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Interim Report

Heat and Momentum Transfer to Internal Turbulent Flow of Helium-Argon Mixtures in Circular Tubes

by Paul E. Pickett

CONVECTIVE HEAT TRANSFER FOR SHIP PROPULSION

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The results of an experimental investigation of friction and heat transfer parameters for turbulent flow of helium-argon mixtures in smooth, electrically heated, circular tubes are presented. Experimental results are compared to existing experimental correlations and to analytical results. The variation of turbulent Prandtl number with respect to Reynolds number and molecular Prandtl number is also inspected.

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Interim Report

HEAT AND MOMENTUM TRANSFER TO INTERNAL, TURBULENT FLOW OF HELIUM-ARGON MIXTURES IN CIRCULAR TUBES

by

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ABSTRACT

The results of an ~~experimental~~ investigation of friction and heat transfer parameters for turbulent flow of helium-argon mixtures in smooth, electrically heated, circular tubes are presented. Experimental results are compared to existing experimental correlations and to analytical results. Results of air and helium from the same experimental apparatus are included for comparison.

In this experiment helium~~-argon~~ He-A mixtures with molecular weights between 15.3 and 29.7 are used, resulting ~~This~~ range ~~resulted~~ in Prandtl numbers between 0.42 and 0.49. Inlet Reynolds numbers range from 31200 to 102000, maximum wall temperatures from 392 to 828°K, maximum wall-to-bulk temperature ratios to 1.82, maximum wall heat flux values to 511 KW/m^2, and pressures from 469 to 967KPa (4.7 to 9.7 atmospheres).

Existing experimental correlations, developed using gases with Prandtl numbers of approximately 0.7, are compared to the measured friction and heat transfer results. Adiabatic friction factors and friction factors with heat addition are predicted within ±4 and ±10 percent, respectively. Nusselt numbers for fully developed, constant property conditions are predicted within ±5.0 percent. An empirical equation that correlates the helium-argon data within ±15 ~~percent~~, and includes entrance and variable

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property effects is presented.

Using a recently developed technique that compares numerically calculated and measured constant property Nusselt numbers, turbulent Prandtl numbers in the wall region for helium-argon mixtures are determined. The validity of using these turbulent Prandtl numbers in a variable property numerical analysis is examined. The variation of turbulent Prandtl number with respect to Reynolds number and molecular Prandtl number is also inspected.

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NOMENCLATURE

a,	exponent used to account for temperature variation of viscosity;
a_i,	array of system parameters;
A',	calibration constant for the laminar flow element;
A_{cs},	cross sectional area of tube;
b,	exponent used to account for temperature variation of conductivity;
B',	calibration constant for the laminar flow element;
c,	velocity of sound;
c_p,	specific heat at constant pressure;
D,	inside diameter;
E,	voltage drop;
g,	gravitational constant;
g_c,	dimensional conversion factor;
G,	mass flow rate per unit area;
h,	heat transfer coefficient;
i,	enthalpy per unit mass;
k,	force constant in Lennard-Jones (6-12) potential;
K,	thermal conductivity;
L,	length between pressure taps in laminar flow element;
ℓ,	mixing length;
$\dot{m}$,	mass flow rate;
$\hat{M}$,	molal mass;

ΔP,	pressure drop;
P,	power;
q,	heat transfer rate;
q',	heat transfer rate per unit length;
q'',	heat flux;
Q,	volume flow rate;
r,	radius;
R,	gas constant for a particular gas;
R',	resistance per unit length;
$\mathcal{R}$,	universal gas constant;
T,	temperature;
u,	velocity in axial direction;
x,	axial distance from start of heating;
y,	radial distance from wall;
Y_i,	array of measured values;
Z,	a calculated quantity.

Greek symbols

α,	thermal diffusivity, $K/c_p\rho$;
ε,	force constant in Lennard-Jones potential;
ε_H,	eddy diffusivity for heat;
ε_M,	eddy diffusivity for momentum;
γ,	ratio of specific heats, c_p/c_v;
κ,	von Karman constant 0.4;
μ,	absolute viscosity;
ν,	kinematic viscosity;

ρ,	density;
σ,	variance or standard deviation;
τ,	shear stress.

Non-dimensional parameters

f,	friction factor, $2g_c\rho\tau_w/G^2$;
Gr,	Grashof number based on wall heat flux, $gD^4q''_w/(\nu^2\mu c_pT)_i$;
M	Mach number, j/c
Nu,	Nusselt number, hD/K;
Pr,	Prandtl number, $c_p\mu/K$;
q^+,	heat flux parameter, $q''_w/(Gc_{p,i}T_i)$;
Re,	Reynolds number, GD/μ;
y^+,	wall distance parameter, $y(g_c\tau_w\rho)^{\frac{1}{2}}/\nu$;
y_ℓ^+	empirical constant in van Driest mixing length model, 26.

Subscripts

b,	evaluated at bulk temperature;
cond,	heat conduction;
cp,	constant property condition;
DB,	Dittus-Boelter;
gen,	heat generation;
i,	inlet; an index;
Max,	maximum;
ref,	reference;
t,	turbulent;
VD,	van Driest;
w,	wall;
Xe,	xenon;
∞,	environment conditions.

INTRODUCTION

The closed Brayton cycle using inert gases as working fluids has been considered for use in many current applications. The Navy has investigated its use for undersea and surface ship propulsion. NASA has examined it for future space missions requiring relatively large amounts of electric power (100 - 500 Kw) [1,2,3,4]. Binary mixtures of helium and heavier inert gases, such as argon or xenon, have been considered as possible working fluids in these closed Brayton systems. The increase in density, due to the heavier inert gas, reduces the size of the compressor and turbine. The thermal conductivity of the binary mixture is lower than that of helium, thus causing an increase in the size of the heat exchangers. At an intermediate molecular weight an optimum can be attained.

Fig. 1 illustrates the relative heat transfer of helium-argon and helium-xenon mixtures compared to the pure gases and air. The relative heat transfer coefficients were calculated using the Dittus-Boelter type relation

$$h = 0.021\, Re^{0.8}\, Pr^{0.4}\, (K/D) \tag{1}$$

and were normalized with respect to the lowest value. The geometry and mass flux were kept constant. This resulted in a relative heat transfer coefficient of the form

$$h/h_{Xe} = (c_p \mu_{Xe}/c_{pXe}\mu)^{0.4} (K/K_{Xe})^{0.6}. \tag{2}$$

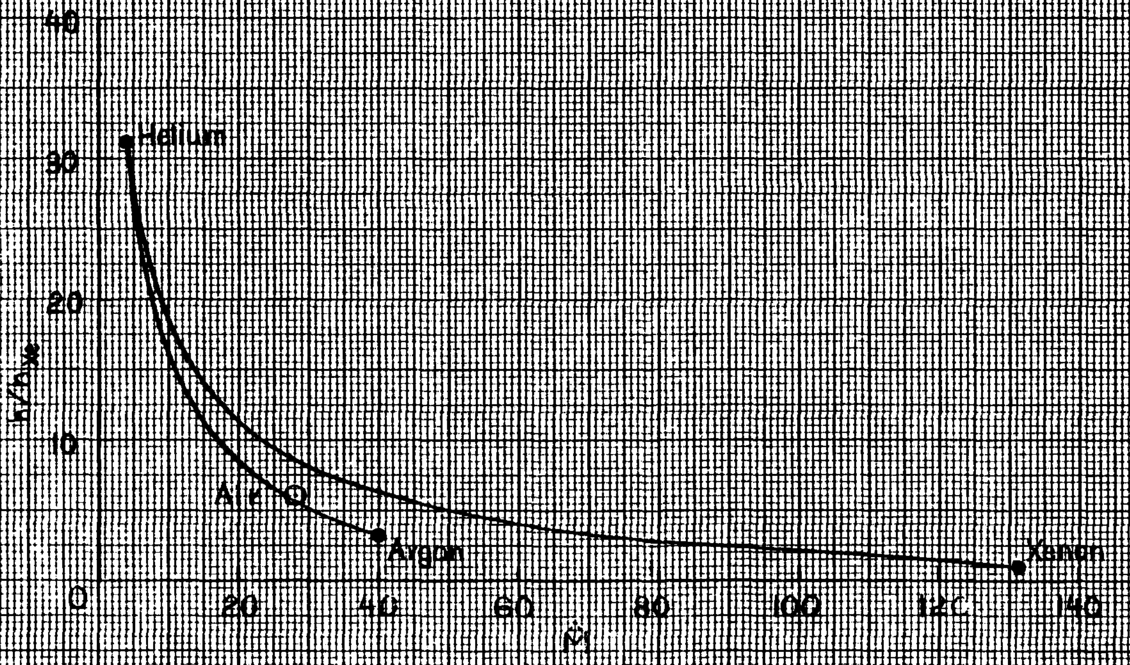


Fig. 1. Relative heat transfer coefficients of mixtures of helium-argon and helium-xenon compared to air and the pure gases, helium, argon, and xenon. Properties were taken at 860K and 101KPa.

All properties were taken at 860K and 101KPa. Vanco [4] performed a similar analysis, but kept the geometry and molal flow rate constant, which gave quite different curves. Examination of Fig. 1 shows why helium-xenon is the prime candidate for a working fluid in the closed Brayton cycle. Helium-argon has been investigated initially due to expense and convenience of experimental apparatus.

The purpose of this research was to determine, for turbulent flow in tubes, the momentum and heat transfer characteristics of helium-argon mixtures. No basic momentum and heat transfer experimental work for fluids with Prandtl numbers between 0.1 and 0.67 presently exists in the literature. Until recently, it was thought that no fluids existed in this Prandtl number range [5,6]. The mixtures of helium and heavier inert gases fill this void, having Prandtl numbers between 0.25 and 0.67. Fig. 2 shows the variation of molecular Prandtl number, Pr, as a function of molecular weight and temperature for helium-argon and helium-xenon [7]. It can be seen that the Prandtl number varies little with temperature.

Experimental correlations, such as equation 1, were developed using air ($Pr \simeq 0.7$) and helium ($Pr = 0.67$). Extension of similar experimental correlations for calculating adiabatic friction factors, average friction factors with heat addition, Nusselt numbers at constant property

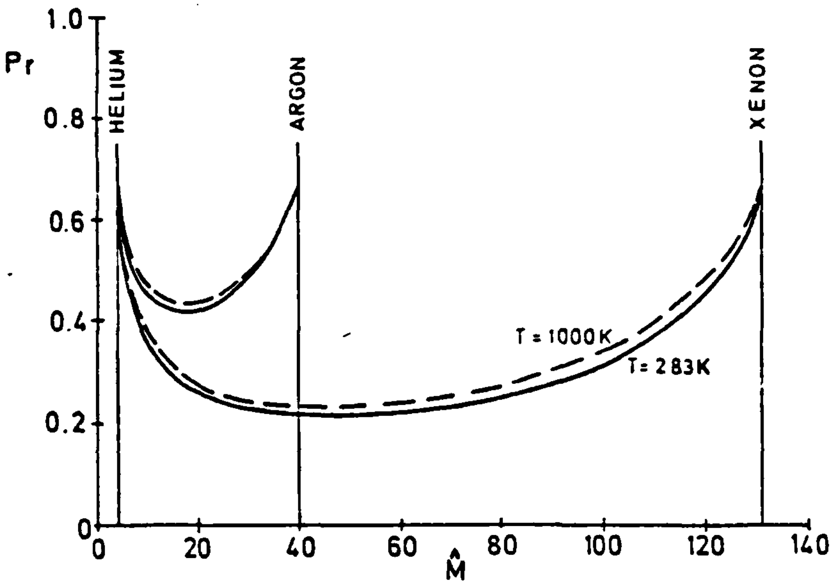


Fig. 2. Variation of Prandtl number with respect to molecular weight for helium-argon and helium-xenon.

conditions, and Nusselt numbers with variable property and thermal entry effects included were examined in this study using helium-argon mixtures. Mixtures at molecular weights of approximately 15 ($Pr = 0.42$), 27 ($Pr = 0.46$), and 30 ($Pr = 0.49$) were used. For comparison, experiments with air and helium were also performed. Experimental studies similar to this one, except using air, helium, or hydrogen include those by Perkins and Worsøe-Schmidt [8], McEligot and Magee [9], Taylor [10], and Dalle Donne and Bowditch [11].

In many analyses that predict turbulent heat transfer results, the value of the turbulent Prandtl number is needed [12]. The turbulent Prandtl number, Pr_t, is defined as the ratio of eddy diffusivity of momentum and eddy diffusivity of heat, $\varepsilon_M/\varepsilon_H$. The eddy diffusivities are defined by the transport relationships,

$$\begin{aligned} \tau/\rho &= (\nu + \varepsilon_M)\frac{\partial u}{\partial y} \\ q''/\rho c_p &= -(\alpha + \varepsilon_H)\frac{\partial T}{\partial y} \end{aligned} \tag{3}$$

and are used to account for the additional momentum and heat transport caused by turbulent mixing.

Much work has been done, both analytical and experimental, to develop methods to predict Pr_t. As of yet, no generally accepted method exists. Reynolds [13] examined more than thirty ways that have been developed to determine Pr_t. For more background information his review can be consulted. Quarmby and Quirk [14] demonstrated the wide range of Pr_t values that are predicted by different analyses and measured data. For air and other common gases, they showed that different methods predict Pr_t near the wall from 0.5 to infinity.

Due to large uncertainties [15], experimental measurements haven't clarified the discrepancies. The measurements have indicated that Pr_t is a function of Pr, position in the flow, and turbulence intensity [13]. It has been generally observed that Pr_t increases as the wall is approached, and that the relationship between Pr_t and Pr is [12,13]

$$Pr_t \lessgtr 1 \text{ for } Pr \gtrless 1 \text{ unless } Pr \sim 1. \tag{4}$$

A recent technique, developed by McEligot, Pickett, and Taylor [16], determines Pr_t in the wall region by comparing the experimentally measured and numerically calculated axial variation of Nusselt number. The Nusselt numbers are calculated for the constant properties condition, and the measured Nusselt numbers are extrapolated to a constant properties condition. The technique was used in this investigation to determine Pr_t in the wall region for mixtures of helium-argon. By comparing Pr_t for helium-argon mixtures with results for air [16], the variation of Pr_t as a function of Pr was examined. The variation of Pr_t as a function of Reynolds number was also examined.

Relatively high heating rates could possibly occur in the heater tubes of the closed Brayton cycle. These high heating rates cause significant variation of properties, and the constant properties idealization becomes invalid. To calculate bulk Nusselt numbers of helium-argon mixtures at these conditions, the Pr_t determined for constant properties was used in a numerical analysis in which the properties were allowed to vary. To validate using Pr_t determined for constant property conditions in a variable properties analysis, calculated and measured bulk Nusselt numbers were compared. By examining this comparison, the possibility that the helium and argon had separated, due to the Soret effect [17], was examined.

GAS PROPERTIES

The properties needed for this study were the compressibility, viscosity, thermal conductivity, specific heat, enthalpy, speed of sound, and gas constant. The properties of air have been studied extensively, and tables listing these properties are readily available. The Tables of the Thermal Properties of Gases [18] were used in this investigation. The properties of helium and helium-argon mixtures were calculated theoretically. For all of the gases, the viscosity and thermal conductivity were assumed to be independent of pressure.

The helium and helium-argon mixtures were assumed to be ideal gases, thus making the compressibility equal to a constant value of one. This is a reasonable assumption for the range of pressures (101.3 - 967.3KPa) and temperatures (294 - 828°K) used in this experiment. Since helium and argon are monatomic, and the temperatures used in this study were not too great, the equation [19]

$$c_p = (5/2)R \tag{5}$$

was used to calculate the specific heat. The specific heat was assumed to be constant, and the gas constant was calculated from the relation

$$R = \mathcal{R}/\hat{M}. \tag{6}$$

Using the ideal gas and constant specific heat assumptions, simple equations for the enthalpy and speed of sound can be derived [20]

$$i = c_p (T - T_{ref}) \tag{7}$$

$$c = \sqrt{\gamma R T} = \sqrt{5/3 R T} \tag{8}$$

T_{ref} is an arbitrary reference temperature. From the assumptions already mentioned, the ratio of specific heats, γ, becomes a constant value of 5/3.

The viscosity and thermal conductivity of the helium and helium-argon mixtures were calculated using the Lennard-Jones (6-12) potential in the Chapman-Enskog kinetic theory [17]. The predicted properties were compared with experimental measurements.

The force constants, ε/k and σ, suggested by Hirschfelder, Curtiss and Bird [17] were tried originally. The predicted properties were compared with the experimental values only for the range of temperatures used in this study. The predicted helium viscosities were five percent below the experimental measurements of Dawe and Smith [21] and Kalelkar and Kestin [22]. The predicted thermal conductivities of helium agreed within one percent of the measurements by Saxena and Saxena [23], but were five percent below the values calculated from experimental viscosity measurements of Kalelkar and Kestin [22]. The predicted viscosities of helium-argon mixtures at 870°K were three to five percent below the measured values of Kalelkar and Kestin [22]. The predicted thermal conductivities of helium-argon mixtures at 790°K were five to nine percent below the measured values of the Thermophysical Properties Research Center [24], and the measured values of von Ubisch repeated by Gandhi and Saxena [25].

In an attempt to get better agreement between predicted and measured values, force constants suggested by DiPippo and Kestin [26] were tried. With these force constants, the predicted viscosities of both helium and helium-argon agreed within one percent of the measured values mentioned in the previous paragraph. The predicted thermal conductivities of helium agreed within one percent of the values of Kalelkar and Kestin [22], but were five percent above the measurements of Saxena and Saxena [23]. The predicted thermal conductivities of helium-argon were essentially unchanged. Since the agreement between the predicted and measured viscosities was improved, and the agreement between the predicted and measured thermal conductivities remained approximately the same, the force constants suggested by DiPippo and Kestin [26] were used. The calculated properties of helium and the helium-argon mixtures used in this investigation are listed in Appendix A.

The properties were inserted in tabular form in the numerical programs that reduced the experimental friction and heat transfer measurements. In the numerical program used to predict heat transfer results, the properties were inserted in equation form. The ideal gas law was used, the specific heat was assumed constant, and the variation of viscosity and thermal conductivity with temperature was accounted for with the following relations.

$$\mu/\mu_{ref} = (T/T_{ref})^{a} \tag{9}$$

$$K/K_{ref} = (T/T_{ref})^{b} \tag{10}$$

As discussed by McEligot, Taylor, and Durst [7], the exponent "a" ranges from 0.7 to 0.8, and the exponent "b" ranges from 0.7 to 0.75 for the inert gases and their mixtures. The exponents, "a" and "b", of air for the range of temperatures in this study are 0.67 and 0.81, respectively. Thus, the viscosity and thermal conductivity of air, helium, and helium-argon vary with temperature in approximately the same manner.

For the present study the following values of the exponents were used for the mixtures:

at $\hat{M} = 15.83$, $a = 0.745$ and $b = 0.718$

at $\hat{M} = 27.53$, $a = 0.772$ and $b = 0.741$.

EXPERIMENTAL APPARATUS AND PROCEDURE

The experimental apparatus, arrangement, and procedure was similar to that used by Perkins, Schade, and McEligot [27]. Only differences in the two experiments will be noted here. Instead of a square duct, a circular tube made of Hastelloy-X was used as a test section. The tube had an inside diameter of 0.312 cm. and a wall thickness of 0.056 cm. The test section consisted of a heated section 98 diameters in length preceded by an unheated section 92 diameters in length. The unheated section ensured that the velocity profile was fully developed at the inlet of the heated section. For attachment of the a.c. power cables, stainless steel electrodes were brazed at the upper and lower ends of the heated section. Two pressure taps were used. One was located in the lower electrode and the other 8.0 diameters below the upper electrode. Sixteen premium grade chromel-alumel thermocouples (0.013 cm. diameter) were spot welded to the heated section of the tube using the parallel junction suggested by Moen [28].

In addition to the power supply used by Perkins et al. [27], an a.c. Lincoln welder was used in order to reach the high temperatures at the larger Reynolds numbers used in this experiment. To measure the higher flow rates, the positive displacement meter was replaced by a Meriam laminar flow element. The latter was calibrated to measure the flow rate within ±1.5 percent. Heise gages, inclined water manometers, and vertical mercury or water manometers were used to measure static pressure and pressure drop.

A vacuum external enviromment was not used in this experiment. The test section was completely enclosed with a heat shield that restricted the convective air currents and helped stabilize the heat loss from the tube to the environment.

The experimental procedure was slightly different than that used by Perkins et al. [27]. The "radiating thermocouple conduction error", discussed by Hess [29], was not exactly appropriate since the test section was surrounded by air at atmospheric pressure. Instead a correlation for natural convection from small wires was introduced, in addition to radiation, as detailed in Appendix E. The heat loss from the tube to the environment was determined using the method described by Campbell and Perkins [30].

To reduce the heat transfer data the same computer program that was used by Perkins et al. [27], was employed in this study, but was modified for use with a circular tube. The basics of this computer program are described in other reports [30,31,32]. Table 1 summarizes the range of variables covered in this investigation. A more detailed discussion of the experiment is contained in Appendix B. A list of the experimental data is contained Appendix D.

TABLE 1

Range of Variables in the Present Experiment

	Air	Helium	Helium-Argon
Experimental runs	25	4	28
Molecular weight	28.97	4.003	15.30 - 29.70
Inlet bulk Reynolds number	32,900 - 100,000	30,200	31,200 - 102,000
Exit bulk Reynolds number	19,900 - 89,000	18,400 - 26,600	17,000 - 68,000
Inlet bulk Prandtl number	0.719	0.667	0.419 - 0.486
Exit bulk Prandtl number	0.682 - 0,708	0.667	0.426 - 0.495
Maximum T_w/T_b	1.90	1.75	1.82
Maximum T_w (^{o}K)	817	789	828
Maximum q^+	0.0027	0.0027	0.0032
Maximum Gr/Re_i^2	8.90×10^{-5}	4.84×10^{-5}	3.22×10^{-3}
Maximum Mach number	0.26	0.25	0.33
x/D for local bulk Nusselt numbers	2.1 - 82.0	2.1 - 82.0	2.1 - 82.0

EXPERIMENTAL RESULTS

Friction Results

Adiabatic friction factors were measured before each series of heated runs. These were compared to other researcher's results, and were also used as a check of the pressure, mixture molecular weight, and flow rate measurements. The method described by Shapiro [33] was used to calculate the adiabatic friction factors. The measured friction factors were compared to the experimental correlation of Drew, Koo, and McAdams [34],

$$f = 0.0014 + 0.125\ \mathrm{Re}^{-0.32}. \tag{11}$$

This correlation is for turbulent flow in tubes, and was used because of its simplicity and close agreement with the Kármán-Nikuradse relation. Fig. 3 shows the measured friction factor divided by that calculated from equation (11) plotted as a function of Reynolds number. Air and helium data points are included for comparison. All the measured friction factors are within ±4.0 percent of equation (11), and 76 percent are within ±2.0 percent.

Since only two pressure taps were used, local friction factors could not be determined for experiments with heat addition. Average friction factors were determined in the manner of Humble, Lowdermilk, and Desmon [35]. The average friction factors were compared to an experimental correlation suggested by Taylor [36]. This correlation is for turbulent flow in tubes with heat addition.

$$f = (0.0014 + 0.125\ Re_w^{-0.32})\ (T_w/T_b)^{-0.5} \qquad (12)$$

This relation is similar to equation (11), but the bulk Reynolds number is replaced by the modified wall Reynolds number. The term $(T_w/T_b)^{-0.5}$ is included to account for variation of properties with temperature. Equation (12) was used by Taylor to correlate average friction coefficients measured by several different people. It predicted most of the data within ±10 percent.

Fig. 4 shows the average friction factors with heat addition as measured in this investigation. The friction coefficients are divided by equation (12) and plotted as a function of modified wall Reynolds number. Again, helium and air are included for comparison. All of the data is predicted to within ±10 percent by equation (12) and 84 percent is predicted to within ±4.0 percent.

Heat Transfer Results

To determine the effects of the lower helium-argon Prandtl number on the heat transfer results, the variation of properties with temperature, and the entrance effects were minimized. The entrance effects were minimized by considering primarily the results at which fully developed conditions existed (x/D>20). A method described by Malina and Sparrow [37] was used to approach the constant properties idealization.

For the method described by Malina and Sparrow, a

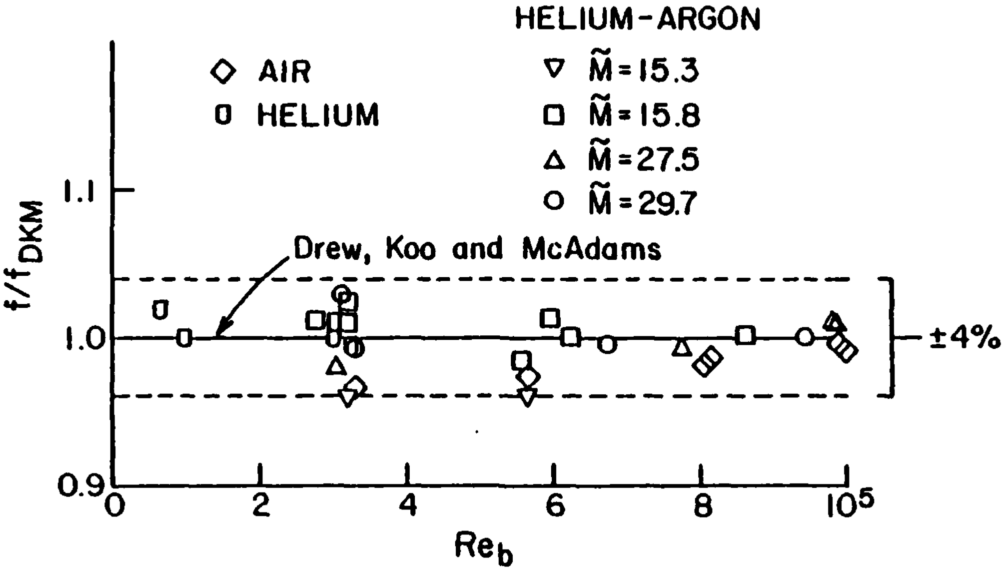


Figure 3. Comparison of Adiabatic Friction Factors to Drew, Koo and McAdams Correlation for Air, Helium and Helium-Argon Mixtures.

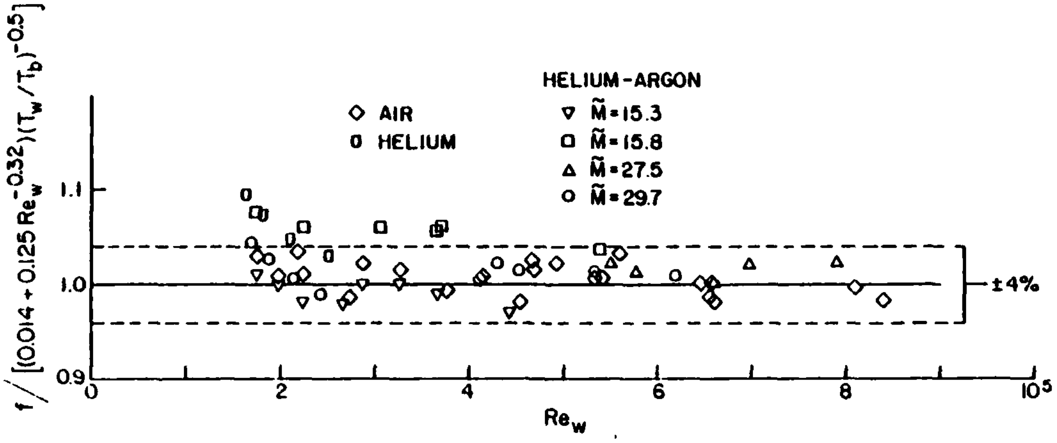


Figure 4 Comparison of Average Friction Factors to Taylor Variable Properties Correlation for Air, Helium and Helium-Argon Mixtures.

fixed inlet Reynolds number is maintained while the wall-to-bulk temperature difference is varied. At a particular axial location, the ratio of experimentally determined bulk Nusselt number to a Dittus-Boelter type correlation is plotted as a function of the difference between wall and bulk temperature. Extrapolation to a difference of zero between the wall and bulk temperature gives a ratio that can be directly used to calculate a constant property Nusselt number, Nu_{cp}. Since the ratio of bulk Nusselt number to a Dittus-Boelter type correlation partially eliminates any effects caused by small deviations of the Reynolds number, these deviations should be kept as small as possible.

The procedure described in the previous paragraph is demonstrated in Fig. 5 for a helium-argon mixture with a molecular weight of 15.30, inlet Reynolds number of 55200, and inlet Prandtl number of 0.419. Extrapolation for four different axial locations is shown. For this investigation the Dittus-Boelter type correlation used was (equation 1 rearranged)

$$Nu_{DB} = 0.021\ Re^{0.8} Pr^{0.4}. \tag{13}$$

For a sequence of runs at a nominal inlet Reynolds number, all individual runs had inlet Reynolds numbers within 1.8 percent of the nominal value.

The dashed lines in Fig. 5 show how the error in the constant property Nusselt number was estimated. This

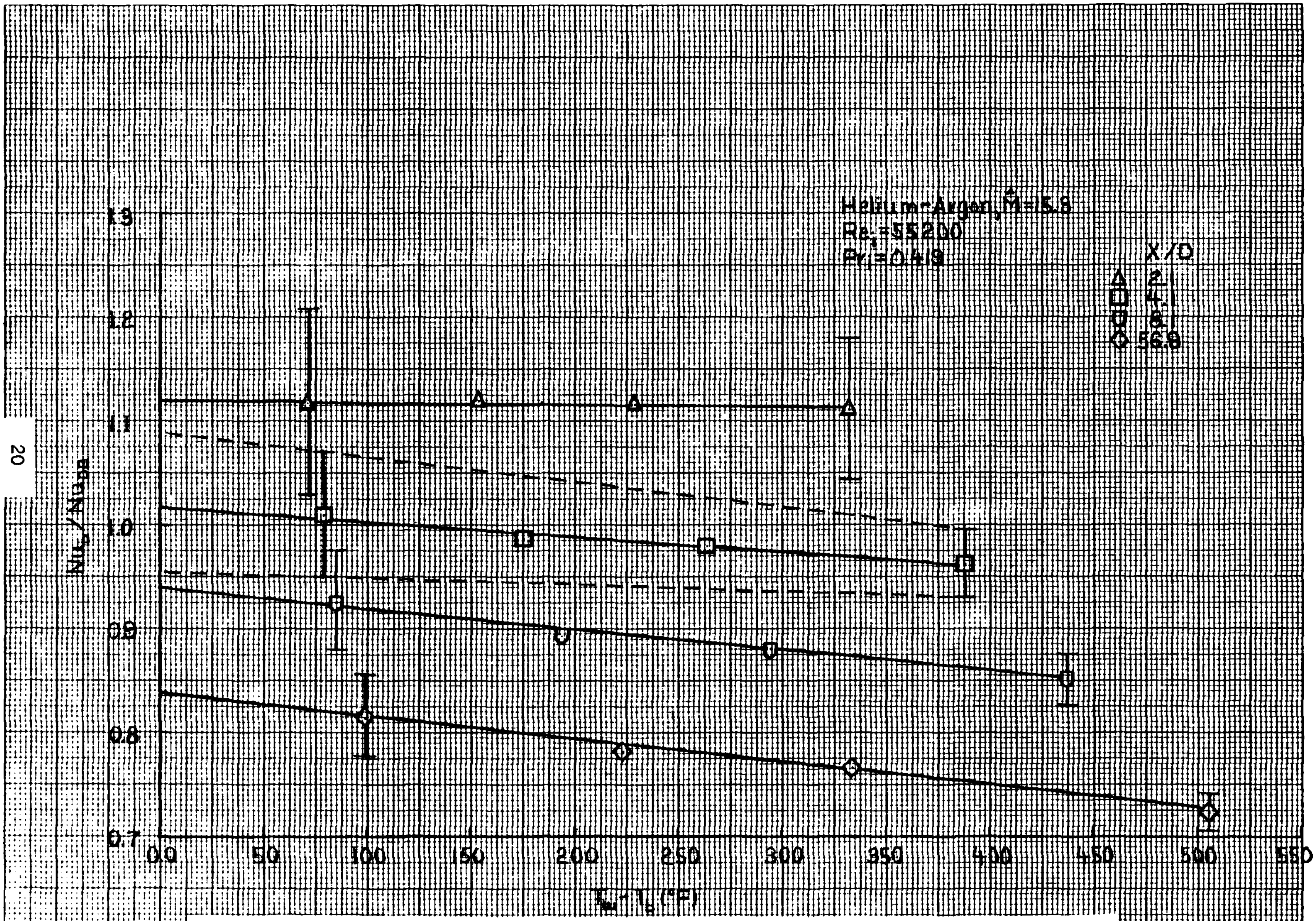


Fig. 5. Technique for determining constant property Nusselt numbers.

technique was used by Reynolds, Swearingen, and McEligot [38]. The error in this investigation varied from ±9 percent at small x/D to ±5.4 percent at large x/D. The dominant uncertainty in the Nusselt number is due to uncertainty in the wall-to-bulk temperature difference. This difference is small in the entrance region, thus causing a large error in the Nusselt number. At large x/D, the flow is fully developed and the wall-to-bulk temperature difference is relatively constant. The error in the Nusselt number becomes a minimum, and then increases with increasing x/D due to greater uncertainty in the bulk temperature. Appendix C describes the method used for calculating error in the measured Nusselt number.

For fully developed conditions (x/D>20), with air or helium as the experimental fluid, the ratio Nu_{cp}/Nu_{DB} varied from 0.94 to 1.00. No dependence on Reynolds number was noticed for the Reynolds number range used in this experiment. For fully developed conditions, with helium-argon mixtures as the experimental fluid, the ratio Nu_{cp}/Nu_{DB} varied from 0.83 to 0.93. For a helium-argon mixture at a molecular weight of 15.30, inlet Reynolds number of 55200, and x/D value of 56.9, Fig. 5 shows the ratio Nu_{cp}/Nu_{DB} to be approximately 0.84. From these results, it was determined that the Dittus-Boelter type equation (equation 13) did not predict correct Nusselt numbers for the Prandtl number range between 0.42 and 0.50.

A correlation suggested by Kays [39] predicted the constant property Nusselt numbers of the helium-argon mixtures within ±6.0 percent.

$$Nu = 0.022\ Re^{0.8} Pr^{0.6} \qquad (14)$$

This equation was recommended for fluids with Prandtl numbers between 0.5 and 1.0, constant properties, a constant heat flux boundary condition, and fully developed turbulent flow. If the coefficient of this equation is changed to 0.021, and the Prandtl number exponent adjusted so that approximately equivalent results are obtained, the resulting equation is

$$Nu = 0.021\ Re^{0.8} Pr^{0.55}. \qquad (15)$$

This equation shows that the exponent of the Prandtl number in equation (13) should be changed from 0.4 to 0.55 in order to accurately predict the constant property Nusselt numbers of the helium-argon mixtures. Fig. 6 shows the constant property Nusselt number divided by equation (15) plotted as a function of Prandtl number for the mixtures. Results are plotted for three Prandtl numbers, four Reynolds numbers, and axial positions at which the flow was fully developed. From the figure it can be seen that equation (15) predicts the constant property Nusselt numbers within ±5.0 percent. At a Reynolds number of 32000, a small effect of the Prandtl number varying between 0.419 and 0.486 can be noticed.

A dependence on Reynolds number was observed for the

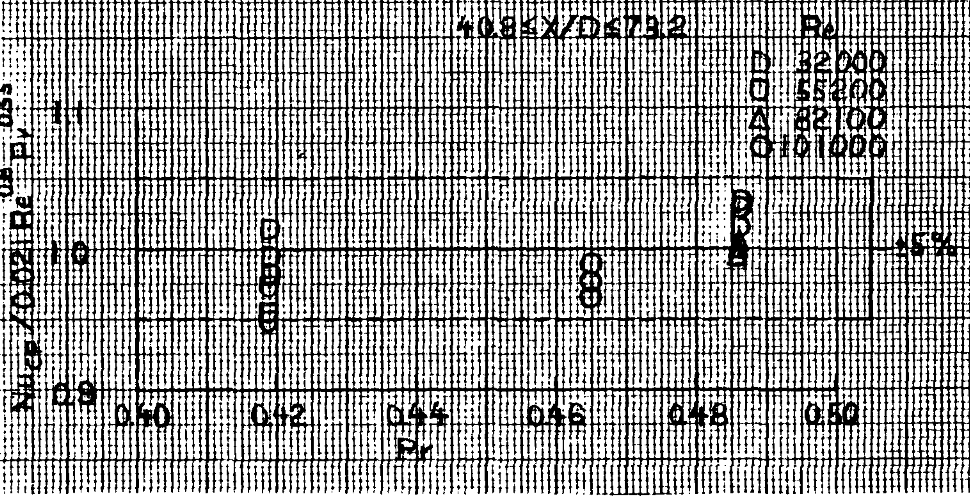


Fig. 6. Comparison of constant property Nusselt numbers to equation 15 for fully developed conditions of helium-argon mixtures.

helium-argon mixtures. Since the effect on the constant property Nusselt number was about equivalent to the error in the constant property Nusselt number, only general trends can be discussed. Two trends were observed (Fig. 6). For a particular Prandtl number the ratio of Nu_{cp} divided by equation (15) decreased as the Reynolds number increased, and this effect became more pronounced as the Prandtl number decreased.

To account for the variation of properties and entrance effects in this investigation, the correction factors suggested by Magee [40] were used.

$$[(T_w/T_b)^{-0.4} + 0.6D/x] \qquad (16)$$

The term $(T_w/T_b)^{-0.4}$ accounts for the variation of properties, and the term 0.6D/x accounts for the entrance effects. If these correction factors are applied to equation (13), the resulting equation is

$$Nu_b = 0.021\ Re_b^{0.8}\ Pr_b^{0.4}[(T_w/T_b)^{-0.4} + 0.6D/x]. \qquad (17)$$

For x/D between 2.1 and 81.6 this equation predicted all of the present measured Nusselt numbers for air and helium within ±15 percent and 97 percent of the Nusselt numbers within ±10 percent.

If the correction factors (16) are applied to equation (15) the resulting relation is

$$Nu_b = 0.021\ Re_b^{0.8}\ Pr_b^{0.55}[(T_w/T_b)^{-0.4} + 0.6D/x]. \qquad (18)$$

This equation predicted the helium-argon Nusselt numbers in the fully developed region within ±13 percent, but underpredicted the Nusselt numbers in the entrance region by as much as 22 percent. To have the same type of accuracy with the helium-argon data that was obtained with the air and helium data changes to the correlation were necessary.

As previously discussed, the transport properties of helium-argon vary with temperature in approximately the same manner as those of air and helium. For this reason the term $(T_w/T_b)^{-0.4}$ was retained as a reasonably accurate correction factor for the variation of properties. Kays [39] discusses the effect of different Prandtl numbers in the thermal entrance region of circular tubes. He shows that as the Prandtl number decreases, the effect of the entrance region on the Nusselt number is more pronounced. Because of this, the coefficient in the term 0.6D/x of equation (18) was changed. Since helium-argon has a lower Prandtl number than air, one would expect the coefficient to have a larger value than 0.6. Different values for the coefficient of the entrance effects term were used in equation (18), and compared to the experimentally determined bulk Nusselt numbers of helium-argon. From this comparison it was determined that a value of 0.85 worked best for the coefficient of the entrance effects term. The complete correlation, accounting for entrance effects and variation of properties is

$$Nu_b = 0.021\, Re_b^{0.8}\, Pr_b^{0.55}\, [(T_w/T_b)^{-0.4} + 0.85D/x]. \quad (19)$$

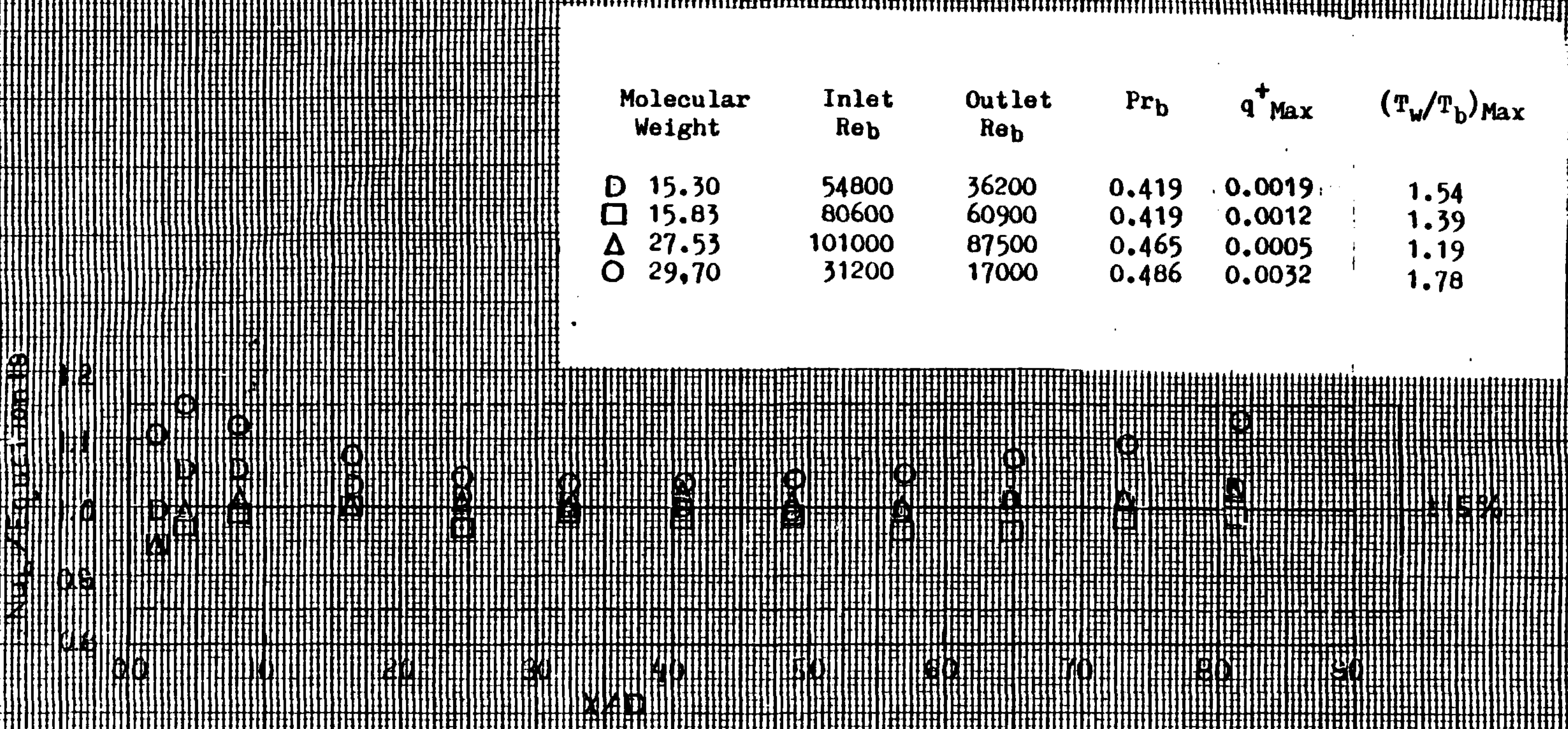
For x/D between 2.1 and 81.6 this equation predicted all of the measured bulk Nusselt numbers for helium-argon within ±15 percent and 92 percent within ±10 percent.

Measured bulk Nusselt numbers divided by equation (19) are plotted on Fig. 7 as a function of x/D. For clarity, only results from four helium-argon experimental runs were plotted. The data plotted are from experimental runs that include the complete range of experimental variables for the helium-argon mixtures. The greatest difference between the experimental data and equation (19) occurred at high heating rates in the x/D range between 4.0 and 16.0. In this range equation (19) underpredicted the measured Nusselt numbers by 5 to 15 percent.

Few correlations for gases with Prandtl numbers between 0.1 and 0.67 presently exist in the literature. Sleicher and Rouse [41] suggest a correlation for Prandtl numbers between 0.1 and 10^5, and Reynolds numbers between 10^4 and 10^6. The correlation is for fully developed conditions, and accounts for property variation.

$$\begin{aligned} Nu_b &= 5 + 0.015\, Re_f^{\,m}\, Pr_w^{\,n} \\ m &= 0.88 - 0.24/(4 + Pr_w) \qquad (20) \\ n &= 1/3 + 0.5 \exp(-0.6\, Pr_w) \end{aligned}$$

For the helium-argon mixtures, this equation predicted Nusselt numbers that were 15 to 40 percent lower than the Nusselt numbers measured in the fully developed region of this investigation. Equation (19) correlated the data more accurately.



	Molecular Weight	Inlet Re_b	Outlet Re_b	Pr_b	q^+_{Max}	$(T_w/T_b)_{Max}$
D	15.30	54800	36200	0.419	0.0019	1.54
□	15.83	80600	60900	0.419	0.0012	1.39
Δ	27.53	101000	87500	0.465	0.0005	1.19
O	29.70	31200	17000	0.486	0.0032	1.78

Fig. 7. Comparison of local bulk Nusselt numbers to equation 19 for helium-argon mixtures.

NUMERICAL ANALYSIS

Procedure for Determining the Turbulent Prandtl Number

To determine Pr_t for helium-argon mixtures, the numerical method of Bankston and McEligot [42] was used in conjunction with the technique developed by McEligot, Pickett, and Taylor [16]. The numerical method uses finite control volume approximations. It was developed to solve the coupled, partial differential, axisymmetric, boundary layer equations; but can also be used for constant property conditions which uncouples the boundary layer equations. The boundary conditions are the no-slip and impermeable-wall conditions, the inlet conditions, and the wall heat flux.

The technique of McEligot et al. [16] uses the axial variation of the Nusselt number to determine Pr_t in the wall region. By examination of the simplified energy equation,

$$u \frac{\partial T}{\partial x} = 1/r \frac{\partial}{\partial r}[r(\alpha + \varepsilon_M/Pr_t) \frac{\partial T}{\partial r}] \qquad (21)$$

they showed that the functional dependence of the Nusselt number is

$$Nu = Nu \{x, u(r), \varepsilon_M(r), Pr_t\}. \qquad (22)$$

The energy equation was simplified from the general form by using the following assumptions: the axisymmetric boundary layer approximations, hydrodynamic fully developed flow, steady flow at low velocities, and constant fluid properties. By using one of the semi-empirical relationships for $\varepsilon_M(r)$ to determine the velocity profile, u(r), they obtained the result Nu = Nu $\{x, Pr_t\}$. They inverted this relationship to obtain $Pr_t = Pr_t\ \{Nu(x)\}$. If Pr_t is considered one-dimensional, comparison of experimental measurements of Nu(x) with calculated values of Nu(x) can be used to determine $Pr_t(r)$. McEligot et al. [16] pointed out that direct inversion would be difficult, and iterative use of the numerical procedure described in the previous paragraph was used. The radial variation of the turbulent Prandtl number was assumed to be

$$P_r = Pr_{t,w} + \frac{d(Pr_t)}{d(y/r_w)}\ (y/r_w). \tag{23}$$

The results of McEligot et al. [16] showed that a change of Pr_t in the wall region from 1 to ½ caused changes of 30 to 45 percent in Nu(x), whereas a change of Pr_t in the core only caused small changes. For air at a Reynolds number of 44500 and a Prandtl number of 0.72 they determined that

$$Pr_{t,w} = 0.9 \pm 0.1 \text{ and } \frac{d(Pr_t)}{d(y/r_w)} = 0. \tag{24}$$

The typical errors of the experimentally measured Nusselt numbers did not allow calculation of $\frac{d(Pr_t)}{d(y/r_w)}$.

To determine $\varepsilon_M(r)$ in this investigation, the van Driest mixing length model [43] was used in conjunction with the

Reichardt middle law [54].

$$\ell_{VD} = \kappa y[1 - \exp(-y^+/y_\ell^+)]$$

$$\varepsilon_{VD} = \ell_{VD}^2 \frac{\partial u}{\partial y} \text{ and } \varepsilon_M = \varepsilon_{VD} \cdot (2-\frac{y}{r_w}) \cdot [1+2(\frac{r}{r_w})^2]/6 \qquad (25)$$

The values of κ and y_ℓ^+ were 0.4 and 26, respectively. With these constants, the predicted friction factors agreed within one percent of equation (11) for the range of Reynolds numbers used in this study. In this study, as in the study by McEligot et al. [16], the errors in the experimentally measured Nusselt numbers did not allow calculation of $\frac{d(Pr_t)}{d(y/r_w)}$. The inlet Reynolds number, inlet Prandtl number, constant properties condition, wall heat flux variation, and different values of Pr_t were used as input to the numerical procedure. For the first three diameters, the experimental axial wall heat flux variation resembled an exponential approach to a constant value as x increased. For the remaining length, the wall heat flux was constant within two percent. The same axial variation of wall heat flux was used for all of the constant property numerical calculations.

From the numerical analysis the axial variation of Nu_{cp} was calculated. By comparing graphs of the experimentally measured Nu_{cp} and the calculated Nu_{cp} (examples in Fig. 8), $Pr_{t,w}$ for helium-argon mixtures was determined. The variation of $Pr_{t,w}$ with respect to Reynolds number was examined by comparing Nu_{cp} at different Reynolds numbers,

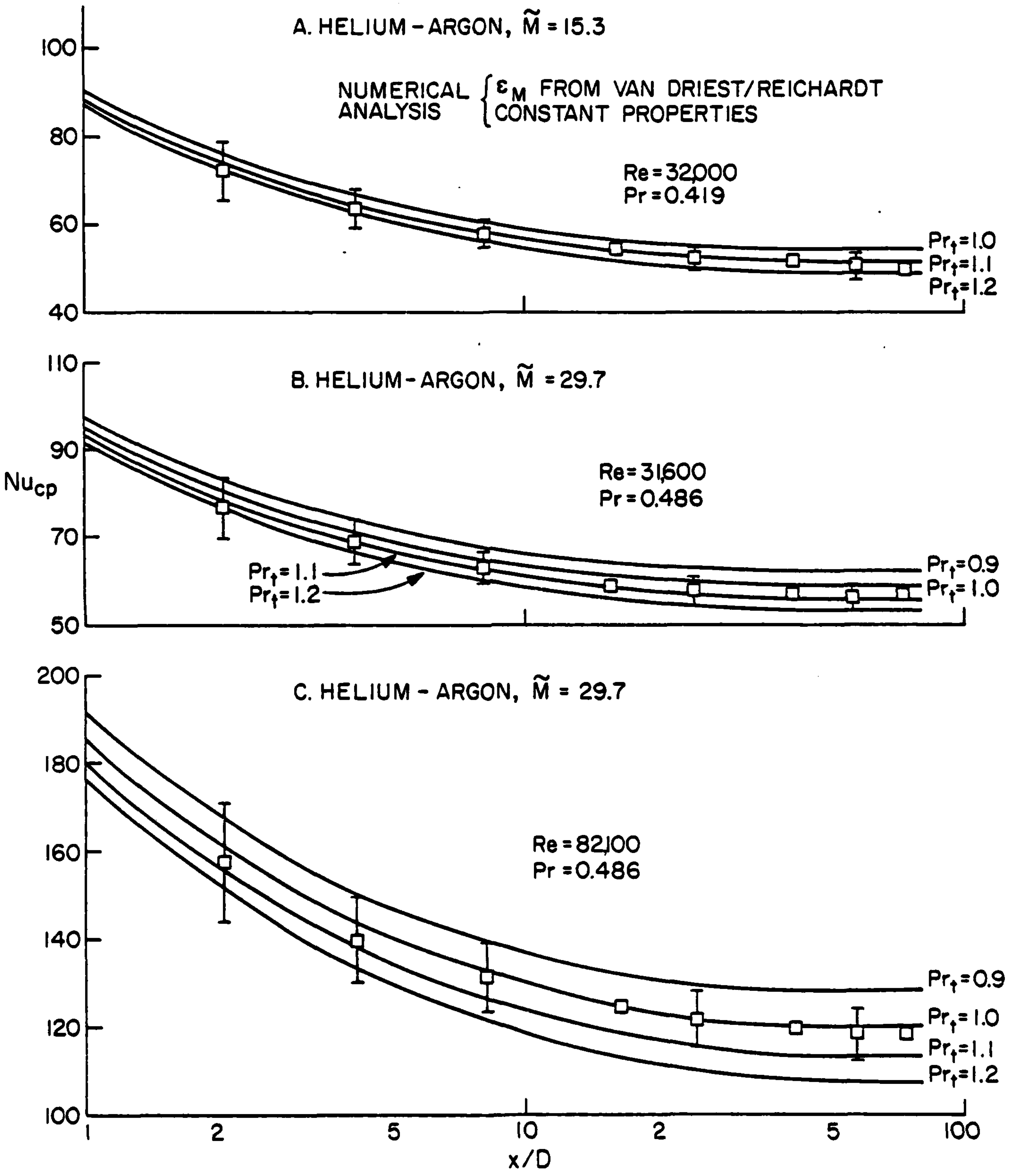


Figure 8. Examples of the Comparisons Between Measured $Nu_{cp}(x)$ and Predicted $Nu(x)$ as Used to Deduce Pr_{tw} for Constant Properties.

but the same Prandtl number. The variation of $Pr_{t,w}$ with respect to Prandtl number was examined by comparing Nu_{cp} at different Prandtl numbers, but the same Reynolds number.

Procedure for Studying High Heating Rates

As mentioned in the Introduction, relatively high heating rates could possibly occur in the heater tubes of the closed Brayton cycle. To calculate Nu_b for helium-argon mixtures at these high heating rates, the numerical method of Bankston and McEligot [42], discussed in the previous section, was used. Properties were allowed to vary, and the relations (9,10) discussed in the Gas Properties section were used. The simple van Driest/Reichardt model eqn. (25), and $Pr_{t,w}$ determined for helium-argon at constant property conditions were incorporated. No radial variation of Pr_t was included, thus, $Pr_t = Pr_{t,w}$. The axial variation of wall heat flux was similar to the one used for the constant property calculations, but was modified slightly for each experimental run to agree with the wall heat flux variation determined from the experimental measurements.

The axial variation of measured Nu_b from two helium-argon experimental runs was compared to the calculated axial variation of Nu_b. From a series of runs with approximately equivalent inlet Reynolds and Prandtl numbers, the runs with the highest and lowest heating rate were chosen. Since the Pr_t used was for constant properties, one would expect agreement of measured and calculated Nu_b at the low heating rate. If the measured and calculated Nu_b at the high heating rate agreed, this would validate the use of Pr_t determined from constant property conditions for conditions in which properties varied significantly. If the results at the high heating rate did not agree, this might indicate that either, Pr_t determined for constant properties couldnot be used for variable property conditions, or that some other phenomenon, such as the Soret effect, was acting.

Turbulent Prandtl Number Results and Discussion

Fig. 8 illustrates examples of the comparisons between measured Nu_{cp} and calculated Nu_{cp} used to determine $Pr_{t,w}$. Examples for three Reynolds numbers and two Prandtl numbers are shown. Curves of the calculated Nu_{cp} are included at four different Pr_t (0.9,1.0,1.1,1.2). Brackets indicating the experimental error of the measured Nu_{cp} are also included. Because of the large error in the immediate thermal entry, only results for x/D greater than eight were used to determine $Pr_{t,w}$.

Fig. 8a shows the measured and calculated Nu_{cp} for a helium-argon mixture with a molecular weight of 15.30, Prandtl number of 0.419, and Reynolds number of 32000. By examining results of similar graphs, $Pr_{t,w}$ was determined to be 1.1 ± 0.1 for helium-argon mixtures with molecular weights of approximately 15, Prandtl numbers of 0.42, and Reynolds numbers between 32000 and 55200. The measured and calculated Nu_{cp} are shown in Fig. 8b and 8c for a helium-argon mixture at a molecular weight of 29.70, Prandtl number of 0.486, and Reynolds numbers of 31600 and 82100. From results of similar graphs, $Pr_{t,w}$ was determined to be 1.0 ± 0.1 for helium-argon mixtures with molecular weights between 27 and 30, Prandtl numbers between 0.46 and 0.49, and Reynolds numbers between 31600 and 102000.

The effect of Reynolds number on $Pr_{t,w}$ can be examined qualitatively using the results in Fig. 8b and 8c. These results are for the same Prandtl number ($Pr = 0.486$), but Reynolds numbers of 31600 and 82100. For x/D greater than eight, and at the low Reynolds number, the measured Nu_{cp} are slightly below the calculated Nu_{cp} for a $Pr_{t,w}$ of 1.0. At the high Reynolds number and same axial length, the measured Nu_{cp} are slightly above the calculated Nu_{cp} for a $Pr_{t,w}$ of 1.0. For the stated conditions, it appears that $Pr_{t,w}$ has a weak dependence on Reynolds number, and decreases slightly as the Reynolds number increases.

The effect of molecular Prandtl number on $Pr_{t,w}$ can be examined using the results from Fig. 8a and 8c summarized in Table 2. The results (24) of McEligot, Pickett and Taylor [16] for air may also be used since the mixture results appear to show that $Pr_{t,w}$ varies only slightly with Reynolds number.

Table 2. Variation of $Pr_{t,w}$ with respect to Prandtl number.

Gas	Molecular Weight	Prandtl Number	$Pr_{t,w}$	Reynolds Number
Helium-argon	15.30	0.419	1.1 ± 0.1	32000
Helium-argon	29.70	0.486	1.0 ± 0.1	31600
Air	28.97	0.72	0.9 ± 0.1	44500

For the range of Prandtl numbers in Table 2, $Pr_{t,w}$ has a relatively strong dependence on Prandtl number and decreases as Prandtl number increases. This dependence agrees with that (equation 4) noted by Reynolds [13].

High Heating Rate Results and Discussion

Fig. 9 shows the results of the measured and calculated axial variation of Nu_b for the two experimental runs that were investigated. The two runs were for a helium-argon mixture at a molecular weight of 29.70, inlet Prandtl number of 0.486, inlet Reynolds numbers of 32000 and 31200, and maximum heating rates of $q^+ = 0.0006$ and $q^+ = 0.0032$. Since at a Pr_t value of 1.0, the measured Nu_{cp} in Fig. 8b were slightly below the calculated Nu_{cp}, a Pr_t value of 1.02 was used. The constants, "a" and "b" in equations (9) and (10) were 0.772 and 0.741, respectively. For both heating rates, the calculated axial variation of Nu_b in Fig. 9 agreed with the measured axial variation of Nu_b, within the accuracy of the measured values. From this example, it appears that $Pr_{t,w}$ determined from constant property results can be used to calculate Nu_b for variable property conditions with heating rates up to, $q^+ = 0.0032$.

At high heating rates a large temperature gradient exists from the wall to the centerline of the tube. At sufficiently high heating rates, the possibility of separation of the helium and argon due to the Soret effect arises. If separation did occur, Nu_b at a particular axial location would be expected to change since pure helium or argon have higher Prandtl numbers than helium-argon mixtures. For the high heating experimental run in Fig. 9, the largest wall-to-bulk temperature ratios occur in the axial range, $8.1<x/D<16.4$. In this axial range, the measured Nu_b do fall slightly above the calculated Nu_b, but this can not necessarily be attributed to the Soret effect, since the calculated Nu_b are within the experimental accuracies of the measured Nu_b.

The effect of high heating on the axial variation of Nu_b can be examined by comparing the low and high heating rate results in Fig. 9. Since the thermal conductivity and viscosity of helium-argon increase as the temperature increases (equations 9,10), this causes Nu_b for high heat flux conditions to be lower than Nu_b for low heat flux conditions. In the immediate thermal entrance region ($x/D<5$), the small rise in bulk gas temperature has not caused significant bulk property variation, and the Nu_b for the two heating rates are approximately the same. In the fully developed region, the large rise in bulk gas temperature has caused large property variations, and Nu_b are quite different. At $x/D = 57$, Nu_b for $q^+_{Max} = 0.0032$ is 29 percent lower than Nu_b for $q^+_{Max} = 0.0006$.

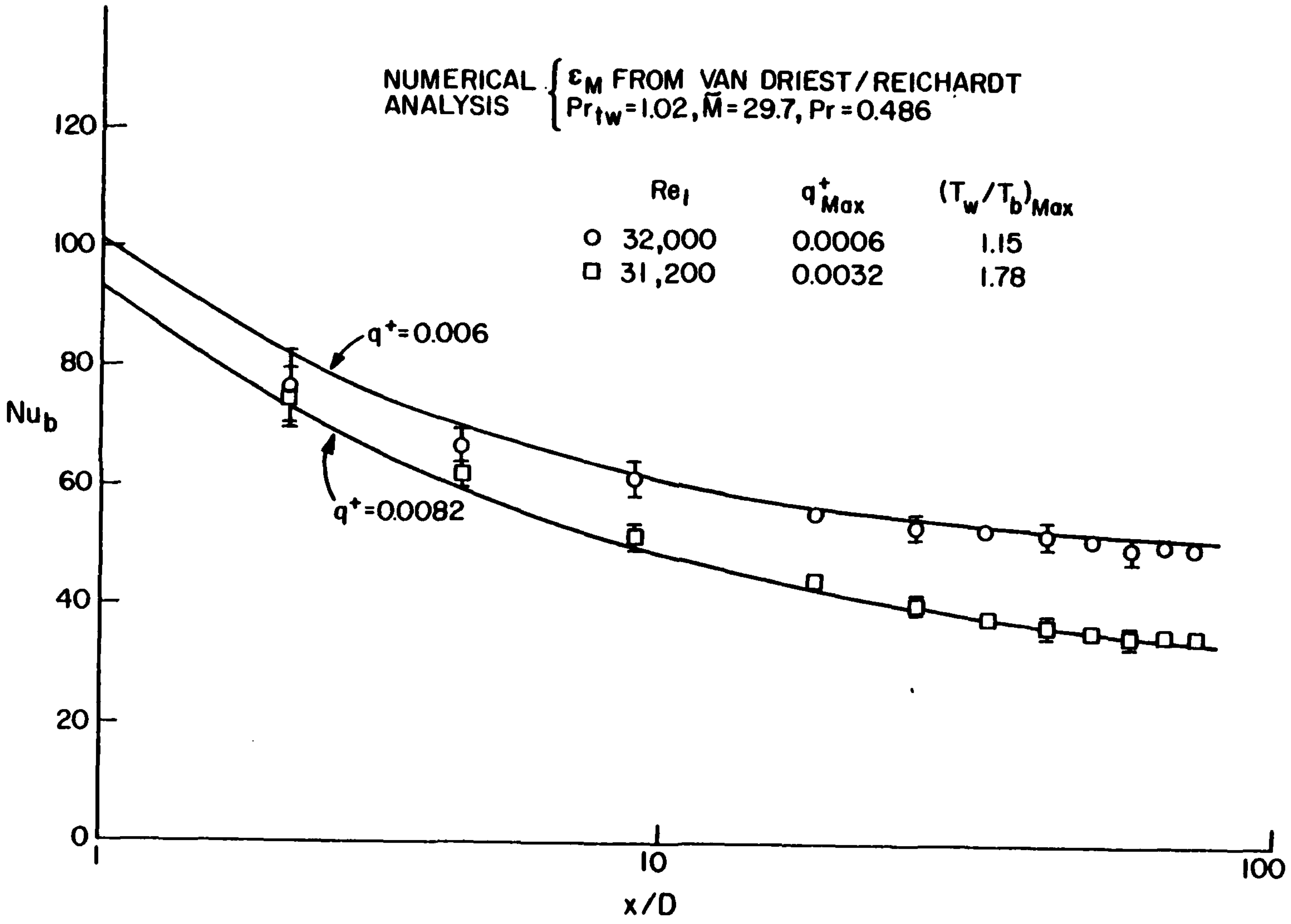


Figure 9. Comparison of Data to Numerical Predictions Accounting for Transport Property Variation.

CONCLUSIONS

The object of this investigation was to study the momentum and heat transfer characteristics for turbulent flow of helium-argon mixtures in tubes. Experimental results were compared to existing experimental correlations, and to results from a numerical analysis. From this investigation the following conclusions have been made:

1. Existing experimental correlations, such as the Drew, Koo, and McAdams relation [34],

$$f = 0.0014 + 0.125\ Re^{-0.32}$$

predict the helium-argon adiabatic friction factors within ±4.0 percent for turbulent flow in tubes with Reynolds numbers between 31200 and 102000.

2. A correlation suggested by Taylor [36],

$$f = (0.0014 + 0.125\ Re_w^{-0.32})\ (T_w/T_b)^{-0.5}$$

predicts average friction factors within ±10 percent for heated turbulent flow of helium-argon mixtures in tubes with inlet Reynolds numbers between 31200 and 102000.

3. Dittus-Boelter type correlations developed from air and helium experimental data

$$Nu = 0.021\ Re^{0.8}\ Pr^{0.4}$$

overpredict helium-argon Nusselt numbers for constant property, fully developed conditions by as much as 17 percent. An equation of similar form,

$$Nu = 0.021\ Re^{0.8}\ Pr^{0.55}$$

but with the exponent of the Prandtl number changed to 0.55 predicts constant property Nusselt numbers of helium-argon mixtures within ±5.0 percent. The range of Prandtl numbers was between 0.419 and 0.486, and the range of Reynolds numbers was between 31200 and 102000.

4. For the same range of Reynolds numbers and Prandtl numbers, the entrance and properties variation effects can be accounted for by using the equation

$$Nu_b = 0.021\ Re_b^{0.8}\ Pr_b^{0.55}\ [(T_w/T_b)^{-0.4} + 0.85\ D/x].$$

This equation predicted the bulk Nusselt numbers of helium-argon mixtures within ±15 percent for x/D between 2.1 and 81.6 and a maximum wall-to-bulk temperature ratio of 1.82.

5. For helium-argon mixtures with molecular weights between 14 and 20, Prandtl numbers of 0.42, Reynolds numbers between 32000 and 55000, and constant property conditions the turbulent Prandtl number in the wall region, $Pr_{t,w}$ was determined to be 1.1 ± 0.1.

6. For helium-argon mixtures with molecular weights between 27 and 30, Prandtl numbers between 0.46 and 0.49, Reynolds numbers between 32000 and 102000, and constant property conditions $Pr_{t,w}$ was determined to be 1.0 ± 0.1.

7. For Reynolds numbers between 30000 and 100000, $Pr_{t,w}$ is a weak function of Reynolds number. For the Prandtl number range between 0.42 and 0.72, $Pr_{t,w}$ is

a strong function of Prandtl number, and decreases as Prandtl number increases.

8. At maximum wall heating rates of $q^+ = 0.0032$ ($(T_w/T_b)_{Max} = 1.78$), $Pr_{t,w}$ determined from constant property conditions can be used in a variable properties numerical analysis to calculate $Nu_b(x)$. For the particular experimental run studied ($Re_i = 31200$, $Pr_i = 0.486$, $Pr_{t,w} = Pr_t = 1.02$), calculated $Nu_b(x)$ agreed with measured $Nu_b(x)$, within the accuracy of the measured values. No separation of the helium-argon mixture was apparent.

APPENDICES

APPENDIX A.
Gas Properties

Helium

Molecular Weight = 4.0026

Specific Heat at Constant Pressure = 1.24036 BTU/LB-R

Temperature (F)	Viscosity (LB/FT-HR)	Conductivity (BTU/HR-FT-F)	Sound Velocity (FT/SEC)
40.00000	4.5339250E-02	8.4353958E-02	3.2161071E+03
70.00000	4.7348801E-02	8.8092741E-02	3.3112430E+03
100.00000	4.9301672E-02	9.1726070E-02	3.4037209E+03
130.00000	5.1202696E-02	9.5262937E-02	3.4937518E+03
160.00000	5.3056299E-02	9.8711577E-02	3.5815203E+03
190.00000	5.4866529E-02	1.0207952E-01	3.6671887E+03
220.00000	5.6637084E-02	1.0537365E-01	3.7509011E+03
250.00000	5.8371342E-02	1.0860025E-01	3.8327355E+03
280.00000	6.0072394E-02	1.1176507E-01	3.9129567E+03
310.00000	6.1743066E-02	1.1487336E-01	3.9915180E+03
340.00000	6.3612572E-02	1.1835159E-01	4.0685526E+03
370.00000	6.5192576E-02	1.2129120E-01	4.1441751E+03
400.00000	6.6752529E-02	1.2419350E-01	4.2184325E+03
430.00000	6.8293346E-02	1.2706020E-01	4.2914052E+03
460.00000	6.9815869E-02	1.2989286E-01	4.3631576E+03
490.00000	7.1320879E-02	1.3269294E-01	4.4337490E+03
520.00000	7.2809100E-02	1.3546179E-01	4.5032339E+03
550.00000	7.4281207E-02	1.3820065E-01	4.5716629E+03
580.00000	7.5737825E-02	1.4091070E-01	4.6390826E+03
610.00000	7.7179543E-02	1.4359302E-01	4.7055364E+03
640.00000	7.8606908E-02	1.4624864E-01	4.7710647E+03
670.00000	8.0020435E-02	1.4887852E-01	4.8357051E+03
700.00000	8.1420607E-02	1.5148355E-01	4.8994928E+03
730.00000	8.2807878E-02	1.5406458E-01	4.9624606E+03
760.00000	8.4182678E-02	1.5662240E-01	5.0246394E+03
790.00000	8.5545409E-02	1.5915777E-01	5.0860581E+03
820.00000	8.6896453E-02	1.6167140E-01	5.1467439E+03
850.00000	8.8236173E-02	1.6416395E-01	5.2067224E+03
880.00000	8.9564910E-02	1.6663608E-01	5.2660179E+03
910.00000	9.0882989E-02	1.6908837E-01	5.3246530E+03
940.00000	9.2190718E-02	1.7152141E-01	5.3826495E+03
970.00000	9.3488391E-02	1.7393574E-01	5.4400277E+03
1000.00000	9.4776287E-02	1.7633188E-01	5.4968070E+03
1030.00000	9.6054671E-02	1.7871032E-01	5.5530057E+03
1060.00000	9.7323797E-02	1.8107153E-01	5.6086414E+03
1090.00000	9.8583908E-02	1.8341598E-01	5.6637306E+03
1120.00000	9.9835234E-02	1.8574408E-01	5.7182390E+03
1150.00000	1.0107800E-01	1.8805625E-01	5.7723319E+03
1180.00000	1.0231241E-01	1.9035286E-01	5.8258734E+03
1210.00000	1.0353867E-01	1.9263435E-01	5.8789273E+03
1240.00000	1.0475693E-01	1.9490102E-01	5.9315068E+03
1270.00000	1.0596752E-01	1.9715323E-01	5.9836242E+03
1300.00000	1.0717047E-01	1.9939133E-01	6.0352915E+03

Helium cont.

Temperature (F)	Enthalpy (BTU/LB)
40.00000	6.1979399E+02
70.00000	6.5700470E+02
100.00000	6.9421541E+02
130.00000	7.3142612E+02
160.00000	7.6863683E+02
190.00000	8.0584754E+02
220.00000	8.4305825E+02
250.00000	8.8026896E+02
280.00000	9.1747967E+02
310.00000	9.5469038E+02
340.00000	9.9190109E+02
370.00000	1.0291118E+03
400.00000	1.0663225E+03
430.00000	1.1035332E+03
460.00000	1.1407439E+03
490.00000	1.1779546E+03
520.00000	1.2151654E+03
550.00000	1.2523761E+03
580.00000	1.2895868E+03
610.00000	1.3267975E+03
640.00000	1.3640082E+03
670.00000	1.4012189E+03
700.00000	1.4384296E+03
730.00000	1.4756403E+03
760.00000	1.5128510E+03
790.00000	1.5500617E+03
820.00000	1.5872725E+03
850.00000	1.6244832E+03
880.00000	1.6616939E+03
910.00000	1.6989046E+03
940.00000	1.7361153E+03
970.00000	1.7733260E+03
1000.00000	1.8105367E+03
1030.00000	1.8477474E+03
1060.00000	1.8849581E+03
1090.00000	1.9221689E+03
1120.00000	1.9593796E+03
1150.00000	1.9965903E+03
1180.00000	2.0338010E+03
1210.00000	2.0710117E+03
1240.00000	2.1082224E+03
1270.00000	2.1454331E+03
1300.00000	2.1826438E+03

Helium-Argon

Molecular Weight = 15.30

Specific Heat at Constant Pressure = 0.32449 BTU/LB-R

Temperature (F)	Viscosity (LB/FT-HR)	Conductivity (BTU/HR-FT-F)	Sound Velocity (FT/SEC)
40.00000	5.2301378E-02	4.0625810E-02	1.6449620E+03
70.00000	5.4834472E-02	4.2473701E-02	1.6936218E+03
100.00000	5.7302310E-02	4.4276174E-02	1.7409220E+03
130.00000	5.9708821E-02	4.6036461E-02	1.7869707E+03
160.00000	6.2057765E-02	4.7757544E-02	1.8318622E+03
190.00000	6.4352726E-02	4.9442169E-02	1.8755795E+03
220.00000	6.6597095E-02	5.1092872E-02	1.9184964E+03
250.00000	6.8794071E-02	5.2711988E-02	1.9603783E+03
280.00000	7.0946667E-02	5.4301672E-02	2.0013840E+03
310.00000	7.3057709E-02	5.5863917E-02	2.0415562E+03
340.00000	7.5139265E-02	5.7479805E-02	2.0809727E+03
370.00000	7.7215247E-02	5.8979570E-02	2.1196467E+03
400.00000	7.9207939E-02	6.0458079E-02	2.1576276E+03
430.00000	8.1169245E-02	6.1916424E-02	2.1949514E+03
460.00000	8.3100948E-02	6.3355619E-02	2.2316510E+03
490.00000	8.5004721E-02	6.4776608E-02	2.2677568E+03
520.00000	8.6862134E-02	6.6180270E-02	2.3032967E+03
550.00000	8.8734662E-02	6.7567427E-02	2.3382965E+03
580.00000	9.0719997E-02	6.9036919E-02	2.3727301E+03
610.00000	9.2501848E-02	7.0372762E-02	2.4067596E+03
640.00000	9.4263821E-02	7.1695393E-02	2.4402858E+03
670.00000	9.6006740E-02	7.3005294E-02	2.4733478E+03
700.00000	9.7731386E-02	7.4302920E-02	2.5059737E+03
730.00000	9.9438497E-02	7.5588697E-02	2.5381302E+03
760.00000	1.0112877E-01	7.6863031E-02	2.5699332E+03
790.00000	1.0280286E-01	7.8126300E-02	2.6013974E+03
820.00000	1.0446140E-01	7.9378864E-02	2.6324367E+03
850.00000	1.0610497E-01	8.0621064E-02	2.6631143E+03
880.00000	1.0773413E-01	8.1853224E-02	2.6934425E+03
910.00000	1.0934943E-01	8.3075648E-02	2.7234330E+03
940.00000	1.1103629E-01	8.4303934E-02	2.7530968E+03
970.00000	1.1265272E-01	8.5506316E-02	2.7824444E+03
1000.00000	1.1422746E-01	8.6699878E-02	2.8114856E+03
1030.00000	1.1578082E-01	8.7884858E-02	2.8402299E+03
1060.00000	1.1732311E-01	8.9061480E-02	2.8686863E+03
1090.00000	1.1885461E-01	9.0229963E-02	2.8968531E+03
1120.00000	1.2037559E-01	9.1390511E-02	2.9247584E+03
1150.00000	1.2188632E-01	9.2543323E-02	2.9524100E+03
1180.00000	1.2338706E-01	9.3688588E-02	2.9797953E+03
1210.00000	1.2487803E-01	9.4826487E-02	3.0069311E+03
1240.00000	1.2635947E-01	9.5957195E-02	3.0338242E+03
1270.00000	1.2783161E-01	9.7080676E-02	3.0604310E+03
1300.00000	1.2929465E-01	9.8197693E-02	3.0869076E+03

Helium-Argon, M = 15.30 cont.

Temperature (F)	Enthalpy (BTU/LB)
40.00000	1.6214297E+02
70.00000	1.7187758E+02
100.00000	1.8161220E+02
130.00000	1.9134681E+02
160.00000	2.0108142E+02
190.00000	2.1081604E+02
220.00000	2.2055065E+02
250.00000	2.3028527E+02
280.00000	2.4001988E+02
310.00000	2.4975449E+02
340.00000	2.5948911E+02
370.00000	2.6922372E+02
400.00000	2.7895833E+02
430.00000	2.8869295E+02
460.00000	2.9842756E+02
490.00000	3.0816217E+02
520.00000	3.1789679E+02
550.00000	3.2763140E+02
580.00000	3.3736602E+02
610.00000	3.4710063E+02
640.00000	3.5683524E+02
670.00000	3.6656986E+02
700.00000	3.7630447E+02
730.00000	3.8603908E+02
760.00000	3.9577370E+02
790.00000	4.0550831E+02
820.00000	4.1524292E+02
850.00000	4.2497754E+02
880.00000	4.3471215E+02
910.00000	4.4444677E+02
940.00000	4.5418138E+02
970.00000	4.6391599E+02
1000.00000	4.7365061E+02
1030.00000	4.8338522E+02
1060.00000	4.9311983E+02
1090.00000	5.0285445E+02
1120.00000	5.1258906E+02
1150.00000	5.2232367E+02
1180.00000	5.3205829E+02
1210.00000	5.4179290E+02
1240.00000	5.5152752E+02
1270.00000	5.6126213E+02
1300.00000	5.7099674E+02

Helium-Argon

Molecular Weight = 15.83

Specific Heat at Constant Pressure = 0.31362 BTU/LB-R

Temperature (F)	Viscosity (LB/FT-HR)	Conductivity (BTU/HR-FT-F)	Sound Velocity (FT/SEC)
40.00000	5.2384618E-02	3.9396159E-02	1.6171903E+03
70.00000	5.4928517E-02	4.1190434E-02	1.6650286E+03
100.00000	5.7407116E-02	4.2940783E-02	1.7115303E+03
130.00000	5.9824291E-02	4.4650306E-02	1.7568015E+03
160.00000	6.2183763E-02	4.6321867E-02	1.8009351E+03
190.00000	6.4489079E-02	4.7958105E-02	1.8440127E+03
220.00000	6.6743604E-02	4.9561456E-02	1.8861067E+03
250.00000	6.8950516E-02	5.1134167E-02	1.9272815E+03
280.00000	7.1112809E-02	5.2678312E-02	1.9675949E+03
310.00000	7.3233298E-02	5.4195807E-02	2.0070987E+03
340.00000	7.5370145E-02	5.5761774E-02	2.0458399E+03
370.00000	7.7405684E-02	5.7219141E-02	2.0838609E+03
400.00000	7.9407606E-02	5.8655777E-02	2.1212006E+03
430.00000	8.1377829E-02	6.0072747E-02	2.1579943E+03
460.00000	8.3318152E-02	6.1471042E-02	2.1939743E+03
490.00000	8.5230263E-02	6.2851587E-02	2.2294706E+03
520.00000	8.7115747E-02	6.4215242E-02	2.2644104E+03
550.00000	8.8976092E-02	6.5562812E-02	2.2988193E+03
580.00000	9.0968306E-02	6.6992407E-02	2.3327207E+03
610.00000	9.2757737E-02	6.8289597E-02	2.3661364E+03
640.00000	9.4527012E-02	6.9573938E-02	2.3990867E+03
670.00000	9.6277033E-02	7.0845900E-02	2.4315906E+03
700.00000	9.8008596E-02	7.2105926E-02	2.4636656E+03
730.00000	9.9722451E-02	7.3354433E-02	2.4953284E+03
760.00000	1.0141931E-01	7.4591815E-02	2.5265945E+03
790.00000	1.0309984E-01	7.5818442E-02	2.5574783E+03
820.00000	1.0476467E-01	7.7034665E-02	2.5879936E+03
850.00000	1.0641441E-01	7.8240817E-02	2.6181532E+03
880.00000	1.0804964E-01	7.9437212E-02	2.6479694E+03
910.00000	1.0967089E-01	8.0624150E-02	2.6774536E+03
940.00000	1.1142182E-01	8.1818356E-02	2.7066166E+03
970.00000	1.1300326E-01	8.2985687E-02	2.7354687E+03
1000.00000	1.1457297E-01	8.4144452E-02	2.7640196E+03
1030.00000	1.1613127E-01	8.5294890E-02	2.7922787E+03
1060.00000	1.1767846E-01	8.6437221E-02	2.8202546E+03
1090.00000	1.1921483E-01	8.7571654E-02	2.8479557E+03
1120.00000	1.2074066E-01	8.8698389E-02	2.8753899E+03
1150.00000	1.2225620E-01	8.9817619E-02	2.9025648E+03
1180.00000	1.2376172E-01	9.0929526E-02	2.9294877E+03
1210.00000	1.2525745E-01	9.2034287E-02	2.9561654E+03
1240.00000	1.2674362E-01	9.3132070E-02	2.9826045E+03
1270.00000	1.2822046E-01	9.4223037E-02	3.0088113E+03
1300.00000	1.2968818E-01	9.5307343E-02	3.0347917E+03

Helium-Argon, M = 15.83 cont.

Temperature (F)	Enthalpy (BTU/LB)
40.00000	1.5671430E+02
70.00000	1.6612300E+02
100.00000	1.7553169E+02
130.00000	1.8494038E+02
160.00000	1.9434907E+02
190.00000	2.0375776E+02
220.00000	2.1316645E+02
250.00000	2.2257515E+02
280.00000	2.3198384E+02
310.00000	2.4139253E+02
340.00000	2.5080122E+02
370.00000	2.6020991E+02
400.00000	2.6961860E+02
430.00000	2.7902730E+02
460.00000	2.8843599E+02
490.00000	2.9784468E+02
520.00000	3.0725337E+02
550.00000	3.1666206E+02
580.00000	3.2607075E+02
610.00000	3.3547945E+02
640.00000	3.4488814E+02
670.00000	3.5429683E+02
700.00000	3.6370552E+02
730.00000	3.7311421E+02
760.00000	3.8252290E+02
790.00000	3.9193160E+02
820.00000	4.0134029E+02
850.00000	4.1074898E+02
880.00000	4.2015767E+02
910.00000	4.2956636E+02
940.00000	4.3897505E+02
970.00000	4.4838375E+02
1000.00000	4.5779244E+02
1030.00000	4.6720113E+02
1060.00000	4.7660982E+02
1090.00000	4.8601851E+02
1120.00000	4.9542720E+02
1150.00000	5.0483589E+02
1180.00000	5.1424459E+02
1210.00000	5.2365328E+02
1240.00000	5.3306197E+02
1270.00000	5.4247066E+02
1300.00000	5.5187935E+02

Helium-Argon

Molecular Weight = 27.53

Specific Heat at Constant Pressure = 0.18034 BTU/LB-R

Temperature (F)	Viscosity (LB/FT-HR)	Conductivity (BTU/HR-FT-F)	Sound Velocity (FT/SEC)
40.00000	5.2563842E-02	2.0434522E-02	1.2263050E+03
70.00000	5.5227557E-02	2.1402132E-02	1.2625304E+03
100.00000	5.7827260E-02	2.2347336E-02	1.2978423E+03
130.00000	6.0365858E-02	2.3271434E-02	1.3321712E+03
160.00000	6.2846258E-02	2.4175647E-02	1.3656374E+03
190.00000	6.5271322E-02	2.5061130E-02	1.3983029E+03
220.00000	6.7643847E-02	2.5928965E-02	1.4302225E+03
250.00000	6.9966537E-02	2.6780169E-02	1.4614451E+03
280.00000	7.2241997E-02	2.7615696E-02	1.4920145E+03
310.00000	7.4472722E-02	2.8436438E-02	1.5219700E+03
340.00000	7.6670221E-02	2.9253647E-02	1.5513471E+03
370.00000	7.8817021E-02	3.0045581E-02	1.5801783E+03
400.00000	8.0926015E-02	3.0825225E-02	1.6084927E+03
430.00000	8.2999207E-02	3.1593220E-02	1.6363173E+03
460.00000	8.5038497E-02	3.2350167E-02	1.6636765E+03
490.00000	8.7045687E-02	3.3096632E-02	1.6905931E+03
520.00000	8.9022481E-02	3.3833145E-02	1.7170378E+03
550.00000	9.0970492E-02	3.4560205E-02	1.7431798E+03
580.00000	9.2894234E-02	3.5334411E-02	1.7688870E+03
610.00000	9.4864927E-02	3.6032088E-02	1.7942259E+03
640.00000	9.6721845E-02	3.6722246E-02	1.8192119E+03
670.00000	9.8556091E-02	3.7405190E-02	1.8438594E+03
700.00000	1.0036871E-01	3.8081209E-02	1.8681317E+03
730.00000	1.0216070E-01	3.8750575E-02	1.8921914E+03
760.00000	1.0393299E-01	3.9413547E-02	1.9159002E+03
790.00000	1.0568648E-01	4.0070366E-02	1.9393192E+03
820.00000	1.0742201E-01	4.0721264E-02	1.9624588E+03
850.00000	1.0914040E-01	4.1366460E-02	1.9853287E+03
880.00000	1.1084239E-01	4.2006162E-02	2.0079381E+03
910.00000	1.1252871E-01	4.2640566E-02	2.0302957E+03
940.00000	1.1450619E-01	4.3315536E-02	2.0524098E+03
970.00000	1.1613465E-01	4.3935632E-02	2.0742382E+03
1000.00000	1.1775107E-01	4.4551214E-02	2.0959382E+03
1030.00000	1.1935579E-01	4.5162402E-02	2.1173569E+03
1060.00000	1.2094912E-01	4.5769313E-02	2.1385808E+03
1090.00000	1.2253134E-01	4.6372057E-02	2.1595364E+03
1120.00000	1.2410274E-01	4.6970738E-02	2.1803396E+03
1150.00000	1.2566359E-01	4.7565458E-02	2.2009961E+03
1180.00000	1.2721415E-01	4.8156313E-02	2.2214116E+03
1210.00000	1.2875466E-01	4.8743396E-02	2.2415411E+03
1240.00000	1.3028537E-01	4.9326796E-02	2.2616897E+03
1270.00000	1.3180649E-01	4.9906596E-02	2.2815621E+03
1300.00000	1.3331826E-01	5.0482880E-02	2.3012629E+03

Helium-Argon, M = 27.53 cont.

Temperature (F)	Enthalpy (BTU/LB)
40.00000	9.0112148E+01
70.00000	9.5522231E+01
100.00000	1.0093231E+02
130.00000	1.0634240E+02
160.00000	1.1175248E+02
190.00000	1.1716256E+02
220.00000	1.2257265E+02
250.00000	1.2798273E+02
280.00000	1.3339281E+02
310.00000	1.3880290E+02
340.00000	1.4421298E+02
370.00000	1.4962306E+02
400.00000	1.5503315E+02
430.00000	1.6044323E+02
460.00000	1.6585331E+02
490.00000	1.7126340E+02
520.00000	1.7667348E+02
550.00000	1.8208356E+02
580.00000	1.8749364E+02
610.00000	1.9290373E+02
640.00000	1.9831381E+02
670.00000	2.0372389E+02
700.00000	2.0913398E+02
730.00000	2.1454406E+02
760.00000	2.1995414E+02
790.00000	2.2536423E+02
820.00000	2.3077431E+02
850.00000	2.3618439E+02
880.00000	2.4159448E+02
910.00000	2.4700456E+02
940.00000	2.5241464E+02
970.00000	2.5782473E+02
1000.00000	2.6323481E+02
1030.00000	2.6864489E+02
1060.00000	2.7405497E+02
1090.00000	2.7946506E+02
1120.00000	2.8487514E+02
1150.00000	2.9028522E+02
1180.00000	2.9569531E+02
1210.00000	3.0110539E+02
1240.00000	3.0651547E+02
1270.00000	3.1192556E+02
1300.00000	3.1733564E+02

Helium-Argon

Molecular Weight = 29.70

Specific Heat at Constant Pressure = 0.16716 BTU/LB-R

Temperature (F)	Viscosity (LB/FT-HR)	Conductivity (BTU/HR-FT-F)	Sound Velocity (FT/SEC)
40.00000	5.2418661E-02	1.8071935E-02	1.1806560E+03
70.00000	5.5089766E-02	1.8936920E-02	1.2155311E+03
100.00000	5.7697317E-02	1.9781962E-02	1.2495304E+03
130.00000	6.0244079E-02	2.0608217E-02	1.2825314E+03
160.00000	6.2732833E-02	2.1416669E-02	1.3148018E+03
190.00000	6.5166339E-02	2.2208326E-02	1.3462513E+03
220.00000	6.7547299E-02	2.2984125E-02	1.3769827E+03
250.00000	6.9878341E-02	2.3744946E-02	1.4070430E+03
280.00000	7.2162005E-02	2.4491622E-02	1.4364745E+03
310.00000	7.4400728E-02	2.5224934E-02	1.4653149E+03
340.00000	7.6602596E-02	2.5952060E-02	1.4935985E+03
370.00000	7.8757404E-02	2.6659758E-02	1.5213564E+03
400.00000	8.0874035E-02	2.7356255E-02	1.5486168E+03
430.00000	8.2954484E-02	2.8042132E-02	1.5754056E+03
460.00000	8.5000641E-02	2.8717935E-02	1.6017465E+03
490.00000	8.7014303E-02	2.9384180E-02	1.6275511E+03
520.00000	8.8997171E-02	3.0041350E-02	1.6531695E+03
550.00000	9.0950857E-02	3.0689903E-02	1.6782902E+03
580.00000	9.2953808E-02	3.1376622E-02	1.7030405E+03
610.00000	9.4841908E-02	3.1999396E-02	1.7274352E+03
640.00000	9.6705728E-02	3.2615263E-02	1.7514921E+03
670.00000	9.8546407E-02	3.3224512E-02	1.7752220E+03
700.00000	1.0036503E-01	3.3827417E-02	1.7986390E+03
730.00000	1.0216262E-01	3.4424234E-02	1.8217549E+03
760.00000	1.0394016E-01	3.5015209E-02	1.8445812E+03
790.00000	1.0569856E-01	3.5600570E-02	1.8671254E+03
820.00000	1.0743871E-01	3.6180539E-02	1.8894066E+03
850.00000	1.0916143E-01	3.6755321E-02	1.9114252E+03
880.00000	1.1086752E-01	3.7325114E-02	1.9331929E+03
910.00000	1.1255773E-01	3.7890104E-02	1.9547133E+03
940.00000	1.1456435E-01	3.8502097E-02	1.9760092E+03
970.00000	1.1619396E-01	3.9053187E-02	1.9970732E+03
1000.00000	1.1781154E-01	3.9600255E-02	2.0179173E+03
1030.00000	1.1941741E-01	4.0143436E-02	2.0385482E+03
1060.00000	1.2101187E-01	4.0662804E-02	2.0589725E+03
1090.00000	1.2259524E-01	4.1218466E-02	2.0791961E+03
1120.00000	1.2416778E-01	4.1750517E-02	2.0992249E+03
1150.00000	1.2572976E-01	4.2279046E-02	2.1190544E+03
1180.00000	1.2728145E-01	4.2804138E-02	2.1387199E+03
1210.00000	1.2882309E-01	4.3325877E-02	2.1581964E+03
1240.00000	1.3035492E-01	4.3844340E-02	2.1774987E+03
1270.00000	1.3187716E-01	4.4359603E-02	2.1966314E+03
1300.00000	1.3339004E-01	4.4871739E-02	2.2155988E+03

Helium-Argon, M = 29.70 cont.

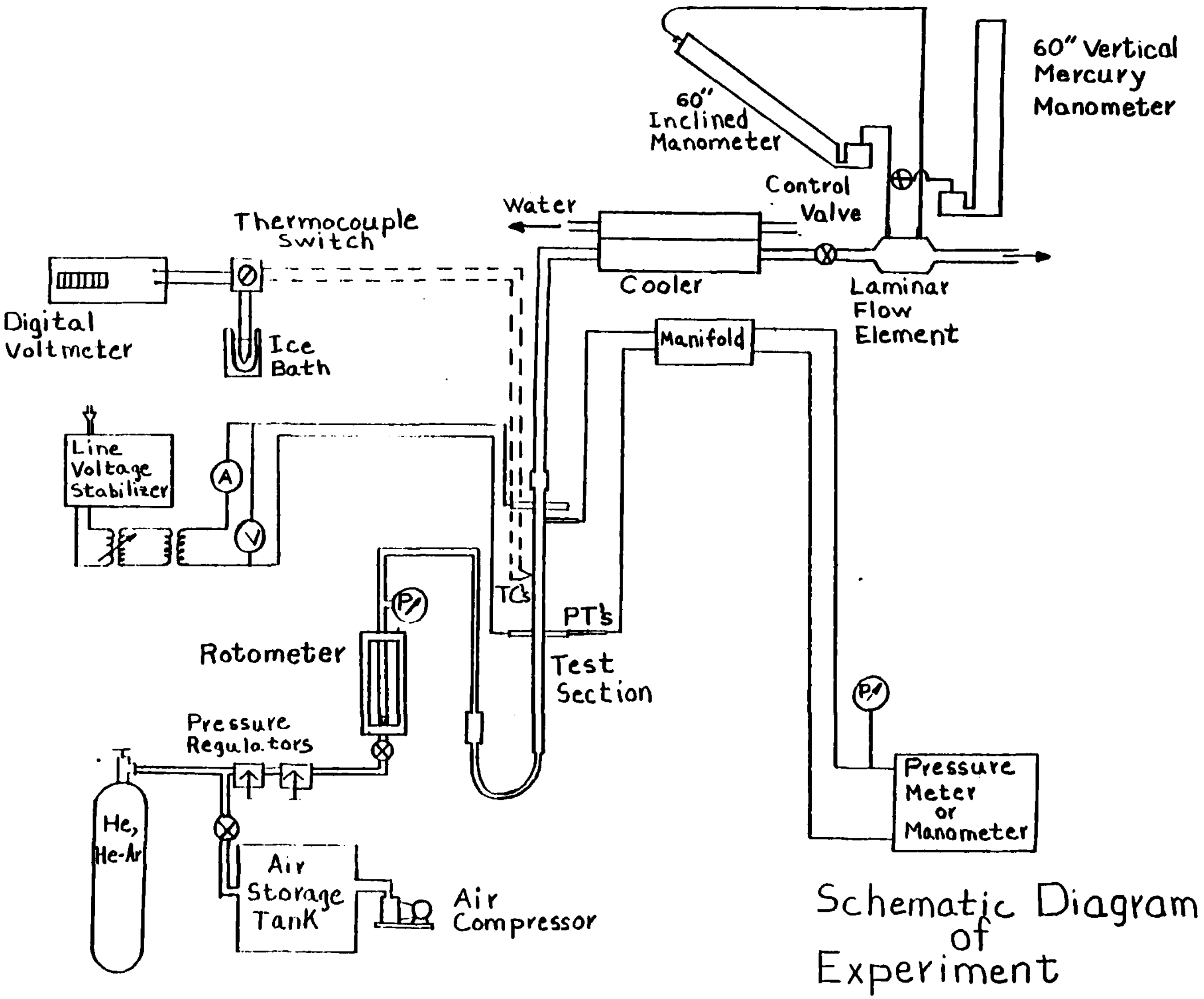
Temperature (F)	Enthalpy (BTU/LB)
40.00000	8.3528196E+01
70.00000	8.8542997E+01
100.00000	9.3557798E+01
130.00000	9.8572599E+01
160.00000	1.0358740E+02
190.00000	1.0860220E+02
220.00000	1.1361700E+02
250.00000	1.1863180E+02
280.00000	1.2364660E+02
310.00000	1.2866141E+02
340.00000	1.3367621E+02
370.00000	1.3869101E+02
400.00000	1.4370581E+02
430.00000	1.4872061E+02
460.00000	1.5373541E+02
490.00000	1.5875021E+02
520.00000	1.6376501E+02
550.00000	1.6877981E+02
580.00000	1.7379461E+02
610.00000	1.7880941E+02
640.00000	1.8382422E+02
670.00000	1.8883902E+02
700.00000	1.9385382E+02
730.00000	1.9886862E+02
760.00000	2.0388342E+02
790.00000	2.0889822E+02
820.00000	2.1391302E+02
850.00000	2.1892782E+02
880.00000	2.2394262E+02
910.00000	2.2895742E+02
940.00000	2.3397223E+02
970.00000	2.3898703E+02
1000.00000	2.4400183E+02
1030.00000	2.4901663E+02
1060.00000	2.5403143E+02
1090.00000	2.5904623E+02
1120.00000	2.6406103E+02
1150.00000	2.6907583E+02
1180.00000	2.7409063E+02
1210.00000	2.7910543E+02
1240.00000	2.8412024E+02
1270.00000	2.8913504E+02
1300.00000	2.9414984E+02

APPENDIX B.
EXPERIMENT

Apparatus

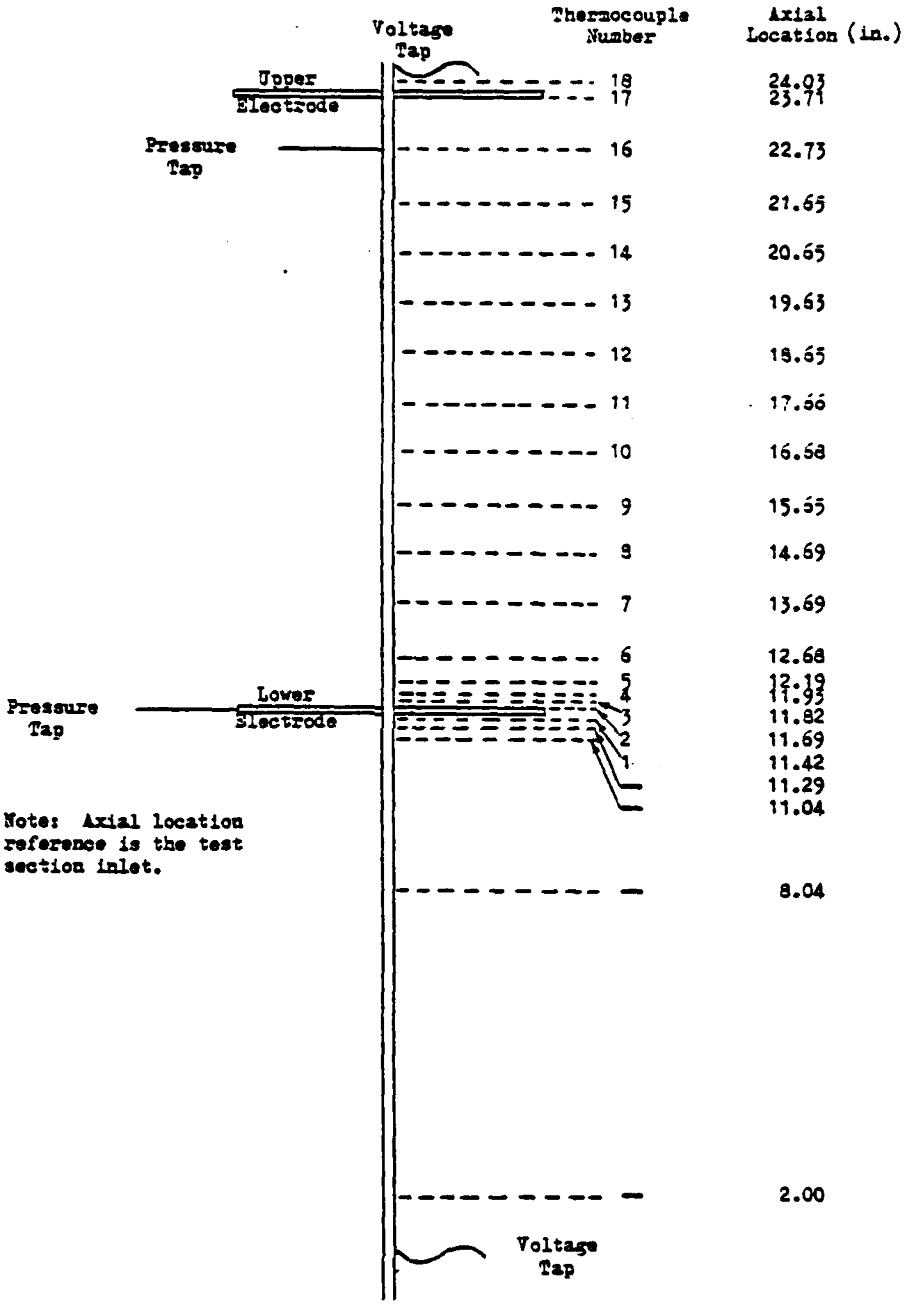
A schematic diagram of the experiment is shown in Fig. B1. The helium and helium-argon mixtures were bought from manufacturers in high pressure bottles. The air was obtained from a large storage tank that was replenished by a compressor. Two regulators were used to reduce and stabilize the pressure. A Brooks rotometer was used to obtain a rough measurement of the flow rate. A Bourdon tube Heise gage measured the pressure just downstream of the rotometer. A small tank constructed to mix the gas, and instrumented with a thermocouple measured the inlet stagnation temperature. A sketch of the test section from the inlet to just below the outlet mixing tank, and displaying the location of thermocouples, pressure taps, electrodes, and voltage taps is shown in Fig. B2.

Power was measured using a Fluke differential voltmeter and Weston ammeter in the same manner as Perkins et al. [27]. Whenever possible the power supply described by Perkins et al. [27] was used. When it did not supply sufficient power an a.c. Lincoln welder (Model TM-500/500) was used. To determine a power factor when the welder was used, the power measured with a Weston watt meter was compared to that calculated from voltage (Fluke voltmeter)



Schematic Diagram of Experiment

Fig. B1.



Note: Axial location reference is the test section inlet.

Fig. B2. Diagram of test section.

and current (Weston ammeter) measurements. A power factor of 1.0 was used since the two measurements agreed within 3.3 percent.

Thermocouple output was measured with a Hewlett Packard digital voltmeter. An ice bath was used as a reference for all of the thermocouples. Thermocouples were selected for measurement using a manual switch. The numbered thermocouples on Fig. B2 were used in the computer program that reduced the experimental data for the heated runs. This computer program is described by a number of people [30,31,32,44]. The unnumbered thermocouples were used to determine the amount of preheating of the gas before it entered the heated section.

Pressure drop in the test section was measured with Meriam 60 inch vertical water or mercury manometers. Inlet static pressure was measured with a Bourdon tube Heise gage.

After the gas passed through the test section, it was cooled by a chilled water counterflow heat exchanger. The valve used to control the flow rate was located just downstream of the heat exchanger. The heat exchanger was necessary in order that a Meriam laminar flow element could be used. The laminar flow element was used to obtain an accurate measurement of the flow rate. A Meriam 60 inch inclined water manometer with a 10 inch range was used to measure pressure drop across the laminar flow element. The temperature of the gas in the flow element was measured with a thermocouple, and the pressure was measured with a Meriam 60 inch vertical mercury manometer. The accuracies of the instruments used in this investigation are listed in appendix C (Table C1).

Procedure

Before any experimental runs with gas flow were performed, the test section was heated without flow in order that the heat lost to the environment and the resistance of the test section could be determined. These items are discussed in detail in the following two sections.

The system was purged and all of the instruments zeroed before each set of experimental runs. The purging was done by pressurizing the system to approximately 100 psig with the gas to be used. The system was then allowed to blow down to approximately 10 psig. This sequence was performed four times.

The desired inlet Reynolds number was established by adjusting the pressure level and mass flow rate. Before power was supplied to the test section, measurements were taken so that calculation of the adiabatic friction coefficient was possible. The measured adiabatic friction coefficients were compared to the Drew, Koo, and McAdams correlation [34] (equation 11), and agreement ensured that the pressure measurements, mass flow rate measurements, and mixture molecular weights were correct.

The test section was then heated to the desired level. Since a small period of time elapsed while the thermocouples were manually recorded, pressure drop, pressure level, voltage, current, and mass flow rate measurements were taken before and after the thermocouple measurements. The average of the two measurements was used for data reduction. The inlet Reynolds number was maintained approximately constant while the test section wall temperature was varied by varying the power input. Measurements were taken for a number of different power inputs.

Heat Loss Calibration

In order to calculate the heat transfer coefficient, the heat addition to the gas, q'_{gas}, must be determined. If an energy balance for a small section of the tube is performed, the result is:

$$q'_{gas} = q'_{gen} - (q'_{cond} + q'_{loss}). \tag{B1}$$

The heat generated in the small section of the tube, q'_{gen}, is:

$$q'_{gen} = I^2R'. \tag{B2}$$

The current was measured, and the calculation of the resistance per unit length is discussed in the next section. The axial heat loss due to conduction is:

$$q'_{cond} = -K\ A_{cs}\ d^2T_w/dx^2. \tag{B3}$$

The second derivative was determined using a numerical parabolic fit described by McEligot [31]. The variation of thermal conductivity with temperature for Hastelloy-X was determined from data supplied by the manufacturer [46].

$$K = [5.1 + (0.00622)(T)](\text{Btu/hr-ft-F}) \qquad \text{(B4)}$$
$$(T \text{ in degrees Fahrenheit})$$

To determine the heat loss, q'_{loss}, the test section was heated at different levels without gas flow. A program described by Coon [32] was used to calculate the heat loss at each thermocouple. The heat loss was determined as a function of the tube wall and environment temperature difference. The environment temperature was measured with a thermocouple a few inches away from the test section. Figures B3, B4, B5, and B6 show the results for each thermocouple (thermocouple 4 is not included). Except for thermocouple three and four, the data for each thermocouple was fitted with an equation of the form:

$$q'_{loss} = C_1(T_w-T_\infty) + C_2(T_w-T_\infty)^2 + C_3(T_w-T_\infty)^3 \quad (\text{Btu/hr-ft}) \qquad \text{(B5)}$$
$$(T_w - T_\infty \text{ in degrees Fahrenheit})$$

The numerical values of C_1, C_2, and C_3 are listed below.

Thermocouple	C_1	C_2	C_3
2	2.43E+00	9.43E-03	-2.53E-05
5	1.22E-01	1.84E-04	-1.64E-08
6	9.83E-02	2.30E-04	-6.57E-08
7	8.84E-02	1.66E-04	-3.79E-09
8	8.30E-02	1.35E-04	3.07E-08
9	8.16E-02	1.03E-04	6.04E-08
10	7.89E-02	1.12E-04	4.96E-08
11	7.70E-02	8.82E-05	7.13E-08
12	7.40E-02	1.03E-04	5.50E-08
13	7.54E-02	8.08E-05	7.59E-08
14	7.31E-02	9.77E-05	5.73E-08
15	8.09E-02	8.07E-05	7.46E-08
16	1.18E-01	1.59E-04	5.59E-08
17	2.76E-01	1.14E-03	1.19E-06

The data for thermocouple three was fitted with a straight line determined using the method of least squares.

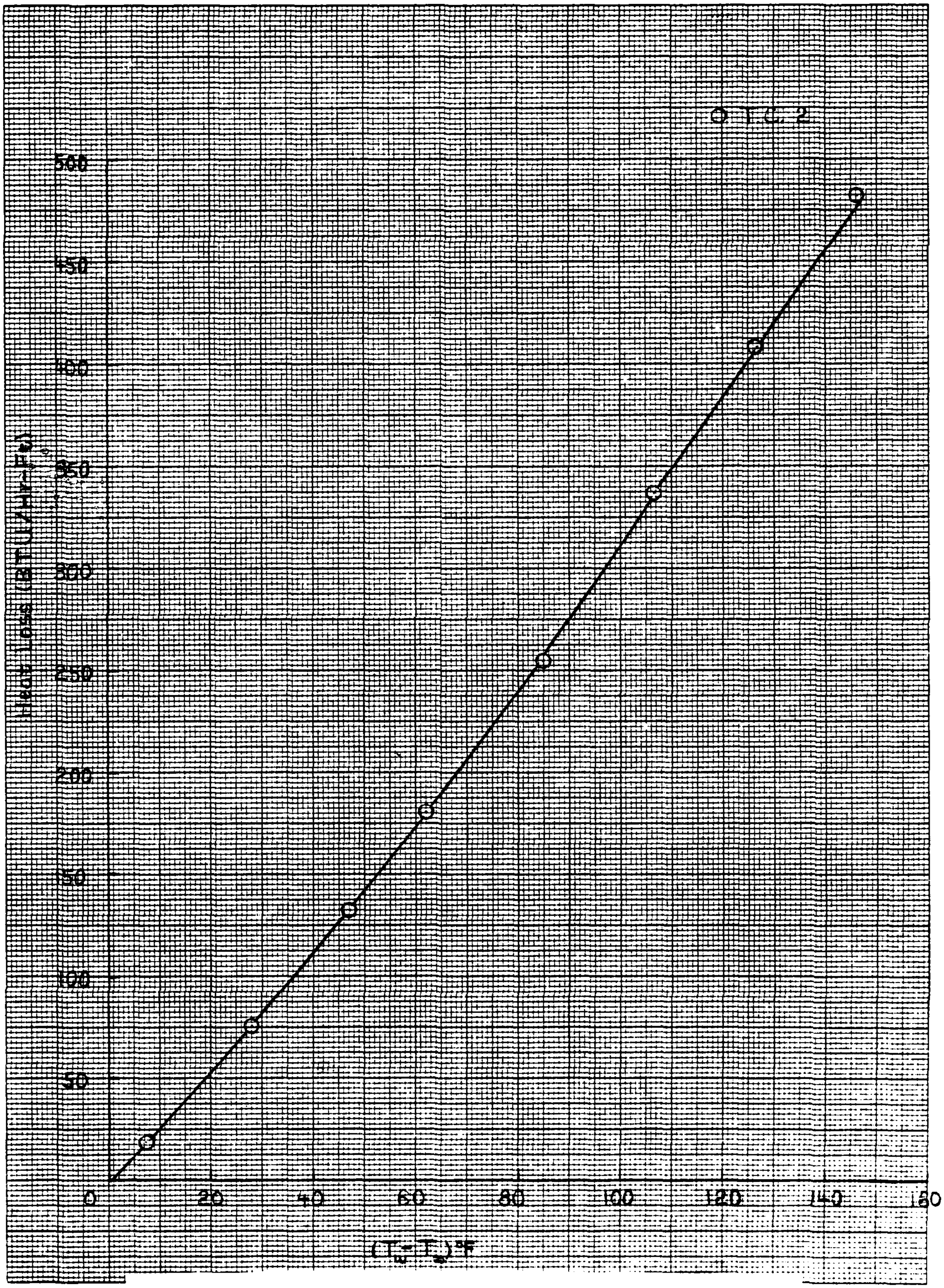


Fig. B3. Heat loss calibration for thermocouple 2.

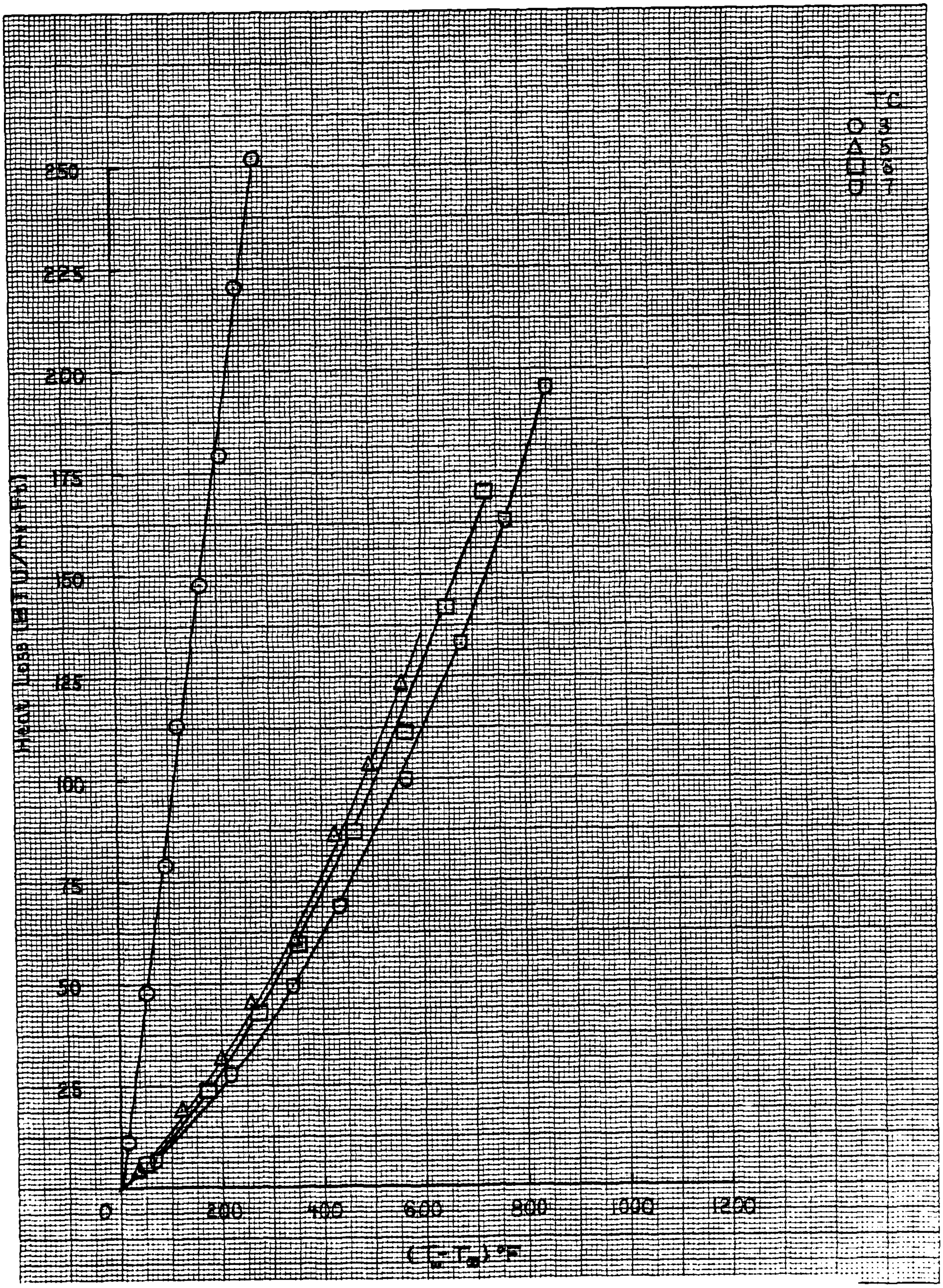


Fig. B4. Heat loss calibration for thermocouples 3, 5, 6, and 7.

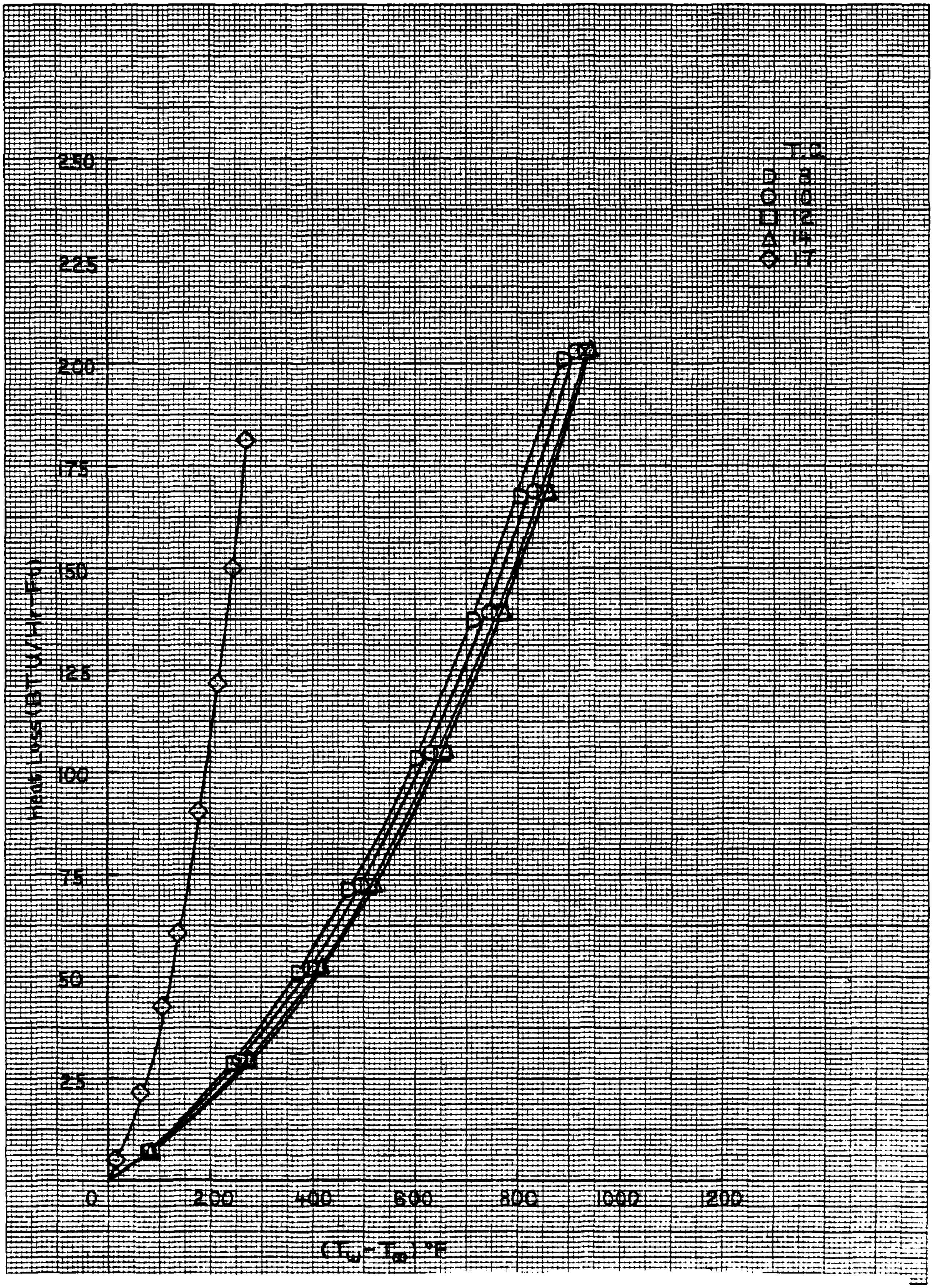


Fig. B5. Heat loss calibration for thermocouples 8, 10, 12, 14, and 17.

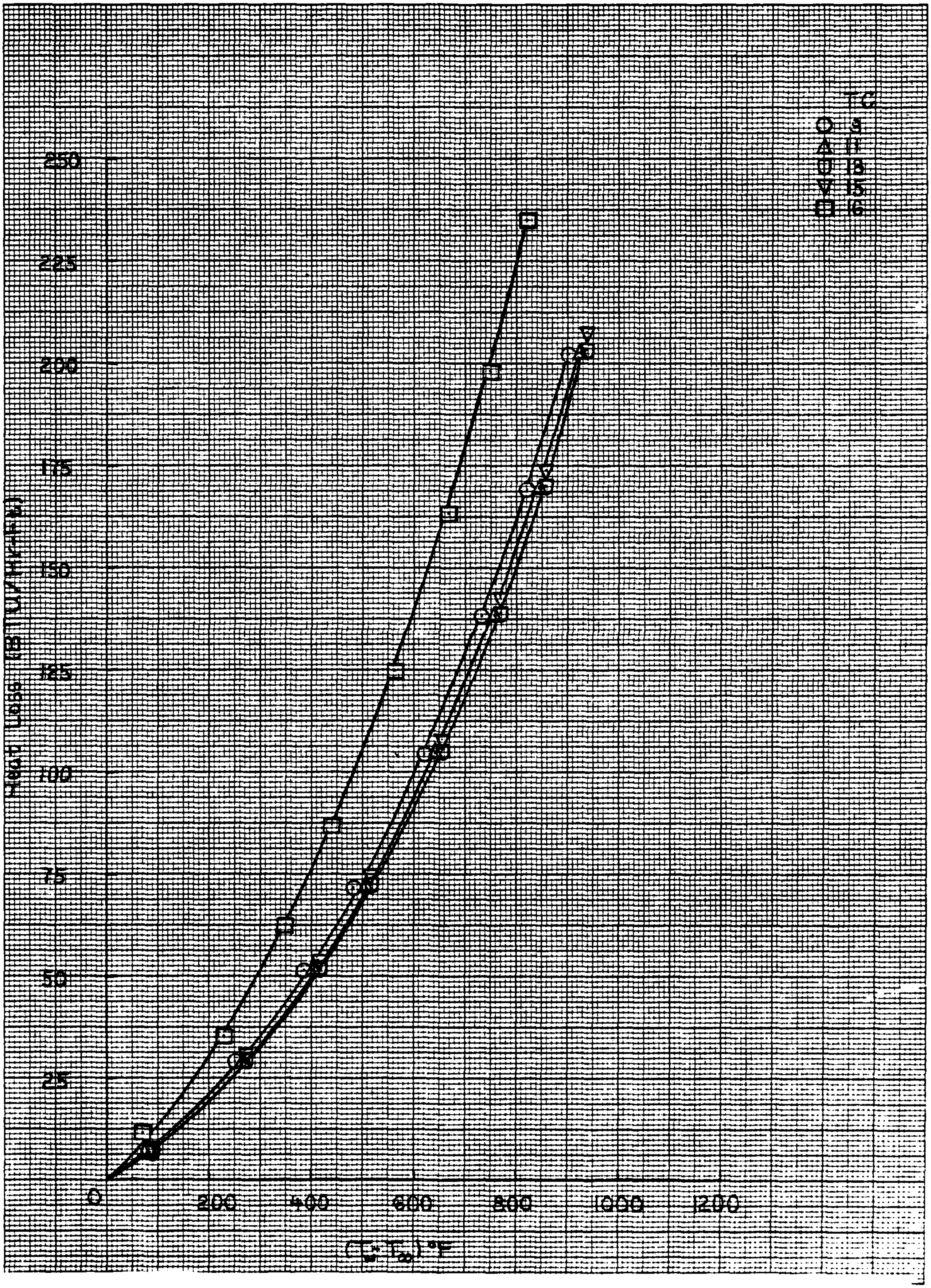


Fig. B6. Heat loss calibration for thermocouples 9, 11, 13, 15, and 16.

$$q'_{loss}(\text{T.C. } 3) = 0.91(T_w - T_\infty) - 2.20(\text{Btu/hr-ft}) \quad \text{(B6)}$$
$$(T_w - T_\infty \text{ in degrees Fahrenheit})$$

The data for thermocouple four was scattered and a representative curve could not be fitted. For this reason the heat loss at this thermocouple was neglected. This introduced only a small error since the heat loss for thermocouple four, even at the highest heating rates, was less than five percent of the heat added to the gas. The fitted curves are also shown on Figures B3, B4, B5, and B6.

Measurement of Test Section Resistance

The variation of resistance with temperature was measured by heating the test section without gas flow in the same manner as was done for the heat loss calibration. Using the thermocouple wires as voltage taps, a measurement of the voltage drop between thermocouple 14 and the lowermost thermocouple on the tube was taken. Another measurement of the voltage drop between thermocouple 12 and the lowermost thermocouple was taken. The difference between these two measurements gave the voltage drop between thermocouples 12 and 14. The section of the tube between thermocouples 12 and 14 was used since the wall temperature for this length was approximately constant.

For a particular power setting the voltage drop discussed in the previous paragraph, the current, and the average of the temperatures at thermocouples 12, 13, and

14 were recorded. Using these measurements the resistance per unit length was determined as a function of temperature. The results are shown on Fig. B7. Also shown on Fig. B7 is the line that was used to approximate the variation of resistance with temperature.

$$R' = [3.98 \times 10^{-4}(T) + 4.745] \ (m\Omega/in) \qquad \text{(B7)}$$

(T in degrees Fahrenheit)

Meriam Laminar Flow Element Calibration

The laminar flow element was calibrated using a Parkinson-Cowan Type D1 positive displacement flow meter as a standard. It is specified to have 1/2 percent accuracy at ambient conditions and was calibrated by Tucson Gas and Electric before being used. Meriam [45] suggests the following equation for the laminar flow element:

$$\Delta P = A'Q\mu L/D^4 + B'\rho Q^2/D^4. \qquad \text{(B8)}$$

A' and B' are the constants to be determined by calibration. Since the length, L, and the hydraulic diameter, D, of the laminar flow element passages remain constant, they can be incorporated into new calibration constants, A and B.

$$A = A'L/D^4 \qquad B = B'/D^4$$

Equation B8 now becomes:

$$\Delta P = AQ\mu + B\rho Q^2. \qquad \text{(B9)}$$

If this equation is solved for Q the result is:

$$Q = [-A\mu/B + \sqrt{(A\mu/B)^2 + 4\rho\Delta P/B}]/2\rho. \qquad \text{(B10)}$$

If both sides of this equation are multiplied by the density, ρ, the result is:

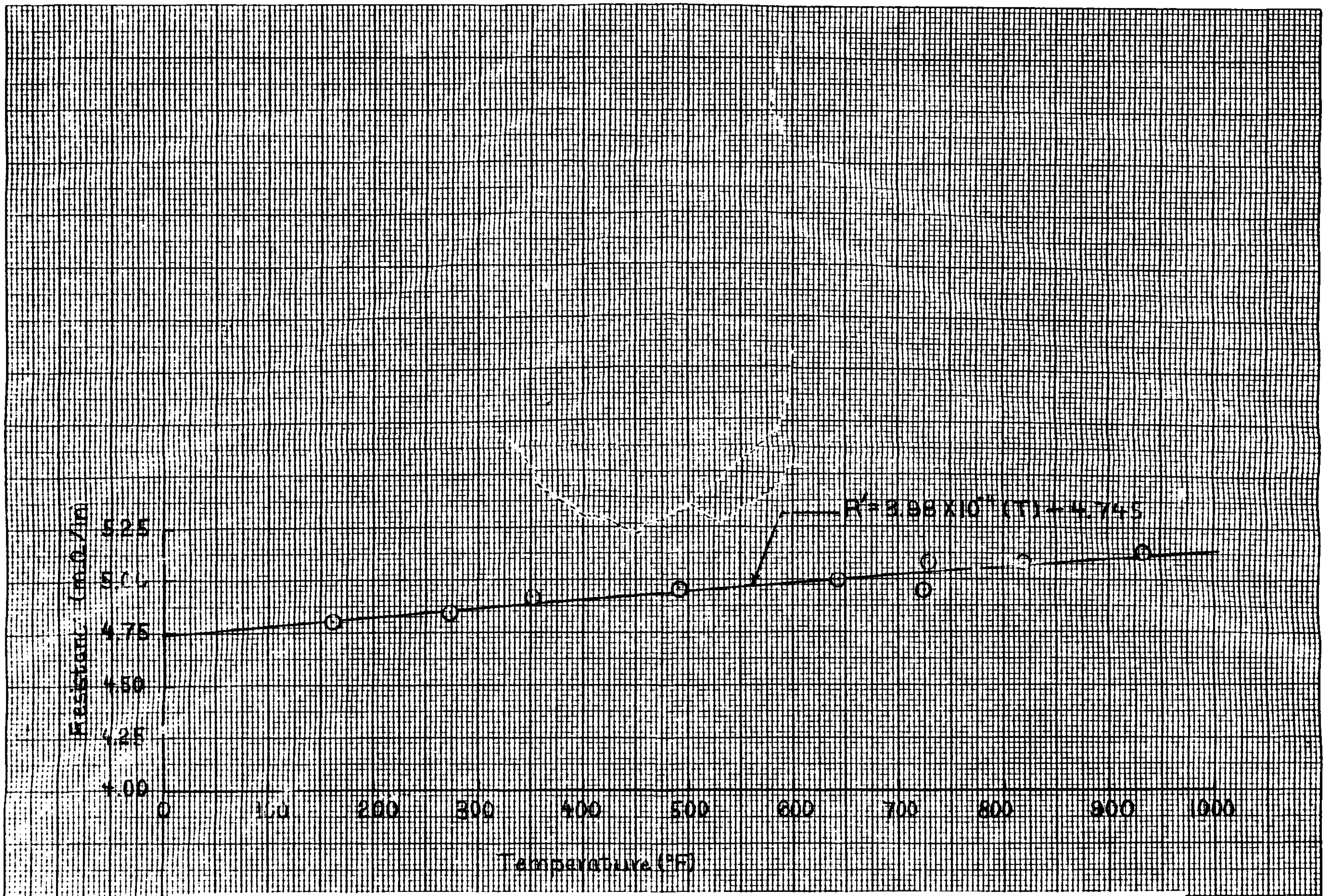


Fig. B7. Variation of test section resistance with respect to temperature.

$$\dot{m} = \rho Q = 1/2[-A\mu/B + \sqrt{(A\mu/B)^2 + 4\rho\Delta P/B}]. \qquad \text{(B11)}$$

Mass flow rate measurements were taken simultaneously with the positive displacement flow meter and the laminar flow element. Both air and helium were used. These gases bound the range of helium-argon mixture molecular weights that were used. From these measurements, A and B were determined so that the maximum difference between the positive displacement flow meter measurements and the laminar flow element measurements was 1.5 percent. The numerical values of A and B were 1375 and 672, respectively, if the parameters in equation B11 have the following units.

m - lb/sec
μ - lb/hr-ft
ρ - lb/ft^3
ΔP - inches of water

APPENDIX C
Uncertainty Analysis

An analysis to determine the uncertainty of the results calculated from the measured experimental data was performed. The uncertainties of the directly measured quantities were determined from manufacturers' specifications and experience. Table C1 lists the uncertainties of the instruments used in this investigation. The error propagated to the calculated results from the uncertainties in the measured quantities was determined using a method described by Bottaccini [47]. The general equation used was

$$\begin{aligned} \sigma_Z^2 = {} & \left(\frac{\partial Z}{\partial Y_i}\right)^2 \sigma_{Y_i}^2 + \left(\frac{\partial Z}{\partial Y_2}\right)^2 \sigma_{Y_2}^2 + \ldots \\ & + \left(\frac{\partial Z}{\partial a_i}\right)^2 \sigma_{a_i}^2 + \left(\frac{\partial Z}{\partial a_2}\right)^2 \sigma_{a_2}^2 + \ldots \end{aligned} \qquad \text{(C1)}$$

σ_x is the variance or standard deviation of the xth quantity. Z is the calculated quantity, and Y_i and a_i are the measured values and system parameters used to calculate Z.

To illustrate the above technique, a simple example will be done. The power supplied to the tube can be determined using the relation (assuming a power factor of one)

$$P = E\ I. \qquad \text{(C2)}$$

If equation C1 is applied, the error or variance in the power caused by uncertainties in the voltage and current measurements is

$$\sigma_P = \sqrt{(I)^2\sigma_E^2 + (E)^2\sigma_I^2}. \qquad (C3)$$

The result can be presented in the following form so that the percent of uncertainty can easily be determined.

$$\sigma_P/P = \sqrt{(\sigma_E/E)^2 + (\sigma_I/I)^2} \qquad (C4)$$

TABLE C1
Uncertainties of Measured Values

Measured quantity	Instrument	Uncertainty
Current	Weston 370 AC/DC ammeter	±0.25% of full scale
Voltage	Fluke 883AB differential voltmeter	±0.1% of input
Mass flow rate	Meriam 50MH10-1 laminar flow element	±1.5% of flow rate
Wall and inlet bulk temperature	Premium grade chromel-alumel thermocouples	±2°F, 3/8% of reading above 535°F
Thermocouple location Pressure tap location	Gaertner M911 Cathetometer	±0.1mm
Diameter	Manufacturers' specifications	±0.001 in.
Pressure	12 inch Heise gage	±0.15 psi
Pressure drop	60" Meriam 30EB25 vertical H_2O manometer 60" Meriam 30EB25 vertical Hg manometer	±0.05 in-H_2O ±0.05 in-Hg

Table C2 lists the percentage uncertainty in the measured bulk Nusselt numbers for two representative helium-argon runs. The dominant uncertainty in the bulk Nusselt number is the bulk stagnation temperature. For convenience no uncertainty was included for the gas properties. The values used were assumed to be precise.

TABLE C2
Percentage Uncertainties in the Measured Bulk Nusselt Numbers of Helium-Argon

Run	126H	131H
Molecular weight	15.30	15.30
Re_i	56100	54700
$(T_w/T_b)_{MAX}$	1.17	1.77
x/D	Percentage Uncertainty	
1.17	13	10
2.07	8	6
4.14	6	4
8.13	5	3
24.52	4	3
40.79	4	3
56.88	4	3

APPENDIX D
Helium-Argon Experimental Data

The headings and their definitions used in the listing of the adiabatic friction data are below.

Heading	Definition
Run	Experiment run number
Date	Date on which experimental run was made
Gas	Gas used in the experiment
Molec. wt.	Molecular weight
T_i	Inlet mixer temperature
$\dot{m}$	Gas flow rate
Re_i	Inlet Reynolds number
P_1	Static pressure at inlet pressure tap
P_2	Static pressure at outlet pressure tap
Static $Mach_1$	Static mach number at inlet pressure tap
Static $Mach_2$	Static mach number at outlet pressure tap
f_{ad}	Adiabatic friction factor

Table D-1 HELIUM-ARGON ADIABATIC FRICTION FACTOR DATA

Run	Date	Gas	Molec. Wt.	T_1 (^oF)	$\dot{m}$ (lb/hr)	Re_1	P_1 (psia)	P_2 (psia)	Static $Mach_1$	Static $Mach_2$	f_{ad}
77A	8/27/75	He	4.003	71.5	3.8	9950	105.4	104.7	0.0521	0.0524	0.00796
81A	8/30/75	He	4.003	72.7	3.7	9660	102.0	101.3	0.0524	0.0527	0.00817
83A	8/30/75	He	4.003	78.0	12.7	32900	80.1	71.6	0.228	0.255	0.00582
85A	9/10/75	He	4.003	75.5	12.5	32500	76.4	67.6	0.235	0.265	0.00586
86A	9/12/75	He-Ar	15.83	72.3	12.3	27800	97.7	96.1	0.0916	0.0931	0.00619
87A	9/12/75	He-Ar	15.83	72.7	24.6	55400	76.0	68.6	0.233	0.258	0.00509
88A	10/ 8/75	He-Ar	15.83	73.0	26.5	59700	74.6	65.4	0.255	0.290	0.00515
91A	10/ 8/75	He-Ar	15.83	72.7	27.7	62400	83.0	74.4	0.240	0.267	0.00503
92A	10/13/75	He-Ar	15.83	72.3	14.1	31700	95.8	93.8	0.106	0.109	0.00607
95A	10/13/75	He-Ar	15.83	72.7	14.1	31800	95.5	93.5	0.107	0.110	0.00597
96A	10/20/75	He-Ar	15.83	72.7	38.3	86100	96.3	82.3	0.285	0.331	0.00468
99A	11/17/75	He-Ar	29.70	70.0	41.8	94200	74.5	63.1	0.293	0.344	0.00458
100A	11/17/75	He-Ar	29.70	70.0	29.9	67300	91.7	87.3	0.172	0.180	0.00493
101A	1/28/76	He-Ar	29.70	71.0	37.0	83200	110.5	105.5	0.176	0.185	0.00447
106A	1/28/76	He-Ar	29.70	72.7	13.9	31100	93.0	91.9	0.0790	0.0799	0.00614
110A	1/29/76	He-Ar	29.70	67.0	14.3	32400	93.4	92.2	0.0810	0.0819	0.00585
113A	2/ 6/76	He-Ar	27.53	73.0	13.5	30200	89.8	88.7	0.0828	0.0838	0.00588
114A	2/ 6/76	He-Ar	27.53	74.0	34.7	77500	110.2	105.0	0.173	0.181	0.00476
115A	2/21/76	He-Ar	27.53	70.5	43.8	98300	96.7	87.1	0.247	0.273	0.00457
121A	2/21/76	He-Ar	27.53	71.0	43.6	97800	95.3	85.5	0.249	0.277	0.00459
122A	3/ 1/76	He-Ar	15.30	70.5	24.7	55700	77.5	70.2	0.232	0.256	0.00497
123A	3/ 1/76	He-Ar	15.30	70.5	14.2	32200	92.8	90.7	0.113	0.115	0.00568

The headings and their definitions used in the listing of the heated flow data are below. The headings that are self-explanatory, or that were used in the listing of the adiabatic friction data are not included.

Heading	Definition
TIN	Inlet mixer temperature
TOUT	Outlet mixer temperature
I	Alternating current
E	Voltage drop between voltage taps
TC	Thermocouple number
X/D	Corresponds to x/D in text
TW	Inside tube wall temperature
TW/TB	Wall-to-bulk temperature ratio
QGAS	Wall heat flux
Q^+	Non-dimensional heat flux parameter. Corresponds to q^+ in text.
PT	Pressure tap: 1-inlet, 2-outlet
TB	Bulk static temperature

```
                 RUN 89HP, DATE 10/08/75, GAS HE-AR, MOLECULAR WT. =  15.83
TIN = 72.8 F, TOUT = 308.7 F, MASS FLOW RATE = 24.1 LB/HR, I = 100.2 AMPS, E =  5.765 VOLTS
PR,IN =  .418, GR/RESQ =   .725E-04, MACH(2) =  .217, MACH(16) =  .305, T,SURR =  75.5 F

TC     X/D      TW        TW/TB      BULK      HL/QGAS     BULK          QGAS          Q+
                (F)                REYNOLDS               NUSSELT      BTU/HRFT2
 2      .1     130.0      1.122     54772.      .062      250.36        57728.3      .001195
 3     1.2     194.6      1.239     54528.      .105      116.28        55763.4      .001144
 4     2.1     224.4      1.290     54334.      .030      101.37        59976.7      .001231
 5     4.1     256.0      1.336     53891.      .020       86.42        60655.1      .001245
 6     8.1     297.5      1.369     53073.      .018       76.37        60965.9      .001251
 7    16.4     319.1      1.374     51479.      .016       71.00        61192.5      .001256
 8    24.5     348.4      1.375     50042.      .018       66.62        61233.2      .001257
 9    32.4     366.7      1.360     48742.      .017       65.88        61329.4      .001259
10    40.8     390.0      1.351     47451.      .019       63.36        61308.0      .001258
11    48.7     407.1      1.336     46315.      .019       63.70        61400.4      .001260
12    56.3     430.6      1.330     45229.      .021       61.64        61359.4      .001259
13    64.8     448.1      1.318     44229.      .022       61.42        61417.9      .001261
14    73.1     472.0      1.313     43249.      .025       59.52        61349.9      .001259
15    81.3     487.3      1.298     42351.      .027       60.07        61282.7      .001258
16    90.1     493.5      1.269     41452.      .044       63.05        60274.0      .001237
17    98.0     435.6      1.165     40749.      .198       92.24        52321.3      .001074

                                     PT     X/D       STATIC        TW/TB       TB        PRESS
                                                   PRESS. (PSIA)               (F)       DEFECT
                                     1      -.5        80.3         1.10       65.5    -.516E-02
                                     2     90.1        67.8         1.27      291.4     .199E+01

                                     AVERAGE PARAMETERS BETWEEN PRESSURE TAPS
               AVERAGE BULK REYNOLDS       AVERAGE WALL REYNOLDS       AVERAGE FRICTION FACTOR
                    48128.                        36951.                         .00554
```

```
                 RUN 90HP, DATE 10/08/75, GAS HE-AR, MOLECULAR WT. =  15.83
TIN = 72.8 F, TOUT = 547.4 F, MASS FLOW RATE = 25.1 LB/HR, I = 142.7 AMPS, E =  8.520 VOLTS
PR,IN =  .418, GR/RESQ =   .166E-03, MACH(2) =  .204, MACH(16) =  .340, T,SURR =  79.5 F

TC     X/D      TW        TW/TB      BULK      HL/QGAS     BULK          QGAS          Q+
                (F)                REYNOLDS               NUSSELT      BTU/HRFT2
 2      .1     199.2      1.248     56716.      .073      232.29       116516.4      .002300
 3     1.2     325.0      1.472     56221.      .105      115.33       114231.8      .002255
 4     2.1     383.0      1.568     55827.      .031      101.32       122912.0      .002425
 5     4.1     444.9      1.651     54951.      .023       86.38       124446.7      .002457
 6     8.1     519.2      1.723     53350.      .023       73.34       125056.8      .002469
 7    16.4     593.1      1.725     50410.      .022       65.08       125787.1      .002483
 8    24.6     653.0      1.708     47907.      .025       59.80       126040.6      .002488
 9    32.5     698.3      1.675     45769.      .026       56.92       126287.1      .002493
10    40.9     745.2      1.642     43763.      .029       54.25       126315.1      .002494
11    48.9     784.6      1.608     42033.      .030       52.55       126508.3      .002497
12    57.0     829.8      1.584     40478.      .034       50.41       126455.6      .002495
13    65.0     864.6      1.551     39108.      .036       49.56       126499.2      .002497
14    73.3     893.2      1.512     37806.      .036       49.66       126498.6      .002497
15    81.5     921.8      1.478     36650.      .042       49.70       126223.4      .002492
16    90.3     928.3      1.422     35538.      .066       51.93       123450.7      .002437
17    98.3     796.6      1.246     34792.      .437       65.98        90759.6      .001792

                                     PT     X/D       STATIC        TW/TB       TB        PRESS
                                                   PRESS. (PSIA)               (F)       DEFECT
                                     1      -.5        88.7         1.19       67.6    -.512E-02
                                     2     90.4        71.5         1.42      516.7     .280E+01

                                     AVERAGE PARAMETERS BETWEEN PRESSURE TAPS
               AVERAGE BULK REYNOLDS       AVERAGE WALL REYNOLDS       AVERAGE FRICTION FACTOR
                    46161.                        30486.                         .00549
```

```
                  RUN 93HF, DATE 10/13/75, GAS HE-AR, MOLECULAR WT. =  15.83
TIN = 72.3 F, TOUT = 348.8 F, MASS FLOW RATE = 14.1 LB/HR, I =  80.0 AMPS, E =  4.535 VOLTS
PR,IN =  .418, GR/RESQ =   .187E-03, MACH(2) =  .107, MACH(16) =  .134, T,SURR =  75.0 F

TC     X/D        TW          TW/TB        BULK       HL/QGAS       BULK             QGAS           Q+
                  (F)                    REYNOLDS                  NUSSELT        BTU/HRFT2
 2       .1      120.3        1.091       31673.        .067        194.11          36616.7        .001289
 3      1.2      178.1        1.193       31523.        .140         83.56          34390.1        .001211
 4      2.1      209.2        1.246       31401.        .054         70.53          37309.7        .001314
 5      4.1      236.1        1.282       31125.        .026         61.97          38384.3        .001351
 6      8.1      257.7        1.313       30607.        .024         54.12          38555.7        .001357
 7     16.4      306.1        1.326       29597.        .024         48.48          38649.4        .001361
 8     24.5      331.3        1.316       28687.        .025         46.71          38705.0        .001363
 9     32.4      355.5        1.307       27872.        .026         45.13          38717.9        .001363
10     40.8      377.9        1.293       27067.        .028         44.32          38702.5        .001363
11     48.7      404.3        1.288       26354.        .031         42.46          38687.9        .001362
12     56.8      421.8        1.271       25679.        .032         42.73          38674.3        .001362
13     64.8      439.8        1.255       25060.        .033         42.92          38684.6        .001362
14     73.1      462.7        1.246       24451.        .037         42.11          38599.9        .001359
15     81.3      482.5        1.234       23885.        .042         41.90          38481.3        .001355
16     90.1      491.9        1.207       23323.        .073         43.63          37399.8        .001317
17     98.0      411.6        1.078       22912.        .273         97.21          31339.4        .001103

                                   PT     X/D       STATIC      TW/TB       TB        PRESS
                                                 PRESS.(PSIA)              (F)       DEFECT
                                    1      -.5       95.9        1.07       71.5    -.589E-02
                                    2     90.1       92.3        1.21      328.7     .197E+01

                              AVERAGE PARAMETERS BETWEEN PRESSURE TAPS
          AVERAGE BULK REYNOLDS       AVERAGE WALL REYNOLDS       AVERAGE FRICTION FACTOR
               27508.                        22429.                        .00638
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                  RUN 94HF, DATE 10/13/75, GAS HE-AR, MOLECULAR WT. =  15.83
TIN = 72.8 F, TOUT = 583.2 F, MASS FLOW RATE = 14.1 LB/HR, I = 118.6 AMPS, E =  7.085 VOLTS
PR,IN =  .418, GR/RESQ =   .407E-03, MACH(2) =  .107, MACH(16) =  .161, T,SURR =  73.5 F

TC     X/D        TW          TW/TB        BULK       HL/QGAS       BULK             QGAS           Q+
                  (F)                    REYNOLDS                  NUSSELT        BTU/HRFT2
 2       .1      199.0        1.234       31584.        .093        158.74          79013.0        .002775
 3      1.2      322.9        1.449       31259.        .148         77.42          75890.4        .002667
 4      2.1      390.9        1.560       31001.        .053         66.89          83189.3        .002923
 5      4.1      462.6        1.652       30411.        .037         56.25          84907.8        .002984
 6      8.1      544.2        1.720       29343.        .036         47.47          85470.4        .003003
 7     16.4      635.2        1.721       27407.        .037         41.08          85947.1        .003020
 8     24.6      705.5        1.693       25803.        .041         37.37          85991.8        .003022
 9     32.5      754.9        1.644       24462.        .043         35.69          86094.4        .003025
10     40.9      803.9        1.595       23203.        .048         34.25          85989.1        .003022
11     48.9      852.3        1.556       22169.        .052         33.00          85945.7        .003020
12     57.0      892.4        1.511       21237.        .057         32.47          85817.6        .003015
13     65.0      924.8        1.464       20417.        .059         32.62          85795.5        .003014
14     73.4      969.3        1.430       19640.        .066         32.01          85537.3        .003006
15     81.5     1006.2        1.395       18924.        .074         31.88          85060.9        .002983
16     90.4     1015.7        1.335       18282.        .119         33.33          81739.7        .002872
17     98.4      831.7        1.130       17894.        .885         49.25          47896.7        .001683

                                   PT     X/D       STATIC      TW/TB       TB        PRESS
                                                 PRESS.(PSIA)              (F)       DEFECT
                                    1      -.5       95.8        1.18       73.2    -.589E-02
                                    2     90.4       90.4        1.33      545.4     .300E+01

                              AVERAGE PARAMETERS BETWEEN PRESSURE TAPS
          AVERAGE BULK REYNOLDS       AVERAGE WALL REYNOLDS       AVERAGE FRICTION FACTOR
               24956.                        17318.                        .00655
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                       RUN 98HP, DATE 10/20/75, GAS HE-AR, MOLECULAR WT. =  15.83
TIN = 73.2 F, TOUT = 570.4 F, MASS FLOW RATE = 30.8 LB/HR, I = 160.9 AMPS, E =  9.670 VOLTS
PR,IN =  .418, GR/RESQ =   .213E-03, MACH(2) =  .204, MACH(16)  =  .340, T,SURR =  79.0 F

TC     X/D       TW         TW/TB       BULK      HL/QGAS     BULK          QGAS          Q+
                 (F)                  REYNOLDS              NUSSELT      BTU/HRFT2
 2       .1     235.9       1.259      59554.       .058      285.58      150418.8      .002417
 3      1.2     350.4       1.517      68910.       .092      135.09      147299.2      .002366
 4      2.1     418.9       1.631      68401.       .029      115.83      157043.5      .002523
 5      4.1     490.3       1.729      67285.       .022       97.85      158841.7      .002552
 6      9.1     559.8       1.787      65254.       .020       85.50      160013.2      .002571
 7     16.4     641.1       1.791      61530.       .020       75.28      160888.0      .002585
 8     24.6     705.7       1.772      58370.       .022       68.94      161295.3      .002591
 9     32.5     759.6       1.744      55688.       .024       64.72      161619.2      .002597
10     40.9     809.6       1.707      53172.       .026       61.55      161776.9      .002599
11     48.9     859.6       1.680      51003.       .029       58.48      161951.9      .002602
12     57.0     894.3       1.636      49083.       .030       57.53      162082.3      .002604
13     65.0     931.9       1.601      47376.       .033       56.32      162139.7      .002605
14     73.4     970.6       1.568      45758.       .035       55.27      162139.8      .002605
15     81.5     996.8       1.527      44325.       .039       55.60      161899.3      .002601
16     90.4    1002.0       1.465      42947.       .059       57.99      158784.5      .002551
17     98.4     861.7       1.282      41994.       .407       71.18      118411.6      .001902

                                  PT     X/D       STATIC     TW/TB      TB       PRESS
                                                PRESS.(PSIA)            (F)      DEFECT
                                   1     -.5       109.4      1.20      68.2    -.488E-02
                                   2    90.4        88.7      1.46     537.9     .275E+01

                                  AVERAGE PARAMETERS BETWEEN PRESSURE TAPS
               AVERAGE BULK REYNOLDS    . AVERAGE WALL REYNOLDS     AVERAGE FRICTION FACTOR
                     56296.                     36396.                      .00517
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                       RUN 97HP, DATE 10/20/75, GAS HE-AR, MOLECULAR WT. =  15.83
TIN = 72.3 F, TOUT = 298.2 F, MASS FLOW RATE = 35.3 LB/HR, I = 117.2 AMPS, E =  5.790 VOLTS
PR,IN =  .418, GR/RESQ =   .336E-04, MACH(2) =  .238, MACH(16)  =  .337, T,SURR =  75.0 F

TC     X/D       TW         TW/TB       BULK      HL/QGAS     BULK          QGAS          Q+
                 (F)                  REYNOLDS              NUSSELT      BTU/HRFT2
 2       .1     131.5       1.129      80349.       .049      333.86       79993.4      .001124
 3      1.2     199.2       1.253      80006.       .078      156.22       78204.2      .001099
 4      2.1     231.6       1.309      79735.       .024      132.51       82555.1      .001160
 5      4.1     264.6       1.359      79124.       .017      112.68       83345.5      .001171
 6      9.1     291.3       1.385      77995.       .013      102.45       83824.7      .001179
 7     16.4     321.0       1.389      75803.       .012       95.65       84077.0      .001181
 8     24.5     351.3       1.396      73808.       .013       89.06       84153.5      .001182
 9     32.4     366.9       1.379      71996.       .013       88.74       84302.6      .001184
10     40.8     390.2       1.373      70209.       .014       85.66       84314.8      .001184
11     48.7     408.2       1.361      68614.       .014       84.61       84435.8      .001186
12     56.8     433.1       1.360      67089.       .016       81.05       84434.7      .001186
13     64.8     452.9       1.352      65693.       .017       79.45       84496.5      .001187
14     73.1     468.2       1.337      64312.       .017       79.78       84511.9      .001187
15     81.3     486.2       1.328      63048.       .020       78.99       84428.2      .001186
16     90.1     488.0       1.295      61787.       .031       84.33       83508.6      .001173
17     98.0     447.8       1.213      60798.       .159      105.05       74059.2      .001040

                                  PT     X/D       STATIC     TW/TB      TB       PRESS
                                                PRESS.(PSIA)            (F)      DEFECT
                                   1     -.5       106.9      1.10      63.5    -.473E-02
                                   2    90.1        98.5      1.29     272.3     .193E+01

                                  AVERAGE PARAMETERS BETWEEN PRESSURE TAPS
               AVERAGE BULK REYNOLDS      AVERAGE WALL REYNOLDS     AVERAGE FRICTION FACTOR
                     71091.                     53547.                      .00491
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                  RUN 102H, DATE 01/28/76, GAS HE-AR, MOLECULAR WT. =  29.70
TIN = 70.1 F, TOUT = 573.9 F, MASS FLOW RATE = 36.4 LB/HR, I = 127.8 AMPS, E =  7.670 VOLTS
PR,IN =  .486, GR/RESQ =   .755E-03, MACH(2) =  .173, MACH(16) =  .258, T,SURR =  77.0 F

TC     X/D        TW         TW/TB       BULK       HL/QGAS     BULK           QGAS           Q+
                  (F)                  REYNOLDS                NUSSELT       BTU/HRFT2
 2       .1      197.7       1.246      82080.       .074      403.77         93352.5       .002397
 3      1.2      353.3       1.526      81302.       .157      171.51         87626.9       .002250
 4      2.1      429.8       1.656      80694.       .052      149.61         96930.4       .002449
 5      4.1      497.2       1.747      79314.       .034      129.60         99071.8       .002543
 6      8.1      573.2       1.815      76799.       .033      111.67         99727.5       .002563
 7     16.4      663.5       1.832      72178.       .034       96.47        100240.4       .002573
 8     24.6      726.4       1.807      68290.       .037       88.45        100391.2       .002577
 9     32.5      776.3       1.770      64994.       .040       83.42        100492.6       .002580
10     40.9      820.5       1.723      61915.       .043       79.88        100454.8       .002579
11     48.9      864.9       1.687      59322.       .046       76.59        100466.7       .002579
12     57.0      903.3       1.646      56964.       .050       74.42        100362.5       .002577
13     65.0      931.0       1.599      54893.       .052       74.06        100379.9       .002577
14     73.4      969.6       1.565      52922.       .057       72.35        100180.5       .002572
15     81.5      993.6       1.520      51185.       .062       72.78         99864.0       .002564
16     90.4      999.8       1.458      49522.       .098       74.44         96569.4       .002479
17     98.4      786.6       1.205      48437.       .568      114.98         66686.2       .001712

                                    PT     X/D       STATIC      TW/TB        TB        PRESS
                                                  PRESS.(PSIA)               (F)       DEFECT
                                     1      -.5       110.6       1.20        67.0    -.470E-02
                                     2     90.4        97.1       1.46       541.2     .245E+01


                  RUN 103H, DATE 01/28/76, GAS HE-AR, MOLECULAR WT. =  29.70
TIN = 71.0 F, TOUT = 471.8 F, MASS FLOW RATE = 36.2 LB/HR, I = 113.8 AMPS, E =  6.715 VOLTS
PR,IN =  .486, GR/RESQ =   .593E-03, MACH(2) =  .173, MACH(16) =  .251, T,SURR =  80.0 F

TC     X/D        TW         TW/TB       BULK       HL/QGAS     BULK           QGAS           Q+
                  (F)                  REYNOLDS                NUSSELT       BTU/HRFT2
 2       .1      191.6       1.234      81602.       .109      326.29         71673.1       .001847
 3      1.2      299.7       1.428      81002.       .146      169.15         69860.6       .001800
 4      2.1      354.5       1.521      80522.       .046      150.74         76889.8       .001982
 5      4.1      412.7       1.604      79421.       .035      127.99         77996.3       .002013
 6      8.1      462.8       1.646      77393.       .029      114.59         78785.5       .002030
 7     16.4      526.0       1.655      73587.       .029      101.97         79123.1       .002039
 8     24.5      574.6       1.642      70293.       .031       94.48         79231.0       .002042
 9     32.4      610.7       1.614      67433.       .032       90.55         79364.3       .002045
10     40.8      649.4       1.588      64701.       .035       86.49         79300.6       .002044
11     48.8      682.5       1.561      62360.       .037       83.90         79390.5       .002045
12     56.9      715.0       1.534      60196.       .040       81.57         79301.2       .002044
13     64.9      740.6       1.502      58258.       .041       80.88         79336.5       .002045
14     73.3      767.8       1.472      56404.       .045       80.13         79237.5       .002042
15     81.5      793.0       1.443      54743.       .050       79.75         79005.6       .002036
16     90.3      799.1       1.393      53137.       .082       82.02         76660.3       .001976
17     98.2      634.9       1.175      52034.       .382      144.05         59365.5       .001530

                                    PT     X/D       STATIC      TW/TB        TB        PRESS
                                                  PRESS.(PSIA)               (F)       DEFECT
                                     1      -.5       110.0       1.19        67.4    -.471E-02
                                     2     90.3        98.3       1.39       444.1     .212E+01

                           AVERAGE PARAMETERS BETWEEN PRESSURE TAPS
          AVERAGE BULK REYNOLDS      AVERAGE WALL REYNOLDS      AVERAGE FRICTION FACTOR
                67411.                      45005.                        .00483
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                 RUN 104H, DATE 01/28/76, GAS HE-AR, MOLECULAR WT. =  29.70
TIN = 72.3 F, TOUT = 305.7 F, MASS FLOW RATE = 36.2 LB/HR, I =  87.4 AMPS, E =  5.020 VOLTS
PR,IN =  .486, GR/RESQ =   .348E-03, MACH(2) =  .173, MACH(16) =  .223, T,SURR =  80.0 F

TC     X/D       TW         TW/TB       BULK      HL/QGAS     BULK          QGAS           Q+
                 (F)                  REYNOLDS               NUSSELT      BTU/HRFT2
 2       .1     149.3       1.153      81625.      .119      295.35        41733.4       .001072
 3      1.2     208.2       1.259      81275.      .141      167.11        41120.4       .001056
 4      2.1     237.5       1.309      80994.      .042      151.83        45115.3       .001159
 5      4.1     264.5       1.347      80344.      .026      135.08        45939.1       .001180
 6      8.1     293.8       1.377      79119.      .023      121.02        46169.8       .001186
 7     16.4     329.5       1.390      76716.      .022      109.88        46304.3       .001190
 8     24.5     355.5       1.387      74536.      .023      104.34        46353.7       .001191
 9     32.4     374.3       1.374      72577.      .023      102.42        46423.2       .001193
10     40.8     398.9       1.368      70620.      .026       98.20        46381.5       .001192
11     48.7     421.0       1.361      68880.      .027       95.15        46416.0       .001192
12     56.8     439.4       1.348      67234.      .028       93.75        46389.1       .001192
13     64.8     455.6       1.333      65708.      .029       93.40        46417.5       .001192
14     73.1     475.9       1.323      64201.      .032       91.55        46346.5       .001191
15     81.3     492.0       1.309      62827.      .036       91.29        46244.0       .001188
16     90.1     496.1       1.278      61452.      .060       95.16        45192.9       .001161
17     98.0     414.5       1.142      60411.      .225      161.89        38861.3       .000998

                              PT     X/D       STATIC      TW/TB       TB       PRESS
                                            PRESS.(PSIA)              (F)      DEFECT
                               1      -.5      110.1       1.12       68.0   -.471E-02
                               2     90.1      101.1       1.28      288.4    .162E+01

                              AVERAGE PARAMETERS BETWEEN PRESSURE TAPS
            AVERAGE BULK REYNOLDS      AVERAGE WALL REYNOLDS      AVERAGE FRICTION FACTOR
                  71562.                      53128.                      .00484




                 RUN 105H, DATE 01/28/76, GAS HE-AR, MOLECULAR WT. =  29.70
TIN = 71.9 F, TOUT = 197.5 F, MASS FLOW RATE = 36.3 LB/HR, I =  64.9 AMPS, E =  3.585 VOLTS
PR,IN =  .486, GR/RESQ =   .193E-03, MACH(2) =  .173, MACH(16) =  .204, T,SURR =  79.5 F

TC     X/D       TW         TW/TB       BULK      HL/QGAS     BULK          QGAS           Q+
                 (F)                  REYNOLDS               NUSSELT      BTU/HRFT2
 2       .1     118.1       1.096      81892.      .119      268.31        22971.3       .000590
 3      1.2     147.5       1.149      81699.      .136      164.83        22663.3       .000582
 4      2.1     161.3       1.173      81541.      .028      155.74        25079.0       .000644
 5      4.1     177.1       1.186      81177.      .025      135.57        25186.5       .000647
 6      8.1     189.7       1.208      80493.      .018      126.54        25382.8       .000652
 7     16.4     207.6       1.216      79108.      .018      117.60        25418.4       .000653
 8     24.5     221.9       1.218      77799.      .018      112.70        25428.0       .000653
 9     32.4     233.2       1.215      76596.      .019      110.75        25442.0       .000653
10     40.7     246.7       1.215      75357.      .020      107.18        25419.6       .000653
11     48.7     257.9       1.212      74225.      .021      105.46        25432.2       .000653
12     56.8     269.2       1.209      73129.      .022      103.81        25414.1       .000653
13     64.7     278.2       1.202      72086.      .023      104.13        25421.3       .000653
14     73.1     290.3       1.200      71032.      .025      101.97        25385.4       .000652
15     81.2     298.9       1.193      70048.      .028      102.70        25328.5       .000650
16     90.0     300.7       1.175      69037.      .046      108.99        24836.6       .000639
17     97.9     262.1       1.098      68229.      .145      182.22        22686.8       .000582

                              PT     X/D       STATIC      TW/TB       TB       PRESS
                                            PRESS.(PSIA)              (F)      DEFECT
                               1      -.5      110.5       1.08       67.2   -.471E-02
                               2     90.0      103.3       1.17      187.7    .130E+01

                              AVERAGE PARAMETERS BETWEEN PRESSURE TAPS
            AVERAGE BULK REYNOLDS      AVERAGE WALL REYNOLDS      AVERAGE FRICTION FACTOR
                  75477.                      61625.                      .00480
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                    RUN 107H, DATE 01/28/76, GAS HE-AR, MOLECULAR WT. =  29.70
TIN = 72.8 F, TOUT = 709.6 F, MASS FLOW RATE = 13.9 LB/HR, I =  90.0 AMPS, E =  5.370 VOLTS
PR,IN =  .486, GR/RESQ =   .153E-02, MACH(2) =  .083, MACH(16) =  .123, T,SUBB =  79.5 F

TC     X/D       TW        TW/TB       BULK      HL/QGAS     BULK          QGAS          Q+
                 (F)                 REYNOLDS              NUSSELT      BTU/HRFT2
 2       .1     190.6      1.216      31054.      .115      209.01        44574.7      .002976
 3      1.2     326.7      1.454      30713.      .273       86.07        39412.0      .002631
 4      2.1     411.0      1.594      30439.      .118       74.00        45145.0      .003014
 5      4.1     498.1      1.711      29799.      .077       61.81        47167.0      .003149
 6      8.1     591.6      1.792      28043.      .073       51.61        47659.6      .003182
 7     16.4     694.5      1.795      26570.      .076       43.93        47860.4      .003195
 8     24.6     763.8      1.753      24880.      .084       40.09        47739.3      .003187
 9     32.5     816.7      1.699      23484.      .090       37.93        47630.8      .003180
10     40.9     862.4      1.636      22208.      .099       36.57        47402.5      .003165
11     48.9     903.7      1.582      21155.      .105       35.71        47285.2      .003157
12     57.0     944.7      1.533      20215.      .114       34.94        47010.1      .003139
13     65.0     978.6      1.484      19396.      .122       34.84        46812.6      .003125
14     73.4    1015.0      1.439      18621.      .131       34.74        46536.3      .003107
15     81.6    1043.2      1.394      17947.      .146       35.18        46017.5      .003072
16     90.4    1049.3      1.331      17328.      .239       35.66        42564.3      .002843
17     98.4     739.5      1.026      17003.     1.463      255.03        20977.5      .001401

                              PT     X/D        STATIC       TW/TB      TB       PRESS
                                             PRESS.(PSIA)              (F)      DEFECT
                               1     -.5         89.1        1.18      74.0   -.591E-02
                               2    90.4         86.1        1.33     674.0    .297E+01

                              AVERAGE PARAMETERS BETWEEN PRESSURE TAPS
           AVERAGE BULK REYNOLDS      AVERAGE WALL REYNOLDS      AVERAGE FRICTION FACTOR
                 24213.                      16879.                       .00642


                    RUN 108H, DATE 01/28/76, GAS HE-AR, MOLECULAR WT. =  29.70
TIN = 73.2 F, TOUT = 519.7 F, MASS FLOW RATE = 14.0 LB/HR, I =  75.1 AMPS, E =  4.320 VOLTS
PR,IN =  .486, GR/RESQ =   .106E-02, MACH(2) =  .083, MACH(16) =  .113, T,SUBB =  80.0 F

TC     X/D       TW        TW/TB       BULK      HL/QGAS     BULK          QGAS          Q+
                 (F)                 REYNOLDS              NUSSELT      BTU/HRFT2
 2       .1     168.6      1.177      31204.      .180      168.79        29260.3      .001945
 3      1.2     254.2      1.326      30974.      .265       84.21        27464.7      .001825
 4      2.1     306.1      1.413      30783.      .102       75.72        31662.7      .002105
 5      4.1     360.4      1.487      30329.      .066       64.54        32856.8      .002184
 6      8.1     414.5      1.534      29489.      .056       56.27        33280.0      .002212
 7     16.4     490.8      1.544      27915.      .058       49.23        33380.3      .002219
 8     24.5     526.7      1.524      26566.      .062       45.93        33377.5      .002218
 9     32.4     566.0      1.499      25407.      .066       43.74        33345.6      .002216
10     40.8     599.5      1.464      24312.      .072       42.58        33242.9      .002210
11     48.8     635.5      1.439      23377.      .076       41.14        33176.1      .002205
12     56.9     662.7      1.405      22520.      .082       40.90        33071.3      .002198
13     64.9     690.9      1.376      21758.      .086       40.67        33008.9      .002194
14     73.3     723.3      1.352      21030.      .096       39.93        32776.7      .002179
15     81.4     745.4      1.321      20384.      .105       40.59        32558.9      .002164
16     90.2     756.7      1.279      19770.      .191       40.47        30236.4      .002010
17     98.2     551.6      1.033      19389.      .759      243.12        20186.9      .001342

                              PT     X/D        STATIC       TW/TB      TB       PRESS
                                             PRESS.(PSIA)              (F)      DEFECT
                               1     -.5         88.9        1.14      73.6   -.590E-02
                               2    90.2         86.5        1.28     491.6    .239E+01

                              AVERAGE PARAMETERS BETWEEN PRESSURE TAPS
           AVERAGE BULK REYNOLDS      AVERAGE WALL REYNOLDS      AVERAGE FRICTION FACTOR
                 25502.                      18693.                       .00627
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                  RUN 109H, DATE 01/28/76, GAS HE-AR, MOLECULAR WT. =   29.70
TIN = 74.1 F, TOUT = 361.3 F, MASS FLOW RATE = 13.9 LB/HR, I =  60.0 AMPS, E =  3.300 VOLTS
PR,IN =  .486, GR/RESQ =    .681E-03, MACH(2) =  .083, MACH(16) =  .103, T,SURR =  80.7 F

TC     X/D       TW         TW/TB       BULK       HL/QGAS      BULK           QGAS         Q+
                 (F)                  REYNOLDS                NUSSELT       BTU/HRFT2
 2       .1     139.2       1.121      31140.       .197       154.86         18371.4     .001222
 3      1.2     190.3       1.211      30995.       .256        83.98         17579.7     .001159
 4      2.1     220.8       1.262      30872.       .090        77.30         20293.9     .001349
 5      4.1     251.8       1.305      30578.       .053        67.56         21071.6     .001401
 6      8.1     286.5       1.340      30020.       .047        58.82         21225.7     .001411
 7     16.4     323.3       1.346      28945.       .046        53.72         21314.3     .001417
 8     24.5     350.8       1.337      27983.       .047        51.31         21324.8     .001418
 9     32.4     377.3       1.329      27121.       .051        49.09         21292.0     .001416
10     40.8     397.8       1.309      26276.       .054        48.71         21263.6     .001414
11     48.7     423.0       1.300      25534.       .058        47.04         21225.5     .001411
12     56.8     442.3       1.283      24835.       .062        46.37         21170.3     .001408
13     64.8     460.3       1.265      24198.       .064        47.11         21159.7     .001407
14     73.1     481.9       1.252      23573.       .071        46.55         21051.3     .001400
15     81.3     500.6       1.237      23005.       .080        46.52         20897.9     .001390
16     90.1     504.2       1.203      22452.       .145        48.68         19730.9     .001312
17     98.0     384.0       1.028      22064.       .429    .  299.26         15665.4     .001042

                                    PT     X/D      STATIC      TW/TB       TB       PRESS
                                                 PRESS.(PSIA)              (F)       DEFECT
                                     1     -.5       89.1        1.10       73.9   -.591E-02
                                     2     90.1      87.1        1.20      341.5    .191E+01

                                  AVERAGE PARAMETERS BETWEEN PRESSURE TAPS
                AVERAGE BULK REYNOLDS      AVERAGE WALL REYNOLDS      AVERAGE FRICTION FACTOR
                      26805.                        21228.                         .00612


                  RUN 111H, DATE 01/29/76, GAS HE-AR, MOLECULAR WT. =   29.70
TIN = 67.0 F, TOUT = 247.1 F, MASS FLOW RATE = 14.2 LB/HR, I =  48.0 AMPS, E =  2.820 VOLTS
PR,IN =  .486, GR/RESQ =    .446E-03, MACH(2) =  .084, MACH(16) =  .097, T,SURR =  72.0 F

TC     X/D       TW         TW/TB       BULK       HL/QGAS      BULK           QGAS         Q+
                 (F)                  REYNOLDS                NUSSELT       BTU/HRFT2
 2       .1     101.7       1.067      32094.       .116       201.07         12579.6     .000833
 3      1.2     139.0       1.134      31993.       .269        86.56         11087.9     .000734
 4      2.1     160.0       1.170      31911.       .095        78.39         12874.2     .000852
 5      4.1     179.7       1.199      31718.       .048        69.21         13474.3     .000892
 6      8.1     201.9       1.223      31345.       .042        60.50         13576.4     .000899
 7     16.4     227.2       1.234      30601.       .041        54.85         13607.2     .000901
 8     24.5     245.2       1.233      29918.       .042        52.62         13609.5     .000901
 9     32.4     261.4       1.229      29286.       .045        51.03         13595.0     .000900
10     40.7     276.8       1.223      28656.       .048        50.07         13565.2     .000898
11     48.7     292.1       1.218      28084.       .050        48.99         13557.2     .000897
12     56.8     307.0       1.212      27536.       .054        48.07         13514.3     .000895
13     64.7     319.3       1.203      27022.       .056        48.15         13507.5     .000894
14     73.1     334.4       1.198      26513.       .062        47.30         13449.8     .000890
15     81.2     348.1       1.191      26039.       .071        46.68         13350.4     .000884
16     90.0     352.7       1.171      25572.       .130        47.67         12651.5     .000838
17     97.9     266.0       1.027      25217.       .286       280.55         11048.9     .000731

                                    PT     X/D      STATIC      TW/TB       TB       PRESS
                                                 PRESS.(PSIA)              (F)       DEFECT
                                     1     -.5       89.4        1.05       66.5   -.587E-02
                                     2     90.0      87.7        1.17      234.1    .158E+01

                                  AVERAGE PARAMETERS BETWEEN PRESSURE TAPS
                AVERAGE BULK REYNOLDS      AVERAGE WALL REYNOLDS      AVERAGE FRICTION FACTOR
                      28839.                        24231.                         .00593
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                  RUN 112H, DATE 01/29/76, GAS HE-AR, MOLECULAR WT. =  29.70
TIN = 67.9 F, TOUT = 182.9 F, MASS FLOW RATE = 14.2 LB/HR, I =  38.4 AMPS, E =  2.250 VOLTS
PR,IN =  .486, GR/RESQ =   .284E-03, MACH(2) =  .084, MACH(16) =  .093, T,SURR =  72.3 F

TC     X/D       TW        TW/TB       BULK       HL/QGAS      BULK            QGAS         Q+
                 (F)                 REYNOLDS                NUSSELT        BTU/HRFT2
 2       .1     95.6       1.054      32001.       .172       151.80          7658.6      .000507
 3      1.2    116.4       1.091      31938.       .227        84.67          7331.5      .000486
 4      2.1    129.6       1.114      31884.       .067        75.75          8283.5      .000549
 5      4.1    142.5       1.133      31759.       .050        66.48          8530.1      .000568
 6      8.1    153.9       1.144      31520.       .036        61.16          8705.5      .000577
 7     16.4    170.7       1.154      31032.       .038        55.38          8702.2      .000576
 8     24.5    182.5       1.155      30571.       .039        53.28          8698.6      .000576
 9     32.3    192.1       1.153      30141.       .040        52.53          8693.5      .000576
10     40.7    202.5       1.151      29702.       .044        51.48          8670.0      .000574
11     48.7    211.7       1.147      29296.       .044        51.12          8670.9      .000574
12     56.8    222.9       1.148      28900.       .049        49.42          8636.6      .000572
13     64.7    230.5       1.142      28528.       .050        49.90          8633.2      .000572
14     73.0    240.0       1.139      28147.       .054        49.45          8607.2      .000570
15     81.2    249.9       1.137      27790.       .064        48.35          8536.4      .000565
16     89.9    253.5       1.125      27432.       .116        49.39          8140.6      .000539
17     97.9    200.1       1.027      27149.       .234       217.49          7332.2      .000486

                           PT     X/D       STATIC      TW/TB       TB        PRESS
                                         PRESS.(PSIA)              (F)       DEFECT
                            1      -.5       89.3        1.04      67.1    -.587E-02
                            2     90.0       87.9        1.12     174.4     .140E+01

                       AVERAGE PARAMETERS BETWEEN PRESSURE TAPS
           AVERAGE BULK REYNOLDS     AVERAGE WALL REYNOLDS     AVERAGE FRICTION FACTOR
                  29720.                    25898.                     .00590
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                  RUN 116H, DATE 02/21/76, GAS HE-AR, MOLECULAR WT. =  27.53
TIN = 70.1 F, TOUT = 154.2 F, MASS FLOW RATE = 44.1 LB/HR, I =  65.2 AMPS, E =  3.760 VOLTS
PR,IN =  .465, GR/RESQ =   .808E-04, MACH(2) =  .247, MACH(16) =  .307, T,SURR =  73.0 F

TC     X/D       TW        TW/TB       BULK       HL/QGAS      BULK            QGAS         Q+
                 (F)                 REYNOLDS                NUSSELT        BTU/HRFT2
 2       .1     96.0       1.069     100497.       .057       430.23         24488.4      .000481
 3      1.2    128.4       1.129     100309.       .130       188.90         22968.8      .000451
 4      2.1    140.6       1.151     100162.       .027       174.52         25297.7      .000497
 5      4.1    152.5       1.169      99822.       .018       154.26         25530.3      .000501
 6      8.1    163.5       1.181      99179.       .014       142.00         25658.4      .000504
 7     15.4    178.0       1.190      97897.       .014       131.66         25689.4      .000505
 8     24.5    187.6       1.190      96690.       .014       128.76         25710.6      .000505
 9     32.3    197.6       1.192      95548.       .015       124.98         25705.2      .000505
10     40.7    204.5       1.187      94370.       .015       125.98         25714.7      .000505
11     48.7    214.2       1.188      93303.       .016       122.87         25714.5      .000505
12     56.8    223.7       1.188      92249.       .017       120.28         25703.5      .000505
13     64.7    230.9       1.184      91243.       .017       120.46         25707.0      .000505
14     73.0    239.5       1.183      90219.       .018       119.31         25691.2      .000505
15     81.2    246.7       1.180      89268.       .021       119.52         25642.6      .000504
16     89.9    248.5       1.157      88285.       .035       126.47         25304.6      .000497
17     97.9    215.2       1.099      87476.       .096       225.52         23824.8      .000468

                           PT     X/D       STATIC      TW/TB       TB        PRESS
                                         PRESS.(PSIA)              (F)       DEFECT
                            1      -.5       97.1        1.06      60.0    -.450E-02
                            2     90.0       84.2        1.17     147.3     .131E+01

                       AVERAGE PARAMETERS BETWEEN PRESSURE TAPS
           AVERAGE BULK REYNOLDS     AVERAGE WALL REYNOLDS     AVERAGE FRICTION FACTOR
                  94402.                    78875.                     .00464
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                  RUN 117H, DATE 02/21/76, GAS HE-AR, MOLECULAR WT. =  27.53
TIN = 70.1 F, TOUT = 287.8 F, MASS FLOW RATE = 44.2 LB/HR, I = 100.7 AMPS, E =  5.750 VOLTS
PR,IN =  .465, GR/RESQ =   .195E-03, MACH(2) =  .246, MACH(16) =  .352, T,SURR =  74.0 F

TC      X/D       TW         TW/TB       BULK      HL/QGAS     BULK          QGAS          Q+
                  (F)                  REYNOLDS               NUSSELT      BTU/HRFT2
 2        .1     131.7       1.136     100521.       .065      451.90       58166.6      .001140
 3       1.2     202.9       1.267     100069.       .114      206.43       55920.5      .001096
 4       2.1     235.7       1.324      99712.       .037      179.63       60203.2      .001190
 5       4.1     262.7       1.363      98903.       .020      160.09       61333.4      .001202
 6       8.1     292.1       1.393      97414.       .017      143.53       61607.4      .001208
 7      15.4     331.4       1.413      94475.       .018      128.26       61761.0      .001211
 8      24.5     356.1       1.409      91846.       .018      122.80       61965.7      .001213
 9      32.4     379.0       1.403      89457.       .019      118.39       61922.7      .001214
10      40.8     398.6       1.389      87095.       .020      116.34       61944.0      .001214
11      48.7     422.0       1.385      85011.       .021      112.17       61992.2      .001215
12      56.8     439.1       1.371      83026.       .022      111.32       61981.4      .001215
13      64.8     454.0       1.355      81207.       .022      111.68       62031.4      .001216
14      73.1     473.8       1.346      79419.       .024      109.87       61931.5      .001215
15      81.3     490.4       1.334      77779.       .027      109.50       61885.8      .001213
16      90.1     491.8       1.300      76162.       .045      116.51       60861.7      .001193
17      98.0     415.6       1.170      74930.       .175      195.34       53799.3      .001055

                                  PT     X/D        STATIC      TW/TB        TB       PRESS
                                                PRESS.(PSIA)                (F)       DEFECT
                                   1       -.5       97.8       1.11        60.7    -.450E-02
                                   2      90.1       80.5       1.30       272.1     .177E+01

                                 AVERAGE PARAMETERS BETWEEN PRESSURE TAPS
          AVERAGE BULK REYNOLDS       AVERAGE WALL REYNOLDS       AVERAGE FRICTION FACTOR
                88371.                      65677.                         .00453
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                  RUN 118H, DATE 02/21/76, GAS HE-AR, MOLECULAR WT. =  27.53
TIN = 70.1 F, TOUT = 407.9 F, MASS FLOW RATE = 44.9 LB/HR, I = 123.4 AMPS, E =  7.220 VOLTS
PR,IN =  .465, GR/RESQ =   .354E-03, MACH(2) =  .223, MACH(16) =  .339, T,SURR =  78.5 F

TC      X/D       TW         TW/TB       BULK      HL/QGAS     BULK          QGAS          Q+
                  (F)                  REYNOLDS               NUSSELT      BTU/HRFT2
 2        .1     179.3       1.221     101647.       .084      382.46       86114.1      .001662
 3       1.2     278.0       1.400     100972.       .111      200.05       84677.8      .001634
 4       2.1     327.6       1.486     100431.       .036      174.60       91095.0      .001758
 5       4.1     375.2       1.554      99234.       .025      151.19       92425.8      .001784
 6       8.1     420.1       1.594      97016.       .021      135.21       93059.2      .001796
 7      16.4     475.3       1.605      92800.       .021      121.31       93442.4      .001804
 8      24.5     519.6       1.601      89109.       .022      112.57       93605.2      .001807
 9      32.4     554.4       1.584      85870.       .023      107.43       93754.0      .001810
10      40.8     585.9       1.560      82755.       .025      103.88       93771.6      .001810
11      48.8     613.6       1.535      80063.       .026      101.56       93909.9      .001813
12      56.9     643.5       1.515      77558.       .028       98.75       93879.8      .001812
13      64.9     670.2       1.494      75304.       .029       97.03       93934.8      .001813
14      73.3     694.5       1.469      73127.       .032       96.28       93886.6      .001812
15      81.4     713.5       1.441      71175.       .034       96.96       93763.3      .001810
16      90.2     721.4       1.399      69273.       .057       99.87       91823.8      .001772
17      98.2     605.4       1.227      67918.       .283      147.20       75005.9      .001448

                                  PT     X/D        STATIC      TW/TB        TB       PRESS
                                                PRESS.(PSIA)                (F)       DEFECT
                                   1       -.5      109.6       1.18        63.0    -.448E-02
                                   2      90.2       90.6       1.40       384.6     .209E+01

                                 AVERAGE PARAMETERS BETWEEN PRESSURE TAPS
          AVERAGE BULK REYNOLDS       AVERAGE WALL REYNOLDS       AVERAGE FRICTION FACTOR
                85507.                      57344.                         .00456
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                RUN 119H, DATE 02/21/76, GAS HE-AR, MOLECULAR WT. =  27.53
TIN = 71.9 F, TOUT = 452.4 F, MASS FLOW RATE = 44.7 LB/HR, I = 130.8 AMPS, E =  7.720 VOLTS
PR,IN =  .465, GR/RESQ =   .392E-03, MACH(2) =  .224, MACH(16) =  .355, T,SURR =  81.5 F

TC    X/D      TW        TW/TB      BULK       HL/QGAS     BULK           QGAS          Q+
               (F)                REYNOLDS                NUSSELT       BTU/HRFT2
 2      .1    195.0      1.247    101063.       .088      379.79         96546.3     .001862
 3     1.2    310.6      1.455    100308.       .116      194.69         94971.1     .001830
 4     2.1    360.7      1.540     99719.       .033      175.36        102932.5     .001985
 5     4.1    411.2      1.609     98383.       .024      152.65        104166.2     .002009
 6     8.1    463.2      1.655     95919.       .022      135.40        104820.5     .002021
 7    16.4    531.4      1.675     91295.       .022      119.03        105273.4     .002030
 8    24.5    584.8      1.671     87300.       .024      109.16        105467.6     .002034
 9    32.4    624.4      1.650     83833.       .025      103.80        105644.3     .002037
10    40.8    657.5      1.616     80532.       .027      100.70        105689.0     .002038
11    48.8    690.9      1.590     77699.       .028       97.66        105821.9     .002041
12    56.9    723.9      1.565     75087.       .031       94.94        105796.1     .002040
13    64.9    752.5      1.538     72748.       .032       93.43        105865.9     .002042
14    73.3    783.7      1.514     70509.       .035       91.64        105789.9     .002040
15    81.5    807.1      1.485     68517.       .039       91.62        105602.2     .002037
16    90.3    807.6      1.429     66592.       .061       96.25        103362.8     .001993
17    98.2    675.3      1.243     65258.       .329      137.89         81768.2     .001577

                                 PT     X/D      STATIC      TW/TB      TB       PRESS
                                               PRESS.(PSIA)             (F)      DEFECT
                                  1      -.5      109.1      1.19       64.8   -.449E-02
                                  2     90.3       88.5      1.43      427.0    .227E+01

                               AVERAGE PARAMETERS BETWEEN PRESSURE TAPS
          AVERAGE BULK REYNOLDS      AVERAGE WALL REYNOLDS      AVERAGE FRICTION FACTOR
                 83880.                     54686.                       .00460


                RUN 120H, DATE 02/21/76, GAS HE-AR, MOLECULAR WT. =  27.53
TIN = 71.9 F, TOUT = 208.2 F, MASS FLOW RATE = 43.7 LB/HR, I =  80.8 AMPS, E =  4.750 VOLTS
PR,IN =  .465, GR/RESQ =   .121E-03, MACH(2) =  .249, MACH(16) =  .330, T,SURR =  80.7 F

TC    X/D      TW        TW/TB      BULK       HL/QGAS     BULK           QGAS          Q+
               (F)                REYNOLDS                NUSSELT       BTU/HRFT2
 2      .1    131.0      1.132     99419.       .103      299.31         36159.9     .000713
 3     1.2    165.5      1.195     99143.       .096      188.89         36484.6     .000720
 4     2.1    185.4      1.230     98914.       .031      167.61         38836.4     .000766
 5     4.1    204.1      1.258     98394.       .021      148.35         39274.5     .000775
 6     8.1    217.9      1.269     97431.       .014      140.04         39555.2     .000780
 7    16.4    242.7      1.285     95506.       .015      127.00         39501.2     .000781
 8    24.5    262.5      1.292     93706.       .016      119.40         39614.7     .000781
 9    32.4    272.0      1.281     92068.       .015      120.33         39678.3     .000783
10    40.7    289.6      1.283     90392.       .017      115.16         39645.0     .000782
11    48.7    302.7      1.279     88882.       .017      113.39         39631.8     .000783
12    56.8    316.8      1.276     87421.       .019      110.87         39661.3     .000782
13    64.7    327.3      1.269     86044.       .019      111.05         39684.8     .000783
14    73.1    341.5      1.266     84681.       .021      108.85         39648.9     .000782
15    81.2    352.0      1.259     83404.       .024      109.06         39585.8     .000781
16    90.0    353.9      1.237     82119.       .038      115.36         39029.6     .000770
17    97.9    316.2      1.161     81098.       .146      161.25         35272.3     .000696

                                 PT     X/D      STATIC      TW/TB      TB       PRESS
                                               PRESS.(PSIA)             (F)      DEFECT
                                  1      -.5       95.5      1.11       61.7   -.451E-02
                                  2     90.0       80.6      1.24      197.8    .151E+01

                               AVERAGE PARAMETERS BETWEEN PRESSURE TAPS
          AVERAGE BULK REYNOLDS      AVERAGE WALL REYNOLDS      AVERAGE FRICTION FACTOR
                 90788.                     69459.                       .00464
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                    RUN 124H, DATE 03/01/76, GAS HE-AR, MOLECULAR WT. =  15.30
TIN = 70.5 F, TOUT = 183.2 F, MASS FLOW RATE = 14.2 LB/HR, I =  52.7 AMPS, E =  3.070 VOLTS
PR,IN =  .419, GR/RESQ =   .682E-04, MACH(2) =  .113, MACH(16) =  .127, T,SURR =  74.0 F

TC      X/D       TW          TW/TB        BULK       HL/QGAS      BULK          QGAS           Q+
                  (F)                    REYNOLDS                NUSSELT       BTU/HRFT2
 2        .1      91.7        1.043       32217.       .057       183.33        15990.7       .000540
 3       1.2     116.6        1.088       32152.       .145        79.76        14790.6       .000500
 4       2.1     128.4        1.108       32102.       .040        70.71        16309.8       .000551
 5       4.1     140.0        1.125       31984.       .023        61.57        16583.2       .000560
 6       8.1     151.9        1.137       31758.       .018        55.39        16676.9       .000563
 7      16.4     167.3        1.145       31301.       .019        50.77        16693.4       .000564
 8      24.5     179.2        1.146       30867.       .019        48.72        16694.2       .000564
 9      32.3     189.2        1.145       30465.       .020        47.73        16691.6       .000564
10      40.7     199.6        1.144       30051.       .022        46.80        16676.9       .000563
11      48.7     209.6        1.143       29668.       .023        45.92        16675.6       .000563
12      56.9     219.9        1.142       29294.       .025        44.97        16658.2       .000563
13      64.7     228.9        1.139       28939.       .026        44.68        16650.8       .000562
14      73.0     239.2        1.137       28576.       .028        43.84        16625.3       .000562
15      81.2     247.8        1.134       28236.       .032        43.78        16571.5       .000560
16      89.9     251.9        1.122       27888.       .055        45.84        16219.9       .000548
17      97.9     219.0        1.056       27604.       .148        93.90        14866.6       .000502

                                  PT     X/D       STATIC       TW/TB       TB       PRESS
                                                PRESS.(PSIA)               (F)      DEFECT
                                   1      -.5       92.7        1.03       68.8   -.585E-02
                                   2     90.0       90.0        1.12      174.5    .140E+01

                                  AVERAGE PARAMETERS BETWEEN PRESSURE TAPS
              AVERAGE BULK REYNOLDS      AVERAGE WALL REYNOLDS      AVERAGE FRICTION FACTOR
                    30057.                      26548.                      .00584
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                    RUN 125H, DATE 03/01/76, GAS HE-AR, MOLECULAR WT. =  15.30
TIN = 71.0 F, TOUT = 345.8 F, MASS FLOW RATE = 14.2 LB/HR, I =  81.5 AMPS, E =  4.305 VOLTS
PR,IN =  .419, GR/RESQ =   .163E-03, MACH(2) =  .113, MACH(16) =  .142, T,SURR =  75.5 F

TC      X/D       TW          TW/TB        BULK       HL/QGAS      BULK          QGAS           Q+
                  (F)                    REYNOLDS                NUSSELT       BTU/HRFT2
 2        .1     126.4        1.106       32051.       .083       166.09        37434.2       .001267
 3       1.2     182.3        1.205       31902.       .140        79.94        35721.2       .001209
 4       2.1     210.8        1.253       31782.       .044        70.18        39079.5       .001323
 5       4.1     239.1        1.292       31504.       .027        60.73        39823.1       .001348
 6       8.1     269.3        1.320       30978.       .023        53.68        40054.8       .001356
 7      16.4     307.3        1.332       29961.       .023        48.25        40154.4       .001359
 8      24.5     335.2        1.327       29044.       .024        45.79        40192.7       .001360
 9      32.4     358.5        1.316       28218.       .025        44.46        40223.7       .001361
10      40.8     382.3        1.305       27407.       .028        43.29        40192.0       .001360
11      48.7     405.4        1.295       26689.       .029        42.22        40217.4       .001361
12      56.8     428.4        1.285       26007.       .032        41.22        40165.1       .001359
13      64.8     448.2        1.272       25381.       .033        40.94        40176.9       .001360
14      73.1     470.7        1.261       24765.       .037        40.25        40101.7       .001357
15      81.3     491.3        1.250       24203.       .041        39.84        39978.7       .001353
16      90.1     502.1        1.225       23635.       .072        40.91        38357.9       .001315
17      98.0     421.0        1.093       23210.       .275        81.51        32487.7       .001100

                                  PT     X/D       STATIC       TW/TB       TB       PRESS
                                                PRESS.(PSIA)               (F)      DEFECT
                                   1      -.5       92.7        1.08       69.9   -.587E-02
                                   2     90.1       89.0        1.22      325.8    .187E+01

                                  AVERAGE PARAMETERS BETWEEN PRESSURE TAPS
              AVERAGE BULK REYNOLDS      AVERAGE WALL REYNOLDS      AVERAGE FRICTION FACTOR
                    27853.                      22239.                      .00589
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                      RUN 126H, DATE 03/01/76, GAS HE-AR, MOLECULAR WT. =  15.30
TIN = 71.9 F, TOUT = 167.5 F, MASS FLOW RATE = 24.5 LB/HR, I =  68.2 AMPS, E =  3.955 VOLTS
PR,IN =  .419, GR/RESQ =   .273E-04, MACH(2) =  .234, MACH(16) =  .291, T,SURR =  76.0 F

TC     X/D      TW        TW/TB      BULK      HL/QGAS     BULK         QGAS         Q+
                (F)               REYNOLDS               NUSSELT     BTU/HRFT2
 2      .1     103.4      1.077    56023.       .071      194.39      26468.8     .000519
 3     1.2     126.6      1.119    55916.       .090      114.68      26052.6     .000509
 4     2.1     138.0      1.139    55829.       .024      102.74      27754.4     .000543
 5     4.1     148.1      1.153    55630.       .014       92.56      28043.2     .000548
 6     8.1     159.6      1.165    55256.       .012       84.37      28128.7     .000550
 7    15.4     174.6      1.174    54509.       .012       78.11      28161.5     .000551
 8    24.5     186.3      1.176    53802.       .012       75.05      28172.5     .000551
 9    32.3     195.9      1.175    53134.       .013       73.75      28180.6     .000551
10    40.7     205.9      1.174    52458.       .014       72.53      28176.2     .000551
11    48.7     216.1      1.174    51836.       .014       70.88      28181.5     .000551
12    56.8     226.0      1.174    51221.       .015       69.59      28173.7     .000551
13    64.7     234.6      1.171    50638.       .016       69.27      28174.0     .000551
14    73.0     244.0      1.170    50053.       .017       68.55      28150.4     .000551
15    81.2     252.6      1.167    49498.       .020       68.27      28108.0     .000550
16    89.9     254.8      1.153    48925.       .031       72.99      27790.9     .000543
17    97.9     234.7      1.107    48460.       .106      103.78      25883.9     .000505

                        PT     X/D       STATIC      TW/TB       TB       PRESS
                                      PRESS.(PSIA)               (F)      DEFECT
                         1     -.5        76.7       1.06       62.8    -.514E-02
                         2    90.0        66.8       1.15      159.8     .142E+01

                        AVERAGE PARAMETERS BETWEEN PRESSURE TAPS
          AVERAGE BULK REYNOLDS     AVERAGE WALL REYNOLDS     AVERAGE FRICTION FACTOR
                52481.                      44157.                     .00504


                      RUN 127H, DATE 03/01/76, GAS HE-AR, MOLECULAR WT. =  15.30
TIN = 73.2 F, TOUT = 510.4 F, MASS FLOW RATE = 14.1 LB/HR, I = 102.2 AMPS, E =  5.990 VOLTS
PR,IN =  .419, GR/RESQ =   .256E-03, MACH(2) =  .112, MACH(16) =  .156, T,SURR =  78.5 F

TC     X/D      TW        TW/TB      BULK      HL/QGAS     BULK         QGAS         Q+
                (F)               REYNOLDS               NUSSELT     BTU/HRFT2
 2      .1     152.7      1.149    31735.       .074      184.51      59526.6     .002016
 3     1.2     246.1      1.313    31502.       .146       80.63      56131.8     .001901
 4     2.1     290.2      1.385    31316.       .046       71.05      61737.6     .002091
 5     4.1     334.9      1.443    30885.       .029       61.06      62919.0     .002131
 6     8.1     383.9      1.484    30094.       .027       53.20      63302.9     .002144
 7    16.4     444.9      1.492    28608.       .027       46.97      63534.8     .002152
 8    24.5     489.5      1.476    27325.       .029       43.95      63620.6     .002155
 9    32.4     525.6      1.451    26210.       .031       42.31      63695.6     .002158
10    40.8     560.4      1.423    25151.       .034       41.16      63651.5     .002156
11    48.8     594.0      1.399    24240.       .035       40.21      63739.0     .002159
12    56.9     639.7      1.391    23383.       .041       37.65      63552.0     .002153
13    64.9     670.4      1.367    22626.       .043       37.22      63580.9     .002154
14    73.2     701.5      1.344    21905.       .047       36.90      63462.2     .002150
15    81.4     731.0      1.321    21258.       .053       36.71      63232.0     .002142
16    90.2     744.5      1.291    20629.       .090       37.92      61124.7     .002070
17    98.2     613.6      1.106    20199.       .455       73.31      45405.6     .001538

                        PT     X/D       STATIC      TW/TB       TB       PRESS
                                      PRESS.(PSIA)               (F)      DEFECT
                         1     -.5        92.7       1.12       72.8    -.588E-02
                         2    90.2        88.1       1.28      480.4     .236E+01

                        AVERAGE PARAMETERS BETWEEN PRESSURE TAPS
          AVERAGE BULK REYNOLDS     AVERAGE WALL REYNOLDS     AVERAGE FRICTION FACTOR
                26198.                      19810.                     .00605
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                   RUN 128H, DATE 03/01/76, GAS HE-AR, MOLECULAR WT. =  15.30
TIN = 74.1 F, TOUT = 688.6 F, MASS FLOW RATE = 14.1 LB/HR, I = 121.2 AMPS, E =  7.280 VOLTS
PR,IN =  .419, GR/RESQ =    .355E-03, MACH(2) =  .113, MACH(16) =  .171, T,SURR =  81.5 F

TC     X/D       TW          TW/TB        BULK       HL/QGAS      BULK            QGAS          Q+
                 (F)                    REYNOLDS                 NUSSELT        BTU/HRFT2
 2      .1      198.0        1.229       31682.        .082       165.34          83373.1      .002816
 3     1.2      326.6        1.453       31357.        .145        77.77          79470.5      .002684
 4     2.1      395.4        1.564       31095.        .051        67.10          87057.8      .002940
 5     4.1      469.0        1.659       30496.        .036        56.17          88738.3      .002997
 6     8.1      548.2        1.723       29427.        .034        47.83          89461.2      .003021
 7    16.4      647.6        1.735       27484.        .036        40.68          89974.5      .003035
 8    24.6      717.2        1.704       25876.        .040        37.13          89973.3      .003038
 9    32.5      771.0        1.660       24527.        .043        35.15          90049.4      .003041
10    40.9      821.7        1.611       23266.        .048        33.63          89939.8      .003037
11    48.9      867.3        1.567       22229.        .051        32.63          89946.1      .003038
12    57.0      911.3        1.525       21293.        .056        31.84          89781.9      .003032
13    65.0      945.9        1.480       20470.        .060        31.78          89569.4      .003025
14    73.4      970.2        1.425       19694.        .061        32.82          89734.8      .003030
15    81.5     1026.5        1.408       18974.        .074        31.14          88954.9      .003004
16    90.4     1037.3        1.349       18330.        .117        32.38          85589.3      .002890
17    98.4      848.7        1.139       17941.        .875        46.57          50360.7      .001701

                                   PT     X/D      STATIC       TW/TB      TB      PRESS
                                                PRESS.(PSIA)               (F)     DEFECT
                                   1      -.5       92.7        1.18       74.4   -.588E-02
                                   2     90.4       87.0        1.35      650.4    .290E+01

                                 AVERAGE PARAMETERS BETWEEN PRESSURE TAPS
                 AVERAGE BULK REYNOLDS      AVERAGE WALL REYNOLDS      AVERAGE FRICTION FACTOR
                       25029.                     17357.                       .00616




                   RUN 129H, DATE 03/01/76, GAS HE-AR, MOLECULAR WT. =  15.30
TIN = 75.4 F, TOUT = 306.3 F, MASS FLOW RATE = 24.4 LB/HR, I = 102.4 AMPS, E =  5.925 VOLTS
PR,IN =  .419, GR/RESQ =    .609E-04, MACH(2) =  .233, MACH(16) =  .335, T,SURR =  82.0 F

TC     X/D       TW          TW/TB        BULK       HL/QGAS      BULK            QGAS          Q+
                 (F)                    REYNOLDS                 NUSSELT        BTU/HRFT2
 2      .1      145.2        1.148       55262.        .079       204.06          59450.1      .001162
 3     1.2      202.0        1.249       55020.        .096       113.76          58758.9      .001149
 4     2.1      229.0        1.295       54830.        .026       101.31          62852.8      .001229
 5     4.1      256.0        1.333       54396.        .018        88.79          63512.7      .001242
 6     8.1      284.9        1.361       53582.        .015        79.42          63791.5      .001247
 7    16.4      321.9        1.376       51992.        .015        71.72          63959.8      .001251
 8    24.5      349.3        1.375       50553.        .016        67.93          64045.7      .001252
 9    32.4      371.8        1.367       49261.        .017        65.87          64119.4      .001254
10    40.8      394.6        1.358       47980.        .018        64.05          64126.6      .001254
11    48.7      416.7        1.350       46841.        .019        62.36          64191.1      .001255
12    56.8      437.9        1.342       45765.        .020        61.05          64179.8      .001255
13    64.8      456.3        1.331       44774.        .021        60.53          64223.2      .001256
14    73.1      476.6        1.321       43796.        .023        59.71          64189.6      .001255
15    81.3      495.4        1.311       42906.        .026        59.21          64093.8      .001253
16    90.1      500.3        1.281       42019.        .042        62.50          63112.5      .001234
17    98.0      447.0        1.183       41340.        .194        86.43          54878.2      .001073

                                   PT     X/D      STATIC       TW/TB      TB      PRESS
                                                PRESS.(PSIA)               (F)     DEFECT
                                   1      -.5       76.7        1.12       67.0   -.515E-02
                                   2     90.1       63.3        1.28      289.7    .194E+01

                                 AVERAGE PARAMETERS BETWEEN PRESSURE TAPS
                 AVERAGE BULK REYNOLDS      AVERAGE WALL REYNOLDS      AVERAGE FRICTION FACTOR
                       48657.                     36411.                       .00516
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                   RUN 130H, DATE 03/01/76, GAS HE-AR, MOLECULAR WT. =  15.30
TIN = 76.3 F, TOUT = 453.5 F, MASS FLOW RATE = 24.3 LB/HR, I = 126.0 AMPS, E =  7.440 VOLTS
PR,IN =  .419, GR/RESQ =   .143E-03, MACH(2) =  .186, MACH(16) =  .272, T,SURR =  84.7 F

TC    X/D      TW        TW/TB      BULK      HL/QGAS     BULK          QGAS          Q+
               (F)               REYNOLDS              NUSSELT      BTU/HRFT2
 2      .1    176.9      1.196     54594.      .074     218.59       90605.1       .001775
 3     1.2    269.7      1.360     54232.      .100     113.25       89109.7       .001747
 4     2.1    312.8      1.432     53942.      .030      99.83       95469.5       .001871
 5     4.1    355.8      1.489     53283.      .020      86.74       96646.6       .001894
 6     8.1    402.4      1.530     52069.      .018      76.53       97152.0       .001904
 7    16.4    461.6      1.545     49774.      .019      67.78       97526.1       .001912
 8    24.5    504.2      1.534     47770.      .020      63.44       97719.8       .001915
 9    32.4    539.1      1.514     46013.      .021      60.84       97882.8       .001919
10    40.8    573.9      1.491     44322.      .023      58.65       97915.0       .001919
11    48.8    607.3      1.472     42858.      .024      56.74       98040.9       .001922
12    56.9    637.7      1.450     41496.      .026      55.49       98031.8       .001921
13    64.9    662.7      1.424     40251.      .027      55.18       98127.4       .001923
14    73.2    693.9      1.405     39056.      .030      54.06       98054.9       .001922
15    81.4    717.8      1.381     37995.      .033      54.19       97928.3       .001919
16    90.2    726.5      1.338     36954.      .053      56.62       96081.4       .001883
17    98.2    635.8      1.199     36201.      .299      77.10       77413.0       .001517

                          PT      X/D       STATIC      TW/TB       TB        PRESS
                                        PRESS.(PSIA)              (F)       DEFECT
                           1       -.5       96.3        1.15       71.9    -.516E-02
                           2      90.2       84.1        1.34      426.8     .222E+01

                          AVERAGE PARAMETERS BETWEEN PRESSURE TAPS
          AVERAGE BULK REYNOLDS      AVERAGE WALL REYNOLDS      AVERAGE FRICTION FACTOR
                45799.                      32455.                      .00524


                   RUN 131H, DATE 03/01/76, GAS HE-AR, MOLECULAR WT. =  15.30
TIN = 76.8 F, TOUT = 623.6 F, MASS FLOW RATE = 24.2 LB/HR, I = 151.1 AMPS, E =  9.100 VOLTS
PR,IN =  .419, GR/RESQ =   .206E-03, MACH(2) =  .186, MACH(16) =  .305, T,SURR =  87.0 F

TC    X/D      TW        TW/TB      BULK      HL/QGAS     BULK          QGAS          Q+
               (F)               REYNOLDS              NUSSELT      BTU/HRFT2
 2      .1    216.8      1.268     54345.      .067     228.80      131587.2       .002582
 3     1.2    354.1      1.509     53822.      .101     113.99      129787.5       .002527
 4     2.1    421.2      1.618     53404.      .033      98.69      138017.9       .002709
 5     4.1    489.8      1.707     52465.      .024      84.12      139860.7       .002745
 6     8.1    563.7      1.767     50784.      .022      72.77      140826.2       .002764
 7    16.4    658.6      1.783     47695.      .024      62.50      141568.6       .002778
 8    24.6    725.6      1.758     45111.      .026      57.26      141910.8       .002785
 9    32.5    779.4      1.722     42927.      .028      54.00      142163.9       .002790
10    40.9    829.3      1.678     40888.      .031      51.60      142237.3       .002791
11    48.9    875.3      1.640     39149.      .033      49.69      142391.6       .002794
12    57.0    917.6      1.601     37603.      .036      48.40      142387.7       .002794
13    65.0    950.2      1.556     36241.      .038      48.16      142450.1       .002795
14    73.4    988.4      1.519     34946.      .041      47.63      142406.5       .002745
15    81.6   1021.4      1.482     33801.      .045      47.56      142363.1       .002793
16    90.4   1029.2      1.421     32649.      .070      49.63      138833.6       .002725
17    98.4    881.1      1.237     31940.      .504      61.94       97824.7       .001920

                          PT      X/D       STATIC      TW/TB       TB        PRESS
                                        PRESS.(PSIA)              (F)       DEFECT
                           1       -.5       96.3        1.21       73.1    -.517E-02
                           2      90.4       80.9        1.42      588.0     .280E+01

                          AVERAGE PARAMETERS BETWEEN PRESSURE TAPS
          AVERAGE BULK REYNOLDS      AVERAGE WALL REYNOLDS      AVERAGE FRICTION FACTOR
                43534.                      28483.                      .00526
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                     RUN 133H, DATE 03/10/76, GAS    HE, MOLECULAR WT. = 4.0026
TIN = 78.1 F, TOUT = 174.6 F, MASS FLOW RATE = 11.6 LB/HR, I =  87.1 AMPS, E =  4.925 VOLTS
PR,IN =  .667, GR/RESQ =   .112E-04, MACH(2) =  .162, MACH(16) =  .188, T,SURR =  75.5 F

TC    X/D      TW       TW/TB      BULK     HL/QGAS     BULK          QGAS         Q+
               (F)               REYNOLDS             NUSSELT      BTU/HRFT2
 2      .1     99.5     1.048     30117.     .040      240.47       44446.3     .000476
 3     1.2    131.5     1.105     30065.     .072       95.70       43227.7     .000463
 4     2.1    142.2     1.124     30026.     .014       85.14       45754.2     .000490
 5     4.1    152.4     1.138     29935.     .010       75.59       45964.4     .000493
 6     8.1    162.5     1.148     29765.     .008       69.48       46085.2     .000494
 7    16.4    175.7     1.154     29425.     .008       64.99       46138.3     .000494
 8    24.5    185.3     1.154     29100.     .008       63.51       46169.3     .000495
 9    32.3    194.0     1.153     28791.     .008       62.57       46185.4     .000495
10    40.7    201.8     1.149     28476.     .008       62.70       46198.7     .000495
11    48.7    211.1     1.149     28184.     .009       61.46       46215.1     .000495
12    56.8    220.1     1.148     27894.     .009       60.51       46219.4     .000495
13    64.7    227.3     1.144     27616.     .009       60.84       46233.4     .000495
14    73.0    236.3     1.143     27337.     .010       60.09       46227.2     .000495
15    81.2    242.6     1.137     27070.     .011       61.22       46195.3     .000495
16    89.9    244.9     1.125     26791.     .018       66.07       45902.2     .000492
17    97.9    230.6     1.088     26556.     .064       91.05       43854.7     .000470

                             PT     X/D       STATIC      TW/TB      TB        PRESS
                                          PRESS.(PSIA)              (F)       DEFECT
                             1      -.5      103.1       1.04      73.9     -.596E-02
                             2     90.0       96.3       1.12     166.8      .151E+01

                          AVERAGE PARAMETERS BETWEEN PRESSURE TAPS
        AVERAGE BULK REYNOLDS      AVERAGE WALL REYNOLDS      AVERAGE FRICTION FACTOR
              28457.                     25098.                       .00622


                     RUN 134H, DATE 03/10/76, GAS    HE, MOLECULAR WT. = 4.0026
TIN = 77.7 F, TOUT = 320.1 F, MASS FLOW RATE = 11.6 LB/HR, I = 135.4 AMPS, E =  7.890 VOLTS
PR,IN =  .667, GR/RESQ =   .272E-04, MACH(2) =  .162, MACH(16) =  .211, T,SURR =  78.0 F

TC    X/D      TW       TW/TB      BULK     HL/QGAS     BULK          QGAS         Q+
               (F)               REYNOLDS             NUSSELT      BTU/HRFT2
 2      .1    142.6     1.128     30140.     .051      192.97      106721.3     .001143
 3     1.2    211.5     1.250     30016.     .063       93.96      106024.3     .001135
 4     2.1    238.1     1.295     29919.     .016       82.75      111182.7     .001190
 5     4.1    263.0     1.328     29705.     .011       73.42      111915.1     .001198
 6     8.1    289.3     1.351     29305.     .009       66.58      112277.2     .001202
 7    16.4    322.8     1.360     28516.     .009       61.08      112565.3     .001205
 8    24.5    346.7     1.354     27799.     .009       58.80      112741.7     .001207
 9    32.4    366.9     1.343     27148.     .010       57.56      112881.9     .001208
10    40.8    386.1     1.328     26497.     .010       56.92      112966.1     .001209
11    48.7    407.8     1.321     25914.     .011       55.47      113097.4     .001211
12    56.8    427.7     1.310     25358.     .012       54.63      113157.9     .001211
13    64.8    444.8     1.297     24841.     .012       54.52      113264.0     .001213
14    73.1    464.7     1.287     24327.     .013       53.92      113295.2     .001213
15    81.3    481.8     1.274     23854.     .015       53.99      113261.7     .001213
16    90.1    483.6     1.240     23340.     .023       58.76      112379.0     .001203
17    98.0    452.4     1.169     22896.     .119       74.49      102462.4     .001097

                             PT     X/D       STATIC      TW/TB      TB        PRESS
                                          PRESS.(PSIA)              (F)       DEFECT
                             1      -.5      103.3       1.10      74.1     -.596E-02
                             2     90.1       94.2       1.24     301.4      .199E+01

                          AVERAGE PARAMETERS BETWEEN PRESSURE TAPS
        AVERAGE BULK REYNOLDS      AVERAGE WALL REYNOLDS      AVERAGE FRICTION FACTOR
              26749.                     20976.                       .00634
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                   RUN 135H, DATE 03/10/76, GAS     HE, MOLECULAR WT. = 4.0026
TIN = 77.7 F, TOUT = 471.7 F, MASS FLOW RATE = 11.6 LB/HR, I = 171.2 AMPS, E = 10.170 VOLTS
PR,IN =  .667, GR/RESQ =   .435E-04, MACH(2) =  .163, MACH(16) =  .235, T,SURR =  82.0 F

TC    X/D       TW        TW/TB      BULK      HL/QGAS      BULK          QGAS          Q+
               (F)                REYNOLDS               NUSSELT     BTU/HRFT2
 2      .1     190.3      1.215     30091.      .055       178.22      170678.3      .001827
 3     1.2     294.1      1.398     29894.      .061        93.56      170966.9      .001830
 4     2.1     338.5      1.471     29741.      .017        81.58      178844.3      .001915
 5     4.1     379.5      1.523     29402.      .012        72.05      180275.8      .001930
 6     8.1     423.6      1.557     28772.      .011        64.59      181028.5      .001938
 7    16.4     479.8      1.563     27580.      .011        58.17      181743.6      .001946
 8    24.5     520.2      1.545     26536.      .012        55.06      182172.1      .001950
 9    32.4     552.4      1.518     25616.      .012        53.40      182524.9      .001954
10    40.8     583.9      1.499     24725.      .013        52.20      182743.1      .001956
11    48.8     616.6      1.467     23949.      .013        50.81      183058.2      .001960
12    56.9     648.0      1.445     23168.      .015        49.64      183221.5      .001962
13    64.9     673.7      1.418     22484.      .015        49.42      183458.5      .001964
14    73.3     703.2      1.396     21861.      .017        48.97      183569.7      .001965
15    81.4     728.4      1.371     21295.      .019        49.15      183551.8      .001965
16    90.2     731.5      1.321     20735.      .028        53.24      181637.3      .001947
17    98.2     680.5      1.224     20303.      .183        64.29      157493.5      .001686

                          PT     X/D        STATIC       TW/TB      TB        PRESS
                                         PRESS.(PSIA)              (F)       DEFECT
                           1     -.5        103.1        1.16       74.7    -.596E-02
                           2    90.3         91.6        1.32      442.3     .253E+01

                           AVERAGE PARAMETERS BETWEEN PRESSURE TAPS
          AVERAGE BULK REYNOLDS      AVERAGE WALL REYNOLDS      AVERAGE FRICTION FACTOR
                25428.                     18139.                       .00652
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                   RUN 136H, DATE 03/10/76, GAS     HE, MOLECULAR WT. = 4.0026
TIN = 76.8 F, TOUT = 618.7 F, MASS FLOW RATE = 11.6 LB/HR, I = 199.6 AMPS, E = 12.015 VOLTS
PR,IN =  .667, GR/RESQ =   .598E-04, MACH(2) =  .162, MACH(16) =  .258, T,SURR =  86.5 F

TC    X/D       TW        TW/TB      BULK      HL/QGAS      BULK          QGAS          Q+
               (F)                REYNOLDS               NUSSELT     BTU/HRFT2
 2      .1     230.2      1.289     30055.      .050       179.54      233859.2      .002510
 3     1.2     369.2      1.533     29786.      .060        94.72      233974.0      .002511
 4     2.1     434.9      1.640     29578.      .019        81.07      244549.5      .002625
 5     4.1     493.7      1.711     29117.      .013        70.94      246839.2      .002649
 6     8.1     559.9      1.760     28281.      .013        62.43      248133.9      .002663
 7    16.4     642.3      1.760     26735.      .013        55.00      249459.0      .002677
 8    24.6     699.2      1.725     25427.      .014        51.41      250214.1      .002686
 9    32.5     744.9      1.682     24303.      .015        49.27      250806.7      .002692
10    40.9     787.2      1.633     23201.      .016        47.77      251208.9      .002696
11    48.9     829.0      1.594     22265.      .017        46.40      251684.4      .002701
12    57.0     867.2      1.554     21460.      .018        45.68      251989.9      .002705
13    65.0     899.8      1.513     20737.      .019        45.58      252310.2      .002708
14    73.4     938.4      1.479     20042.      .021        45.15      252560.5      .002711
15    81.6     972.9      1.446     19419.      .024        45.11      252496.9      .002710
16    90.4     977.2      1.382     18813.      .035        48.57      249770.0      .002681
17    98.4     897.4      1.258     18368.      .260        57.04      204094.9      .002191

                          PT     X/D        STATIC       TW/TB      TB        PRESS
                                         PRESS.(PSIA)              (F)       DEFECT
                           1     -.5        103.2        1.22       74.5    -.596E-02
                           2    90.4         89.2        1.38      579.9     .309E+01

                           AVERAGE PARAMETERS BETWEEN PRESSURE TAPS
          AVERAGE BULK REYNOLDS      AVERAGE WALL REYNOLDS      AVERAGE FRICTION FACTOR
                24454.                     16195.                       .00669
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                 RUN 1494, DATE 04/02/76, GAS AIR  , MOLECULAR WT. =  28.97
TIN = 74.5 F, TOUT = 153.5 F, MASS FLOW RATE = 35.6 LB/HR, I =  64.2 AMPS, E =  3.555 VOLTS
PR.IN =  .720, GR/RESQ =   .162E-03, MACH(2) =  .225, MACH(16) =  .260, T.SURR =  76.7 F

TC     X/D       TW        TW/TB      BULK      HL/QGAS     BULK          QGAS           Q+
                 (F)               REYNOLDS              NUSSELT      BTU/HRFT2
 2       .1     103.8      1.064    100225.      .074      350.66       23386.1       .000417
 3      1.2     137.5      1.126    100058.      .145      244.03       21993.2       .000392
 4      2.1     149.9      1.148     99947.      .031      229.05       24454.6       .000436
 5      4.1     160.9      1.164     99657.      .019      204.87       24745.1       .000441
 6      8.1     171.5      1.176     99137.      .015      189.03       24662.9       .000443
 7     16.4     185.0      1.185     98056.      .015      175.74       24899.5       .000444
 8     24.5     195.5      1.188     97025.      .015      163.74       24911.1       .000444
 9     32.4     203.3      1.186     96050.      .015      158.21       24922.1       .000445
10     40.7     211.6      1.185     95072.      .016      153.54       24917.4       .000444
11     48.7     220.2      1.185     94161.      .016      160.06       24923.1       .000445
12     56.8     223.3      1.184     93254.      .017      157.48       24915.6       .000444
13     64.7     235.0      1.180     92392.      .018      159.94       24915.8       .000444
14     73.0     242.7      1.178     91485.      .019      155.42       24904.3       .000444
15     81.2     249.9      1.176     90529.      .022      154.10       24847.9       .000443
16     89.9     248.5      1.158     89740.      .035      166.39       24527.5       .000437
17     97.9     212.1      1.086     89002.      .092      304.19       23179.2       .000423

                                     PT     X/D       STATIC     TW/TB       TB        PRESS
                                                  PRESS.(PSIA)              (F)       DEFECT
                                      1      -.5       92.1       1.05       69.6    -.450E-02
                                      2     90.0       84.4       1.16      151.7     .117E+01

                                     AVERAGE PARAMETERS BETWEEN PRESSURE TAPS
              AVERAGE BULK REYNOLDS        AVERAGE WALL REYNOLDS        AVERAGE FRICTION FACTOR
                     94992.                       80621.                         .00451
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                 RUN 1504, DATE 04/02/76, GAS AIR  , MOLECULAR WT. =  29.97
TIN = 75.9 F, TOUT = 296.5 F, MASS FLOW RATE = 35.4 LB/HR, I =  69.1 AMPS, E =  5.720 VOLTS
PR.IN =  .720, GR/RESQ =   .386E-03, MACH(2) =  .224, MACH(16) =  .293, T.SURR =  79.5 F

TC     X/D       TW        TW/TB      BULK      HL/QGAS     BULK          QGAS           Q+
                 (F)               REYNOLDS              NUSSELT      BTU/HRFT2
 2       .1     151.5      1.150     99494.      .092      504.00       55011.5       .000963
 3      1.2     230.2      1.293     99120.      .137      240.35       53151.4       .000950
 4      2.1     265.3      1.354     98827.      .041      215.14       58175.8       .001039
 5      4.1     295.0      1.397     98164.      .025      191.52       59249.8       .001058
 6      8.1     322.4      1.425     96918.      .021      174.64       59609.6       .001065
 7     16.4     355.4      1.437     94489.      .020      160.24       59797.0       .001068
 8     24.5     379.2      1.433     92278.      .020      152.72       59685.4       .001070
 9     32.4     398.8      1.424     90227.      .020      143.02       59959.7       .001071
10     40.6     413.1      1.414     88145.      .022      143.35       59952.2       .001071
11     48.7     437.5      1.403     86299.      .022      140.05       60020.3       .001072
12     56.8     455.0      1.393     84540.      .024      139.95       59995.6       .001072
13     64.8     470.9      1.379     82926.      .024      135.99       60037.7       .001073
14     73.2     485.6      1.365     81338.      .026      134.64       60004.9       .001072
15     81.3     502.5      1.353     79850.      .029      133.03       59893.3       .001070
16     90.1     501.8      1.317     78341.      .047      139.46       58821.6       .001051
17     98.0     408.5      1.163     77201.      .166      244.07       52513.7       .000938

                                     PT     X/D       STATIC     TW/TB       TB        PRESS
                                                  PRESS.(PSIA)              (F)       DEFECT
                                      1      -.5       92.1       1.12       71.5    -.451E-02
                                      2     90.1       82.0       1.32      270.7     .155E+01

                                     AVERAGE PARAMETERS BETWEEN PRESSURE TAPS
              AVERAGE BULK REYNOLDS        AVERAGE WALL REYNOLDS        AVERAGE FRICTION FACTOR
                     88742.                       65447.                         .00452
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                      RUN 1514, DATE 04/02/76, GAS AIR   , MOLECULAR WT. =  28.97
TIN = 77.2 F, TOUT = 404.9 F, MASS FLOW RATE = 35.3 LB/HR, I = 122.7 AMPS, E =  7.290 VOLTS
PR,IN =  .720, GR/RESQ =   .589E-03, MACH(2) =  .224, MACH(16) =  .324, T,SURR =  83.0 F

TC     X/D      TW        TW/TB       BULK       HL/QGAS      BULK           QGAS           Q+
                (F)                 REYNOLDS                NUSSELT       BTU/HRFT2
 2       .1    197.9      1.233      98836.       .100       482.05        83998.6       .001502
 3      1.2    320.3      1.453      98264.       .141       233.80        81761.5       .001402
 4      2.1    373.6      1.544      97616.       .041       211.39        89933.5       .001606
 5      4.1    422.1      1.613      96803.       .029       185.75        91335.6       .001633
 6      8.1    469.2      1.655      94937.       .025       166.63        91976.3       .001645
 7     16.4    523.7      1.669      91413.       .024       149.46        92374.0       .001652
 8     24.5    564.4      1.659      89214.       .025       139.39        92544.2       .001655
 9     32.4    595.6      1.639      85332.       .026       133.24        92701.3       .001658
10     40.8    630.5      1.619      82659.       .029       127.31        92684.7       .001658
11     48.8    658.6      1.595      80314.       .029       123.50        92919.4       .001660
12     56.9    687.7      1.574      78058.       .032       119.03        92766.7       .001659
13     64.9    709.4      1.546      75601.       .032       117.36        92648.7       .001660
14     73.3    735.4      1.523      74101.       .035       114.94        92752.2       .001659
15     81.5    754.0      1.495      72304.       .038       114.60        92603.9       .001656
16     90.2    752.8      1.441      70598.       .062       118.65        90512.9       .001619
17     98.2    597.9      1.223      69364.       .266       194.04        75101.4       .001343

                                   PT     X/D       STATIC       TW/TB       TB        PRESS
                                                 PRESS.(PSIA)              (F)       DEFECT
                                    1      -.5       91.9        1.18       73.3    -.451E-02
                                    2     90.3       79.3        1.44      381.6     .194E+01

                                   AVERAGE PARAMETERS BETWEEN PRESSURE TAPS
              AVERAGE BULK REYNOLDS      AVERAGE WALL REYNOLDS      AVERAGE FRICTION FACTOR
                    84755.                      55947.                       .00462
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                      RUN 1524, DATE 04/02/76, GAS AIR   , MOLECULAR WT. =  28.97
TIN = 77.7 F, TOUT = 527.6 F, MASS FLOW RATE = 35.2 LB/HR, I = 143.2 AMPS, E =  8.635 VOLTS
PR,IN =  .719, GR/RESQ =   .806E-03, MACH(2) =  .223, MACH(16) =  .354, T,SURR =  87.0 F

TC     X/D      TW        TW/TB       BULK       HL/QGAS      BULK           QGAS           Q+
                (F)                 REYNOLDS                NUSSELT       BTU/HRFT2
 2       .1    247.4      1.322      98212.       .098       469.44       115141.7       .002066
 3      1.2    410.8      1.514      97433.       .141       233.27       112076.7       .002011
 4      2.1    489.3      1.747      96817.       .044       207.59       123202.4       .002211
 5      4.1    559.5      1.843      95442.       .033       180.55       125160.4       .002246
 6      8.1    629.4      1.902      92990.       .029       159.56       126173.9       .002264
 7     16.5    709.2      1.911      88346.       .029       140.11       126843.2       .002276
 8     24.6    766.5      1.885      84330.       .032       129.16       127081.4       .002281
 9     32.5    811.7      1.848      80933.       .033       122.25       127274.2       .002284
10     40.9    856.1      1.807      77683.       .036       115.67       127275.5       .002284
11     48.9    895.9      1.770      74936.       .038       110.80       127383.2       .002286
12     57.0    932.7      1.732      72383.       .041       107.38       127344.9       .002285
13     65.0    961.0      1.689      70157.       .043       105.41       127369.6       .002286
14     73.4    994.1      1.652      67995.       .046       102.79       127290.3       .002284
15     81.6   1015.1      1.607      66031.       .050       102.80       126958.7       .002279
16     90.4   1009.6      1.535      64208.       .077       105.95       123773.8       .002221
17     98.4    790.8      1.266      62993.       .405       159.49        93440.9       .001677

                                   PT     X/D       STATIC       TW/TB       TB        PRESS
                                                 PRESS.(PSIA)              (F)       DEFECT
                                    1      -.5       91.8        1.25       74.3    -.452E-02
                                    2     90.4       76.7        1.53      497.7     .234E+01

                                   AVERAGE PARAMETERS BETWEEN PRESSURE TAPS
              AVERAGE BULK REYNOLDS      AVERAGE WALL REYNOLDS      AVERAGE FRICTION FACTOR
                    81264.                      48907.                       .00453
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                    RUN 154H, DATE 04/02/76, GAS AIR  , MOLECULAR WT. =  28.97
TIN = 77.7 F, TOUT = 171.2 F, MASS FLOW RATE = 29.3 LB/HR, I =  59.5 AMPS, E =  3.260 VOLTS
PR.IN =  .719, GR/RESQ =   .239E-03, MACH(2) =  .170, MACH(16) =  .185, T.SURR =  32.0 F

TC     X/D       TW          TW/TB       BULK      HL/QGAS      BULK           QGAS          Q+
                 (F)                   REYNOLDS                NUSSELT       BTU/HRFT2
 2      .1      109.1        1.063      81164.       .083       441.12        20128.3      .000437
 3     1.2      141.8        1.123      81031.       .105       203.32        18753.6      .000408
 4     2.1      154.7        1.145      80928.       .037       191.53        21098.0      .000459
 5     4.1      166.1        1.162      80686.       .022       172.24        21415.7      .000465
 6     8.1      177.6        1.174      80227.       .018       158.06        21523.5      .000468
 7    16.4      190.6        1.181      79293.       .017       144.59        21564.5      .000469
 8    24.5      201.1        1.182      78407.       .017       143.31        21577.3      .000469
 9    32.4      208.9        1.180      77595.       .017       141.75        21584.6      .000469
10    40.7      218.7        1.180      76750.       .019       137.54        21569.2      .000469
11    48.7      227.3        1.179      75963.       .019       135.48        21576.9      .000469
12    56.8      235.8        1.177      75181.       .020       133.22        21565.6      .000469
13    64.7      243.0        1.174      74425.       .021       132.66        21555.2      .000469
14    73.0      251.6        1.172      73655.       .022       130.72        21546.3      .000468
15    81.2      253.8        1.168      72918.       .026       130.10        21492.7      .000467
16    89.9      259.3        1.153      72152.       .042       137.91        21146.7      .000460
17    97.9      220.1        1.077      71526.       .109       261.59        19818.5      .000431

                                    PT     X/D        STATIC       TW/TB       TB        PRESS
                                                   PRESS.(PSIA)               (F)       DEFECT
                                     1     -.5          99.9        1.05       75.0    -.472E-02
                                     2    90.0          95.2        1.15      163.8     .115E+01

                                     AVERAGE PARAMETERS BETWEEN PRESSURE TAPS
               AVERAGE BULK REYNOLDS      AVERAGE WALL REYNOLDS      AVERAGE FRICTION FACTOR
                     76666.                      65365.                     .00469
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                    RUN 155H, DATE 04/02/76, GAS AIR  , MOLECULAR WT. =  28.97
TIN = 78.6 F, TOUT = 278.5 F, MASS FLOW RATE = 29.1 LB/HR, I =  90.6 AMPS, E =  5.220 VOLTS
PR.IN =  .719, GR/RESQ =   .544E-03, MACH(2) =  .170, MACH(16) =  .212, T.SURR =  33.0 F

TC     X/D       TW          TW/TB       BULK      HL/QGAS      BULK           QGAS          Q+
                 (F)                   REYNOLDS                NUSSELT       BTU/HRFT2
 2      .1      151.4        1.139      81065.       .099       432.69        45674.3      .000990
 3     1.2      225.4        1.274      80761.       .156       204.97        43058.3      .000946
 4     2.1      262.4        1.336      80519.       .051       182.45        48171.9      .001044
 5     4.1      293.0        1.381      79970.       .029       161.92        49300.8      .001068
 6     8.1      321.3        1.409      78934.       .024       146.96        49643.6      .001076
 7    16.4      354.2        1.420      76941.       .023       134.84        49809.0      .001079
 8    24.5      378.0        1.416      75103.       .023       129.55        49878.1      .001081
 9    32.4      397.1        1.405      73397.       .023       124.29        49941.7      .001082
10    40.6      413.3        1.396      71665.       .025       120.56        49916.5      .001082
11    48.7      437.7        1.386      70159.       .026       117.56        49969.3      .001083
12    56.8      457.1        1.376      68696.       .028       114.58        49926.3      .001082
13    64.8      471.0        1.360      67383.       .028       114.33        49972.1      .001083
14    73.2      489.4        1.349      66059.       .031       112.09        49903.7      .001081
15    81.3      503.2        1.334      64820.       .034       111.60        49810.9      .001079
16    90.1      506.0        1.302      63575.       .058       114.93        48688.9      .001055
17    98.0      405.0        1.140      62655.       .169       216.54        43005.3      .000932

                                    PT     X/D        STATIC       TW/TB       TB        PRESS
                                                   PRESS.(PSIA)               (F)       DEFECT
                                     1     -.5          99.9        1.11       76.4    -.472E-02
                                     2    90.1          93.7        1.30      262.0     .151E+01

                                     AVERAGE PARAMETERS BETWEEN PRESSURE TAPS
               AVERAGE BULK REYNOLDS      AVERAGE WALL REYNOLDS      AVERAGE FRICTION FACTOR
                     72340.                      54080.                     .00475
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                RUN 1564, DATE 04/02/76, GAS AIR   , MOLECULAR WT. =  28.97
TIN = 79.0 F, TOUT = 423.3 F, MASS FLOW RATE = 29.0 LB/HR, I = 112.9 AMPS, E =  6.665 VOLTS
PR.IN =   .719, GR/RESQ =    .542E-03, MACH(2) =   .170, MACH(16) =   .231, T,SURR =   85.5 F

TC     X/D        TW          TW/TB        BULK        HL/QGAS       BULK            QGAS            Q+
                  (F)                    REYNOLDS                  NUSSELT       BTU/HRFT2
 2        .1     195.2        1.213       80768.        .108        413.54          70496.4       .001529
 3       1.2     312.7        1.429       80297.        .161        200.83          67435.5       .001471
 4       2.1     368.3        1.522       79523.        .050        130.37          75253.7       .001633
 5       4.1     417.3        1.591       79074.        .033        138.54          76617.0       .001665
 6       8.1     464.2        1.634       77528.        .029        141.86          77402.1       .001679
 7      16.4     519.3        1.645       74557.        .028        127.21          77745.6       .001686
 8      24.5     559.1        1.632       71632.        .029        113.89          77876.0       .001689
 9      32.4     590.1        1.568       69534.        .030        114.18          75602.3       .001692
10      40.8     622.6        1.565       67231.        .033        109.49          77960.6       .001691
11      48.8     650.8        1.561       65313.        .033        106.14          78061.5       .001693
12      56.9     679.1        1.533       63438.        .036        102.50          77988.4       .001692
13      64.9     700.7        1.509       61770.        .037        101.40          78046.2       .001693
14      73.3     723.9        1.484       60134.        .040         99.62          77945.7       .001691
15      81.4     743.4        1.456       58667.        .044         99.44          77769.6       .001687
16      90.2     743.9        1.404       57233.        .073        102.38          75692.3       .001642
17      98.2     583.3        1.181       56201.        .296        153.10          61953.0       .001344

                                         PT     X/D       STATIC      TW/TB        TB        PRESS
                                                       PRESS.(PSIA)               (F)        DEFECT
                                          1      -.5       99.7        1.17        77.3     -.472E-02
                                          2     90.3       92.1        1.40       398.3      .146E+01

                                AVERAGE PARAMETERS BETWEEN PRESSURE TAPS
            AVERAGE BULK REYNOLDS      AVERAGE WALL REYNOLDS      AVERAGE FRICTION FACTOR
                   69032.                     46754.                        .00479
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                RUN 1574, DATE 04/02/76, GAS AIR   , MOLECULAR WT. =  28.97
TIN = 79.5 F, TOUT = 555.5 F, MASS FLOW RATE = 28.9 LB/HR, I = 132.2 AMPS, E =  7.960 VOLTS
PR.IN =   .719, GR/RESQ =    .116E-02, MACH(2) =   .170, MACH(16) =   .253, T,SURR =   88.7 F

TC     X/D        TW          TW/TB        BULK        HL/QGAS       BULK            QGAS            Q+
                  (F)                    REYNOLDS                  NUSSELT       BTU/HRFT2
 2        .1     243.2        1.305       80324.        .109        408.61          97116.6       .002112
 3       1.2     401.4        1.584       79677.        .161        200.90          93758.3       .002039
 4       2.1     479.5        1.715       79162.        .051        179.67         104179.0       .002266
 5       4.1     549.2        1.809       79001.        .037        156.22         106092.6       .002309
 6       8.1     615.5        1.863       75953.        .033        138.27         107029.2       .002328
 7      16.4     694.8        1.865       72630.        .033        121.73         107583.7       .002340
 8      24.6     749.5        1.834       69674.        .036        112.82         107761.3       .002344
 9      32.5     792.4        1.792       65646.        .037        107.22         107908.5       .002347
10      40.9     834.9        1.748       63119.        .041        101.69         107864.1       .002346
11      48.9     873.1        1.708       60837.        .043         97.97         107938.7       .002348
12      57.0     903.6        1.667       58718.        .046         95.21         107852.5       .002346
13      65.0     933.3        1.619       56859.        .047         94.25         107667.3       .002347
14      73.4     965.1        1.581       55036.        .051         92.52         107779.1       .002344
15      81.6     992.1        1.543       53430.        .056         91.46         107419.6       .002336
16      90.4     993.9        1.479       51898.        .088         93.42         104245.4       .002267
17      98.4     766.1        1.207       50863.        .445        155.92          77331.6       .001652

                                         PT     X/D       STATIC      TW/TB        TB        PRESS
                                                       PRESS.(PSIA)               (F)        DEFECT
                                          1      -.5       99.6        1.24        78.3     -.472E-02
                                          2     90.4       90.6        1.48       523.5      .223E+01

                                AVERAGE PARAMETERS BETWEEN PRESSURE TAPS
            AVERAGE BULK REYNOLDS      AVERAGE WALL REYNOLDS      AVERAGE FRICTION FACTOR
                   66150.                     41168.                        .00479
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                    RUN 159H, DATE 04/08/76, GAS AIR  , MOLECULAR WT. =  28.97
TIN = 73.7 F, TOUT = 175.5 F, MASS FLOW RATE = 20.1 LB/HR, I =  52.2 AMPS, E =  2.830 VOLTS
PR.IN =  .720, GR/RESQ =    .214E-03, MACH(2) =  .157, MACH(16) =  .174, T,SURR =  76.0 F

TC     X/D        TW         TW/TB        BULK       HL/QGAS      BULK           QGAS            Q+
                  (F)                   REYNOLDS                 NUSSELT      BTU/HRFT2
 2      .1      103.6        1.060       56552.        .104      344.49        15033.3        .000475
 3     1.2      135.9        1.119       56454.        .209      155.02        13769.7        .000435
 4     2.1      151.6        1.146       56375.        .059      142.42        15737.2        .000497
 5     4.1      165.6        1.163       56192.        .034      125.79        16132.0        .000509
 6     8.1      177.5        1.181       55841.        .025      110.12        16236.2        .000514
 7    16.4      192.3        1.188       55128.        .024      105.12        16315.9        .000515
 8    24.5      203.2        1.189       54448.        .025      104.58        16325.7        .000516
 9    32.4      212.8        1.188       53830.        .025      102.22        16325.1        .000515
10    40.7      222.2        1.186       53189.        .027      100.45        16314.1        .000515
11    48.7      232.1        1.185       52593.        .028       97.94        16309.9        .000515
12    56.8      240.2        1.181       52002.        .029       97.37        16303.0        .000515
13    64.7      248.8        1.179       51435.        .030       96.20        16291.2        .000515
14    73.1      257.3        1.175       50853.        .032       95.35        16273.4        .000514
15    81.2      265.9        1.172       50299.        .037       94.06        16207.2        .000512
16    89.9      266.8        1.157       49729.        .063       98.64        15809.2        .000499
17    97.9      215.0        1.060       49284.        .139      247.11        14695.1        .000464

                                 PT     X/D        STATIC      TW/TB       TB        PRESS
                                                PRESS.(PSIA)               (F)       DEFECT
                                  1     -.5         74.5       1.05       71.5    -.513E-02
                                  2    90.0         71.2       1.15      168.5     .125E+01

                              AVERAGE PARAMETERS BETWEEN PRESSURE TAPS
          AVERAGE BULK REYNOLDS      AVERAGE WALL REYNOLDS       AVERAGE FRICTION FACTOR
                53146.                      45344.                        .00508




                    RUN 160H, DATE 04/08/76, GAS AIR  , MOLECULAR WT. =  28.97
TIN = 74.5 F, TOUT = 316.2 F, MASS FLOW RATE = 20.1 LB/HR, I =  79.2 AMPS, E =  4.495 VOLTS
PR.IN =  .720, GR/RESQ =    .491E-03, MACH(2) =  .157, MACH(16) =  .198, T,SURR =  78.0 F

TC     X/D        TW         TW/TB        BULK       HL/QGAS      BULK           QGAS            Q+
                  (F)                   REYNOLDS                 NUSSELT      BTU/HRFT2
 2      .1      144.6        1.134       56288.        .119      340.41        34269.2        .001083
 3     1.2      219.3        1.268       56063.        .205      154.56        31995.5        .001011
 4     2.1      258.1        1.336       55882.        .071      138.02        36103.5        .001141
 5     4.1      292.2        1.386       55464.        .040      121.46        37254.7        .001177
 6     8.1      322.8        1.415       54673.        .033      109.86        37620.2        .001189
 7    16.4      358.9        1.428       53151.        .032      100.05        37752.9        .001193
 8    24.5      384.5        1.422       51758.        .032       95.15        37800.4        .001194
 9    32.4      404.9        1.409       50471.        .033       92.39        37844.7        .001196
10    40.8      426.1        1.395       49185.        .035       89.68        37804.3        .001194
11    48.7      446.3        1.384       48060.        .036       87.58        37839.0        .001196
12    56.9      466.5        1.372       46993.        .039       85.44        37776.1        .001194
13    64.8      482.8        1.356       46018.        .040       84.90        37800.5        .001194
14    73.2      503.3        1.345       45038.        .044       82.74        37702.9        .001191
15    81.3      517.6        1.327       44126.        .048       82.60        37598.7        .001188
16    90.1      521.6        1.294       43251.        .084       84.31        36348.3        .001148
17    98.0      400.0        1.108       42597.        .250      147.80        31255.0        .000988

                                 PT     X/D        STATIC      TW/TB       TB        PRESS
                                                PRESS.(PSIA)               (F)       DEFECT
                                  1     -.5         74.5       1.11       72.9    -.513E-02
                                  2    90.1         70.2       1.29      298.5     .164E+01

                              AVERAGE PARAMETERS BETWEEN PRESSURE TAPS
          AVERAGE BULK REYNOLDS      AVERAGE WALL REYNOLDS       AVERAGE FRICTION FACTOR
                49783.                      37493.                        .00513
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                        RUN 1614, DATE 04/08/76, GAS AIR   , MOLECULAR WT. =  28.97
TIN = 75.4 F, TOUT = 445.3 F, MASS FLOW RATE = 20.0 LB/HR, I =  97.6 AMPS, E =  5.725 VOLTS
PR.IN =  .720, GR/RESQ =   .753E-03, MACH(2) =  .136, MACH(16) =  .214, T.SURR =  80.3 F

TC     X/D       TW        TW/TB       BULK       HL/QGAS      BULK          QGAS           Q+
                 (F)                 REYNOLDS                NUSSELT      BTU/HRFT2
 2       .1     183.5      1.213      55890.       .138       315.26       51343.0       .001627
 3      1.2     299.0      1.410      55550.       .206       152.23       46344.3       .001548
 4      2.1     357.8      1.510      55275.       .071       135.52       55245.4       .001751
 5      4.1     411.4      1.586      54645.       .046       113.72       56758.2       .001799
 6      8.1     460.1      1.630      53489.       .039       106.10       57367.6       .001819
 7     16.4     513.4      1.640      51290.       .038        94.52       57619.6       .001825
 8     24.5     559.0      1.622      49308.       .040        88.34       57698.0       .001828
 9     32.4     591.3      1.596      47595.       .041        84.82       57774.4       .001831
10     40.6     624.7      1.569      45964.       .045        81.35       57668.5       .001828
11     48.8     655.4      1.545      44531.       .046        78.44       57731.9       .001830
12     56.9     685.0      1.520      43198.       .051        75.85       57610.9       .001826
13     64.9     705.2      1.488      42002.       .052        75.44       57651.4       .001827
14     73.3     733.9      1.463      40628.       .057        73.99       57468.4       .001822
15     81.4     753.8      1.433      39798.       .062        73.76       57279.7       .001815
16     90.2     753.5      1.380      38778.       .103        75.79       55121.4       .001747
17     98.2     567.0      1.134      38070.       .392       165.80       43121.0       .001367

                                  PT      X/D       STATIC       TW/TB       TB        PRESS
                                                PRESS.(PSIA)                (F)       DEFECT
                                   1       -.5       74.7        1.17       74.3    -.514E-02
                                   2      90.3       69.5        1.33      419.8     .203E+01

                                  AVERAGE PARAMETERS BETWEEN PRESSURE TAPS
             AVERAGE BULK REYNOLDS      AVERAGE WALL REYNOLDS      AVERAGE FRICTION FACTOR
                   47355.                     32532.                       .00526
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                        RUN 1624, DATE 04/08/76, GAS AIR   , MOLECULAR WT. =  28.97
TIN = 76.8 F, TOUT = 586.5 F, MASS FLOW RATE = 20.0 LB/HR, I = 114.8 AMPS, E =  6.890 VOLTS
PR.IN =  .719, GR/RESQ =   .103E-02, MACH(2) =  .157, MACH(16) =  .234, T.SURR =  84.7 F

TC     X/D       TW        TW/TB       BULK       HL/QGAS      BULK          QGAS           Q+
                 (F)                 REYNOLDS                NUSSELT      BTU/HRFT2
 2       .1     236.8      1.298      55787.       .138       338.36       71310.5       .002251
 3      1.2     383.5      1.566      55319.       .208       151.00       57684.7       .002143
 4      2.1     470.7      1.704      54940.       .072       135.46       76985.6       .002430
 5      4.1     549.7      1.813      54073.       .052       115.80       78553.2       .002489
 6      8.1     624.9      1.876      52541.       .046       101.25       79743.6       .002517
 7     16.4     710.4      1.879      49627.       .047        89.12       80165.1       .002531
 8     24.6     770.3      1.845      47167.       .050        81.14       80210.0       .002532
 9     32.5     815.8      1.799      45112.       .053        76.60       80261.9       .002534
10     40.9     860.6      1.751      43155.       .058        72.71       80112.7       .002529
11     48.9     899.1      1.705      41502.       .061        70.30       80108.1       .002529
12     57.0     935.8      1.661      40009.       .065        68.12       79945.1       .002524
13     65.0     963.2      1.613      38674.       .069        67.21       79895.4       .002522
14     73.4     994.9      1.570      37386.       .073        66.24       79717.1       .002517
15     81.6    1019.8      1.527      36270.       .081        65.65       79258.7       .002503
16     90.4    1016.5      1.457      35182.       .126        67.60       75066.3       .002401
17     98.4     751.4      1.159      34529.       .522       131.91       51867.8       .001637

                                  PT      X/D       STATIC       TW/TB       TB        PRESS
                                                PRESS.(PSIA)                (F)       DEFECT
                                   1       -.5       74.6        1.24       75.2    -.514E-02
                                   2      90.4       68.3        1.45      553.9     .244E+01

                                  AVERAGE PARAMETERS BETWEEN PRESSURE TAPS
             AVERAGE BULK REYNOLDS      AVERAGE WALL REYNOLDS      AVERAGE FRICTION FACTOR
                   45515.                     28654.                       .00530
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                    RUN 163H, DATE 04/08/76, GAS AIR   , MOLECULAR WT. =  28.97
TIN = 76.8 F, TOUT = 345.4 F, MASS FLOW RATE = 11.8 LB/HR, I =  64.4 AMPS, E =  3.635 VOLTS
PR.IN =   .719, GR/RESQ =    .572E-03, MACH(2) =   .116, MACH(16) =   .145, T,SURR =   83.0 F

TC      X/D       TW          TW/TB        BULK       HL/QGAS      BULK            QGAS          Q+
                  (F)                    REYNOLDS                 NUSSELT        BTU/HRFT2
 2       .1      152.0        1.140       32842.        .201       194.33         21115.9       .001133
 3      1.2      215.8        1.255       32706.        .252        99.01         19981.1       .001067
 4      2.1      255.2        1.321       32594.        .104        90.78         23143.7       .001242
 5      4.1      292.9        1.377       32326.        .063        79.01         24107.3       .001296
 6      8.1      325.6        1.410       31818.        .050        70.96         24466.2       .001313
 7     16.4      365.0        1.419       30830.        .049        64.45         24565.7       .001319
 8     24.5      392.0        1.410       29959.        .050        61.30         24599.1       .001320
 9     32.4      415.0        1.397       29141.        .051        59.22         24602.4       .001321
10     40.8      439.8        1.383       28349.        .056        57.27         24533.4       .001317
11     48.7      462.3        1.372       27650.        .058        55.52         24528.5       .001317
12     56.9      482.5        1.356       26998.        .062        54.46         24456.1       .001313
13     64.8      499.9        1.338       26389.        .063        54.08         24463.0       .001313
14     73.2      523.5        1.328       25783.        .071        52.19         24321.5       .001305
15     81.3      539.1        1.309       25247.        .078        52.21         24198.7       .001299
16     90.1      544.5        1.277       24714.        .143        52.17         22817.7       .001225
17     98.1      393.1        1.065       24334.        .385       181.09         18639.4       .001000

                                  PT     X/D        STATIC      TW/TB       TB        PRESS
                                                 PRESS.(PSIA)              (F)       DEFECT
                                   1      -.5        59.2        1.12       75.3    -.533E-02
                                   2     90.1        57.1        1.28      325.6     .138E+01

                              AVERAGE PARAMETERS BETWEEN PRESSURE TAPS
            AVERAGE BULK REYNOLDS      AVERAGE WALL REYNOLDS      AVERAGE FRICTION FACTOR
                 28736.                       21742.                       .00612
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                    RUN 164H, DATE 04/08/76, GAS AIR   , MOLECULAR WT. =  28.97
TIN = 77.2 F, TOUT = 473.1 F, MASS FLOW RATE = 11.9 LB/HR, I =  79.0 AMPS, E =  4.565 VOLTS
PR.IN =   .719, GR/RESQ =    .644E-03, MACH(2) =   .117, MACH(16) =   .159, T,SURR =   84.0 F

TC      X/D       TW          TW/TB        BULK       HL/QGAS      BULK            QGAS          Q+
                  (F)                    REYNOLDS                 NUSSELT        BTU/HRFT2
 2       .1      179.9        1.190       32977.        .176       219.43         32530.2       .001734
 3      1.2      280.5        1.367       32771.        .291       102.21         29850.6       .001592
 4      2.1      338.2        1.465       32602.        .106        93.49         34992.6       .001866
 5      4.1      395.6        1.547       32203.        .069        80.22         36350.3       .001938
 6      8.1      444.3        1.594       31475.        .057        70.66         36896.2       .001967
 7     16.4      509.8        1.603       30079.        .057        62.60         37052.3       .001976
 8     24.5      550.9        1.582       28842.        .059        58.65         37081.2       .001977
 9     32.4      585.0        1.554       27779.        .062        56.22         37093.5       .001978
10     40.8      613.4        1.523       26772.        .068        54.03         36969.4       .001971
11     48.8      649.6        1.497       25886.        .070        52.17         36956.6       .001971
12     56.9      679.7        1.470       25083.        .077        50.65         36809.3       .001963
13     64.9      703.5        1.439       24345.        .079        50.45         36794.3       .001962
14     73.3      731.2        1.412       23654.        .087        49.51         36011.0       .001952
15     81.4      754.6        1.385       23024.        .096        49.05         36347.7       .001938
16     90.2      753.1        1.336       22410.        .168        49.35         34115.2       .001819
17     98.2      536.9        1.063       22026.        .564       196.02         25089.3       .001338

                                  PT     X/D        STATIC      TW/TB       TB        PRESS
                                                 PRESS.(PSIA)              (F)       DEFECT
                                   1      -.5        59.1        1.16       77.2    -.583E-02
                                   2     90.3        56.6        1.33      451.9     .222E+01

                              AVERAGE PARAMETERS BETWEEN PRESSURE TAPS
            AVERAGE BULK REYNOLDS      AVERAGE WALL REYNOLDS      AVERAGE FRICTION FACTOR
                 27706.                       19706.                       .00599
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                  RUN 165H, DATE 04/08/76, GAS AIR   , MOLECULAR WT. =  28.97
TIN = 77.7 F, TOUT = 623.1 F, MASS FLOW RATE = 11.8 LB/HR, I =  93.0 AMPS, E =  5.535 VOLTS
PR.IN =  .719, GR/RESQ =    .116E-02, MACH(2) =  .117, MACH(16) =  .172, T,SURR =  85.5 F

TC     X/D       TW         TW/TB      BULK      HL/QGAS      BULK            QGAS          Q+
                 (F)                 REYNOLDS               NUSSELT        BTU/HRFT2
 2       .1     220.1       1.262     32826.       .174      220.03          45309.1     .002420
 3      1.2     361.7       1.510     32541.       .300      100.67          41322.3     .002267
 4      2.1     443.9       1.647     32307.       .110       92.11          48679.7     .002500
 5      4.1     530.8       1.758     31754.       .080       77.17          50346.0     .002669
 6      8.1     612.7       1.838     30792.       .070       66.52          51122.5     .002731
 7     16.4     704.5       1.841     28953.       .072       57.21          51352.9     .002743
 8     24.6     763.0       1.798     27443.       .077       52.68          51316.7     .002741
 9     32.5     809.5       1.746     26163.       .081       50.01          51273.8     .002739
10     40.9     851.3       1.691     24977.       .089       47.72          51064.9     .002728
11     48.9     889.7       1.642     23975.       .093       46.33          50962.7     .002723
12     57.0     925.6       1.595     23077.       .101       45.01          50765.7     .002712
13     65.0     954.2       1.546     22264.       .105       44.63          50651.5     .002706
14     73.4     989.3       1.506     21515.       .114       43.74          50361.8     .002691
15     81.6    1015.9       1.464     20841.       .126       43.62          49917.9     .002666
16     90.4    1019.0       1.402     20216.       .204       43.56          46680.7     .002493
17     98.4     707.4       1.073     19871.       .967      144.55          27984.6     .001495

                                    PT     X/D        STATIC      TW/TB       TB       PRESS
                                                  PRESS.(PSIA)              (F)      DEFECT
                                     1      -.5        59.1       1.22       78.2   -.583E-02
                                     2     90.4        56.0       1.40      595.5    .266E+01

                                 AVERAGE PARAMETERS BETWEEN PRESSURE TAPS
              AVERAGE BULK REYNOLDS      AVERAGE WALL REYNOLDS      AVERAGE FRICTION FACTOR
                     26540.                     17482.                      .00613
```

```
                  RUN 167H, DATE 04/08/76, GAS AIR   , MOLECULAR WT. =  28.97
TIN = 75.4 F, TOUT = 177.1 F, MASS FLOW RATE = 11.8 LB/HR, I =  39.8 AMPS, E =  2.310 VOLTS
PR.IN =  .720, GR/RESQ =    .218E-03, MACH(2) =  .117, MACH(16) =  .127, T,SURR =  80.0 F

TC     X/D       TW         TW/TB      BULK      HL/QGAS      BULK            QGAS          Q+
                 (F)                 REYNOLDS               NUSSELT        BTU/HRFT2
 2       .1      99.9       1.047     33124.       .109      247.28           8711.1     .000468
 3      1.2     125.0       1.094     33070.       .273      105.44           7597.3     .000407
 4      2.1     140.6       1.120     33025.       .091       96.19           8873.1     .000475
 5      4.1     154.6       1.141     32922.       .051       83.70           9216.3     .000493
 6      8.1     166.5       1.154     32722.       .037       75.53           9353.6     .000501
 7     16.4     180.1       1.161     32313.       .035       71.49           9375.0     .000502
 8     24.5     190.1       1.161     31927.       .036       69.46           9376.9     .000502
 9     32.3     198.8       1.159     31572.       .037       68.30           9371.3     .000502
10     40.7     207.5       1.156     31204.       .039       67.46           9357.1     .000501
11     48.7     216.4       1.154     30862.       .041       66.33           9353.4     .000501
12     56.8     225.8       1.154     30522.       .044       64.72           9329.8     .000499
13     64.7     233.0       1.149     30197.       .045       64.81           9325.9     .000499
14     73.0     242.5       1.148     29863.       .049       63.35           9295.5     .000498
15     81.2     250.1       1.145     29545.       .056       62.39           9239.5     .000495
16     89.9     252.9       1.133     29221.       .103       64.07           8850.4     .000474
17     97.9     194.3       1.027     29972.       .174      317.76           8274.1     .000443

                                    PT     X/D        STATIC      TW/TB       TB       PRESS
                                                  PRESS.(PSIA)              (F)      DEFECT
                                     1      -.5        59.0       1.04       74.4   -.532E-02
                                     2     90.0        57.5       1.13      169.4    .136E+01

                                 AVERAGE PARAMETERS BETWEEN PRESSURE TAPS
              AVERAGE BULK REYNOLDS      AVERAGE WALL REYNOLDS      AVERAGE FRICTION FACTOR
                     31175.                     27258.                      .00581
```

APPENDIX E.

Thermocouple Conduction Error

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A thermocouple attached to the outside surface of a heated tube acts as a fin or extended surface which lowers the temperature at the point of attachment. Since this point also serves as the thermocouple junction, it measures a wall temperature lower than the value which would occur without its presence. The difference is known as "thermocouple conduction error." Consequently, in an experiment such as the present study, the deduced Nusselt number is systematically increased unless corrected for this effect.

Analyses

Based on extended surface analyses, the normalized thermocouple conduction error θ has been shown by Schneider [48] to be approximately

$$\theta = \frac{t_w - t_{TC}}{t_w - t_\infty} = \left[1 + \frac{2\pi k_{tube}\delta_{tube}}{h_{TC}A_s}\lambda r_o \frac{K_1(\lambda r_o)}{K_o(\lambda r_o)}\right]^{-1} \qquad \text{(E1)}$$

where t_w is the temperature of the undisturbed tube, $h_{TC}A_s$ is the thermocouple conductance and r_o is the effective radius of the thermocouple attachment. K_o and K_1 are modified Bessel functions of the second kind of order zero and one, respectively [49,50]. The quantity λ is defined as

$$\lambda = \frac{h_o + h_i}{k_{tube}\,\delta_{tube}}$$

and the thermocouple conductance is defined by the equation

$q_{TC} = h_{TC}A_s(t_{TC}-t_\infty)$. Thus, in this approximation θ is a function of the non-dimensional parameters λr_o and $M = k_{tube}\delta_{tube}/(h_{TC}A_s)$.

Using approximations to the Bessel functions, valid at small values of the argument, one may reduce equation (E1) further so that it takes the form

$$\theta \approx -\ln(\lambda r_o)/2\pi M \qquad \text{(E2)}$$

when $2\pi M >> 1$. This form is useful for estimates of the maginitude of θ when desiring to determine whether it is significant in a given case. It is presented as Figure E1.

In calibration for thermocouple conduction error data are normally obtained without flow so a probe can be used to measure the tube wall temperature in the vicinity of the thermocouple. In this case, $h_i = 0$. Examining Figure E1, one can see that the effect of flow (i.e., non zero value of h_i) is to increase λr_o and reduce θ for the same thermocouple attachment and environment.

Hess [29] extended and improved Schneider's analysis for application to electrically heated tubes with internal flow such as the present experiment. His representation takes the form

$$\theta = \frac{(1-h_o/h_{TC})}{\dfrac{h_i + h_o}{h_{TC}} + \dfrac{2k_w\delta}{h_{TC}r_o^2}\,\dfrac{\lambda r_o K_1(\lambda r_o)}{K_o(\lambda r_o)}} \qquad \text{(E3)}$$

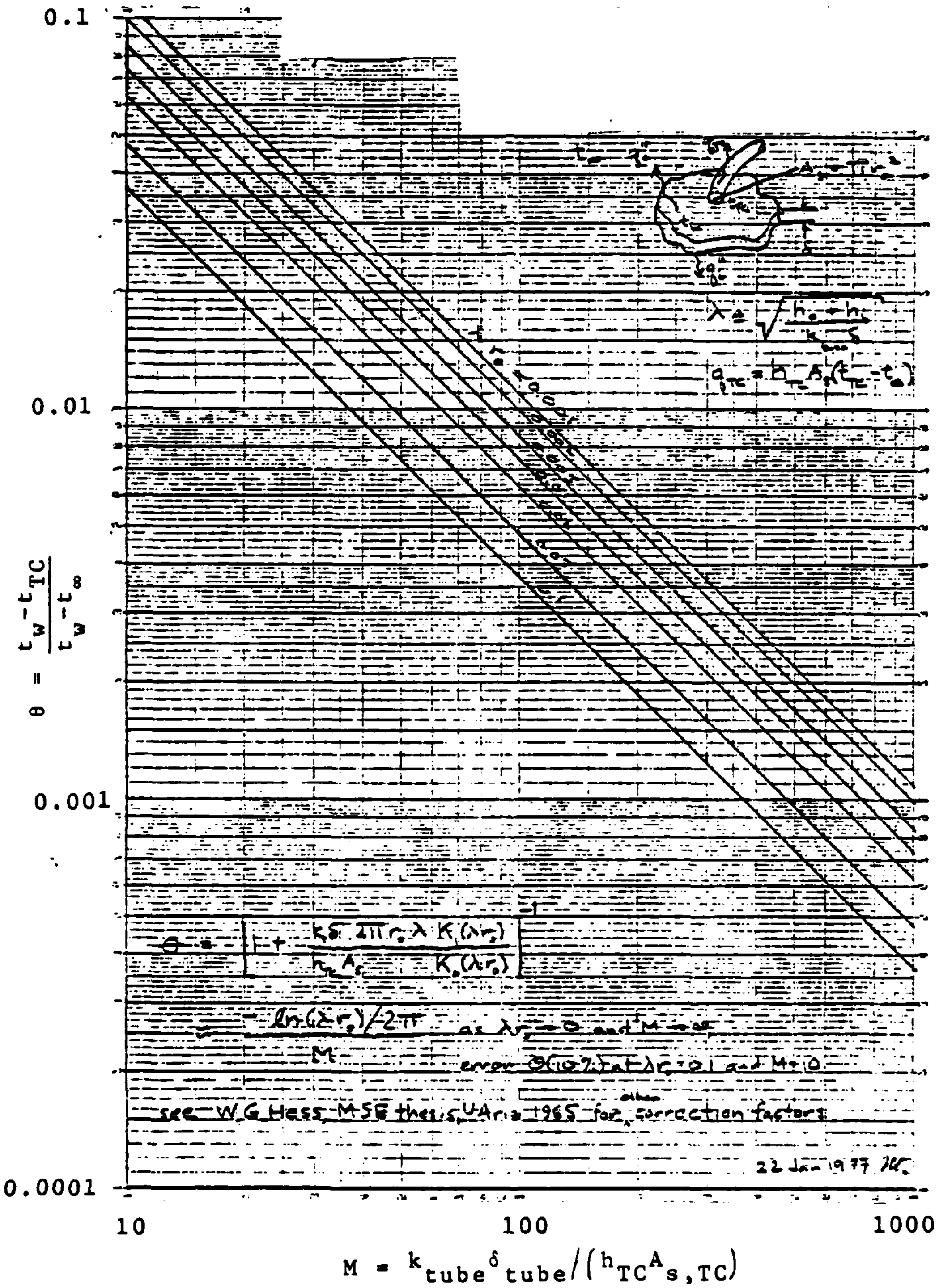

Fig. E1. Approximation to thermocouple conduction error for large values of parameter $M = k_{tube}\delta_{tube}/(h_{TC}A_{s,TC})$.

Evaluation of thermocouple conductance, $h_{TC}A_s$

For fine wire thermocouples in an environment at atmospheric pressure, free convection dominates as the mechanism for heat loss from the thermocouple compared to radiation. As an approximation, one may consider the total heat transfer coefficient and properties to be constant for the thermocouple wire and derive

$$q_{TC} = \sqrt{(h_r + h_{NC})Pk_{TC}A_{CS}}\,(t_{TC}-t_\infty)\tanh m\ell \qquad (E4)$$

as by Schneider [48]. For long wires, i.e., $m\ell = \sqrt{\ell\ hP/kA} \geq 5$, $\tanh m\ell$ approaches unity; then $h_{TC}A_S$ becomes $\sqrt{(h_r + h_{NC})Pk_{TC}A_{CS}}$.

The wire can be considered a small body in large surroundings so

$$h_r \approx \varepsilon\sigma\,[T_{TC}^4 - T_\infty^4]/(T_{TC}-T_\infty) \qquad (E5)$$

The heat transfer coefficient for natural convection can be determined from a correlation of the form $Nu_f = fn(Gr_f Pr)$. The Grashof number is typically small for wires of the size of our thermocouples. For the range $10^{-3} < GrPr < 10^{-1}$ the curve recommended by Kreith [51, Fig.7-3] can be represented as

$$Nu_f = \frac{h_{NC}d}{K_f} = 0.315 + 0.8\,[Gr_f Pr_f]^{0.18} \qquad (E6)$$

In an unpublished note, Hess, Deardorff and McEligot [52, included herein as Appendix F] examined available calibration data for radiating thermocouples attached in the parallel junction form of Moen [28]. From comparisons between predictions and measurements, they concluded that the effective radius of the thermocouple attachment, r_o, was approximately equal to the actual radius of the thermocouple wire. Consequently, $A_s = \pi r_o^2 \approx A_{CS} = \pi d^2/4$. The calibration data of Campbell [53] for an atmospheric environment are also in approximate agreement with the choice of d/2 as r_o.

Application to present experiment

The heat transfer coefficient from the outside of the tube, h_o, may be deduced from the heat loss calibration equation (B5), to be

$$h_o = [C_1 + C_2(t_w - t_\infty) + C_3(t_w - t_\infty)^2]/\pi D \qquad (E7)$$

For h_i either a correlation such as equation (19) or tabular data from the initial data reduction can be employed. In this experiment h_i is typically of the order of 200 Btu/hrft²°F or more.

As an example of the magnitude of thermocouple conduction error to be expected, Figure E2 has been plotted for thermocouple 10. The value of h_i was taken as 200 Btu/hrft²°F and the environmental temperature was assumed to be about 70°F for this presentation. The reduction in θ with flow is clear and it is also seen that in the heat loss runs (no flow) θ decreases slightly as the wall temperature increases.

For the tabular results of Appendix D the thermocouple conduction error was calculated from equations (E3) through (E7) and correlations (19) and (B5). Material and fluid

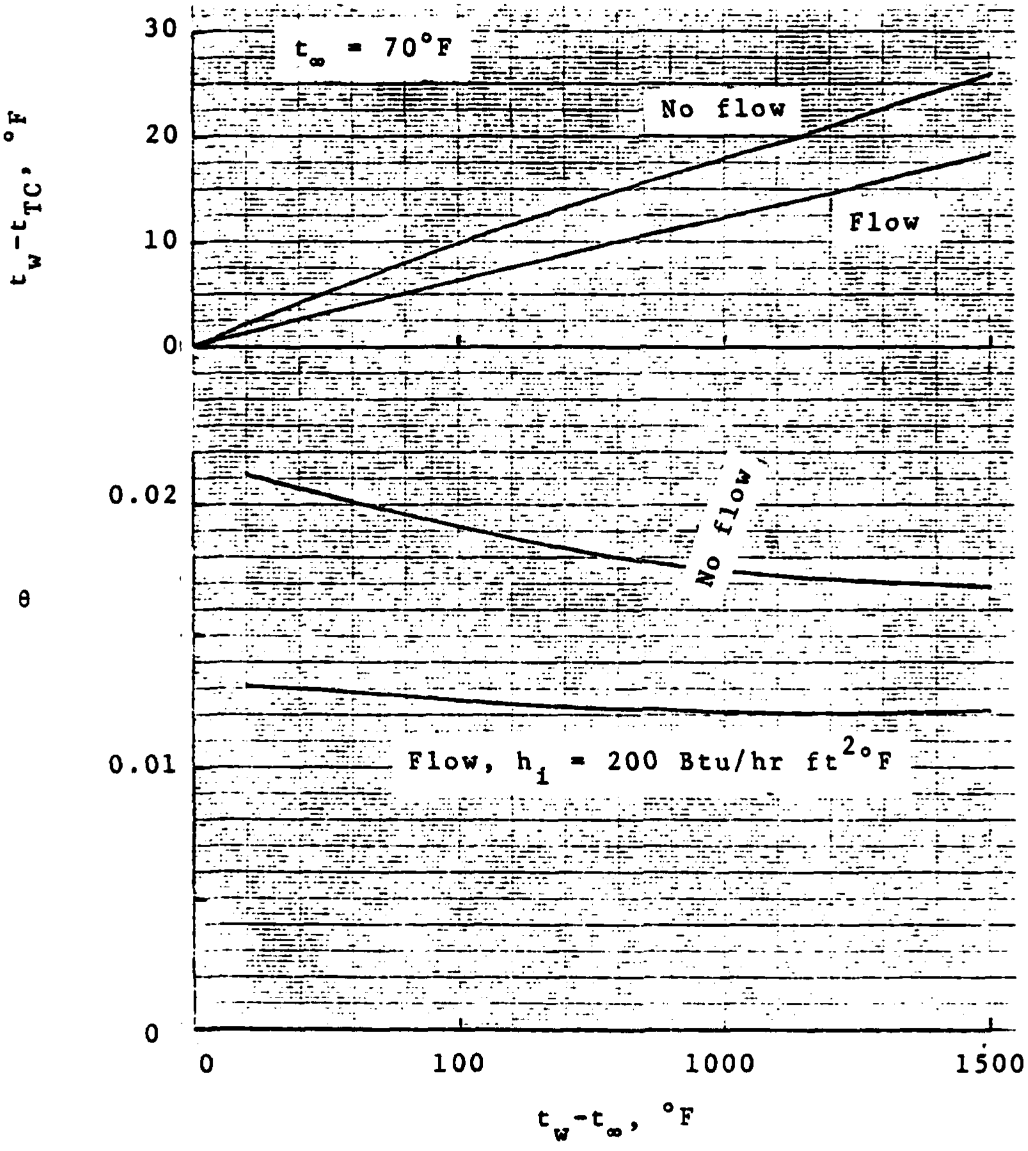

Fig. E2. Predicted thermocouple conduction error for thermocouple 10.

properties used in evaluating the thermocouple conductance were based on the temperature at the junction and its resulting film temperature, $t_f = (t_{TC} + t_\infty)/2$, as appropriate. While a numerical solution could be applied to improve the analysis predicting the thermocouple conductance, such sophistication does not appear warranted due to the uncertain knowledge of several quantities and the small magnitude of θ.

APPENDIX F.

Radiating Thermocouple Conduction Error

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In space environments and space simulation chambers, temperatures are often measured with thermocouples attached to exposed surfaces. The primary means of energy exchange then are conduction through the solid material and thermal radiation. In our Laboratory, we also often use a vacuum environment to minimize and/or localize the heat loss from thin-walled tubes in which we perform internal convective heat transfer measurements [38]. In these situations the thermocouple attachment usually acts as a radiating fin which reduces the local surface temperature near the point of measurement. This systematic effect may be called the radiating thermocouple conduction error.

Schneider [48] presents an analysis to predict the thermocouple conduction error in a convective environment by idealizing the thermocouple as a cylinder mounted perpendicular to the surface at a single point.

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[1] Now with Pratt and Whitney Aircraft Company, West Palm Beach, Florida.

[2] Now with Gulf General Atomics, La Jolla, California.

Including energy generation in the wall by electrical resistive heating and energy transfer from the surface opposite the idealized thermocouple, one may extend Schneider's result to

$$\frac{T_{TC} - T_{w,u}}{T_{w,u} - T_\infty} = \frac{(h_o - h_{TC}) r\, K_o(\lambda r)}{(h_i + h_{TC}) r\, K_o(\lambda r) + 2\lambda k_w \delta K_1(\lambda r)} \qquad \text{(F1)}$$

where the heat transfer coefficients may represent convective or radiative processes as appropriate. In the case of infinite radiating thermocouple leads, the effective heat transfer coefficient over the contact area of the thermocouple may be shown to be

$$h_{TC} = \frac{k_{TC}\left[\frac{2\beta}{5}\left(T_{TC}^5 - 5T_{TC}T_\infty^4 + 4T_\infty^5\right)\right]^{\frac{1}{2}}}{T_{TC} - T_\infty} \qquad \text{(f2)}$$

if its emissivity and thermal conductivity are constant. Thus, provided that the material properties are known, prediction of the radiating thermocouple conduction error reduces to the problem of determining the effective thermocouple radius, r.

For many applications the parallel type thermocouple junction, shown in the insert of Figure F1, is more accurate than the more common cross type junction because the location of the measuring plane is effectively on the tube surface rather than being spread perpendicular to it [28].

Rather than satisfying the idealization of a single cylindrical interface between the thermocouple and the surface, the attachment region for the parallel junction consists of two roughly elliptical areas slightly separated from each other. Accordingly, the objectives of the present work were taken to be (1) to determine r for a parallel junction configuration and (2) to investigate the reproducibility of the conduction error when such thermocouples are produced by using normal laboratory standards for equipment construction.

Measurements were conducted on three circular test sections of 0.010 inch thick Inconel 600, two feet long. Premium grade bare Chromel and Alumel thermocouple wires of 0.005 inch diameter were spot welded to the test section by the electrical discharge technique. Circumferential distance between the two wires was approximately 1/8 inch and the attached area of each covered approximately one to two wire diameters. Tests included about fourteen such thermocouples with all wires taken from the same spools.

These resistively heated test sections were mounted in glass vacuum chambers. With no intermal flow, h_i equals zero and h_o can be determined from the tube emissivity which one also deduces from the tests. "Undisturbed" tube wall temperatures, $T_{w,u}$, were determined with a traveling internal thermocouple probe, also of premium grade Chromel-Alumel, which measured the wall temperature profile axially betwenn the thermocouples. Calculations show the maximum temperature drop through the wall to be less than 0.01°F so the thin wall idealization is valid. Readings were accepted without correction for deviation from standard N.B.S. emf tables since Hoskins Manufacturing Company certified the deviation as less than 1°F.

<u>Results</u> are demonstrated on Figure F1. The dashed curves are predictions based on equations (F1) and (F2) in conjunction with manufacturers' information for emissivities and thermal conductivities of the thermocouple wires and the tube. The solid curve represents predictions based on the measured emissibity of the Inconel tube used by Hess and on an effective thermoucouple radius equal to the actual wire diameter; otherwise the bases are the same.

Hess' data points are averages of the thermocouple readings for the central protion of the tube and they show the effective radius to be approximately equal to the wire diameter or slightly less. The measurements of Swearingen and of Reynolds and Deardorff are from test sections with different thermal histories, hence emissivities, but of the same materials and dimensions. Their calibrations suggest that r is about one-half the wire diameter. Different welding jigs were used for each and, consequently, the region of attachment varied from test section to test section but would be approximately uniform for different thermocouples on the same test section. Accordingly, one would expect the level of the thermocouple conduction error to vary from test section to test section as it does in Figure F1.

We conclude that the effective radius of the thermocouple attachment is approximately one-half to one wire diameter when constructed in the manner described. One may use this observation with manufacturers' information and equations (F1) and (F2) to determine whether the systematic error will be significant in his specific application. (For the results shown, in an internal convective heating experiment with $T_w \simeq 1000°F$ and $T_b \simeq 900°F$, the resulting error in Nusselt number would be 5 to 10 per cent.) If such predictions indicate that the errors would be important, we recommend individual calibration since the values of a number of the pertinent input variables are not readily available.

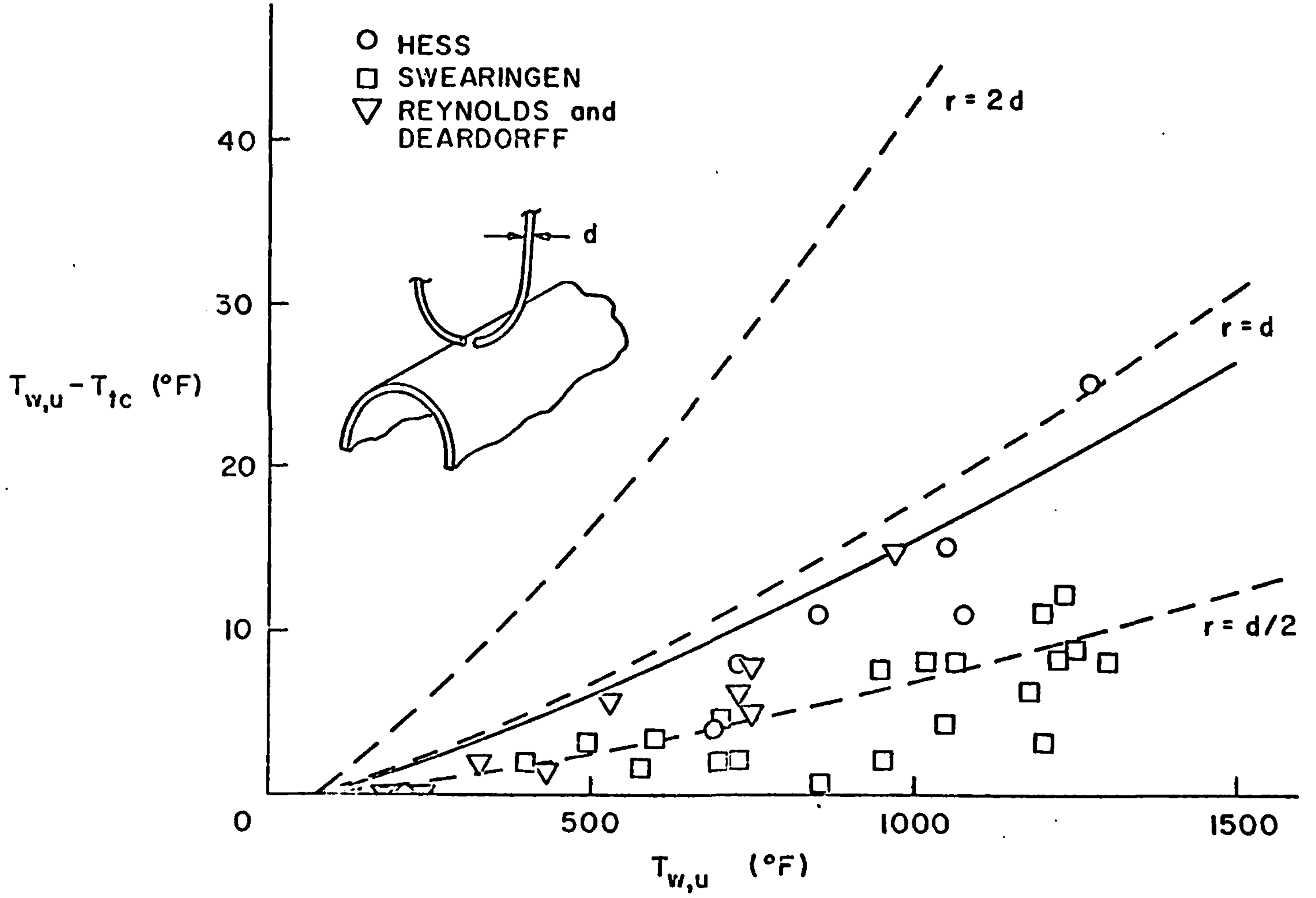

Figure F1. RADIATING THERMOCOUPLE CONDUCTION ERROR FOR PARALLEL TYPE JUNCTION

NOMENCALTURE

h	Heat transfer coefficient; h_i, inner surface: (thermocouple) surface.
k	thermal conductivity
K_o, K_1	Bessel functions
r	effective thermocouple attachment radius
T_{TC}	temperature measured by thermocouple
$T_{w,u}$	"undisturbed" wall temperature
β	thermocouple heat transfer constant, $2\sigma\varepsilon/(k_{TC}r)$
δ	wall thickness
ε	emissivity
λ	wall heat transfer constant, $[h_o + h_i)/(k_w r)]^{1/2}$
σ	Stefan-Boltzman constant

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