

# Microcomputer-Assisted Heat Transfer Measurement/Analysis in a Circular Tube\*

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*An interactive computer program has been developed 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 program also calculates the pertinent fluid flow and heat transfer dimensionless parameters. The test fluids used were water and mixtures of ethylene glycol and water. The computer program can run on any microcomputer. It can be used to reduce the experimental data to a form suitable for development of forced and mixed convection flow heat transfer correlations in an electrically heated horizontal circular tube in the laminar, transitional and turbulent flow regimes.*

## INTRODUCTION

HEAT transfer measurements in pipe flow is essential for assessment of performance of heat exchanging equipment and development of design correlations. Usually, the experimental procedure for a constant wall heat flux boundary condition consists of measuring the tube outside wall surface temperatures at discrete locations and the inlet and outlet bulk temperatures in addition to other measurements like the flow rate, room temperature, voltage drop across the test section and current carried by the test section. The peripheral heat transfer coefficient (local average) and the Nusselt number (dimensionless heat transfer coefficient) thereafter are calculated based on the knowledge of the pipe inside-wall surface temperature. While measurement of inside-wall temperature is difficult, it can be calculated from the measurements of the outside wall temperature, the heat generation within the pipe wall and the thermophysical properties of the pipe material (electrical resistivity and thermal conductivity).

This paper discusses the data gathering, reduction and processing procedures and the finite-difference formulations used for the development of an interactive computer program. The program calculates local inside-wall temperature, local peripheral heat transfer coefficient and other pertinent information from local outside-wall temperature measurements at different axial locations along an electrically-heated horizontal circular tube.

## EXPERIMENTS

A schematic diagram of the overall experimental setup is shown as Fig. 1. The experimental setup shown was also used for pressure drop and intermittency factor measurements. The heat transfer test section is a horizontal seamless 316 stainless steel circular tube with an inside diameter of 0.624 in (15.850 mm) and an outside diameter of 0.748 in (18.999 mm). The total length of the test section is 20 ft (6.10 m) providing a maximum length to diameter ratio ( $L/D$ ) of 385. The end connections of the test section consisted of copper plates which were silver-arc soldered to the ends of the test section to secure a well defined electric circuit through the end plates. The test section was insulated from the environment using fiberglass pipe insulation and vapor-proof pipe tape. The total thickness of the insulation materials is about 1.25 in (3.18 cm). To ensure a uniform fluid bulk temperature at the exit of the test section, a mixing well which consisted of several baffles was utilized. A one-shell and two-tube pass heat exchanger was used to cool the fluid from the test section to an allowable and steady state inlet bulk temperature.

The calming and inlet sections in front of the test section were used to produce a uniform velocity distribution in the test fluid before entering the test section. The calming section consisted of a 7-in (17.8 cm) diameter acrylic plastic cylinder with three perforated acrylic plastic plates followed by tightly packed 4-in (10.2 cm) long soda straws sandwiched between galvanized steel mesh screens. The total length of the calming section is 24.25 in (61.6 cm). Flow leaving the calming section entered the inlet section and flowed undisturbed through 9.25 in (23.5 cm) of a 6.5-in (16.5 cm) diameter acrylic plastic tube before it

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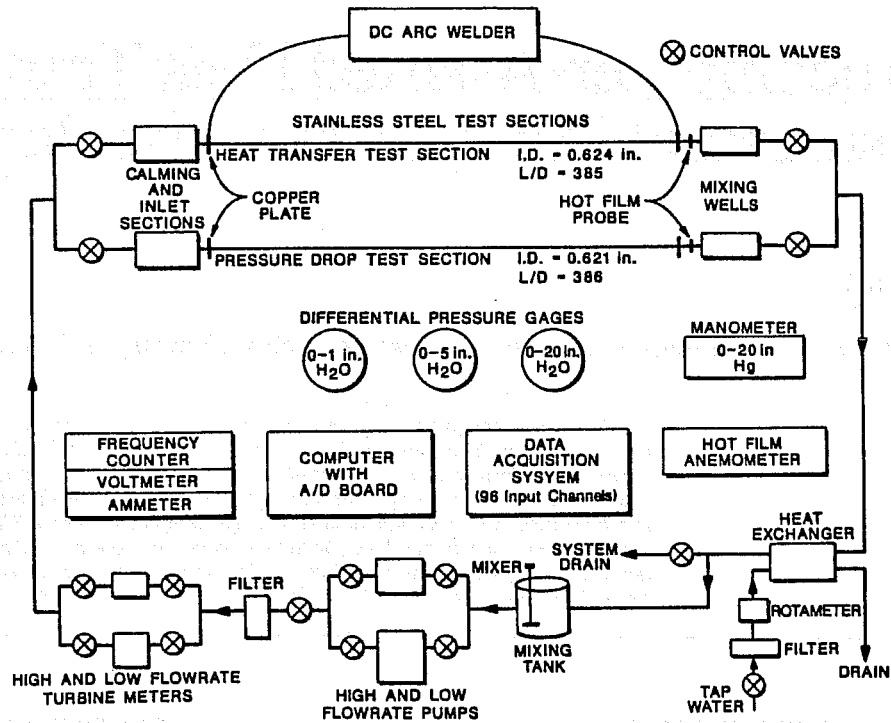


Fig. 1. Schematic of the experimental setup.

entered the test section. The combination of the inlet and test sections produced a square-edged entrance configuration for the test section.

A constant wall heat flux boundary condition was maintained by a Lincoln DC-600 welder. Thermocouples were placed on the outer surface of the tube wall at close intervals near the entrance and at greater intervals further downstream (see Fig. 2 for details). Thirty-one thermocouple stations were designated with four thermocouples at each station. The thermocouples were placed 90 degrees apart around the periphery. Copper-Constantan T-type thermocouples were used. The

thermocouples were attached to the outside of the tube wall with Omegabond 101, an epoxy adhesive with high thermal conductivity and electrical resistivity. The inlet and exit bulk temperatures were measured by means of thermocouple probes inserted in the calming section and the mixing well, respectively. The data acquisition system used for the temperature measurements consisted of a Cole-Parmer MAC-14 datalogger with 96 input channels interfaced with an IBM compatible AT personal computer. The flow rate was measured by a turbine meter located upstream from the test section. The voltage drop across the test section

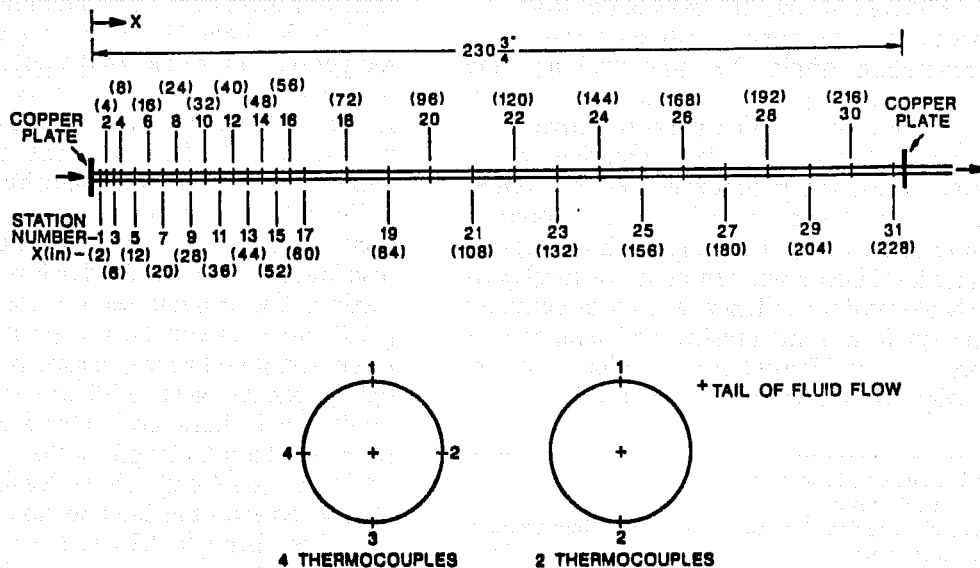


Fig. 2. Heat transfer test section thermocouple distribution.

and the current carried by the test section were measured by a voltmeter and an ammeter, respectively.

The test fluids used in the experiments were distilled water, ethylene glycol and different mixtures of distilled water and ethylene glycol.

### COMPUTER PROGRAM

The computer program consists of four segments, the input data, the finite-difference formulations, the physical properties and the output.

#### 1. Input data

A sample input data for the computer program is given as Fig. 3. Description of the information required for the first two lines of the input data file appear as follows:

Run number	1008
Total number of thermocouple stations used	26
Fluid index (1 = water, 2 = ethylene glycol)	1
Mass concentration of ethylene glycol	0.00
Flow rate (gal/min)	3.8610
Current carried by test section (A)	390.00
Voltage drop across test section (V)	21.55
Inlet bulk temperature (°F)	83.30
Exit bulk temperature (°F)	98.21
Room (ambient) temperature (°F)	79.43

All the subsequent lines (3 through 28) in Fig. 3 correspond to information about the outside tube wall temperatures measured at each station, see Fig. 2 for the layout of thermocouple stations. In lines 3 through 28 of Fig. 3, the first column corresponds to the thermocouple station number, the second column indicates the number of thermocouples at that particular station, the third column is the distance in inches between a given

1008	26						
1	4	0.00	3.8610	390.00	21.55	83.30	98.21 79.43
1	4	2.00	94.61	95.12	95.09	94.90	
3	4	6.00	95.33	95.56	95.83	95.13	
4	4	8.00	95.50	95.66	95.67	95.24	
5	4	12.00	95.86	95.82	96.00	95.81	
6	4	16.00	96.44	96.16	96.14	96.18	
7	4	20.00	96.55	96.43	96.19	96.35	
8	4	24.00	96.93	96.69	96.50	96.53	
9	4	28.00	97.04	96.71	96.88	96.67	
10	4	32.00	97.03	97.20	96.77	96.98	
11	4	36.00	97.44	97.45	97.08	97.32	
12	4	40.00	97.71	97.62	97.17	97.31	
13	4	44.00	98.10	97.54	97.39	97.54	
14	4	48.00	98.04	97.89	97.80	97.71	
15	4	52.00	98.16	98.09	97.94	98.35	
16	4	56.00	98.41	98.42	98.23	97.66	
17	4	60.00	98.79	98.35	98.38	97.83	
18	4	72.00	99.19	99.07	99.24	98.92	
19	4	84.00	99.95	100.10	99.90	99.73	
20	4	96.00	100.47	100.52	100.77	100.19	
21	4	108.00	100.87	101.41	101.67	101.37	
22	4	120.00	101.80	102.44	102.35	101.74	
23	2	132.00	102.74	102.97			
25	2	156.00	104.35	104.24			
27	2	180.00	105.93	105.46			
29	2	204.00	107.60	107.20			
31	2	228.00	109.07	109.61			

Fig. 3. Sample input data file.

thermocouple station and the pipe entrance. The remaining columns (two or four) are the measured outside wall temperatures at each station.

The computer program is capable of handling input data files with as many as eight thermocouples per station along the periphery of any given horizontal pipe. The user has the option of either using the format shown in Fig. 3 or a more generalized format. With the data gathered in the manner described above, the pipe wall inside surface temperature is calculated using a finite-difference method described next.

#### 2. Finite-difference formulations

The numerical solution of the conduction equation with internal heat generation and variable thermal conductivity and electrical resistivity was originally developed by Farukhi [1]. The numerical solution is 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 local inside wall temperature and heat flux and local and average peripheral heat transfer coefficients will be presented next.

##### a. Calculation of the local inside wall temperature and the local inside wall heat flux

The heat balance on a segment (slice) of the tube wall at any particular station is given by (see Fig. 4):

$$Q_g = Q_1 + Q_2 + Q_3 + Q_4 \quad (1)$$

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

$$Q = -KA \frac{dT}{dn} \quad (2)$$

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

$$Q_1 = \frac{(K_{i,j} + K_{i-1,j})}{2} \frac{2\pi \left(r_i + \frac{\Delta r}{2}\right) \Delta z (T_{i,j} - T_{i-1,j})}{N_{TH} \Delta r} \quad (3)$$

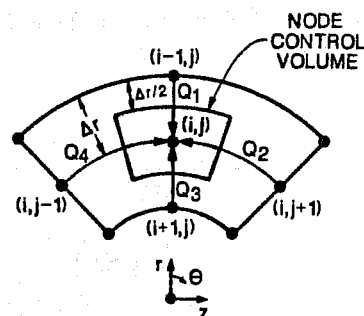


Fig. 4. Finite-difference grid arrangement.

$$Q_2 = \frac{(K_{ij} + K_{i,j+1})}{2} (\Delta r \Delta z) \frac{(T_{ij} - T_{i,j+1})}{\left(\frac{2\pi r_i}{N_{TH}}\right)} \quad (4)$$

$$Q_3 = \frac{(K_{ij} + K_{i+1,j})}{2} \frac{2\pi \left(r_i - \frac{\Delta r}{2}\right) \Delta z}{N_{TH}} \frac{(T_{ij} - T_{i+1,j})}{\Delta r} \quad (5)$$

$$Q_4 = \frac{(K_{ij} + K_{i,j-1})}{2} (\Delta r \Delta z) \frac{(T_{ij} - T_{i,j-1})}{\left(\frac{2\pi r_i}{N_{TH}}\right)} \quad (6)$$

where

- $K$  = thermal conductivity
- $r_i$  = tube inside radius
- $Q$  = rate of heat transfer
- $T$  = temperature
- $\Delta z$  = length of element
- $\Delta r$  = incremental radius
- $N_{TH}$  = number of finite-difference sections in the  $\theta$ -direction (peripheral) which is equal to the number of thermocouples at each station.

$i$  and  $j$  = the indices of the finite-difference grid points,  $i$  is the radial direction starting from the outside surface of the tube and  $j$  is the peripheral direction starting from top of the tube and increasing clockwise.

Heat generated at  $i, j$  element volume is given by:

$$Q_g = I^2 R \quad (7)$$

where

- $I$  = current
- $R = \gamma l / A$  = resistance
- $\gamma$  = electric resistivity of the element
- $l = \Delta z$  = length of the element
- $A = (2\pi r_i / N_{TH}) \Delta r$  = cross-sectional area of the element.

Substituting the above definitions into Equation (7) gives:

$$Q_g = I^2 \frac{\gamma \Delta z}{\left(\frac{2\pi r_i}{N_{TH}}\right) \Delta r} \quad (8)$$

Substitution of Eqns. (3) to (6) and (8) in Eq. (1) and solving for  $T_{i+1,j}$  gives:

$$T_{i+1,j} = T_{i,j} - \left\{ \frac{I^2 \gamma N_{TH}}{(2\pi r_i \Delta r)} - \frac{(K_{ij} + K_{i,j-1})}{\Delta r} \right. \\ \left. \frac{\pi \left(r_i + \frac{\Delta r}{2}\right)}{N_{TH}} (T_{ij} - T_{i,j-1}) \right\}$$

$$\left. \begin{aligned} & - (K_{ij} + K_{i,j+1}) \frac{\Delta r N_{TH}}{4\pi r_i} (T_{ij} - T_{i,j+1}) \\ & - (K_{ij} + K_{i,j-1}) \frac{\Delta r N_{TH}}{4\pi r_i} (T_{ij} - T_{i,j-1}) \end{aligned} \right\} \\ \left\{ (K_{ij} + K_{i+1,j}) \frac{\pi \left(r_i - \frac{\Delta r}{2}\right)}{\Delta r N_{TH}} \right\} \quad (9)$$

Equation (9) is used to calculate the temperature of the interior nodes. In this equation the thermal conductivity and electrical resistivity of each node control volume is determined as a function of temperature from the following equations for 316 stainless steel:

$$K = 7.27 + 0.0038T \quad (10)$$

$$\gamma = 27.67 + 0.0213T \quad (11)$$

where  $T$  in °F,  $K$  in Btu/hr-ft-°F and  $\gamma$  in microhm-in.

Once the local inside wall temperatures are calculated from Eq. (9), the local peripheral inside wall heat flux can be calculated from the heat balance equation, see Eq. (1).

#### b. 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 can be calculated as follows:

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

where

- $h_i$  = local peripheral heat transfer coefficient
- $\dot{q}_i''$  = local peripheral inside wall heat flux
- $T_{wi}$  = local inside wall temperature
- $T_b$  = bulk fluid temperature at the thermocouple station.

Note that in these analyses it is assumed that the bulk fluid temperature increases linearly from the inlet to the outlet according to the following equation:

$$T_b = T_{in} + (T_{out} - T_{in})X/L \quad (13)$$

where

- $T_{in}$  = bulk inlet temperature
- $T_{out}$  = bulk outlet temperature
- $X$  = distance from the pipe inlet to the thermocouple station
- $L$  = total length of the test section.

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

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

where

- $\bar{h}_i$  = local average heat transfer coefficient

- $\dot{q}_i^*$  = average peripheral inside wall heat flux at a station  
 $\bar{T}_{wi}$  = average inside wall temperature at a station.

### 3. Physical properties

The test fluids used in the experiments were distilled water, ethylene glycol and different mixtures of distilled water and ethylene glycol. The equations for physical properties of these fluids are presented next.

#### a. Physical properties of water

The correlation equations used for water were those used by [2] except density [3] and coefficient of thermal expansion [4].

**Density.** The density of water is calculated by the following equation:

$$\rho = 999.86 + 6.1464 \times 10^{-2}T - 8.4648 \times 10^{-3}T^2 + 6.8794 \times 10^{-5}T^3 - 4.4214 \times 10^{-7}T^4 + 1.2505 \times 10^{-9}T^5 \quad (15)$$

where

$$\rho = \text{density, kg/m}^3 \text{ and } T = \text{temperature, } ^\circ\text{C}$$

This equation is valid for the temperature range from 0 to 100°C and is within the accuracy of the steam tables [5] which is  $\pm 0.05 \text{ kg/m}^3$ .

**Viscosity.** The viscosity of water is calculated by the following equation:

$$\log_{10}[\mu_T/\mu_{20}] = \{1.327(20 - T) - 1.053 \times 10^{-3}(20 - T)^2\}/(T + 105) \quad (16)$$

where

$$\mu_{20} = \text{viscosity of water at } 20^\circ\text{C} = 1.0 \times 10^{-3} \text{ N} \cdot \text{s/m}^2$$

$$\mu_T = \text{viscosity of water at } T^\circ\text{C, } \text{N} \cdot \text{s/m}^2$$

$$T = \text{temperature, } ^\circ\text{C}$$

This equation is valid within the temperature range from 10 to 100°C. It has an accuracy within  $\pm 1\%$ .

**Specific heat.** The specific heat of water is calculated by the following equation:

$$C_p = 4.216 - 2.2 \times 10^{-3}T + 3.66 \times 10^{-5}T^2 - 1.475 \times 10^{-7}T^3 \quad (17)$$

where

$$C_p = \text{specific heat, kJ/(kg} \cdot \text{K), and } T = \text{temperature, } ^\circ\text{C}$$

This equation has an accuracy within  $\pm 1\%$  for the range from 0 to 100°C.

**Thermal conductivity.** The thermal conductivity of water is calculated by the following equation:

$$K = 5.6276 \times 10^{-1} + 1.874 \times 10^{-3}T - 6.80 \times 10^{-6}T^2 \quad (18)$$

where

$$K = \text{thermal conductivity of water, } \text{W}/(\text{m} \cdot \text{K}) \text{ and } T = \text{temperature, } ^\circ\text{C}$$

This equation is applied in the temperature range of 0 to 100°C. It has an accuracy within  $\pm 1\%$ .

**Coefficient of thermal expansion.** The thermal expansion coefficient of water is calculated by the following equation:

$$\beta = \{0.0615 - 0.01694T - 2.06 \times 10^{-4}T^2 - 1.77 \times 10^{-6}T^3 + 6.3 \times 10^{-9}T^4\}/\{999.86 + 0.06146T - 0.00847T^2 + 6.879 \times 10^{-5}T^3 - 4.42 \times 10^{-7}T^4 + 1.25 \times 10^{-9}T^5\} \quad (19)$$

where

$$\beta = \text{coefficient of thermal expansion, } 1/\text{K}$$

$$\rho = \text{density at } T, \text{ kg/m}^3$$

$$T = \text{temperature, } ^\circ\text{C}$$

This equation was derived from the relation  $\beta = (1/\rho)(\partial\rho/\partial T)_p$ , with the use of the density correlation listed previously. It is applied in the temperature range of 0 to 100°C and is accurate within the accuracy of the steam tables [5].

#### b. Physical properties of ethylene glycol-water mixtures

The correlation equations used for ethylene glycol-water mixtures were those reported in [6], except thermal expansion coefficient [4].

**Density.** The density of ethylene glycol-water mixture is calculated by the following equation:

$$\rho = \sum_{i=1}^3 \sum_{j=1}^3 A_{ij} X^{(i-1)} T^{(j-1)} \quad (20)$$

where

	Values of $A_{ij}$	
	$j = 1$	$j = 2$
$i = 1$	1.0004	0.17659
$i = 2$	$-1.2379 \times 10^{-4}$	$-9.9189 \times 10^{-4}$
$i = 3$	$-2.9837 \times 10^{-6}$	$2.4164 \times 10^{-6}$
	$j = 3$	
	$-0.049214$	$4.1024 \times 10^{-4}$
	$-9.5278 \times 10^{-8}$	

$$\rho = \text{density, g/cm}^3$$

$$X = \text{mass fraction of ethylene-glycol}$$

$$T = \text{temperature, } ^\circ\text{C}$$

This equation has an accuracy within  $\pm 0.25\%$ . It is applied over the temperature range of 0 to 150°C.

**Viscosity.** The viscosity of ethylene glycol-water mixture is calculated by the following equation:

$$\ln \mu = \sum_{i=1}^2 \sum_{j=1}^3 A_{ij} X^{(i-1)} T^{(j-1)} + \left\{ \sum_{j=1}^3 A_{3j} X^{(j-1)} \right\}^{\frac{1}{4}} T^2 \quad (21)$$

where

Values of $A_{ij}$		
	$j = 1$	$j = 2$
$i = 1$	0.55164	2.6492
$i = 2$	$-2.7633 \times 10^{-2}$	$-3.1496 \times 10^{-2}$
$i = 3$	$-6.0629 \times 10^{-17}$	$2.2389 \times 10^{-15}$
$j = 3$		
	0.82935	
	$4.8136 \times 10^{-3}$	
	$-5.8790 \times 10^{-16}$	

$\mu$  = viscosity, mPa-s

$X$  = mass fraction of ethylene-glycol

$T$  = temperature, °C

This equation has an accuracy within  $\pm 5\%$ . It is applied over the temperature range of  $-10$  to  $100^\circ\text{C}$ .

**Prandtl number.** The Prandtl number of ethylene glycol-water mixture is calculated by the following equation:

$$\ln \text{Pr} = \sum_{i=1}^2 \sum_{j=1}^3 A_{ij} X^{(j-1)} T^{(i-1)} + \left\{ \sum_{j=1}^3 A_{3j} X^{(j-1)} \right\}^{\frac{1}{2}} T^2 \quad (22)$$

where

Values of $A_{ij}$		
	$j = 1$	$j = 2$
$i = 1$	2.5735	3.0411
$i = 2$	$-3.1169 \times 10^2$	$-2.5424 \times 10^{-2}$
$i = 3$	$1.1605 \times 10^{-16}$	$2.5283 \times 10^{-15}$
$j = 3$		
	0.60237	
	$3.7454 \times 10^{-3}$	
	$2.3777 \times 10^{-17}$	

$\text{Pr}$  = Prandtl number,  $\mu C_p / K$

$X$  = mass fraction of ethylene-glycol

$T$  = temperature, °C.

This equation has an accuracy within  $\pm 5\%$ . It is applied over the temperature range of  $0$  to  $150^\circ\text{C}$ .

**Thermal conductivity.** The thermal conductivity of ethylene glycol-water mixture is calculated from the following equation:

$$\begin{aligned} K_w &= 0.56276 + 1.874 \times 10^{-3} T - 6.8 \times 10^{-6} T^2 \\ K_{EG} &= 0.24511 + 1.755 \times 10^{-4} T - 8.52 \times 10^{-7} T^2 \\ K_F &= 0.6635 - 0.3698 X - 8.85 \times 10^{-4} T \\ K_M &= (1 - X) K_w + X K_{EG} - K_F (K_w - K_{EG}) (1 - X) X \end{aligned} \quad (23)$$

where

$K_w$  = thermal conductivity of pure water,  $W/m - K$

$K_{EG}$  = thermal conductivity of pure ethylene glycol,  $W/m - K$

$K_F$  = Filippov's constant

$K_M$  = thermal conductivity of ethylene glycol-water mixture,  $W/m - K$

$X$  = mass fraction of ethylene glycol

$T$  = temperature, °C

The equation has an accuracy within  $\pm 1\%$ . It is applied over the temperature range of  $0$  to  $150^\circ\text{C}$ .

**Coefficient of Thermal Expansion.** The thermal expansion coefficient of ethylene glycol-water mixture is calculated by the following equation:

$$\beta = -(1/\rho) \{-1.2379 \times 10^{-4} - 9.9189 \times 10^{-4} X + 4.1024 \times 10^{-4} X^2 + 2(-2.9837 \times 10^{-6} \times T + 2.4614 \times 10^{-6} X T - 9.5278 \times 10^{-8} X^2 T)\} \quad (24)$$

where

$\beta$  = coefficient of thermal expansion,  $1/^\circ\text{C}$

$\rho$  = density,  $\text{g}/\text{m}^3$

$X$  = mass fraction of ethylene glycol

$T$  = temperature, °C.

This equation was derived from the relation  $\beta = (1/\rho)(\partial\rho/\partial T)_p$ , with the use of the density correlation listed previously. It is applied over the temperature range of  $0$  to  $150^\circ\text{C}$ .

#### 4. Output

A sample output data file from the computer program is given as Figs 5a to 5d. The user has the option of specifying SI or English units for the output data. The output file starts with a summary of some of the important information about the experimental run for quick reference and then lists the measured outside wall temperatures, see Fig. 5a. In Fig. 5b the calculated inside wall temperatures and the Reynolds number of the flow based on the inside wall temperature are displayed. Next, the inside surface peripheral heat fluxes and the peripheral heat transfer coefficients for each thermocouple station along the pipe are shown as Fig. 5c. Finally, Fig. 5d gives a tabular summary of the most important results of the experiments. This table gives for each station its location from the tube entrance, the bulk fluid temperature, the bulk Reynolds, Prandtl, Nusselt and Grashof numbers, the ratio of bulk to wall absolute viscosities, the ratio of top to bottom peripheral heat transfer coefficients and finally the local average heat transfer coefficient.

In addition to the complete output presented in Figs. 5a to 5d, the user has the option of creating a short version of the output file (similar to Fig. 5d). This version of the output file is created in a headingless format and can be used for further analysis of the experimental results. For example it can be used as an input data file for a graphics software for developing plots or a curve fitting software for development of heat transfer correlations.

The output presented in Figs 5a to 5d contain all the necessary information for an in depth analysis of the experiments. For example, if the ratio of bulk to wall absolute viscosities is greater than  $1.0$  this

```

*-----*
          RUN NUMBER 1008
          TEST FLUID IS DISTILLED WATER
*-----*

VOLUMETRIC FLOW RATE =      3.86      GPM
MASS FLOW RATE       =     1925.4     LBM/HR
MASS FLUX            =     906637     LBM/(SQ.FT-HR)
FLUID VELOCITY       =      4.03      FT/S
ROOM TEMPERATURE    =      79.43     F
INLET TEMPERATURE   =      83.30     F
OUTLET TEMPERATURE  =      98.21     F
AVERAGE RE NUMBER   =     25829
AVERAGE PR NUMBER   =      5.11
CURRENT TO TUBE      =     390.0      AMPS
VOLTAGE DROP IN TUBE =     21.55     VOLTS
AVERAGE HEAT FLUX   =      9129     BTU/(SQ.FT-HR)
Q=AMP*VOLT           =     28677     BTU/HR
Q=M*C*(T2-T1)        =     28648     BTU/HR
HEAT BALANCE ERROR   =      .10      %

```

OUTSIDE SURFACE TEMPERATURES - DEGREES F

	1	3	4	5	6	7	8	9	10
1	94.61	95.33	95.50	95.86	96.44	96.55	96.93	97.04	97.03
2	95.12	95.56	95.66	95.82	96.16	96.43	96.69	96.71	97.20
3	95.09	95.83	95.67	96.00	96.14	96.19	96.50	96.88	96.77
4	94.90	95.13	95.24	95.81	96.18	96.35	96.53	96.67	96.98
	11	12	13	14	15	16	17	18	19
1	97.44	97.71	98.10	98.04	98.16	98.41	98.79	99.19	99.95
2	97.45	97.62	97.54	97.89	98.09	98.42	98.35	99.07	100.10
3	97.08	97.17	97.39	97.80	97.94	98.23	98.38	99.24	99.90
4	97.32	97.31	97.54	97.71	98.35	97.66	97.83	98.92	99.73
	20	21	22	23	25	27	29	31	
1	100.47	100.87	101.80	102.74	104.35	105.93	107.60	109.07	
2	100.52	101.41	102.44						
3	100.77	101.67	102.35	102.97	104.24	105.46	107.20	109.61	
4	100.19	101.37	101.74						

Fig. 5a. Sample output data file (page 1).

indicates large variations of that property and constant property analysis should not be used. Another interesting result is the ratio of top to bottom peripheral heat transfer coefficients. If this ratio is close to 1.0, forced convection dominates and heat transfer is primarily dependent on the Reynolds and Prandtl numbers. However, if the ratio is less than 1.0, natural convection exists and heat transfer is by mixed convection. In this case secondary flow caused by the difference between the fluid density at the wall and at the pipe center also affects the temperature profile. For mixed convection the heat transfer in addition to Reynolds and Prandtl numbers is dependent on the Grashof number (which accounts for the variation in density of the test fluid). In extreme cases, where the ratio is much less than 1.0, free convection dominates and heat transfer primarily depends on the Prandtl and Grashof numbers.

## SUMMARY

The development of an interactive computer program for heat transfer measurement/analysis has been described. The program uses finite-difference formulation to calculate local inside wall temperatures and local peripheral heat transfer coefficients from measured local outside wall temperatures and other pertinent experimental data. In the analysis both radial and peripheral heat conduction exists. However, axial heat conduction has been neglected. The program also calculates important dimensionless parameters such as Nusselt, Prandtl, Reynolds and Grashof numbers.

The type of computer program described in this study can be utilized as an effective design or instructional tool. As a design tool it can be used to perform parametric studies on the influence of certain parameters on the heat transfer characteristics of the flow or to develop heat transfer correlations in terms of pertinent dimensionless

\*-----\*  
 RUN NUMBER 1008  
 \*-----\*

## INSIDE SURFACE TEMPERATURES - DEGREES F

	1	3	4	5	6	7	8	9	10
1	91.83	92.56	92.73	93.09	93.67	93.78	94.16	94.27	94.26
2	92.35	92.79	92.89	93.05	93.38	93.66	93.92	93.93	94.43
3	92.32	93.06	92.90	93.23	93.37	93.41	93.72	94.11	93.99
4	92.13	92.35	92.46	93.04	93.41	93.58	93.75	93.89	94.21
	11	12	13	14	15	16	17	18	19
1	94.67	94.94	95.34	95.27	95.38	95.64	96.03	96.42	97.18
2	94.68	94.85	94.76	95.12	95.32	95.65	95.57	96.29	97.33
3	94.30	94.39	94.61	95.03	95.16	95.46	95.61	96.47	97.12
4	94.55	94.53	94.76	94.93	95.58	94.87	95.04	96.14	96.95
	20	21	22	23	25	27	29	31	
1	97.70	98.09	99.02	99.96	101.57	103.15	104.82	106.29	
2	97.74	98.64	99.67						
3	98.00	98.90	99.58	100.19	101.46	102.68	104.42	106.83	
4	97.41	98.60	98.96						

## REYNOLDS NUMBER AT THE INSIDE TUBE WALL

	1	3	4	5	6	7	8	9	10
1	26148	26363	26414	26521	26696	26728	26843	26876	26871
2	26302	26432	26462	26509	26610	26692	26769	26774	26923
3	26293	26515	26466	26564	26605	26619	26712	26827	26792
4	26236	26302	26335	26506	26616	26667	26720	26762	26856
	11	12	13	14	15	16	17	18	19
1	26994	27076	27195	27175	27210	27288	27404	27522	27752
2	26998	27049	27023	27129	27189	27289	27267	27484	27798
3	26884	26911	26978	27102	27143	27232	27278	27537	27736
4	26958	26954	27023	27074	27269	27057	27107	27438	27684
	20	21	22	23	25	27	29	31	
1	27910	28028	28313	28602	29098	29587	30107	30566	
2	27924	28196	28512						
3	28002	28276	28484	28673	29063	29440	29981	30738	
4	27822	28184	28294						

Fig. 5b. Sample output data file (page 2).



\*-----\*  
 RUN NUMBER 1008  
 \*-----\*

INSIDE SURFACE HEAT FLUXES BTU/HR/FT<sup>2</sup>

	1	3	4	5	6	7	8	9	10
1	8485	8470	8467	8469	8460	8466	8461	8460	8481
2	8453	8469	8465	8477	8480	8471	8477	8489	8464
3	8461	8446	8459	8463	8476	8484	8482	8469	8493
4	8464	8490	8486	8477	8478	8476	8485	8491	8475
	11	12	13	14	15	16	17	18	19
1	8477	8469	8455	8472	8488	8468	8453	8482	8494
2	8471	8472	8492	8485	8484	8480	8496	8498	8487
3	8495	8495	8490	8484	8499	8477	8473	8479	8497
4	8477	8488	8492	8493	8471	8517	8522	8505	8506
	20	21	22	23	25	27	29	31	
1	8494	8530	8524	8517	8521	8524	8536	8561	
2	8504	8498	8491						
3	8479	8490	8496	8511	8524	8538	8547	8546	
4	8520	8500	8526						

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

	1	3	4	5	6	7	8	9	10
1	1009	955	950	939	905	921	908	923	953
2	947	930	933	944	936	934	934	961	933
3	951	900	931	924	938	961	955	940	984
4	973	980	981	945	934	943	952	966	958
	11	12	13	14	15	16	17	18	19
1	937	934	919	954	972	969	954	1000	1004
2	935	944	984	972	979	970	1011	1017	985
3	978	998	1001	983	998	991	1003	994	1010
4	949	980	984	994	948	1069	1082	1037	1032
	20	21	22	23	25	27	29	31	
1	1035	1090	1068	1044	1037	1033	1019	1033	
2	1030	1015	983						
3	996	983	994	1015	1052	1098	1073	967	
4	1076	1020	1076						

Fig. 5c. Sample output data file (page 3).

\*-----\*  
 RUN NUMBER 1008  
 SUMMARY  
 \*-----\*

	X/D	TBULK	RE NUMBER	PR NUMBER	NU NUMBER	GR NUMBER	MUB/ MUW	HTOP/ HBOT	H AVG
1	3.21	83.43	23699	5.63	142.9	81194	1.107	1.06	969
3	9.62	83.69	23773	5.61	138.6	84633	1.111	1.06	940
4	12.82	83.82	23810	5.60	139.7	84379	1.110	1.02	948
5	19.23	84.07	23884	5.58	138.2	86193	1.111	1.02	938
6	25.64	84.33	23958	5.56	136.7	88056	1.112	.97	928
7	32.05	84.59	24032	5.54	138.3	87923	1.110	.96	939
8	38.46	84.85	24106	5.52	137.9	89079	1.110	.95	937
9	44.87	85.11	24180	5.50	139.3	89051	1.109	.98	947
10	51.28	85.36	24255	5.48	140.7	89085	1.107	.97	957
11	57.69	85.62	24329	5.46	139.6	90707	1.108	.96	949
12	64.10	85.88	24404	5.45	141.6	90322	1.106	.94	963
13	70.51	86.14	24478	5.43	142.6	90538	1.105	.92	971
14	76.92	86.39	24553	5.41	143.3	91034	1.105	.97	976
15	83.33	86.65	24628	5.39	143.0	92134	1.105	.97	974
16	89.74	86.91	24703	5.37	146.5	90788	1.102	.98	998
17	96.15	87.17	24778	5.35	148.2	90615	1.100	.95	1011
18	115.38	87.94	25003	5.30	148.3	93278	1.100	1.01	1012
19	134.62	88.72	25229	5.25	147.5	96532	1.100	.99	1008
20	153.85	89.49	25456	5.20	151.1	96949	1.097	1.04	1033
21	173.08	90.26	25684	5.14	149.8	100609	1.097	1.11	1025
22	192.31	91.04	25912	5.09	150.1	103246	1.096	1.07	1029
23	211.54	91.81	26141	5.04	150.1	106178	1.095	1.03	1029
25	250.00	93.36	26602	4.95	151.9	110771	1.093	.99	1044
27	288.46	94.91	27066	4.85	154.6	114840	1.090	.94	1065
29	326.92	96.45	27533	4.76	151.5	123502	1.091	.95	1045
31	365.38	98.00	28002	4.67	144.5	136378	1.095	1.07	999

NOTE: TBULK IS GIVEN IN DEGREES "F"  
 H(AVG) IS GIVEN IN BTU/(FT<sup>2</sup>\*HR\*F)

Fig. 5d. Sample output data file (page 4).

parameters in a given flow regime. In a classroom setting, the program can be employed to demonstrate the basic principles of heat conduction and convection.

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