25   78.22   78.27   78.25   78.28   78.80   78.82
  2   77.88   77.98   78.24   78.16   78.21   78.26   78.30   78.27   78.77   78.83
  3   77.77   77.84   78.20   78.04   78.18   78.12   78.26   78.12   78.86   79.07
  4   77.82   78.09   78.21   78.29   78.24   78.27   78.28   78.62   78.77   78.32

                    REYNOLDS NUMBER AT THE INSIDE TUBE WALL

        1       2       3       4       5       6       7       8       9      10

  1   3487    3495    3501    3502    3500    3503    3502    3503    3526    3527
  2   3486    3490    3501    3498    3500    3502    3504    3503    3525    3527
  3   3481    3484    3500    3492    3499    3496    3502    3496    3529    3538
  4   3483    3495    3500    3504    3501    3503    3503    3518    3525    3505

                      INSIDE SURFACE HEAT FLUXES BTU/HR/FT2

        1       2       3       4       5       6       7       8       9      10

  1    120     120     122     122     122     122     123     126     121     116
  2    121     122     122     122     122     120     121     120     123     125
  3    124     127     123     127     123     126     123     130     120     110
  4    123     119     122     119     121     120     122     112     123     137

                               *---------------*
                                RUN NUMBER 2030
                               *---------------*

               PERIPHERAL HEAT TRANSFER COEFFICIENT BTU/(SQ.FT-HR-F)

        1       2       3       4       5       6       7       8       9      10

  1     77      72      71      73      78      80      86      91      66      65
  2     79      78      70      77      78      79      81      87      68      70
  3     88      90      72      87      81      91      85     105      63      54
  4     84      72      72      69      76      78      83      64      68     107

                               *---------------*
                                RUN NUMBER 2030
                                    SUMMARY
                               *---------------*

ST      RE       PR     X/D     MUB     MUW      TB      TW     DENS      NU

 1    3419.42   6.21    6.4   2.171   2.131   76.35   77.85   62.25    21.47
 2    3422.77   6.20   15.5   2.169   2.127   76.43   78.00   62.25    20.40
 3    3426.12   6.19   24.6   2.167   2.121   76.51   78.22   62.25    18.73
 4    3429.47   6.19   33.7   2.165   2.122   76.58   78.18   62.24    20.05
 5    3432.82   6.18   42.8   2.163   2.121   76.66   78.21   62.24    20.67
 6    3436.17   6.17   52.0   2.161   2.121   76.74   78.23   62.24    21.50
 7    3439.52   6.17   61.1   2.159   2.120   76.82   78.27   62.24    22.01
 8    3442.88   6.16   70.2   2.157   2.118   76.89   78.32   62.24    22.38
 9    3446.23   6.15   79.3   2.155   2.106   76.97   78.80   62.24    17.51
10    3449.59   6.15   88.4   2.152   2.107   77.05   78.76   62.24    18.71

                    NOTE: TBULK IS GIVEN IN DEGREES FAHRENHEIT
                          MUB AND MUW ARE GIVEN IN LBM/(FT*HR)
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              *-----------------------------------------*
                          RUN NUMBER 5168
                    TEST FLUID IS DISTILLED WATER
              *-----------------------------------------*
              VOLUMETRIC FLOW RATE =      1.28   GPM
              MASS FLOW RATE       =     639.5   LBM/HR
              MASS FLUX            =     97433   LBM/(SQ.FT-HR)
              FLUID VELOCITY       =       .43   FT/S
              ROOM TEMPERATURE     =     71.22   F
              INLET TEMPERATURE    =     70.29   F
              OUTLET TEMPERATURE   =     75.19   F
              AVERAGE RE NUMBER    =      3914
              AVERAGE PR NUMBER    =      6.54
              CURRENT TO TUBE      =     327.3   AMPS
              VOLTAGE DROP IN TUBE =      2.61   VOLTS
              AVERAGE HEAT FLUX    =      1176   BTU/(SQ.FT-HR)
              Q=AMP*VOLT           =      2915   BTU/HR
              Q=M*C*(T2-T1)        =      3130   BTU/HR
              HEAT BALANCE ERROR   =     -7.40   %

                OUTSIDE SURFACE TEMPERATURES - DEGREES F

        1       2       3       4       5       6       7       8       9      10

 1    78.64   80.15   81.27   81.70   81.97   82.40   82.76   83.21   83.99   84.44
 2    78.73   80.27   81.56   81.92   82.35   82.87   83.32   83.65   84.54   84.96
 3    78.76   80.00   81.63   82.10   82.83   83.12   83.74   83.57   84.92   85.21
 4    78.58   80.46   81.47   81.90   82.31   82.70   83.10   83.93   84.40   84.06

                INSIDE SURFACE TEMPERATURES - DEGREES F

        1       2       3       4       5       6       7       8       9      10

 1    78.01   79.52   80.64   81.07   81.33   81.76   82.12   82.57   83.35   83.81
 2    78.10   79.64   80.93   81.29   81.72   82.24   82.69   83.02   83.91   84.33
 3    78.13   79.37   81.00   81.47   82.21   82.49   83.12   82.94   84.30   84.59
 4    77.95   79.84   80.84   81.27   81.68   82.07   82.47   83.31   83.77   83.42

                REYNOLDS NUMBER AT THE INSIDE TUBE WALL

        1       2       3       4       5       6       7       8       9      10

 1    4188    4268    4327    4350    4364    4387    4407    4431    4473    4498
 2    4193    4274    4343    4362    4385    4413    4437    4455    4503    4526
 3    4195    4260    4347    4372    4411    4427    4460    4450    4524    4540
 4    4185    4285    4338    4361    4383    4404    4425    4470    4495    4476

                  INSIDE SURFACE HEAT FLUXES BTU/HR/FT2

        1       2       3       4       5       6       7       8       9      10

 1    1085    1091    1093    1093    1097    1098    1100    1103    1102    1091
 2    1084    1081    1084    1087    1089    1085    1087    1082    1087    1086
 3    1082    1095    1084    1083    1075    1080    1075    1094    1078    1072
 4    1088    1076    1087    1087    1090    1090    1092    1075    1091    1109

                             *---------------*
                              RUN NUMBER 5168
                             *---------------*

           PERIPHERAL HEAT TRANSFER COEFFICIENT BTU/(SQ.FT-HR-F)

        1       2       3       4       5       6       7       8       9      10

 1     146     129     120     121     124     124     126     127     122     122
 2     144     126     115     117     118     117     117     118     114     114
 3     144     132     114     114     110     113     111     121     108     110
 4     148     123     117     117     118     119     121     114     116     129

                             *---------------*
                              RUN NUMBER 5168
                                  SUMMARY
                             *---------------*

ST     RE        PR     X/D     MUB     MUW      TB      TW     DENS      NU

 1   3807.01    6.75    6.4    2.340   2.125   70.62   78.05   62.29    38.54
 2   3830.90    6.70   15.5    2.325   2.085   71.09   79.59   62.29    33.70
 3   3854.85    6.65   24.6    2.311   2.053   71.56   80.85   62.29    30.83
 4   3878.86    6.61   33.7    2.296   2.042   72.03   81.27   62.28    30.99
 5   3902.93    6.56   42.8    2.282   2.031   72.50   81.73   62.28    31.01
 6   3927.06    6.52   52.0    2.268   2.021   72.98   82.14   62.28    31.22
 7   3951.25    6.47   61.1    2.254   2.009   73.45   82.60   62.27    31.25
 8   3975.50    6.43   70.2    2.240   2.001   73.92   82.96   62.27    31.62
 9   3999.81    6.38   79.3    2.227   1.980   74.39   83.83   62.26    30.28
10   4024.18    6.34   88.4    2.213   1.975   74.86   84.04   62.26    31.14

                NOTE: TBULK IS GIVEN IN DEGREES FAHRENHEIT
                      MUB AND MUW ARE GIVEN IN LBM/(FT*HR)
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                  *----------------------------------------*
                              RUN NUMBER 5169
                        TEST FLUID IS DISTILLED WATER
                  *----------------------------------------*
                  VOLUMETRIC FLOW RATE =      1.76   GPM
                  MASS FLOW RATE       =     880.5   LBM/HR
                  MASS FLUX            =    134148   LBM/(SQ.FT-HR)
                  FLUID VELOCITY       =       .59   FT/S
                  ROOM TEMPERATURE     =     72.36   F
                  INLET TEMPERATURE    =     70.11   F
                  OUTLET TEMPERATURE   =     73.57   F
                  AVERAGE RE NUMBER    =      5326
                  AVERAGE PR NUMBER    =      6.63
                  CURRENT TO TUBE      =     313.6   AMPS
                  VOLTAGE DROP IN TUBE =      2.49   VOLTS
                  AVERAGE HEAT FLUX    =      1075   BTU/(SQ.FT-HR)
                  Q=AMP*VOLT           =      2664   BTU/HR
                  Q=M*C*(T2-T1)        =      3044   BTU/HR
                  HEAT BALANCE ERROR   =    -14.27   %

                    OUTSIDE SURFACE TEMPERATURES - DEGREES F

        1       2       3       4       5       6       7       8       9      10

 1    76.51   77.37   78.06   78.36   78.55   78.85   79.08   79.37   80.18   80.39
 2    76.53   77.20   78.09   78.30   78.65   78.97   79.22   79.47   80.24   80.52
 3    76.34   76.74   78.04   78.34   78.67   78.81   79.23   79.24   80.33   80.77
 4    76.31   77.35   78.05   78.31   78.67   78.83   79.13   79.83   80.16   79.82

                    INSIDE SURFACE TEMPERATURES - DEGREES F

        1       2       3       4       5       6       7       8       9      10

 1    75.93   76.79   77.48   77.78   77.97   78.27   78.50   78.79   79.60   79.81
 2    75.95   76.62   77.51   77.72   78.07   78.39   78.64   78.89   79.66   79.94
 3    75.76   76.15   77.46   77.76   78.09   78.23   78.65   78.66   79.75   80.20
 4    75.73   76.78   77.47   77.73   78.09   78.25   78.55   79.26   79.58   79.23

                    REYNOLDS NUMBER AT THE INSIDE TUBE WALL

        1       2       3       4       5       6       7       8       9      10

 1    5617    5679    5728    5750    5764    5785    5802    5823    5882    5898
 2    5618    5666    5731    5746    5771    5794    5812    5831    5887    5907
 3    5605    5633    5727    5749    5772    5783    5813    5813    5893    5926
 4    5602    5677    5728    5746    5772    5784    5806    5857    5881    5855

                      INSIDE SURFACE HEAT FLUXES BTU/HR/FT2

        1       2       3       4       5       6       7       8       9      10

 1     992     992     995     994     998     997     998    1003     997     991
 2     991     991     994     997     994     992     994     992     997     998
 3     996    1008     996     994     995     998     995    1006     994     982
 4     997     987     995     996     994     996     997     983     999    1016

                              *---------------*
                               RUN NUMBER 5169
                              *---------------*

               PERIPHERAL HEAT TRANSFER COEFFICIENT BTU/(SQ.FT-HR-F)

        1       2       3       4       5       6       7       8       9      10

 1     177     162     153     154     158     159     162     164     151     153
 2     176     166     152     156     155     155     157     159     149     151
 3     183     184     154     154     155     160     157     168     147     143
 4     185     161     154     155     154     159     160     149     151     172

                              *---------------*
                               RUN NUMBER 5169
                                   SUMMARY
                              *---------------*

ST      RE        PR     X/D     MUB     MUW      TB      TW     DENS      NU

 1    5222.29    6.77    6.4    2.348   2.186   70.34   75.84   62.30    47.69
 2    5245.48    6.74   15.5    2.338   2.165   70.68   76.59   62.29    44.39
 3    5268.70    6.71   24.6    2.328   2.141   71.01   77.48   62.29    40.54
 4    5291.97    6.67   33.7    2.317   2.133   71.34   77.75   62.29    40.94
 5    5315.28    6.64   42.8    2.307   2.125   71.67   78.06   62.29    41.09
 6    5338.63    6.61   52.0    2.297   2.119   72.01   78.29   62.28    41.75
 7    5362.02    6.58   61.1    2.287   2.111   72.34   78.59   62.28    41.96
 8    5385.45    6.55   70.2    2.277   2.103   72.67   78.90   62.28    42.08
 9    5408.92    6.51   79.3    2.267   2.083   73.00   79.65   62.28    39.44
10    5432.44    6.48   88.4    2.257   2.080   73.34   79.80   62.27    40.56

                     NOTE: TBULK IS GIVEN IN DEGREES FAHRENHEIT
                           MUB AND MUW ARE GIVEN IN LBM/(FT*HR)
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                    *-----------------------------------------*
                              RUN NUMBER 5105
                        TEST FLUID IS DISTILLED WATER
                    *-----------------------------------------*
                    VOLUMETRIC FLOW RATE =      1.73    GPM
                    MASS FLOW RATE       =     864.4    LBM/HR
                    MASS FLUX            =    131690    LBM/(SQ.FT-HR)
                    FLUID VELOCITY       =       .58    FT/S
                    ROOM TEMPERATURE     =     70.68    F
                    INLET TEMPERATURE    =     82.33    F
                    OUTLET TEMPERATURE   =     87.94    F
                    AVERAGE RE NUMBER    =      6176
                    AVERAGE PR NUMBER    =      5.50
                    CURRENT TO TUBE      =     415.0    AMPS
                    VOLTAGE DROP IN TUBE =      3.33    VOLTS
                    AVERAGE HEAT FLUX    =      1903    BTU/(SQ.FT-HR)
                    Q=AMP*VOLT           =      4715    BTU/HR
                    Q=M*C*(T2-T1)        =      4840    BTU/HR
                    HEAT BALANCE ERROR   =     -2.65    %


                      OUTSIDE SURFACE TEMPERATURES - DEGREES F

         1       2       3       4       5       6       7       8       9      10

  1    92.93   94.32   95.13   95.71   95.82   96.50   97.06   97.63   98.50   98.76
  2    93.06   94.83   95.68   95.95   96.55   97.37   97.89   98.41   99.14   99.76
  3    92.72   94.68   96.08   96.39   97.08   97.24   98.01   97.99   99.41   99.75
  4    92.39   94.69   95.55   96.33   96.31   97.23   97.55   98.17   99.09   99.27


                      INSIDE SURFACE TEMPERATURES - DEGREES F

         1       2       3       4       5       6       7       8       9      10

  1    91.92   93.30   94.11   94.69   94.79   95.47   96.03   96.60   97.47   97.73
  2    92.05   93.82   94.67   94.93   95.54   96.36   96.88   97.40   98.13   98.75
  3    91.70   93.66   95.07   95.38   96.07   96.22   97.00   96.97   98.40   98.74
  4    91.37   93.68   94.53   95.32   95.29   96.22   96.53   97.16   98.08   98.25


                      REYNOLDS NUMBER AT THE INSIDE TUBE WALL

         1       2       3       4       5       6       7       8       9      10

  1    6683    6788    6850    6894    6903    6955    6998    7042    7109    7129
  2    6693    6828    6893    6913    6959    7023    7063    7104    7160    7209
  3    6667    6816    6924    6947    7001    7012    7072    7070    7181    7207
  4    6641    6817    6882    6943    6941    7012    7036    7085    7156    7170


                        INSIDE SURFACE HEAT FLUXES BTU/HR/FT2

         1       2       3       4       5       6       7       8       9      10

  1    1757    1775    1778    1777    1782    1788    1785    1785    1786    1790
  2    1756    1756    1763    1768    1764    1754    1759    1753    1765    1757
  3    1762    1766    1753    1759    1750    1769    1760    1776    1762    1764
  4    1773    1759    1767    1759    1770    1758    1768    1759    1766    1770


                                *---------------*
                                 RUN NUMBER 5105
                                *---------------*

                PERIPHERAL HEAT TRANSFER COEFFICIENT BTU/(SQ.FT-HR-F)

         1       2       3       4       5       6       7       8       9      10

  1     190     176     172     171     179     177     176     176     170     176
  2     188     166     162     166     165     160     160     160     159     157
  3     195     169     155     159     156     163     159     169     154     157
  4     204     168     164     160     169     162     166     164     159     165


                                *---------------*
                                 RUN NUMBER 5105
                                     SUMMARY
                                *---------------*

 ST      RE       PR      X/D     MUB     MUW      TB       TW     DENS       NU

  1   5999.28    5.68     6.4   2.007   1.804   82.71   91.76   62.19     50.48
  2   6038.57    5.64    15.5   1.994   1.767   83.25   93.61   62.18     44.10
  3   6077.97    5.60    24.6   1.981   1.748   83.79   94.59   62.18     42.31
  4   6117.46    5.56    33.7   1.968   1.738   84.33   95.08   62.17     42.50
  5   6157.05    5.52    42.8   1.955   1.732   84.87   95.42   62.17     43.27
  6   6196.74    5.48    52.0   1.943   1.720   85.40   96.07   62.16     42.83
  7   6236.53    5.44    61.1   1.930   1.709   85.94   96.61   62.15     42.80
  8   6276.41    5.40    70.2   1.918   1.701   86.48   97.03   62.15     43.26
  9   6316.39    5.36    79.3   1.906   1.683   87.02   98.02   62.14     41.51
 10   6356.47    5.33    88.4   1.894   1.677   87.56   98.37   62.14     42.22

                      NOTE: TBULK IS GIVEN IN DEGREES FAHRENHEIT
                            MUB AND MUW ARE GIVEN IN LBM/(FT*HR)
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```
                    *-----------------------------------------*
                            RUN NUMBER 5172
                       TEST FLUID IS DISTILLED WATER
                    *-----------------------------------------*
                    VOLUMETRIC FLOW RATE =     2.20   GPM
                    MASS FLOW RATE       =   1097.3   LBM/HR
                    MASS FLUX            =   167185   LBM/(SQ.FT-HR)
                    FLUID VELOCITY       =      .74   FT/S
                    ROOM TEMPERATURE     =    75.28   F
                    INLET TEMPERATURE    =    71.93   F
                    OUTLET TEMPERATURE   =    76.81   F
                    AVERAGE RE NUMBER    =     6861
                    AVERAGE PR NUMBER    =     6.39
                    CURRENT TO TUBE      =    449.5   AMPS
                    VOLTAGE DROP IN TUBE =     3.58   VOLTS
                    AVERAGE HEAT FLUX    =     2216   BTU/(SQ.FT-HR)
                    Q=AMP*VOLT           =     5490   BTU/HR
                    Q=M*C*(T2-T1)        =     5349   BTU/HR
                    HEAT BALANCE ERROR   =     2.57   %

                     OUTSIDE SURFACE TEMPERATURES - DEGREES F

        1       2       3       4       5       6       7       8       9      10

 1    82.27   83.49   84.35   84.85   85.13   85.60   86.01   86.55   86.96   87.52
 2    82.22   83.38   84.44   84.81   85.30   85.82   86.29   86.75   87.69   88.19
 3    81.47   83.42   84.55   84.99   85.47   85.76   86.33   86.66   87.38   88.10
 4    81.70   83.38   84.39   84.79   85.26   85.68   86.10   87.00   87.59   87.32

                     INSIDE SURFACE TEMPERATURES - DEGREES F

        1       2       3       4       5       6       7       8       9      10

 1    81.09   82.30   83.16   83.66   83.94   84.41   84.82   85.36   85.76   86.33
 2    81.04   82.19   83.25   83.62   84.11   84.63   85.10   85.56   86.51   87.01
 3    80.27   82.23   83.36   83.80   84.28   84.57   85.14   85.47   86.19   86.92
 4    80.51   82.19   83.20   83.60   84.07   84.49   84.91   85.82   86.41   86.12

                     REYNOLDS NUMBER AT THE INSIDE TUBE WALL

        1       2       3       4       5       6       7       8       9      10

 1    7467    7578    7658    7704    7730    7773    7812    7862    7900    7953
 2    7462    7568    7666    7700    7746    7794    7838    7881    7970    8017
 3    7392    7572    7676    7717    7762    7789    7842    7872    7940    8008
 4    7414    7568    7661    7698    7742    7781    7820    7905    7960    7934

                        INSIDE SURFACE HEAT FLUXES BTU/HR/FT2

        1       2       3       4       5       6       7       8       9      10

 1    2043    2050    2056    2054    2060    2060    2062    2066    2076    2066
 2    2042    2055    2055    2058    2056    2053    2054    2054    2046    2049
 3    2063    2052    2051    2050    2051    2056    2054    2063    2065    2051
 4    2055    2055    2056    2058    2057    2056    2059    2048    2048    2072

                                 *---------------*
                                  RUN NUMBER 5172
                                 *---------------*

              PERIPHERAL HEAT TRANSFER COEFFICIENT BTU/(SQ.FT-HR-F)

        1       2       3       4       5       6       7       8       9      10

 1     231     214     206     205     210     210     211     210     213     209
 2     232     217     204     206     206     204     204     205     194     194
 3     257     215     201     202     202     206     204     207     203     196
 4     249     217     205     207     207     208     209     199     197     214

                                 *---------------*
                                  RUN NUMBER 5172
                                      SUMMARY
                                 *---------------*

ST      RE       PR     X/D     MUB     MUW      TB      TW     DENS     NU

 1   6675.45    6.58     6.4   2.290   2.056   72.26   80.73   62.28   63.74
 2   6716.63    6.54    15.5   2.275   2.018   72.73   82.23   62.28   56.83
 3   6757.92    6.50    24.6   2.262   1.994   73.20   83.24   62.27   53.75
 4   6799.30    6.45    33.7   2.248   1.983   73.67   83.67   62.27   53.95
 5   6840.79    6.41    42.8   2.234   1.973   74.14   84.10   62.27   54.15
 6   6882.38    6.36    52.0   2.221   1.963   74.60   84.53   62.26   54.37
 7   6924.08    6.32    61.1   2.207   1.952   75.07   84.99   62.26   54.36
 8   6965.87    6.28    70.2   2.194   1.939   75.54   85.55   62.25   53.87
 9   7007.76    6.24    79.3   2.181   1.924   76.01   86.22   62.25   52.82
10   7049.75    6.20    88.4   2.168   1.916   76.48   86.59   62.25   53.29

                  NOTE: TBULK IS GIVEN IN DEGREES FAHRENHEIT
                        MUB AND MUW ARE GIVEN IN LBM/(FT*HR)
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                    *----------------------------------------*
                               RUN NUMBER 2115
                         TEST FLUID IS DISTILLED WATER
                    *----------------------------------------*
                    VOLUMETRIC FLOW RATE =      2.16   GPM
                    MASS FLOW RATE       =    1077.4   LBM/HR
                    MASS FLUX            =    164144   LBM/(SQ.FT-HR)
                    FLUID VELOCITY       =       .73   FT/S
                    ROOM TEMPERATURE     =     78.07   F
                    INLET TEMPERATURE    =     90.28   F
                    OUTLET TEMPERATURE   =     94.00   F
                    AVERAGE RE NUMBER    =      8351
                    AVERAGE PR NUMBER    =      5.02
                    CURRENT TO TUBE      =     390.0   AMPS
                    VOLTAGE DROP IN TUBE =      3.13   VOLTS
                    AVERAGE HEAT FLUX    =      1681   BTU/(SQ.FT-HR)
                    Q=AMP*VOLT           =      4165   BTU/HR
                    Q=M*C*(T2-T1)        =      3999   BTU/HR
                    HEAT BALANCE ERROR   =      3.98   %

                     OUTSIDE SURFACE TEMPERATURES - DEGREES F

         1       2       3       4       5       6       7       8       9      10

 1    97.30   98.57   99.30   99.89   99.92  100.72  101.14  101.60  102.29  102.57
 2    97.47   98.86   99.55   99.69  100.25  100.87  101.40  101.83  102.53  102.89
 3    96.79   97.79   99.57  100.11  100.64  100.88  101.63  101.64  102.84  103.07
 4    96.93   98.47   99.24  100.08  100.13  101.01  101.10  101.83  102.53  102.51

                     INSIDE SURFACE TEMPERATURES - DEGREES F

         1       2       3       4       5       6       7       8       9      10

 1    96.40   97.67   98.40   98.99   99.02   99.82  100.24  100.70  101.39  101.67
 2    96.58   97.97   98.65   98.79   99.35   99.97  100.50  100.93  101.63  101.99
 3    95.89   96.88   98.67   99.21   99.75   99.98  100.74  100.74  101.95  102.18
 4    96.03   97.58   98.34   99.18   99.23  100.11  100.20  100.93  101.63  101.61

                     REYNOLDS NUMBER AT THE INSIDE TUBE WALL

         1       2       3       4       5       6       7       8       9      10

 1     8758    8880    8951    9009    9011    9089    9130    9175    9243    9270
 2     8775    8910    8976    8989    9044    9104    9156    9198    9267    9302
 3     8708    8804    8978    9030    9082    9105    9179    9179    9298    9320
 4     8722    8871    8945    9027    9032    9118    9126    9198    9267    9264

                       INSIDE SURFACE HEAT FLUXES BTU/HR/FT2

         1       2       3       4       5       6       7       8       9      10

 1     1558    1565    1566    1564    1571    1571    1568    1572    1573    1571
 2     1550    1545    1560    1572    1565    1563    1565    1560    1568    1565
 3     1571    1585    1559    1558    1553    1566    1556    1571    1559    1558
 4     1564    1555    1568    1562    1568    1560    1573    1560    1568    1575

                                  *---------------*
                                  RUN NUMBER 2115
                                  *---------------*

                PERIPHERAL HEAT TRANSFER COEFFICIENT BTU/(SQ.FT-HR-F)

         1       2       3       4       5       6       7       8       9      10

 1      265     230     218     211     222     209     207     205     196     198
 2      256     218     210     218     211     204     200     197     190     189
 3      293     264     209     204     199     204     193     203     182     184
 4      284     232     221     206     215     200     209     197     190     200

                                  *---------------*
                                  RUN NUMBER 2115
                                      SUMMARY
                                  *---------------*

ST      RE       PR     X/D     MUB     MUW      TB      TW     DENS      NU

 1   8199.97   5.13     6.4   1.830   1.717   90.53   96.22   62.10   70.36
 2   8233.60   5.10    15.5   1.822   1.692   90.89   97.52   62.10   60.40
 3   8267.28   5.08    24.6   1.815   1.674   91.25   98.52   62.10   55.14
 4   8301.01   5.06    33.7   1.808   1.665   91.60   99.04   62.09   53.88
 5   8334.79   5.03    42.8   1.800   1.659   91.96   99.34   62.09   54.34
 6   8368.63   5.01    52.0   1.793   1.648   92.32   99.97   62.08   52.38
 7   8402.51   4.99    61.1   1.786   1.640   92.68  100.42   62.08   51.76
 8   8436.45   4.97    70.2   1.779   1.633   93.03  100.83   62.08   51.42
 9   8470.44   4.94    79.3   1.772   1.619   93.39  101.65   62.07   48.53
10   8504.48   4.92    88.4   1.764   1.615   93.75  101.86   62.07   49.39

                     NOTE: TBULK IS GIVEN IN DEGREES FAHRENHEIT
                           MUB AND MUW ARE GIVEN IN LBM/(FT*HR)
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                    *---------------------------------------*
                              RUN NUMBER 5170
                        TEST FLUID IS DISTILLED WATER
                    *---------------------------------------*
                    VOLUMETRIC FLOW RATE =      2.75   GPM
                    MASS FLOW RATE       =    1375.7   LBM/HR
                    MASS FLUX            =    209590   LBM/(SQ.FT-HR)
                    FLUID VELOCITY       =       .93   FT/S
                    ROOM TEMPERATURE     =     73.75   F
                    INLET TEMPERATURE    =     71.06   F
                    OUTLET TEMPERATURE   =     75.29   F
                    AVERAGE RE NUMBER    =      8469
                    AVERAGE PR NUMBER    =      6.50
                    CURRENT TO TUBE      =     437.7   AMPS
                    VOLTAGE DROP IN TUBE =      3.48   VOLTS
                    AVERAGE HEAT FLUX    =      2098   BTU/(SQ.FT-HR)
                    Q=AMP*VOLT           =      5197   BTU/HR
                    Q=M*C*(T2-T1)        =      5813   BTU/HR
                    HEAT BALANCE ERROR   =    -11.87   %

                      OUTSIDE SURFACE TEMPERATURES - DEGREES F

        1       2       3       4       5       6       7       8       9       10

 1    79.95   80.74   81.26   81.66   81.89   82.28   82.61   82.99   83.83   84.22
 2    79.87   80.81   81.27   81.51   81.92   82.28   82.64   83.04   83.89   84.29
 3    79.81   80.81   81.32   81.47   81.95   82.13   82.61   82.83   84.03   84.58
 4    79.43   80.70   81.22   81.58   81.93   82.28   82.51   83.30   83.80   83.51

                      INSIDE SURFACE TEMPERATURES - DEGREES F

        1       2       3       4       5       6       7       8       9       10

 1    78.83   79.61   80.13   80.54   80.76   81.15   81.48   81.86   82.70   83.10
 2    78.74   79.68   80.14   80.38   80.79   81.15   81.51   81.91   82.76   83.16
 3    78.69   79.68   80.19   80.34   80.82   81.00   81.48   81.70   82.91   83.46
 4    78.30   79.57   80.09   80.45   80.80   81.15   81.38   82.18   82.67   82.37

                      REYNOLDS NUMBER AT THE INSIDE TUBE WALL

        1       2       3       4       5       6       7       8       9       10

 1    9103    9192    9251    9297    9323    9368    9406    9450    9547    9593
 2    9093    9200    9252    9280    9327    9368    9410    9456    9554    9600
 3    9086    9200    9258    9275    9330    9351    9406    9431    9570    9635
 4    9042    9187    9247    9288    9328    9368    9395    9486    9543    9509

                        INSIDE SURFACE HEAT FLUXES BTU/HR/FT2

        1       2       3       4       5       6       7       8       9       10

 1    1934    1943    1943    1941    1945    1945    1944    1950    1947    1939
 2    1941    1942    1944    1945    1944    1943    1944    1942    1948    1950
 3    1937    1941    1941    1946    1944    1949    1944    1954    1942    1930
 4    1953    1944    1945    1943    1944    1943    1948    1936    1950    1970

                                  *---------------*
                                   RUN NUMBER 5170
                                  *---------------*

                 PERIPHERAL HEAT TRANSFER COEFFICIENT BTU/(SQ.FT-HR-F)

        1       2       3       4       5       6       7       8       9       10

 1     258     247     243     243     249     250     252     254     240     239
 2     262     244     243     248     248     249     251     251     238     239
 3     263     244     241     250     247     255     252     260     233     228
 4     280     248     245     246     248     249     256     242     241     267

                                  *---------------*
                                   RUN NUMBER 5170
                                       SUMMARY
                                  *---------------*

ST      RE        PR     X/D     MUB     MUW      TB      TW     DENS      NU

 1    8268.46    6.67     6.4   2.317   2.110   71.34   78.64   62.29    70.14
 2    8312.98    6.63    15.5   2.305   2.084   71.75   79.64   62.29    64.87
 3    8357.61    6.59    24.6   2.293   2.071   72.16   80.14   62.28    64.08
 4    8402.33    6.56    33.7   2.280   2.063   72.56   80.43   62.28    65.03
 5    8447.15    6.52    42.8   2.268   2.054   72.97   80.80   62.28    65.33
 6    8492.07    6.48    52.0   2.256   2.046   73.38   81.12   62.27    66.04
 7    8537.08    6.44    61.1   2.244   2.037   73.79   81.47   62.27    66.51
 8    8582.18    6.40    70.2   2.233   2.026   74.19   81.91   62.27    66.14
 9    8627.38    6.36    79.3   2.221   2.005   74.60   82.76   62.26    62.58
10    8672.68    6.33    88.4   2.209   1.999   75.01   83.02   62.26    63.68

                       NOTE: TBULK IS GIVEN IN DEGREES FAHRENHEIT
                             MUB AND MUW ARE GIVEN IN LBM/(FT*HR)
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                    *----------------------------------------*
                           RUN NUMBER  604
                      TEST FLUID IS DISTILLED WATER
                    *----------------------------------------*
                    VOLUMETRIC FLOW RATE =      2.62   GPM
                    MASS FLOW RATE       =    1308.6   LBM/HR
                    MASS FLUX            =    199378   LBM/(SQ.FT-HR)
                    FLUID VELOCITY       =       .88   FT/S
                    ROOM TEMPERATURE     =     72.56   F
                    INLET TEMPERATURE    =     79.27   F
                    OUTLET TEMPERATURE   =     80.43   F
                    AVERAGE RE NUMBER    =      8770
                    AVERAGE PR NUMBER    =      5.91
                    CURRENT TO TUBE      =     215.0   AMPS
                    VOLTAGE DROP IN TUBE =      1.71   VOLTS
                    AVERAGE HEAT FLUX    =       506   BTU/(SQ.FT-HR)
                    Q=AMP*VOLT           =      1254   BTU/HR
                    Q=M*C*(T2-T1)        =      1515   BTU/HR
                    HEAT BALANCE ERROR   =    -20.83   \

                     OUTSIDE SURFACE TEMPERATURES - DEGREES F

          1       2       3       4       5       6       7       8       9      10

  1     81.75   81.91   82.07   82.21   82.21   82.35   82.40   82.45   82.83   82.94
  2     81.70   81.86   82.10   82.11   82.25   82.33   82.43   82.42   82.80   82.91
  3     81.52   81.69   82.07   81.99   82.19   82.14   82.28   82.16   82.82   83.12
  4     81.57   81.91   82.08   82.26   82.28   82.38   82.37   82.62   82.82   82.56

                     INSIDE SURFACE TEMPERATURES - DEGREES F

          1       2       3       4       5       6       7       8       9      10

  1     81.48   81.64   81.80   81.94   81.94   82.08   82.13   82.18   82.56   82.67
  2     81.43   81.59   81.83   81.84   81.98   82.06   82.16   82.15   82.53   82.64
  3     81.25   81.42   81.80   81.72   81.92   81.87   82.01   81.88   82.55   82.85
  4     81.30   81.64   81.81   81.99   82.01   82.11   82.10   82.35   82.55   82.26

                     REYNOLDS NUMBER AT THE INSIDE TUBE WALL

          1       2       3       4       5       6       7       8       9      10

  1     8947    8965    8982    8998    8998    9013    9019    9024    9066    9078
  2     8942    8959    8986    8987    9002    9011    9022    9021    9063    9075
  3     8922    8940    8982    8973    8995    8990    9005    8992    9065    9098
  4     8928    8965    8983    9003    9006    9017    9015    9043    9065    9035

                       INSIDE SURFACE HEAT FLUXES BTU/HR/FT2

          1       2       3       4       5       6       7       8       9      10

  1      466     468     470     468     470     469     469     471     469     464
  2      467     467     468     469     468     467     467     466     470     472
  3      471     474     470     474     471     474     472     478     469     460
  4      470     466     469     465     467     466     468     461     469     481

                                *---------------*
                                RUN NUMBER  604
                                *---------------*

                 PERIPHERAL HEAT TRANSFER COEFFICIENT BTU/(SQ.FT-HR-F)

          1       2       3       4       5       6       7       8       9      10

  1      218     215     211     207     219     216     222     230     202     200
  2      224     219     207     217     214     217     218     230     205     206
  3      248     242     211     233     222     242     237     272     203     183
  4      241     214     209     201     211     211     225     207     203     249

                                *---------------*
                                RUN NUMBER  604
                                    SUMMARY
                                *---------------*

ST     RE        PR     X/D     MUB     MUW      TB      TW      DENS      NU

 1   8715.75    5.95     6.4   2.091   2.040   79.35   81.36   62.22    60.66
 2   8727.85    5.94    15.5   2.088   2.035   79.46   81.57   62.22    57.91
 3   8739.95    5.93    24.6   2.085   2.029   79.57   81.81   62.22    54.66
 4   8752.05    5.92    33.7   2.083   2.027   79.68   81.87   62.22    55.87
 5   8764.16    5.91    42.8   2.080   2.025   79.79   81.96   62.22    56.42
 6   8776.28    5.90    52.0   2.077   2.023   79.91   82.03   62.21    57.59
 7   8788.41    5.90    61.1   2.074   2.022   80.02   82.10   62.21    58.74
 8   8800.54    5.89    70.2   2.071   2.021   80.13   82.14   62.21    60.74
 9   8812.68    5.88    79.3   2.068   2.011   80.24   82.55   62.21    53.01
10   8824.82    5.87    88.4   2.065   2.009   80.35   82.61   62.21    54.11

                      NOTE: TBULK IS GIVEN IN DEGREES FAHRENHEIT
                            MUB AND MUW ARE GIVEN IN LBM/(FT*HR)
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                    *----------------------------------------*
                               RUN NUMBER  606
                         TEST FLUID IS DISTILLED WATER
                    *----------------------------------------*
                    VOLUMETRIC FLOW RATE =      2.62   GPM
                    MASS FLOW RATE       =    1308.5   LBM/HR
                    MASS FLUX            =    199364   LBM/(SQ.FT-HR)
                    FLUID VELOCITY       =       .88   FT/S
                    ROOM TEMPERATURE     =     72.57   F
                    INLET TEMPERATURE    =     79.73   F
                    OUTLET TEMPERATURE   =     81.46   F
                    AVERAGE RE NUMBER    =      8850
                    AVERAGE PR NUMBER    =      5.85
                    CURRENT TO TUBE      =     265.0   AMPS
                    VOLTAGE DROP IN TUBE =      2.11   VOLTS
                    AVERAGE HEAT FLUX    =       770   BTU/(SQ.FT-HR)
                    Q=AMP*VOLT           =      1907   BTU/HR
                    Q=M*C*(T2-T1)        =      2260   BTU/HR
                    HEAT BALANCE ERROR   =    -18.47   %

                     OUTSIDE SURFACE TEMPERATURES - DEGREES F

       1       2       3       4       5       6       7       8       9      10

1    83.37   83.64   83.88   84.06   84.14   84.28   84.40   84.50   84.93   85.06
2    83.31   83.61   83.92   83.94   84.14   84.28   84.44   84.49   84.88   85.03
3    83.07   83.42   83.83   83.79   84.06   84.06   84.33   84.25   84.92   85.14
4    83.09   83.61   83.84   84.10   84.14   84.32   84.36   84.63   84.89   84.68

                     INSIDE SURFACE TEMPERATURES - DEGREES F

       1       2       3       4       5       6       7       8       9      10

1    82.96   83.23   83.47   83.65   83.73   83.87   83.99   84.09   84.52   84.65
2    82.90   83.20   83.51   83.53   83.73   83.87   84.03   84.08   84.47   84.62
3    82.66   83.00   83.42   83.37   83.65   83.64   83.92   83.83   84.51   84.73
4    82.68   83.20   83.43   83.69   83.73   83.91   83.95   84.22   84.48   84.26

                     REYNOLDS NUMBER AT THE INSIDE TUBE WALL

       1       2       3       4       5       6       7       8       9      10

1     9109    9139    9165    9185    9194    9210    9223    9234    9282    9297
2     9103    9136    9170    9172    9194    9210    9228    9233    9276    9293
3     9076    9114    9160    9155    9185    9185    9215    9206    9281    9306
4     9078    9136    9161    9190    9194    9214    9219    9249    9277    9253

                       INSIDE SURFACE HEAT FLUXES BTU/HR/FT2

       1       2       3       4       5       6       7       8       9      10

1      709     713     714     713     714     714     714     715     713     709
2      711     711     712     713     713     711     712     711     715     716
3      716     718     715     719     716     720     716     722     713     707
4      716     711     714     709     713     710     714     708     715     725

                                *---------------*
                                 RUN NUMBER  606
                                *---------------*

               PERIPHERAL HEAT TRANSFER COEFFICIENT BTU/(SQ.FT-HR-F)

       1       2       3       4       5       6       7       8       9      10

1      227     221     217     215     222     224     227     232     213     214
2      233     223     214     224     221     223     223     231     217     218
3      255     240     220     237     228     242     233     255     214     208
4      253     223     220     212     221     219     230     220     216     248

                                *---------------*
                                 RUN NUMBER  606
                                     SUMMARY
                                *---------------*

ST      RE       PR     X/D     MUB     MUW      TB      TW      DENS      NU

 1    8769.22   5.91    6.4   2.078   2.005   79.85   82.80   62.21   62.98
 2    8787.30   5.90   15.5   2.074   1.996   80.01   83.16   62.21   59.10
 3    8805.40   5.88   24.6   2.070   1.989   80.18   83.45   62.21   56.73
 4    8823.50   5.87   33.7   2.066   1.986   80.35   83.56   62.21   57.81
 5    8841.63   5.86   42.8   2.061   1.983   80.51   83.71   62.21   58.14
 6    8859.77   5.84   52.0   2.057   1.980   80.68   83.82   62.21   59.08
 7    8877.92   5.83   61.1   2.053   1.976   80.84   83.97   62.21   59.43
 8    8896.08   5.82   70.2   2.049   1.974   81.01   84.05   62.20   61.01
 9    8914.26   5.80   79.3   2.045   1.964   81.18   84.49   62.20   56.02
10    8932.46   5.79   88.4   2.040   1.962   81.34   84.56   62.20   57.65

                     NOTE: TBULK IS GIVEN IN DEGREES FAHRENHEIT
                           MUB AND MUW ARE GIVEN IN LBM/(FT*HR)
```

```
           *----------------------------------------*
                     RUN NUMBER  606
                 TEST FLUID IS DISTILLED WATER
           *----------------------------------------*
           VOLUMETRIC FLOW RATE =     2.62   GPM
           MASS FLOW RATE       =   1308.5   LBM/HR
           MASS FLUX            =   199364   LBM/(SQ.FT-HR)
           FLUID VELOCITY       =      .88   FT/S
           ROOM TEMPERATURE     =    72.57   F
           INLET TEMPERATURE    =    79.73   F
           OUTLET TEMPERATURE   =    81.46   F
           AVERAGE RE NUMBER    =     8850
           AVERAGE PR NUMBER    =     5.85
           CURRENT TO TUBE      =    265.0   AMPS
           VOLTAGE DROP IN TUBE =     2.11   VOLTS
           AVERAGE HEAT FLUX    =      770   BTU/(SQ.FT-HR)
           Q=AMP*VOLT           =     1907   BTU/HR
           Q=M*C*(T2-T1)        =     2260   BTU/HR
           HEAT BALANCE ERROR   =   -18.47   %

             OUTSIDE SURFACE TEMPERATURES - DEGREES F

        1       2       3       4       5       6       7       8       9      10

 1    83.37   83.64   83.88   84.06   84.14   84.28   84.40   84.50   84.93   85.06
 2    83.31   83.61   83.92   83.94   84.14   84.28   84.44   84.49   84.88   85.03
 3    83.07   83.42   83.83   83.79   84.06   84.06   84.33   84.25   84.92   85.14
 4    83.09   83.61   83.84   84.10   84.14   84.32   84.36   84.63   84.89   84.68

             INSIDE SURFACE TEMPERATURES - DEGREES F

        1       2       3       4       5       6       7       8       9      10

 1    82.96   83.23   83.47   83.65   83.73   83.87   83.99   84.09   84.52   84.65
 2    82.90   83.20   83.51   83.53   83.73   83.87   84.03   84.08   84.47   84.62
 3    82.66   83.00   83.42   83.37   83.65   83.64   83.92   83.83   84.51   84.73
 4    82.68   83.20   83.43   83.69   83.73   83.91   83.95   84.22   84.48   84.26

             REYNOLDS NUMBER AT THE INSIDE TUBE WALL

        1       2       3       4       5       6       7       8       9      10

 1     9109    9139    9165    9185    9194    9210    9223    9234    9282    9297
 2     9103    9136    9170    9172    9194    9210    9228    9233    9276    9293
 3     9076    9114    9160    9155    9185    9185    9215    9206    9281    9306
 4     9078    9136    9161    9190    9194    9214    9219    9249    9277    9253

               INSIDE SURFACE HEAT FLUXES BTU/HR/FT2

        1       2       3       4       5       6       7       8       9      10

 1      709     713     714     713     714     714     714     715     713     709
 2      711     711     712     713     713     711     712     711     715     716
 3      716     718     715     719     716     720     716     722     713     707
 4      716     711     714     709     713     710     714     708     715     725

                          *---------------*
                          RUN NUMBER  606
                          *---------------*

        PERIPHERAL HEAT TRANSFER COEFFICIENT BTU/(SQ.FT-HR-F)

        1       2       3       4       5       6       7       8       9      10

 1      227     221     217     215     222     224     227     232     213     214
 2      233     223     214     224     221     223     223     231     217     218
 3      255     240     220     237     228     242     233     255     214     208
 4      253     223     220     212     221     219     230     220     216     248

                          *---------------*
                          RUN NUMBER  606
                             SUMMARY
                          *---------------*

ST     RE        PR     X/D    MUB     MUW     TB      TW     DENS      NU

 1   8769.22   5.91     6.4   2.078   2.005   79.85   82.80   62.21    62.98
 2   8787.30   5.90    15.5   2.074   1.996   80.01   83.16   62.21    59.10
 3   8805.40   5.88    24.6   2.070   1.989   80.18   83.45   62.21    56.73
 4   8823.50   5.87    33.7   2.066   1.986   80.35   83.56   62.21    57.81
 5   8841.63   5.86    42.8   2.061   1.983   80.51   83.71   62.21    58.14
 6   8859.77   5.84    52.0   2.057   1.980   80.68   83.82   62.21    59.08
 7   8877.92   5.83    61.1   2.053   1.976   80.84   83.97   62.21    59.43
 8   8896.08   5.82    70.2   2.049   1.974   81.01   84.05   62.20    61.01
 9   8914.26   5.80    79.3   2.045   1.964   81.18   84.49   62.20    56.02
10   8932.46   5.79    88.4   2.040   1.962   81.34   84.56   62.20    57.65

             NOTE: TBULK IS GIVEN IN DEGREES FAHRENHEIT
                   MUB AND MUW ARE GIVEN IN LBM/(FT*HR)
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                       *----------------------------------------*
                                 RUN NUMBER  607
                             TEST FLUID IS DISTILLED WATER
                       *----------------------------------------*
                       VOLUMETRIC FLOW RATE =     2.62   GPM
                       MASS FLOW RATE       =   1308.5   LBM/HR
                       MASS FLUX            =   199352   LBM/(SQ.FT-HR)
                       FLUID VELOCITY       =      .88   FT/S
                       ROOM TEMPERATURE     =    72.96   F
                       INLET TEMPERATURE    =    80.13   F
                       OUTLET TEMPERATURE   =    83.68   F
                       AVERAGE RE NUMBER    =     8993
                       AVERAGE PR NUMBER    =     5.74
                       CURRENT TO TUBE      =    392.0   AMPS
                       VOLTAGE DROP IN TUBE =     3.13   VOLTS
                       AVERAGE HEAT FLUX    =     1690   BTU/(SQ.FT-HR)
                       Q=AMP*VOLT           =     4186   BTU/HR
                       Q=M*C*(T2-T1)        =     4637   BTU/HR
                       HEAT BALANCE ERROR   =   -10.77   %


                         OUTSIDE SURFACE TEMPERATURES - DEGREES F

        1        2        3        4        5        6        7        8        9       10

 1    87.62    88.79    89.05    89.54    89.50    90.13    90.35    90.63    91.22    91.32
 2    87.94    88.76    89.31    89.40    89.71    90.24    90.56    90.99    91.34    91.76
 3    87.47    88.50    89.10    89.47    89.87    89.94    90.63    90.49    91.57    91.79
 4    87.20    88.59    89.12    89.73    89.60    90.25    90.27    90.79    91.40    91.46

                         INSIDE SURFACE TEMPERATURES - DEGREES F

        1        2        3        4        5        6        7        8        9       10

 1    86.72    87.89    88.14    88.63    88.59    89.22    89.44    89.72    90.31    90.41
 2    87.04    87.86    88.41    88.49    88.81    89.34    89.66    90.09    90.43    90.86
 3    86.56    87.59    88.19    88.56    88.97    89.03    89.73    89.58    90.67    90.89
 4    86.29    87.68    88.22    88.83    88.69    89.35    89.36    89.89    90.49    90.55

                         REYNOLDS NUMBER AT THE INSIDE TUBE WALL

        1        2        3        4        5        6        7        8        9       10

 1    9527     9658     9687     9743     9738     9810     9835     9866     9933     9945
 2    9563     9655     9717     9727     9762     9823     9859     9908     9947     9996
 3    9510     9625     9693     9735     9781     9788     9867     9850     9974     9999
 4    9479     9636     9696     9765     9750     9824     9825     9885     9954     9961

                           INSIDE SURFACE HEAT FLUXES BTU/HR/FT2

        1        2        3        4        5        6        7        8        9       10

 1    1565     1564     1572     1569     1572     1572     1571     1576     1574     1578
 2    1556     1564     1562     1571     1568     1564     1568     1559     1572     1565
 3    1569     1572     1571     1571     1563     1577     1564     1580     1565     1566
 4    1575     1569     1567     1562     1570     1563     1575     1564     1570     1573

                                    *---------------*
                                     RUN NUMBER  607
                                    *---------------*

                    PERIPHERAL HEAT TRANSFER COEFFICIENT BTU/(SQ.FT-HR-F)

        1        2        3        4        5        6        7        8        9       10

 1     246      218      221      216      229      219      223      226      218      226
 2     233      218      212      221      221      215      216      212      214      211
 3     253      228      219      219      216      226      213      231      206      210
 4     266      225      218      210      225      215      226      219      212      221

                                    *---------------*
                                     RUN NUMBER  607
                                         SUMMARY
                                    *---------------*

ST      RE        PR      X/D     MUB      MUW      TB       TW      DENS      NU

 1    8825.52    5.87     6.4    2.065    1.914    80.37    86.65    62.21    64.85
 2    8862.73    5.84    15.5    2.056    1.890    80.71    87.75    62.21    57.87
 3    8900.00    5.81    24.6    2.048    1.879    81.05    88.24    62.20    56.70
 4    8937.33    5.79    33.7    2.039    1.871    81.39    88.63    62.20    56.31
 5    8974.72    5.76    42.8    2.031    1.868    81.73    88.76    62.20    57.94
 6    9012.17    5.73    52.0    2.022    1.857    82.08    89.23    62.19    56.90
 7    9049.68    5.70    61.1    2.014    1.851    82.42    89.55    62.19    57.11
 8    9087.25    5.68    70.2    2.005    1.845    82.76    89.82    62.19    57.65
 9    9124.88    5.65    79.3    1.997    1.831    83.10    90.48    62.18    55.19
10    9162.58    5.63    88.4    1.989    1.827    83.44    90.68    62.18    56.25

                         NOTE: TBULK IS GIVEN IN DEGREES FAHRENHEIT
                               MUB AND MUW ARE GIVEN IN LBM/(FT*HR)
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                *-----------------------------------------*
                          RUN NUMBER  608
                     TEST FLUID IS DISTILLED WATER
                *-----------------------------------------*
                VOLUMETRIC FLOW RATE =     2.62   GPM
                MASS FLOW RATE       =   1308.3   LBM/HR
                MASS FLUX            =   199333   LBM/(SQ.FT-HR)
                FLUID VELOCITY       =      .88   FT/S
                ROOM TEMPERATURE     =    73.32   F
                INLET TEMPERATURE    =    80.74   F
                OUTLET TEMPERATURE   =    87.07   F
                AVERAGE RE NUMBER    =     9213
                AVERAGE PR NUMBER    =     5.59
                CURRENT TO TUBE      =    535.0   AMPS
                VOLTAGE DROP IN TUBE =     4.29   VOLTS
                AVERAGE HEAT FLUX    =     3161   BTU/(SQ.FT-HR)
                Q=AMP*VOLT           =     7831   BTU/HR
                Q=M*C*(T2-T1)        =     8267   BTU/HR
                HEAT BALANCE ERROR   =    -5.57   %


                  OUTSIDE SURFACE TEMPERATURES - DEGREES F

        1       2       3       4       5       6       7       8       9      10

1     93.99   95.63   96.36   97.01   97.01   97.88   98.40   98.97   99.78  100.26
2     94.21   96.01   96.72   96.94   97.56   98.30   98.89   99.53  100.20  100.90
3     93.67   95.70   96.86   97.19   97.87   98.23   99.10   99.25  100.59  101.33
4     93.24   95.59   96.49   97.23   97.37   98.22   98.53   99.30  100.04  100.34


                  INSIDE SURFACE TEMPERATURES - DEGREES F

        1       2       3       4       5       6       7       8       9      10

1     92.31   93.94   94.67   95.32   95.31   96.18   96.71   97.27   98.08   98.56
2     92.53   94.33   95.03   95.25   95.87   96.61   97.20   97.85   98.51   99.21
3     91.98   94.01   95.18   95.50   96.19   96.54   97.42   97.56   98.91   99.65
4     91.54   93.90   94.80   95.54   95.68   96.53   96.84   97.61   98.35   98.64


                  REYNOLDS NUMBER AT THE INSIDE TUBE WALL

        1       2       3       4       5       6       7       8       9      10

1     10161   10349   10434   10509   10509   10610   10671   10738   10833   10889
2     10186   10394   10476   10501   10574   10660   10729   10805   10883   10966
3     10123   10357   10493   10531   10610   10652   10754   10771   10930   11018
4     10073   10345   10449   10535   10551   10651   10687   10778   10864   10899


                    INSIDE SURFACE HEAT FLUXES BTU/HR/FT2

        1       2       3       4       5       6       7       8       9      10

1      2923    2938    2942    2939    2950    2949    2949    2953    2953    2954
2      2920    2925    2933    2941    2934    2933    2936    2931    2943    2942
3      2932    2937    2929    2934    2927    2940    2930    2946    2931    2926
4      2946    2936    2939    2933    2940    2935    2946    2937    2947    2957


                              *---------------*
                              RUN NUMBER   608
                              *---------------*

           PERIPHERAL HEAT TRANSFER COEFFICIENT BTU/(SQ.FT-HR-F)

        1       2       3       4       5       6       7       8       9      10

1      262     241     239     238     251     246     248     249     245     247
2      257     233     231     240     239     236     237     235     235     234
3      271     240     229     234     232     238     232     242     227     224
4      283     242     236     233     243     238     245     241     239     246


                              *---------------*
                              RUN NUMBER   608
                                  SUMMARY
                              *---------------*

ST     RE        PR      X/D     MUB      MUW      TB       TW      DENS      NU

 1   8911.67    5.80     6.4    2.045    1.798    81.17    92.09    62.20    69.71
 2   8978.30    5.75    15.5    2.030    1.759    81.77    94.04    62.20    62.10
 3   9045.13    5.71    24.6    2.015    1.742    82.38    94.92    62.19    60.77
 4   9112.15    5.66    33.7    2.000    1.732    82.99    95.40    62.18    61.35
 5   9179.36    5.61    42.8    1.985    1.725    83.60    95.76    62.18    62.56
 6   9246.76    5.57    52.0    1.971    1.712    84.21    96.47    62.17    62.05
 7   9314.36    5.52    61.1    1.956    1.701    84.82    97.04    62.17    62.21
 8   9382.14    5.48    70.2    1.942    1.691    85.43    97.57    62.16    62.58
 9   9450.11    5.43    79.3    1.928    1.675    86.04    98.46    62.15    61.15
10   9518.27    5.39    88.4    1.914    1.665    86.64    99.02    62.15    61.39

                 NOTE: TBULK IS GIVEN IN DEGREES FAHRENHEIT
                       MUB AND MUW ARE GIVEN IN LBM/(FT*HR)
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                    *-----------------------------------------*
                              RUN NUMBER 5106
                        TEST FLUID IS DISTILLED WATER
                    *-----------------------------------------*
                    VOLUMETRIC FLOW RATE =      2.65   GPM
                    MASS FLOW RATE       =    1322.1   LBM/HR
                    MASS FLUX            =    201436   LBM/(SQ.FT-HR)
                    FLUID VELOCITY       =       .89   FT/S
                    ROOM TEMPERATURE     =     71.18   F
                    INLET TEMPERATURE    =     82.75   F
                    OUTLET TEMPERATURE   =     86.60   F
                    AVERAGE RE NUMBER    =      9396
                    AVERAGE PR NUMBER    =      5.53
                    CURRENT TO TUBE      =     417.5   AMPS
                    VOLTAGE DROP IN TUBE =      3.33   VOLTS
                    AVERAGE HEAT FLUX    =      1915   BTU/(SQ.FT-HR)
                    Q=AMP*VOLT           =      4743   BTU/HR
                    Q=M*C*(T2-T1)        =      5081   BTU/HR
                    HEAT BALANCE ERROR   =     -7.11   %

                     OUTSIDE SURFACE TEMPERATURES - DEGREES F

          1       2       3       4       5       6       7       8       9      10

 1    90.86   91.56   92.21   92.65   92.71   93.12   93.56   93.90   94.54   94.96
 2    90.72   91.47   92.27   92.40   92.85   93.24   93.66   93.97   94.59   94.99
 3    90.43   91.12   92.31   92.43   92.82   93.00   93.60   93.68   94.66   95.09
 4    90.22   91.36   92.13   92.54   92.77   93.22   93.52   94.02   94.63   94.45

                     INSIDE SURFACE TEMPERATURES - DEGREES F

          1       2       3       4       5       6       7       8       9      10

 1    89.84   90.53   91.18   91.62   91.68   92.09   92.53   92.87   93.51   93.94
 2    89.69   90.44   91.24   91.37   91.82   92.21   92.63   92.94   93.56   93.96
 3    89.40   90.09   91.28   91.40   91.79   91.97   92.57   92.65   93.63   94.07
 4    89.19   90.33   91.10   91.51   91.74   92.19   92.49   93.00   93.60   93.41

                     REYNOLDS NUMBER AT THE INSIDE TUBE WALL

          1       2       3       4       5       6       7       8       9      10

 1     9983   10063   10138   10189   10195   10243   10294   10334   10408   10458
 2     9966   10052   10145   10159   10212   10257   10306   10342   10414   10461
 3     9933   10011   10149   10163   10208   10229   10299   10308   10422   10473
 4     9908   10040   10128   10176   10202   10255   10289   10348   10419   10397

                       INSIDE SURFACE HEAT FLUXES BTU/HR/FT2

          1       2       3       4       5       6       7       8       9      10

 1     1770    1778    1782    1778    1786    1786    1785    1787    1787    1780
 2     1778    1778    1782    1786    1781    1779    1782    1780    1786    1787
 3     1781    1789    1780    1784    1783    1789    1784    1793    1784    1776
 4     1791    1781    1786    1783    1783    1780    1786    1779    1785    1800

                                *---------------*
                                 RUN NUMBER 5106
                                *---------------*

                 PERIPHERAL HEAT TRANSFER COEFFICIENT BTU/(SQ.FT-HR-F)

          1       2       3       4       5       6       7       8       9      10

 1      259     248     239     236     248     247     244     245     237     234
 2      266     251     237     246     242     241     240     242     235     234
 3      278     266     236     245     244     251     243     254     232     229
 4      290     256     242     241     245     242     245     240     233     254

                                *---------------*
                                 RUN NUMBER 5106
                                     SUMMARY
                                *---------------*

ST       RE       PR     X/D     MUB     MUW      TB      TW    DENS      NU

 1   9210.17    5.66     6.4   1.999   1.851   83.01   89.53   62.18   70.78
 2   9251.46    5.63    15.5   1.990   1.834   83.38   90.35   62.18   66.22
 3   9292.82    5.60    24.6   1.982   1.816   83.75   91.20   62.18   61.94
 4   9334.25    5.58    33.7   1.973   1.810   84.12   91.48   62.17   62.73
 5   9375.76    5.55    42.8   1.964   1.804   84.49   91.76   62.17   63.47
 6   9417.33    5.52    52.0   1.955   1.797   84.86   92.12   62.17   63.56
 7   9458.98    5.49    61.1   1.947   1.788   85.23   92.56   62.16   62.95
 8   9500.70    5.47    70.2   1.938   1.782   85.60   92.86   62.16   63.47
 9   9542.48    5.44    79.3   1.930   1.768   85.97   93.58   62.15   60.62
10   9584.34    5.41    88.4   1.921   1.763   86.34   93.84   62.15   61.43

                     NOTE: TBULK IS GIVEN IN DEGREES FAHRENHEIT
                           MUB AND MUW ARE GIVEN IN LBM/(FT*HR)
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                    *-----------------------------------------*
                                RUN NUMBER 5175
                         TEST FLUID IS DISTILLED WATER
                    *-----------------------------------------*
                    VOLUMETRIC FLOW RATE =     3.24   GPM
                    MASS FLOW RATE       =   1620.4   LBM/HR
                    MASS FLUX            =   246881   LBM/(SQ.FT-HR)
                    FLUID VELOCITY       =     1.09   FT/S
                    ROOM TEMPERATURE     =    74.32   F
                    INLET TEMPERATURE    =    70.22   F
                    OUTLET TEMPERATURE   =    73.17   F
                    AVERAGE RE NUMBER    =     9784
                    AVERAGE PR NUMBER    =     6.64
                    CURRENT TO TUBE      =    426.6   AMPS
                    VOLTAGE DROP IN TUBE =     3.30   VOLTS
                    AVERAGE HEAT FLUX    =     1939   BTU/(SQ.FT-HR)
                    Q=AMP*VOLT           =     4803   BTU/HR
                    Q=M*C*(T2-T1)        =     4776   BTU/HR
                    HEAT BALANCE ERROR   =      .57   %

                      OUTSIDE SURFACE TEMPERATURES - DEGREES F

          1       2       3       4       5       6       7       8       9      10

 1    77.63   78.11   78.49   78.77   78.97   79.27   79.48   79.75   79.99   80.43
 2    77.47   78.02   78.43   78.64   78.94   79.24   79.47   79.75   80.58   80.91
 3    77.33   78.05   78.45   78.58   78.96   79.07   79.41   79.57   80.14   80.78
 4    77.06   78.02   78.39   78.66   78.94   79.19   79.35   80.13   80.48   80.14

                      INSIDE SURFACE TEMPERATURES - DEGREES F

          1       2       3       4       5       6       7       8       9      10

 1    76.57   77.04   77.42   77.70   77.90   78.20   78.41   78.68   78.91   79.36
 2    76.40   76.95   77.36   77.57   77.87   78.17   78.40   78.68   79.52   79.84
 3    76.26   76.98   77.38   77.51   77.89   78.00   78.34   78.49   79.06   79.71
 4    75.98   76.95   77.32   77.59   77.87   78.12   78.28   79.07   79.42   79.06

                      REYNOLDS NUMBER AT THE INSIDE TUBE WALL

          1       2       3       4       5       6       7       8       9      10

 1    10421   10484   10534   10572   10598   10638   10666   10702   10733   10793
 2    10399   10472   10526   10554   10594   10634   10665   10702   10815   10858
 3    10381   10476   10529   10546   10597   10611   10657   10678   10754   10841
 4    10344   10472   10521   10557   10594   10628   10649   10754   10801   10754

                        INSIDE SURFACE HEAT FLUXES BTU/HR/FT2

          1       2       3       4       5       6       7       8       9      10

 1     1832    1840    1841    1840    1843    1842    1842    1849    1859    1848
 2     1841    1844    1844    1844    1844    1842    1843    1842    1832    1838
 3     1840    1841    1842    1845    1843    1847    1844    1854    1855    1839
 4     1852    1844    1845    1843    1844    1843    1846    1833    1835    1857

                                 *---------------*
                                  RUN NUMBER 5175
                                 *---------------*

               PERIPHERAL HEAT TRANSFER COEFFICIENT BTU/(SQ.FT-HR-F)

          1       2       3       4       5       6       7       8       9      10

 1      298     290     286     286     290     289     292     294     298     289
 2      307     295     289     292     291     290     293     293     268     267
 3      314     293     288     295     290     299     296     304     290     272
 4      332     295     291     291     291     293     299     275     272     305

                                 *---------------*
                                  RUN NUMBER 5175
                                      SUMMARY
                                 *---------------*

ST       RE       PR    X/D     MUB     MUW      TB      TW     DENS       NU

 1    9620.57    6.77    6.4   2.346   2.173   70.42   76.30   62.30    82.58
 2    9656.95    6.74   15.5   2.337   2.154   70.70   76.98   62.29    77.41
 3    9693.40    6.71   24.6   2.328   2.144   70.99   77.37   62.29    76.11
 4    9729.89    6.68   33.7   2.320   2.138   71.27   77.59   62.29    76.83
 5    9766.45    6.65   42.8   2.311   2.130   71.55   77.88   62.29    76.73
 6    9803.05    6.63   52.0   2.302   2.123   71.84   78.12   62.28    77.25
 7    9839.72    6.60   61.1   2.294   2.117   72.12   78.36   62.28    77.83
 8    9876.44    6.57   70.2   2.285   2.107   72.40   78.73   62.28    76.73
 9    9913.21    6.54   79.3   2.277   2.094   72.69   79.23   62.28    74.22
10    9950.04    6.52   88.4   2.268   2.087   72.97   79.49   62.28    74.39

                       NOTE: TBULK IS GIVEN IN DEGREES FAHRENHEIT
                             MUB AND MUW ARE GIVEN IN LBM/(FT*HR)
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                  *-----------------------------------------*
                              RUN NUMBER 6570
                       TEST FLUID IS DISTILLED WATER
                  *-----------------------------------------*
                  VOLUMETRIC FLOW RATE =      3.17   GPM
                  MASS FLOW RATE       =    1584.7   LBM/HR
                  MASS FLUX            =    241438   LBM/(SQ.FT-HR)
                  FLUID VELOCITY       =      1.07   FT/S
                  ROOM TEMPERATURE     =     73.49   F
                  INLET TEMPERATURE    =     77.71   F
                  OUTLET TEMPERATURE   =     80.56   F
                  AVERAGE RE NUMBER    =     10526
                  AVERAGE PR NUMBER    =      5.97
                  CURRENT TO TUBE      =     390.0   AMPS
                  VOLTAGE DROP IN TUBE =      3.10   VOLTS
                  AVERAGE HEAT FLUX    =      1665   BTU/(SQ.FT-HR)
                  Q=AMP*VOLT           =      4125   BTU/HR
                  Q=M*C*(T2-T1)        =      4509   BTU/HR
                  HEAT BALANCE ERROR   =     -9.33   %

                    OUTSIDE SURFACE TEMPERATURES - DEGREES F

       1       2       3       4       5       6       7       8       9      10

 1   84.72   85.14   85.58   85.84   86.01   86.15   86.37   86.62   87.38   87.66
 2   84.66   84.92   85.64   85.72   85.97   86.19   86.40   86.67   87.38   87.61
 3   84.49   84.77   85.64   85.77   85.96   86.04   86.39   86.44   87.50   87.99
 4   84.24   84.87   85.52   85.75   85.94   86.11   86.26   86.95   87.31   86.87

                    INSIDE SURFACE TEMPERATURES - DEGREES F

       1       2       3       4       5       6       7       8       9      10

 1   83.83   84.25   84.68   84.95   85.12   85.25   85.48   85.72   86.48   86.77
 2   83.77   84.02   84.75   84.82   85.07   85.30   85.50   85.78   86.48   86.71
 3   83.60   83.87   84.75   84.88   85.06   85.14   85.50   85.54   86.61   87.10
 4   83.34   83.97   84.62   84.85   85.04   85.21   85.36   86.06   86.41   85.96

                    REYNOLDS NUMBER AT THE INSIDE TUBE WALL

       1       2       3       4       5       6       7       8       9      10

 1   11148   11205   11263   11299   11321   11340   11370   11403   11507   11545
 2   11140   11175   11271   11282   11316   11346   11374   11411   11507   11537
 3   11117   11154   11272   11289   11315   11325   11373   11379   11523   11591
 4   11083   11168   11255   11286   11312   11335   11355   11449   11497   11436

                      INSIDE SURFACE HEAT FLUXES BTU/HR/FT2

       1       2       3       4       5       6       7       8       9      10

 1    1540    1541    1548    1545    1547    1548    1548    1554    1549    1540
 2    1545    1548    1547    1550    1549    1546    1548    1546    1551    1555
 3    1546    1550    1546    1547    1548    1551    1547    1558    1546    1531
 4    1556    1549    1550    1549    1549    1548    1552    1538    1553    1574

                              *---------------*
                               RUN NUMBER 6570
                              *---------------*

               PERIPHERAL HEAT TRANSFER COEFFICIENT BTU/(SQ.FT-HR-F)

       1       2       3       4       5       6       7       8       9      10

 1     259     253     248     248     252     258     261     263     242     240
 2     263     264     245     254     254     256     259     259     242     245
 3     271     272     245     251     255     264     260     272     237     227
 4     286     267     251     252     256     260     266     246     245     281

                              *---------------*
                               RUN NUMBER 6570
                                   SUMMARY
                              *---------------*

ST      RE        PR     X/D     MUB     MUW      TB      TW     DENS      NU

 1   10365.25    6.07     6.4   2.129   1.984   77.90   83.63   62.23    70.47
 2   10400.99    6.05    15.5   2.122   1.975   78.18   84.03   62.23    68.98
 3   10436.77    6.03    24.6   2.115   1.959   78.45   84.70   62.23    64.62
 4   10472.61    6.00    33.7   2.108   1.955   78.72   84.87   62.23    65.64
 5   10508.49    5.98    42.8   2.100   1.950   79.00   85.07   62.22    66.42
 6   10544.42    5.96    52.0   2.093   1.947   79.27   85.23   62.22    67.77
 7   10580.40    5.93    61.1   2.086   1.941   79.55   85.46   62.22    68.23
 8   10616.42    5.91    70.2   2.079   1.934   79.82   85.77   62.22    67.75
 9   10652.50    5.89    79.3   2.072   1.918   80.09   86.50   62.21    63.01
10   10688.62    5.87    88.4   2.065   1.915   80.37   86.64   62.21    64.34

                    NOTE: TBULK IS GIVEN IN DEGREES FAHRENHEIT
                          MUB AND MUW ARE GIVEN IN LBM/(FT*HR)
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                    *----------------------------------------*
                              RUN NUMBER 6580
                        TEST FLUID IS DISTILLED WATER
                    *----------------------------------------*
                    VOLUMETRIC FLOW RATE =     3.17   GPM
                    MASS FLOW RATE       =   1584.6   LBM/HR
                    MASS FLUX            =   241423   LBM/(SQ.FT-HR)
                    FLUID VELOCITY       =     1.07   FT/S
                    ROOM TEMPERATURE     =    74.06   F
                    INLET TEMPERATURE    =    78.14   F
                    OUTLET TEMPERATURE   =    83.12   F
                    AVERAGE RE NUMBER    =    10722
                    AVERAGE PR NUMBER    =     5.85
                    CURRENT TO TUBE      =    555.0   AMPS
                    VOLTAGE DROP IN TUBE =     4.45   VOLTS
                    AVERAGE HEAT FLUX    =     3402   BTU/(SQ.FT-HR)
                    Q=AMP*VOLT           =     8427   BTU/HR
                    Q=M*C*(T2-T1)        =     7879   BTU/HR
                    HEAT BALANCE ERROR   =     6.50   %

                     OUTSIDE SURFACE TEMPERATURES - DEGREES F

         1       2       3       4       5       6       7       8       9      10

  1    90.77   92.40   92.65   93.02   92.03   94.29   94.16   95.27   95.59   95.60
  2    91.41   92.65   93.97   93.01   94.22   94.17   95.13   95.86   96.23   95.60
  3    91.09   92.87   93.17   94.12   93.97   94.77   95.46   95.26   96.41   96.54
  4    90.53   91.68   92.81   93.89   92.97   94.15   94.22   95.91   95.70   97.04

                     INSIDE SURFACE TEMPERATURES - DEGREES F

         1       2       3       4       5       6       7       8       9      10

  1    88.95   90.59   90.82   91.20   90.19   92.47   92.34   93.44   93.77   93.77
  2    89.60   90.83   92.17   91.19   92.42   92.35   93.32   94.05   94.42   93.78
  3    89.28   91.06   91.35   92.31   92.16   92.96   93.66   93.43   94.60   94.73
  4    88.71   89.85   90.99   92.08   91.15   92.33   92.39   94.10   93.88   95.24

                     REYNOLDS NUMBER AT THE INSIDE TUBE WALL

         1       2       3       4       5       6       7       8       9      10

  1   11843   12068   12100   12152   12013   12330   12310   12465   12510   12511
  2   11932   12102   12287   12151   12322   12312   12448   12550   12601   12511
  3   11887   12134   12174   12307   12286   12398   12495   12464   12627   12645
  4   11809   11966   12124   12275   12146   12309   12319   12557   12526   12717

                       INSIDE SURFACE HEAT FLUXES BTU/HR/FT2

         1       2       3       4       5       6       7       8       9      10

  1    3152    3144    3171    3164    3193    3151    3169    3173    3168    3178
  2    3134    3149    3124    3167    3120    3164    3146    3142    3152    3171
  3    3143    3131    3157    3135    3141    3138    3134    3173    3146    3152
  4    3157    3175    3155    3144    3153    3164    3171    3140    3166    3133

                                 *---------------*
                                 RUN NUMBER 6580
                                 *---------------*

                PERIPHERAL HEAT TRANSFER COEFFICIENT BTU/(SQ.FT-HR-F)

         1       2       3       4       5       6       7       8       9      10

  1     300     270     278     280     325     271     288     273     276     289
  2     281     265     245     280     259     275     262     257     260     288
  3     291     258     264     252     266     259     254     273     255     264
  4     308     291     272     258     293     276     287     255     273     251

                                 *---------------*
                                 RUN NUMBER 6580
                                     SUMMARY
                                 *---------------*

ST      RE        PR      X/D     MUB      MUW      TB       TW      DENS      NU

 1   10439.42   6.02     6.4   2.114    1.860    78.48    89.13    62.23    77.00
 2   10502.07   5.98    15.5   2.102    1.829    78.95    90.58    62.22    70.60
 3   10564.87   5.94    24.6   2.089    1.813    79.43    91.33    62.22    68.99
 4   10627.81   5.90    33.7   2.077    1.806    79.91    91.69    62.21    69.66
 5   10690.90   5.87    42.8   2.064    1.810    80.39    91.48    62.21    73.94
 6   10754.13   5.83    52.0   2.052    1.789    80.87    92.53    62.21    70.34
 7   10817.52   5.79    61.1   2.040    1.781    81.35    92.93    62.20    70.81
 8   10881.04   5.75    70.2   2.028    1.764    81.83    93.76    62.20    68.71
 9   10944.72   5.71    79.3   2.017    1.756    82.31    94.17    62.19    69.10
10   11008.53   5.68    88.4   2.005    1.752    82.78    94.38    62.19    70.65

                  NOTE: TBULK IS GIVEN IN DEGREES FAHRENHEIT
                        MUB AND MUW ARE GIVEN IN LBM/(FT*HR)
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                    *-----------------------------------------*
                             RUN NUMBER 5104
                      TEST FLUID IS DISTILLED WATER
                    *-----------------------------------------*
                    VOLUMETRIC FLOW RATE =     3.02   GPM
                    MASS FLOW RATE       =   1504.7   LBM/HR
                    MASS FLUX            =   229256   LBM/(SQ.FT-HR)
                    FLUID VELOCITY       =     1.02   FT/S
                    ROOM TEMPERATURE     =    73.66   F
                    INLET TEMPERATURE    =    84.53   F
                    OUTLET TEMPERATURE   =    88.87   F
                    AVERAGE RE NUMBER    =    10954
                    AVERAGE PR NUMBER    =     5.39
                    CURRENT TO TUBE      =    478.5   AMPS
                    VOLTAGE DROP IN TUBE =     3.82   VOLTS
                    AVERAGE HEAT FLUX    =     2517   BTU/(SQ.FT-HR)
                    Q=AMP*VOLT           =     6236   BTU/HR
                    Q=M*C*(T2-T1)        =     6518   BTU/HR
                    HEAT BALANCE ERROR   =    -4.51   %


                      OUTSIDE SURFACE TEMPERATURES - DEGREES F

       1       2       3       4       5       6       7       8       9      10

 1   94.29   94.92   95.62   96.13   96.17   96.67   97.14   97.56   98.23   98.66
 2   94.14   94.87   95.68   95.86   96.33   96.72   97.22   97.55   98.30   98.71
 3   93.65   94.51   95.88   96.00   96.37   96.59   97.18   97.35   98.39   98.89
 4   93.53   94.66   95.57   95.98   96.24   96.69   97.02   97.58   98.11   98.07

                      INSIDE SURFACE TEMPERATURES - DEGREES F

       1       2       3       4       5       6       7       8       9      10

 1   92.95   93.57   94.27   94.78   94.82   95.32   95.79   96.21   96.88   97.31
 2   92.79   93.52   94.33   94.51   94.98   95.37   95.87   96.20   96.95   97.36
 3   92.30   93.16   94.53   94.65   95.02   95.24   95.83   96.00   97.04   97.55
 4   92.17   93.31   94.22   94.63   94.89   95.34   95.67   96.23   96.76   96.71

                      REYNOLDS NUMBER AT THE INSIDE TUBE WALL

       1       2       3       4       5       6       7       8       9      10

 1   11771   11854   11947   12015   12020   12087   12150   12206   12296   12355
 2   11750   11847   11955   11978   12042   12094   12161   12205   12306   12361
 3   11685   11799   11982   11997   12047   12076   12155   12178   12318   12386
 4   11668   11819   11940   11995   12029   12090   12133   12209   12280   12273

                        INSIDE SURFACE HEAT FLUXES BTU/HR/FT2

       1       2       3       4       5       6       7       8       9      10

 1    2332    2341    2347    2342    2351    2350    2349    2350    2351    2345
 2    2340    2341    2349    2353    2346    2346    2348    2348    2352    2353
 3    2349    2352    2340    2346    2346    2352    2348    2356    2346    2339
 4    2356    2347    2352    2350    2349    2347    2353    2347    2357    2370

                                *---------------*
                                RUN NUMBER 5104
                                *---------------*

                PERIPHERAL HEAT TRANSFER COEFFICIENT BTU/(SQ.FT-HR-F)

       1       2       3       4       5       6       7       8       9      10

 1     287     281     272     269     282     279     277     277     269     268
 2     293     282     270     279     276     277     274     277     267     268
 3     314     297     263     273     275     282     276     285     264     260
 4     320     290     274     274     279     278     282     276     274     291

                                *---------------*
                                RUN NUMBER 5104
                                    SUMMARY
                                *---------------*

ST      RE       PR     X/D     MUB     MUW      TB      TW     DENS     NU

 1  10713.09   5.52     6.4   1.956   1.788   84.82   92.55   62.17   78.42
 2  10766.51   5.49    15.5   1.947   1.772   85.24   93.39   62.16   74.39
 3  10820.04   5.46    24.6   1.937   1.753   85.66   94.34   62.16   69.85
 4  10873.67   5.43    33.7   1.927   1.747   86.07   94.64   62.15   70.74
 5  10927.40   5.40    42.8   1.918   1.741   86.49   94.93   62.15   71.83
 6  10981.24   5.37    52.0   1.909   1.734   86.91   95.32   62.14   72.05
 7  11035.17   5.34    61.1   1.899   1.725   87.33   95.79   62.14   71.56
 8  11089.21   5.31    70.2   1.890   1.718   87.74   96.16   62.13   71.94
 9  11143.35   5.29    79.3   1.881   1.704   88.16   96.91   62.13   69.23
10  11197.58   5.26    88.4   1.872   1.698   88.58   97.23   62.13   69.94

                  NOTE: TBULK IS GIVEN IN DEGREES FAHRENHEIT
                        MUB AND MUW ARE GIVEN IN LBM/(FT*HR)
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                    *------------------------------------------*
                                RUN NUMBER 5107
                          TEST FLUID IS DISTILLED WATER
                    *------------------------------------------*
                    VOLUMETRIC FLOW RATE =     3.90   GPM
                    MASS FLOW RATE       =   1945.4   LBM/HR
                    MASS FLUX            =   296391   LBM/(SQ.FT-HR)
                    FLUID VELOCITY       =     1.32   FT/S
                    ROOM TEMPERATURE     =    71.73   F
                    INLET TEMPERATURE    =    83.30   F
                    OUTLET TEMPERATURE   =    87.14   F
                    AVERAGE RE NUMBER    =    13916
                    AVERAGE PR NUMBER    =     5.49
                    CURRENT TO TUBE      =    503.5   AMPS
                    VOLTAGE DROP IN TUBE =     4.03   VOLTS
                    AVERAGE HEAT FLUX    =     2795   BTU/(SQ.FT-HR)
                    Q=AMP*VOLT           =     6923   BTU/HR
                    Q=M*C*(T2-T1)        =     7456   BTU/HR
                    HEAT BALANCE ERROR   =    -7.70   %

                      OUTSIDE SURFACE TEMPERATURES - DEGREES F

        1       2       3       4       5       6       7       8       9      10

 1    92.34   92.93   93.53   94.09   94.05   94.62   95.03   95.43   96.00   96.35
 2    92.18   92.79   93.54   93.67   94.09   94.54   94.98   95.34   95.95   96.37
 3    91.90   92.40   93.69   93.87   94.12   94.33   94.97   95.03   96.10   96.53
 4    91.60   92.64   93.43   93.88   94.01   94.55   94.81   95.31   95.84   95.97

                      INSIDE SURFACE TEMPERATURES - DEGREES F

        1       2       3       4       5       6       7       8       9      10

 1    90.85   91.44   92.04   92.60   92.55   93.13   93.54   93.94   94.51   94.86
 2    90.69   91.30   92.04   92.17   92.59   93.05   93.48   93.85   94.45   94.87
 3    90.41   90.90   92.20   92.38   92.63   92.83   93.48   93.53   94.61   95.04
 4    90.10   91.14   91.93   92.38   92.51   93.06   93.31   93.82   94.34   94.47

                      REYNOLDS NUMBER AT THE INSIDE TUBE WALL

        1       2       3       4       5       6       7       8       9      10

 1    14861   14960   15062   15159   15151   15249   15319   15388   15486   15547
 2    14832   14936   15064   15085   15158   15235   15310   15372   15477   15550
 3    14785   14869   15090   15120   15163   15198   15309   15318   15504   15578
 4    14733   14910   15045   15122   15144   15237   15281   15367   15456   15479

                        INSIDE SURFACE HEAT FLUXES BTU/HR/FT2

        1       2       3       4       5       6       7       8       9      10

 1     2580    2587    2594    2587    2596    2594    2594    2595    2597    2595
 2     2590    2590    2597    2603    2596    2595    2598    2595    2602    2601
 3     2592    2601    2589    2593    2594    2602    2595    2606    2594    2591
 4     2605    2594    2599    2598    2598    2595    2602    2596    2605    2612

                                  *---------------*
                                  RUN NUMBER 5107
                                  *---------------*

                 PERIPHERAL HEAT TRANSFER COEFFICIENT BTU/(SQ.FT-HR-F)

        1       2       3       4       5       6       7       8       9      10

 1     353     344     335     326     345     336     334     333     324     325
 2     363     351     335     346     343     339     336     336     327     325
 3     378     373     327     336     341     350     337     352     320     317
 4     398     359     340     336     347     339     345     338     332     344

                                  *---------------*
                                  RUN NUMBER 5107
                                      SUMMARY
                                  *---------------*

ST      RE        PR     X/D     MUB     MUW      TB      TW     DENS      NU

 1   13641.94    5.62     6.4   1.986   1.830   83.56   90.51   62.18   96.58
 2   13702.69    5.59    15.5   1.977   1.816   83.93   91.20   62.17   92.38
 3   13763.54    5.56    24.6   1.969   1.798   84.30   92.05   62.17   86.58
 4   13824.51    5.53    33.7   1.960   1.792   84.67   92.38   62.17   87.00
 5   13885.57    5.51    42.8   1.951   1.788   85.04   92.57   62.16   89.04
 6   13946.74    5.48    52.0   1.943   1.779   85.40   93.01   62.16   88.17
 7   14008.01    5.45    61.1   1.934   1.770   85.77   93.45   62.16   87.37
 8   14069.38    5.43    70.2   1.926   1.764   86.14   93.78   62.15   87.80
 9   14130.86    5.40    79.3   1.917   1.750   86.51   94.48   62.15   84.21
10   14192.44    5.37    88.4   1.909   1.744   86.88   94.81   62.14   84.58

                    NOTE: TBULK IS GIVEN IN DEGREES FAHRENHEIT
                          MUB AND MUW ARE GIVEN IN LBM/(FT*HR)
```

```
                  *-------------------------------------------*
                                 RUN NUMBER 5176
                          TEST FLUID IS DISTILLED WATER
                  *-------------------------------------------*
                  VOLUMETRIC FLOW RATE =     4.74   GPM
                  MASS FLOW RATE       =   2366.9   LBM/HR
                  MASS FLUX            =   360610   LBM/(SQ.FT-HR)
                  FLUID VELOCITY       =     1.60   FT/S
                  ROOM TEMPERATURE     =    75.43   F
                  INLET TEMPERATURE    =    70.60   F
                  OUTLET TEMPERATURE   =    72.75   F
                  AVERAGE RE NUMBER    =    14288
                  AVERAGE PR NUMBER    =     6.64
                  CURRENT TO TUBE      =    442.0   AMPS
                  VOLTAGE DROP IN TUBE =     3.42   VOLTS
                  AVERAGE HEAT FLUX    =     2082   BTU/(SQ.FT-HR)
                  Q=AMP*VOLT           =     5157   BTU/HR
                  Q=M*C*(T2-T1)        =     5085   BTU/HR
                  HEAT BALANCE ERROR   =     1.40   %

                    OUTSIDE SURFACE TEMPERATURES - DEGREES F

         1       2       3       4       5       6       7       8       9      10

  1    76.69   76.97   77.28   77.55   77.71   77.92   78.06   78.27   76.48   78.81
  2    76.57   76.42   77.23   77.40   77.63   77.81   77.99   78.25   78.96   79.18
  3    76.59   76.61   77.26   77.48   77.65   77.73   77.95   78.10   78.52   79.07
  4    76.17   76.42   77.17   77.34   77.68   77.76   77.92   78.66   78.91   78.42

                    INSIDE SURFACE TEMPERATURES - DEGREES F

         1       2       3       4       5       6       7       8       9      10

  1    75.55   75.83   76.13   76.40   76.56   76.77   76.91   77.12   77.33   77.66
  2    75.42   75.27   76.08   76.25   76.48   76.66   76.84   77.10   77.82   78.04
  3    75.45   75.47   76.11   76.33   76.50   76.58   76.80   76.95   77.37   77.93
  4    75.02   75.27   76.02   76.19   76.53   76.61   76.77   77.52   77.77   77.26

                    REYNOLDS NUMBER AT THE INSIDE TUBE WALL

         1       2       3       4       5       6       7       8       9      10

  1   15025   15080   15138   15191   15221   15262   15289   15329   15369   15434
  2   15001   14972   15128   15161   15206   15240   15275   15326   15465   15507
  3   15006   15010   15134   15177   15209   15225   15267   15296   15377   15486
  4   14923   14972   15117   15149   15215   15231   15261   15406   15455   15357

                      INSIDE SURFACE HEAT FLUXES BTU/HR/FT2

         1       2       3       4       5       6       7       8       9      10

  1     1966    1961    1974    1971    1975    1973    1974    1982    1989    1978
  2     1976    1984    1977    1979    1978    1977    1977    1976    1966    1972
  3     1969    1970    1974    1973    1977    1978    1977    1986    1988    1971
  4     1987    1984    1978    1980    1976    1978    1979    1965    1967    1991

                                  *---------------*
                                  RUN NUMBER 5176
                                  *---------------*

              PERIPHERAL HEAT TRANSFER COEFFICIENT BTU/(SQ.FT-HR-F)

         1       2       3       4       5       6       7       8       9      10

  1      409     401     396     391     395     395     400     402     403     391
  2      422     459     401     405     402     404     407     402     362     363
  3      418     436     398     397     400     411     410     417     400     370
  4      465     459     406     410     398     409     413     369     366     427

                                  *---------------*
                                  RUN NUMBER 5176
                                      SUMMARY
                                  *---------------*

ST      RE        PR      X/D     MUB      MUW      TB       TW      DENS      NU

 1   14113.56   6.73      6.4   2.336    2.199    70.74    75.36    62.29   112.92
 2   14152.35   6.71     15.5   2.329    2.196    70.95    75.46    62.29   115.57
 3   14191.19   6.69     24.6   2.323    2.179    71.16    76.09    62.29   105.66
 4   14230.07   6.67     33.7   2.317    2.173    71.36    76.29    62.29   105.63
 5   14269.00   6.65     42.8   2.310    2.167    71.57    76.52    62.29   105.23
 6   14307.97   6.63     52.0   2.304    2.163    71.78    76.66    62.29   106.70
 7   14346.98   6.61     61.1   2.298    2.158    71.99    76.83    62.28   107.38
 8   14386.03   6.59     70.2   2.292    2.149    72.19    77.17    62.28   104.51
 9   14425.13   6.57     79.3   2.285    2.138    72.40    77.57    62.28   100.65
10   14464.27   6.55     88.4   2.279    2.134    72.61    77.72    62.28   101.70

                     NOTE: TBULK IS GIVEN IN DEGREES FAHRENHEIT
                           MUB AND MUW ARE GIVEN IN LBM/(FT*HR)
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                 *-----------------------------------------*
                            RUN NUMBER 5108
                      TEST FLUID IS DISTILLED WATER
                 *-----------------------------------------*
                 VOLUMETRIC FLOW RATE =      5.10   GPM
                 MASS FLOW RATE       =    2545.3   LBM/HR
                 MASS FLUX            =    387785   LBM/(SQ.FT-HR)
                 FLUID VELOCITY       =      1.72   FT/S
                 ROOM TEMPERATURE     =     72.07   F
                 INLET TEMPERATURE    =     83.43   F
                 OUTLET TEMPERATURE   =     86.36   F
                 AVERAGE RE NUMBER    =     18136
                 AVERAGE PR NUMBER    =      5.52
                 CURRENT TO TUBE      =     505.0   AMPS
                 VOLTAGE DROP IN TUBE =      4.05   VOLTS
                 AVERAGE HEAT FLUX    =      2817   BTU/(SQ.FT-HR)
                 Q=AMP*VOLT           =      6978   BTU/HR
                 Q=M*C*(T2-T1)        =      7444   BTU/HR
                 HEAT BALANCE ERROR   =     -6.67   %

                   OUTSIDE SURFACE TEMPERATURES - DEGREES F

          1       2       3       4       5       6       7       8       9      10

  1     91.20   91.50   91.94   92.48   92.34   92.89   93.19   93.47   93.99   94.22
  2     90.99   91.28   91.95   92.04   92.40   92.75   93.09   93.32   93.83   94.15
  3     90.88   91.07   92.10   92.23   92.43   92.52   93.02   93.03   93.98   94.34
  4     90.44   91.14   91.84   92.27   92.32   92.77   92.90   93.35   93.77   93.77

                   INSIDE SURFACE TEMPERATURES - DEGREES F

          1       2       3       4       5       6       7       8       9      10

  1     89.70   90.00   90.44   90.98   90.84   91.39   91.69   91.97   92.49   92.72
  2     89.49   89.78   90.45   90.53   90.90   91.25   91.59   91.82   92.32   92.64
  3     89.38   89.56   90.60   90.73   90.93   91.01   91.52   91.52   92.48   92.84
  4     88.93   89.63   90.33   90.77   90.82   91.27   91.39   91.85   92.26   92.26

                   REYNOLDS NUMBER AT THE INSIDE TUBE WALL

          1       2       3       4       5       6       7       8       9      10

  1     19189   19254   19351   19472   19440   19562   19629   19692   19808   19860
  2     19140   19205   19353   19372   19453   19531   19606   19658   19771   19843
  3     19117   19158   19387   19415   19460   19479   19591   19592   19806   19887
  4     19017   19173   19328   19424   19435   19535   19563   19665   19758   19757

                     INSIDE SURFACE HEAT FLUXES BTU/HR/FT2

          1       2       3       4       5       6       7       8       9      10

  1      2593    2598    2606    2599    2609    2605    2604    2606    2606    2605
  2      2606    2606    2609    2616    2607    2608    2610    2608    2615    2614
  3      2601    2610    2602    2606    2606    2615    2609    2618    2606    2601
  4      2621    2610    2612    2610    2610    2607    2615    2607    2616    2625

                              *----------------*
                               RUN NUMBER 5108
                              *----------------*

               PERIPHERAL HEAT TRANSFER COEFFICIENT BTU/(SQ.FT-HR-F)

          1       2       3       4       5       6       7       8       9      10

  1       426     426     417     399     428     410     408     409     394     397
  2       444     444     417     431     424     419     416     419     405     403
  3       452     461     406     416     422     437     420     442     395     389
  4       494     455     425     414     430     418     430     417     410     430

                              *----------------*
                               RUN NUMBER 5108
                                   SUMMARY
                              *----------------*

ST       RE        PR     X/D     MUB     MUW      TB      TW     DENS      NU

 1    17863.29    5.61     6.4   1.985   1.854   83.63   89.37   62.18   117.41
 2    17923.94    5.59    15.5   1.978   1.847   83.91   89.74   62.17   115.63
 3    17984.68    5.57    24.6   1.971   1.832   84.19   90.45   62.17   107.74
 4    18045.49    5.55    33.7   1.964   1.825   84.47   90.75   62.17   107.45
 5    18106.38    5.53    42.8   1.958   1.823   84.75   90.87   62.17   110.31
 6    18167.36    5.51    52.0   1.951   1.815   85.04   91.23   62.16   108.90
 7    18228.41    5.49    61.1   1.945   1.809   85.32   91.55   62.16   108.26
 8    18289.54    5.47    70.2   1.938   1.804   85.60   91.79   62.16   108.93
 9    18350.75    5.45    79.3   1.932   1.792   85.88   92.39   62.15   103.61
10    18412.04    5.43    88.4   1.925   1.787   86.16   92.62   62.15   104.46

                   NOTE: TBULK IS GIVEN IN DEGREES FAHRENHEIT
                         MUB AND MUW ARE GIVEN IN LBM/(FT*HR)
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                    *-----------------------------------------*
                              RUN NUMBER 5177
                        TEST FLUID IS DISTILLED WATER
                    *-----------------------------------------*
                    VOLUMETRIC FLOW RATE =     6.42   GPM
                    MASS FLOW RATE       =   3205.6   LBM/HR
                    MASS FLUX            =   488385   LBM/(SQ.FT-HR)
                    FLUID VELOCITY       =     2.17   FT/S
                    ROOM TEMPERATURE     =    76.95   F
                    INLET TEMPERATURE    =    71.27   F
                    OUTLET TEMPERATURE   =    73.11   F
                    AVERAGE RE NUMBER    =    19482
                    AVERAGE PR NUMBER    =     6.59
                    CURRENT TO TUBE      =    472.4   AMPS
                    VOLTAGE DROP IN TUBE =     3.67   VOLTS
                    AVERAGE HEAT FLUX    =     2388   BTU/(SQ.FT-HR)
                    Q=AMP*VOLT           =     5915   BTU/HR
                    Q=M*C*(T2-T1)        =     5893   BTU/HR
                    HEAT BALANCE ERROR   =      .37   %

                      OUTSIDE SURFACE TEMPERATURES - DEGREES F

        1       2       3       4       5       6       7       8       9      10

 1    77.06   77.31   77.54   77.76   77.87   78.02   78.11   78.28   78.52   78.80
 2    76.93   77.04   77.39   77.53   77.75   77.91   78.02   78.25   78.96   79.21
 3    76.74   77.13   77.28   77.91   77.72   77.83   77.97   78.08   78.49   79.08
 4    76.84   77.04   77.39   77.45   77.80   77.79   77.95   78.69   78.85   78.36

                      INSIDE SURFACE TEMPERATURES - DEGREES F

        1       2       3       4       5       6       7       8       9      10

 1    75.75   76.00   76.23   76.45   76.56   76.71   76.80   76.97   77.20   77.49
 2    75.62   75.73   76.08   76.21   76.44   76.60   76.71   76.94   77.65   77.90
 3    75.43   75.82   75.97   76.60   76.41   76.52   76.66   76.76   77.17   77.77
 4    75.53   75.73   76.08   76.13   76.49   76.48   76.64   77.39   77.54   77.04

                      REYNOLDS NUMBER AT THE INSIDE TUBE WALL

        1       2       3       4       5       6       7       8       9      10

 1    20403   20468   20528   20586   20614   20654   20677   20720   20783   20858
 2    20368   20396   20488   20524   20582   20624   20653   20713   20901   20967
 3    20318   20421   20459   20626   20574   20603   20640   20667   20775   20932
 4    20344   20396   20488   20502   20595   20592   20634   20831   20872   20740

                        INSIDE SURFACE HEAT FLUXES BTU/HR/FT2

        1       2       3       4       5       6       7       8       9      10

 1     2252    2250    2253    2251    2256    2254    2255    2264    2269    2260
 2     2256    2261    2258    2265    2259    2258    2259    2257    2248    2253
 3     2260    2255    2260    2247    2259    2259    2259    2269    2270    2252
 4     2258    2261    2258    2268    2258    2262    2261    2246    2251    2275

                                *---------------*
                                RUN NUMBER 5177
                                *---------------*

                  PERIPHERAL HEAT TRANSFER COEFFICIENT BTU/(SQ.FT-HR-F)

        1       2       3       4       5       6       7       8       9      10

 1      516     507     502     497     505     508     519     522     516     501
 2      533     544     521     528     521     522     531     524     464     458
 3      560     530     535     480     524     532     537     549     520     470
 4      546     544     521     538     514     538     540     472     475     561

                                *---------------*
                                RUN NUMBER 5177
                                    SUMMARY
                                *---------------*

ST      RE        PR     X/D     MUB     MUW      TB      TW     DENS      NU

 1   19279.55    6.67     6.4   2.316   2.193   71.39   75.58   62.29   141.99
 2   19324.67    6.65    15.5   2.310   2.186   71.57   75.82   62.29   139.96
 3   19369.83    6.63    24.6   2.305   2.179   71.75   76.09   62.29   136.95
 4   19415.04    6.62    33.7   2.300   2.172   71.92   76.35   62.28   134.30
 5   19460.29    6.60    42.8   2.294   2.168   72.10   76.47   62.28   135.95
 6   19505.58    6.58    52.0   2.289   2.165   72.28   76.58   62.28   138.28
 7   19550.91    6.57    61.1   2.284   2.162   72.46   76.70   62.28   139.95
 8   19596.29    6.55    70.2   2.278   2.153   72.63   77.01   62.28   135.62
 9   19641.70    6.53    79.3   2.273   2.143   72.81   77.39   62.28   129.62
10   19687.16    6.52    88.4   2.268   2.139   72.99   77.55   62.28   130.15

                      NOTE: TBULK IS GIVEN IN DEGREES FAHRENHEIT
                            MUB AND MUW ARE GIVEN IN LBM/(FT*HR)
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                     *-----------------------------------------*
                                  RUN NUMBER 1503
                           TEST FLUID IS DISTILLED WATER
                     *-----------------------------------------*
                     VOLUMETRIC FLOW RATE =      6.45   GPM
                     MASS FLOW RATE       =    3222.8   LBM/HR
                     MASS FLUX            =    491008   LBM/(SQ.FT-HR)
                     FLUID VELOCITY       =      2.18   FT/S
                     ROOM TEMPERATURE     =     73.22   F
                     INLET TEMPERATURE    =     72.64   F
                     OUTLET TEMPERATURE   =     73.65   F
                     AVERAGE RE NUMBER    =     19833
                     AVERAGE PR NUMBER    =      6.50
                     CURRENT TO TUBE      =     318.3   AMPS
                     VOLTAGE DROP IN TUBE =      2.51   VOLTS
                     AVERAGE HEAT FLUX    =      1100   BTU/(SQ.FT-HR)
                     Q=AMP*VOLT           =      2726   BTU/HR
                     Q=M*C*(T2-T1)        =      3252   BTU/HR
                     HEAT BALANCE ERROR   =    -19.30   %

                      OUTSIDE SURFACE TEMPERATURES - DEGREES F

       1       2       3       4       5       6       7       8       9      10

 1   75.28   75.46   75.58   75.71   75.80   75.87   75.91   76.02   76.61   76.73
 2   75.23   75.30   75.52   75.61   75.75   75.83   75.88   75.99   76.57   76.72
 3   75.17   74.97   75.47   75.50   75.72   75.72   75.84   75.88   76.68   76.96
 4   75.20   75.44   75.54   75.66   75.81   75.83   75.86   76.40   76.54   76.12

                      INSIDE SURFACE TEMPERATURES - DEGREES F

       1       2       3       4       5       6       7       8       9      10

 1   74.69   74.87   74.99   75.12   75.21   75.28   75.32   75.42   76.02   76.14
 2   74.64   74.71   74.92   75.01   75.15   75.24   75.28   75.40   75.97   76.12
 3   74.57   74.37   74.87   74.90   75.12   75.12   75.24   75.28   76.09   76.37
 4   74.60   74.85   74.95   75.07   75.22   75.24   75.26   75.81   75.94   75.51

                      REYNOLDS NUMBER AT THE INSIDE TUBE WALL

       1       2       3       4       5       6       7       8       9      10

 1   20234   20281   20312   20346   20369   20388   20398   20426   20582   20614
 2   20220   20239   20296   20320   20356   20377   20390   20419   20571   20610
 3   20205   20151   20283   20290   20348   20348   20379   20389   20600   20675
 4   20212   20276   20301   20333   20372   20377   20385   20528   20563   20450

                        INSIDE SURFACE HEAT FLUXES BTU/HR/FT2

       1       2       3       4       5       6       7       8       9      10

 1    1022    1021    1022    1022    1023    1023    1023    1028    1023    1017
 2    1023    1021    1024    1023    1024    1023    1024    1023    1026    1027
 3    1024    1033    1025    1027    1025    1026    1024    1032    1021    1011
 4    1024    1018    1023    1022    1022    1023    1024    1013    1027    1042

                                 *---------------*
                                  RUN NUMBER 1503
                                 *---------------*

                 PERIPHERAL HEAT TRANSFER COEFFICIENT BTU/(SQ.FT-HR-F)

       1       2       3       4       5       6       7       8       9      10

 1     516     495     490     482     485     491     505     505     404     397
 2     531     537     506     507     497     501     513     509     412     404
 3     549     660     520     539     505     532     524     545     392     362
 4     540     498     501     494     482     501     519     418     417     539

                                 *---------------*
                                  RUN NUMBER 1503
                                      SUMMARY
                                 *---------------*

ST     RE        PR     X/D     MUB     MUW      TB      TW     DENS      NU

 1  19721.06   6.54     6.4   2.276   2.220   72.71   74.62   62.28   140.44
 2  19746.13   6.53    15.5   2.273   2.218   72.81   74.70   62.28   142.24
 3  19771.21   6.52    24.6   2.270   2.211   72.90   74.93   62.28   132.59
 4  19796.30   6.51    33.7   2.267   2.209   73.00   75.02   62.28   132.88
 5  19821.41   6.50    42.8   2.265   2.204   73.10   75.17   62.27   129.51
 6  19846.53   6.50    52.0   2.262   2.203   73.19   75.22   62.27   132.97
 7  19871.66   6.49    61.1   2.259   2.202   73.29   75.28   62.27   135.45
 8  19896.81   6.48    70.2   2.256   2.196   73.39   75.48   62.27   128.77
 9  19921.96   6.47    79.3   2.253   2.181   73.48   76.00   62.27   106.82
10  19947.14   6.46    88.4   2.250   2.180   73.58   76.04   62.27   109.62

                       NOTE: TBULK IS GIVEN IN DEGREES FAHRENHEIT
                             MUB AND MUW ARE GIVEN IN LBM/(FT*HR)
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                  *------------------------------------------*
                              RUN NUMBER 2111
                       TEST FLUID IS DISTILLED WATER
                  *------------------------------------------*
                  VOLUMETRIC FLOW RATE =      5.20   GPM
                  MASS FLOW RATE       =    2590.0   LBM/HR
                  MASS FLUX            =    394607   LBM/(SQ.FT-HR)
                  FLUID VELOCITY       =      1.75   FT/S
                  ROOM TEMPERATURE     =     77.37   F
                  INLET TEMPERATURE    =     90.38   F
                  OUTLET TEMPERATURE   =     93.57   F
                  AVERAGE RE NUMBER    =     20040
                  AVERAGE PR NUMBER    =      5.03
                  CURRENT TO TUBE      =     527.0   AMPS
                  VOLTAGE DROP IN TUBE =      4.23   VOLTS
                  AVERAGE HEAT FLUX    =      3070   BTU/(SQ.FT-HR)
                  Q=AMP*VOLT           =      7606   BTU/HR
                  Q=M*C*(T2-T1)        =      8244   BTU/HR
                  HEAT BALANCE ERROR   =     -8.39   %

                    OUTSIDE SURFACE TEMPERATURES - DEGREES F

        1       2       3       4       5       6       7       8       9      10

 1    98.78   99.02   99.45   99.94  100.07  100.36  100.80  101.06  101.65  101.91
 2    98.48   99.13   99.39   99.54   99.88  100.29  100.60  100.94  101.49  101.92
 3    98.17   98.65   99.54   99.52   99.99  100.02  100.54  100.63  101.64  102.05
 4    97.83   98.74   99.26   99.72   99.84  100.34  100.49  100.83  101.48  101.37

                    INSIDE SURFACE TEMPERATURES - DEGREES F

        1       2       3       4       5       6       7       8       9      10

 1    97.15   97.38   97.81   98.30   98.43   98.72   99.16   99.42  100.01  100.27
 2    96.84   97.49   97.75   97.90   98.24   98.65   98.96   99.30   99.85  100.28
 3    96.53   97.01   97.90   97.88   98.35   98.38   98.90   98.99  100.00  100.42
 4    96.18   97.10   97.62   98.08   98.20   98.70   98.85   99.19   99.84   99.72

                    REYNOLDS NUMBER AT THE INSIDE TUBE WALL

        1       2       3       4       5       6       7       8       9      10

 1    21228   21282   21382   21497   21527   21594   21698   21758   21897   21958
 2    21157   21309   21368   21402   21482   21578   21650   21730   21858   21959
 3    21085   21195   21404   21398   21508   21514   21636   21656   21894   21992
 4    21004   21217   21337   21445   21472   21590   21624   21704   21856   21828

                      INSIDE SURFACE HEAT FLUXES BTU/HR/FT2

        1       2       3       4       5       6       7       8       9      10

 1     2836    2851    2851    2847    2850    2855    2850    2853    2855    2853
 2     2852    2846    2857    2860    2860    2854    2859    2855    2863    2861
 3     2852    2861    2849    2858    2852    2864    2857    2864    2855    2849
 4     2869    2856    2861    2855    2860    2852    2862    2858    2863    2875

                                *---------------*
                                RUN NUMBER 2111
                                *---------------*

                PERIPHERAL HEAT TRANSFER COEFFICIENT BTU/(SQ.FT-HR-F)

        1       2       3       4       5       6       7       8       9      10

 1      432     440     431     419     431     433     423     427     410     412
 2      456     431     436     448     445     437     438     435     421     413
 3      480     468     425     449     436     458     442     458     410     403
 4      513     460     446     434     448     433     446     443     421     451

                                *---------------*
                                RUN NUMBER 2111
                                    SUMMARY
                                *---------------*

ST      RE        PR     X/D     MUB     MUW      TB      TW     DENS      NU

 1   19727.46    5.12     6.4   1.829   1.708   90.59   96.68   62.10   120.38
 2   19796.80    5.10    15.5   1.822   1.697   90.90   97.25   62.10   115.39
 3   19866.22    5.08    24.6   1.816   1.688   91.21   97.77   62.10   111.56
 4   19935.74    5.06    33.7   1.810   1.683   91.51   98.04   62.09   112.16
 5   20005.36    5.04    42.8   1.803   1.678   91.82   98.31   62.09   112.86
 6   20075.06    5.02    52.0   1.797   1.672   92.13   98.61   62.09   112.83
 7   20144.85    5.00    61.1   1.791   1.666   92.44   98.97   62.08   111.99
 8   20214.73    4.98    70.2   1.785   1.661   92.74   99.22   62.08   112.81
 9   20284.71    4.97    79.3   1.778   1.649   93.05   99.92   62.08   106.38
10   20354.78    4.95    88.4   1.772   1.645   93.36  100.17   62.07   107.28

                     NOTE: TBULK IS GIVEN IN DEGREES FAHRENHEIT
                           MUB AND MUW ARE GIVEN IN LBM/(FT*HR)
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                *-------------------------------------------*
                             RUN NUMBER 1504
                       TEST FLUID IS DISTILLED WATER
                *-------------------------------------------*
                VOLUMETRIC FLOW RATE =     6.45   GPM
                MASS FLOW RATE       =   3220.1   LBM/HR
                MASS FLUX            =   490596   LBM/(SQ.FT-HR)
                FLUID VELOCITY       =     2.18   FT/S
                ROOM TEMPERATURE     =    75.48   F
                INLET TEMPERATURE    =    73.71   F
                OUTLET TEMPERATURE   =    75.47   F
                AVERAGE RE NUMBER    =    20192
                AVERAGE PR NUMBER    =     6.37
                CURRENT TO TUBE      =    431.0   AMPS
                VOLTAGE DROP IN TUBE =     3.41   VOLTS
                AVERAGE HEAT FLUX    =     2024   BTU/(SQ.FT-HR)
                Q=AMP*VOLT           =     5014   BTU/HR
                Q=M*C*(T2-T1)        =     5661   BTU/HR
                HEAT BALANCE ERROR   =   -12.89   %

                  OUTSIDE SURFACE TEMPERATURES - DEGREES F

        1        2        3        4        5        6        7        8        9       10

1     78.44    78.78    78.96    79.16    79.28    79.41    79.52    79.70    80.31    80.50
2     78.34    78.55    78.84    78.97    79.19    79.35    79.45    79.66    80.24    80.47
3     78.24    78.47    78.76    78.85    79.16    79.19    79.41    79.50    80.39    80.86
4     78.29    78.68    78.83    79.01    79.24    79.33    79.41    79.97    80.18    79.89

                  INSIDE SURFACE TEMPERATURES - DEGREES F

        1        2        3        4        5        6        7        8        9       10

1     77.35    77.69    77.87    78.07    78.19    78.32    78.43    78.61    79.22    79.41
2     77.25    77.46    77.75    77.88    78.10    78.26    78.36    78.57    79.15    79.38
3     77.15    77.38    77.67    77.76    78.07    78.10    78.32    78.40    79.30    79.78
4     77.20    77.59    77.74    77.92    78.15    78.24    78.32    78.88    79.09    78.79

                  REYNOLDS NUMBER AT THE INSIDE TUBE WALL

        1        2        3        4        5        6        7        8        9       10

1    20916    21005    21053    21106    21138    21172    21201    21248    21411    21463
2    20889    20944    21021    21055    21113    21156    21182    21238    21392    21453
3    20862    20922    20999    21023    21105    21113    21172    21194    21433    21560
4    20875    20979    21018    21066    21127    21151    21172    21322    21376    21296

                    INSIDE SURFACE HEAT FLUXES BTU/HR/FT2

        1        2        3        4        5        6        7        8        9       10

1     1877     1877     1878     1877     1880     1880     1880     1885     1881     1875
2     1880     1883     1882     1882     1883     1881     1883     1881     1886     1889
3     1882     1885     1883     1885     1883     1886     1883     1890     1879     1866
4     1882     1879     1882     1881     1881     1881     1883     1873     1887     1903

                                 *---------------*
                                  RUN NUMBER 1504
                                 *---------------*

             PERIPHERAL HEAT TRANSFER COEFFICIENT BTU/(SQ.FT-HR-F)

        1        2        3        4        5        6        7        8        9       10

1      533      508      507      502      510      515      524      524      466      461
2      549      544      525      531      524      524      535      529      475      469
3      567      557      538      551      528      551      542      557      456      421
4      558      523      527      525      516      528      542      484      483      554

                                 *---------------*
                                  RUN NUMBER 1504
                                      SUMMARY
                                 *---------------*

ST      RE       PR     X/D     MUB      MUW      TB       TW      DENS      NU

 1   19994.29   6.44     6.4   2.243    2.147    73.83    77.24    62.27   144.93
 2   20038.20   6.42    15.5   2.238    2.139    74.00    77.53    62.27   139.87
 3   20082.15   6.40    24.6   2.233    2.133    74.17    77.76    62.27   137.59
 4   20126.14   6.39    33.7   2.228    2.129    74.34    77.91    62.26   138.31
 5   20170.17   6.37    42.8   2.224    2.123    74.51    78.13    62.26   136.36
 6   20214.23   6.36    52.0   2.219    2.121    74.67    78.23    62.26   138.91
 7   20258.34   6.34    61.1   2.214    2.117    74.84    78.36    62.26   140.54
 8   20302.48   6.33    70.2   2.209    2.110    75.01    78.62    62.26   136.99
 9   20346.66   6.31    79.3   2.204    2.095    75.18    79.19    62.26   123.22
10   20390.88   6.30    88.4   2.199    2.091    75.35    79.34    62.26   123.80

                     NOTE: TBULK IS GIVEN IN DEGREES FAHRENHEIT
                           MUB AND MUW ARE GIVEN IN LBM/(FT*HR)
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                    *----------------------------------------*
                                RUN NUMBER 5109
                          TEST FLUID IS DISTILLED WATER
                    *----------------------------------------*
                    VOLUMETRIC FLOW RATE =     6.05   GPM
                    MASS FLOW RATE       =   3017.7   LBM/HR
                    MASS FLUX            =   459757   LBM/(SQ.FT-HR)
                    FLUID VELOCITY       =     2.04   FT/S
                    ROOM TEMPERATURE     =    72.49   F
                    INLET TEMPERATURE    =    83.64   F
                    OUTLET TEMPERATURE   =    86.30   F
                    AVERAGE RE NUMBER    =    21522
                    AVERAGE PR NUMBER    =     5.51
                    CURRENT TO TUBE      =    510.0   AMPS
                    VOLTAGE DROP IN TUBE =     4.07   VOLTS
                    AVERAGE HEAT FLUX    =     2859   BTU/(SQ.FT-HR)
                    Q=AMP*VOLT           =     7082   BTU/HR
                    Q=M*C*(T2-T1)        =     8012   BTU/HR
                    HEAT BALANCE ERROR   =   -13.13   %

                      OUTSIDE SURFACE TEMPERATURES - DEGREES F

          1       2       3       4       5       6       7       8       9      10

 1    90.83   90.94   91.41   91.87   91.88   92.19   92.54   92.78   93.27   93.50
 2    90.52   90.76   91.36   91.45   91.75   92.06   92.32   92.50   93.07   93.41
 3    90.47   90.60   91.63   91.67   91.79   91.88   92.29   92.30   93.22   93.65
 4    90.10   90.58   91.26   91.58   91.78   92.06   92.25   92.57   92.91   92.78

                      INSIDE SURFACE TEMPERATURES - DEGREES F

          1       2       3       4       5       6       7       8       9      10

 1    89.31   89.41   89.88   90.34   90.35   90.66   91.01   91.25   91.74   91.97
 2    88.99   89.23   89.82   89.91   90.22   90.53   90.79   90.97   91.53   91.87
 3    88.94   89.07   90.10   90.14   90.26   90.34   90.76   90.76   91.69   92.12
 4    88.56   89.04   89.72   90.04   90.25   90.53   90.71   91.04   91.37   91.23

                      REYNOLDS NUMBER AT THE INSIDE TUBE WALL

          1       2       3       4       5       6       7       8       9      10

 1    22645   22673   22796   22918   22919   23001   23093   23157   23286   23348
 2    22562   22625   22782   22805   22884   22966   23034   23082   23232   23322
 3    22550   22583   22854   22864   22895   22918   23027   23028   23273   23388
 4    22451   22577   22755   22839   22892   22966   23015   23101   23189   23153

                        INSIDE SURFACE HEAT FLUXES BTU/HR/FT2

          1       2       3       4       5       6       7       8       9      10

 1     2643    2650    2656    2649    2656    2656    2653    2654    2654    2651
 2     2659    2657    2662    2667    2661    2659    2662    2661    2666    2666
 3     2652    2659    2650    2655    2658    2664    2660    2666    2655    2647
 4     2671    2662    2665    2663    2660    2659    2664    2659    2670    2682

                                *---------------*
                                RUN NUMBER 5109
                                *---------------*

                 PERIPHERAL HEAT TRANSFER COEFFICIENT BTU/(SQ.FT-HR-F)

          1       2       3       4       5       6       7       8       9      10

 1      481     496     478     460     482     477     469     470     451     453
 2      514     515     484     500     495     489     490     496     470     463
 3      518     532     459     478     490     507     492     517     455     441
 4      563     535     494     488     492     489     497     490     484     524

                                *---------------*
                                RUN NUMBER 5109
                                    SUMMARY
                                *---------------*

ST      RE        PR     X/D     MUB      MUW      TB       TW      DENS      NU

 1   21227.63   5.60     6.4   1.980    1.864   83.82    88.95   62.18   134.13
 2   21292.97   5.58    15.5   1.974    1.858   84.07    89.19   62.17   134.52
 3   21358.39   5.56    24.6   1.968    1.844   84.33    89.88   62.17   123.91
 4   21423.89   5.54    33.7   1.962    1.839   84.59    90.11   62.17   124.52
 5   21489.46   5.52    42.8   1.956    1.835   84.84    90.27   62.17   126.75
 6   21555.11   5.50    52.0   1.950    1.830   85.10    90.51   62.16   126.92
 7   21620.84   5.48    61.1   1.944    1.824   85.35    90.82   62.16   125.82
 8   21686.64   5.47    70.2   1.938    1.820   85.61    91.00   62.16   127.38
 9   21752.52   5.45    79.3   1.932    1.808   85.87    91.58   62.15   120.18
10   21818.48   5.43    88.4   1.926    1.804   86.12    91.80   62.15   120.97

                      NOTE: TBULK IS GIVEN IN DEGREES FAHRENHEIT
                            MUB AND MUW ARE GIVEN IN LBM/(FT*HR)
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                    *----------------------------------------*
                               RUN NUMBER 5110
                        TEST FLUID IS DISTILLED WATER
                    *----------------------------------------*
                    VOLUMETRIC FLOW RATE =     6.87   GPM
                    MASS FLOW RATE       =   3425.6   LBM/HR
                    MASS FLUX            =   521905   LBM/(SQ.FT-HR)
                    FLUID VELOCITY       =     2.32   FT/S
                    ROOM TEMPERATURE     =    72.83   F
                    INLET TEMPERATURE    =    83.63   F
                    OUTLET TEMPERATURE   =    85.87   F
                    AVERAGE RE NUMBER    =    24367
                    AVERAGE PR NUMBER    =     5.53
                    CURRENT TO TUBE      =    510.0   AMPS
                    VOLTAGE DROP IN TUBE =     4.07   VOLTS
                    AVERAGE HEAT FLUX    =     2859   BTU/(SQ.FT-HR)
                    Q=AMP*VOLT           =     7082   BTU/HR
                    Q=M*C*(T2-T1)        =     7659   BTU/HR
                    HEAT BALANCE ERROR   =    -8.14   %

                      OUTSIDE SURFACE TEMPERATURES - DEGREES F

         1       2       3       4       5       6       7       8       9      10

 1     90.14   90.36   90.68   91.12   91.06   91.41   91.65   91.85   92.26   92.40
 2     90.03   90.03   90.69   90.72   90.95   91.27   91.46   91.68   92.09   92.35
 3     89.71   89.75   90.73   90.95   91.03   91.05   91.50   91.35   92.26   92.52
 4     89.46   89.92   90.54   90.92   90.92   91.29   91.36   91.71   92.04   92.04

                      INSIDE SURFACE TEMPERATURES - DEGREES F

         1       2       3       4       5       6       7       8       9      10

 1     88.61   88.83   89.15   89.59   89.53   89.88   90.12   90.32   90.73   90.87
 2     88.50   88.50   89.16   89.18   89.42   89.74   89.93   90.15   90.55   90.82
 3     88.18   88.21   89.20   89.42   89.50   89.51   89.97   89.81   90.73   90.99
 4     87.92   88.39   89.00   89.39   89.39   89.76   89.82   90.18   90.50   90.50

                      REYNOLDS NUMBER AT THE INSIDE TUBE WALL

         1       2       3       4       5       6       7       8       9      10

 1     25501   25567   25660   25792   25773   25877   25949   26009   26131   26173
 2     25468   25467   25663   25670   25740   25835   25891   25958   26079   26157
 3     25372   25383   25675   25740   25764   25769   25904   25857   26131   26210
 4     25297   25434   25618   25731   25730   25841   25861   25967   26064   26063

                        INSIDE SURFACE HEAT FLUXES BTU/HR/FT2

         1       2       3       4       5       6       7       8       9      10

 1      2645    2645    2655    2649    2654    2654    2652    2654    2655    2655
 2      2652    2656    2657    2665    2660    2657    2661    2656    2664    2662
 3      2656    2661    2654    2654    2655    2664    2656    2668    2655    2651
 4      2667    2659    2661    2660    2660    2656    2664    2655    2665    2671

                                 *---------------*
                                  RUN NUMBER 5110
                                 *---------------*

                 PERIPHERAL HEAT TRANSFER COEFFICIENT BTU/(SQ.FT-HR-F)

         1       2       3       4       5       6       7       8       9      10

 1       547     546     537     513     543     528     525     527     508     515
 2       562     590     537     560     557     544     548     546     527     522
 3       604     631     532     531     546     572     542     589     508     503
 4       644     605     555     536     561     542     560     543     533     558

                                 *---------------*
                                  RUN NUMBER 5110
                                      SUMMARY
                                 *---------------*

ST      RE        PR     X/D     MUB     MUW      TB      TW     DENS      NU

 1   24085.99    5.60     6.4   1.981   1.878   83.78   88.30   62.18   152.06
 2   24148.43    5.58    15.5   1.976   1.874   84.00   88.48   62.17   153.23
 3   24210.94    5.57    24.6   1.971   1.860   84.21   89.13   62.17   139.87
 4   24273.51    5.55    33.7   1.966   1.854   84.43   89.39   62.17   138.40
 5   24336.14    5.54    42.8   1.960   1.853   84.64   89.46   62.17   142.76
 6   24398.84    5.52    52.0   1.955   1.847   84.86   89.72   62.17   141.29
 7   24461.59    5.50    61.1   1.950   1.842   85.07   89.96   62.16   140.64
 8   24524.41    5.49    70.2   1.945   1.839   85.29   90.11   62.16   142.37
 9   24587.29    5.47    79.3   1.940   1.828   85.50   90.63   62.16   134.07
10   24650.23    5.46    88.4   1.936   1.824   85.72   90.79   62.16   135.38

                      NOTE: TBULK IS GIVEN IN DEGREES FAHRENHEIT
                            MUB AND MUW ARE GIVEN IN LBM/(FT*HR)
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                  *----------------------------------------*
                              RUN NUMBER 5178
                        TEST FLUID IS DISTILLED WATER
                  *----------------------------------------*
                  VOLUMETRIC FLOW RATE =     8.10   GPM
                  MASS FLOW RATE       =   4048.3   LBM/HR
                  MASS FLUX            =   616782   LBM/(SQ.FT-HR)
                  FLUID VELOCITY       =     2.73   FT/S
                  ROOM TEMPERATURE     =    77.64   F
                  INLET TEMPERATURE    =    71.68   F
                  OUTLET TEMPERATURE   =    73.20   F
                  AVERAGE RE NUMBER    =    24685
                  AVERAGE PR NUMBER    =     6.57
                  CURRENT TO TUBE      =    482.3   AMPS
                  VOLTAGE DROP IN TUBE =     3.74   VOLTS
                  AVERAGE HEAT FLUX    =     2484   BTU/(SQ.FT-HR)
                  Q=AMP*VOLT           =     6154   BTU/HR
                  Q=M*C*(T2-T1)        =     6148   BTU/HR
                  HEAT BALANCE ERROR   =      .10   %


                    OUTSIDE SURFACE TEMPERATURES - DEGREES F

        1       2       3       4       5       6       7       8       9      10

 1    76.95   76.98   77.17   77.37   77.53   77.64   77.73   77.85   78.45   78.65
 2    76.80   76.64   77.12   77.25   77.42   77.54   77.61   77.83   78.81   79.00
 3    76.79   76.76   77.13   77.36   77.44   77.48   77.59   77.68   78.40   78.88
 4    76.47   76.64   77.08   77.18   77.51   77.47   77.59   78.54   78.72   77.92


                    INSIDE SURFACE TEMPERATURES - DEGREES F

        1       2       3       4       5       6       7       8       9      10

 1    75.59   75.62   75.80   76.01   76.16   76.28   76.37   76.48   77.08   77.29
 2    75.43   75.27   75.75   75.88   76.05   76.17   76.24   76.46   77.45   77.64
 3    75.43   75.40   75.76   76.00   76.07   76.11   76.22   76.31   77.03   77.52
 4    75.10   75.27   75.71   75.81   76.14   76.10   76.22   77.18   77.36   76.54


                    REYNOLDS NUMBER AT THE INSIDE TUBE WALL

        1       2       3       4       5       6       7       8       9      10

 1    25713   25723   25784   25850   25903   25939   25969   26006   26205   26274
 2    25662   25608   25767   25810   25866   25906   25929   26002   26328   26390
 3    25659   25649   25771   25847   25873   25886   25922   25949   26188   26351
 4    25552   25608   25754   25786   25896   25882   25922   26240   26298   26027


                      INSIDE SURFACE HEAT FLUXES BTU/HR/FT2

        1       2       3       4       5       6       7       8       9      10

 1     2344    2343    2351    2349    2352    2350    2350    2363    2363    2350
 2     2354    2358    2354    2356    2355    2354    2355    2353    2345    2349
 3     2348    2349    2352    2349    2354    2354    2354    2367    2364    2344
 4     2362    2358    2354    2358    2353    2356    2355    2334    2348    2377


                              *---------------*
                               RUN NUMBER 5178
                              *---------------*

               PERIPHERAL HEAT TRANSFER COEFFICIENT BTU/(SQ.FT-HR-F)

        1       2       3       4       5       6       7       8       9      10

 1      616     635     630     620     619     624     634     643     572     561
 2      644     705     640     643     639     643     657     643     521     517
 3      644     677     637     622     635     654     660     676     580     530
 4      712     705     647     656     623     656     661     533     533     690


                              *---------------*
                               RUN NUMBER 5178
                                   SUMMARY
                              *---------------*

ST      RE        PR     X/D     MUB     MUW      TB      TW     DENS      NU

 1   24473.34    6.63    6.4   2.304   2.198   71.78   75.39   62.29   171.90
 2   24520.50    6.62   15.5   2.299   2.198   71.93   75.39   62.28   179.00
 3   24567.71    6.60   24.6   2.295   2.188   72.07   75.76   62.28   168.14
 4   24614.94    6.59   33.7   2.291   2.183   72.22   75.92   62.28   167.26
 5   24662.22    6.57   42.8   2.286   2.178   72.37   76.11   62.28   165.52
 6   24709.53    6.56   52.0   2.282   2.177   72.51   76.17   62.28   169.52
 7   24756.88    6.55   61.1   2.278   2.174   72.66   76.26   62.28   171.78
 8   24804.27    6.53   70.2   2.273   2.164   72.81   76.61   62.28   162.81
 9   24851.69    6.52   79.3   2.269   2.148   72.95   77.23   62.28   144.81
10   24899.15    6.50   88.4   2.265   2.147   73.10   77.25   62.27   149.27

                    NOTE: TBULK IS GIVEN IN DEGREES FAHRENHEIT
                          MUB AND MUW ARE GIVEN IN LBM/(FT*HR)
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                    *----------------------------------------*
                              RUN NUMBER 5111
                        TEST FLUID IS DISTILLED WATER
                    *----------------------------------------*
                    VOLUMETRIC FLOW RATE =      7.69   GPM
                    MASS FLOW RATE       =    3835.2   LBM/HR
                    MASS FLUX            =    584314   LBM/(SQ.FT-HR)
                    FLUID VELOCITY       =      2.60   FT/S
                    ROOM TEMPERATURE     =     72.78   F
                    INLET TEMPERATURE    =     83.27   F
                    OUTLET TEMPERATURE   =     85.33   F
                    AVERAGE RE NUMBER    =     27134
                    AVERAGE PR NUMBER    =      5.56
                    CURRENT TO TUBE      =     510.0   AMPS
                    VOLTAGE DROP IN TUBE =      4.07   VOLTS
                    AVERAGE HEAT FLUX    =      2859   BTU/(SQ.FT-HR)
                    Q=AMP*VOLT           =      7082   BTU/HR
                    Q=M*C*(T2-T1)        =      7886   BTU/HR
                    HEAT BALANCE ERROR   =    -11.35   %

                      OUTSIDE SURFACE TEMPERATURES - DEGREES F

         1       2       3       4       5       6       7       8        9       10

 1     89.58   89.56   89.93   90.29   90.24   90.54   90.76   90.97    91.34   91.59
 2     89.25   89.32   89.93   89.89   90.23   90.34   90.60   90.69    91.19   91.30
 3     89.02   89.04   90.10   90.03   90.15   90.24   90.53   90.52    91.24   91.53
 4     88.92   89.18   89.79   90.06   90.16   90.38   90.52   90.88    91.03   90.91

                      INSIDE SURFACE TEMPERATURES - DEGREES F

         1       2       3       4       5       6       7       8        9       10

 1     88.06   88.03   88.40   88.76   88.71   89.01   89.23   89.44    89.81   90.06
 2     87.72   87.79   88.40   88.35   88.70   88.81   89.07   89.16    89.66   89.76
 3     87.49   87.50   88.57   88.50   88.62   88.71   89.00   88.98    89.71   90.00
 4     87.38   87.65   88.25   88.53   88.63   88.85   88.99   89.35    89.49   89.37

                      REYNOLDS NUMBER AT THE INSIDE TUBE WALL

         1       2       3       4       5       6       7       8        9       10

 1     28366   28359   28480   28600   28582   28683   28756   28826    28949   29034
 2     28254   28278   28479   28465   28579   28615   28701   28731    28897   28933
 3     28178   28184   28537   28513   28552   28582   28678   28674    28915   29013
 4     28144   28231   28432   28522   28555   28629   28674   28795    28843   28801

                        INSIDE SURFACE HEAT FLUXES BTU/HR/FT2

         1       2       3       4       5       6       7       8        9       10

 1      2641    2646    2653    2647    2655    2651    2651    2652     2652    2645
 2      2655    2653    2657    2662    2655    2657    2658    2658     2660    2664
 3      2656    2660    2649    2654    2657    2659    2657    2664     2654    2647
 4      2664    2657    2661    2658    2657    2656    2660    2653     2664    2675

                                *---------------*
                                RUN NUMBER 5111
                                *---------------*

                PERIPHERAL HEAT TRANSFER COEFFICIENT BTU/(SQ.FT-HR-F)

         1       2       3       4       5       6       7       8        9       10

 1       568     597     577     556     589     575     572     571      550     543
 2       616     634     578     612     590     603     594     609      570     582
 3       651     682     555     590     601     617     604     636      562     550
 4       670     657     598     587     600     597     606     582      592     640

                                *---------------*
                                RUN NUMBER 5111
                                    SUMMARY
                                *---------------*

ST      RE        PR      X/D     MUB      MUW       TB       TW      DENS       NU

 1   26845.54    5.63     6.4    1.990    1.892    83.41    87.66    62.18    161.73
 2   26909.72    5.61    15.5    1.985    1.890    83.61    87.74    62.18    166.22
 3   26973.96    5.60    24.6    1.980    1.875    83.80    88.41    62.18    149.47
 4   27038.26    5.58    33.7    1.976    1.873    84.00    88.53    62.17    151.69
 5   27102.62    5.57    42.8    1.971    1.870    84.20    88.66    62.17    154.07
 6   27167.03    5.55    52.0    1.966    1.866    84.40    88.84    62.17    154.67
 7   27231.51    5.54    61.1    1.962    1.861    84.60    89.07    62.17    153.65
 8   27296.04    5.53    70.2    1.957    1.857    84.80    89.23    62.17    154.86
 9   27360.64    5.51    79.3    1.952    1.848    84.99    89.67    62.16    147.01
10   27425.29    5.50    88.4    1.948    1.845    85.19    89.80    62.16    149.09

                      NOTE: TBULK IS GIVEN IN DEGREES FAHRENHEIT
                            MUB AND MUW ARE GIVEN IN LBM/(FT*HR)
```

```
                    *-----------------------------------------*
                                RUN NUMBER 5112
                        TEST FLUID IS DISTILLED WATER
                    *-----------------------------------------*
                    VOLUMETRIC FLOW RATE =     8.34   GPM
                    MASS FLOW RATE       =   4157.5   LBM/HR
                    MASS FLUX            =   633420   LBM/(SQ.FT-HR)
                    FLUID VELOCITY       =     2.81   FT/S
                    ROOM TEMPERATURE     =    72.72   F
                    INLET TEMPERATURE    =    83.41   F
                    OUTLET TEMPERATURE   =    85.35   F
                    AVERAGE RE NUMBER    =    29443
                    AVERAGE PR NUMBER    =     5.56
                    CURRENT TO TUBE      =    510.0   AMPS
                    VOLTAGE DROP IN TUBE =     4.10   VOLTS
                    AVERAGE HEAT FLUX    =     2880   BTU/(SQ.FT-HR)
                    Q=AMP*VOLT           =     7134   BTU/HR
                    Q=M*C*(T2-T1)        =     8051   BTU/HR
                    HEAT BALANCE ERROR   =   -12.84   %

                      OUTSIDE SURFACE TEMPERATURES - DEGREES F

          1        2        3        4        5        6        7        8        9        10

  1     89.45    89.45    89.78    90.13    90.07    90.37    90.56    90.73    91.13    91.35
  2     89.16    89.16    89.73    89.75    89.96    90.17    90.36    90.48    90.96    91.13
  3     88.90    88.87    89.88    89.92    90.00    90.02    90.31    90.26    91.04    91.31
  4     88.73    89.06    89.62    89.90    89.94    90.21    90.29    90.60    90.87    90.70

                      INSIDE SURFACE TEMPERATURES - DEGREES F

          1        2        3        4        5        6        7        8        9        10

  1     87.93    87.92    88.25    88.60    88.54    88.84    89.03    89.20    89.60    89.82
  2     87.63    87.63    88.20    88.21    88.43    88.64    88.83    88.95    89.43    89.59
  3     87.37    87.33    88.35    88.39    88.47    88.48    88.78    88.72    89.51    89.78
  4     87.19    87.53    88.08    88.37    88.41    88.68    88.76    89.07    89.33    89.16

                      REYNOLDS NUMBER AT THE INSIDE TUBE WALL

          1        2        3        4        5        6        7        8        9        10

  1     30703    30703    30820    30946    30924    31032    31101    31162    31306    31387
  2     30597    30597    30801    30807    30883    30959    31027    31070    31243    31304
  3     30504    30492    30856    30870    30898    30904    31009    30990    31273    31372
  4     30441    30561    30761    30861    30876    30974    31001    31114    31210    31146

                        INSIDE SURFACE HEAT FLUXES BTU/HR/FT2

          1        2        3        4        5        6        7        8        9        10

  1      2640     2645     2652     2647     2652     2651     2650     2651     2652     2646
  2      2654     2654     2657     2662     2657     2656     2658     2657     2661     2662
  3      2655     2660     2650     2653     2654     2660     2657     2664     2654     2647
  4      2665     2656     2660     2658     2658     2655     2660     2653     2663     2674

                                  *---------------*
                                  RUN NUMBER 5112
                                  *---------------*

                 PERIPHERAL HEAT TRANSFER COEFFICIENT BTU/(SQ.FT-HR-F)

          1        2        3        4        5        6        7        8        9        10

  1       602      630      611      588      623      607      606      609      580      574
  2       649      680      620      647      642      638      638      648      605      608
  3       693      737      597      618      634      663      645      687      593      580
  4       730      699      637      623      645      631      649      628      619      679

                                  *---------------*
                                  RUN NUMBER 5112
                                      SUMMARY
                                  *---------------*

ST      RE        PR     X/D     MUB      MUW      TB       TW      DENS      NU

 1   29147.98    5.62     6.4   1.987    1.895    83.54    87.53    62.18    172.40
 2   29213.54    5.60    15.5   1.982    1.893    83.73    87.60    62.18    177.33
 3   29279.16    5.59    24.6   1.978    1.879    83.91    88.22    62.17    159.63
 4   29344.84    5.58    33.7   1.973    1.876    84.10    88.39    62.17    160.13
 5   29410.56    5.56    42.8   1.969    1.874    84.29    88.46    62.17    164.67
 6   29476.35    5.55    52.0   1.964    1.870    84.47    88.66    62.17    164.12
 7   29542.20    5.54    61.1   1.960    1.866    84.66    88.85    62.17    164.07
 8   29608.10    5.52    70.2   1.956    1.863    84.85    88.98    62.17    165.98
 9   29674.05    5.51    79.3   1.951    1.852    85.03    89.47    62.16    154.93
10   29740.07    5.49    88.4   1.947    1.850    85.22    89.59    62.16    157.18

                     NOTE: TBULK IS GIVEN IN DEGREES FAHRENHEIT
                           MUB AND MUW ARE GIVEN IN LBM/(FT*HR)
```

APPENDIX C

COMPUTER PROGRAMS

C.1 Program Datared98F

Datated98F reduces the data obtained from the data logger (MAC-14) and creates an output file which will be used as an input file for Program RHt98 for the calculation of heat balance error, Nusselt number, heat transfer coefficient, and several other flow parameters. The original code was developed by Y. H. Zurigat in 1989 and modified by D. Kim and V. K. Ryali in 1998 for specific application to the test runs presented in Appendix B. The following is a complete listing of this modified program.

```
C*********************************************************************
C
C                                 DATARED98F.FOR
C
C        THIS PROGRAM TAKES A DATA FILE FROM THE DATA LOGGER AND CONVERTS
C        IT TO A FORM THAT THE HT PROGRAM CAN READ.
C        NOTE: THE AMBIENT TEMPERATURE IS #15
C
C*********************************************************************

        CHARACTER FNAME*10, ONAME*10, JUNK*4, RUN*4
        DIMENSION T(45), SUM(45), x(10)

        PRINT*,' '
        PRINT*,' '
        PRINT*,' ENTER THE RUN NUMBER (4 digits) '
        READ(*,10) RUN
 10     FORMAT(A4)

        FNAME='RN'//RUN//'.TMP'
        OPEN (UNIT=5,FILE=FNAME,STATUS='OLD')

        DO 20 I=1,45
           SUM(I) = 0.0
 20     CONTINUE
```

```
         READ(5,30) JUNK
 30      FORMAT(4(/),A4)
         NPTS=0

         DO 60 WHILE(.NOT.EOF(5))
            READ(5,40) (T(I),I=1,45)
 40         FORMAT(11X,45(F10.5,1x))
            DO 50 I=1,45
               SUM(I)=SUM(I)+T(I)
 50         CONTINUE
            NPTS=NPTS+1
         Write(*,*) 'Reading Line =',NPTS
 60      CONTINUE
         WRITE(*,*) T(2)
         pause

         DO 70 I = 1,45
            T(I) = SUM(I)/NPTS
 70      CONTINUE

kdw      convert temp's from 'C to 'F
         Do k=1,45
        T(K)=1.8*T(k)+32.0
        enddo


 80      PRINT*, ' '
         PRINT*, ' '
         PRINT*, 'FLUID INDEX (1 = water, 2 = ethylene glycol)'
         READ*,  IFLUID

         IF (IFLUID.EQ.1) THEN
            ETH = 0.0
         ELSEIF (IFLUID.EQ.2) THEN
            PRINT*, ' '
            PRINT*, ' '
            PRINT*, 'MASS CONCENTRATION OF ETHYLENE GLYCOL (0 < X <= 1)'
            READ*,  ETH
         ELSE
            PRINT*, ' '
            PRINT*, ' '
            PRINT*, 'MUST ENTER EITHER 1 OR 2'
            GOTO 80
         ENDIF

         PRINT*, ' '
         PRINT*, ' '
         PRINT*, 'FLOW RATE (gal/min)'
         READ*,  FLOW

         PRINT*, ' '
         PRINT*, ' '
         PRINT*, 'CURRENT (amps)'
         READ*, CURR

         PRINT*, ' '
         PRINT*, ' '
         PRINT*, 'VOLTAGE DROP ACROSS TEST SECTION (volts)'
         READ*, VOLT

         ONAME='RN'//RUN//'.DAT'
         OPEN (UNIT=3,FILE=ONAME)
```

```
        WRITE (3,100) RUN,IFLUID,ETH,FLOW,CURR,VOLT,T(42),T(43),T(44)
  90    FORMAT(3(/),1X,A4,1X,'03',/,2X,I1,2X,F6.4,2X,F6.4,2X,F6.2,2X,
     +          F6.2,2X,F6.2,2X,F6.2,2X,F6.2)
 100    FORMAT(A4,1X,'10',/,1X,I1,2X,F3.2,2X,F6.4,2X,F6.2,2X,F6.2,
     +          2X,F6.2,2X,F6.2,2X,F6.2)

kim     Calculate the local length      x(10)
        x(1)=7.0
        Do J=2,10
          x(J)=x(j-1)+10.0
        Write(*,*) x(j)
        Enddo

        Initial=2
        Do J=1,10
        WRITE (3,120) J,X(J),(T(I), I=Initial,Initial+3)
        Initial=Initial+4
        Enddo
        Write(3,123)
 123    FORmat(2x,'0')
 110    FORMAT(2X,'16',2X,'4',3X,'144.00',2X,4(F6.2,2X))
 120    FORMAT(1X,I2,2X,'4',3X,F6.2,2X,4(F6.2,2X))

        STOP
        END
```

C.2 Program RHt98F

Program Rht98F takes the output file obtained from program Datared98F. and then calculates the heat balance error, Nusselt number, and several other flow parameters as explained in Chapter IV. This code was first developed by the students of Dr. J. D. Parker and Dr. K. J. Bell. It was later modified by Y.H. Zurigat and Mailello in 1989. It has been modified for the test cases presented herein by D. Kim and V. K. Ryali (1999). The following is complete listing of this modified program.

```
C   ******************************************************************
C   *                              " HT "                            *
C   *                                                                *
C   *   A PROGRAM TO CALCULATE THE INSIDE WALL TEMPERATURES AND      *
C   *   LOCAL HEAT TRANSFER COEFFICIENTS FOR GIVEN OUTSIDE WALL      *
C   *   TEMPERATURES FOR SINGLE PHASE HEAT TRANSFER STUDIES IN       *
C   *   HORIZONTAL TUBES.  THE PROGRAM ALSO CALCULATES THE PERTINENT *
C   *   FLUID FLOW & HEAT TRANSFER DIMENSIONLESS NUMBERS.            *
C   *                                                                *
C   *   THE MATHEMATICAL ALGORITHM OF THIS PROGRAM HAS BEEN DEVELOPED *
C   *   BY THE STUDENTS OF DR. J.D. PARKER & DR. K.J. BELL OF        *
C   *   OKLAHOMA STATE UNIVERSITY.                                   *
C   *                                                                *
C   *   THE PROGRAM WAS MODIFIED BY:                                 *
C   *                                                                *
C   *                 Y. H. ZURIGAT  (APRIL 1989)                    *
C   *                                                                *
C   *   AND REMODIFIED FOR INTERACTIVE USE ON PC's BY:               *
C   *                                                                *
C   *                 D. R. MAIELLO  (DECEMBER 1989)                 *
C   *                                                                *
C   *   AND REMODIFIED FOR A SPECIFIC PURPOSE BY:                    *
C   *                                                                *
C   *                 DARREN WARNECKER   (NOVEMBER 1994)             *
C   *                                                                *
C   *   UNDER THE SUPERVISION OF: DR. A.J. GHAJAR                    *
C   *                             SCHOOL OF MECHANICAL &             *
C   *                                AEROSPACE ENGINEERING           *
C   *                             OKLAHOMA STATE UNIVERSITY          *
C   *                             STILLWATER, OK 74078               *
C   *                                                                *
C   ******************************************************************
C
C   ******************************************************************
C   *                                                                *
C   *                       SUBROUTINE LISTING                       *
C   *                                                                *
C   *       NAME          FUNCTION                                   *
C   *     --------        ------------------------------------       *
C   *       GEOM          Prompts for pipe dimensions and            *
C   *                     calculates geometry for finite             *
C   *                     differencing                               *
C   *                                                                *
```

```
C  *     BET           Calculates fluid Thermal Expansion Coefficient *
C  *                                                                  *
C  *     CONDFL        Calculates fluid Thermal Conductivity          *
C  *                                                                  *
C  *     DENS          Calculates fluid Density                       *
C  *                                                                  *
C  *     MEW           Calculates fluid Viscosity                     *
C  *                                                                  *
C  *     PRNUM         Calculates fluid Prandtl Number                *
C  *                                                                  *
C  *     SPHEAT        Calculates fluid Specific Heat                 *
C  *                                                                  *
C  *     PRNT          Prints calculated data to output files         *
C  *                                                                  *
C  ********************************************************************
C
C
C  ********************************************************************
C  *                                                                  *
C  *                        MAIN PROGRAM                              *
C  *                                                                  *
C  ********************************************************************


      CHARACTER INFILE*36,SUMFILE*11,FNAME*4,RUN*4
      DIMENSION TCHCK1(8),TCHCK2(8),QAVG(31),DELX(10),
     +          CONDK(31,8),RSVTY(31,8)
       INTEGER   RSWT,STN
       COMMON/STATION/STN

      COMMON /PRINT/ IPICK,REN(31,8),TBULK(31),VEL,REYNO,PRNO,GW,
     +               HTCOFF(31,8),H(31),RENO(31),GRNO(31),PR(31),
     +               SNUS(31),VISBW(31),SHTHB(32),QFLXID(31,8),QFLXAV,
     +               QGEXPT,QBALC,QPCT,IPMAX,TAVG(31),VISCA(31),
     +               VISWLA(31),ROWA(31)
     +       /INPUT/ TROOM,VOLTS,TAMPS,RMFL,MFLUID,X2,FLOWRT,NRUN,VFLOW,
     +               TIN,TOUT,TOSURF(31,8),TISURF(31,8),IP(32),KST(32)
     +       /TEMP1/ TWALL(31,8),AMPS(31,8),RESIS(31,8),POWERS(32),
     +               TPOWER
     +       /MAIN1/ IST,KOUNT,NSTN
     +       /GEOM1/ XAREA(31),R(31),LTP(32),LTH(32),DELZ(31),LHEAT,
     +               LTEST,LOD(31),DOUT,DIN,DELR,NODES,NSLICE,PI

      REAL*4 LTH,LTP,LTEST,LHEAT,H,HTCOFF,LOD,LENGTH
      DATA DELX/6.75,16.75,26.75,36.75,46.75,56.75,66.75,76.75,86.75
     +         ,96.75/

C     DELX, LENGTH WERE CREATED BY RYALI TO CALCULATE THE TBULK FOR HIS
C     SETUP
      LENGTH=103.5D0
C ----------------------------------------------
C ----- INITIALIZE OUTPUT DATA ARRAYS TO ZERO -----
C ----------------------------------------------
      WRITE(*,*)'ENTER THE STATION NUMBER TO CALCULATE'
      READ(*,*)STN

      OPEN(8,FILE="STN.DAT")

 1200 WRITE(*,*)


    1 DO 101 I=1,8
        DO 101 J=1,31
```

```
          TOSURF(J,I)=0.
          TISURF(J,I)=0.
          REN(J,I)=0.
          QFLXID(J,I)=0.
  101     HTCOFF(J,I)=0.

      G=32.174

C ------------------------------------------
C ----- ASSIGN FOR INPUT DATA FILE NAME -----
C ------------------------------------------

      PRINT*, ' '
      PRINT*, ' '
      PRINT*, 'Enter the file number.'
      READ(*,1003) RUN

      DO 2 J=1,18
    2 INFILE='RN'//RUN//'.DAT'
      OPEN(5,FILE=INFILE)

      READ(5,1003)FNAME
      REWIND 5

C ------------------------------------------------------------
C ----- ASSIGN FILE NAMES TO VARIABLES AND OPEN OUTPUT FILES -----
C ------------------------------------------------------------

C$$$$$ *.CMP CREATED BY RYALI TO PRINT OUT  THE hSP VALUES WITH OTHER
C$$$$$   CORRELATIONS

      SUMFILE='RN'//FNAME//'.HTI'
      OPEN(6,FILE=SUMFILE)
      SUMFILE='RN'//FNAME//'.CMP'
      OPEN(7,FILE=SUMFILE)
C ---------------------------------
C ----- ASSIGN FOR UNITS INPUT -----
C ---------------------------------

    7 IPICK = 1

C -----------------------------------------------------
C ----- READ RUN NUMBER AND # STATIONS FROM INPUT FILE -----
C -----------------------------------------------------

    8 READ(5,1004) NRUN,NSTN

C --------------------------------
C ----- CHECK FOR END OF FILE -----
C --------------------------------

      IF (NRUN .EQ. 0) GO TO 99

C ------------------------------------
C ----- READ DATA FROM INPUT FILE -----
C ------------------------------------

      X2=0.0
      IPMAX=0
      READ(5,1005)MFLUID,X2,FLOWRT,TAMPS,VOLTS,TIN,TOUT,TROOM
      Write(*,*) 'Tin =', Tin
C     Pause
```

```
      IF(X2.LT.0.0.OR.X2.GT.1.0)THEN
      WRITE(*,*)' WARNING : MASS CONCENTRATION IS OUT OF RANGE'
      STOP
      END IF

      DO 9 IST=1,NSTN
       READ(5,1006)KST(IST),IP(IST),LTH(IST),
     +     (TOSURF(IST,IPR),IPR=1,IP(IST))
       IF(IST.NE.1)THEN
          IF(IP(IST).GE.IPMAX)IPMAX=IP(IST)
       ELSE
    9  ENDIF

      VFLOW=FLOWRT

C ---------------------------------------------------
C -----CALCULATION OF MASS FLOW RATE IN LBM/HR -----
C ---------------------------------------------------

      CALL DENS(TIN,MFLUID,X2,ROW)
      RMFL=VFLOW*0.133666*60.0*ROW

C --------------------
      CALL GEOM
C --------------------

      NNODE=NODES-1

C -----------------------------------------
C ----- START SOLUTION WITH STATION 1 -----
C -----------------------------------------

      DO 30 IST=1,NSTN
        IPP= IP(IST)
        DO 10 IPR=1,IPP
   10       TCHCK1(IPR)=0.0

C -----------------------------------------------
C -----  SET ALL RADIAL TEMPERATURES EQUAL  -----
C ----- TO THE OUTSIDE SURFACE TEMPERATURES -----
C -----------------------------------------------

         DO 11 ISL=1,NODES
            DO 11 IPR=1,IPP
   11           TWALL(ISL,IPR)=TOSURF(IST,IPR)
         KOUNT=1

C -------------------------------------------------------------
C ----- CALCULATE THERMAL CONDUCTIVITY OF STAINLESS STEEL -----
C -----      FOR EACH NODE IN BTU/(HR-FT-DEGF)           -----
C -------------------------------------------------------------

   12 DO 13 ISL=1,NODES
        DO 13 IPR=1,IPP
        CONDK(ISL,IPR)=7.27+0.0038*TWALL(ISL,IPR)
   13 CONTINUE

C ---------------------------------------------------------------
C ----- CALCULATE ELECTRICAL RESISTIVITY OF STAINLESS STEEL -----
C -----        FOR EACH NODE IN OHMS-SQIN/IN                -----
C ---------------------------------------------------------------

      DO 14 ISL=1,NODES
```

```
        IPP= IP(IST)
        DO 14 IPR=1,IPP
           RSVTY(ISL,IPR)=(27.67+0.0213*TWALL(ISL,IPR))/1.E6
   14 CONTINUE

C ----------------------------------------------------------------
C -----      CALCULATE RESISTANCE FOR EACH SEGMENT, ALSO     -----
C ----- CALCULATE EQUIVALENT RESISTANCE FOR PARALLEL CIRCUITS -----
C ----------------------------------------------------------------

      DELR = (DOUT-DIN)/2.0/NSLICE
      R(1) = DOUT/2.0
      DO 15  I=1,NSLICE
   15    R(I+1)=R(I)-DELR
      IPP= IP(IST)
      XAREA(1)=(R(1)-DELR/4.0)*PI*DELR/IPP
      XAREA(NODES)=(R(NODES)+DELR/4.0)  *PI*DELR/IPP
      DO 16 I=2,NSLICE
   16    XAREA (I)= 2.0*R(I)*PI*DELR/IPP

      RINV = 0.0
      DO 17 ISL=1,NODES
        DO 17 IPR=1,IPP
           RESIS(ISL,IPR) = RSVTY(ISL,IPR)*DELZ(IST)/XAREA(ISL)
           RINV = RINV +1.0/RESIS(ISL,IPR)
   17 CONTINUE

C ----------------------------------------------
C ----- CALCULATE CURRENT FOR EACH SEGMENT -----
C ----------------------------------------------

      OHMS = 1.0/RINV
      AMP=0.0
      DO 18 ISL=1,NODES
        DO 18 IPR=1,IPP
           AMPS(ISL,IPR) = TAMPS*OHMS/RESIS(ISL,IPR)
           AMP=AMP+AMPS(ISL,IPR)
   18 CONTINUE

C ----------------------------------------------------------------
C -----           CALCULATE TEMPERATURES AT NODE 2           -----
C ----- TEMPERATURES AT NODE 1 ARE OUTSIDE WALL TEMPERATURES -----
C ----------------------------------------------------------------

         ISL=1
         DO 20 IPR=1,IPP
            ITHCTL=IPP
            IMINS=IPR-1
            IPLUS=IPR+1
            NMINS = ISL - 1
            NPLUS = ISL + 1
              IF(IMINS.EQ.0 .AND. IPP.EQ. ITHCTL) IMINS=ITHCTL
              IF(IPLUS.EQ.(ITHCTL+1) .AND.  IPP.EQ. ITHCTL) IPLUS=1
            A= 3.41214*12.0*AMPS(ISL,IPR)*AMPS(ISL,IPR)
     +             *RSVTY(ISL,IPR)/XAREA(ISL)
            B = IPP*DELR*(CONDK(ISL,IPR)+CONDK(ISL,IPLUS))
     +             *(TWALL(ISL,IPR)-TWALL(ISL,IPLUS))/(8.0*PI*R(ISL))
            C = IPP*DELR*(CONDK(ISL,IPR)+CONDK(ISL,IMINS))
     +             *(TWALL(ISL,IPR)-TWALL(ISL,IMINS))/(8.0*PI*R(ISL))
            X = PI*(R(ISL)-DELR/2.0)*(CONDK(ISL,IPR)+CONDK(NPLUS,IPR))
     +             /(IPP*DELR)
   20        TWALL(NPLUS,IPR) = TWALL(ISL,IPR)-(A-B-C)/X
```

```
C --------------------------------------------------
C ----- CALCULATE REMAINING NODAL TEMPERATURES -----
C --------------------------------------------------

         DO 21 ISL=2,NNODE
           DO 21 IPR=1,IPP
             ITHCTL=IPP
             IMINS=IPR-1
             IPLUS=IPR+1
             NMINS=ISL-1
             NPLUS=ISL+1
             IF(IMINS.EQ.0 .AND. IPP .EQ. ITHCTL) IMINS=ITHCTL
             IF(IPLUS.EQ.(ITHCTL+1) .AND. IPP .EQ. ITHCTL) IPLUS=1
             A= 3.41214*12.0*AMPS(ISL,IPR)*AMPS(ISL,IPR)
     +              *RSVTY(ISL,IPR)/XAREA(ISL)
             B =PI*(R(ISL)+DELR/2.)*(CONDK(ISL,IPR)+CONDK(NMINS,IPR))
     +               * (TWALL(ISL,IPR)-TWALL(NMINS,IPR))/(IPP*DELR)
             C = IPP*DELR*(CONDK(ISL,IPR)+CONDK(ISL,IPLUS))
     +                *(TWALL(ISL,IPR)-TWALL(ISL,IPLUS))/(4.0*PI*R(ISL))
             D = IPP*DELR*(CONDK(ISL,IPR)+CONDK(ISL,IMINS))
     +                *(TWALL(ISL,IPR)-TWALL(ISL,IMINS))/(4.0*PI*R(ISL))
             X =PI*(R(ISL)-DELR/2.)*(CONDK(ISL,IPR)+CONDK(NPLUS,IPR))
     +                /(IPP*DELR)
   21        TWALL(NPLUS,IPR) = TWALL(ISL,IPR)- (A-B-C-D)/X

C --------------------------------------------------------------
C ----- CHECK FOR THE CONVERGENCE OF THE WALL TEMPERATURES -----
C --------------------------------------------------------------

         TCHCK = 0.0
         DO 22 IPR=1,IPP
            TCHCK2(IPR)=TWALL(NODES,IPR)
   22        TCHCK = TCHCK + ABS(TCHCK2(IPR)-TCHCK1(IPR))
         IF (TCHCK .GT. 0.001) GO TO 23
         GO TO 26
   23     DO 24 IPR=1,IPP
   24        TCHCK1(IPR) = TCHCK2(IPR)
         KOUNT = KOUNT+1
         GO TO 12
         WRITE(6,1007) IST,KOUNT
   26     DO 27 IPR=1,IPP
   27        TISURF( IST ,IPR)=TWALL(NODES,IPR)

C -----------------------------------------------------------------
C ----- CALCULATE POWER GENERATED IN EACH SEGMENT IN BTU/HOUR -----
C -----------------------------------------------------------------

         POWER =0.0
         DO 28 ISL=1,NODES
            DO 28 IPR=1,IPP
            POWER=POWER+AMPS(ISL,IPR)*AMPS(ISL,IPR)*RESIS(ISL,IPR)
   28     CONTINUE

         POWERS(IST)=POWER*3.41214

C -------------------------------------------------
C ----- CALCULATE HEAT FLUX AT INSIDE SURFACE -----
C -------------------------------------------------

      ISL=NODES
      IPP= IP(IST)
        ITHCTL=IPP
      DO 29 IPR=1,IPP
```

```
        IPLUS=IPR+1
        IMINS=IPR-1
        IF(IMINS.EQ.0 .AND. IPP .EQ. ITHCTL) IMINS=ITHCTL
        IF(IPLUS.EQ.(ITHCTL+1).AND. IPP.EQ. ITHCTL) IPLUS=1
        Q1 = PI*(CONDK(ISL-1,IPR)+CONDK(ISL,IPR))*(R(ISL-1)-DELR/2.0)*
     +         (TWALL(ISL,IPR)-TWALL(ISL-1,IPR))/(IPP*DELR)
        Q2 = IPP*(CONDK(ISL,IPLUS)+CONDK(ISL,IPR))*DELR
     +        *(TWALL(ISL,IPR)-TWALL(ISL,IPLUS))/(PI*R(ISL)*8.0)
        Q4 = IPP*(CONDK(ISL,IPR)+CONDK(ISL,IMINS))*DELR
     +        *(TWALL(ISL,IPR)-TWALL(ISL,IMINS))/(PI*R(ISL)*8.0)
        QGEN=3.41214*12.0*AMPS(ISL,IPR)*AMPS(ISL,IPR)
     +        *RSVTY(ISL,IPR)/XAREA(ISL)
   29    QFLXID(IST,IPR) =(QGEN-Q1-Q2-Q4)*IPP*12.0/(2.0*PI*R(ISL))

   30 CONTINUE

C -------------------------------------------------------------
C ----- CALCULATE REYNOLDS NUMBERS AT INSIDE TUBE SURFACE -----
C -------------------------------------------------------------

      DO 40 IST=1,NSTN
        IPP= IP(IST)
        DO 40 IPR=1,IPP
           TR=TISURF(IST,IPR)
           CALL MEW(TR,MFLUID,X2,VISS)
           REN(IST,IPR)=RMFL*48.0/(PI*DIN*VISS)

   40 CONTINUE

C -------------------------------------------------------
C ----- CALCULATE TOTAL POWER GENERATED IN BTU/HOUR -----
C -------------------------------------------------------

      TPOWER=0.0
      DO 45 IST=1,NSTN
   45 TPOWER=TPOWER+POWERS(IST)

C -------------------------------------------------------------------
C ----- CALCULATE BULK FLUID TEMPERATURE AT EACH STATION,DEG.F -----
C -------------------------------------------------------------------

      TBULK(1)=TIN+(TOUT-TIN)*LTP(1)/LTEST
      DO 50 IST =2,NSTN
 50   TBULK(IST) = TBULK(IST-1) + (TOUT-TIN)*LTP(IST)/LTEST

C ----------------------------------------------------------------------
C ----- CALCULATION OF INPUT AND OUTPUT HEAT TRANSFER RATE,BTU/HR -----
C -----    AND OVERALL AVERAGE REYNOLDS AND PRANDTL NUMBERS        -----
C ----------------------------------------------------------------------

      QGCALC=TPOWER
      QGEXPT =TAMPS*VOLTS*3.41214
      QIN=QGEXPT
      QFLXAV=QIN/(3.1416*DIN/12.0*(LHEAT/12.0))

C ----- CALCULATE FLUID PROPERTIES AT TAVE -----

      T=(TOUT+TIN)/2.0
      CALL SPHEAT(T,MFLUID,X2,SPHT)
      CALL MEW(T,MFLUID,X2,VISC)
      CALL CONDFL(T,MFLUID,X2,COND)

      QBALC=RMFL*SPHT*(TOUT-TIN)
```

```
      QPCT=(QIN-QBALC)*100.0/QIN
      AID=PI*DIN*DIN/4.0/144.0
      GW=RMFL/AID
      REYNO=GW*DIN/12.0/VISC
      PRNO=VISC*SPHT/COND

C ----------------------------------------------------------------
C ----- CALCULATION OF PERIPHERAL HEAT TRANSFER COEFFICIENT -----
C -----    FROM EXPERIMENTAL DATA,BTU/(HR-SQ.FT-DEG.F)       -----
C ----------------------------------------------------------------

      DO 55 IST=1,NSTN
        IPP= IP(IST)
        DO 55 IPR=1,IPP
        HTCOFF(IST,IPR) =QFLXID(IST,IPR)/(TISURF(IST,IPR)-TBULK(IST))
   55 CONTINUE

C ---------------------------------------------------------------------
C ----- CALCULATE RATIO OF TOP/BOTTOM HEAT TRANSFER COEFFICIENTS -----
C ---------------------------------------------------------------------

      DO 65 IST=1,NSTN
        IPP= IP(IST)
        IF (IPP.EQ. 4) GO TO 60
           SHTHB(IST)=HTCOFF(IST,1)/HTCOFF(IST,2)
           GO TO 65
   60    SHTHB(IST)=HTCOFF(IST,1)/HTCOFF(IST,3)
   65 CONTINUE

C --------------------------------------------------------------
C ----- CALCULATION OF OVERALL HEAT TRANSFER COEFFICIENT -----
C --------------------------------------------------------------

      DO 75 IST=1,NSTN
        QQ=0.0
        TT=0.0
        IPP= IP(IST)
        DO 70 J=1,IPP
           TT=TT+TISURF(IST,J)
           QQ=QQ+QFLXID(IST,J)
   70    CONTINUE
        TAVG(IST)=TT/IPP
        QAVG(IST)=QQ/IPP
        H(IST)=QAVG(IST)/(TAVG(IST)-TBULK(IST))

   75 CONTINUE

C --------------------------------------
C ----- CALCULATE FLUID PROPERTIES -----
C --------------------------------------

      DO 85 IST=1,NSTN
         T=TBULK(IST)
         CALL MEW(T,MFLUID,X2,VISC)
         CALL SPHEAT(T,MFLUID,X2,SPHT)
         CALL CONDFL(T,MFLUID,X2,COND)
         CALL DENS(T,MFLUID,X2,ROW)
         CALL BET(T,MFLUID,X2,BETA)
         VISCA(IST)=VISC
         ROWA(IST) =ROW
         PR(IST) = VISC*SPHT/COND
         RENO(IST) = GW*DIN/(12.0*VISC)
         GRNO(IST)=G*BETA*ROW**2*(DIN/12)**3*(TAVG(IST)-TBULK(IST))
```

```
     +          /VISC**2 *3600.0**2
         TIS=0.0
         IPP= IP(IST)
         DO 80 IPR=1,IPP
   80        TIS=TIS+TISURF(IST,IPR)
         T=TIS/IPP
         CALL MEW(T,MFLUID,X2,VISWL)
         VISWLA(IST)= VISWL
         VISBW(IST) = VISC/VISWL
         SNUS(IST)=H(IST)*DIN/(12.0*COND)
         TWALL(IST,1)=TAVG(IST)
   85 CONTINUE

C ----------------------------------------------
C ----- CALCULATE FLUID VELOCITY IN FT/SEC -----
C ----------------------------------------------

         VEL = VFLOW/(2.462557*DIN*DIN)

C --------------------------
C ----- PRODUCE OUTPUT -----
C --------------------------

      CALL PRNT

C ---------------------------------------------------------------
C ----- PROMPT USER FOR PROGRAM TERMINATION OR CONTINUATION -----
C ---------------------------------------------------------------

       WRITE(*,*)'WANT TO PROCEED PRESS 1 ELSE 0'
       READ(*,*)RSWT

       IF(RSWT.EQ.1)THEN
       GOTO 1200
       ENDIF

      KEEP = 2
      GO TO 8

   99 STOP

 1002 FORMAT(A36)
 1003 FORMAT(A4)
 1004 FORMAT(I4,I3)
 1005 FORMAT(I2,F5.2,F8.4,5F8.2)
 1006 FORMAT(I3,I3,F9.2,8F8.2)
 1007 FORMAT(//5X,'TEMPERATURES AT STATION',I3,' DO NOT CONVERGE AFTER',
     +       I3,' ITERATIONS. JUMP TO NEXT STATION')
 1008 FORMAT(//////////////,6X,'DATA REDUCTION COMPLETED FOR RUN # ',I4,
     +     /////////)
        CLOSE(6)
        CLOSE(7)
      END

C   **********************************************************************
C   *                                                                    *
C   *                       SUBROUTINE GEOM                              *
C   *                                                                    *
C   *                     ALL LENGTH IN INCHES                           *
C   *                                                                    *
C   **********************************************************************

      SUBROUTINE GEOM
```

```
      COMMON /MAIN1/ IST,KOUNT,NSTN
     +       /GEOM1/ XAREA(31),R(31),LTP(32),LTH(32),DELZ(31),LHEAT,
     +               LTEST,LOD(31),DOUT,DIN,DELR,NODES,NSLICE,PI

      REAL*4 LTH,LTP,LTEST,LHEAT,LOD

      NSLICE=10
      NODES= NSLICE + 1

C --------------------------------
C ----- PROMPT FOR PIPE SIZE -----
C --------------------------------

    1 IPSO = 2

      DOUT=1.315
      DIN=1.097
      LHEAT=103.5
C ------------------------------------------------------
C ----- CALCULATE GEOMETRY FOR FINITE DIFFERENCING -----
C ------------------------------------------------------

    2 PI = 3.141592654
      LTEST = LHEAT+0.5

      DO 3 I=1,NSTN
    3    LOD(I)=LTH(I)/DIN
      LTH(NSTN+1)=LHEAT
      LTP(1)=LTH(1)
      SUM=LTP(1)
       DO 4 I=2,NSTN
        LTP(I) =  LTH(I)-LTH(I-1)
    4    SUM=SUM+LTP(I)
        LTP(NSTN+1)=LHEAT-SUM
      DELZ(1) = LTH(1)+( LTH(2)-LTH(1))/2.0
      DO 5 I=2,NSTN
    5    DELZ(I) = ( LTH(I+1)-LTH(I-1))/2.0
      RETURN
      END
C ********************************************************************
C *                                                                  *
C *                       SUBROUTINE BET                             *
C *                                                                  *
C *   CALCULATES THE THERMAL EXPANSION COEFFICIENT (BETA) FOR PURE   *
C *  WATER AND ANY CONCENTRATION OF ETHYLENE GLYCOL/WATER SOLUTION.  *
C *   THE INPUT IS TEMPERATURE IN DEGREES F AND THE OUTPUT IS 1/F.   *
C *                                                                  *
C ********************************************************************

      SUBROUTINE BET(TF,MFLUID,X,BETA)
      T = (TF-32.0)/1.8

C ----- PURE WATER -----

      IF(MFLUID.GT.1)GO TO 1
       PDRT=0.0615-0.01693*T+2.06E-4*T**2-1.77E-6*T**3+6.3E-9*T**4
       GO TO 2

C ----- ETHYLENE GLYCOL -----

    1  PDRTA = -1.2379*1.E-4 - 9.9189*1.E-4*X +4.1024*1.E-4*X*X
```

```
       PDRTB = 2.*((-2.9837E-06*T+2.4614E-06*X*T -9.5278E-8*X*X*T))
       PDRT=(PDRTA+PDRTB)*1000.
    2 CALL DENS(TF,MFLUID,X,ROW)
      ROW=ROW/.062427
      BETAC= -(1.0/ROW)*(PDRT)
      BETAF =(1.0/BETAC)*1.8
      BETA  = 1.0/BETAF

      RETURN
      END

C **********************************************************************
C *                                                                    *
C *                        SUBROUTINE CONDFL                           *
C *                                                                    *
C *     CALCULATES THE THERMAL CONDUCTIVITY (COND) FOR PURE WATER      *
C *      AND ANY CONCENTRATION OF ETHYLENE GLYCOL/WATER SOLUTION.      *
C *              THE INPUT IS TEMPERATURE IN DEGREES F                 *
C *               AND THE OUTPUT IS IN BTU/HR-FT-'F                    *
C *                                                                    *
C *           TEMPERATURE RANGE:                                       *
C *                PURE WATER           0 - 100 C                      *
C *                E.G. MIXTURES        0 - 150 C                      *
C *                                                                    *
C **********************************************************************

       SUBROUTINE CONDFL(TF,MFLUID,X,COND)

      T=(TF-32.0)/1.8
      CONW=0.56276+1.874E-3*T-6.8E-6*T**2


      IF(MFLUID.GT.1) GO TO 1

C ----- PURE WATER -----

      IF(T.LT.0.0.OR.T.GT.115.0)THEN
       WRITE(*,*)' TEMPERATURE IS OUT OF RANGE IN SUBROUTINE CONDFL'
       STOP
      END IF

       COND=CONW*0.5778
       GO TO 2

C ----- ETHYLENE GLYCOL -----

    1 IF(T.LT.0.0.OR.T.GT.150.0)THEN
       WRITE(*,*)' TEMPERATURE IS OUT OF RANGE IN SUBROUTINE CONDFL'
       STOP
      END IF

       CETH=0.24511+0.0001755*T-8.52E-7*T*T
       CF=0.6635-0.3698*X-0.000885*T
       COND=(1.0-X)*CONW+X*CETH-CF*(CONW-CETH)*(1.0-X)*X
      COND=COND*0.5778
    2 RETURN
      END

C **********************************************************************
C *                                                                    *
C *                     SUBROUTINE DENS                                *
C *                                                                    *
C *        CALCULATES THE FLUID DENSITY (ROW) FOR PURE WATER           *
```

```
C *       AND ANY CONCENTRATION OF ETHYLENE GLYCOL/WATER SOLUTION.     *
C * THE INPUT IS TEMPERATURE IN DEGREES F AND THE OUTPUT IS LB/FT**3. *
C *                                                                    *
C *           TEMPERATURE RANGE:                                       *
C *                PURE WATER            0 - 100 C                     *
C *                E.G. MIXTURES         0 - 150 C                     *
C *                                                                    *
C **********************************************************************

      SUBROUTINE DENS(TF,MFLUID,X,ROW)
      DIMENSION D(3,3),AD(3,3)

      T=(TF-32.0)/1.8
      IF(MFLUID.GT.1) GO TO 1

C ----- PURE WATER -----

      IF(T.LT.0..OR.T.GT.115.0)THEN
      WRITE(*,*)' TEMPERATURE IS OUT OF RANGE IN SUBROUTINE DENS'
      STOP
      END IF

      ROWSI=999.86+.061464*T-.0084648*T**2+6.8794E-5*T**3-4.4214E-7
     +      *T**4+1.2505E-9*T**5
      ROW=ROWSI*0.062427
C     CALCULATING THE ROW WITH T IF DEGREE F
C     BY RYALI
C      ROW=1/(2.101E-8*TF**2-1.303E-6*TF+0.01602)

      GO TO 4

C ----- ETHYLENE GLYCOL -----

    1 IF(T.LT.0.0.OR.T.GT.150.0)THEN
      WRITE(*,*)' TEMPERATURE IS OUT OF RANGE IN SUBROUTINE DENS'
      STOP
      END IF

      AD(1,1)=1.0004
      AD(1,2)=0.17659
      AD(1,3)=-0.049214
      AD(2,1)=-1.2379E-04
      AD(2,2)=-9.9189E-04
      AD(2,3)= 4.1024E-04
      AD(3,1)=-2.9837E-06
      AD(3,2)= 2.4614E-06
      AD(3,3)= -9.5278E-08

      DO 2 I=1,3
       DO 2 J=1,3
    2    D(I,J)=AD(I,J)*X**(J-1)*T**(I-1)
      SUM=0.0
      DO 3 I=1,3
       DO 3 J=1,3
    3    SUM=SUM+D(I,J)
      SUM=SUM*1.E6/1000.0
      ROW=SUM*0.062427

    4 RETURN
      END

C **********************************************************************
C *                                                                    *
```

```
C *                      SUBROUTINE MEW                                 *
C *                                                                     *
C *       CALCULATES THE DYNAMIC VISCOSITY (VISC) FOR PURE WATER        *
C *      AND ANY CONCENTRATION OF ETHYLENE GLYCOL/WATER SOLUTION.       *
C * THE INPUT IS TEMPERATURE IN DEGREES F AND THE OUTPUT IS LB/HR.FT.   *
C *                                                                     *
C *           TEMPERATURE RANGE:                                        *
C *                PURE WATER          10 - 100 C                       *
C *                E.G. MIXTURES        0 - 150 C                       *
C *                                                                     *
C **********************************************************************

      SUBROUTINE MEW(TF,MFLUID,X,VISC)
      DIMENSION V(3,3),AV(3,3),V2(3)

      T=(TF-32.0)/1.8
      IF(MFLUID.GT.1) GO TO 1

C ----- PURE WATER -----

      IF(T.LT.10..OR.T.GT.115.0)THEN
       WRITE(*,*)' TEMPERATURE IS OUT OF RANGE IN SUBROUTINE MEW'
       STOP
      END IF

      VISC=2.4189*1.0019*10.0**((1.3272*(20.0-T)-0.001053*(20-T)
     +     **2)/(T+105.0))
      GO TO 4

C ----- ETHYLENE GLYCOL -----

    1 IF(T.LT.0..OR.T.GT.150.0)THEN
       WRITE(*,*)' TEMPERATURE IS OUT OF RANGE IN SUBROUTINE MEW'
       STOP
      END IF

      AV(1,1)=0.55164
      AV(1,2)=2.6492
      AV(1,3)=0.82935
      AV(2,1)=-0.027633
      AV(2,2)=-0.031496
      AV(2,3)= 0.0048136
      AV(3,1)= 6.0629E-17
      AV(3,2)= 2.2389E-15
      AV(3,3)= 5.879E-16

      DO 2 I=1,2
      DO 2 J=1,3
          V(I,J)=AV(I,J)*X**(J-1)*T**(I-1)
    2     V2(J)=AV(3,J)*X**(J-1)

        SUM=0.0
      DO 3 I=1,3
    3   SUM=SUM+V2(I)
       V3=SUM**0.25*T*T
       VISC=V3 + V(1,1)+V(1,2)+V(1,3)+V(2,1)+V(2,2)+V(2,3)
      VISC=EXP(VISC)*2.4189

    4 RETURN
      END

C  ******************************************************************
C  *                                                                *
```

```
C  *                      SUBROUTINE PRNUM                                 *
C  *                                                                       *
C  *         CALCULATES THE PRANDTL NO.(PRN) FOR PURE WATER                *
C  *     AND ANY CONCENTRATION OF ETHYLENE GLYCOL/WATER SOLUTION.          *
C  *            THE INPUT IS TEMPERATURE IN DEGREES F.                     *
C  *                                                                       *
C  *            TEMPERATURE RANGE:                                         *
C  *                 PURE WATER           10 - 100 C                       *
C  *                 E.G. MIXTURES         0 - 150 C                       *
C  *                                                                       *
C  *********************************************************************

      SUBROUTINE PRNUM(TF,MFLUID,X,PRN)
      DIMENSION P(3,3),AP(3,3),P2(3)

      T=(TF-32.0)/1.8
      IF(MFLUID.GT.1) GO TO 1

C ----- PURE WATER -----

      IF(T.LT.10.OR.T.GT.115.0)THEN
       WRITE(*,*)' TEMPERATURE IS OUT OF RANGE IN SUBROUTINE PRNUM'
       STOP
      END IF

       CALL SPHEAT(TF,MFLUID,X,SPHT)
       CALL MEW(TF,MFLUID,X,VISC)
       CALL CONDFL(TF,MFLUID,X,COND)
       PRN=SPHT*VISC/COND
       RETURN

C ----- ETHYLENE GLYCOL -----

    1 IF(T.LT.0.0.OR.T.GT.150.0)THEN
       WRITE(*,*)' TEMPERATURE IS OUT OF RANGE IN SUBROUTINE PRNUM'
       STOP
      END IF

      AP(1,1)=2.5735
      AP(1,2)=3.0411
      AP(1,3)=0.60237
      AP(2,1)=-0.031169
      AP(2,2)=-0.025424
      AP(2,3)= 0.0037454
      AP(3,1)= 1.1605E-16
      AP(3,2)= 2.5283E-15
      AP(3,3)= 2.3777E-16

      DO 2 I=1,2
      DO 2 J=1,3
          P(I,J)=AP(I,J)*X**(J-1)*T**(I-1)
    2     P2(J)=AP(3,J)*X**(J-1)

       SUM=0.0

       DO 3 I=1,3
    3     SUM=SUM+P2(I)
       P3=SUM**0.25*T*T
       PRN=P3+P(1,1)+P(1,2)+P(1,3)+P(2,1)+P(2,2)+P(2,3)
      PRN=EXP(PRN)

      RETURN
      END
```

```
C ******************************************************************
C *                                                                *
C *                     SUBROUTINE SPHEAT                          *
C *                                                                *
C *        CALCULATES THE SPECIFIC HEAT (SPHT) FOR PURE WATER      *
C *     AND ANY CONCENTRATION OF ETHYLENE GLYCOL/WATER SOLUTION.   *
C *             THE INPUT IS TEMPERATURE IN DEGREES F              *
C *               AND THE OUTPUT IS IN BTU/(LBM-DEGF).             *
C *                                                                *
C *           TEMPERATURE RANGE:                                   *
C *                PURE WATER          0 - 100 C                   *
C *                E.G. MIXTURES       0 - 150 C                   *
C *                                                                *
C ******************************************************************

      SUBROUTINE SPHEAT(TF,MFLUID,X,SPHT)

      T=(TF-32.0)/1.8
      IF(MFLUID .GT. 1.0)GO TO 1

C ----- PURE WATER -----

      IF(T.LT.0.0.OR.T.GT.115.0)THEN
       WRITE(*,*)' TEMPERATURE IS OUT OF RANGE IN SUBROUTINE SPHT'
       STOP
      END IF

      SPHT=-1.475E-7*T**3+3.66E-5*T*T-.0022*T+4.216
      SPHT=SPHT/4.1868

      RETURN

C ----- ETHYLENE GLYCOL -----

    1 IF(T.LT.0.0.OR.T.GT.150.0)THEN
       WRITE(*,*)' TEMPERATURE IS OUT OF RANGE IN SUBROUTINE SPHT'
       STOP
      END IF

       CALL MEW(TF,MFLUID,X,VISC)
       CALL CONDFL(TF,MFLUID,X,COND)
       CALL PRNUM(TF,MFLUID,X,PRN)
       SPHT = PRN*COND/VISC
      RETURN
      END

C  ******************************************************************
C  *                                                                *
C  *                     SUBROUTINE PRINT-OUT                       *
C  *                                                                *
C  *          PRINTS DATA TO OUTPUT FILES:                          *
C  *                                                                *
C  *                 "RN(run #).SUM"      - Device #6               *
C  *                 "RN(run #).DAT"      - Device #9               *
C  *                                                                *
C  ******************************************************************

      SUBROUTINE PRNT

      INTEGER IREN(31,8),IDFLX(31,8),hHAU(10,4),hSDT(10,4)
      INTEGER STN
      COMMON /PRINT/ IPICK,REN(31,8),TBULK(31),VEL,REYNO,PRNO,GW,
```

```
     +             HTCOFF(31,8),H(31),RENO(31),GRNO(31),PR(31),
     +             SNUS(31),VISBW(31),SHTHB(32),QFLXID(31,8),QFLXAV,
     +             QGEXPT,QBALC,QPCT,IPMAX,TAVG(31),VISCA(31),
     +             VISWLA(31),ROWA(31)
     +      /INPUT/ TROOM,VOLTS,TAMPS,RMFL,MFLUID,X2,FLOWRT,NRUN,VFLOW,
     +             TIN,TOUT,TOSURF(31,8),TISURF(31,8),IP(32),KST(32)
     +      /TEMP1/ TWALL(31,8),AMPS(31,8),RESIS(31,8),POWERS(32),
     +             TPOWER
     +      /MAIN1/ IST,KOUNT,NSTN
     +      /GEOM1/ XAREA(31),R(31),LTP(32),LTH(32),DELZ(31),LHEAT,
     +             LTEST,LOD(31),DOUT,DIN,DELR,NODES,NSLICE,PI

       REAL*4 LTH,LTP,LTEST,LHEAT,H,HTCOFF,LOD
       REAL*8 muW(10),Twl(10),muB(10),Tbl(10),kL(10),nHAU(10),nSDTT(10)
     +        ,aPTP,fPTP,fGNL,nDTB(10),nPTP(10),nGNL(10),nCLB(10),
     +        nSDTL(10),TMP,AmBmW,fCHR,nCHRL,nCHRT,nCHR(10),nGHJL(10),
     +        nGHJT(10),cPTP
      REAL*8 LovD,DovL,IHCOF(31,8)
      COMMON/STATION/STN
      LovD=94.80401d0
      DovL=0.010548d0
      AmBmW=0.0
      DO 5000 IST=1,10
      nGNL(IST)=0.0
      nGHJt(IST)=0.0
      nPTP(IST)=0.0
 5000 CONTINUE
C ---------------------------------------------
C ----- SET FLAG FOR STATION OUTPUT CONTROL -----
C ---------------------------------------------

CC        ATST=NSTN/9.
       ATST=NSTN/11.
       IFST=INT(ATST)+1

C ------------------------------------
C ----- PRINT RUN NUMBER & TUBE DATA -----
C ------------------------------------

C ----- ENGLISH UNITS -----

      WRITE(6,2001)NRUN

C ----- PRINT FLUID-TYPE DESCRIPTION -----

      IF(MFLUID.EQ.1)THEN
       WRITE(6,2003)
      ELSE
       WRITE(6,2004)X2
      ENDIF

C ----- PRINT TUBE DATA -----

      IGW=GW
      IREYN=REYNO
      IFXA=QFLXAV
      IQEX=QGEXPT
      IQBL=QBALC

      WRITE(6,2016)VFLOW,RMFL,IGW,VEL,TROOM,TIN,TOUT,IREYN,PRNO,
     +             TAMPS,VOLTS,IFXA,IQEX,IQBL,QPCT

C ----------------------------------------------
```

```
C ----- PRINT TUBE OUTSIDE SURFACE TEMPERATURES -----
C ---------------------------------------------------

C ----- ENGLISH UNITS -----

      DO 5 K=1,NSTN
      IF(IP(K).EQ.2)THEN
        TOSURF(K,3)=TOSURF(K,2)
        TOSURF(K,2)=0.0
        TOSURF(K,4)=0.0
       ELSE
    5 ENDIF

      WRITE(6,2005)
      DO 7 ICNT=1,IFST
cc          KMIN=1+(ICNT-1)*9
cc          KMAX=KMIN+8
       KMIN=1+(ICNT-1)*10
       KMAX=KMIN+9
       IF(NSTN.LT.KMAX)KMAX=NSTN
       DO 6 IPR=1,IPMAX
        IF(IPR.EQ.1)WRITE(6,2006)(KST(K),K=KMIN,KMAX)
        IF(IPR.EQ.1 .AND. KMAX.LT.(KMIN+9))WRITE(6,2007)
         WRITE(6,2008)IPR,(TOSURF(IST,IPR),IST=KMIN,KMAX)

     6 CONTINUE
     7 CONTINUE

C ------------------------------------------------------------
C ----- PRINT INSIDE SURFACE TEMPERATURES TO OUTPUT FILE -----
C ------------------------------------------------------------

C ----- ENGLISH UNITS -----

      DO 14 K=1,NSTN
      IF(IP(K).EQ.2)THEN
        TISURF(K,3)=TISURF(K,2)
        TISURF(K,2)=0.0
        TISURF(K,4)=0.0
      ELSE
   14 ENDIF

      WRITE(6,2010)
      DO 16 ICNT=1,IFST
       KMIN=1+(ICNT-1)*10
       KMAX=KMIN+9
       IF(NSTN.LT.KMAX)KMAX=NSTN
       DO 15 IPR=1,IPMAX
        IF(IPR.EQ.1)WRITE(6,2006)(KST(K),K=KMIN,KMAX)
        IF(IPR.EQ.1 .AND. KMAX.LT.(KMIN+9))WRITE(6,2007)
         WRITE(6,2008)IPR,(TISURF(IST,IPR),IST=KMIN,KMAX)


   15   CONTINUE
   16  CONTINUE

C$$$$$$$$$$$$$  calculating the muW AND mub at each location (BY RYALI)$$$$$$$

       DO 151 IST=1,10
           Twl(IST)=(TAVG(IST)-32.0)/1.8

           Tbl(IST)=(TBULK(IST)-32.0)/1.8
           muB(IST)=2.4189*1.0019*10.0**((1.3272*(20.0-Tbl(IST))-
```

```
     +            0.001053*(20-Tbl(IST))**2)/(Tbl(IST)
     +            +105.0))
         muW(IST)=2.4189*1.0019*10.0**((1.3272*(20.0-Twl(IST))-
     +            0.001053*(20-Twl(IST))**2)/(Twl(IST)+105.0))

         kL(IST)=(0.56276+1.874E-3*Tbl(IST)-6.8E-6*Tbl(IST)**2)*0.5778D0

         AmBmW=AmBmW+(muB(IST)/muW(IST))

 151    CONTINUE

         AmBmW=AmBmW/10
C$$$$$$$$$$$$   END BY RYALI $$$$$$$$$$$$$$$$$$$


C ------------------------------------------------
C ----- PRINT REYNOLDS NUMBERS TO OUTPUT FILE -----
C ------------------------------------------------

   22 DO 29 K=1,NSTN
      IF(IP(K).EQ.2)THEN
        IREN(K,1)=INT(REN(K,1))
        IREN(K,3)=INT(REN(K,2))
        IREN(K,2)=0
        IREN(K,4)=0
       ELSE
       DO 28 L=1,IPMAX
   28    IREN(K,L)=INT(REN(K,L))
   29 ENDIF

      WRITE(6,2014)
      DO 31 ICNT=1,IFST
cc       KMIN=1+(ICNT-1)*9
cc       KMAX=KMIN+8
       KMIN=1+(ICNT-1)*10
       KMAX=KMIN+9
       IF(NSTN.LT.KMAX)KMAX=NSTN
      DO 30 IPR=1,IPMAX
       IF(IPR.EQ.1)WRITE(6,2006)(KST(K),K=KMIN,KMAX)
       IF(IPR.EQ.1 .AND. KMAX.LT.(KMIN+9))WRITE(6,2007)

           WRITE(6,2015)IPR,(IREN(IST,IPR),IST=KMIN,KMAX)
   30    CONTINUE
   31  CONTINUE

C ------------------------------------------------
C ----- PRINT INSIDE HEAT FLUXES TO OUTPUT FILE -----
C ------------------------------------------------

C ----- ENGLISH UNITS -----

      DO 35 K=1,NSTN
      IF(IP(K).EQ.2)THEN
        IDFLX(K,1)=INT(QFLXID(K,1))
        IDFLX(K,3)=INT(QFLXID(K,2))
        IDFLX(K,2)=0
        IDFLX(K,4)=0
      ELSE
        DO 34 L=1,IPMAX
   34    IDFLX(K,L)=INT(QFLXID(K,L))
   35 ENDIF

      WRITE(6,2020)
```

```
      DO 37 ICNT=1,IFST
cc         KMIN=1+(ICNT-1)*9
cc         KMAX=KMIN+8
       KMIN=1+(ICNT-1)*10
       KMAX=KMIN+9
       IF(NSTN.LT.KMAX)KMAX=NSTN
       DO 36 IPR=1,IPMAX
        IF(IPR.EQ.1)WRITE(6,2006)(KST(K),K=KMIN,KMAX)
        IF(IPR.EQ.1 .AND. KMAX.LT.(KMIN+9))WRITE(6,2007)
          WRITE(6,2021)IPR,(IDFLX(IST,IPR),IST=KMIN,KMAX)
   36   CONTINUE
   37  CONTINUE

C --------------------------------------------------------
C ---- PRINT PERIPHERAL HEAT TRANSFER COEFFICIENTS -----
C --------------------------------------------------------

        WRITE(6,2017)NRUN
C ----- ENGLISH UNITS -----

      DO 46 K=1,NSTN
      IF(IP(K).EQ.2)THEN
        IHCOF(K,1)=HTCOFF(K,1)
        IHCOF(K,3)=HTCOFF(K,2)
        IHCOF(K,2)=0
        IHCOF(K,4)=0
       ELSE
        DO 45 L=1,IPMAX
   45     IHCOF(K,L)=HTCOFF(K,L)
   46 ENDIF

      WRITE(6,2023)
      DO 48 ICNT=1,IFST
cc         KMIN=1+(ICNT-1)*9
cc         KMAX=KMIN+8
       KMIN=1+(ICNT-1)*10
       KMAX=KMIN+9
       IF(NSTN.LT.KMAX)KMAX=NSTN
       DO 47 IPR=1,IPMAX

       IF(IPR.EQ.1)WRITE(6,2006)(KST(K),K=KMIN,KMAX)
       IF(IPR.EQ.1 .AND. KMAX.LT.(KMIN+9))WRITE(6,2007)
           WRITE(6,2021)IPR,(INT(IHCOF(IST,IPR)),IST=KMIN,KMAX)

   47  CONTINUE
   48  CONTINUE

C ----------------------------------------------
C ----- PRINT SUMMATION DATA FOR OUTPUT FILE -----
C ----------------------------------------------

   55 WRITE(6,2028)NRUN

      WRITE(7,2028)NRUN

      WRITE(6,2029)
      WRITE(7,3029)
      DO 56 J=1,NSTN
      WRITE(6,2030)KST(J),RENO(J),PR(J),LOD(J),VISCA(J),VISWLA(J),
     +              TBULK(J),TAVG(J),ROWA(J),SNUS(J)

C      PRINT OUT TO *.CMP FILE HTOP/HBOT
```

```
      WRITE(7,3030)KST(J),LOD(J),TBULK(J),RENO(J),PR(J),SNUS(J),
     +             GRNO(J),VISCA(J)/VISWLA(J),IHCOF(J,1)/IHCOF(J,3)

C      PRINT OUT TO *.CMP FILE HTOP/HBOT

   56 CONTINUE


C ----- PRINT NOTE GIVING UNITS -----

      WRITE(6,2032)
      RETURN

 2001 FORMAT(/,18X,'*',41('-'),'*',/32X,'RUN NUMBER ',I4)
 2003 FORMAT(25X,'TEST FLUID IS DISTILLED WATER',/18X,'*',41('-'),'*')
 2004 FORMAT(19X,'MASS FRACTION OF ETHYLENE GLYCOL =',F8.4,/18X,'*',
     +       41('-'),'*')
 2005 FORMAT(//20X,'OUTSIDE SURFACE TEMPERATURES - DEGREES F')
 2006 FORMAT(/,9X,I2,6X,I2,6X,I2,6X,I2,6X,I2,6X,I2,6X,I2,6X,I2,6X,I2,
     +       6X,I2,/)
 2007 FORMAT(' ')
 2008 FORMAT(3X,I1,1X,10F8.2)
 2010 FORMAT(//20X,'INSIDE SURFACE TEMPERATURES - DEGREES F')
 2014 FORMAT(//20X,'REYNOLDS NUMBER AT THE INSIDE TUBE WALL')
 2015 FORMAT(3X,I1,10I8)
 2016 FORMAT(/,18X,'VOLUMETRIC FLOW RATE =',F9.2,3X,'GPM',
     +       /18X,'MASS FLOW RATE',7X,'=',F9.1,3X,'LBM/HR',
     +       /18X,'MASS FLUX',12X,'=',I9,3X,'LBM/(SQ.FT-HR)',
     +       /18X,'FLUID VELOCITY',7X,'=',F9.2,3X,'FT/S',
     +       /18X,'ROOM TEMPERATURE',5X,'=',F9.2,3X,'F',
     +       /18X,'INLET TEMPERATURE',4X,'=',F9.2,3X,'F',
     +       /18X,'OUTLET TEMPERATURE',3X,'=',F9.2,3X,'F',
     +       /18X,'AVERAGE RE NUMBER',4X,'=',I9,
     +       /18X,'AVERAGE PR NUMBER',4X,'=',F9.2,
     +       /18X,'CURRENT TO TUBE',6X,'=',F9.1,3X,'AMPS',
     +       /18X,'VOLTAGE DROP IN TUBE =',F9.2,3X,'VOLTS',
     +       /18X,'AVERAGE HEAT FLUX',4X,'=',I9,3X,'BTU/(SQ.FT-HR)'
     +       /18X,'Q=AMP*VOLT',11X,'=',I9,3X,'BTU/HR',
     +       /18X,'Q=M*C*(T2-T1)',8X,'=',I9,3X,'BTU/HR',
     +       /18X,'HEAT BALANCE ERROR',3X,'=',F9.2,3X,'%')
 2017 FORMAT(//31X,'*',15('-'),'*',/32X,'RUN NUMBER ',I4,/31X,'*',
     +         15('-'),'*')
 2020 FORMAT(//22X,'INSIDE SURFACE HEAT FLUXES BTU/HR/FT2')
 2021 FORMAT(3X,I1,10I8)
 2023 FORMAT(/14X,'PERIPHERAL HEAT TRANSFER COEFFICIENT BTU/',
     +       '(SQ.FT-HR-F)')
 2028 FORMAT(//31X,'*',15('-'),'*',/32X,'RUN NUMBER ',I4,/36X,
     +       'SUMMARY',/31X,'*',15('-'),'*')
 2029 FORMAT(/1X,'ST',6X,'RE',7X,'PR',5X,'X/D',5X,'MUB',5X,'MUW',
     +       5X,'TB',6X,'TW',5X,'DENS',6X,'NU',/)
 2030 FORMAT(1X,I2,3X,F8.2,2X,F5.2,3X,F5.1,3X,F5.3,3X,F5.3,
     +       2(2X,F6.2),3X,F5.2,3X,F6.2)
 2032 FORMAT(/,20X,'NOTE: TBULK IS GIVEN IN DEGREES FAHRENHEIT',/,
     +          26X,'MUB AND MUW ARE GIVEN IN LBM/(FT*HR)')

      END
```

C.3 Program CAL-TUB2

This program was coded by D. Kim in 1999 in order to calibrate the liquid turbine flow meters as mentioned in Chapter III. The voltage information from the totalizer and the time to fill the five gallon container with water were recorded in a file. The complete program listing is as follows:

```
/* This program is Written by Dongwoo Kim
   for the Experimental Study of Two-Phase Flow and Heat Transfer
   in a Horizontal Pipe
   Purpose:
   Calibtate the Liquid Flowrate Totalizer in (L/min).
   (Last Modified: Apr. 07, 1999) */

#include <stdio.h>
#include <conio.h>
#include <stdlib.h>
#include <dos.h>
#include <math.h>
#include <time.h>
#include <bios.h>
#include "c:\cb\c\cb.h"
#include <ctype.h>

#define TMR_INTERRUPT     0x8         /* Timer interrupt vector */
#define KBD_INTERRUPT     0x9         /* Keyboard interrupt vector */
#define TIMER_OSCILLATOR 1193180.0    /* Timer oscillator frequency */
#define ISR_8259          0x0020      /* i8259 in-service reg addr */
#define EOI_8259          0x20        /* i8259 none-specific end of intrrpt */
#define CWR_8253          0x0043      /* control word register addr */
#define CTR0_8253         0x0040      /* timer 0 counter addr */
#define SET_CTR0_8253     0x0036      /* binary mode 3, ctr 0 */
#define Max_time          450000


void interrupt (*TIMER_handler) (void);
void interrupt (*KEYB_handler) (void);
void interrupt click(void);
void interrupt keyb(void);
void Chan_Setting(void);

//Gloval variable
int quit=0;
int seconds=0;
unsigned C_CLICK = 0;
int Flag, Sign=1;
char str[10];
int  Bit_On=3;
int Chan_LiqVIn=2;
int  STOP=1000, WAIT=1;
FILE *ofp1, *ofp2;

//Main Program
int main(void)
```

```
{
//Open Raw Data File
 ofp1=fopen("Cal-fVol.dat","w");
//Open Averaged Value Data File
 ofp2=fopen("Cal-fVol.avg","w");

 float interval = 50; /*** INTERRUPT LATENCY IN MILLISECONDS ***/
 int i_interval = TIMER_OSCILLATOR*interval/1000.0 + 0.5;
 int BoardNum=0, PortNum, Direction, Gain, iter, j;
 unsigned int DataValueV; //DataValueP
 float R_VLiq, VLiq, period; //R_PGas, R_TGas, R_PAir, PGas, LperM
 double sum_VLiq, AVLiq, RavgVLiq; //sum_PGas
 char more;

 int Bit_Off=0; // Range=BIP10VOLTS;

 //DAS Board Connection Checking
 cbErrHandling(PRINTALL, STOPALL);
 PortNum=FIRSTPORTA;
 Direction=DIGITALOUT;
 cbDConfigPort (BoardNum, PortNum, Direction);
 Gain = BIP10VOLTS;

  RavgVLiq=0.0;

 //Set Control Bit Values according to A/D Board Channel Connection
 Chan_Setting();

 printf("\n%s\n",
 "Type the reading value of Liquid FREQUENCY (Hz) from Totalizer");
 scanf("%f", &R_VLiq);

 TIMER_handler = getvect(TMR_INTERRUPT);
 disable();

/******************* CHANGE TIMER RESOLUTION *********************/
 outportb(CWR_8253, SET_CTR0_8253);
 outportb(CTR0_8253, i_interval & 0xff);
 outportb(CTR0_8253, (i_interval & 0xff00) >> 8);

/******************* SET TIMER INTERRUPT **********************/
 setvect(TMR_INTERRUPT, click);
 enable();

/******************* SET KEYBOARD INTERRUPT *****************/
 KEYB_handler = getvect(KBD_INTERRUPT) ;
 disable();
 setvect(KBD_INTERRUPT, keyb);
 enable() ;

/*********** Time measurement for Data Collection in SECOND *******/
 clock_t start, end;
 start = clock();

for (j=1; !quit; j+=1)     //
{
 sum_VLiq=0.0;

/************** MAIN LOOP ***********************************/
 for(iter=1; iter<=STOP; iter+=1)     //&& !quit
 {
       if(Sign==1)
       {
```

```
        cbAIn(BoardNum, Chan_LiqVIn, Gain, &DataValueV);
        cbToEngUnits(BoardNum, Gain, DataValueV, &VLiq);

        fprintf(ofp1, "%f     %f\n", R_VLiq, 2*VLiq); //R_PGas, PGas);

        sum_VLiq=sum_VLiq+VLiq;
      }     //Endif

     C_CLICK = 0;

     if(Sign==-1)
     {
     //Send a Bit to turn the scanivalve channel
     cbDOut(BoardNum, PortNum, Bit_On);
     while(C_CLICK < WAIT); /**** WAIT UNTIL 0.1 SECOND ****/
     C_CLICK=0.0;

     //Turn off the Bit
     cbDOut(BoardNum, PortNum, Bit_Off);

     // The "Sign" Value Bact to 1
     Sign=1;
     }
  }      //End for


AVLiq=sum_VLiq/(iter-1);
RavgVLiq += (AVLiq-RavgVLiq) / j;

   seconds++;
}
end = clock();
period = (end - start) / CLK_TCK ;
printf("\n %s%d%s%f\n",
  "The time period (sec) for ",STOP," data collection  = ", period);
fprintf(ofp2,"\n %s%d%s%f\n",
  "The time period (sec) for ",STOP," data collection  = ", period);
fprintf(ofp2,"\n\n %s\n %s\n",
  "The averaged VOLTS of Liquid Flowrate measurements was",
  "Read f (Hz)                   Measured V (volt)");
fprintf(ofp2,"%s%f%s%lf%s%lf\n",
  "    ",R_VLiq,"       ",2*AVLiq,"       ",2*RavgVLiq);
fclose(ofp1);
fclose(ofp2);

/************ CLEANUP TIMER & KEYBOARD INTERRRUPT *********/
disable();
outportb(CWR_8253, SET_CTR0_8253);
outportb(CTR0_8253, 0x0);
outportb(CTR0_8253, 0x0);
setvect(TMR_INTERRUPT , TIMER_handler);
enable() ;

disable();
setvect(KBD_INTERRUPT, KEYB_handler);
enable() ;

}


/*********   SOURCE CODE FOR click()          **************
********* Increments counter and sets flag   **************/
```

```
void interrupt click(void)
{
        ++C_CLICK;
        TIMER_handler();
        outportb(ISR_8259, EOI_8259);
}


/************************** USER DEFINED KEYBOARD HANDLER ***********/
void Key_Handler(void)
{
        int key = toupper(getch()), n, j; //change, sign;
        char number;
        static int cnt=0;
        switch(key)
        {
                case 27: quit = 1; break;                //'ESC' key
                case 'Q': quit=1; break;
                case 'R': Sign=-1; break;
                case 'S':
                {Flag = 1; cnt=0; }  break;
                case 13:
                {n=atoi(str);  Flag=0; //change=1;       //String to a Integer
                 for(j=0; j<=11; j++) str[j]='\n'; }     //Cleanup the String
                 break;

                case '1': case '2':case '3': case '4':case '5': case '6':
                case '7': case '8':case '9': case '0':
                {number=key;
                 if(Flag==1)
                { str[cnt]=number; cnt++; }        //Make a String
                }
                }
}


/************************ SOURCE CODE FOR keyb()*******************
**********                 Keyboard Interrupt   **********/
void interrupt keyb(void)
{
        KEYB_handler();
        if (kbhit()) Key_Handler();
}


/* Hardware Channel Settings for A_In & D_Out */
void Chan_Setting(void)
{
 char ans;
 printf("\n %s\n %s\n",
    "Type a STOP number for a Max. Iterations (Integer)",
    "  EX.) Default STOP = 1000 for 1000 data collection");
    scanf("%d", &STOP);
 printf("\n %s%d\n %s\n %s\n %s\n %s\n %s\n",
    "Your STOP value = ", STOP,
    "Channel Setting Information for A/D Board",
    "Current Channel Settings are : ",
    "       AIn_V_Ground=17,   AIn_V_Gasmeter (L/min)=0",
    "       AIn_V_GasPressure (psi)=1, AIn_V_Liquid (L/min)=2",
    "Do You Want to Change Channel Settings ? (Type y/n)");
    scanf(" %c", &ans);
    if (ans=='Y' || ans=='y') {
```

```
      do {
      printf("\n %s\n %s\n",
       "Type a STOP number for the maximum iteration (Integer)",
       "  EX.) Default STOP = 1000 for 1000 data collection");
      scanf("%d", &STOP);
      printf("\n Input Channel Number for Chan_Liq_VIn (L/min) :  ");
      scanf("%d", &Chan_LiqVIn);
      printf("\n %s\n %s%d\n",
       "  Your Channel Settings are : ",
       "   AIn_V_LiqVIn = ",Chan_LiqVIn);
      printf("\n %s\n",
        "Do You Want to Change Channel Settings ? (Type y/n)");
      scanf(" %c", &ans);
      } while (ans=='Y' || ans=='y');

    }
}
```

C.4 Program GAS_PV2

This program was coded by D. Kim in 1999 in order to calibrate the gas volumetric flow meter and the gas absolute pressure transducer as mentioned in Chapter III. The voltage information from the gas flow meter and gas pressure transducer were recorded in a file. The complete program listing is as follows:

```
/* This program is Written by Dongwoo Kim
   for the Experimental Study of Two-Phase Flow and Heat Transfer
   in a Horizontal Pipe
   Purpose:
   Calibtate the gas flow meter (L/min) and abs. Pressure
   Transducer (in_Hg)
   (Last Modified: Fbe. 10, 1999) */

#include <stdio.h>
#include <conio.h>
#include <stdlib.h>
#include <dos.h>
#include <math.h>
#include <time.h>
#include <bios.h>
#include "c:\cb\c\cb.h"
#include <ctype.h>

#define TMR_INTERRUPT    0x8          /* Timer interrupt vector */
#define KBD_INTERRUPT    0x9          /* Keyboard interrupt vector */
#define TIMER_OSCILLATOR 1193180.0    /* Timer oscillator frequency */
#define ISR_8259         0x0020       /* i8259 in-service reg addr */
#define EOI_8259         0x20         /* i8259 none-specific end of intrrpt */
#define CWR_8253         0x0043       /* control word register addr */
#define CTR0_8253        0x0040       /* timer 0 counter addr */
#define SET_CTR0_8253    0x0036       /* binary mode 3, ctr 0 */
#define Max_time         450000


void interrupt (*TIMER_handler) (void);
void interrupt (*KEYB_handler) (void);
void interrupt click(void);
void interrupt keyb(void);
void Chan_Setting(void);
float convertV(float);

//Gloval variable
int quit=0;
int seconds=0;
unsigned C_CLICK = 0;
int Flag, Sign=1;
char str[10];
int  Bit_On=3;

//Gloval variable
int Chan_GasVIn=0;
int Chan_GasPIn=1;
```

```
int STOP=100, WAIT=1;
FILE *ofp1, *ofp2;

//Main Program
int main(void)
{
//Open Raw Data File
 ofp1=fopen("C_GasPV2.dat","w");
//Open Averaged Value Data File
 ofp2=fopen("C_GasPV2.avg","w");

 float interval = 50; /*** INTERRUPT LATENCY IN MILLISECONDS ***/
 int i_interval = TIMER_OSCILLATOR*interval/1000.0 + 0.5;

 int BoardNum=0, PortNum, Direction, Gain, iter;
 unsigned int DataValueV, DataValueP;
 float R_PGas,R_VGas, R_TGas, R_PAir, VGas, PGas, LperM, period;
 float sum_VGas, sum_PGas;
 char more;

 int Bit_Off=0; // Range=BIP10VOLTS;

 //DAS Board Connection Checking
 cbErrHandling(PRINTALL, STOPALL);
 PortNum=FIRSTPORTA;
 Direction=DIGITALOUT;
 cbDConfigPort (BoardNum, PortNum, Direction);
 Gain = BIP5VOLTS;

 do {
 sum_VGas=0.0;
 sum_PGas=0.0;

 //Set Control Bit Values according to A/D Board Channel Connection
 Chan_Setting();

 printf("\n%s\n",
 "Type the reading value of Gas Flowrate (L/min) from flowmeter");
 scanf("%f", &R_VGas);

 printf("\n%s\n",
 "Type the reading value of Gas Temperature ('C)");
 scanf("%f", &R_TGas);

 printf("\n%s\n",
 "Type the reading value of AIR ABS. Pressure (mm_Hg) from manometer");
 scanf("%f", &R_PAir);

 printf("\n%s\n",
 "Type the reading value of Gas Pressure (in_Hg) from manometer");
 scanf("%f", &R_PGas);

 //Compensate the Gas ABS. Pressure in in_Hg
 R_PGas = R_PGas + R_PAir/25.4;

 TIMER_handler = getvect(TMR_INTERRUPT);
 disable();

/******************* CHANGE TIMER RESOLUTION *********************/
 outportb(CWR_8253, SET_CTR0_8253);
 outportb(CTR0_8253, i_interval & 0xff);
 outportb(CTR0_8253, (i_interval & 0xff00) >> 8);
```

```
/******************** SET TIMER INTERRUPT ************************/
 setvect(TMR_INTERRUPT, click);
 enable();

/******************** SET KEYBOARD INTERRUPT *******************/
 KEYB_handler = getvect(KBD_INTERRUPT) ;
 disable();
 setvect(KBD_INTERRUPT, keyb);
 enable() ;

/*********** Time measurement for Data Collection in SECOND *******/
 clock_t start, end;
 start = clock();


/*************** MAIN LOOP *************************************/
 for(iter=1; iter<=STOP && !quit; iter+=1)
 {
     if(Sign==1)
      {
        cbAIn(BoardNum, Chan_GasVIn, Gain, &DataValueV);
        cbToEngUnits(BoardNum, Gain, DataValueV, &VGas);

        LperM = convertV(VGas);

        cbAIn(BoardNum, Chan_GasPIn, Gain, &DataValueP);
        cbToEngUnits(BoardNum, Gain, DataValueP, &PGas);

        fprintf(ofp1, "%f    %f    %f    %f\n", R_VGas, VGas, R_PGas, PGas);

        sum_VGas=sum_VGas+VGas;
        sum_PGas=sum_PGas+PGas;

       C_CLICK = 0;
      }     //Endif
     C_CLICK = 0;

     if(Sign==-1)
    {
     //Send a Bit to turn the scanivalve channel
     cbDOut(BoardNum, PortNum, Bit_On);
     while(C_CLICK < WAIT); /**** WAIT UNTIL 0.1 SECOND ****/

     //Turn off the Bit
     cbDOut(BoardNum, PortNum, Bit_Off);

     // The "Sign" Value Bact to 1
     Sign=1;
     }
   C_CLICK = 0;
   seconds++;
  }      //End for

end = clock();
period = (end - start) / CLK_TCK ;
printf("\n %s%d%s%f\n %s\n",
  "The time period (sec) for ",STOP*2," data  = ", period,
  "(Note: Flowrate & Pressure makes twice the total Number Data point)");


VGas=sum_VGas/iter;
PGas=sum_PGas/iter;
```

```
fprintf(ofp2,"\n %s%f\n",
  "The reading temperature = ", R_TGas);
fprintf(ofp2,"\n %s%d%s%f\n",
  "The time period (sec) for ",STOP*2," data  = ", period);
fprintf(ofp2,"\n\n %s\n %s\n",
  "The averaged VOLTS of Flowrate and Pressure of the measurements were",
  "Read V (L/min) Measured V (volt) Reading ABS. (in_Hg) Measured P (volt)");
fprintf(ofp2,"%s%f%s%f%s%f%s%f\n",
  "    ",R_VGas,"      ",VGas,"         ",R_PGas,"              ",PGas);

/************ CLEANUP TIMER & KEYBOARD INTERRRUPT *********/
disable();
outportb(CWR_8253, SET_CTR0_8253);
outportb(CTR0_8253, 0x0);
outportb(CTR0_8253, 0x0);
setvect(TMR_INTERRUPT , TIMER_handler);
enable() ;

disable();
setvect(KBD_INTERRUPT, KEYB_handler);
enable() ;

printf("\n %s\n",
  "Do You Want to Continue to collect Data ? (Type y/n)");
  scanf(" %c", &more);

} while (more=='Y' || more=='y');

fclose(ofp1);
fclose(ofp2);

}


/*********   SOURCE CODE FOR click()            **************
********* Increments counter and sets flag    **************/
void interrupt click(void)
{
  ++C_CLICK;
  TIMER_handler();
  outportb(ISR_8259, EOI_8259);
}


/************************** USER DEFINED KEYBOARD HANDLER ***********/
void Key_Handler(void)
{
  int key = toupper(getch()), n, j; //change, sign;
  char number;
  static int cnt=0;

  switch(key)
  {
   case 27: quit = 1; break;                  //'ESC' key
   case 'Q': quit=1; break;
   case 'R':
     Sign=-1; break;
   case 'S':
     {Flag = 1; cnt=0; }  break;
   case 13:
     {n=atoi(str);  Flag=0; //change=1;         //String to a Integer
      for(j=0; j<=11; j++) str[j]='\n'; }       //Cleanup the String
      break;
```

```
   case '1': case '2':case '3': case '4':case '5': case '6':
   case '7': case '8':case '9': case '0':
       {number=key;
        if(Flag==1)
          { str[cnt]=number; cnt++; }          //Make a String
       }
   }

}


/************************ SOURCE CODE FOR keyb()******************
**********                 Keyboard Interrupt   **********/
void interrupt keyb(void)
{
    KEYB_handler();
    if (kbhit()) Key_Handler();
}


/* Hardware Channel Settings for A_In & D_Out */
void Chan_Setting(void)
{
 char ans;
/* printf("\n %s\n %s\n",
   "Type a WAIT number (Integer)",
   "EX.) WAIT=1 equals 0.05 second (20 Hz) and 10 equals 0.5 second (2 Hz)");
   scanf("%d", &WAIT);    */
 printf("\n %s\n %s\n",
   "Type a STOP number for a Max. Iterations (Integer)",
   "  EX.) Default STOP = 100 sor 100 data collection");
   scanf("%d", &STOP);
 printf("\n %s%d\n %s\n %s\n %s\n %s\n %s\n",
   "Your STOP value = ", STOP,
   "Channel Setting Information for A/D Board",
   "Current Channel Settings are : ",
   "       AIn_V_Ground=17,   AIn_V_Gasmeter (L/min)=0",
   "       AIn_V_GasPressure (psi)=1",
   "Do You Want to Change Channel Settings ? (Type y/n)");
   scanf(" %c", &ans);
   if (ans=='Y' || ans=='y') {
     do {
     printf("\n %s\n %s\n",
       "Type a STOP number for the maximum iteration (Integer)",
       "  EX.) Default STOP = 100 for 100 data collection");
     scanf("%d", &STOP);
     printf("\n Input Channel Number for Chan_Gas_VIn (L/min) :  ");
     scanf("%d", &Chan_GasVIn);
     printf("\n %s\n %s%d\n",
       "  Your Channel Settings are : ",
       "   AIn_V_GasVIn = ",Chan_GasVIn);
     printf("\n Input Channel Number for Chan_Gas_PIn (psi) :  ");
     scanf("%d", &Chan_GasPIn);
     printf("\n %s\n %s%d\n",
       "  Your Channel Settings are : ",
       "   AIn_V_GasPIn = ",Chan_GasPIn);
     printf("\n %s\n",
       "Do You Want to Change Channel Settings ? (Type y/n)");
     scanf(" %c", &ans);
     } while (ans=='Y' || ans=='y');

   }
```

```
}

/* Converting the measured value of Volts to the calibrated
   Flowrate (L/min) of Gas */
float convertV(float VGas)
{
 float LperMin;
 LperMin=(VGas-0.035048)/0.049741;
 return LperMin;
}
```

C.5 Program LIQ_PSI

This program was coded by D. Kim in 1999 in order to calibrate the system pressure transducer as mentioned in Chapter III. The voltage information from the liquid pressure transducer was recorded in a file. The complete program listing is as follows:

```
/* This program is Written by Dongwoo Kim
   for the Experimental Study of Two-Phase Flow and Heat Transfer
   in a Horizontal Pipe
   Purpose:
   Calibtate the Liquid Pressure  Transducer (psi)
   (Last Modified: Jun. 16, 1999) */

#include <stdio.h>
#include <conio.h>
#include <stdlib.h>
#include <dos.h>
#include <math.h>
#include <time.h>
#include <bios.h>
#include "c:\cb\c\cb.h"
#include <ctype.h>

#define TMR_INTERRUPT    0x8          /* Timer interrupt vector */
#define KBD_INTERRUPT    0x9          /* Keyboard interrupt vector */
#define TIMER_OSCILLATOR 1193180.0    /* Timer oscillator frequency */
#define ISR_8259         0x0020       /* i8259 in-service reg addr */
#define EOI_8259         0x20         /* i8259 none-specific end of intrrpt */
#define CWR_8253         0x0043       /* control word register addr */
#define CTR0_8253        0x0040       /* timer 0 counter addr */
#define SET_CTR0_8253    0x0036       /* binary mode 3, ctr 0 */
#define Max_time         450000


void interrupt (*TIMER_handler) (void);
void interrupt (*KEYB_handler) (void);
void interrupt click(void);
void interrupt keyb(void);
void Chan_Setting(void);

//Gloval variable
int quit=0;
int seconds=0;
unsigned C_CLICK = 0;
int Flag, Sign=1;
char str[10];
int  Bit_On=3;
int Chan_GasVIn=0;
int Chan_LiqPIn=4;

int STOP=1000, WAIT=1;
FILE *ofp1, *ofp2;

//Main Program
int main(void)
{
```

```
//Open Raw Data File
 ofp1=fopen("GasVLiqP.dat","w");
//Open Averaged Value Data File
 ofp2=fopen("GasVLiqP.avg","w");

 float interval = 50; /*** INTERRUPT LATENCY IN MILLISECONDS ***/
 int i_interval = TIMER_OSCILLATOR*interval/1000.0 + 0.5;

 int BoardNum=0, PortNum, Direction, Gain, iter, j;
 unsigned int DataValueV, DataValueP;
 float R_PLiq,R_VGas, VGas, PLiq, period;
 double sum_VGas, sum_PLiq;
 double AVGas, APLiq, RavgVGas, RavgPLiq;
 char more;

 int Bit_Off=0; // Range=BIP10VOLTS;

 //DAS Board Connection Checking
 cbErrHandling(PRINTALL, STOPALL);
 PortNum=FIRSTPORTA;
 Direction=DIGITALOUT;
 cbDConfigPort (BoardNum, PortNum, Direction);
 Gain = BIP5VOLTS;

 do {

 //Set Control Bit Values according to A/D Board Channel Connection
 Chan_Setting();

 printf("\n%s\n",
 "Type the reading value of Gas Flowrate (L/min) from flowmeter");
 scanf("%f", &R_VGas);

 printf("\n%s\n",
 "Type the reading value of Liquid Pressure (psi) from dial gage");
 scanf("%f", &R_PLiq);

 TIMER_handler = getvect(TMR_INTERRUPT);
 disable();

/******************* CHANGE TIMER RESOLUTION **********************/
 outportb(CWR_8253, SET_CTR0_8253);
 outportb(CTR0_8253, i_interval & 0xff);
 outportb(CTR0_8253, (i_interval & 0xff00) >> 8);

/******************* SET TIMER INTERRUPT ***********************/
 setvect(TMR_INTERRUPT, click);
 enable();

/******************* SET KEYBOARD INTERRUPT *****************/
 KEYB_handler = getvect(KBD_INTERRUPT) ;
 disable();
 setvect(KBD_INTERRUPT, keyb);
 enable() ;

/*********** Time measurement for Data Collection in SECOND *******/
 clock_t start, end;
 start = clock();

 RavgVGas=0.0;     RavgPLiq=0.0;
 /************** MAIN LOOP **********************************/
 for (j=1; j<=3 && !quit; j+=1)
 {
```

```
 sum_VGas=0.0;
 sum_PLiq=0.0;
   for(iter=1; iter<=STOP && !quit; iter+=1)
    {
        cbAIn(BoardNum, Chan_GasVIn, Gain, &DataValueV);
        cbToEngUnits(BoardNum, Gain, DataValueV, &VGas);

        cbAIn(BoardNum, Chan_LiqPIn, Gain, &DataValueP);
        cbToEngUnits(BoardNum, Gain, DataValueP, &PLiq);

        fprintf(ofp1, "%f    %f    %f    %f\n", R_VGas, VGas, R_PLiq, PLiq);

        sum_VGas=sum_VGas+VGas;
        sum_PLiq=sum_PLiq+PLiq;

       C_CLICK = 0;
       seconds++;
     }      //End for (i)

  AVGas=sum_VGas/iter;
  APLiq=sum_PLiq/iter;
//Real-Time Average for j iteration
  RavgVGas += (AVGas-RavgVGas) / j;
  RavgPLiq += (APLiq-RavgPLiq) / j;

  while(C_CLICK < WAIT*2);  /*** WAIT UNTIL 0.1 SECOND ***/
  C_CLICK = 0;

  }    //End for (j)

  end = clock();
  period = (end - start) / CLK_TCK ;
  printf("\n %s%f\n %s\n",
    "The time period (sec) for this measurement was  = ", period,
    "(Note: Flowrate & Pressure makes twice the total Number Data points)");

fprintf(ofp2,"\n %s%f\n",
  "The time period (sec) for this measurement was  = ", period);
fprintf(ofp2,"\n\n %s\n %s\n",
  "The averaged VOLTS of Flowrate and Pressure of the measurements were",
  "Read V (L/min) Measured V (volt) Reading Press. (psi) Measured P (volt)");
fprintf(ofp2,"%s%f%s%f%s%f%s%f\n",
  "         ",R_VGas,"              ",RavgVGas,"                     ",R_PLiq,"
",RavgPLiq);

 /************ CLEANUP TIMER & KEYBOARD INTERRRUPT *********/
disable();
outportb(CWR_8253, SET_CTR0_8253);
outportb(CTR0_8253, 0x0);
outportb(CTR0_8253, 0x0);
setvect(TMR_INTERRUPT , TIMER_handler);
enable() ;

disable();
setvect(KBD_INTERRUPT, KEYB_handler);
enable() ;

printf("\n %s\n",
  "Do You Want to Continue to collect Data ? (Type y/n)");
  scanf(" %c", &more);

} while (more=='Y' || more=='y');
```

```
fclose(ofp1);
fclose(ofp2);

}


/*********    SOURCE CODE FOR click()          **************
********* Increments counter and sets flag    **************/
void interrupt click(void)
{
  ++C_CLICK;
  TIMER_handler();
  outportb(ISR_8259, EOI_8259);
}


/************************** USER DEFINED KEYBOARD HANDLER ***********/
void Key_Handler(void)
{
  int key = toupper(getch()), n, j; //change, sign;
  char number;
  static int cnt=0;

  switch(key)
  {
   case 27: quit = 1; break;                   //'ESC' key
   case 'Q': quit=1; break;
   case 'R':
     Sign=-1; break;
   case 'S':
     {Flag = 1; cnt=0; }  break;
   case 13:
     {n=atoi(str);  Flag=0; //change=1;          //String to a Integer
      for(j=0; j<=11; j++) str[j]='\n'; }       //Cleanup the String
      break;

   case '1': case '2':case '3': case '4':case '5': case '6':
   case '7': case '8':case '9': case '0':
      {number=key;
       if(Flag==1)
         { str[cnt]=number; cnt++; }          //Make a String
      }
   }

}


/************************ SOURCE CODE FOR keyb()*****************
**********                  Keyboard Interrupt   **********/
void interrupt keyb(void)
{
    KEYB_handler();
    if (kbhit()) Key_Handler();
}


/* Hardware Channel Settings for A_In & D_Out */
void Chan_Setting(void)
{
 char ans;
 printf("\n %s\n %s\n",
   "Type a STOP number for a Max. Iterations (Integer)",
   "  EX.) Default STOP = 1000 for 1000 data collection");
```

```
   scanf("%d", &STOP);
 printf("\n %s%d\n %s\n %s\n %s\n %s\n %s\n",
   "Your STOP value = ", STOP,
   "Channel Setting Information for A/D Board",
   "Current Channel Settings are : ",
   "       AIn_V_Ground=17,   AIn_V_Gasmeter (L/min)=0",
   "       AIn_V_LiqPressure (psi)=4",
   "Do You Want to Change Channel Settings ? (Type y/n)");
   scanf(" %c", &ans);
   if (ans=='Y' || ans=='y') {
     do {
     printf("\n %s\n %s\n",
      "Type a STOP number for the maximum iteration (Integer)",
      "  EX.) Default STOP = 100 for 100 data collection");
     scanf("%d", &STOP);
     printf("\n Input Channel Number for Chan_Gas_VIn (L/min) :  ");
     scanf("%d", &Chan_GasVIn);
     printf("\n %s\n %s%d\n",
      "  Your Channel Settings are : ",
      "   AIn_V_GasVIn = ",Chan_GasVIn);
     printf("\n Input Channel Number for Chan_Gas_PIn (psi) :  ");
     scanf("%d", &Chan_LiqPIn);
     printf("\n %s\n %s%d\n",
      "  Your Channel Settings are : ",
      "   AIn_V_LiqPIn = ",Chan_LiqPIn);
     printf("\n %s\n",
       "Do You Want to Change Channel Settings ? (Type y/n)");
     scanf(" %c", &ans);
     } while (ans=='Y' || ans=='y');

   }
}
```

C.6 Program CA_PV_LQ

This program was coded by D. Kim in 1999 in order to calibrate the differential pressure transducer as mentioned in Chapter III. The voltage information from the differential pressure transducer was recorded in a file. The complete program listing is as follows:

```
/* This program is Written by Dongwoo Kim
   for the Experimental Study of Two-Phase Flow and Heat Transfer
   in a Horizontal Pipe
   Purpose:
   Calibtate the Liquid Pressure Drop
   from the Pressure Tranceduce (Volts) and reversed U-Tube
   Manometer in (in_H2O).
   (Last Modified: May. 20, 1999) */

#include <stdio.h>
#include <conio.h>
#include <stdlib.h>
#include <dos.h>
#include <math.h>
#include <time.h>
#include <bios.h>
#include "c:\cb\c\cb.h"
#include <ctype.h>

#define TMR_INTERRUPT     0x8           /* Timer interrupt vector */
#define KBD_INTERRUPT     0x9           /* Keyboard interrupt vector */
#define TIMER_OSCILLATOR 1193180.0      /* Timer oscillator frequency */
#define ISR_8259          0x0020        /* i8259 in-service reg addr */
#define EOI_8259          0x20          /* i8259 none-specific end of intrrpt */
#define CWR_8253          0x0043        /* control word register addr */
#define CTR0_8253         0x0040        /* timer 0 counter addr */
#define SET_CTR0_8253     0x0036        /* binary mode 3, ctr 0 */
#define Max_time          450000


void interrupt (*TIMER_handler) (void);
void interrupt (*KEYB_handler) (void);
void interrupt click(void);
void interrupt keyb(void);
void Chan_Setting(void);

//Gloval variable
int quit=0;
int seconds=0;
unsigned C_CLICK = 0;
int Flag, Sign=1;
char str[10];
int  Bit_On=3;

int Chan_LiqPIn=3;
int Chan_LiqVIn=2;

int STOP=1000, WAIT=1;
```

```
FILE *ofp1, *ofp2;

//Main Program
int main(void)
{
//Open Raw Data File
 ofp1=fopen("C_LiqPV.dat","w");
//Open Averaged Value Data File
 ofp2=fopen("C_LiqPV.avg","w");

 float interval = 50; /*** INTERRUPT LATENCY IN MILLISECONDS ***/
 int i_interval = TIMER_OSCILLATOR*interval/1000.0 + 0.5;

 int BoardNum=0, PortNum, Direction, Gain, iter, j;
 unsigned int DataValueP, DataValueV; //DataValueP
 float R_PLiq, PLiq, VLiq, Galpmin, period; //R_PGas, R_TGas, R_PAir, PGas,
LperM
 double sum_PLiq, sum_VLiq, APLiq, AVLiq, RavgPLiq, RavgVLiq; //sum_PGas
 double AGalpmin, Tot_Data;
 char more;

 int Bit_Off=0; // Range=BIP10VOLTS;

 //DAS Board Connection Checking
 cbErrHandling(PRINTALL, STOPALL);
 PortNum=FIRSTPORTA;
 Direction=DIGITALOUT;
 cbDConfigPort (BoardNum, PortNum, Direction);
 Gain = BIP5VOLTS;

 //Set Control Bit Values according to A/D Board Channel Connection
 Chan_Setting();

 TIMER_handler = getvect(TMR_INTERRUPT);
 disable();

 do {

 printf("\n%s\n",
 "Type the reading value of Pressure Difference (in_H2O) from Manometer");
 scanf("%f", &R_PLiq);

/******************* CHANGE TIMER RESOLUTION **********************/
 outportb(CWR_8253, SET_CTR0_8253);
 outportb(CTR0_8253, i_interval & 0xff);
 outportb(CTR0_8253, (i_interval & 0xff00) >> 8);

/******************* SET TIMER INTERRUPT ***********************/
 setvect(TMR_INTERRUPT, click);
 enable();

/******************* SET KEYBOARD INTERRUPT ******************/
 KEYB_handler = getvect(KBD_INTERRUPT) ;
 disable();
 setvect(KBD_INTERRUPT, keyb);
 enable() ;

 RavgPLiq=0.0;
 RavgVLiq=0.0;

/*********** Time measurement for Data Collection in SECOND *******/
 clock_t start, end;
 start = clock();
```

```
/************** MAIN LOOP ***********************************/
 for(j=1; j<=100 && !quit; j+=1)
   {
       sum_PLiq=0.0;
       sum_VLiq=0.0;
       for(iter=1; iter<=STOP; iter+=1)
        {
       if(Sign==1)
        {
        //Pressure Transeducer Reading
        cbAIn(BoardNum, Chan_LiqPIn, Gain, &DataValueP);
        cbToEngUnits(BoardNum, Gain, DataValueP, &PLiq);
        sum_PLiq=sum_PLiq+PLiq;

        //Totalizer Reading for Liquid Flow_Rate
        cbAIn(BoardNum, Chan_LiqVIn, Gain, &DataValueV);
        cbToEngUnits(BoardNum, Gain, DataValueV, &VLiq);
        VLiq=2.0*VLiq;                        //Modified for 2 times scale
        sum_VLiq=sum_VLiq+VLiq;

       C_CLICK = 0;
     }     //Endif
     C_CLICK = 0;

     if(Sign==-1)
    {
     //Send a Bit to turn the scanivalve channel
     cbDOut(BoardNum, PortNum, Bit_On);
     while(C_CLICK < WAIT); /**** WAIT UNTIL 0.1 SECOND ****/

     //Turn off the Bit
     cbDOut(BoardNum, PortNum, Bit_Off);

     // The "Sign" Value Bact to 1
     Sign=1;
     }
   C_CLICK = 0;
     seconds++;
     }      //End for

     APLiq=sum_PLiq/(iter-1);
     RavgPLiq += (APLiq-RavgPLiq) / j;
     AVLiq=sum_VLiq/(iter-1);
     Galpmin=0.8933*AVLiq+0.0221;
     fprintf(ofp1, "%f       %f       %f\n", R_PLiq, APLiq, Galpmin); //R_PLiq,
PLiq);
     RavgVLiq += (AVLiq-RavgVLiq) / j;
  }      //End for

end = clock();
period = (end - start) / CLK_TCK ;

Tot_Data=STOP*100.0*2.0;
printf("\n %s%10.1e%s%f\n",
  "The time period (sec) for ",Tot_Data," data collection  = ", period);


fprintf(ofp2,"\n %s%10.1e%s%f\n",
  "The time period (sec) for ",Tot_Data," data collection  = ", period);

     AGalpmin=0.8933*RavgVLiq+0.0221;
```

```
fprintf(ofp2,"\n\n %s\n %s\n",
  "The averaged VOLTS of Liquid Pressure Drop measurements was",
  "Read dP (in_H2O)  Measured V (volt)       Flowrate (gal/min)");
fprintf(ofp2,"%s%f%s%lf%s%lf\n",
  "    ",R_PLiq,"          ",RavgPLiq,"                  ",AGalpmin);

/************* CLEANUP TIMER & KEYBOARD INTERRRUPT *********/
disable();
outportb(CWR_8253, SET_CTR0_8253);
outportb(CTR0_8253, 0x0);
outportb(CTR0_8253, 0x0);
setvect(TMR_INTERRUPT , TIMER_handler);
enable() ;

disable();
setvect(KBD_INTERRUPT, KEYB_handler);
enable() ;
printf("\n %s\n",
  "Do You Want to Continue to collect Data ? (Type y/n)");
  scanf(" %c", &more);

} while (more=='Y' || more=='y');

fclose(ofp1);
fclose(ofp2);

}


/*********   SOURCE CODE FOR click()          **************
********* Increments counter and sets flag    **************/
void interrupt click(void)
{
      ++C_CLICK;
      TIMER_handler();
      outportb(ISR_8259, EOI_8259);
}


/*************************** USER DEFINED KEYBOARD HANDLER ***********/
void Key_Handler(void)
{
      int key = toupper(getch()), n, j; //change, sign;
      char number;
      static int cnt=0;
      switch(key)
      {   case 27: quit = 1; break;                         //'ESC' key
          case 'Q': quit=1; break;
          case 'R': Sign=-1; break;
          case 'S':
               {Flag = 1; cnt=0; }  break;
          case 13:
               {n=atoi(str);  Flag=0; //change=1;          //String to a Integer
               for(j=0; j<=11; j++) str[j]='\n'; }         //Cleanup the String
          break;
          case '1': case '2':case '3': case '4':case '5': case '6':
          case '7': case '8':case '9': case '0':
               {number=key;
                if(Flag==1)
                { str[cnt]=number; cnt++; }               //Make a String
               }
      }
 }
```

```
 /************************* SOURCE CODE FOR keyb()******************
 **********                Keyboard Interrupt   **********/
 void interrupt keyb(void)
 {
       KEYB_handler();
       if (kbhit()) Key_Handler();
 }


/* Hardware Channel Settings for A_In & D_Out */
void Chan_Setting(void)
{
 char ans;
 printf("\n %s\n %s\n",
   "Type a STOP number for a Max. Iterations (Integer)",
   "  EX.) Default STOP = 1000 for 1000 data collection");
   scanf("%d", &STOP);
 printf("\n %s%d\n %s\n %s\n %s\n %s\n %s\n %s\n",
   "Your STOP value = ", STOP,
   "Channel Setting Information for A/D Board",
   "Current Channel Settings are : ",
   "       AIn_V_Ground=17,   AIn_V_Gasmeter (L/min)=0",
   "       AIn_V_GasPressure (psi)=1, AIn_V_Liquid (L/min)=2",
   "       AIn_P_Liquid (in_H2O)=3",
   "Do You Want to Change Channel Settings ? (Type y/n)");
   scanf(" %c", &ans);
   if (ans=='Y' || ans=='y') {
     do {
     printf("\n %s\n %s\n",
      "Type a STOP number for the maximum iteration (Integer)",
      "  EX.) Default STOP = 1000 for 1000 data collection");
     scanf("%d", &STOP);
     printf("\n Input Channel Number for Chan_Liq_VIn (L/min) :  ");
     scanf("%d", &Chan_LiqPIn);
     printf("\n %s\n %s%d\n",
      "  Your Channel Settings are : ",
      "   AIn_P_LiqVIn = ",Chan_LiqPIn);

     printf("\n %s\n",
       "Do You Want to Change Channel Settings ? (Type y/n)");
     scanf(" %c", &ans);
     } while (ans=='Y' || ans=='y');

   }
}
```

C.7 Program Bptt17

This program was coded by D. Kim in 1999 and modifed by the present author in order to measure the necessary experimental independent properties (except the information of the temperature measurement in the test section) and to calculate the dependent properties for the two-phase air-water flow experiment.

```
/* This program is Written by Dongwoo Kim and Modified by Jae-yong Kim
   for the Experimental Study of Two-Phase Flow and Heat Transfer
   in a Horizontal Pipe
   Purpose:
   Calculate X and j*g for Breber (1980) Flow Pattern Map
   Using Big and Small Two Turbine Meters.
   (Last Modified  Sep. 14, 1999)*/

#include <stdio.h>
#include <conio.h>
#include <stdlib.h>
#include <dos.h>
#include <math.h>
#include <time.h>
#include <bios.h>
#include "c:\cb\c\cb.h"
#include <ctype.h>

#define TMR_INTERRUPT     0x8          /* Timer interrupt vector */
#define KBD_INTERRUPT     0x9          /* Keyboard interrupt vector */
#define TIMER_OSCILLATOR 1193180.0     /* Timer oscillator frequency */
#define ISR_8259          0x0020       /* i8259 in-service reg addr */
#define EOI_8259          0x20         /* i8259 none-specific end of intrrpt */
#define CWR_8253          0x0043       /* control word register addr */
#define CTR0_8253         0x0040       /* timer 0 counter addr */

#define SET_CTR0_8253     0x0036       /* binary mode 3, ctr 0 */
#define Max_time          450000

void interrupt (*TIMER_handler) (void);
void interrupt (*KEYB_handler) (void);
void interrupt click(void);
void interrupt keyb(void);

void Chan_Setting(void);
double ViscosityL(float);
double ViscosityG(float);
double DensityL(float);
double DensityG(double, float);

//Gloval variable for iteration and time control
int quit=0, seconds=0;
unsigned C_CLICK = 0;
int Flag, Sign=1;
char str[10];

int  Bit_On=3;
```

```
int STOP=1000, WAIT=1;

//Gloval variable for the channel setting
int Chan_SysPIn=4;
int Chan_LiqPIn=3;
int Chan_LiqVIn=2;
int Chan_GasPIn=1;
int Chan_GasVIn=0;

FILE *ofp1, *ofp2, *ofp3, *ofp4;

//Main Program
int main(void)
{
//Open Raw Data File
 ofp1=fopen("BPat-Raw.dat","w");
//Open Averaged Value Data File
 ofp2=fopen("BPat-Avg.dat","w");
 ofp3=fopen("BPa-Para.dat","w");
 ofp4=fopen("Format.dat","w");

 float interval = 50; /*** INTERRUPT LATENCY IN MILLISECONDS ***/
 int i_interval = TIMER_OSCILLATOR*interval/1000.0 + 0.5;

 float Gain;
 float pie=3.141592, VSL, VSG, ReSL, ReSG, rowH, K, Alp, kL, kG;
 float CpL, CpG, PrL, PrG;
 int BoardNum=0, PortNum, Direction, iter, j, k, Turb_Meter;
 unsigned int DataGasP, DataGasV, DataLiqV, DataLiqP, DataSysP; //DataValueP
 float R_PGas, PLiq, VLiq, PGas, VGas, Galpmin, period, PSys;
 float Lpmin, psia, psi, psig, Tot_Data, R_TGas, R_TLiq;
 float DP1,DP2,DP3,DP4,DP5,DP6,DP7,DP8,DP9,DP10;
 double sum_PLiq1, sum_VLiq, APLiq1, AVLiq, RavgPLiq1, RavgVLiq; //sum_PGas
 double sum_PLiq2,sum_PLiq3,sum_PLiq4,sum_PLiq5,sum_PLiq6,sum_PLiq7;
 double sum_PLiq8,sum_PLiq9,sum_PLiq10,sum_PSys;
 double sum_PGas, sum_VGas, APGas, AVGas, RavgPGas, RavgVGas, APSys;
 double APLiq2,APLiq3,APLiq4,APLiq5,APLiq6,APLiq7,APLiq8,APLiq9,APLiq10;
 double RavgPLiq2,RavgPLiq3,RavgPLiq4,RavgPLiq5,RavgPLiq6,RavgPLiq7,RavgPLiq8;
 double RavgPLiq9,RavgPLiq10, RavgPSys;
 double AGalpmin, ALpmin, Apsia, Apsi, Apsig;
 double ADP1,ADP2,ADP3,ADP4,ADP5,ADP6,ADP7,ADP8,ADP9,ADP10;
 double rowL, rowG, muL, muG, QL, QG, mdotL, mdotG, XX, x, Jg, Di, Ac, Gt;
 char more;

 int Bit_Off=0; // Range=BIP10VOLTS;

 //DAS Board Connection Checking
 cbErrHandling(PRINTALL, STOPALL);
 PortNum=FIRSTPORTA;
 Direction=DIGITALOUT;
 cbDConfigPort (BoardNum, PortNum, Direction);
 Gain = BIP10VOLTS;

 //Set Control Bit Values according to A/D Board Channel Connection
 Chan_Setting();

 TIMER_handler = getvect(TMR_INTERRUPT);
 disable();


 do {

 printf("\n%s\n%s\n",
```

```
 "Do you want to use Big (1) or Small (2) Turbine Meter???",
 "Type the appropriate Integer Number for the Turbine Meter [1 or 2]");
 scanf("%d", &Turb_Meter);
 printf("\n%s\n",
 "Type the reading value of Gas Atmosphere Pressure (mmHg) from Manometer");
 scanf("%f", &R_PGas);
 printf("\n%s\n",
 "Type the reading value of Gas Temperature ('C) from Thermometer");
 scanf("%f", &R_TGas);
 printf("\n%s\n",
 "Type the reading value of Liquid Inlet Bulk Temperature ('C) from
Thermometer");
 scanf("%f", &R_TLiq);
 printf("\n%s%d\n","Your Turbine Meter is ",Turb_Meter);

/******************* CHANGE TIMER RESOLUTION ***********************/
outportb(CWR_8253, SET_CTR0_8253);
 outportb(CTR0_8253, i_interval & 0xff);
 outportb(CTR0_8253, (i_interval & 0xff00) >> 8);

/******************* SET TIMER INTERRUPT ************************/
 setvect(TMR_INTERRUPT, click);
 enable();

/******************* SET KEYBOARD INTERRUPT *******************/
 KEYB_handler = getvect(KBD_INTERRUPT) ;
 disable();
 setvect(KBD_INTERRUPT, keyb);

 enable() ;

 RavgPGas=0.0;  RavgVGas=0.0;
 RavgPLiq1=0.0; RavgVLiq=0.0;  RavgPSys=0.0;
 RavgPLiq2=0.0; RavgPLiq3=0.0; RavgPLiq4=0.0; RavgPLiq5=0.0; RavgPLiq6=0.0;
 RavgPLiq7=0.0; RavgPLiq8=0.0; RavgPLiq9=0.0; RavgPLiq10=0.0;

/*********** Time measurement for Data Collection in SECOND *******/
 clock_t start, end;
 start = clock();

/************** MAIN LOOP ************************************/
 for(j=1; j<=20 && !quit; j+=1)
 {
    sum_VLiq=0.0;  sum_PGas=0.0;  sum_VGas=0.0;  sum_PSys=0.0;
    sum_PLiq1=0.0; sum_PLiq2=0.0; sum_PLiq3=0.0; sum_PLiq4=0.0; sum_PLiq5=0.0;
    sum_PLiq6=0.0; sum_PLiq7=0.0; sum_PLiq8=0.0; sum_PLiq9=0.0; sum_PLiq10=0.0;

   for(iter=1; iter<=STOP; iter+=1)
   {
     if(Sign==1)
      {
        //Pressure Transeducer Reading for Gas (psia)
        cbAIn(BoardNum, Chan_GasPIn, Gain, &DataGasP);
        cbToEngUnits(BoardNum, Gain, DataGasP, &PGas);
        /*** Adjust the Voltage Reading according to the BIP10VOLTS
             Hardware settings on CIO-AD 08 Board ***/
        PGas *=2;
        sum_PGas=sum_PGas+PGas;

        //Totalizer Reading for Liquid Flow_Rate
        cbAIn(BoardNum, Chan_LiqVIn, Gain, &DataLiqV);
        cbToEngUnits(BoardNum, Gain, DataLiqV, &VLiq);
        /*** Adjust the Voltage Reading according to the BIP10VOLTS
```

```
             Hardware settings on CIO-AD 08 Board ***/
        VLiq *=2;
        sum_VLiq=sum_VLiq+VLiq;

        //Flowmeter Reading for Gas Flow_Rate
        cbAIn(BoardNum, Chan_GasVIn, Gain, &DataGasV);
        cbToEngUnits(BoardNum, Gain, DataGasV, &VGas);
        /*** Adjust the Voltage Reading according to the BIP10VOLTS
             Hardware settings on CIO-AD 08 Board ***/
        VGas *=2;
        sum_VGas=sum_VGas+VGas;

        //Pressure Transeducer Reading for Pipe System (psig)
        cbAIn(BoardNum, Chan_SysPIn, Gain, &DataSysP);
        cbToEngUnits(BoardNum, Gain, DataSysP, &PSys);
        /*** Adjust the Voltage Reading according to the BIP10VOLTS
             Hardware settings on CIO-AD 08 Board ***/
        PSys *=2;
        sum_PSys=sum_PSys+PSys;

      }      //Endif
     C_CLICK = 0;

     if(Sign==-1)
     {
     //Send a Bit to turn the scanivalve channel
     cbDOut(BoardNum, PortNum, Bit_On);
     while(C_CLICK < WAIT); /**** WAIT UNTIL 0.1 SECOND ****/
     C_CLICK = 0;
     //Turn off the Bit
     cbDOut(BoardNum, PortNum, Bit_Off);

     // The "Sign" Value Bact to 1
     Sign=1;
     }     //Endif
   seconds++;
   }       //End for

     AVLiq=sum_VLiq/(iter-1);
     APGas=sum_PGas/(iter-1);
     AVGas=sum_VGas/(iter-1);
     APSys=sum_PSys/(iter-1);

     //Real-time Average for the j iterations
     RavgVLiq += (AVLiq-RavgVLiq) / j;
     RavgPGas += (APGas-RavgPGas) / j;
     RavgVGas += (AVGas-RavgVGas) / j;
     RavgPSys += (APSys-RavgPSys) / j;

}       //End for

//Next, Pressure Drop Measurement for the Wafer Chnnel 1
for(j=1; j<=20 && !quit; j+=1)
{
     for(iter=1; iter<=STOP; iter+=1)
     {
     //Pressure Transeducer Reading for Liquid
       cbAIn(BoardNum, Chan_LiqPIn, Gain, &DataLiqP);
       cbToEngUnits(BoardNum, Gain, DataLiqP, &PLiq);
       /*** Adjust the Voltage Reading according to the BIP10VOLTS
             Hardware settings on CIO-AD 08 Board ***/
       PLiq *=2;
       sum_PLiq1=sum_PLiq1+PLiq;
```

```
     }
     APLiq1=sum_PLiq1/(iter-1);
     RavgPLiq1 += (APLiq1-RavgPLiq1) / j;
     sum_PLiq1=0.0;
     while(C_CLICK < WAIT*20); /**** WAIT UNTIL 1 SECOND ****/
     C_CLICK = 0;
  }      //End for
     /**** Calculate & Print Out the Time Depedent Values ****/
     if (Turb_Meter==1)
     {
       AGalpmin=0.00425*200*2*AVLiq+0.0210; //for Liquid flow rate (gal/min)
     }
     if (Turb_Meter==2)
     {
       AGalpmin=0.0466*20*AVLiq+0.1162; //for Liquid flow rate (gal/min)
     }
     ALpmin=20.103*AVGas-0.7211;        //for Gas Flow Rate (liter/min)
     Apsia=20.339*APGas-2.844;          //for Gas Pressure (psia)
     Apsi=Apsia-R_PGas*0.019337;        //for Gas Pressure (psi)
     Apsig=8.0398*APSys-9.8147;         //for System Pressure (psig)

     ADP1=1.43783*RavgPLiq1-1.43733;        //for Liquid Pressure Drop (in_H2O)
     ADP2=1.43783*RavgPLiq2-1.43733;        //for Liquid Pressure Drop (in_H2O)
     ADP3=1.43783*RavgPLiq3-1.43733;        //for Liquid Pressure Drop (in_H2O)
     ADP4=1.43783*RavgPLiq4-1.43733;        //for Liquid Pressure Drop (in_H2O)
     ADP5=1.43783*RavgPLiq5-1.43733;        //for Liquid Pressure Drop (in_H2O)
     ADP6=1.43783*RavgPLiq6-1.43733;        //for Liquid Pressure Drop (in_H2O)
     ADP7=1.43783*RavgPLiq7-1.43733;        //for Liquid Pressure Drop (in_H2O)
     ADP8=1.43783*RavgPLiq8-1.43733;        //for Liquid Pressure Drop (in_H2O)
     ADP9=1.43783*RavgPLiq9-1.43733;        //for Liquid Pressure Drop (in_H2O)
     ADP10=1.43783*RavgPLiq10-1.43733;      //for Liquid Pressure Drop (in_H2O)

 fprintf(ofp1, "%f       %f       %f       %f       %f       %f       %f       %f
%f       %f       %f       %f       %f       %f\n",
         AGalpmin, ALpmin, Apsi, Apsig, ADP1, ADP2, ADP3, ADP4, ADP5, ADP6,
ADP7, ADP8,
         ADP9, ADP10);

     //Send a Bit to turn the scanivalve to channel 2

      cbDOut(BoardNum, PortNum, Bit_On);
      while(C_CLICK < WAIT*2); /**** WAIT UNTIL 0.1 SECOND ****/
      C_CLICK = 0;
     //Turn off the Bit
     cbDOut(BoardNum, PortNum, Bit_Off);
     printf("\n%s",
     "Your Wafer Chnanel Connection is 2");

     for (k=1; k<=2; k+=1)
     {
     sound(800);
     while(C_CLICK < WAIT*6); /**** WAIT UNTIL 0.3 SECOND ****/
     C_CLICK = 0;
     nosound();
     while(C_CLICK < WAIT*6); /**** WAIT UNTIL 0.3 SECOND ****/
     C_CLICK = 0;
     }

     printf("\n%s%f\n",
     "Liquid Flow Rate is = [gal/min] ",AGalpmin);
     ALpmin=20.103*AVGas-0.7211;        //for Gas Flow Rate (liter/min)
     printf("\n%s%f\n",
     "Gas Flow Rate is [L/min] = ",ALpmin);
```

```
    Apsia=20.339*APGas-2.844;          //for Gas Pressure (psia)
    Apsi=Apsia-R_PGas*0.019337;        //for Gas Pressure (psi)
    printf("\n%s%f\n",
    "Gas Pressure is [psi] = ",Apsi);
    Apsig=8.0398*APSys-9.8147;         //for System Pressure (psig)
    printf("\n%s%f\n",
    "System Pressure is [psi] = ",Apsig);

     C_CLICK = 0;
for(j=21; j<=40 && !quit; j+=1)
{
   sum_VLiq=0.0;  sum_PGas=0.0;  sum_VGas=0.0;  sum_PSys=0.0;
   sum_PLiq1=0.0; sum_PLiq2=0.0; sum_PLiq3=0.0; sum_PLiq4=0.0; sum_PLiq5=0.0;
   sum_PLiq6=0.0; sum_PLiq7=0.0; sum_PLiq8=0.0; sum_PLiq9=0.0; sum_PLiq10=0.0;

  for(iter=1; iter<=STOP; iter+=1)
  {
       //Pressure Transeducer Reading for Gas (psia)
       cbAIn(BoardNum, Chan_GasPIn, Gain, &DataGasP);
       cbToEngUnits(BoardNum, Gain, DataGasP, &PGas);
       /*** Adjust the Voltage Reading according to the BIP10VOLTS
            Hardware settings on CIO-AD 08 Board ***/
       PGas *=2;
       sum_PGas=sum_PGas+PGas;

       //Totalizer Reading for Liquid Flow_Rate
       cbAIn(BoardNum, Chan_LiqVIn, Gain, &DataLiqV);
       cbToEngUnits(BoardNum, Gain, DataLiqV, &VLiq);
       /*** Adjust the Voltage Reading according to the BIP10VOLTS
            Hardware settings on CIO-AD 08 Board ***/
       VLiq *=2;
       sum_VLiq=sum_VLiq+VLiq;

       //Flowmeter Reading for Gas Flow_Rate
       cbAIn(BoardNum, Chan_GasVIn, Gain, &DataGasV);
       cbToEngUnits(BoardNum, Gain, DataGasV, &VGas);
       /*** Adjust the Voltage Reading according to the BIP10VOLTS
            Hardware settings on CIO-AD 08 Board ***/
       VGas *=2;
       sum_VGas=sum_VGas+VGas;

       //Pressure Transeducer Reading for Pipe System (psig)
       cbAIn(BoardNum, Chan_SysPIn, Gain, &DataSysP);
       cbToEngUnits(BoardNum, Gain, DataSysP, &PSys);
       /*** Adjust the Voltage Reading according to the BIP10VOLTS
            Hardware settings on CIO-AD 08 Board ***/
       PSys *=2;
       sum_PSys=sum_PSys+PSys;

  seconds++;
    }      //End for

    AVLiq=sum_VLiq/(iter-1);
    APGas=sum_PGas/(iter-1);
    AVGas=sum_VGas/(iter-1);
    APSys=sum_PSys/(iter-1);

    //Real-time Average for the j iterations
    RavgVLiq += (AVLiq-RavgVLiq) / j;
    RavgPGas += (APGas-RavgPGas) / j;
    RavgVGas += (AVGas-RavgVGas) / j;
    RavgPSys += (APSys-RavgPSys) / j;
```

```
  }      //End for

 for(j=1; j<=20 && !quit; j+=1)
 {
   for(iter=1; iter<=STOP; iter+=1)
    {
        //Pressure Transeducer Reading for Liquid
        cbAIn(BoardNum, Chan_LiqPIn, Gain, &DataLiqP);
        cbToEngUnits(BoardNum, Gain, DataLiqP, &PLiq);
        /*** Adjust the Voltage Reading according to the BIP10VOLTS
             Hardware settings on CIO-AD 08 Board ***/
        PLiq *=2;
        sum_PLiq2=sum_PLiq2+PLiq;
     }      //End for
     APLiq2=sum_PLiq2/(iter-1);
   //Real-time Average for the j iterations
   RavgPLiq2 += (APLiq2-RavgPLiq2) / j;
   sum_PLiq2=0.0;
   while(C_CLICK < WAIT*20); /**** WAIT UNTIL 1 SECOND ****/
   C_CLICK = 0;
  }      //End for

     if (Turb_Meter==1)
     {
       AGalpmin=0.00425*200*2*AVLiq+0.0210; //for Liquid flow rate (gal/min)
      }
     if (Turb_Meter==2)
     {
       AGalpmin=0.0466*20*AVLiq+0.1162; //for Liquid flow rate (gal/min)
     }
     ALpmin=20.103*AVGas-0.7211;        //for Gas Flow Rate (liter/min)
     Apsia=20.339*APGas-2.844;          //for Gas Pressure (psia)
     Apsi=Apsia-R_PGas*0.019337;
     Apsig=8.0398*APSys-9.8147;         //for System Pressure (psig)

     ADP1=1.43783*RavgPLiq1-1.43733;        //for Liquid Pressure Drop (in_H2O)
     ADP2=1.43783*RavgPLiq2-1.43733;        //for Liquid Pressure Drop (in_H2O)
     ADP3=1.43783*RavgPLiq3-1.43733;        //for Liquid Pressure Drop (in_H2O)
     ADP4=1.43783*RavgPLiq4-1.43733;        //for Liquid Pressure Drop (in_H2O)
     ADP5=1.43783*RavgPLiq5-1.43733;        //for Liquid Pressure Drop (in_H2O)
     ADP6=1.43783*RavgPLiq6-1.43733;        //for Liquid Pressure Drop (in_H2O)
     ADP7=1.43783*RavgPLiq7-1.43733;        //for Liquid Pressure Drop (in_H2O)
     ADP8=1.43783*RavgPLiq8-1.43733;        //for Liquid Pressure Drop (in_H2O)
     ADP9=1.43783*RavgPLiq9-1.43733;        //for Liquid Pressure Drop (in_H2O)
     ADP10=1.43783*RavgPLiq10-1.43733;      //for Liquid Pressure Drop (in_H2O)

 fprintf(ofp1, "%f       %f       %f       %f       %f       %f       %f       %f
%f       %f       %f       %f       %f       %f\n",
        AGalpmin, ALpmin, Apsi, Apsig, ADP1, ADP2, ADP3, ADP4, ADP5, ADP6,
ADP7, ADP8,
         ADP9, ADP10);

     //Send a Bit to turn the scanivalve to channel 3
      cbDOut(BoardNum, PortNum, Bit_On);
      while(C_CLICK < WAIT*2); /**** WAIT UNTIL 0.1 SECOND ****/
      C_CLICK = 0;
     //Turn off the Bit
      cbDOut(BoardNum, PortNum, Bit_Off);
     printf("\n%s",
     "Your Wafer Chnanel Connection is 3");
     for (k=1; k<=3; k+=1)
     {
     sound(800);
```

```
    while(C_CLICK < WAIT*6); /**** WAIT UNTIL 0.3 SECOND ****/
    C_CLICK = 0;
    nosound();
    while(C_CLICK < WAIT*6); /**** WAIT UNTIL 0.3 SECOND ****/
    C_CLICK = 0;
    }
     C_CLICK = 0;
for(j=41; j<=60 && !quit; j+=1)
{
   sum_VLiq=0.0;  sum_PGas=0.0;  sum_VGas=0.0;  sum_PSys=0.0;
   sum_PLiq1=0.0; sum_PLiq2=0.0; sum_PLiq3=0.0; sum_PLiq4=0.0; sum_PLiq5=0.0;
   sum_PLiq6=0.0; sum_PLiq7=0.0; sum_PLiq8=0.0; sum_PLiq9=0.0; sum_PLiq10=0.0;

  for(iter=1; iter<=STOP; iter+=1)
  {
       //Pressure Transeducer Reading for Gas (psia)
       cbAIn(BoardNum, Chan_GasPIn, Gain, &DataGasP);
       cbToEngUnits(BoardNum, Gain, DataGasP, &PGas);
       /*** Adjust the Voltage Reading according to the BIP10VOLTS
            Hardware settings on CIO-AD 08 Board ***/
       PGas *=2;
       sum_PGas=sum_PGas+PGas;

       //Totalizer Reading for Liquid Flow_Rate
       cbAIn(BoardNum, Chan_LiqVIn, Gain, &DataLiqV);
       cbToEngUnits(BoardNum, Gain, DataLiqV, &VLiq);
       /*** Adjust the Voltage Reading according to the BIP10VOLTS
            Hardware settings on CIO-AD 08 Board ***/
       VLiq *=2;
       sum_VLiq=sum_VLiq+VLiq;

       //Flowmeter Reading for Gas Flow_Rate
       cbAIn(BoardNum, Chan_GasVIn, Gain, &DataGasV);
       cbToEngUnits(BoardNum, Gain, DataGasV, &VGas);
       /*** Adjust the Voltage Reading according to the BIP10VOLTS
            Hardware settings on CIO-AD 08 Board ***/
       VGas *=2;
       sum_VGas=sum_VGas+VGas;

       //Pressure Transeducer Reading for Pipe System (psig)
       cbAIn(BoardNum, Chan_SysPIn, Gain, &DataSysP);
       cbToEngUnits(BoardNum, Gain, DataSysP, &PSys);
       /*** Adjust the Voltage Reading according to the BIP10VOLTS
            Hardware settings on CIO-AD 08 Board ***/
       PSys *=2;
       sum_PSys=sum_PSys+PSys;

  seconds++;
    }      //End for

    AVLiq=sum_VLiq/(iter-1);
    APGas=sum_PGas/(iter-1);
    AVGas=sum_VGas/(iter-1);
    APSys=sum_PSys/(iter-1);

    //Real-time Average for the j iterations
    RavgVLiq += (AVLiq-RavgVLiq) / j;
    RavgPGas += (APGas-RavgPGas) / j;
    RavgVGas += (AVGas-RavgVGas) / j;
    RavgPSys += (APSys-RavgPSys) / j;

 }      //End for
```

```
 for(j=1; j<=20 && !quit; j+=1)
 {
   for(iter=1; iter<=STOP; iter+=1)
    {
        //Pressure Transeducer Reading for Liquid
        cbAIn(BoardNum, Chan_LiqPIn, Gain, &DataLiqP);
        cbToEngUnits(BoardNum, Gain, DataLiqP, &PLiq);
        /*** Adjust the Voltage Reading according to the BIP10VOLTS
             Hardware settings on CIO-AD 08 Board ***/
        PLiq *=2;
        sum_PLiq3=sum_PLiq3+PLiq;
    }       //End for
    APLiq3=sum_PLiq3/(iter-1);
   //Real-time Average for the j iterations
   RavgPLiq3 += (APLiq3-RavgPLiq3) / j;
   sum_PLiq3=0.0;
   while(C_CLICK < WAIT*20); /**** WAIT UNTIL 1 SECOND ****/
   C_CLICK = 0;
  }      //End for

    if (Turb_Meter==1)
    {
      AGalpmin=0.00425*200*2*AVLiq+0.0210; //for Liquid flow rate (gal/min)
    }
    if (Turb_Meter==2)
    {
      AGalpmin=0.0466*20*AVLiq+0.1162; //for Liquid flow rate (gal/min)
    }
    ALpmin=20.103*AVGas-0.7211;        //for Gas Flow Rate (liter/min)
    Apsia=20.339*APGas-2.844;          //for Gas Pressure (psia)
    Apsi=Apsia-R_PGas*0.019337;
    Apsig=8.0398*APSys-9.8147;         //for System Pressure (psig)

    ADP1=1.43783*RavgPLiq1-1.43733;       //for Liquid Pressure Drop (in_H2O)
    ADP2=1.43783*RavgPLiq2-1.43733;       //for Liquid Pressure Drop (in_H2O)
    ADP3=1.43783*RavgPLiq3-1.43733;       //for Liquid Pressure Drop (in_H2O)
    ADP4=1.43783*RavgPLiq4-1.43733;       //for Liquid Pressure Drop (in_H2O)
    ADP5=1.43783*RavgPLiq5-1.43733;       //for Liquid Pressure Drop (in_H2O)
    ADP6=1.43783*RavgPLiq6-1.43733;       //for Liquid Pressure Drop (in_H2O)
    ADP7=1.43783*RavgPLiq7-1.43733;       //for Liquid Pressure Drop (in_H2O)
    ADP8=1.43783*RavgPLiq8-1.43733;       //for Liquid Pressure Drop (in_H2O)
    ADP9=1.43783*RavgPLiq9-1.43733;       //for Liquid Pressure Drop (in_H2O)
    ADP10=1.43783*RavgPLiq10-1.43733;     //for Liquid Pressure Drop (in_H2O)

 fprintf(ofp1, "%f      %f      %f      %f      %f      %f      %f      %f
%f      %f      %f      %f      %f      %f\n",
        AGalpmin, ALpmin, Apsi, Apsig, ADP1, ADP2, ADP3, ADP4, ADP5, ADP6,
ADP7, ADP8,
        ADP9, ADP10);

    //Send a Bit to turn the scanivalve to channel 4
     cbDOut(BoardNum, PortNum, Bit_On);
     while(C_CLICK < WAIT*2); /**** WAIT UNTIL 0.1 SECOND ****/
     C_CLICK = 0;
    //Turn off the Bit
     cbDOut(BoardNum, PortNum, Bit_Off);
    printf("\n%s",
    "Your Wafer Chnanel Connection is 4");
    for (k=1; k<=4; k+=1)
    {
    sound(800);
    while(C_CLICK < WAIT*6); /**** WAIT UNTIL 0.3 SECOND ****/
```

```
    C_CLICK = 0;
    nosound();
    while(C_CLICK < WAIT*6); /**** WAIT UNTIL 0.3 SECOND ****/
    C_CLICK = 0;
    }
    while(C_CLICK < WAIT*3600); /**** WAIT UNTIL 180 SECOND ****/
     C_CLICK = 0;
for(j=61; j<=80 && !quit; j+=1)
{
   sum_VLiq=0.0;  sum_PGas=0.0;  sum_VGas=0.0;  sum_PSys=0.0;
   sum_PLiq1=0.0; sum_PLiq2=0.0; sum_PLiq3=0.0; sum_PLiq4=0.0; sum_PLiq5=0.0;
   sum_PLiq6=0.0; sum_PLiq7=0.0; sum_PLiq8=0.0; sum_PLiq9=0.0; sum_PLiq10=0.0;

  for(iter=1; iter<=STOP; iter+=1)
  {
       //Pressure Transeducer Reading for Gas (psia)
       cbAIn(BoardNum, Chan_GasPIn, Gain, &DataGasP);
       cbToEngUnits(BoardNum, Gain, DataGasP, &PGas);
       /*** Adjust the Voltage Reading according to the BIP10VOLTS
            Hardware settings on CIO-AD 08 Board ***/
       PGas *=2;
       sum_PGas=sum_PGas+PGas;

       //Totalizer Reading for Liquid Flow_Rate
       cbAIn(BoardNum, Chan_LiqVIn, Gain, &DataLiqV);
       cbToEngUnits(BoardNum, Gain, DataLiqV, &VLiq);
       /*** Adjust the Voltage Reading according to the BIP10VOLTS
            Hardware settings on CIO-AD 08 Board ***/
       VLiq *=2;
       sum_VLiq=sum_VLiq+VLiq;

       //Flowmeter Reading for Gas Flow_Rate
       cbAIn(BoardNum, Chan_GasVIn, Gain, &DataGasV);
       cbToEngUnits(BoardNum, Gain, DataGasV, &VGas);
       /*** Adjust the Voltage Reading according to the BIP10VOLTS
            Hardware settings on CIO-AD 08 Board ***/
       VGas *=2;
       sum_VGas=sum_VGas+VGas;

       //Pressure Transeducer Reading for Pipe System (psig)
       cbAIn(BoardNum, Chan_SysPIn, Gain, &DataSysP);
       cbToEngUnits(BoardNum, Gain, DataSysP, &PSys);
       /*** Adjust the Voltage Reading according to the BIP10VOLTS
            Hardware settings on CIO-AD 08 Board ***/
       PSys *=2;
       sum_PSys=sum_PSys+PSys;

  seconds++;
    }      //End for

    AVLiq=sum_VLiq/(iter-1);
    APGas=sum_PGas/(iter-1);
    AVGas=sum_VGas/(iter-1);
    APSys=sum_PSys/(iter-1);

    //Real-time Average for the j iterations
    RavgVLiq += (AVLiq-RavgVLiq) / j;
    RavgPGas += (APGas-RavgPGas) / j;
    RavgVGas += (AVGas-RavgVGas) / j;
    RavgPSys += (APSys-RavgPSys) / j;

 }      //End for
```

```
 for(j=1; j<=20 && !quit; j+=1)
 {
   for(iter=1; iter<=STOP; iter+=1)
    {
        //Pressure Transeducer Reading for Liquid
        cbAIn(BoardNum, Chan_LiqPIn, Gain, &DataLiqP);
        cbToEngUnits(BoardNum, Gain, DataLiqP, &PLiq);
        /*** Adjust the Voltage Reading according to the BIP10VOLTS
             Hardware settings on CIO-AD 08 Board ***/
        PLiq *=2;
        sum_PLiq4=sum_PLiq4+PLiq;
     }      //End for
     APLiq4=sum_PLiq4/(iter-1);
   //Real-time Average for the j iterations
   RavgPLiq4 += (APLiq4-RavgPLiq4) / j;
   sum_PLiq4=0.0;
   while(C_CLICK < WAIT*20); /**** WAIT UNTIL 1 SECOND ****/
   C_CLICK = 0;
  }      //End for

     if (Turb_Meter==1)
     {
       AGalpmin=0.00425*200*2*AVLiq+0.0210; //for Liquid flow rate (gal/min)
     }
     if (Turb_Meter==2)
     {
       AGalpmin=0.0466*20*AVLiq+0.1162; //for Liquid flow rate (gal/min)
     }
     ALpmin=20.103*AVGas-0.7211;        //for Gas Flow Rate (liter/min)
     Apsia=20.339*APGas-2.844;          //for Gas Pressure (psia)
     Apsi=Apsia-R_PGas*0.019337;
     Apsig=8.0398*APSys-9.8147;         //for System Pressure (psig)

     ADP1=1.43783*RavgPLiq1-1.43733;        //for Liquid Pressure Drop (in_H2O)
     ADP2=1.43783*RavgPLiq2-1.43733;        //for Liquid Pressure Drop (in_H2O)
     ADP3=1.43783*RavgPLiq3-1.43733;        //for Liquid Pressure Drop (in_H2O)
     ADP4=1.43783*RavgPLiq4-1.43733;        //for Liquid Pressure Drop (in_H2O)
     ADP5=1.43783*RavgPLiq5-1.43733;        //for Liquid Pressure Drop (in_H2O)
     ADP6=1.43783*RavgPLiq6-1.43733;        //for Liquid Pressure Drop (in_H2O)
     ADP7=1.43783*RavgPLiq7-1.43733;        //for Liquid Pressure Drop (in_H2O)
     ADP8=1.43783*RavgPLiq8-1.43733;        //for Liquid Pressure Drop (in_H2O)
     ADP9=1.43783*RavgPLiq9-1.43733;        //for Liquid Pressure Drop (in_H2O)
     ADP10=1.43783*RavgPLiq10-1.43733;      //for Liquid Pressure Drop (in_H2O)

 fprintf(ofpl, "%f      %f      %f      %f      %f      %f      %f      %f
%f      %f      %f      %f      %f      %f\n",
         AGalpmin, ALpmin, Apsi, Apsig, ADP1, ADP2, ADP3, ADP4, ADP5, ADP6,
ADP7, ADP8,
         ADP9, ADP10);

     //Send a Bit to turn the scanivalve to channel 5
      cbDOut(BoardNum, PortNum, Bit_On);
      while(C_CLICK < WAIT*2); /**** WAIT UNTIL 0.1 SECOND ****/
      C_CLICK = 0;
     //Turn off the Bit
      cbDOut(BoardNum, PortNum, Bit_Off);
     printf("\n%s",
     "Your Wafer Chnanel Connection is 5");
     for (k=1; k<=5; k+=1)
     {
     sound(800);
     while(C_CLICK < WAIT*6); /**** WAIT UNTIL 0.3 SECOND ****/
```

```
    C_CLICK = 0;
    nosound();
    while(C_CLICK < WAIT*6); /**** WAIT UNTIL 0.3 SECOND ****/
    C_CLICK = 0;
    }
    while(C_CLICK < WAIT*3600); /**** WAIT UNTIL 180 SECOND ****/
     C_CLICK = 0;
for(j=81; j<=100 && !quit; j+=1)
{
   sum_VLiq=0.0;  sum_PGas=0.0;  sum_VGas=0.0;  sum_PSys=0.0;
   sum_PLiq1=0.0; sum_PLiq2=0.0; sum_PLiq3=0.0; sum_PLiq4=0.0; sum_PLiq5=0.0;
   sum_PLiq6=0.0; sum_PLiq7=0.0; sum_PLiq8=0.0; sum_PLiq9=0.0; sum_PLiq10=0.0;

  for(iter=1; iter<=STOP; iter+=1)
  {
       //Pressure Transeducer Reading for Gas (psia)
       cbAIn(BoardNum, Chan_GasPIn, Gain, &DataGasP);
       cbToEngUnits(BoardNum, Gain, DataGasP, &PGas);
       /*** Adjust the Voltage Reading according to the BIP10VOLTS
            Hardware settings on CIO-AD 08 Board ***/
       PGas *=2;
       sum_PGas=sum_PGas+PGas;

       //Totalizer Reading for Liquid Flow_Rate
       cbAIn(BoardNum, Chan_LiqVIn, Gain, &DataLiqV);
       cbToEngUnits(BoardNum, Gain, DataLiqV, &VLiq);
       /*** Adjust the Voltage Reading according to the BIP10VOLTS
            Hardware settings on CIO-AD 08 Board ***/
       VLiq *=2;
       sum_VLiq=sum_VLiq+VLiq;

       //Flowmeter Reading for Gas Flow_Rate
       cbAIn(BoardNum, Chan_GasVIn, Gain, &DataGasV);
       cbToEngUnits(BoardNum, Gain, DataGasV, &VGas);
       /*** Adjust the Voltage Reading according to the BIP10VOLTS
            Hardware settings on CIO-AD 08 Board ***/
       VGas *=2;
       sum_VGas=sum_VGas+VGas;

       //Pressure Transeducer Reading for Pipe System (psig)
       cbAIn(BoardNum, Chan_SysPIn, Gain, &DataSysP);
       cbToEngUnits(BoardNum, Gain, DataSysP, &PSys);
       /*** Adjust the Voltage Reading according to the BIP10VOLTS
            Hardware settings on CIO-AD 08 Board ***/
       PSys *=2;
       sum_PSys=sum_PSys+PSys;

  seconds++;
    }      //End for

    AVLiq=sum_VLiq/(iter-1);
    APGas=sum_PGas/(iter-1);
    AVGas=sum_VGas/(iter-1);
    APSys=sum_PSys/(iter-1);

    //Real-time Average for the j iterations
    RavgVLiq += (AVLiq-RavgVLiq) / j;
    RavgPGas += (APGas-RavgPGas) / j;
    RavgVGas += (AVGas-RavgVGas) / j;
    RavgPSys += (APSys-RavgPSys) / j;

 }      //End for
```

```
 for(j=1; j<=20 && !quit; j+=1)
 {
   for(iter=1; iter<=STOP; iter+=1)
    {
        //Pressure Transeducer Reading for Liquid
        cbAIn(BoardNum, Chan_LiqPIn, Gain, &DataLiqP);
        cbToEngUnits(BoardNum, Gain, DataLiqP, &PLiq);
        /*** Adjust the Voltage Reading according to the BIP10VOLTS
             Hardware settings on CIO-AD 08 Board ***/
        PLiq *=2;
        sum_PLiq5=sum_PLiq5+PLiq;
     }      //End for
     APLiq5=sum_PLiq5/(iter-1);
   //Real-time Average for the j iterations
   RavgPLiq5 += (APLiq5-RavgPLiq5) / j;
   sum_PLiq5=0.0;
   while(C_CLICK < WAIT*20); /**** WAIT UNTIL 1 SECOND ****/
   C_CLICK = 0;
  }      //End for

     if (Turb_Meter==1)
     {
       AGalpmin=0.00425*200*2*AVLiq+0.0210; //for Liquid flow rate (gal/min)
     }
     if (Turb_Meter==2)
     {
       AGalpmin=0.0466*20*AVLiq+0.1162; //for Liquid flow rate (gal/min)
     }
     ALpmin=20.103*AVGas-0.7211;       //for Gas Flow Rate (liter/min)
     Apsia=20.339*APGas-2.844;         //for Gas Pressure (psia)
     Apsi=Apsia-R_PGas*0.019337;
     Apsig=8.0398*APSys-9.8147;        //for System Pressure (psig)

     ADP1=1.43783*RavgPLiq1-1.43733;       //for Liquid Pressure Drop (in_H2O)
     ADP2=1.43783*RavgPLiq2-1.43733;       //for Liquid Pressure Drop (in_H2O)
     ADP3=1.43783*RavgPLiq3-1.43733;       //for Liquid Pressure Drop (in_H2O)
     ADP4=1.43783*RavgPLiq4-1.43733;       //for Liquid Pressure Drop (in_H2O)
     ADP5=1.43783*RavgPLiq5-1.43733;       //for Liquid Pressure Drop (in_H2O)
     ADP6=1.43783*RavgPLiq6-1.43733;       //for Liquid Pressure Drop (in_H2O)
     ADP7=1.43783*RavgPLiq7-1.43733;       //for Liquid Pressure Drop (in_H2O)
     ADP8=1.43783*RavgPLiq8-1.43733;       //for Liquid Pressure Drop (in_H2O)
     ADP9=1.43783*RavgPLiq9-1.43733;       //for Liquid Pressure Drop (in_H2O)
     ADP10=1.43783*RavgPLiq10-1.43733;     //for Liquid Pressure Drop (in_H2O)

 fprintf(ofp1, "%f      %f      %f      %f      %f      %f      %f      %f
%f      %f      %f      %f      %f      %f\n",
         AGalpmin, ALpmin, Apsi, Apsig, ADP1, ADP2, ADP3, ADP4, ADP5, ADP6,
ADP7, ADP8,
         ADP9, ADP10);

     //Send a Bit to turn the scanivalve to channel 6
      cbDOut(BoardNum, PortNum, Bit_On);
      while(C_CLICK < WAIT*2); /**** WAIT UNTIL 0.1 SECOND ****/
      C_CLICK = 0;
     //Turn off the Bit
      cbDOut(BoardNum, PortNum, Bit_Off);
     printf("\n%s",
     "Your Wafer Chnanel Connection is 6");
     for (k=1; k<=6; k+=1)
     {
     sound(800);
     while(C_CLICK < WAIT*6); /**** WAIT UNTIL 0.3 SECOND ****/
```

```
    C_CLICK = 0;
    nosound();
    while(C_CLICK < WAIT*6); /**** WAIT UNTIL 0.3 SECOND ****/
    C_CLICK = 0;
    }
    while(C_CLICK < WAIT*3600); /**** WAIT UNTIL 180 SECOND ****/
     C_CLICK = 0;
for(j=101; j<=120 && !quit; j+=1)
{
   sum_VLiq=0.0;  sum_PGas=0.0;  sum_VGas=0.0;  sum_PSys=0.0;
   sum_PLiq1=0.0; sum_PLiq2=0.0; sum_PLiq3=0.0; sum_PLiq4=0.0; sum_PLiq5=0.0;
   sum_PLiq6=0.0; sum_PLiq7=0.0; sum_PLiq8=0.0; sum_PLiq9=0.0; sum_PLiq10=0.0;

  for(iter=1; iter<=STOP; iter+=1)
  {
       //Pressure Transeducer Reading for Gas (psia)
       cbAIn(BoardNum, Chan_GasPIn, Gain, &DataGasP);
       cbToEngUnits(BoardNum, Gain, DataGasP, &PGas);
       /*** Adjust the Voltage Reading according to the BIP10VOLTS
            Hardware settings on CIO-AD 08 Board ***/
       PGas *=2;
       sum_PGas=sum_PGas+PGas;

       //Totalizer Reading for Liquid Flow_Rate
       cbAIn(BoardNum, Chan_LiqVIn, Gain, &DataLiqV);
       cbToEngUnits(BoardNum, Gain, DataLiqV, &VLiq);
       /*** Adjust the Voltage Reading according to the BIP10VOLTS
            Hardware settings on CIO-AD 08 Board ***/
       VLiq *=2;
       sum_VLiq=sum_VLiq+VLiq;

       //Flowmeter Reading for Gas Flow_Rate
       cbAIn(BoardNum, Chan_GasVIn, Gain, &DataGasV);
       cbToEngUnits(BoardNum, Gain, DataGasV, &VGas);
       /*** Adjust the Voltage Reading according to the BIP10VOLTS
            Hardware settings on CIO-AD 08 Board ***/
       VGas *=2;
       sum_VGas=sum_VGas+VGas;

       //Pressure Transeducer Reading for Pipe System (psig)
       cbAIn(BoardNum, Chan_SysPIn, Gain, &DataSysP);
       cbToEngUnits(BoardNum, Gain, DataSysP, &PSys);
       /*** Adjust the Voltage Reading according to the BIP10VOLTS
            Hardware settings on CIO-AD 08 Board ***/
       PSys *=2;
       sum_PSys=sum_PSys+PSys;

  seconds++;
    }      //End for

    AVLiq=sum_VLiq/(iter-1);
    APGas=sum_PGas/(iter-1);
    AVGas=sum_VGas/(iter-1);
    APSys=sum_PSys/(iter-1);

    //Real-time Average for the j iterations
    RavgVLiq += (AVLiq-RavgVLiq) / j;
    RavgPGas += (APGas-RavgPGas) / j;
    RavgVGas += (AVGas-RavgVGas) / j;
    RavgPSys += (APSys-RavgPSys) / j;

 }      //End for
```

```
 for(j=1; j<=20 && !quit; j+=1)
 {
   for(iter=1; iter<=STOP; iter+=1)
    {
        //Pressure Transeducer Reading for Liquid
        cbAIn(BoardNum, Chan_LiqPIn, Gain, &DataLiqP);
        cbToEngUnits(BoardNum, Gain, DataLiqP, &PLiq);
        /*** Adjust the Voltage Reading according to the BIP10VOLTS
             Hardware settings on CIO-AD 08 Board ***/
        PLiq *=2;
        sum_PLiq6=sum_PLiq6+PLiq;
     }      //End for
     APLiq6=sum_PLiq6/(iter-1);
   //Real-time Average for the j iterations
   RavgPLiq6 += (APLiq6-RavgPLiq6) / j;
   sum_PLiq6=0.0;
   while(C_CLICK < WAIT*20); /**** WAIT UNTIL 1 SECOND ****/
   C_CLICK = 0;
  }      //End for

     if (Turb_Meter==1)
     {
       AGalpmin=0.00425*200*2*AVLiq+0.0210; //for Liquid flow rate (gal/min)
     }
     if (Turb_Meter==2)
     {
       AGalpmin=0.0466*20*AVLiq+0.1162; //for Liquid flow rate (gal/min)
     }
     ALpmin=20.103*AVGas-0.7211;       //for Gas Flow Rate (liter/min)
     Apsia=20.339*APGas-2.844;         //for Gas Pressure (psia)
     Apsi=Apsia-R_PGas*0.019337;
     Apsig=8.0398*APSys-9.8147;        //for System Pressure (psig)

     ADP1=1.43783*RavgPLiq1-1.43733;       //for Liquid Pressure Drop (in_H2O)
     ADP2=1.43783*RavgPLiq2-1.43733;       //for Liquid Pressure Drop (in_H2O)
     ADP3=1.43783*RavgPLiq3-1.43733;       //for Liquid Pressure Drop (in_H2O)
     ADP4=1.43783*RavgPLiq4-1.43733;       //for Liquid Pressure Drop (in_H2O)
     ADP5=1.43783*RavgPLiq5-1.43733;       //for Liquid Pressure Drop (in_H2O)
     ADP6=1.43783*RavgPLiq6-1.43733;       //for Liquid Pressure Drop (in_H2O)
     ADP7=1.43783*RavgPLiq7-1.43733;       //for Liquid Pressure Drop (in_H2O)
     ADP8=1.43783*RavgPLiq8-1.43733;       //for Liquid Pressure Drop (in_H2O)
     ADP9=1.43783*RavgPLiq9-1.43733;       //for Liquid Pressure Drop (in_H2O)
     ADP10=1.43783*RavgPLiq10-1.43733;     //for Liquid Pressure Drop (in_H2O)

 fprintf(ofp1, "%f      %f      %f      %f      %f      %f      %f      %f
%f      %f      %f      %f      %f      %f\n",
        AGalpmin, ALpmin, Apsi, Apsig, ADP1, ADP2, ADP3, ADP4, ADP5, ADP6,
ADP7, ADP8,
         ADP9, ADP10);

     //Send a Bit to turn the scanivalve to channel 7
      cbDOut(BoardNum, PortNum, Bit_On);
      while(C_CLICK < WAIT*2); /**** WAIT UNTIL 0.1 SECOND ****/
      C_CLICK = 0;
     //Turn off the Bit
      cbDOut(BoardNum, PortNum, Bit_Off);
     printf("\n%s",
     "Your Wafer Chnanel Connection is 7");
     for (k=1; k<=7; k+=1)
     {
     sound(800);
     while(C_CLICK < WAIT*6); /**** WAIT UNTIL 0.3 SECOND ****/
```

```
    C_CLICK = 0;
    nosound();
    while(C_CLICK < WAIT*6); /**** WAIT UNTIL 0.3 SECOND ****/
    C_CLICK = 0;
    }
    while(C_CLICK < WAIT*3600); /**** WAIT UNTIL 180 SECOND ****/
     C_CLICK = 0;
for(j=121; j<=140 && !quit; j+=1)
{
   sum_VLiq=0.0;  sum_PGas=0.0;   sum_VGas=0.0;   sum_PSys=0.0;
   sum_PLiq1=0.0; sum_PLiq2=0.0;  sum_PLiq3=0.0;  sum_PLiq4=0.0; sum_PLiq5=0.0;
   sum_PLiq6=0.0; sum_PLiq7=0.0;  sum_PLiq8=0.0;  sum_PLiq9=0.0; sum_PLiq10=0.0;

  for(iter=1; iter<=STOP; iter+=1)
  {
       //Pressure Transeducer Reading for Gas (psia)
       cbAIn(BoardNum, Chan_GasPIn, Gain, &DataGasP);
       cbToEngUnits(BoardNum, Gain, DataGasP, &PGas);
       /*** Adjust the Voltage Reading according to the BIP10VOLTS
            Hardware settings on CIO-AD 08 Board ***/
       PGas *=2;
       sum_PGas=sum_PGas+PGas;

       //Totalizer Reading for Liquid Flow_Rate
       cbAIn(BoardNum, Chan_LiqVIn, Gain, &DataLiqV);
       cbToEngUnits(BoardNum, Gain, DataLiqV, &VLiq);
       /*** Adjust the Voltage Reading according to the BIP10VOLTS
            Hardware settings on CIO-AD 08 Board ***/
       VLiq *=2;
       sum_VLiq=sum_VLiq+VLiq;

       //Flowmeter Reading for Gas Flow_Rate
       cbAIn(BoardNum, Chan_GasVIn, Gain, &DataGasV);
       cbToEngUnits(BoardNum, Gain, DataGasV, &VGas);
       VGas *=2;
       sum_VGas=sum_VGas+VGas;

       //Pressure Transeducer Reading for Pipe System (psig)
       cbAIn(BoardNum, Chan_SysPIn, Gain, &DataSysP);
       cbToEngUnits(BoardNum, Gain, DataSysP, &PSys);
       /*** Adjust the Voltage Reading according to the BIP10VOLTS
            Hardware settings on CIO-AD 08 Board ***/
       PSys *=2;
       sum_PSys=sum_PSys+PSys;

  seconds++;
    }      //End for

    AVLiq=sum_VLiq/(iter-1);
    APGas=sum_PGas/(iter-1);
    AVGas=sum_VGas/(iter-1);
    APSys=sum_PSys/(iter-1);

    //Real-time Average for the j iterations
    RavgVLiq += (AVLiq-RavgVLiq) / j;
    RavgPGas += (APGas-RavgPGas) / j;
    RavgVGas += (AVGas-RavgVGas) / j;
    RavgPSys += (APSys-RavgPSys) / j;

 }      //End for

for(j=1; j<=20 && !quit; j+=1)
{
```

```
   for(iter=1; iter<=STOP; iter+=1)
    {
        //Pressure Transeducer Reading for Liquid
        cbAIn(BoardNum, Chan_LiqPIn, Gain, &DataLiqP);
        cbToEngUnits(BoardNum, Gain, DataLiqP, &PLiq);
        /*** Adjust the Voltage Reading according to the BIP10VOLTS
             Hardware settings on CIO-AD 08 Board ***/
        PLiq *=2;
        sum_PLiq7=sum_PLiq7+PLiq;
      }       //End for
     APLiq7=sum_PLiq7/(iter-1);
   //Real-time Average for the j iterations
   RavgPLiq7 += (APLiq7-RavgPLiq7) / j;
   sum_PLiq7=0.0;
   while(C_CLICK < WAIT*20); /**** WAIT UNTIL 1 SECOND ****/
   C_CLICK = 0;
  }       //End for

     if (Turb_Meter==1)
     {
       AGalpmin=0.00425*200*2*AVLiq+0.0210; //for Liquid flow rate (gal/min)
     }
     if (Turb_Meter==2)
     {
       AGalpmin=0.0466*20*AVLiq+0.1162; //for Liquid flow rate (gal/min)
     }
     ALpmin=20.103*AVGas-0.7211;        //for Gas Flow Rate (liter/min)
     Apsia=20.339*APGas-2.844;          //for Gas Pressure (psia)
     Apsi=Apsia-R_PGas*0.019337;
     Apsig=8.0398*APSys-9.8147;         //for System Pressure (psig)

     ADP1=1.43783*RavgPLiq1-1.43733;        //for Liquid Pressure Drop (in_H2O)
     ADP2=1.43783*RavgPLiq2-1.43733;        //for Liquid Pressure Drop (in_H2O)
     ADP3=1.43783*RavgPLiq3-1.43733;        //for Liquid Pressure Drop (in_H2O)
     ADP4=1.43783*RavgPLiq4-1.43733;        //for Liquid Pressure Drop (in_H2O)
     ADP5=1.43783*RavgPLiq5-1.43733;        //for Liquid Pressure Drop (in_H2O)
     ADP6=1.43783*RavgPLiq6-1.43733;        //for Liquid Pressure Drop (in_H2O)
     ADP7=1.43783*RavgPLiq7-1.43733;        //for Liquid Pressure Drop (in_H2O)
     ADP8=1.43783*RavgPLiq8-1.43733;        //for Liquid Pressure Drop (in_H2O)
     ADP9=1.43783*RavgPLiq9-1.43733;        //for Liquid Pressure Drop (in_H2O)
     ADP10=1.43783*RavgPLiq10-1.43733;      //for Liquid Pressure Drop (in_H2O)

 fprintf(ofpl, "%f      %f      %f      %f      %f      %f      %f      %f
%f      %f      %f      %f      %f      %f\n",
         AGalpmin, ALpmin, Apsi, Apsig, ADP1, ADP2, ADP3, ADP4, ADP5, ADP6,
ADP7, ADP8,
         ADP9, ADP10);

     //Send a Bit to turn the scanivalve to channel 8
      cbDOut(BoardNum, PortNum, Bit_On);
      while(C_CLICK < WAIT*2); /**** WAIT UNTIL 0.1 SECOND ****/
      C_CLICK = 0;
     //Turn off the Bit
      cbDOut(BoardNum, PortNum, Bit_Off);
     printf("\n%s",
     "Your Wafer Chnanel Connection is 8");
     for (k=1; k<=8; k+=1)
     {
     sound(800);
     while(C_CLICK < WAIT*6); /**** WAIT UNTIL 0.3 SECOND ****/
     C_CLICK = 0;
     nosound();
     while(C_CLICK < WAIT*6); /**** WAIT UNTIL 0.3 SECOND ****/
```

```
     C_CLICK = 0;
     }
//      while(C_CLICK < WAIT*2400); /**** WAIT UNTIL 120 SECOND ****/
     while(C_CLICK < WAIT*3600); /**** WAIT UNTIL 180 SECOND ****/
      C_CLICK = 0;
 for(j=141; j<=160 && !quit; j+=1)
 {
    sum_VLiq=0.0;  sum_PGas=0.0;  sum_VGas=0.0;  sum_PSys=0.0;
    sum_PLiq1=0.0; sum_PLiq2=0.0; sum_PLiq3=0.0; sum_PLiq4=0.0; sum_PLiq5=0.0;
    sum_PLiq6=0.0; sum_PLiq7=0.0; sum_PLiq8=0.0; sum_PLiq9=0.0; sum_PLiq10=0.0;

   for(iter=1; iter<=STOP; iter+=1)
   {
        //Pressure Transeducer Reading for Gas (psia)
        cbAIn(BoardNum, Chan_GasPIn, Gain, &DataGasP);
        cbToEngUnits(BoardNum, Gain, DataGasP, &PGas);
        /*** Adjust the Voltage Reading according to the BIP10VOLTS
             Hardware settings on CIO-AD 08 Board ***/
        PGas *=2;
        sum_PGas=sum_PGas+PGas;

        //Totalizer Reading for Liquid Flow_Rate
        cbAIn(BoardNum, Chan_LiqVIn, Gain, &DataLiqV);
        cbToEngUnits(BoardNum, Gain, DataLiqV, &VLiq);
        /*** Adjust the Voltage Reading according to the BIP10VOLTS
             Hardware settings on CIO-AD 08 Board ***/
        VLiq *=2;
        sum_VLiq=sum_VLiq+VLiq;

        //Flowmeter Reading for Gas Flow_Rate
        cbAIn(BoardNum, Chan_GasVIn, Gain, &DataGasV);
        cbToEngUnits(BoardNum, Gain, DataGasV, &VGas);
        /*** Adjust the Voltage Reading according to the BIP10VOLTS
             Hardware settings on CIO-AD 08 Board ***/
        VGas *=2;
        sum_VGas=sum_VGas+VGas;

        //Pressure Transeducer Reading for Pipe System (psig)
        cbAIn(BoardNum, Chan_SysPIn, Gain, &DataSysP);
        cbToEngUnits(BoardNum, Gain, DataSysP, &PSys);
        /*** Adjust the Voltage Reading according to the BIP10VOLTS
             Hardware settings on CIO-AD 08 Board ***/
        PSys *=2;
        sum_PSys=sum_PSys+PSys;

   seconds++;
     }      //End for

     AVLiq=sum_VLiq/(iter-1);
     APGas=sum_PGas/(iter-1);
     AVGas=sum_VGas/(iter-1);
     APSys=sum_PSys/(iter-1);

     //Real-time Average for the j iterations
     RavgVLiq += (AVLiq-RavgVLiq) / j;
     RavgPGas += (APGas-RavgPGas) / j;
     RavgVGas += (AVGas-RavgVGas) / j;
     RavgPSys += (APSys-RavgPSys) / j;

  }      //End for

 for(j=1; j<=20 && !quit; j+=1)
 {
```

```
   for(iter=1; iter<=STOP; iter+=1)
    {
        //Pressure Transeducer Reading for Liquid
        cbAIn(BoardNum, Chan_LiqPIn, Gain, &DataLiqP);
        cbToEngUnits(BoardNum, Gain, DataLiqP, &PLiq);
        /*** Adjust the Voltage Reading according to the BIP10VOLTS
             Hardware settings on CIO-AD 08 Board ***/
        PLiq *=2;
        sum_PLiq8=sum_PLiq8+PLiq;
     }      //End for
     APLiq8=sum_PLiq8/(iter-1);
   //Real-time Average for the j iterations
   RavgPLiq8 += (APLiq8-RavgPLiq8) / j;
   sum_PLiq8=0.0;
   while(C_CLICK < WAIT*20); /**** WAIT UNTIL 1 SECOND ****/
   C_CLICK = 0;
  }      //End for

     if (Turb_Meter==1)
     {
       AGalpmin=0.00425*200*2*AVLiq+0.0210; //for Liquid flow rate (gal/min)
     }
     if (Turb_Meter==2)
     {
       AGalpmin=0.0466*20*AVLiq+0.1162; //for Liquid flow rate (gal/min)
     }
     ALpmin=20.103*AVGas-0.7211;       //for Gas Flow Rate (liter/min)
     Apsia=20.339*APGas-2.844;         //for Gas Pressure (psia)
     Apsi=Apsia-R_PGas*0.019337;
     Apsig=8.0398*APSys-9.8147;        //for System Pressure (psig)

     ADP1=1.43783*RavgPLiq1-1.43733;       //for Liquid Pressure Drop (in_H2O)
     ADP2=1.43783*RavgPLiq2-1.43733;       //for Liquid Pressure Drop (in_H2O)
     ADP3=1.43783*RavgPLiq3-1.43733;       //for Liquid Pressure Drop (in_H2O)
     ADP4=1.43783*RavgPLiq4-1.43733;       //for Liquid Pressure Drop (in_H2O)
     ADP5=1.43783*RavgPLiq5-1.43733;       //for Liquid Pressure Drop (in_H2O)
     ADP6=1.43783*RavgPLiq6-1.43733;       //for Liquid Pressure Drop (in_H2O)
     ADP7=1.43783*RavgPLiq7-1.43733;       //for Liquid Pressure Drop (in_H2O)
     ADP8=1.43783*RavgPLiq8-1.43733;       //for Liquid Pressure Drop (in_H2O)
     ADP9=1.43783*RavgPLiq9-1.43733;       //for Liquid Pressure Drop (in_H2O)
     ADP10=1.43783*RavgPLiq10-1.43733;     //for Liquid Pressure Drop (in_H2O)

 fprintf(ofp1, "%f      %f      %f      %f      %f      %f      %f      %f
%f      %f      %f      %f      %f      %f\n",
         AGalpmin, ALpmin, Apsi, Apsig, ADP1, ADP2, ADP3, ADP4, ADP5, ADP6,
ADP7, ADP8,
         ADP9, ADP10);

     //Send a Bit to turn the scanivalve to channel 9
      cbDOut(BoardNum, PortNum, Bit_On);
      while(C_CLICK < WAIT*2); /**** WAIT UNTIL 0.1 SECOND ****/
      C_CLICK = 0;
     //Turn off the Bit
      cbDOut(BoardNum, PortNum, Bit_Off);
     printf("\n%s",
     "Your Wafer Chnanel Connection is 9");
     for (k=1; k<=9; k+=1)
     {
     sound(800);
     while(C_CLICK < WAIT*6); /**** WAIT UNTIL 0.3 SECOND ****/
     C_CLICK = 0;
     nosound();
     while(C_CLICK < WAIT*6); /**** WAIT UNTIL 0.3 SECOND ****/
```

```
     C_CLICK = 0;
     }
      C_CLICK = 0;
for(j=161; j<=180 && !quit; j+=1)
{
    sum_VLiq=0.0;  sum_PGas=0.0;  sum_VGas=0.0;  sum_PSys=0.0;
    sum_PLiq1=0.0; sum_PLiq2=0.0; sum_PLiq3=0.0; sum_PLiq4=0.0; sum_PLiq5=0.0;
    sum_PLiq6=0.0; sum_PLiq7=0.0; sum_PLiq8=0.0; sum_PLiq9=0.0; sum_PLiq10=0.0;

   for(iter=1; iter<=STOP; iter+=1)
   {
        //Pressure Transeducer Reading for Gas (psia)
        cbAIn(BoardNum, Chan_GasPIn, Gain, &DataGasP);
        cbToEngUnits(BoardNum, Gain, DataGasP, &PGas);
        /*** Adjust the Voltage Reading according to the BIP10VOLTS
             Hardware settings on CIO-AD 08 Board ***/
        PGas *=2;
        sum_PGas=sum_PGas+PGas;

        //Totalizer Reading for Liquid Flow_Rate
        cbAIn(BoardNum, Chan_LiqVIn, Gain, &DataLiqV);
        cbToEngUnits(BoardNum, Gain, DataLiqV, &VLiq);
        /*** Adjust the Voltage Reading according to the BIP10VOLTS
             Hardware settings on CIO-AD 08 Board ***/
        VLiq *=2;
        sum_VLiq=sum_VLiq+VLiq;

        //Flowmeter Reading for Gas Flow_Rate
        cbAIn(BoardNum, Chan_GasVIn, Gain, &DataGasV);
        cbToEngUnits(BoardNum, Gain, DataGasV, &VGas);
        /*** Adjust the Voltage Reading according to the BIP10VOLTS
             Hardware settings on CIO-AD 08 Board ***/
        VGas *=2;
        sum_VGas=sum_VGas+VGas;

        //Pressure Transeducer Reading for Pipe System (psig)
        cbAIn(BoardNum, Chan_SysPIn, Gain, &DataSysP);
        cbToEngUnits(BoardNum, Gain, DataSysP, &PSys);
        PSys *=2;
        sum_PSys=sum_PSys+PSys;

   seconds++;
     }       //End for

     AVLiq=sum_VLiq/(iter-1);
     APGas=sum_PGas/(iter-1);
     AVGas=sum_VGas/(iter-1);
     APSys=sum_PSys/(iter-1);

     //Real-time Average for the j iterations
     RavgVLiq += (AVLiq-RavgVLiq) / j;
     RavgPGas += (APGas-RavgPGas) / j;
     RavgVGas += (AVGas-RavgVGas) / j;
     RavgPSys += (APSys-RavgPSys) / j;

  }       //End for

for(j=1; j<=20 && !quit; j+=1)
{
   for(iter=1; iter<=STOP; iter+=1)
    {
        //Pressure Transeducer Reading for Liquid
        cbAIn(BoardNum, Chan_LiqPIn, Gain, &DataLiqP);
```

```
        cbToEngUnits(BoardNum, Gain, DataLiqP, &PLiq);
        /*** Adjust the Voltage Reading according to the BIP10VOLTS
             Hardware settings on CIO-AD 08 Board ***/
        PLiq *=2;
        sum_PLiq9=sum_PLiq9+PLiq;
      }      //End for
     APLiq9=sum_PLiq9/(iter-1);
   //Real-time Average for the j iterations
   RavgPLiq9 += (APLiq9-RavgPLiq9) / j;
   sum_PLiq9=0.0;
   while(C_CLICK < WAIT*20); /**** WAIT UNTIL 1 SECOND ****/
   C_CLICK = 0;
  }      //End for

     if (Turb_Meter==1)
     {
       AGalpmin=0.00425*200*2*AVLiq+0.0210; //for Liquid flow rate (gal/min)
     }
     if (Turb_Meter==2)
     {
       AGalpmin=0.0466*20*AVLiq+0.1162; //for Liquid flow rate (gal/min)
     }
     ALpmin=20.103*AVGas-0.7211;        //for Gas Flow Rate (liter/min)
     Apsia=20.339*APGas-2.844;          //for Gas Pressure (psia)
     Apsi=Apsia-R_PGas*0.019337;
     Apsig=8.0398*APSys-9.8147;         //for System Pressure (psig)

     ADP1=1.43783*RavgPLiq1-1.43733;        //for Liquid Pressure Drop (in_H2O)
     ADP2=1.43783*RavgPLiq2-1.43733;        //for Liquid Pressure Drop (in_H2O)
     ADP3=1.43783*RavgPLiq3-1.43733;        //for Liquid Pressure Drop (in_H2O)
     ADP4=1.43783*RavgPLiq4-1.43733;        //for Liquid Pressure Drop (in_H2O)
     ADP5=1.43783*RavgPLiq5-1.43733;        //for Liquid Pressure Drop (in_H2O)
     ADP6=1.43783*RavgPLiq6-1.43733;        //for Liquid Pressure Drop (in_H2O)
     ADP7=1.43783*RavgPLiq7-1.43733;        //for Liquid Pressure Drop (in_H2O)
     ADP8=1.43783*RavgPLiq8-1.43733;        //for Liquid Pressure Drop (in_H2O)
     ADP9=1.43783*RavgPLiq9-1.43733;        //for Liquid Pressure Drop (in_H2O)
     ADP10=1.43783*RavgPLiq10-1.43733;      //for Liquid Pressure Drop (in_H2O)

 fprintf(ofp1, "%f     %f      %f      %f      %f      %f      %f      %f
%f      %f      %f      %f      %f      %f\n",
         AGalpmin, ALpmin, Apsi, Apsig, ADP1, ADP2, ADP3, ADP4, ADP5, ADP6,
ADP7, ADP8,
         ADP9, ADP10);

     //Send a Bit to turn the scanivalve to channel 10
      cbDOut(BoardNum, PortNum, Bit_On);
      while(C_CLICK < WAIT*2); /**** WAIT UNTIL 0.1 SECOND ****/
      C_CLICK = 0;
     //Turn off the Bit
      cbDOut(BoardNum, PortNum, Bit_Off);
     printf("\n%s",
     "Your Wafer Chnanel Connection is 10");
     for (k=1; k<=10; k+=1)
     {
     sound(800);
     while(C_CLICK < WAIT*6); /**** WAIT UNTIL 0.5 SECOND ****/
     C_CLICK = 0;
     nosound();
     while(C_CLICK < WAIT*6); /**** WAIT UNTIL 0.5 SECOND ****/
     C_CLICK = 0;
     }
      C_CLICK = 0;
 for(j=181; j<=200 && !quit; j+=1)
```

```
{
   sum_VLiq=0.0;  sum_PGas=0.0;  sum_VGas=0.0;  sum_PSys=0.0;
   sum_PLiq1=0.0; sum_PLiq2=0.0; sum_PLiq3=0.0; sum_PLiq4=0.0; sum_PLiq5=0.0;
   sum_PLiq6=0.0; sum_PLiq7=0.0; sum_PLiq8=0.0; sum_PLiq9=0.0; sum_PLiq10=0.0;

  for(iter=1; iter<=STOP; iter+=1)
  {
       //Pressure Transeducer Reading for Gas (psia)
       cbAIn(BoardNum, Chan_GasPIn, Gain, &DataGasP);
       cbToEngUnits(BoardNum, Gain, DataGasP, &PGas);
       /*** Adjust the Voltage Reading according to the BIP10VOLTS
            Hardware settings on CIO-AD 08 Board ***/
       PGas *=2;
       sum_PGas=sum_PGas+PGas;

       //Totalizer Reading for Liquid Flow_Rate
       cbAIn(BoardNum, Chan_LiqVIn, Gain, &DataLiqV);
       cbToEngUnits(BoardNum, Gain, DataLiqV, &VLiq);
       /*** Adjust the Voltage Reading according to the BIP10VOLTS
            Hardware settings on CIO-AD 08 Board ***/
       VLiq *=2;
       sum_VLiq=sum_VLiq+VLiq;

       //Flowmeter Reading for Gas Flow_Rate
       cbAIn(BoardNum, Chan_GasVIn, Gain, &DataGasV);
       cbToEngUnits(BoardNum, Gain, DataGasV, &VGas);
       /*** Adjust the Voltage Reading according to the BIP10VOLTS
            Hardware settings on CIO-AD 08 Board ***/
       VGas *=2;
       sum_VGas=sum_VGas+VGas;

       //Pressure Transeducer Reading for Pipe System (psig)
       cbAIn(BoardNum, Chan_SysPIn, Gain, &DataSysP);
       cbToEngUnits(BoardNum, Gain, DataSysP, &PSys);
       /*** Adjust the Voltage Reading according to the BIP10VOLTS
            Hardware settings on CIO-AD 08 Board ***/
       PSys *=2;
       sum_PSys=sum_PSys+PSys;

  seconds++;
    }      //End for

    AVLiq=sum_VLiq/(iter-1);
    APGas=sum_PGas/(iter-1);
    AVGas=sum_VGas/(iter-1);
    APSys=sum_PSys/(iter-1);

    //Real-time Average for the j iterations
    RavgVLiq += (AVLiq-RavgVLiq) / j;
    RavgPGas += (APGas-RavgPGas) / j;
    RavgVGas += (AVGas-RavgVGas) / j;
    RavgPSys += (APSys-RavgPSys) / j;

 }      //End for

for(j=1; j<=20 && !quit; j+=1)
{
  for(iter=1; iter<=STOP; iter+=1)
   {
       //Pressure Transeducer Reading for Liquid
       cbAIn(BoardNum, Chan_LiqPIn, Gain, &DataLiqP);
       cbToEngUnits(BoardNum, Gain, DataLiqP, &PLiq);
       /*** Adjust the Voltage Reading according to the BIP10VOLTS
```

```
             Hardware settings on CIO-AD 08 Board ***/
        PLiq *=2;
        sum_PLiq10=sum_PLiq10+PLiq;
      }      //End for
     APLiq10=sum_PLiq10/(iter-1);
   //Real-time Average for the j iterations
   RavgPLiq10 += (APLiq10-RavgPLiq10) / j;
   sum_PLiq10=0.0;
   while(C_CLICK < WAIT*20); /**** WAIT UNTIL 1 SECOND ****/
   C_CLICK = 0;
  }      //End for

     while(C_CLICK < WAIT*10); /**** WAIT UNTIL 0.1 SECOND ****/
     C_CLICK = 0;

     if (Turb_Meter==1)
     {
       AGalpmin=0.00425*200*2*AVLiq+0.0210; //for Liquid flow rate (gal/min)
     }
     if (Turb_Meter==2)
     {
       AGalpmin=0.0466*20*AVLiq+0.1162; //for Liquid flow rate (gal/min)
     }
     ALpmin=20.103*AVGas-0.7211;        //for Gas Flow Rate (liter/min)
     Apsia=20.339*APGas-2.844;          //for Gas Pressure (psia)
     Apsi=Apsia-R_PGas*0.019337;
     Apsig=8.0398*APSys-9.8147;         //for System Pressure (psig)

     ADP1=1.43783*RavgPLiq1-1.43733;        //for Liquid Pressure Drop (in_H2O)
     ADP2=1.43783*RavgPLiq2-1.43733;        //for Liquid Pressure Drop (in_H2O)
     ADP3=1.43783*RavgPLiq3-1.43733;        //for Liquid Pressure Drop (in_H2O)
     ADP4=1.43783*RavgPLiq4-1.43733;        //for Liquid Pressure Drop (in_H2O)
     ADP5=1.43783*RavgPLiq5-1.43733;        //for Liquid Pressure Drop (in_H2O)
     ADP6=1.43783*RavgPLiq6-1.43733;        //for Liquid Pressure Drop (in_H2O)
     ADP7=1.43783*RavgPLiq7-1.43733;        //for Liquid Pressure Drop (in_H2O)
     ADP8=1.43783*RavgPLiq8-1.43733;        //for Liquid Pressure Drop (in_H2O)
     ADP9=1.43783*RavgPLiq9-1.43733;        //for Liquid Pressure Drop (in_H2O)
     ADP10=1.43783*RavgPLiq10-1.43733;      //for Liquid Pressure Drop (in_H2O)

 fprintf(ofp1, "%f      %f      %f      %f      %f      %f      %f      %f
%f      %f      %f      %f      %f      %f\n",
         AGalpmin, ALpmin, Apsi, Apsig, ADP1, ADP2, ADP3, ADP4, ADP5, ADP6,
ADP7, ADP8,
         ADP9, ADP10);

    //Send 15 Bits to turn the scanivalve to channel 1
     for(iter=1; iter<=15; iter+=1)
     {
      cbDOut(BoardNum, PortNum, Bit_On);
      while(C_CLICK < WAIT*2); /**** WAIT UNTIL 0.1 SECOND ****/
      C_CLICK = 0;
     //Turn off the Bit
      cbDOut(BoardNum, PortNum, Bit_Off);
      while(C_CLICK < WAIT*5); /**** WAIT UNTIL 0.1 SECOND ****/
      C_CLICK = 0;
     }

     if (Turb_Meter==1)
     {
       Galpmin=0.00425*200*2*RavgVLiq+0.0210; //for Liquid flow rate (gal/min)
     }
     if (Turb_Meter==2)
     {
```

```
       Galpmin=0.0466*20*RavgVLiq+0.1161; //for Liquid flow rate (gal/min)
     }
     //Galpmin=0.0045*200*RavgVLiq+0.0221;   //for Liquid flow rate (gal/min)
     Lpmin=20.103*RavgVGas-0.7211;     //for Gas Flow Rate (liter/min)
     psia=20.339*RavgPGas-2.844;       //for Gas Pressure (psia)
     psi=psia-R_PGas*0.019337;
     psig=8.0398*RavgPSys-9.8147;      //for System Pressure (psig)

     DP1=1.43783*RavgPLiq1-1.43733;       //for Liquid Pressure Drop (in_H2O)
     DP2=1.43783*RavgPLiq2-1.43733;       //for Liquid Pressure Drop (in_H2O)
     DP3=1.43783*RavgPLiq3-1.43733;       //for Liquid Pressure Drop (in_H2O)
     DP4=1.43783*RavgPLiq4-1.43733;       //for Liquid Pressure Drop (in_H2O)
     DP5=1.43783*RavgPLiq5-1.43733;       //for Liquid Pressure Drop (in_H2O)
     DP6=1.43783*RavgPLiq6-1.43733;       //for Liquid Pressure Drop (in_H2O)
     DP7=1.43783*RavgPLiq7-1.43733;       //for Liquid Pressure Drop (in_H2O)
     DP8=1.43783*RavgPLiq8-1.43733;       //for Liquid Pressure Drop (in_H2O)
     DP9=1.43783*RavgPLiq9-1.43733;       //for Liquid Pressure Drop (in_H2O)
     DP10=1.43783*RavgPLiq10-1.43733;     //for Liquid Pressure Drop (in_H2O)

 fprintf(ofp1, "%f      %f      %f      %f      %f      %f      %f      %f
%f      %f      %f      %f      %f      %f\n",
         Galpmin, Lpmin, psi, psig, DP1, DP2, DP3, DP4, DP5, DP6, DP7, DP8,
         DP9, DP10);

end = clock();
period = (end - start) / CLK_TCK ;

Tot_Data=float(STOP)*float(j)*14.0;
printf("\n %s%10.1e%s%f\n",
  "The time period (sec) for ",Tot_Data," data collection  = ", period);

fprintf(ofp2,"\n %s%10.1e%s%f\n",
  "The time period (sec) for ",Tot_Data," data collection  = ", period);
fprintf(ofp2,"\n %s%10.1e%s\n",
  "Each ",Tot_Data/14.0," data were averaged for this measurement");

fprintf(ofp2,"\n\n %s\n %s\n",
  "The averaged Values of Gas & Liquid measurements were",
"Liquid (gal/min)  Gas Flow (L/min)  Gas Pressure (psi)  System P (psig)
System DP1 (in_H2O)");
fprintf(ofp2,"%s%lf%s%lf%s%lf%s%lf%s%lf\n",
"     ",Galpmin,"        ",Lpmin,"          ",psi,"          ",psig,"
",DP1);

fprintf(ofp2,"\n %s\n",
"System DP2  System DP3  System DP4  System DP5  System DP6  System DP7  System
DP8  System DP9  System DP10");
fprintf(ofp2,"%s%lf%s%lf%s%lf%s%lf%s%lf%s%lf%s%lf%s%lf%s%lf\n",
"    ",DP2,"    ",DP3,"    ",DP4,"    ",DP5,"    ",DP6,"    ",DP7,"    ",DP8,"
",DP9,"    ",DP10);

//Calculate the Breber (1980) Flow Pattern Parameters
 rowG=DensityG(psia, R_TGas);
 rowL=DensityL(R_TLiq);           // [lbm/ft^3]
 muL=ViscosityL(R_TLiq);          // [lbm/(hr-ft)]
 muG=ViscosityG(R_TGas);          // [lbm/(hr-ft)]
 QL=Galpmin*2.228*pow10(-3);    // [Gal/min] ---> [ft^3/sec]
 mdotL=rowL*QL;                  // [lbm/sec]
 QG=(Lpmin*0.264172)*2.228*pow10(-3);  //[L/min] ---> [Gal/min] ---> [ft^3/sec]
 mdotG=rowG*QG;                  // [lbm/sec]
 x=mdotG/(mdotL+mdotG);
 XX=pow((1-x)/x,0.9)*pow(rowG/rowL,0.5)*pow(muL/muG,0.1);
 Di=1.0/12.0;  Ac=3.141592654*Di*Di/4.0;
```

```
 Gt=(mdotL+mdotG)/Ac;       //[lbm/sec]/[ft^2]
 Jg=(Gt*x)/sqrt(Di*rowG*(rowL-rowG)*32.174);  //Wallis Factor
 VSL=4*mdotL/(rowL*pie*Di*Di);      //[ft/sec]
 ReSL=rowL*VSL*3600*Di/muL;
 VSG=4*mdotG/(rowG*pie*Di*Di);
 ReSG=rowG*VSG*3600*Di/muG;
 rowH=1/((1-x)/rowL+x/rowG);
 K=pow(rowL/rowH,0.5);
 Alp=1/(1+K*(1-x)/x*rowG/rowL);
 kL=4.722*pow10(-4)*(R_TLiq*(9.0/5.0)+32.0)+0.3149;
 CpL=1.337*pow10(-6)*(R_TLiq*(9.0/5.0)+32.0)*(R_TLiq*(9.0/5.0)+32.0)-
3.374*pow10(-4)*(R_TLiq*(9.0/5.0)+32.0)+1.018;
 PrL=CpL*muL/kL;
 kG=-6.514*pow10(-
9)*(R_TGas*(9.0/5.0)+32.0)*(R_TGas*(9.0/5.0)+32.0)+2.591*pow10(-
5)*(R_TGas*(9.0/5.0)+32.0)+0.01313;
 CpG=7.540*pow10(-6)*(R_TGas*(9.0/5.0)+32.0)+0.2401;
 PrG=CpG*muG/kG;

 fprintf(ofp3,"\n\n %s\n %s\n",
 "       The averaged Values of Gas & Liquid measurements were",
 "  rowL [lbm/ft^3]   rowG [lbm/ft^3]   muL [lbm/ft-hr]   muG [lbm/ft-hr]");
 fprintf(ofp3,"%s%lf%s%lf%s%lf%s%lf\n",
       "    ",rowL,"          ",rowG,"              ",muL,"              ",muG);
 fprintf(ofp3,"\n\n %s\n %s\n",
 "    The averaged Values of the Breber (1980) Parameters were",
 "  mdotL [lbm/sec]   mdotG [lbm/sec]   X [Matinelli]    J*g [Wallis Factor]");
 fprintf(ofp3,"%s%lf%s%lf%s%lf%s%lf\n",
 "    ",mdotL,"           ",mdotG,"             ",XX,"             ",Jg);
 fprintf(ofp4, "%f       %f       %f       %f       %f       %f       %f       %f
%f       %f       %f       %f       %f       %f       %f\n",
         mdotL*3600, VSL, ReSL, mdotG*3600, VSG, ReSG, XX, R_TLiq, psig, DP10,
psi, Alp, PrL, PrG, Jg);

/************ CLEANUP TIMER & KEYBOARD INTERRRUPT*********/
disable();
outportb(CWR_8253, SET_CTR0_8253);
outportb(CTR0_8253, 0x0);
outportb(CTR0_8253, 0x0);
setvect(TMR_INTERRUPT , TIMER_handler);
enable() ;
disable();
setvect(KBD_INTERRUPT, KEYB_handler);

enable() ;

printf("\n %s\n",
  "Do You Want to Continue to collect Data ? (Type y/n)");
scanf(" %c", &more);

} while (more=='Y' || more=='y');

fclose(ofp1);
fclose(ofp2);
fclose(ofp3);
fclose(ofp4);
}

double DensityL(float R_TLiq)
{
 double rowL, T;
 T=double(R_TLiq)*(9.0/5.0)+32.0;
 rowL=pow(2.101*pow10(-8)*(T*T)-1.303*pow10(-6)*T+0.01602,-1);
```

```
 return rowL;
}

double ViscosityL(float R_TLiq)
{
 double muL, T;
 T=double(R_TLiq)*(9.0/5.0)+32.0;
 muL=pow(1.207*pow10(-5)*(T*T)+3.863*pow10(-3)*T+0.09461,-1);
 return muL;
}

double ViscosityG(float R_TGas)
{
 double muG, T;
 T=double(R_TGas)*(9.0/5.0)+32.0;
 muG=-2.673*pow10(-8)*(T*T)+6.819*pow10(-5)*T+0.03936;
 return muG;
}

double DensityG(double Apsi, float R_TGas)
{
 double rowG, R=53.34, tempGinR, T;
 T=double(R_TGas)*(9.0/5.0)+32.0;
 tempGinR=T+459.67;
 rowG=Apsi*144.0/(R*tempGinR);
 return rowG;
}


/*********   SOURCE CODE FOR click()           **************
********* Increments counter and sets flag    **************/

void interrupt click(void)
{
  ++C_CLICK;
  TIMER_handler();
  outportb(ISR_8259, EOI_8259);

}



/************************** USER DEFINED KEYBOARD HANDLER ***********/
void Key_Handler(void)
{
  int key = toupper(getch()), n, j;
 //change, sign;
  char number;
  static int cnt=0;

 switch(key)

  {
   case 27: quit = 1; break;                   //'ESC' key
   case 'Q': quit=1; break;

   case 'R':
     Sign=-1; break;
   case 'S':
     {Flag = 1; cnt=0; }  break;
   case 13:
     {n=atoi(str);  Flag=0; //change=1;          //String to a Integer
      for(j=0; j<=11; j++) str[j]='\n'; }
```

```
        //Cleanup the String
       break;

   case '1': case '2':case '3': case '4':case '5': case '6':
   case '7': case '8':case '9': case '0':
      {number=key;
       if(Flag==1)
         { str[cnt]=number; cnt++; }
         //Make a String
      }
   }
}

/************************ SOURCE CODE FOR keyb()******************
**********                 Keyboard Interrupt   **********/

void interrupt keyb(void)
{
    KEYB_handler();
    if (kbhit()) Key_Handler();

}


/* Hardware Channel Settings for A_In & D_Out */
void Chan_Setting(void)
{
 char ans;
 printf("\n %s\n %s\n",
   "Type a STOP number for a Max. Iterations (Integer)",
   "  EX.) Default STOP = 1000 for 1000 data collection");
   scanf("%d", &STOP);
 printf("\n %s%d\n %s\n %s\n %s\n %s\n %s\n %s\n",
   "Your STOP value = ", STOP,
   "Channel Setting Information for A/D Board",
   "Current Channel Settings are : ",
   "       AIn_V_Ground=17,   AIn_V_Gasmeter (L/min)=0",
   "       AIn_V_GasPressure (psia)=1, AIn_V_Liquid (L/min)=2",
   "       AIn_P_Liquid (in_H2O)=3, AIn_P_System (psig)=4",
   "Do You Want to Change Channel Settings ? (Type y/n)");
   scanf(" %c", &ans);
   if (ans=='Y' || ans=='y') {
     do {
     printf("\n %s\n %s\n",
      "Type a STOP number for the maximum iteration (Integer)",
      "  EX.) Default STOP = 1000 for 1000 data collection");
     scanf("%d", &STOP);
     printf("\n Input Channel Number for Chan_Liq_VIn (L/min) :  ");
     scanf("%d", &Chan_LiqPIn);
     printf("\n %s\n %s%d\n",
      "  Your Channel Settings are : ",
      "   AIn_P_LiqVIn = ",Chan_LiqPIn);

     printf("\n %s\n",
       "Do You Want to Change Channel Settings ? (Type y/n)");
     scanf(" %c", &ans);
     } while (ans=='Y' || ans=='y');
   }
 printf("\n %s\n %s\n",
   "  ATTENTION: You need to set the ScaniVave Position @ Wafer Number 1",
   "   <========= using ScaniValuve Rotation Program!!!!!");
}
```

APPENDIX D

CALIBRATION CURVES FOR WALL THERMOCOUPLES AND A BULK TEMPERATURE PROBE

The content of this appendix is based on Ryali's (1999) work, and the calibration curves for all of the thermocouples used on the test section and for the outlet bulk temperature probes are given. The regression coefficient for all of these thermocouples is approximately equal to 1.000 (regression: predicting the future values by using the present value; the closer the regression coefficient is to 1, the higher the accuracy to predict the future value). Figures D.1 to D.4 show how the difference between the thermocouple readings and bath temperature changed with the temperature of the bath. As explained in Chapter III, the thermocouples appear to have small, but consistent errors as bath temperature increases. However, these errors are attributable to the bath temperature being more difficult to maintain constant as the bath temperature deviated from the ambient temperature.

T_Y= Thermocouple Reading in °C.

T_X= Temperature of the Bath in °C.

TC 1 : $T_Y = 0.98455T_X + 0.63491$ $R^2 = 1.000$
TC 2 : $T_Y = 0.98340T_X + 0.77146$ $R^2 = 0.9999$
TC 3 : $T_Y = 0.98407T_X + 0.73013$ $R^2 = 0.9999$
TC 4 : $T_Y = 0.98401T_X + 0.67914$ $R^2 = 0.9999$
TC 5 : $T_Y = 0.98377T_X + 0.80521$ $R^2 = 0.9999$
TC 6 : $T_Y = 0.98342T_X + 0.70035$ $R^2 = 0.9999$

TC 7 : $T_Y = 0.98399T_X + 0.81327$ $R^2 = 0.9998$
TC 8 : $T_Y = 0.98336T_X + 0.65161$ $R^2 = 1.000$
TC 9 : $T_Y = 0.98329T_X + 0.78138$ $R^2 = 0.9999$
TC 10 : $T_Y = 0.98304T_X + 0.67196$ $R^2 = 1.000$
TC 11 : $T_Y = 0.98341T_X + 0.76111$ $R^2 = 1.000$
TC 12 : $T_Y = 0.98315T_X + 0.66301$ $R^2 = 1.000$
TC 13 : $T_Y = 0.98275T_X + 0.75573$ $R^2 = 1.000$
TC 14 : $T_Y = 0.98307T_X + 0.69353$ $R^2 = 0.9999$
TC 15 : $T_Y = 0.98393T_X + 0.74268$ $R^2 = 1.000$
TC 16 : $T_Y = 0.98379T_X + 0.64465$ $R^2 = 1.000$
TC 17 : $T_Y = 0.98328T_X + 0.75310$ $R^2 = 1.000$
TC 18 : $T_Y = 0.98288T_X + 0.69838$ $R^2 = 1.000$
TC 19 : $T_Y = 0.98276T_X + 0.78805$ $R^2 = 0.9999$
TC 20 : $T_Y = 0.98354T_X + 0.67677$ $R^2 = 0.9999$
TC 21 : $T_Y = 0.98259T_X + 0.80324$ $R^2 = 1.000$
TC 22 : $T_Y = 0.98243T_X + 0.73387$ $R^2 = 1.000$
TC 23 : $T_Y = 0.98279T_X + 0.79685$ $R^2 = 1.000$
TC 24 : $T_Y = 0.98285T_X + 0.71009$ $R^2 = 1.000$
TC 25 : $T_Y = 0.98390T_X + 0.77747$ $R^2 = 0.9999$
TC 26 : $T_Y = 0.98262T_X + 0.73117$ $R^2 = 1.000$
TC 27 : $T_Y = 0.98293T_X + 0.80048$ $R^2 = 1.000$
TC 28 : $T_Y = 0.98324T_X + 0.71672$ $R^2 = 1.000$
TC 29 : $T_Y = 0.98298T_X + 0.78733$ $R^2 = 1.000$
TC 30 : $T_Y = 0.98418T_X + 0.66775$ $R^2 = 1.000$
TC 31 : $T_Y = 0.98355T_X + 0.79781$ $R^2 = 1.000$
TC 32 : $T_Y = 0.98309T_X + 0.71917$ $R^2 = 1.000$
TC 33 : $T_Y = 0.97965T_X + 0.85128$ $R^2 = 1.000$
TC 34 : $T_Y = 0.98006T_X + 0.96147$ $R^2 = 1.000$
TC 35 : $T_Y = 0.97980T_X + 0.89371$ $R^2 = 1.000$
TC 36 : $T_Y = 0.97950T_X + 0.93583$ $R^2 = 1.000$
TC 37 : $T_Y = 0.97837T_X + 1.01412$ $R^2 = 1.000$
TC 38 : $T_Y = 0.97958T_X + 0.94258$ $R^2 = 0.9998$
TC 39 : $T_Y = 0.98033T_X + 0.95965$ $R^2 = 1.000$
TC 40 : $T_Y = 0.98092T_X + 0.85997$ $R^2 = 0.9999$

The calibration equations for the outlet bulk thermocouple probes is:

$T_Y = 0.98020T_X + 0.67782$ $R^2 = 0.9999$

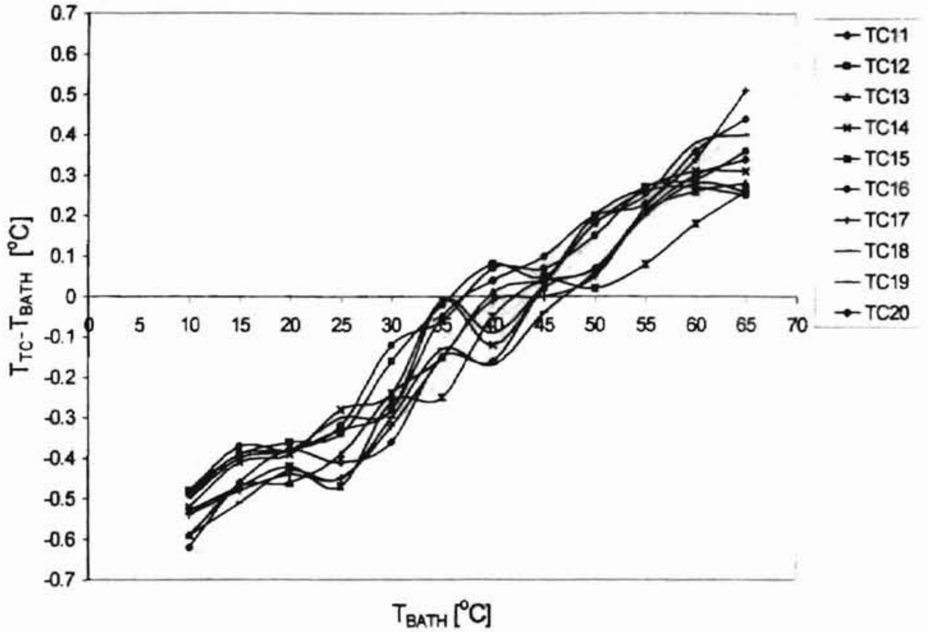

Figure D.1 Trend of Difference between Thermocouples (11-20) and Bath Temperature vs. Bath Temperature

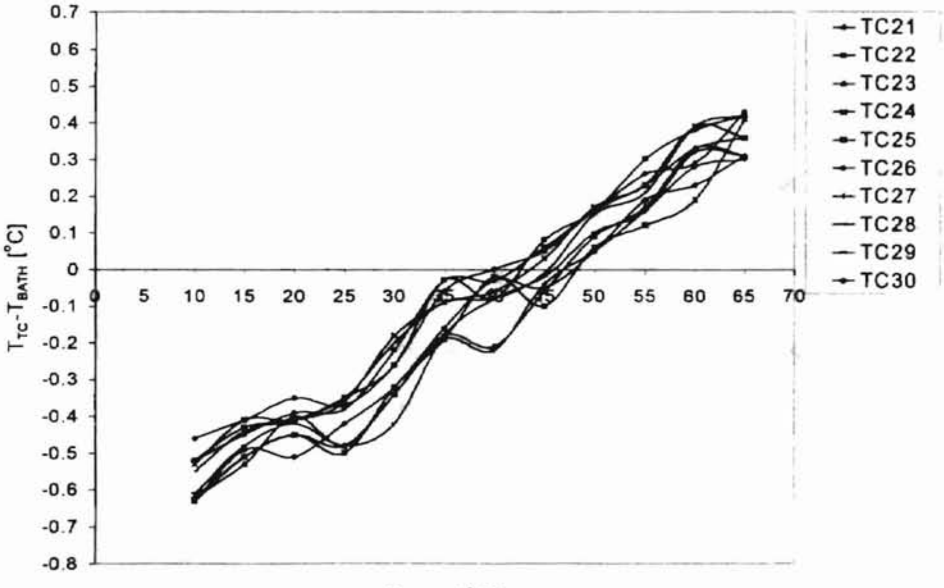

Figure D.2 Trend of Difference between Thermocouples (21-30) and Bath Temperature vs. Bath Temperature

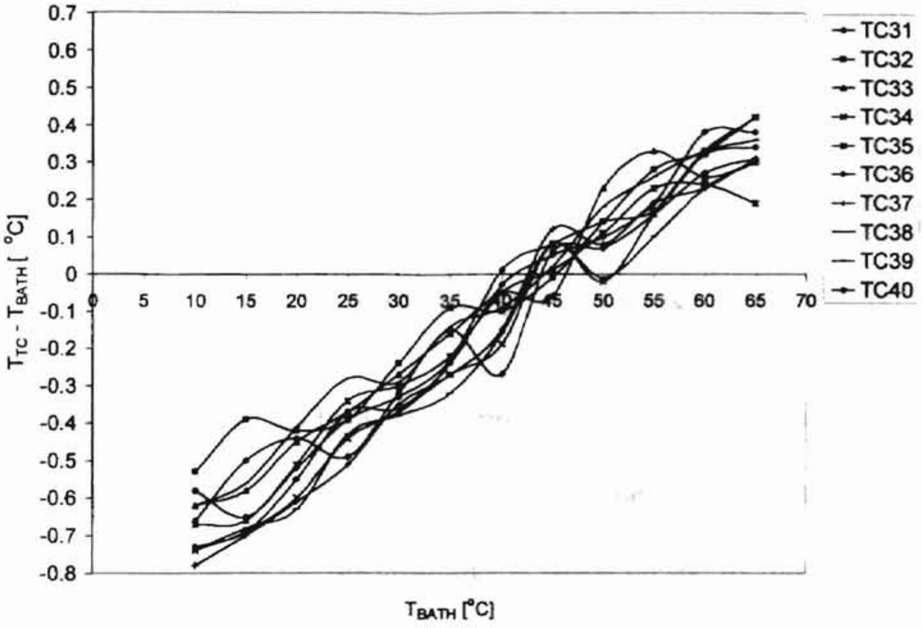

Figure D.3 Trend of Difference between Thermocouples (31-40) and Bath Temperature vs. Bath Temperature

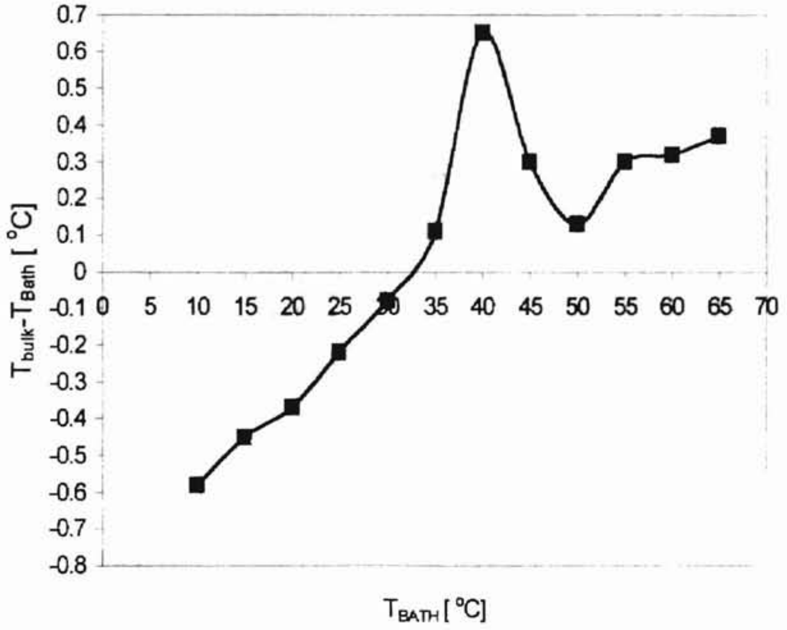

Figure D.4 Trend of Difference between Outlet Bulk Temperature and Bath Temperature vs. Bath Temperature

APPENDIX E

UNCERTAINTY ANALYSIS

In this appendix, an analysis of the probable errors involved in the experimental data of the single-phase heat transfer coefficient and the single-phase friction coefficient is presented. Calculation of the uncertainties is based on the method proposed by Kline and McClintock (1953).

E.1 Uncertainty Analysis of Heat Transfer Coefficient

The heat transfer coefficient is defined as:

$$h = \frac{\dot{q}''}{T_{wi} - T_b} \tag{E-1}$$

The percent probable error for h is given by:

$$w_h = \left[\left(\frac{d\dot{q}''}{\dot{q}''}\right)^2 + \left(\frac{d\Delta T}{\Delta T}\right)^2\right]^{1/2} \tag{E-2}$$

The heat flux is the product of the voltage drop across the test section and the current carried by the tube. Therefore, the heat flux can be written as:

$$\dot{q}'' = \frac{V_D I}{\pi D_i L} \tag{E-3}$$

The uncertainty in the heat flux can then be calculated using the following equation:

$$w_{\dot{q}''} = \left[\left(\frac{dV_D}{V_D} \right)^2 + \left(\frac{dI}{I} \right)^2 + \left(\frac{dD_i}{D_i} \right)^2 + \left(\frac{dL}{L} \right)^2 \right]^{1/2} \tag{E-4}$$

The uncertainty of each variable was estimated as follows:

dV_D The voltmeter has an accuracy of 1 % of reading. The single-phase flow heat transfer experimental data had a voltage range of 0.79 to 4.45 volts, and it gives an average error of 0.0262 volt.

dI The ammeter had an error of 1 % of full scale. The single-phase flow heat transfer experimental data had a current range of 100 to 555 amps, and it gives an average error of 6.55 amps.

dD_i The inside diameter of the test section was measured accurately to 0.001 inch using a caliper, and the inside diameter was 1.097 inches.

dL The heated length of the test section was 110 inches and was measured to within 0.0625 inch.

To evaluate the inside wall temperature, T_{wi}, the heat diffusion equation is solved by using the appropriate boundary conditions.

$$T_{wi} = T_{wo} - \left(\frac{\dot{q}}{2\pi \frac{(D_o^2 - D_i^2)}{4} kL} \right) \left[D_o^2 \ln\left(\frac{D_o}{D_i} \right) - \left(\frac{D_o^2 - D_i^2}{2} \right) \right] \tag{E-5}$$

The bulk temperature at the desired location x is determined by using the following equation:

$$T_b = T_{b,out} - [(T_{b,out} - T_{b,in})(L - x)]/L \tag{E-6}$$

The uncertainty associated with the quantity $(T_{wi} - T_b)$ can be estimated from the following equation:

$$w_t = \left[\left(\frac{|dT_{wo}| + |dT_b| + |dT_2| + |dT_1|}{T_{wi} - T_b} \right)^2 \right]^{1/2} \tag{E-7}$$

where $$T_2 = \left(\frac{\dot{q}}{2\pi \frac{(D_o^2 - D_i^2)}{4} kL} \right) \left[D_o^2 \ln\left(\frac{D_o}{D_i} \right) - \left(\frac{D_o^2 - D_i^2}{2} \right) \right] \tag{E-8}$$

$$T_1 = (T_{b,out} - T_{b,in})(L - x)/L \tag{E-9}$$

For this analysis, the following uncertainties of each term are as follows:

dT_{wo} The assumed error in the outside wall temperature was estimated to be 0.5 °F (0.3°C) within a range of 59 to 104 °F (15 to 40 °C), which was an ordinary temperature variation during the test run, from the calibration runs for the thermocouples.

dT_b The average bulk temperature deviation was assumed to be 0.5 °F (0.3 °C) within a range of 59 to 104 °F (15 to 40 °C), which was an ordinary temperature variation during the test run, from the calibration runs for the thermocouple (inlet) and thermocouple probe (outlet).

dT_2 The deviation ratio, dT_2/T_2 was assumed to be 0.05.

dT_1 The deviation ratio, dT_1/T_1 was assumed to be 0.05.

Applying one of the test runs for single-phase flow heat transfer (at TC station no. 6 of RN5172):

$\dot{q}$ = 5490 Btu/hr

$\dot{q}''$ = 2216 Btu/ft^2-hr

V_D = 3.58 volts

I = 449.5 amps

$T_{b,in}$ = 71.93 °F

$T_{b,out}$ = 76.81 °F

D_o = 1.136 inches

D_i = 1.097 inches

$T_{wo} = 85.72$ °F $\quad k = 7.596$ Btu/hr-ft-°F

$x = 4.75$ ft (57 inches) $\quad$ L = 9.167 ft (110 inches)

Substituting all of the above values into the proper equations, we have

$T_1 = -0.895$ °F

$T_2 = 2.351$ °F

$(T_{wi} - T_b) = 10.366$ °F

These values result in the expected experimental uncertainties of:

$$w_t = \{[(0.3 + 0.3 + 0.05 + 0.05)/10.366]^2\}^{1/2}$$

$$= 0.06753$$

$$w_{\dot{q}''} = [(0.0262/3.58)^2 + (6.55/449.5)^2 + (0.001/1.097)^2 + (0.0625/110)^2]^{1/2}$$

$$= 0.01634$$

$$w_h = [(0.06753)^2 + (0.01634)^2]^{1/2}$$

Finally, the uncertainty for heat transfer coefficient calculations is

$$w_h = 6.95\ \%$$

From the uncertainty analysis, it can be seen that the maximum error corresponding to the experimental heat transfer coefficient is approximately 6.95 %. As shown in this analysis, the uncertainty in heat transfer coefficient is dominated by the accuracy of the measurement of temperatures.

E.2 Uncertainty Analysis of Friction Coefficient

The friction coefficient is defined as follow:

$$\frac{c_f}{2} = \frac{\tau_w}{\rho V^2} \tag{E-10}$$

The wall shear stress in Eq. (E-10) can be obtained by following equation:

$$\tau_w = \frac{\Delta p D_i}{4\Delta L} \tag{E-11}$$

The other terms may be rewritten in terms of the measurable quantities:

$$V = Q / A = Q / (\pi D_i^{\,2} / 4) \tag{E-12}$$

Substituting Eqs. (E-11) and (E-12) into Eq. (E-10) yields

$$c_f = \frac{\pi^2 \Delta p D_i^{\,5}}{32 \rho \Delta L Q^2} \tag{E-13}$$

Therefore, the uncertainty for the friction coefficient according to Kline and Mclintock (1953) can be obtained from the following equation:

$$w_{c_f} = \left[\left(\frac{d\Delta p}{\Delta p} \right)^2 + \left(\frac{5dD_i}{D_i} \right)^2 + \left(\frac{dL}{L} \right)^2 + \left(\frac{d\rho}{\rho} \right)^2 + \left(\frac{2dQ}{Q} \right)^2 \right]^{1\ 2} \tag{E-13}$$

The uncertainty for each variable was estimated as follows:

$d\Delta p$	The differential pressure transducer has an accuracy of 0.25 % of full scale. In the experiment, the diaphragm used in the differential pressure transducer has a range up to 5.5 in H_2O, that is, the deviation is up to 0.01375 in H_2O.
dD_i	As estimated in the previous section, the deviation is 0.001 inch.
$d\rho$	As shown in Table 4.1, the prediction of density of water has an accuracy of 0.1 %, and then the deviation is 0.0624 lb_m/ft^3 estimated at 68 °F.
dL	As estimated in the previous section, the deviation is 0.001 inch.

dQ Liquid Turbine Flow Meter 1 has an accuracy of 1 % of reading (the deviation is 0.105 gpm estimated at the full scale), and Liquid Turbine Flow Meter 2 has an accuracy of 1 % of full scale (the deviation is 0.05 gpm estimated at the full scale).

The following conditions are for the pressure drop test run no. 12 (refer to Appendix B):

$Q_L = 3.36$ gpm (Liquid Turbine Flow Meter 1)

$\rho_L = 62.37\ \mathrm{lb_m/ft^3}$ at 70.7 °F

$D_i = 1.097$ inch

$L = 40$ inches (pressure tap 4 to 8)

$\Delta p = 0.2835$ inch (pressure tap 4 to 8)

Substituting the above conditions into Eq. (E-13),

$$w_{c_f} = [(0.01375/0.2835)^2 + (5\times0.001/1.097)^2 + (0.001/40)^2 + (0.0624/62.37)^2 + (2\times0.105/3.36)^2]^{1/2}$$

Finally, the uncertainty for heat transfer coefficient calculation is

$$w_{c_f} = 7.93\ \%$$

VITA

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Master of Science

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