H. C. PERKINS
P. WORSOE-SCHMIDT

**TURBULENT HEAT AND MOMENTUM
TRANSFER FOR GASES IN A CIRCULAR TUBE
AT WALL-TO-BULK TEMPERATURE
RATIOS TO SEVEN**

MASTER

Technical Report No. SU 247-7

Submitted to
Division of Reactor Development
Atomic Energy Commission
September 1964

**The NUCLEAR TECHNOLOGY LABORATORY
at STANFORD UNIVERSITY
Stanford, California**

PATENT CLEARANCE OBTAINED. RELEASE TO
THE PUBLIC IS APPROVED. PROCEDURES
ARE ON FILE IN THE RECEIVING SECTION.

DISCLAIMER

This report was prepared as an account of work sponsored by an agency of the United States Government. Neither the United States Government nor any agency Thereof, nor any of their employees, makes any warranty, express or implied, or assumes any legal liability or responsibility for the accuracy, completeness, or usefulness of any information, apparatus, product, or process disclosed, or represents that its use would not infringe privately owned rights. Reference herein to any specific commercial product, process, or service by trade name, trademark, manufacturer, or otherwise does not necessarily constitute or imply its endorsement, recommendation, or favoring by the United States Government or any agency thereof. The views and opinions of authors expressed herein do not necessarily state or reflect those of the United States Government or any agency thereof.

DISCLAIMER

Portions of this document may be illegible in electronic image products. Images are produced from the best available original document.

TURBULENT HEAT AND MOMENTUM TRANSFER FOR GASES
IN A CIRCULAR TUBE AT WALL TO BULK
TEMPERATURE RATIOS TO SEVEN

Technical Report SU 247-7

by

H. C. Perkins
P. Worsoe-Schmidt

Submitted to
United States Atomic Energy Commission
Division of Reactor Development

Approved by
George Leppert, Principal Investigator
Contract No. AT(04-3)-247

September 1964

Department of Mechanical Engineering
Stanford University
Stanford, California

LEGAL NOTICE

This report was prepared as an account of Government sponsored work. Neither the United States, nor the Commission, nor any person acting on behalf of the Commission:

- A. makes any warranty or representation, expressed or implied, with respect to the accuracy, completeness, or usefulness of the information contained in this report, or that the use of any information, apparatus, method, or process disclosed in this report may not infringe privately owned rights; or
- B. assumes any liabilities with respect to the use of, or for damages resulting from the use of any information, apparatus, method, or process disclosed in this report.

As used in the above, "person acting on behalf of the Commission" includes any employee or contractor of the Commission, or employee of such contractor, to the extent that such employee or contractor of the Commission, or employee of such contractor, prepares, disseminates, or provides access to, any information pursuant to his employment or contract with the Commission, or his employment with such contractor.

ACKNOWLEDGEMENTS

William N. Lucas and David L. Ludwig assisted in obtaining and correlating the experimental data, while the computer program used for data reduction was written by Dr. Donald M. McEligot.

ABSTRACT

Measurements are reported for local friction and heat transfer coefficients with constant heat flux in an electrically heated circular tube. Precooled nitrogen in turbulent flow was used to obtain local wall to bulk temperature ratios from 1.24 to 7.54. The Inconel test section had a 40 diameter hydrodynamic entry section and a 160 diameter heated section. The bulk inlet Reynolds numbers covered the range from 18,300 to 279,000. Correlations in terms of both the bulk and the modified wall Reynolds numbers are presented for the local friction factors; the local heat transfer results are presented in terms of the wall to bulk temperature ratio with bulk properties and also directly on the modified wall Reynolds number. Both the friction and heat transfer results are shown to be significantly affected by the influence of the variable properties. Entrance region effects for both the heat transfer and friction coefficients are discussed.

TABLE OF CONTENTS

	Page
Acknowledgements	iii
Abstract	iv
Table of Contents	v
List of Illustrations	vi
List of Tables	viii
Nomenclature	ix
Introduction	1
Experimental Apparatus	2
Definitions and Calculations	4
Results and Correlations	6
Friction Results	9
Heat Transfer Results	13
Entry Region Heat Transfer	17
Average Heat Transfer Results	18
Transition Behavior	19
Conclusions	19
Illustrations	21
Tables	37
Bibliography	40
Appendix - Sample Data	42

LIST OF ILLUSTRATIONS

Figure		Page
1	Test Section and Cooling Dewar	21
2	Variation of Experimental Parameters with x/D	22
3	Local Friction Coefficients Normalized On Isothermal Wall Conditions, $16 \leq x/D \leq 114$. Correlation as suggested by Kutateladze and Leont'ev (14).	24
4	Entry Corrections for Friction Coefficients Based on Wall Properties.	25
5a	Local Friction Coefficients Correlated on the Karman-Nikuradse Line, $16 \leq x/D \leq 114$.	26
5b	Low $N_{Re,w}$ Friction Results.	27
6	Local Friction Coefficients Normalized on Isothermal Bulk Conditions, $16 \leq x/D \leq 114$.	28
7	Entry Correction for Friction Coefficients Based on Bulk Properties. Correction of Magee (15) included.	29
8	Comparison of the Friction Results of McEligot et al. (1) and Lel'chuk and Dyadyakin (9) with Present Correlation, Wall Properties Used Throughout. a) reference 9, entry corrected; b) reference 9, downstream; c) reference 1, entry corrected test section 14; d) reference 1), downstream test section 6.	30
9	Local Downstream Heat Transfer Results Based On Bulk Properties, $x/D \geq 65$.	31
10	Local Heat Transfer Results Based On Bulk Properties, $1.2 \leq x/D \leq 144$.	32
11	Comparison of the results of McEligot et al. (1) and Lel'chuk and Dyadyakin (9) with present experiment. Bulk properties used throughout, downstream data only. Solid line is correlation constant of 0.024, dotted line 0.023. Insert shows improvement of entry correction using T_w/T_b in entry parameter.	33

Figure		Page
12	Local Heat Transfer Results Based On Wall Properties, $1.2 \leq x/D \leq 144$.	34
13a	Average Heat Transfer Results for T_w/T_b to 2.46.	35
13b	Average Friction Coefficient Results for T_w/T_b to 2.46.	36

LIST OF TABLES

Table		Page
1	Selected Variable Properties, Turbulent Heat Transfer Experiments	37
2	Range of Variables in the Present Experiment	38
3	Transition Results	39

NOMENCLATURE

D	diameter
G	mass velocity, $\text{lb}_m/\text{ft}^2\text{hr}$
g_c	unit conversion $32.2 \text{ lbm ft}/\text{lb}_f\text{sec}^2$
H	enthalpy
h	heat transfer coefficient, $\text{Btu}/\text{hr}\cdot\text{ft}^2\cdot^\circ\text{F}$
L	length of test section
p	pressure
q''	heat flux, $\text{Btu}/\text{hr ft}^2$
R	gas constant
T	temperature
u	velocity in x direction
V	bulk average velocity
w	mass flow rate, lb_m/hr
x	distance down test section
N_{Re}	Reynolds number, $4w/\pi D \mu$
N_{Nu}	Nusselt number, hD/k
N_{Pr}	Prandtl number, $\mu c_p/k$

Greek letters

ρ	density, lb_m/ft^3
ϕ	impulse function, see equation 5
τ	shear stress
μ	viscosity

Subscripts

aw	adiabatic wall
iso	isothermal conditions
o	stagnation conditions
w	wall
b	bulk

Note: The absence of a subscript on dimensionless parameters and gas properties denotes bulk static properties.

INTRODUCTION

In the light of present day technological interests, particularly nuclear reactor power generation and rocket propulsion, convective heat transfer problems are becoming more involved with the effects of variable properties. Because of interest in these effects an experimental program has been under way at Stanford University for several years to measure friction and heat transfer coefficients with high wall to bulk temperature ratios^(1,2), the wall to bulk temperature ratio being a measure of the effect of the property variation across the flow stream. In order to attain greater ratios than those previously reached, on the order of 2.5, precooled gas was used so that the bulk temperature at the test section inlet was as low as 180°R. Consequently it was possible to reach local wall to bulk temperature ratios as high as 7.54.

The heat transfer apparatus consisted of an Inconel tube with a 40 diameter hydrodynamic entry section and a 160 diameter heated section. Ideally this results in a thermal boundary condition of uniform inlet temperature and a step change in heat flux at the wall. Local friction coefficients at x/D 's from 16 to 114 were determined from pressure drop information taken with 7 pressure taps. Thermocouples were used to measure the local wall temperature variations from which the local heat transfer coefficients could be determined. Average heat transfer and friction coefficients were found from the integrated local wall temperatures and the mean properties in the manner of Humble, et al.⁽³⁾.

Previous results for turbulent internal flow in ducts with precooled gas include those of McCarthy and Wolf⁽⁴⁾ and Wieland⁽⁵⁾. In reference 4 average heat transfer coefficients were measured with hydrogen and helium gas flowing in electrically heated circular tubes with length to diameter ratios

from 20 to 67. Because of the use of these relatively short test sections, a large entry effect on the average heat transfer results was found. Some local data over the downstream segment of the tube are also given. Correlations were determined on the bulk, film, and wall temperature properties with the use of the wall to bulk temperature ratio to some power. Wieland measured local heat transfer coefficients with hydrogen gas flowing in an electrically heated circular tube of some 250 diameters length. He correlated his data with both the wall and film modified Reynolds number. In both references it was found that for large wall to bulk temperature ratios, three or greater, a quite different wall temperature profile resulted than that for the ordinary constant heat flux case. Instead of the usual entrance region rise followed by a linear increase in wall temperature a sharp rise and then a drop in the wall temperature some 20 to 40 diameters downstream from the entrance was found.

Other work on high temperature heat transfer in a circular tube includes that of McEligot, et al.⁽¹⁾, Dalle Donne and Bowditch^(6,7), Taylor⁽⁸⁾, and Lel'chuk and Dyadyakin⁽⁹⁾. In these cases precooling was not used and typical values of the local wall to bulk temperature ratio were 2.5 or less. Taylor did achieve ratios up to 5.6 by using a tungsten tube which permitted wall temperatures to 5600°R. Table 1 summarizes the work and heat transfer results of the various authors. Previously, there have been no local friction coefficient results for temperature ratios greater than 2.5. In the present study, however, local friction coefficients were found at temperature ratios above 7. Table 2 summarizes the range of variables covered in the present work.

EXPERIMENTAL APPARATUS

The heat transfer loop and associated instrumentation

have previously been described in references 1 and 10. Only a brief description will be given here. The loop consists of a gas supply bank, followed by a pressure regulator, a system of filters, and an integral-orifice differential pressure flow meter. The gas passes through the liquid nitrogen cooler to the inlet mixer and then enters the test section after which it is cooled and exhausted to the atmosphere. The flow rate is controlled with a needle valve downstream from the test section. For the cold gas tests a stainless steel liquid nitrogen dewar was installed with a cooling coil. Figure 1 shows the details of the dewar and test section construction. A second container was used inside the dewar to control the temperature of the lower electrode on the test section independently of the inlet gas temperature. Thus the temperature difference between the mixer where the inlet temperature was measured and the lower electrode, where the heating began, could be minimized. By regulating the liquid nitrogen level in the two containers sufficient control was available so that little heat transfer to the gas took place in the 40 diameter hydrodynamic development section between the mixer and the lower electrode.

The test section consisted of an Inconel tube of 0.0216 inch wall and 0.1237 inch inside diameter, some 26 inches long including both the hydrodynamic, unheated, entry length and several diameters length after the last thermocouple. The useful length of the test section was some 144 diameters for heat transfer and 133 diameters for friction factors. Chromel-Alumel thermocouples were spot welded to the test section for temperature measurements and thin wall, 0.006 inch, 0.125 inch outside diameter, Inconel pressure taps were brazed to the test section for local pressure measurements. In all, thirteen thermocouples and ten pressure taps were attached to the tube. The pressure taps were drilled out with a 0.015 inch drill so the tap to tube diameter ratio

was about 0.1. Because of the difficulty in brazing and drilling the taps only 7 of the 10 taps were usable.

Pressure drops were measured on a gas over water and gas over mercury manometer bank. When the pressure drops were too small for accurate measurements on the vertical manometers an inclined water manometer was used. With this system pressure drops from 0.1 inch water to 60 inches of mercury from tap to tap or from any combination of taps could be determined.

Since the tube was heated using a DC welding generator and the thermocouples were directly attached some pick-up by the latter was noted. This was corrected for in the manner of Davenport, et al.⁽¹¹⁾. Several tests were conducted with heating but no flow through the tube to determine the local heat loss to the room during the actual test runs. The assumption was made that there was the same heat loss to the room with flow as occurred with no flow at the same wall temperature. This assumes similarity of wall temperature profiles between the heat loss runs and the actual flow runs. With the exception of the first diameters downstream from the start of heating this was the case.

DEFINITIONS AND CALCULATIONS

The local heat transfer coefficient is defined by the equation

$$q_w'' = h[T_w - T_{aw}] \quad (1)$$

The bulk static temperature is defined, by analogy to the energy equation for constant properties treatments, by the equation

$$C_{p,o} [T_o - T] = V^2/2g_c \quad (2)$$

which uses the definition of the bulk velocity as

$$V = GZRT/p \quad (3)$$

A more exact determination would require a knowledge of the actual variation over the cross section of the two-dimensional functions for H , ρ , and u . The local friction factor is defined as

$$f = \tau_w / V^2 / 2g_c \quad (4)$$

Momentum considerations for the steady flow of fluids through circular tubes lead to the following expression for the wall shear stress, τ_w , in terms of quantities which may be determined experimentally:

$$\tau_w = - \frac{D}{4} \frac{d}{dx} \left[p + \rho \frac{V^2}{2g_c} \right] = - \frac{D}{4} \frac{d\phi}{dx} \quad (5)$$

This expression, which neglects the change in elevation, assumes that the static pressure is uniform across the flow cross section and treats the momentum flux as one-dimensional.

The data reduction was performed on the IBM 7090 at the Stanford University Computation Center. The input consists of the thermocouple readings converted to degrees F, flow rate information, pressure drops from tap to tap, etc. Formulae and tables contained in the program provide gas properties which were taken from NBS 564⁽¹²⁾. Test section characteristics and overall coefficients for the radial heat loss are introduced when needed. In preliminary calculations the program computes the gas flow rate and corrects for the thermal expansion at the thermocouple and pressure tap locations.

Heat transfer results are obtained at the wall thermocouple locations. The wall heat flux is obtained by

subtracting the radial and axial heat losses from the total electrical energy generation. The inside wall temperature is determined from the heat flux and the outside wall temperature. Trapezoidal integration of q_w'' then yields the bulk stagnation enthalpy, hence the bulk stagnation temperature. After the bulk static temperature is found, the desired heat transfer parameters can be calculated.

Local friction factors are determined at the pressure tap locations by interpolating the bulk static temperature to form the specific impulse function, ϕ , then taking its gradient to obtain the wall shear stress. Since the diameter enters these calculations to approximately the fifth power it is corrected for thermal expansion.

Average heat transfer and friction results are calculated in the manner of Humble et al.⁽³⁾. Because the present results have inlet temperatures to 180°R it was necessary to extrapolate the NBS properties for nitrogen by some 10°R.

RESULTS AND CORRELATIONS

The correlation of heat transfer and friction data with high heating rates is complicated by the appreciable property variation across the tube. There are two ways which are commonly used to account for the influence of the property variation: one is to use a reference temperature, selected in such a way that when the properties are evaluated at this temperature the correlation reduces to that for constant properties; the second is to correct for the property effect by using a property or temperature ratio in the correlation which otherwise uses bulk properties. Both methods were used to correlate the present data.

Because of the very large property influence in the present experiment the bulk Reynolds number could decrease by as much as a factor of 5 between the tube inlet and exit. In contrast the wall Reynolds number, defined as:

$$N_{Re,w} = \frac{4w}{\pi D \mu_w} \left[\frac{T_b}{T_w} \right]$$

first decreased rapidly and then gradually increased along the tube, decreasing by as much as a factor of five but then returning at the exit to within a factor of two of the inlet wall Reynolds number. The film Reynolds number is defined in a similar manner using the viscosity evaluated at a temperature mid-way between the wall and the bulk temperature. It followed the same trend as the wall Reynolds number. When used in this manner the wall and film Reynolds number are commonly referred to as modified Reynolds numbers. For a perfect gas we see that the wall Reynolds number becomes equivalent to

$$N_{Re,w} = \left[\frac{V_b \rho_b D}{\mu_w} \right] \frac{\rho_w}{\rho_b} = \frac{V_b \rho_w D}{\mu_w}$$

In a paper dealing with ways of correlating heat transfer data for turbulent gas flow in tubes with appreciable variation of properties, Smith⁽¹³⁾ strongly advocates the use of bulk properties with the use of a wall to bulk temperature ratio to account for the property variation. His arguments are mainly based on the fact that an overall energy balance is directly related to the bulk Stanton number. It may, however, be argued with equal strength that since both heat transfer and wall shear stress in turbulent flow are primarily influenced by the flow field near the wall, either the film or wall properties should be used. The latter point of view gains some support from the fact that in the present study transition from turbulent to laminar-like flow occurred at Reynolds number, based on bulk properties, far above the critical value.

Since neither of the two methods can fully take into

account the rather complex consequences of the property variation, the choice between them is largely a matter of convenience, particularly convenience in application. From this point of view the use of bulk properties may have an advantage, at least for heat transfer calculations.

From equation 5 one can note that the friction coefficient is determined from the results of a momentum balance which includes the wall shear stress and the bulk momentum flux. One might thus be tempted to correlate the bulk friction factors with the wall Reynolds number in the manner of Dalle-Donne and Bowditch⁽⁷⁾.

With these comments in mind we now turn to the results of the present experiment. Figure 2 shows the typical trends for runs with low, moderate and high wall to bulk temperature ratios. Although not shown, the bulk temperature rises linearly as expected for the case of a constant heat flux and the heat flux is nearly constant after the first few diameters which are affected by the axial heat loss. The temperature ratio is seen to rise to a maximum and then to decay towards the value of 1, while the bulk Reynolds number decreases all along the length of the tube. In contrast the wall temperature profile is greatly affected by the degree of property variation present; that is, by the wall to bulk temperature ratio. With large heat fluxes the wall temperature rises as expected but reaches a peak, then decreases, then begins the linear rise characteristic of a constant property, constant heat flux case. This shape profile can be predicted from an equation of the Dittus-Boelter form at large wall to bulk temperature ratios so its existence does not rule out that an equation of that form should provide an adequate correlation of the data.

FRICTION RESULTS

Several runs were made to determine friction coefficients without heating for comparison to the usual correlations for adiabatic friction coefficients. Unfortunately there seems to have been a burr on the test section between taps 2 and 3 causing the isothermal data at tap 2 to fall some 30 per cent higher than the Karman-Nikuradse line while that at tap 3 lay some 7 per cent below the line. Taps 4, 5, and 6 showed good agreement with the Karman-Nikuradse correlation, all points being within 10 percent of the line. Since the computer program for data reduction fits a curve to the pressure distributions for each group of three pressure taps, friction coefficients are not determined at the first and last taps, hence only at taps 2 through 6 are local friction coefficients determined. Because the correlations based on the present data are given in terms of f/f_{iso} the effect of the burr is eliminated and the data is generally applicable.

Figure 3 shows the result of a correlation of the friction coefficients based on bulk properties but normalized by the (experimental) isothermal friction coefficients for the same wall Reynolds number. The solid curve represents the relation

$$f/f_{iso} = \left[\frac{2}{(T_w/T_b)^{1/2} + 1} \right]^2 \quad (6)$$

obtained by Kutateladze and Leont'ev⁽¹⁴⁾ from an analysis of the non-isothermal boundary layer on a flat plate. The expression, which in the above form is valid for the limiting case of subsonic flow at large Reynolds number, has been applied by the above authors to fully developed flow in a tube, however, with the isothermal friction factor based on the bulk Reynolds number. A more exact expression for the

finite Reynolds numbers includes an implicit dependence on the isothermal friction factor as well as the ratio of the centerline to bulk velocities. It is somewhat surprising that with wall Reynolds numbers as low as those found here, 5000 - 50,000, the agreement with the limiting form for large Reynolds numbers is so good. The data at taps 2 and 3 which were located 16 and 53 diameters downstream from the start of heating are corrected for the effect of the thermal entrance region. The corrections were determined in the following manner:

1. The ratio of $f_{\text{bulk}}/f_{\text{iso},w}$, was plotted versus the temperature ratio, T_w/T_b , for each of the five taps at which local friction coefficients were determined.
2. A cross plot was then made of $f_b/f_{\text{iso},w}$ versus x/D for a constant value of the temperature ratio.
3. From this the ratio of $f_b/f_{\text{iso},w}$ divided by $f_b/f_{\text{iso},w}$ downstream, was determined as a function of x/D in the entrance region.

The entry correction, shown in Figure 4, thus involved finding the parameter necessary to reduce the upstream data to the downstream values. Since the upstream results were taken at wall to bulk temperature ratios to 7.47 and the downstream data only covered ratios as high as 3.5 it was necessary to extrapolate the downstream results to these higher temperature ratios. However, the results from the upstream pressure taps paralleled those of the downstream taps so there is little uncertainty in doing this.

As a somewhat simpler alternative to the formulation suggested by Kutateladze and Leont'ev, $f_b(f_{\text{KN}}/f_{\text{iso}})_{N_{\text{Re},w}}$ was plotted versus the modified wall Reynolds number.

For taps 4, 5, and 6 this was equivalent to using f_b while

for taps 2 and 3 this method eliminates the effect of the burr between taps 2 and 3. It is seen in Figure 5a that the factor $(f_{KN}/f_{iso})_{N_{Re,w}} (T_w/T_b)^{-0.6}$ correlates the data to ± 20 per cent, the majority of the points falling within 10 per cent of the Karman-Nikuradse line when treated in this manner. This result is consistent with the fact that the right hand side of equation 6 may be approximated by the temperature ratio raised to the -0.6 power.

The correlation of equation 6 was tried on the bulk Reynolds number and is seen in Figure 6. The scatter here is large but a trend is evident in that an increasing exponent is needed on the temperature ratio to correlate the data. For a ratio from about 1 to 2 the exponent would be -0.1 , from 2 to 4 it would be approximately -0.2 , and above 4 the exponent appears to be -0.3 . Figure 7 shows the entry correction which was made to the bulk data. This correction was determined in the same manner as the correction to the data correlated on the wall Reynolds number except that the bulk Reynolds number was used to determine the isothermal friction coefficients. The correction suggested by Magee⁽¹⁵⁾ on the basis of data reaching a wall to bulk temperature ratio of 2.5 is also included. The agreement is seen to be acceptable. McEligot et al.⁽¹⁾ suggest that $f_b/f_{iso,b}$ should be proportional to $(T_w/T_b)^{-0.1}$ for ratios between 1 and 2.4. This agrees with the present data as shown on Figure 6. Lel'chuk and Dyadyakin⁽⁹⁾ suggest that the exponent on the temperature ratio should be -0.16 , again for ratios up to 2.4. Their data was taken, however, with a simultaneous thermal and hydraulic entry length.

The only data which have been correlated on the wall Reynolds number are those of Dalle Donne and Bowditch⁽⁷⁾. They found that for temperature ratios to 2.5 the data correlated on the Karman-Nikuradse line using the modified wall Reynolds number directly without any further temperature ratio correction. The scatter was some ± 25 per cent. Thus

there is some disagreement between the present results and their results since our data require a temperature ratio to the -0.6 power to correlate on the Karman-Nikuradse line using the wall Reynolds number.

For water Allen and Eckert⁽¹⁶⁾ and Maurer and LeTourneau⁽¹⁷⁾ both found that with significant variable property effects a correlation for the friction coefficients could best be achieved on the wall Reynolds number.

Several runs were taken in which the modified wall Reynolds numbers reached values below 5000. These runs exhibited a behavior characteristic of a transition to laminar flow. Figure 5 includes these friction coefficient results as well as the high Reynolds number results. Our results show the laminar like runs to have friction coefficients some 10 per cent below the isothermal laminar correlation. Dalle Donne and Bowditch⁽⁷⁾ found for laminar data that the correlation $f/2 = 8.5/N_{Re,w}$ worked well. This is some 20 per cent above our results.

Some confusion remains on the use of the relation proposed by Kutateladze and Leont'ev. In reference 14 good agreement is shown for experimental results for wall to bulk temperature ratios to 2.4 but evidently with the isothermal friction coefficients based on the bulk Reynolds number. As shown on figure 6 our results when based on the bulk Reynolds number lie well above the correlation and the -0.6 line which approximates the correlation. It was thought that this might be caused by the inability of the limiting Reynolds number correlation to handle the finite bulk Reynolds results from the present experiment. To check this, results were also calculated using the finite, non-limiting, correlation suggested in reference 14. However, while the results fell closer to the -0.6 line they were still well above it.

As a further check the data of McEligot et al.⁽¹⁾ and of Lel'chuk and Dyadyakin⁽⁹⁾ were correlated in the present manner on the modified wall Reynolds number. Figure 8 shows

the results of this reworking of their data. To determine the modified wall Reynolds number for reference 9 the bulk Reynolds numbers were multiplied by $(T_b/T_w)^{1.75}$, which assumes a viscosity power law of $(T/T_{ref})^{0.75}$. The results were also correlated using the entry correction determined from the present experiment. Good agreement is seen with our data using this correlation.

Film properties, evaluated half way between the wall and the bulk temperature, were also tried. They gave results which lay between the correlation, i.e. the -0.6 line, and the bulk data. No particular correlation was evident using the film properties.

The recommended correlation for friction coefficients to wall to bulk temperature ratios of 7.5 is given by:

$$f/f_{iso,w} = \left[\frac{2}{(T_w/T_b)^{1/2} + 1} \right]^2 \quad (7)$$

In simpler form this reduces to approximately:

$$f/f_{iso,w} = \left[T_w/T_b \right]^{-0.6} \quad (8)$$

The required entry correction is given in Figure 4.

HEAT TRANSFER RESULTS

As mentioned previously the choice of a correlation when significant variable property effects are present is one of convenience. For design purposes a bulk correlation is easier to use so the local heat transfer results were first correlated on the bulk properties. Figure 9 shows the results for the downstream, local heat transfer data taken from thermocouples at x/D 's of 66, 89, 119, 144. The best fit for these results comes with an exponent on the wall to bulk temperature ratio of -0.7 which is slightly larger than what would correspond

to the Russian prediction which Kutateladze and Leon'tev suggest should be applicable to heat transfer as well as friction coefficient results. The resulting correlation is given by:

$$N_{Nu} = 0.024 N_{Re}^{0.8} N_{Pr}^{0.4} (T_w/T_b)^{-0.7} \quad (9)$$

The accuracy of the exponent on the temperature ratio is estimated to be ± 0.1 . Figure 9 shows the correlation to be adequate to within ± 10 per cent except for a few runs which will be seen to have been affected by transition phenomena at the lower Reynolds numbers. The constant of 0.024 is about 5 per cent higher than the usual isothermal constant of 0.023⁽¹⁸⁾.

With this correlation for the downstream heat transfer results as a starting point it was desired to find some suitable form of an entry parameter which would enable a correlation of all the data from the first thermocouple at an x/D of 1.2 to the end of the test section at an x/D of 144. The form of this entry parameter ideally should reduce to one which had proved satisfactory before for low wall to bulk temperature ratios. A correction of the form $(1 + (x/D)^{-0.7})$ has been found satisfactory by both the investigators of references 1 and 19. Consequently an equation of the form $1 + (x/D)^{-0.7} (T_w/T_b)^a$ was tried. Figure 10 shows the final results where the data are seen to be correlated to within ± 20 per cent by the relation:

$$N_{Nu} = 0.024 N_{Re}^{0.8} N_{Pr}^{0.4} (T_w/T_b)^{-0.7} \left[1 + \left(\frac{x}{D} \right)^{-0.7} \left(\frac{T_w}{T_b} \right)^{0.7} \right] \quad (10)$$

The entry correction was applied through and including an x/D of 40. Again several runs at the lower Reynolds numbers were not well correlated. These will be discussed later in this paper.

The entry correction, while adequate, does show some

trends. In general the data at wall to bulk ratios from 2 to 4 are under corrected while at the larger ratios of 6 to 7.5 the data are slightly overcorrected. A tighter correlation might be achieved by using a polynomial in T_w/T_b as a multiplier to the x/D term in the entry parameter. The convenience and simplicity of the present form however, would seem to warrant accepting the 20 per cent scatter in the data.

A comparison of the results of references 1 and 9 for local heat transfer using bulk properties is shown in Figure 11. In this figure the downstream data of McEligot et al. and of Lel'chuk and Dyadyakin are correlated in the manner of the present experiment. An insert on the figure shows the improvement which is found by adding a wall to bulk temperature factor to the entry parameter. The agreement between the three experiments is seen to be good; McEligot's data lies some 5 per cent below the present data in general as does the Russian data.

Another form of a correlation for local heat transfer results has been found by Dalle Donne and Bowditch^(6,7) in which they also use bulk properties with a wall to bulk temperature ratio. However, the exponent on the temperature ratio in their correlation is of the form $a + b(x/D)$ so that any entry effect is included in the exponent. A similar form was tried with the present data; however, the exponent ceased to be a function of test section length after some 40 diameters so that it was felt that an entry parameter with x/D included was more representative of the physical situation. As reference 6 points out the average exponent on the temperature ratio for their tube is about -0.8 in comparison to our exponent of -0.7. The data of reference 6 includes wall to bulk ratios to 2.4. The correlating constant for their local heat transfer data is the same as ours, 0.024.

It thus appears that good agreement is found between the present results, correlated with bulk properties, and the results of references 1, 6, 7 and 9.

The results of McCarthy and Wolf⁽⁴⁾ for incremental average heat transfer data correlate on a wall to bulk temperature ratio to the -0.55 power for temperature ratios to 9. A correlation of the present data with this exponent was also tried. The downstream data could be adequately correlated to within ± 15 per cent with this power and a constant of 0.022. However, a systematic deviation occurred in the data when the entry correction was applied. A correlation of the form of equation 10, but with a value of 0.55 for the exponent on the wall to bulk temperature ratio in both places in which the ratio appears, proved to work well except that points with wall to bulk temperature ratios of 5 or larger fell some 25 per cent below the correlation. When the value of 0.7 was used for the exponent in both the entry and downstream correlation no such systematic deviation was noted. One might argue that the high wall to bulk points occur at the peak in the wall temperature profile, see Figure 1, where there is dissimilarity between the heat loss runs and the flow runs. Since with the high Reynolds number runs the total heat loss was less than 10 per cent this dissimilarity should be a second order effect. The recommended correlation using bulk properties is thus equation 10.

Another correlation which has had common acceptance uses the modified wall Reynolds number in correlating the heat transfer. This method was found to be satisfactory with the present results and is shown in Figure 12. In this case all of the properties are evaluated at the wall temperature in both the Reynolds numbers and the heat transfer parameters. A comparison with the results of other authors may be made from Table 1. Previously data have been correlated in this manner with a constant that ranges from 0.0265 for the data of Kirchgessner and Taylor^(8,19) to 0.0208 for that of Dalle Donne and Bowditch⁽⁷⁾. The present data are seen to be correlated by the relation:

$$N_{Nu,w} = 0.023 N_{Re,w}^{0.8} N_{Pr,w}^{0.4} \left[1 + \left(\frac{x}{D} \right)^{-0.7} \left(\frac{T_w}{T_b} \right)^{0.7} \right] \quad (11)$$

This includes data with wall to bulk ratios of 7.5 in the tube as a whole and 3 in the downstream region. For the wall correlation the entry correction was applied through and including an x/D of 24. A plot of the local heat transfer results versus x/D showed that the entry effect was not felt as far downstream using wall properties as using bulk properties, thus the difference in applying the entrance correction parameter. The downstream results using wall properties correlated best with a constant of 0.022 in equation 11.

A film correlation was also tried but the scatter was markedly larger than that found with the wall correlation. Similar behavior has also been found by Taylor⁽⁸⁾ and Wieland⁽⁵⁾.

The fact that satisfactory correlations can be achieved with both bulk and wall properties should not be surprising since one can start with either correlation and attain the second one by using power laws on temperature for the viscosity and conductivity and the perfect gas law for the density. Using the power laws corresponding to the temperatures in this experiment, one can deduce an exponent of about -0.7 on the wall to bulk temperature ratio from the wall correlation, equation 11.

ENTRY REGION

The entry parameter used in correlating the data from the present experiment has a very large effect at small x/D and large wall to bulk temperature ratios. For example, at an x/D of 4.6 the correction amounts to a factor of 2 at a temperature ratio of 4. In order to check this entry correction the data of both references 1 and 9 were correlated in this manner. In both cases the correlation was good. In

addition a comparison was made with the results of references 5, 6 and 7 in so far as it was possible to do so. In reference 7 Dalle Donne and Bowditch suggest that for the correlation with the modified wall Reynolds number an entry parameter with the form and magnitude of $(1 + 4D/x)$ should be used, in reference 6 they suggest $(1 + 6.2 D/x)$. These give a correction independent of the temperature ratio but of the same size as the correction made in the present experiment. Wieland⁽⁵⁾ shows a plot of the factor $N_{Nu,w}/N_{Re,w}^{0.8} N_{Pr,w}^{0.4}$ versus x/D for two runs with a low and high wall to bulk temperature ratio. Our data agree closely with these results at a corresponding temperature ratio; and consequently, it is thought that our entry correction will work with his data.

Just why the entry effect is so accented by larger wall to bulk ratios is not clear. There is good agreement for constant property results with the entry correlation of Sparrow et al.⁽²⁰⁾ which is much smaller than the parameter found here. It would appear that further work is warranted in the area of entry effects at high wall to bulk temperature ratios.

AVERAGE RESULTS

Figure 13a and b show the average heat transfer and friction coefficient results calculated in the manner of Humble et al.⁽³⁾. In both cases the downstream local correlation works for the average results. It should be noted that the average wall to bulk temperature ratio used in these results is the average wall temperature divided by the average bulk temperature, not the average of the wall to bulk temperature ratio. No entry correction is needed for these results which are based on an L/D of 144 for the heat transfer and a length of test section from an x/D of 16 to 114 for the friction coefficients.

TRANSITION BEHAVIOR

Because of the large increase of viscosity due to the rise in temperature, the local bulk Reynolds number experienced a large decrease through the tube length. Although the bulk Reynolds number never came near the critical value, it was apparently possible to obtain a turbulent to laminar transition in the test section when running at moderate inlet Reynolds numbers and high wall to bulk temperature ratios. The effect of such a transition on the friction coefficients can be seen in Figure 5 where the local coefficients are plotted versus the modified wall Reynolds number. With this particular choice of a Reynolds number the typical transition region is seen in the usual range of Reynolds number. Table 3 shows the range of variables for the runs which show some effects of either laminar flow or transitional flow. For runs 119, 121, and 123 the friction coefficients seem to be only moderately affected. However, these runs show considerable effects on the local heat transfer results as seen in Figures 9, 10, and 12. The other runs in Table 3 are not shown on the heat transfer plots as they are clearly in the laminar or transitional regime.

CONCLUSIONS

Results for both local and average friction and heat transfer coefficients have been correlated for local wall to bulk temperature ratios to 7.5. The recommended correlations are:

Friction Coefficients

$$f/f_{iso,w} = \left[\frac{2}{(T_w/T_b)^{1/2} + 1} \right]^2$$

See Figure 4 for the entry parameter for $x/D > 55$.

Heat Transfer

Bulk Correlation

$$N_{Nu} = 0.024 N_{Re}^{0.8} N_{Pr}^{0.4} (T_w/T_b)^{-0.7} \left[1 + \left(\frac{x}{D}\right)^{-0.7} \left(\frac{T_w}{T_b}\right)^{0.7} \right]$$

with the same correlation without the entry parameter for $x/D > 40$.

Wall Correlation

$$N_{Nu,w} = 0.023 N_{Re,w}^{0.8} N_{Pr,w}^{0.4} \left[1 + \left(\frac{x}{D}\right)^{-0.7} \left(\frac{T_w}{T_b}\right)^{0.7} \right]$$

with the same correlation without the entry parameter for $x/D > 24$.

Figure 1 - Page 21

Figure 2 - Page 22

Figure 2 (cont.) - Page 23

Figure 3 - Page 24

Figure 4 - Page 25

Figure 5a - Page 26

Figure 5b - Page 27

Figure 6 - Page 28

Figure 7 - Page 27

Figure 8 - Page 30

Figure 7 - Page 31

Figure 10 - Page 32

Figure 11 - Page 33

Figure 12 - Page 34

Figure 13a- Page 35

Figure 13b - Page 36

TABLE 1 SELECTED VARIABLE PROPERTIES, TURBULENT HEAT TRANSFER EXPERIMENTS

Investigators	Gas	$T_w/T_{b_{max}}$	x/D	Reference Temperature	Correlation Constant	Exponent on T_w/T_b	Entry Parameter	Remarks
<u>Overall Average Coefficients</u>								
Humble et al. (3)	Air	3.5	30-120	film	0.034	0	$(\frac{L}{D})^{-.1}$ to 60	-
McCarthy and Wolf (4)	Hydrogen	9.9	21-67	film	0.045	-0.7	$(\frac{L}{D})^{-0.15}$	$Re_f = 4w/\pi D \mu_f$
	Helium	9.9	21-67	wall	0.045	0	$(\frac{L}{D})^{-0.15}$	Modified Re.
		9.9	21-67	bulk	0.045	-0.55	$(\frac{L}{D})^{-0.15}$	-
Taylor and Kirchgessner (19)	Helium	2.7	60,92	film	0.021	0	$1 + (\frac{L}{D})^{-.7}$	-
<u>Incremental Average Coefficients</u>								
Taylor and Kirchgessner (19)	Helium	3.9	60,92	film	0.021	0	-	Modified Re.
				wall	0.0265	0	-	Modified Re.
Taylor (8)	Hydrogen	5.6	77	film	0.021	0	-	Modified Re.
McCarthy and Wolf (4)	Helium							
	Hydrogen	11.1	21-67	wall	0.025	0	0	Modified Re.
	Helium			bulk	0.025	-0.55	-	-
<u>Local Coefficients</u>								
Wieland (5)	Helium	2.83	250	film	0.021	0	Downstream only	Modified Re.
	Hydrogen			wall	0.021	-	Downstream only	Modified Re.
McEligot et al. (1)	Air	2.5	160	bulk	0.021	-0.5	$1 + (x/D)^{-.7}$	-
	Helium							
	Nitrogen							
Lel'chuk and Dyadyakin (9)	Air	2.4	147	wall				-
				bulk	0.025	graphic	x/D dependence	
Dalle Donne and Bowditch (6,7)	Air	2.4	180,351	wall	0.0208	0	-	Modified Re
	Helium			bulk	0.022	x/D in exponent on T_w/T_b		-
				entry	0.022	$(T_w/T_{ent.})^{-.30}$	-	
Present experiment	Nitrogen	7.5		wall	0.023	0	$1 + (\frac{x}{D})^{-0.7} (\frac{T_w}{T_b})^{0.7}$	Modified Re.
				bulk	0.024	-0.7	"	-

TABLE 2

RANGE OF VARIABLES IN THE PRESENT EXPERIMENT

Experimental Runs	39
Inlet Bulk Reynolds Number	18,300-359,000
Exit Bulk Reynolds Number	4,300-204,000
Maximum T_w/T_b	7.54
Axial Distances	
Heat Transfer	1.2 -144.0
Friction Coefficients	16.0 -114.0
Maximum Mach Number	
Heat Transfer	0.50
Friction Coefficients	0.46

TABLE 3

TRANSITION RESULTS

Run	Bulk Inlet N_{Re}	Bulk Exit N_{Re}	T_w/T_b Max.	Min. Wall N_{Re}	Symbol
119	18500	6340	2.28	2900	D
120	18200	4250	3.79	1020	◻
121	31700	10000	2.46	4500	◻
122	31500	8200	3.95	1730	◊
123	39400	13300	2.22	6800	◊
124	41000	10600	3.63	2530	◊
125	40500	10600	3.62	2530	◊
126	39700	9100	4.20	1890	◊
127	41700	10000	4.60	1750	◊

BIBLIOGRAPHY

1. D. M. McEligot, P. M. Magee, and G. Leppert, "Effect of Large Temperature Gradients on Convective Heat Transfer: The Downstream Region," ASME paper 64-HT-12.
2. M. E. Davenport and G. Leppert, "The Effect of Transverse Temperature Gradients on the Heat Transfer and Friction for Laminar Flow of Gases," ASME paper 64-HT-10.
3. L. V. Humble, W. H. Lowdermilk, and L. G. Desmon, "Measurements of Average Heat Transfer Coefficients for Subsonic Flow of Air in Smooth Tubes at High Surface and Fluid Temperatures," NACA report 1020, 1951.
4. J. R. McCarthy and H. Wolf, "The Heat Transfer Characteristics of Gaseous Hydrogen and Helium," RR-60-12, Rocketdyne, Canoga Park, California, 1960.
5. W. F. Wieland, "Measurement of Local Heat Transfer Coefficients for Flow of Hydrogen and Helium in a Smooth Tube at High Surface to Fluid Bulk Temperature Ratios," AIChE Symposium on Nuclear Engineering Heat Transfer, Chicago, 1962.
6. M. Dalle Donne and F. H. Bowditch, "High Temperature Heat Transfer," Nuclear Engineering, Vol 8, 20-29, (1963).
7. M. Dalle Donne and F. H. Bowditch, "Experimental Local Heat Transfer and Friction Coefficients for Sub-Sonic Laminar, Transitional, and Turbulent Flow of Air or Helium in a Tube at High Temperatures," Dragon Project D.P. 184, (1963).
8. M. F. Taylor, "Local Heat Transfer Measurements for Forced Convection of Hydrogen and Helium at Surface Temperatures up to 5600°R," Heat Transfer and Fluid Mechanics Institute, 1963, p. 251, Stanford University Press, Stanford, California.
9. V. L. Lel'chuk, and B. V. Dyadyakin, "Heat Transfer from a Wall to a Turbulent Current of Air inside a tube and the Hydraulic Resistance at Large Temperature Differentials," from Problems in Heat Transfer, AEC TR-4511, 1962.
10. D. M. McEligot, "Effect of Large Temperature Gradients on Turbulent Flow of Gases in the Downstream Region of Tubes," Ph.D. Thesis, Mechanical Engineering Department, Stanford University, Stanford, California, 1963.

11. M. E. Davenport, P. M. Magee, and G. Leppert, "Thermocouple Attachment to a Direct Current Heater," Trans. ASME, Journal of Heat Transfer, Vol 84, p. 187, 1962.
12. J. C. Hilsenrath, W. Beckett, W. S. Benedict, L. Fano, H. J. Hoge, J. F. Masi, R. L. Nuttall, Y. S. Touloukian, H. W. Woolley, NBS Circular 564, 1955.
13. A. J. W. Smith, "On the Correlation and Presentation of Information on Turbulent Variable Property Heat Transfer in Tubes," J. Roy. Aero. Soc., 66, p. 397-400, 1962.
14. S. S. Kutateladze and A. I. Leont'ev, "Turbulent Boundary Layers in Compressible Gases," Trans. D. B. Spalding, Arnold Publishers, London, 1964.
15. P. M. Magee, "Turbulent Heat Transfer and Friction in the Thermal Entrance Region of a Tube with Large Transverse Temperature Gradients," Ph.D. Thesis, Mechanical Engineering Department, Stanford University, in preparation.
16. R. W. Allen and E. R. G. Eckert, "Friction and Heat Transfer Measurements to Turbulent Pipe Flow of Water (Pr 7 and 8) at Uniform Wall Heat Flux," ASME paper 63-HT-37.
17. G. W. Maurer and B. LeTourneau, "Friction Factors for Fully Developed Turbulent Flow in Ducts with and without Heat Transfer," ASME Paper, 63-WA-98.
18. W. H. McAdams, "Heat Transmission," 3rd. ed., McGraw-Hill Book Company, New York, 1954.
19. M. F. Taylor and T. A. Kirchgessner, "Measurements of Heat Transfer and Friction Coefficients for Helium Flowing in a Tube at Surface Temperatures up to 5900°R," NASA TN D-133, 1959.
20. E. M. Sparrow, T. M. Hallman, and R. Siegel, "Turbulent Heat Transfer in the Thermal Entrance Region of a Pipe with Uniform Heat Flux," App. Sci. Res. 7, A, p. 37-52, 1957.

APPENDIX - SAMPLE DATA

From the 38 experimental heating runs 10 have been selected for presentation of data and processed results. These 10 were selected to cover the range of variables achieved in the experiment. The table lists a summary of the 38 experimental runs with appropriate comments to some of the runs. An explanation of the computer titles is also given followed by the data.

Self explanatory symbols are not listed.

E	voltage drop over the given distance
TG,IN	inlet mixer temperature
TG,OUT	exit mixer temperature
P,ATM	pressure vessel pressure
GAS FLOW	flow rate through tube
TC	thermocouple on wall
QP,GAS	wall heat flux
FILM COEFF	heat transfer coefficient, h
Tl/2	Note: this is $(T_w/T_b)^{0.7}$
PARAMETER 1	Nusselt $(T_w/T_b)^{0.7}/Prandtl^{0.4}$
RE,WM	Modified Reynolds number with wall properties
PHI	Impulse function
BETA	Deissler beta parameter

SUMMARY OF RUNS

Symbol	run	Reynolds inlet	exit	T _w max.	$\frac{T_{wall}}{T_{bulk}max.}$	Comments
0	102	98,000	33,600	795°F	2.95	data follows
□	103	97,000	28,000	1160°F	3.73	
◇	104	"	"	1158°F	3.69	
△	105	103,000	30,000	1000	3.60	data follows
▽	106	160,000	52,000	1000	3.63	
▷	107	236,000	100,000	448	2.58	
◁	108	223,000	99,000	451	2.44	data follows
△	109	226,000	62,000	1385	5.53	
▽	110	211,000	62,000	1396	5.20	
▷	111	170,000	44,000	1376	5.61	data follows
◁	112	120,000	42,000	585	2.88	
△	113	122,000	29,000	1847	6.48	
▽	114	122,000	27,000	1856	6.24	data follows
▷	115	76,000	37,000	157	1.84	
◁	116	72,700	21,000	867	3.37	
△	117	72,000	21,000	875	3.34	data follows
▽	118	111,000	35,000	861	3.31	
▷	119	18,700	6,400	444	2.29	
◁	120	18,300	4,300	1560	3.78	data follows runs 119 to 127 show some transition effects.
△	121	33,000	11,000	580	2.50	
▽	122	33,000	9,000	1622	4.04	
▷	123	43,000	15,000	419	2.28	
◁	124	44,000	12,000	1141	3.77	
△	125	"	"	1124	3.76	
▽	126	43,000	10,000	1588	4.36	
▷	127	45,000	11,000	1571	4.78	
◁	128	142,000	48,000	558	3.00	
△	129	268,000	96,000	560	3.23	
▽	130	272,000	97,000	"	3.19	
▷	131	157,000	83,000	70	1.80	
◁	132	none	none	none	none	data follows runs 133 to 135 show condensation effects
△	133	352,000	198,000	25.0	1.76	
▽	134	357,000	203,000	4.0	1.78	
▷	135	359,000	204,000	10.5	1.78	
◁	136	279,000	74,800	1295	5.74	
△	137	271,000	"	1299	5.55	
▽	138	266,000	67,000	1658	7.08	data follows
▷	139	"	"	1648	6.85	
◁	140	"	"	1717	7.53	

NITROGEN

RUN 102, DATE 102263, TEST SECTION 1, ID = .12370 IN, WALL THICKNESS = .021600 IN

E = 7.150 VOLTS/16.516 IN, I = 99.80 AMPS, QP,GEN = 1769.50 BTU/HRFT

TG, IN = -245.00 F, TC, OUT = 501.50 F, T,LE = -252.00 F

CRIFICE = 0.159 IN DIA

P,ATM = 30.00 IN HG = 14.74 PSIA, P,DP = 53.63 PSIA, T,DP = 54.0 DEG F
 DELTA P,DP = 10.20 IN HG SCALE = 16.73 IN H2O, GAS FLOW = 14.750 LBM/HR

	LOCATION IN	X/D	T _h ,O F	T _h ,I F	QP,RADIAL BTU/HRFT	QP,AXIAL BTU/HRFT	QP,GAS BTU/HRFT
TC 1	.153	1.23	-75.00	-77.07	413.74	192.49	1163.27
TC 2	.307	2.43	-28.50	-25.44	315.70	94.55	1359.24
TC 3	.565	4.56	145.50	141.49	147.81	58.09	1563.59
TC 4	.998	8.07	237.70	233.47	122.76	15.14	1631.59
TC 5	1.713	13.85	326.00	321.82	123.20	1.61	1644.68
TC 6	2.985	24.13	462.00	457.85	90.64	3.02	1675.83
TC 7	5.008	40.48	580.00	576.18	133.54	1.33	1634.64
TC 8	8.020	64.84	659.30	655.44	106.35	.47	1662.68
TC 9	11.034	89.20	698.30	694.55	120.99	.15	1648.36
TC10	14.675	118.63	728.30	724.59	124.50	-.41	1645.40
TC11	17.834	144.17	795.50	791.92	138.87	-.50	1631.13

RUN 102

	TB,STAG F	V FT/SEC	TB,STAT F	TW,AW F	QPP,GAS BTU/HRFT2	FILM CCEFF BTU/FHRFT2
TC 1	-241.56	76.834	-242.01	-241.59	35920.5	218.34
TC 2	-237.36	78.538	-237.84	-237.39	41971.8	159.69
TC 3	-229.21	81.859	-229.73	-229.25	48282.1	130.23
TC 4	-214.25	88.022	-214.84	-214.29	50381.8	112.52
TC 5	-188.54	98.336	-189.30	-188.60	50786.0	99.50
TC 6	-141.85	117.114	-142.93	-141.94	51747.9	86.28
TC 7	-66.91	147.253	-68.63	-67.07	50475.8	78.47
TC 8	45.15	193.217	42.12	44.84	51341.8	84.08
TC 9	157.96	241.909	153.28	157.44	50899.5	94.77
TC10	293.46	304.405	286.08	292.61	50808.3	117.62
TC11	409.89	362.942	399.45	408.66	50367.4	131.42

PARAMETERS BASED ON BLK TEMPERATURE

	NU,B	RE,B	PR,B	TW/TB	T1/2	PARAMETER 1 :
TC 1	346.58	51362.7	.8204	1.758	1.484	556.74
TC 2	248.92	89796.2	.8166	2.187	1.729	466.78
TC 3	196.15	86901.7	.8092	2.614	1.959	418.32
TC 4	159.58	82048.1	.7956	2.831	2.072	362.30
TC 5	128.40	75186.1	.7804	2.890	2.102	298.06
TC 6	95.85	65399.0	.7620	2.897	2.105	224.97
TC 7	71.70	54406.0	.7468	2.649	1.978	159.37
TC 8	61.39	44647.7	.7226	2.222	1.749	122.26
TC 9	58.21	38436.5	.7052	1.883	1.557	104.25
TC10	61.40	33415.8	.6915	1.588	1.387	98.37
TC11	61.25	30270.1	.6856	1.457	1.301	92.70

RUN102 PARAMETERS BASED ON WALL TEMPERATURE

	T,W(DEGF)	NU,W	RE,wM	PR,w	NU/PR04
TC 1	-77.07	203.54	31511.3	.7489	228.493
TC 2	25.44	120.14	20954.0	.7260	136.552
TC 3	141.49	81.34	14915.5	.7070	93.438
TC 4	233.47	62.38	12426.2	.6963	72.093
TC 5	321.82	50.01	11188.8	.6888	58.047
TC 6	457.85	38.20	9986.5	.6847	44.450
TC 7	576.18	31.65	10046.2	.6854	36.813
TC 8	655.44	32.09	11406.1	.6867	37.293
TC 9	694.55	35.24	13161.4	.6873	40.944
TC10	724.59	42.92	15357.5	.6879	49.853
TC11	791.92	46.05	16165.3	.6895	53.439

AVERAGE HEAT TRANSFER RESULTS, BLK

T,B,AV = 128.25 F, T,w,AV = 624.78 F, Tw/TB,AV = 1.8445, H = 102.998 BTU/HRFTF
 RE,AV = 39638.6, NU,AV = 65.57, PR,AV = .7091, NU/PR,0.4 = 75.235

FRICTION FACTOR RESULTS

PROPERTIES AND INTERPOLATED HEAT TRANSFER RESULTS AT PRESSURE TAPS

	X IN	X/D	T,STAT F	P,STAT PSIA	PHI PSIA	NU	NU/PR.4	TW/TB	MACH	RE,B
PT 1	1.744	6.013	-223.57	50.73600	51.62692	181.03	197.58	2.704	.11228	84827.3
PT 2	1.990	16.087	-179.21	50.42558	51.50016	121.32	134.24	2.892	.12385	72826.9
PT 3	6.520	52.708	-13.03	49.23295	51.00012	66.52	75.26	2.435	.16124	48881.6
PT 4	9.005	72.794	78.43	48.43978	50.60440	60.35	68.94	2.111	.18027	42343.1
PT 5	11.526	93.180	171.25	47.47897	50.06919	58.64	67.51	1.843	.19949	37641.4
PT 6	14.029	113.410	262.52	46.44425	49.47457	60.84	70.41	1.640	.21847	34167.7
PT 7	16.516	133.516	352.15	45.22926	48.72214	61.31	71.20	1.512	.23807	31488.0

RUN102

LOCAL FRICTION FACTORS, BASED ON BULK.

TAU, W	F/2, B	BETA
PSI		

PT 1

PT 2	.0032034	.002981	.C4538
------	----------	---------	--------

PT 3	.0043888	.002484	.C3383
------	----------	---------	--------

PT 4	.0057363	.002650	.C2925
------	----------	---------	--------

PT 5	.0069568	.002686	.C2629
------	----------	---------	--------

PT 6	.0083507	.002756	.C2400
------	----------	---------	--------

AVERAGE FRICTION FACTOR, BULK, PER HUMBLE ET AL

PTS	T, STAT, AV	P, STAT, AV	RE, AV	F/2, AV
	F	PSIA		

1 TO 7	64.29	47.98	43210.6	.002617
--------	-------	-------	---------	---------

2 TO 6	41.66	48.43	44679.4	.002523
--------	-------	-------	---------	---------

NITROGEN

RUN 106, DATE 102963, TEST SECTION 1, ID = .12370 IN, WALL THICKNESS = .021600 IN

E = 9.600 VOLTS/16.551 IN, I = 128.80 AMPS, QP,GEN = 3059.63 BTU/HRFT

TG,IN = -251.50 F, TG,OUT = 582.30 F, T,LE = -262.00 F

ORIFICE = 0.159 IN DIA

P,ATM = 30.00 IN HG = 14.74 PSIA, P,DP = 61.42 PSIA, T,DP = 54.0 DEG F

DELTA P,DP = 15.00 IN HG SCALE = 36.36 IN H2O, GAS FLOW = 23.399 LBM/HR

	LOCATION IN	X/D	T _w ,O F	T _w ,I F	QP,RADIAL BTU/HRFT	QP,AXIAL BTU/HRFT	QP,GAS BTU/HRFT
TC 1	.153	1.23	-15.50	-23.82	640.87	260.54	2158.22
TC 2	.307	2.48	101.00	95.01	487.51	65.10	2507.02
TC 3	.565	4.57	266.00	259.16	240.87	78.86	2739.90
TC 4	.999	8.07	381.00	373.87	192.40	17.02	2850.21
TC 5	1.715	13.86	502.00	495.00	179.20	2.89	2877.54
TC 6	2.989	24.16	682.00	675.22	143.89	4.64	2911.10
TC 7	5.016	40.55	828.00	821.68	192.40	2.04	2865.19
TC 8	8.036	64.97	907.30	901.02	170.77	.79	2888.06
TC 9	11.057	89.39	922.50	916.30	183.47	.01	2876.14
TC10	14.706	118.88	939.30	933.14	188.24	-.51	2871.90
TC11	17.873	144.48	1002.00	996.02	207.39	-.07	2852.30

RUN 106

	TB,STAG F	V FT/SEC	TB,STAT F	TW,AW F	QPP,GAS BTU/HRFT2	FILM CCEFF BTU/FHRFT2
TC 1	-247.60	105.518	-248.43	-247.65	66643.6	297.74
TC 2	-242.94	108.398	-243.84	-243.00	77414.1	229.03
TC 3	-233.71	113.839	-234.70	-233.77	84605.1	171.64
TC 4	-217.18	123.720	-218.35	-217.27	88011.3	148.88
TC 5	-188.86	140.418	-190.40	-188.98	88855.3	129.91
TC 6	-137.41	170.965	-139.72	-137.61	89891.5	110.59
TC 7	-54.76	220.928	-58.63	-55.12	88473.9	100.91
TC 8	69.25	300.211	61.95	68.49	89180.1	107.12
TC 9	193.02	390.361	180.84	191.67	88812.1	122.56
TC10	342.24	520.126	320.71	339.73	88681.2	149.44
TC11	470.23	662.513	435.61	466.12	88076.1	166.21

PARAMETERS BASED ON BLK TEMPERATURE

	NU,B	RE,B	PR,B	TW/TB	T1/2	PARAMETER 1
TC 1	486.39	149134.1	.8295	2.063	1.660	870.24
TC 2	366.49	146055.6	.8222	2.570	1.936	767.38
TC 3	263.97	140638.1	.8137	3.195	2.255	646.40
TC 4	214.10	131896.5	.7988	3.454	2.381	557.79
TC 5	168.30	119696.0	.7810	3.545	2.425	450.59
TC 6	121.71	102803.2	.7614	3.547	2.426	329.28
TC 7	90.09	84531.3	.7443	3.195	2.255	228.61
TC 8	75.62	68781.4	.7194	2.609	1.956	168.78
TC 9	72.56	59061.7	.7020	2.148	1.708	142.76
TC10	75.19	51352.4	.6889	1.785	1.500	130.93
TC11	75.00	46668.5	.6848	1.626	1.405	122.64

RUN106

PARAMETERS BASED ON WALL TEMPERATURE

	T _w (DEGF)	NU _w	RE _w	PR _w	NU/PR ^{0.4}
TC 1	-23.82	246.52	38321.3	.7364	278.626
TC 2	95.01	153.24	25538.2	.7143	175.321
TC 3	259.16	92.32	17020.3	.6937	106.864
TC 4	373.87	71.06	14196.6	.6864	82.608
TC 5	495.00	55.77	12592.8	.6844	64.902
TC 6	675.22	41.65	11207.3	.6870	48.399
TC 7	821.68	34.77	11523.5	.6904	40.322
TC 8	901.02	35.35	13596.8	.6929	40.935
TC 9	916.30	40.12	16398.1	.6934	46.452
TC10	933.14	48.50	19590.4	.6940	56.133
TC11	996.02	52.29	20925.1	.6964	60.431

AVERAGE HEAT TRANSFER RESULTS, BLK

T_b,AV = 165.40 F, T_w,AV = 835.58 F, T_w/T_b,AV = 2.0721, H = 135.189 BTU/HRFTF
 RE,AV = 60118.2, NU,AV = 81.69, PR,AV = .7038, NU/PR^{0.4} = 94.016

FRICTION FACTOR RESULTS

PROPERTIES AND INTERPOLATED HEAT TRANSFER RESULTS AT PRESSURE TAPS

	X IN	X/D	T, STAT F	P, STAT PSIA	PHI PSIA	NU	NU/PR ^{0.4}	TW/TB	MACH	RE, B
PT 1	2.744	6.017	-227.94	56.43600	58.40113	243.36	265.08	3.302	.15856	136887.6
PT 2	1.992	16.106	-179.37	55.70052	58.13073	158.16	174.98	3.546	.17785	115588.7
PT 3	6.533	52.809	1.90	52.94607	57.18064	82.82	93.84	2.901	.24251	75533.4
PT 4	9.023	72.944	100.78	50.99921	56.33957	74.62	85.40	2.458	.27823	65119.2
PT 5	11.551	93.379	199.77	48.49352	55.10638	72.92	84.09	2.099	.31773	57815.6
PT 6	14.059	113.653	295.51	45.73186	53.76672	74.73	86.62	1.849	.36189	52527.4
PT 7	16.551	133.803	387.68	42.23472	51.97806	75.08	87.27	1.692	.41491	48481.4

RUN106

LOCAL FRICTION FACTORS, BASED ON BULK

TAU, W F/2, B BETA
PSI

PT 1			
PT 2	.0066507	.002737	.04713
PT 3	.0090215	.002130	.03553
PT 4	.0127133	.002381	.03002
PT 5	.0158019	.002390	.02739
PT 6	.0192900	.002401	.02538

AVERAGE FRICTION FACTOR, BULK, PER HUMBLE ET AL

PTS	T, STAT, AV F	P, STAT, AV PSIA	RE, AV	F/2, AV
1 TO 7	79.87	49.34	67035.2	.002291
2 TO 6	58.27	50.72	69151.0	.002184

NITROGEN

RUN 107, DATE 111963, TEST SECTION 1, ID = .12370 IN, WALL THICKNESS = .021600 IN

E = 8.000 VOLTS/16.471 IN, I = 114.00 AMPS , QP,GEN = 2267.68 BTU/HRFT

TG,IN = -260.00 F, TG,OUT = 192.00 F, T,LE = -294.00 F

ORIFICE = 0.159 IN DIA

P,ATM = 30.00 IN HG = 14.74 PSIA, P,DP = 82.90 PSIA, T,DP = 36.5 DEG F

DELTA P,DP = 18.55 IN HG SCALE = 50.88 IN H2O, GAS FLOW = 32.795 LBM/HR

	LOCATION IN	X/D	TW,O F	TW,I F	QP,RADIAL BTU/HRFT	QP,AXIAL BTU/HRFT	QP,GAS BTU/HRFT
TC 1	.153	1.23	-120.00	-124.06	363.66	175.99	1728.03
TC 2	.306	2.48	-42.50	-47.74	229.49	78.36	1959.83
TC 3	.564	4.56	39.00	33.02	99.00	44.26	2124.42
TC 4	.997	8.06	95.00	92.89	82.43	14.14	2171.11
TC 5	1.711	12.84	135.50	129.33	70.00	-.26	2197.94
TC 6	2.980	24.09	204.00	197.77	30.67	1.09	2235.92
TC 7	4.998	40.41	274.00	268.01	50.44	.54	2216.70
TC 8	8.002	64.69	335.00	329.07	39.58	.25	2227.85
TC 9	11.006	88.97	372.00	366.17	46.64	.11	2220.92
TC10	14.636	118.32	402.50	396.73	46.69	-.18	2221.17
TC11	17.785	143.79	448.50	442.87	59.03	.19	2208.47

RUN 107

	TR, STAG F	V FT/SEC	TR, STAT F	Th, Ah F	QPP, GAS BTU/HRFT2	FILM CCEFF BTU/FHRFT2
TC 1	-257.74	101.264	-258.48	-257.78	53359.7	399.04
TC 2	-255.14	102.917	-255.90	-255.18	60517.5	291.73
TC 3	-250.31	105.981	-251.13	-250.35	65599.9	231.50
TC 4	-241.66	111.437	-242.61	-241.72	67041.6	200.36
TC 5	-226.49	120.738	-227.60	-226.57	67870.1	190.70
TC 6	-198.97	137.691	-200.45	-199.08	69042.9	173.97
TC 7	-154.42	165.023	-156.57	-154.60	68449.4	161.97
TC 8	-87.33	207.166	-90.73	-87.64	68793.6	165.09
TC 9	-19.73	252.630	-24.82	-20.22	68579.7	177.48
TC10	62.46	313.559	54.49	61.63	68587.4	204.68
TC11	133.42	369.141	122.67	132.26	68195.0	219.55

PARAMETERS BASED ON BULK TEMPERATURE

	NU, B	RE, B	PR, B	Tw/TR	T1/2	PARAMETER 1
TC 1	683.07	219121.6	.8455	1.668	1.431	1045.10
TC 2	493.33	216438.4	.8414	2.021	1.637	865.16
TC 3	382.87	211643.5	.8338	2.362	1.825	751.59
TC 4	318.87	203645.3	.8209	2.545	1.923	663.63
TC 5	284.71	191602.6	.8072	2.538	1.919	595.30
TC 6	233.66	173374.4	.7857	2.536	1.918	493.63
TC 7	187.50	151277.0	.7652	2.401	1.846	385.23
TC 8	159.10	126858.7	.7523	2.138	1.702	303.46
TC 9	147.26	111017.3	.7366	1.899	1.567	260.72
TC10	146.31	97458.3	.7206	1.666	1.429	238.39
TC11	140.91	88752.1	.7100	1.550	1.359	219.61

RUN107 PARAMETERS BASED ON WALL TEMPERATURE

	T _w (DEG F)	NU _w	RE _w	PR _w	NU/PR _{0.4}
TC 1	-124.06	419.99	82710.5	.7587	469.033
TC 2	-47.74	254.11	57324.5	.7416	286.393
TC 3	33.02	171.78	42615.2	.7245	195.424
TC 4	92.89	134.50	36241.6	.7146	153.854
TC 5	129.33	121.21	34679.6	.7089	139.094
TC 6	197.77	100.76	32023.1	.7001	116.208
TC 7	268.01	86.26	31479.7	.6929	99.889
TC 8	329.07	82.36	33417.9	.6885	95.626
TC 9	366.17	85.34	36421.7	.6867	99.186
TC10	396.73	95.64	40496.7	.6857	111.217
TC11	442.87	98.46	41971.9	.6848	114.558

AVERAGE HEAT TRANSFER RESULTS, BLK

T_{B,AV} = -34.00 F, T_{w,AV} = 319.85 F, TW/TB,AV = 1.8312, H = 196.060 BTU/HRFTF
 RE,AV = 112904.5, NU,AV = 165.81, PR,AV = .7385, NU/PR_{0.4} = 187.182

FRICTION FACTOR RESULTS

PROPERTIES AND INTERPOLATED HEAT TRANSFER RESULTS AT PRESSURE TAPS

	X IN	X/D	T,STAT F	P,STAT PSIA	PHI PSIA	NU	NU/PR.4	TW/TB	MACH	RE,B
PT 1	.743	6.009	-247.61	77.93600	80.48618	356.42	384.27	2.438	.15343	208235.3
PT 2	1.988	16.069	-221.69	77.20196	80.12584	273.60	298.76	2.538	.16477	187240.0
PT 3	6.506	52.596	-123.52	74.82787	79.16957	173.24	193.47	2.269	.20414	137764.4
PT 4	8.983	72.622	-69.20	73.28588	78.45394	155.23	174.43	2.060	.22539	121112.0
PT 5	11.497	92.946	-14.09	71.32784	77.39882	147.13	166.46	1.868	.24773	108888.4
PT 6	13.992	113.113	40.42	68.97827	76.02971	146.48	166.73	1.707	.27097	99529.4
PT 7	16.471	133.156	94.23	67.01050	75.05009	143.16	163.78	1.598	.29413	92081.5

RUN107

LOCAL FRICTION FACTORS, BASED ON BULK

TAU,W F/2,R BETA
PSI

PT 1			
PT 2	.0084309	.002883	.03508
PT 3	.0080829	.001862	.03266
PT 4	.0109185	.002113	.02765
PT 5	.0149536	.002463	.02347
PT 6	.0145475	.002063	.02389

AVERAGE FRICTION FACTOR, BULK, PER HUMBLE ET AL

PTS	T, STAT, AV F	P, STAT, AV PSIA	RE, AV	F/2, AV
1 TO 7	-76.69	72.47	123050.5	.002053
2 TO 6	-90.63	73.09	126831.3	.002121

NITROGEN

RUN 109, DATE 111963, TEST SECTION 1, ID = .12370 IN, WALL THICKNESS = .021600 IN

E = 12.400 VOLTS/16.620 IN, I = 166.20 AMPS, QP,GEN = 5078.62 BTU/HRFT

TG,IN = -263.00 F, TG,OUT = 769.00 F, T,LE = -280.00 F

ORIFICE = 0.159 IN DIA

P,ATM = 30.00 IN HG = 14.74 PSIA, P,DP = 86.14 PSIA, T,DP = 44.6 DEG F
 DELTA P,DP = 16.92 IN HG SCALE = 44.21 IN H2O, GAS FLOW = 30.881 LBM/HR

	LOCATION IN	X/D	T _w ,O F	T _w ,I F	QP,RADIAL BTU/HRFT	QP,AXIAL BTU/HRFT	QP,GAS BTU/HRFT
TC 1	.153	1.24	115.00	109.66	1336.09	443.48	3299.05
TC 2	.307	2.48	320.00	313.06	1200.00	185.27	3693.35
TC 3	.566	4.57	563.50	553.81	560.46	116.25	4401.90
TC 4	1.001	8.09	779.30	769.03	375.50	29.79	4673.33
TC 5	1.721	13.91	1027.00	1017.32	369.60	18.13	4690.89
TC 6	3.002	24.27	1278.50	1269.42	373.48	15.89	4689.25
TC 7	5.040	40.75	1256.30	1246.95	330.51	-.24	4748.35
TC 8	8.073	65.26	1238.30	1228.75	291.25	-.47	4787.84
TC 9	11.104	89.77	1255.50	1246.07	310.96	-.17	4767.83
TC10	14.767	119.38	1293.50	1284.27	340.86	-.67	4738.43
TC11	17.946	145.08	1385.00	1376.09	370.94	.95	4706.73

RUN 109

	TB,STAG F	V FT/SEC	TB,STAT F	TW,AW F	QPP,GAS BTU/HRFT2	FILM CCEFF BTU/FHRFT2
TC 1	-258.15	91.752	-258.75	-258.18	101871.1	276.95
TC 2	-252.89	94.746	-253.54	-252.93	114046.6	201.50
TC 3	-242.62	100.513	-243.39	-242.67	135926.0	170.66
TC 4	-222.23	111.533	-223.18	-222.30	144307.4	145.57
TC 5	-187.04	130.441	-188.37	-187.15	144849.5	120.26
TC 6	-123.38	164.745	-125.52	-123.57	144799.0	103.95
TC 7	-20.24	221.224	-24.14	-20.62	146623.8	115.67
TC 8	136.11	311.830	128.44	135.28	147843.2	135.20
TC 9	292.24	413.642	278.59	290.66	147225.3	154.10
TC10	478.77	576.777	452.53	475.65	146317.5	180.95
TC11	637.39	695.309	599.93	632.96	145338.7	195.58

PARAMETERS BASED ON BULK TEMPERATURE

	NU,B	RE,B	PR,B	TW/TB	T1/2	PARAMETER 1
TC 1	474.70	206606.2	.8460	2.833	2.073	1052.19
TC 2	337.00	201549.6	.8377	3.749	2.522	912.23
TC 3	272.55	192396.0	.8217	4.686	2.948	869.18
TC 4	213.43	177328.8	.8032	5.195	3.169	738.33
TC 5	154.70	156945.8	.7800	5.444	3.274	559.46
TC 6	109.85	130431.9	.7590	5.174	3.160	387.64
TC 7	95.84	104409.2	.7364	3.918	2.601	281.75
TC 8	86.05	82970.4	.7091	2.871	2.092	206.58
TC 9	81.11	70454.0	.6921	2.310	1.797	168.89
TC10	80.48	60806.9	.6847	1.912	1.574	147.40
TC11	77.53	54849.6	.6858	1.732	1.469	132.45

RUN109

PARAMETERS BASED ON WALL TEMPERATURE

	T, W (DEGF)	NU, W	RE, W	PR, W	NU/PR0.4
TC 1	109.66	181.21	29986.8	.7120	207.585
TC 2	313.06	102.19	18204.7	.6893	118.589
TC 3	553.81	69.99	12069.9	.6850	81.423
TC 4	769.03	51.71	9601.7	.6889	60.019
TC 5	1017.32	37.45	8174.3	.6973	43.258
TC 6	1269.42	29.03	7804.6	.7033	33.321
TC 7	1246.95	32.59	10387.4	.7074	37.429
TC 8	1228.75	38.37	14271.5	.7066	44.092
TC 9	1246.07	43.43	17622.0	.7074	49.880
TC10	1284.27	50.24	21015.9	.7090	57.649
TC11	1376.09	52.45	22488.9	.7126	60.065

AVERAGE HEAT TRANSFER RESULTS, BULK

T_B, AV = 253.00 F, T_w, AV = 1217.59 F, T_w/T_B, AV = 2.3535, H = 153.602 BTU/HRFTF
 RE, AV = 72211.9, NU, AV = 83.21, PR, AV = .6943, NU/PR, 0.4 = 96.286

FRICTION FACTOR RESULTS

PROPERTIES AND INTERPOLATED HEAT TRANSFER RESULTS AT PRESSURE TAPS

	X IN	X/D	T, STAT F	P, STAT PSIA	PHI PSIA	NU	NU/PR.4	TW/TB	MACH	RE, B
PT 1	.746	6.029	-235.04	80.73600	83.01815	248.11	269.39	4.896	.14379	185867.4
PT 2	2.000	16.164	-174.69	79.79141	82.73435	144.94	160.46	5.385	.16526	150363.1
PT 3	6.563	53.053	52.45	75.94924	81.56949	90.92	103.54	3.393	.23526	92046.4
PT 4	9.063	73.266	177.45	73.15946	80.43526	84.44	97.19	2.688	.27308	78247.0
PT 5	11.600	93.775	302.14	69.67962	78.81313	81.03	93.93	2.256	.31566	68927.0
PT 6	14.117	114.125	421.68	62.83749	74.54458	80.59	93.70	1.982	.36973	62255.1
PT 7	16.620	134.355	538.44	61.05106	74.66092	78.76	91.61	1.807	.41089	57149.0

RUN109

LOCAL FRICTION FACTORS, BASED ON BULK

TAU, W	F/2, R	BETA
PSI		

PT 1

PT 2	.0071925	.002444	.04864
------	----------	---------	--------

PT 3	.0118129	.002102	.03728
------	----------	---------	--------

PT 4	.0168124	.002311	.03197
------	----------	---------	--------

PT 5	.0324646	.003554	.02335
------	----------	---------	--------

PT 6	.0173290	.001480	.03322
------	----------	---------	--------

AVERAGE FRICTION FACTOR, BULK, PER HUMBLE ET AL

PTS	T, STAT, AV	P, STAT, AV	RE, AV	F/2, AV
	F	PSIA		
1 TO 7	151.70	70.89	80624.6	.002161
2 TO 6	123.50	71.31	83486.2	.002926

NITROGEN

RUN 113, DATE 121663, TEST SECTION 1, ID = .12370 IN, WALL THICKNESS = .021600 IN

E = 10.600 VOLTS/16.674 IN, I = 143.90 AMPS, QP,GEN = 3746.71 BTU/HRFT

TG,IN = -270.00 F, TC,OUT = 1029.30 F, T,LE = -266.00 F

ORIFICE = 0.159 IN DIA

P,ATM = 30.00 IN HG = 14.74 PSIA, P,DP = 58.13 PSIA, T,DP = 47.5 DEG F

DELTA P,DP = 10.20 IN HG SCALE = 16.73 IN H₂O, GAS FLOW = 16.731 LBM/HR

	LOCATION IN	X/D	T _w ,O F	T _w ,I F	QP,RADIAL BTU/HRFT	QP,AXIAL BTU/HRFT	QP,GAS BTU/HRFT
TC 1	.153	1.24	95.70	93.20	1185.06	403.70	2157.96
TC 2	.307	2.48	315.00	311.15	1153.28	127.42	2466.01
TC 3	.566	4.57	615.30	609.39	617.54	131.35	2997.83
TC 4	1.002	8.10	924.00	917.42	437.64	31.57	3277.50
TC 5	1.723	13.93	1224.60	1318.73	467.68	20.01	3259.03
TC 6	3.010	24.34	1847.00	1842.46	672.41	18.42	3055.88
TC 7	5.063	40.93	1817.50	1812.56	574.60	5.36	3166.76
TC 8	8.109	65.55	1441.50	1435.30	358.26	-4.68	3393.13
TC 9	11.146	90.11	1413.50	1407.36	381.36	-1.24	3366.59
TC10	14.817	119.78	1498.50	1492.84	481.00	.17	3265.55
TC11	18.003	145.54	1558.00	1552.31	454.50	-3.63	3295.85

RUN 113

	TB,STAG F	V FT/SFC	TR,STAT F	TW,AW F	QPP,GAS BTU/HRFT2	FILM CCEFF BTU/FHRFT2
TC 1	-263.29	60.321	-263.56	-263.30	66635.5	186.92
TC 2	-256.59	62.887	-256.88	-256.61	76147.6	134.12
TC 3	-243.87	67.656	-244.22	-243.89	92569.7	108.49
TC 4	-217.83	77.018	-218.28	-217.86	101205.6	89.15
TC 5	-172.21	93.132	-172.89	-172.27	100635.2	67.50
TC 6	-92.37	121.130	-93.54	-92.48	94362.3	48.77
TC 7	34.47	165.542	32.28	34.25	97786.1	54.99
TC 8	233.66	237.217	229.16	233.15	104776.3	87.16
TC 9	437.31	315.063	429.49	436.39	103956.7	107.06
TC10	674.65	414.180	661.36	673.09	100836.6	123.01
TC11	873.73	507.627	854.40	871.50	101772.2	149.49

PARAMETERS BASED ON BULK TEMPERATURE

	NU, B	RE, B	PR, B	TW/TB	T1/2	PARAMETER 1
TC 1	327.90	114586.6	.8556	2.819	2.066	720.95
TC 2	227.85	110933.9	.8430	3.801	2.546	621.19
TC 3	173.90	104615.2	.8228	4.962	3.069	576.92
TC 4	128.16	94284.2	.7987	5.705	3.383	474.40
TC 5	82.36	81016.4	.7728	6.201	3.587	327.51
TC 6	47.33	65121.3	.7530	6.287	3.622	192.01
TC 7	40.86	51420.3	.7246	4.619	2.919	135.65
TC 8	48.56	40079.0	.6967	2.751	2.031	113.95
TC 9	48.57	33526.2	.6849	2.100	1.681	94.98
TC10	46.76	28652.1	.6868	1.742	1.475	80.13
TC11	50.58	25912.4	.6914	1.531	1.347	78.99

RUN113 PARAMETERS BASED ON WALL TEMPERATURE

	T,w(DEGF)	NU,w	RE,wM	PR,w	NU/PR04
TC 1	93.20	125.42	16688.2	.7146	143.467
TC 2	311.15	68.16	9744.2	.6895	79.086
TC 3	609.39	42.72	5554.5	.6860	49.672
TC 4	917.42	29.17	4413.3	.6935	33.767
TC 5	1318.73	18.49	3469.3	.7104	21.203
TC 6	1842.46	11.27	2941.3	.7277	12.800
TC 7	1812.56	12.82	4034.3	.7268	14.561
TC 8	1435.30	22.88	7529.1	.7148	26.171
TC 9	1407.36	28.39	5552.1	.7138	32.490
TC10	1492.84	31.66	11683.8	.7170	36.166
TC11	1552.31	37.72	13056.9	.7191	43.035

AVERAGE HEAT TRANSFER RESULTS, BULK

T_{B,AV} = 379.65 F, T_{w,AV} = 1491.23 F, T_w/T_{B,AV} = 2.3243, H = 91.460 BTU/HRFTF
 RE_{AV} = 34894.4, NU_{AV} = 43.42, PR_{AV} = .6862, NU/PR_{0.4} = 50.476

FRICTION FACTOR RESULTS

PROPERTIES AND INTERPOLATED HEAT TRANSFER RESULTS AT PRESSURE TAPS

	X IN	X/D	T, STAT F	P, STAT PSIA	PHI PSIA	NU	NU/PR.4	TW/TB	MACH	RE,B
PT 1	1.746	6.031	-233.50	64.73600	65.57472	154.99	168.38	5.269	.09748	100073.6
PT 2	2.003	16.193	-155.62	64.30517	65.43558	74.74	83.04	6.220	.11482	76963.1
PT 3	6.592	53.290	131.12	62.74768	65.01385	44.73	51.28	3.681	.16536	44801.5
PT 4	9.101	73.574	254.60	61.51466	64.49731	48.57	56.24	2.538	.19122	37604.0
PT 5	11.643	94.125	460.87	60.00224	63.73684	48.32	56.21	2.051	.21724	32738.1
PT 6	14.166	114.518	620.24	58.35101	62.84404	47.08	54.72	1.805	.24296	29353.5
PT 7	16.674	134.792	773.86	56.36377	61.66430	48.98	56.84	1.619	.26949	26957.8

RUN113

LOCAL FRICTION FACTORS, BASED ON BULK,
TAU,W F/2,B BETA
PSI

PT 1			
PT 2	.0032980	.002917	.C4852
PT 3	.0051144	.002257	.C3802
PT 4	.0077908	.002612	.C3405
PT 5	.0100976	.002704	.C3007
PT 6	.0127307	.002833	.C2611

AVERAGE FRICTION FACTOR, BULK, PER HUMBLE ET AL

PTS	T, STAT, AV F	P, STAT, AV PSIA	RE, AV	F/2, AV
1 TO 7	270.18	60.55	38475.0	.002457
2 TO 6	232.31	61.33	39950.2	.002278

NITROGEN

RUN 115, DATE 121663, TEST SECTION 1, ID = .12370 IN, WALL THICKNESS = .021600 IN

E = 3.620 VOLTS/16.434 IN, I = 52.00 AMPS, QP,GEN = 469.12 BTU/HRFT

TG,IN = -264.00 F, TG,OUT = 49.30 F, T,LE = -288.00 F

ORIFICE = 0.0995 IN DIA

P,ATM = 30.00 IN HG = 14.74 PSIA, P,DP = 69.44 PSIA, T,DP = 53.0 DEG F
DELTA P,DP = 14.90 IN HG SCALE = 35.95 IN H2O, GAS FLOW = 10.342 LBM/HR

	LOCATION IN	X/D	T _w ,O F	T _w ,I F	QP,RADIAL BTU/HRFT	QP,AXIAL BTU/HRFT	QP,GAS BTU/HRFT
TC 1	.153	1.23	-209.00	-209.21	126.44	95.61	247.07
TC 2	.306	2.48	-171.00	-171.92	61.66	38.64	368.82
TC 3	.564	4.56	-131.50	-132.72	27.85	18.26	423.01
TC 4	.996	8.05	-97.00	-98.34	16.37	5.34	447.41
TC 5	1.709	13.82	-66.00	-67.36	15.20	1.35	452.57
TC 6	2.976	24.06	-31.00	-32.50	-12.45	.34	481.23
TC 7	4.989	40.33	11.50	9.99	-18.20	.33	486.99
TC 8	7.986	64.56	46.00	44.59	-2.76	.04	471.84
TC 9	10.983	88.79	76.70	75.31	-1.75	-.01	470.87
TC10	14.603	118.05	114.50	113.14	.67	-.08	468.53
TC11	17.745	143.45	157.00	155.71	9.15	.37	459.60

RUN 115

	TS, STAG F	V FT/SEC	TR, STAT F	TH, AW F	OPP, GAS BTU/HRFT2	FILM CCEFF BTU/FHRFT2
TC 1	-262.99	35.572	-263.08	-263.00	7629.3	141.85
TC 2	-261.38	35.961	-261.48	-261.39	11388.9	127.30
TC 3	-258.42	36.602	-258.51	-258.42	13062.1	103.91
TC 4	-252.94	37.793	-253.04	-252.95	13815.5	89.36
TC 5	-243.60	39.847	-243.72	-243.60	13975.0	79.29
TC 6	-225.37	43.664	-225.51	-225.38	14859.9	77.04
TC 7	-195.07	49.991	-195.26	-195.08	15037.7	73.33
TC 8	-149.84	59.290	-150.11	-149.86	14570.0	74.93
TC 9	-104.85	68.463	-105.23	-104.89	14540.1	80.69
TC10	-50.44	79.560	-50.94	-50.49	14467.8	88.42
TC11	-3.55	89.155	-4.18	-3.61	14192.0	89.08

PARAMETERS BASED ON BLK TEMPERATURE

	NU, B	RE, B	PR, B	TW/ TB	T1/2	PARAMETER 1
TC 1	248.27	70663.9	.8543	1.274	1.185	313.25
TC 2	221.07	70109.6	.8503	1.452	1.298	306.21
TC 3	177.91	69110.3	.8456	1.625	1.405	267.29
TC 4	149.11	67339.3	.8369	1.749	1.479	236.77
TC 5	126.82	64519.8	.8220	1.817	1.519	208.31
TC 6	114.04	59926.9	.8053	1.824	1.523	189.41
TC 7	96.66	53745.2	.7832	1.776	1.495	159.34
TC 8	85.04	46815.5	.7632	1.629	1.407	133.32
TC 9	80.69	41392.9	.7555	1.509	1.334	120.42
TC10	77.57	36779.5	.7424	1.401	1.266	110.68
TC11	70.89	33740.7	.7322	1.351	1.234	99.13

RUN115

PARAMETERS BASED ON WALL TEMPERATURE

	T, W (DEGF)	NU, W	RE, WM	PR, W	NU/PR0.4
TC 1	-209.21	196.83	44220.3	.7904	216.250
TC 2	-171.92	154.84	34352.7	.7723	171.702
TC 3	-132.72	112.08	27413.2	.7602	125.066
TC 4	-98.34	87.78	23268.1	.7542	98.259
TC 5	-67.36	72.24	20543.0	.7465	81.200
TC 6	-32.50	64.95	19463.6	.7382	73.337
TC 7	9.99	56.76	18538.0	.7291	64.410
TC 8	44.59	54.47	19145.5	.7221	62.045
TC 9	75.31	55.72	19757.8	.7173	63.639
TC10	113.14	57.55	20213.5	.7114	65.950
TC11	155.71	54.54	19891.0	.7049	62.724

AVERAGE HEAT TRANSFER RESULTS, BULK

T_{B,AV} = -107.35 F, T_{w,AV} = 54.25 F, T_w/T_{B,AV} = 1.4587, H = 94.579 BTU/HRFTF
 RE_{AV} = 41621.1, NU_{AV} = 55.12, PR_{AV} = .7559, NU/PR_{0.4} = 106.385

FRICTION FACTOR RESULTS

PROPERTIES AND INTERPOLATED HEAT TRANSFER RESULTS AT PRESSURE TAPS

	X IN	X/D	T, STAT F	P, STAT PSIA	PHI PSIA	NU	NU/PR.4	TW/TB	MACH	RE, B
PT 1	.743	6.003	-256.25	68.23600	68.51330	166.00	177.82	1.676	.05404	68367.0
PT 2	1.985	16.046	-239.76	68.16389	68.46739	124.03	134.39	1.818	.05636	63460.9
PT 3	6.494	52.496	-172.60	67.91585	68.32245	90.82	100.67	1.702	.06523	50034.3
PT 4	8.965	72.474	-135.45	67.77452	68.23745	83.62	93.29	1.590	.06968	44894.3
PT 5	11.473	92.747	-97.88	67.60868	68.12846	80.27	89.88	1.495	.07393	40644.6
PT 6	13.961	112.863	-60.57	67.44644	68.02222	78.13	87.90	1.421	.07797	37511.2
PT 7	16.434	132.855	-23.65	67.26184	67.89312	73.68	83.27	1.372	.08180	34937.1

RUN115

LOCAL FRICTION FACTORS, BASED ON BULK

TAU,W F/2,B BETA
PSI

RT 1

PT 2 .0011106 .003659 .02635

PT 3 .0010391 .002556 .02580

PT 4 .0012028 .002598 .02298

PT 5 .0013321 .002563 .02130

PT 6 .0014678 .002549 .01977

AVERAGE FRICTION FACTOR, BULK, PER HUMBLE ET AL

PTS	T, STAT, AV F	P, STAT, AV PSIA	RE, AV	F/2, AV
1 TO 7	-139.97	67.75	45469.6	.002644
2 TO 6	-150.16	67.81	46822.2	.002571

NITROGEN

RUN 119, DATE 121863, TEST SECTION 1, ID = .12370 IN, WALL THICKNESS = .021600 IN

E = 2.800 VOLTS/16.466 IN, I = 39.60 AMPS, QP,GEN = 275.78 BTU/HRFT

TG, IN = -267.00 F, TG, OUT = 320.30 F, T,LE = -291.00 F

ORIFICE = 0.0595 IN DIA

P,ATM = 30.00 IN HG = 14.74 PSIA, P,DP = 63.57 PSIA, T,DP = 61.5 DEG F
 DELTA P,DP = 10.61 IN HG SCALE = 18.40 IN H2O, GAS FLOW = 2.679 LBM/HR

	LOCATION IN	X/D	T _w ,O F	T _w ,I F	QP,RADIAL BTU/HRFT	QP,AXIAL BTU/HRFT	QP,GAS BTU/HRFT
TC 1	.153	1.23	-222.00	-221.97	105.50	50.74	119.54
TC 2	.306	2.48	-168.50	-168.83	65.48	28.99	181.32
TC 3	.564	4.56	-97.00	-97.48	39.21	28.73	207.84
TC 4	.996	8.05	-26.50	-27.04	45.28	9.86	220.65
TC 5	1.710	13.82	44.30	43.76	50.64	1.11	224.04
TC 6	2.978	24.08	154.30	153.64	22.85	2.15	250.79
TC 7	4.995	40.38	252.00	251.42	35.67	.71	239.40
TC 8	7.999	64.66	340.00	339.47	42.33	.93	232.52
TC 9	11.003	88.95	340.50	339.95	40.60	-.22	235.41
TC10	14.631	118.28	369.00	368.45	39.56	-.46	236.68
TC11	17.780	142.74	444.50	444.04	55.24	.46	220.09

RUN 119

	TC, STAG F	V FT/SEC	TC, STAT F	T _w , A _w F	QPP, GAS BTU/HR FT ²	FILM CCEFF BTU/HR FT ²
TC 1	-265.15	9.807	-265.15	-265.15	3691.3	85.50
TC 2	-261.98	10.022	-261.99	-261.99	5598.9	60.11
TC 3	-256.30	10.365	-256.31	-256.30	6418.0	40.41
TC 4	-245.90	10.596	-245.91	-245.90	6813.3	31.13
TC 5	-227.15	12.089	-227.16	-227.15	6918.0	25.54
TC 6	-190.99	14.169	-191.01	-190.99	7744.2	22.47
TC 7	-130.69	17.561	-130.72	-130.70	7392.3	19.35
TC 8	-43.27	22.410	-43.31	-43.27	7180.1	18.76
TC 9	44.12	27.200	44.06	44.11	7269.2	24.57
TC10	150.77	33.046	150.69	150.76	7308.5	33.57
TC11	240.28	37.940	240.17	240.27	6796.1	33.35

PARAMETERS BASED ON BLK TEMPERATURE

	NU, B	RE, B	PR, B	TW/TB	T1/2	PARAMETER 1
TC 1	151.17	18495.7	.8597	1.222	1.151	184.78
TC 2	104.64	18209.8	.8515	1.471	1.310	146.22
TC 3	68.46	17717.6	.8421	1.781	1.498	109.84
TC 4	50.28	16881.5	.8255	2.024	1.638	88.92
TC 5	38.05	15626.5	.8068	2.165	1.717	71.21
TC 6	29.17	13733.1	.7812	2.283	1.782	57.39
TC 7	20.75	11479.2	.7599	2.162	1.715	39.72
TC 8	16.18	9386.1	.7405	1.919	1.578	28.80
TC 9	17.88	8086.4	.7222	1.587	1.382	28.14
TC10	20.70	7003.9	.7056	1.357	1.238	29.46
TC11	18.34	6346.9	.6956	1.291	1.196	25.36

RUN119

PARAMETERS BASED ON WALL TEMPERATURE

	T, W (DEGF)	NU, W	RE, W	PR, W	NU/PR0.4
TC 1	-221.97	124.75	12532.2	.8021	136.250
TC 2	-168.83	72.37	8711.1	.7709	80.311
TC 3	-97.48	39.60	5907.2	.7540	44.339
TC 4	-27.04	25.95	4499.9	.7371	29.315
TC 5	43.76	18.59	3736.6	.7223	21.174
TC 6	153.64	13.80	3057.4	.7052	15.865
TC 7	251.42	10.50	2903.1	.6945	12.148
TC 8	339.47	9.26	3013.4	.6880	10.756
TC 9	339.95	12.12	3641.8	.6880	14.082
TC10	368.45	16.11	4157.0	.6866	18.722
TC11	444.04	14.94	4111.9	.6848	17.385

AVERAGE HEAT TRANSFER RESULTS, BULK

T_B, AV = 26.65 F, T_w, AV = 295.36 F, T_w/T_B, AV = 1.5525, H = 27.327 BTU/HRFTF
 RE, AV = .8307.5, NU, AV = 20.51, PR, AV = .7258, NU/PR, 0.4 = 23.319

FRICTION FACTOR RESULTS

PROPERTIES AND INTERPOLATED HEAT TRANSFER RESULTS AT PRESSURE TAPS

	X IN	X/C	T, STAT F	P, STAT PSIA	PHI PSIA	NU	NU/PR.4	TW/TB	MACH	RE, B
PT 1	.743	6.003	-252.01	63.23600	63.25655	60.95	65.50	1.881	.01527	17362.1
PT 2	1.986	16.055	-219.29	63.22663	63.25079	36.12	39.47	2.191	.01652	15157.2
PT 3	6.503	52.571	-86.84	63.18967	63.22789	18.46	20.70	2.040	.02079	10276.2
PT 4	8.980	72.595	-14.77	63.17020	63.21594	16.74	18.93	1.811	.02277	8907.1
PT 5	11.494	92.917	58.49	63.14677	63.20015	18.26	20.82	1.556	.02461	7915.8
PT 6	13.988	113.078	131.77	63.11919	63.18020	20.20	23.18	1.398	.02635	7168.9
PT 7	16.466	133.116	202.84	63.09106	63.15936	19.32	22.29	1.319	.02792	6597.8

RUN119

LOCAL FRICTION FACTORS, BASED ON BULK

TAU,W	F/2,B	BETA
PSI		

PT 1

PT 2	.0001462	.006049	.03286
------	----------	---------	--------

PT 3	.0001519	.003974	.02758
------	----------	---------	--------

PT 4	.0001715	.003751	.02495
------	----------	---------	--------

PT 5	.0002209	.004139	.02213
------	----------	---------	--------

PT 6	.0002537	.004158	.02048
------	----------	---------	--------

AVERAGE FRICTION FACTOR, BULK, PER HUMBLE ET AL

PTS	T,STAT,AV	P,STAT,AV	RE,AV	F/2,AV
	F	PSIA		
1 TO 7	-24.59	63.16	9066.2	.004220
2 TO 6	-43.76	63.17	9394.1	.004202

NITROGEN

RUN 122, DATE 121863, TEST SECTION 1, ID = .12370 IN, WALL THICKNESS = .021600 IN

E = 52600 VOLTS/16.628 IN, I = 78.20 AMPS, QP,GEN = 1078.63 BTU/HRFT

TG, IN = -265.00 F, TG, OUT = 668.70 F, T,LE = -284.00 F

ORIFICE = 0.0595 IN DIA

P,ATM = 30.00 IN HG = 14.74 PSIA, P,DP = 62.47 PSIA, T,DP = 62.0 DEG F
 DELTA P,DP = 20.10 IN HG SCALE = 57.22 IN H2O, GAS FLOW = 4.681LBM/HR

	LOCATION IN	X/D	T _w ,O F	T _w ,I F	QP,RADIAL BTU/HRFT	QP,AXIAL BTU/HRFT	QP,GAS BTU/HRFT
TC 1	.153	1.23	-110.50	-110.83	371.68	163.46	543.48
TC 2	.307	2.48	9.50	8.23	313.60	47.69	717.33
TC 3	.565	4.56	182.60	180.84	185.62	65.91	827.09
TC 4	.998	8.07	365.50	363.57	175.61	20.44	882.57
TC 5	1.715	13.86	584.50	582.66	190.00	-.52	889.14
TC 6	2.991	24.18	981.00	979.66	250.35	13.15	815.13
TC 7	5.026	40.63	1202.00	1200.93	313.56	2.50	762.57
TC 8	8.059	65.15	1378.00	1377.09	345.57	1.24	731.82
TC 9	11.097	89.71	1464.50	1463.79	397.40	.10	681.14
TC10	14.770	119.40	1560.00	1559.66	495.45	.25	582.93
TC11	17.958	145.18	1622.50	1622.16	492.89	2.60	583.14

RUN 122

	TB, STAG F	V FT/SEC	TR, STAT F	Tw, AW F	QPP, GAS BTU/HRFT2	FILM CCEFF BTU/FHRFT2
TC 1	-259.92	18.008	-259.95	-259.92	16782.2	112.56
TC 2	-253.69	18.674	-253.71	-253.69	22150.4	84.57
TC 3	-240.71	20.055	-240.74	-240.71	25539.7	60.59
TC 4	-215.46	22.672	-215.50	-215.46	27252.9	47.07
TC 5	-171.51	27.105	-171.57	-171.52	27455.8	36.40
TC 6	-95.20	34.697	-95.29	-95.20	25170.2	23.42
TC 7	18.69	45.854	18.52	18.67	23547.3	19.92
TC 8	180.24	61.613	179.94	180.21	22597.8	18.88
TC 9	332.92	76.508	332.45	332.86	21032.7	18.60
TC10	496.71	92.552	496.04	496.63	18000.2	16.93
TC11	626.24	105.285	625.38	626.14	18006.8	18.08

PARAMETERS BASED ON BLK TEMPERATURE

	NU, B	RE, B	PR, B	TW/TR	T1/2	PARAMETER 1
TC 1	194.04	31497.5	.8479	1.747	1.477	306.25
TC 2	141.55	30575.0	.8379	2.272	1.776	269.82
TC 3	95.64	28841.2	.8192	2.925	2.120	219.58
TC 4	66.92	26102.2	.7962	3.371	2.341	171.65
TC 5	44.23	22576.0	.7722	3.618	2.460	120.66
TC 6	22.83	18290.7	.7535	3.950	2.616	66.87
TC 7	15.18	14701.3	.7274	3.473	2.390	41.20
TC 8	11.19	11827.5	.7021	2.872	2.093	26.98
TC 9	9.25	10166.6	.6883	2.428	1.861	19.98
TC10	7.26	8924.4	.6844	2.113	1.688	14.27
TC11	7.04	8187.5	.6862	1.919	1.578	12.92

RUN122

PARAMETERS BASED ON WALL TEMPERATURE

	T _w (DEGF)	NU _w	RE _w	PR _w	NU/PR ^{0.4}
TC 1	-110.83	114.26	10884.5	.7565	127.756
TC 2	8.23	65.68	6579.2	.7295	74.515
TC 3	180.84	35.87	4038.8	.7020	41.322
TC 4	363.57	22.69	2935.0	.6868	26.368
TC 5	582.66	14.61	2324.4	.6855	16.996
TC 6	979.66	7.43	1735.3	.6957	8.585
TC 7	1200.93	5.72	1806.8	.7054	6.574
TC 8	1377.09	5.06	2055.9	.7127	5.796
TC 9	1463.79	4.83	2365.6	.7159	5.526
TC10	1559.66	4.26	2641.5	.7194	4.862
TC11	1622.16	4.46	2857.1	.7215	5.082

AVERAGE HEAT TRANSFER RESULTS, BLK

T_{B,AV} = 201.85 F, T_{w,AV} = 1291.79 F, T_w/T_{B,AV} = 2.6476, H = 18.574 BTU/HRFTF
 RE_{AV} = 11539.3, NU_{AV} = 10.70, PR_{AV} = .6996, NU/PR^{0.4} = 12.346

FRICTION FACTOR RESULTS

PROPERTIES AND INTERPOLATED HEAT TRANSFER RESULTS AT PRESSURE TAPS

	X IN	X/D	T, STAT F	P, STAT PSIA	PHI PSIA	NU	NU/PR ^{0.4}	TW/TB	MACH	RE _B
RT 1	.744	6.013	-230.30	62.23600	62.30663	83.77	91.15	3.110	.02858	27642.2
PT 2	1.993	16.108	-154.97	62.19634	62.29109	39.57	43.98	3.690	.03325	21492.2
PT 3	6.549	52.940	99.55	62.04672	62.21911	13.18	15.07	3.171	.04544	13048.0
PT 4	9.052	73.175	229.76	61.95406	62.16609	10.56	12.19	2.727	.05067	11206.5
PT 5	11.594	93.727	354.55	61.85744	62.10754	8.98	10.43	2.386	.05528	9971.7
PT 6	14.118	114.133	467.02	61.75649	62.04076	7.61	8.86	2.169	.05917	9117.4
PT 7	16.628	134.422	571.42	61.65987	61.97586	7.13	8.30	2.000	.06266	8472.1

RUN122

LOCAL FRICTION FACTORS, BASED ON BLK,

TAU, W F/2, B BETA
PSI

PT 1			
PT 2	.0004071	.004297	.05100
PT 3	.0005960	.003457	.02828
PT 4	.0006834	.003223	.02437
PT 5	.0007654	.003060	.02105
PT 6	.0008089	.002846	.01806

AVERAGE FRICTION FACTOR, BLK, PER HUMBLE ET AL

PTS	T, STAT, AV F	P, STAT, AV PSIA	RE, AV	F/2, AV
1 TO 7	170.56	61.95	11955.2	.003154
2 TO 6	156.03	61.98	12158.7	.003202

NITROGEN

RUN 131, DATE 21264, TEST SECTION 1, ID = .12370 IN, WALL THICKNESS = .021600 IN

E = 42500 VOLTS/16.427 IN, I = 66.00 AMPS , QP,GEN = 740.50 BTU/HRFT

TG,IN = -272.00 F, TG, OUT = -41.00 F, T,LE = -282.50 F

ORIFICE = 0.159 IN DIA

P,ATM = 30.00 IN HG = 14.74 PSIA, P,DP = 88.04 PSIA, T,DP = 38.5 DEG F

DELTA P,DP = 10.82 IN HG SCALE = 19.26 IN H2O, GAS FLOW = 20.613 LBM/HR

	LOCATION IN	X/D	T _w ,O F	T _w ,I F	QP,RADIAL BTU/HRFT	QP,AXIAL BTU/HRFT	QP,GAS BTU/HRFT
TC 1	1.153	1.23	-209.50	-210.70	116.64	88.60	535.26
TC 2	1.306	2.48	-171.00	-172.77	58.76	45.38	636.35
TC 3	1.564	4.56	-135.00	-137.08	25.89	21.47	693.14
TC 4	1.996	8.05	-112.00	-114.39	-13.26	3.34	750.42
TC 5	1.709	13.82	-90.50	-92.87	-12.40	1.50	751.39
TC 6	2.975	24.05	-75.00	-77.44	-23.89	-.39	764.77
TC 7	4.988	40.33	-35.00	-37.44	-31.72	.42	771.80
TC 8	7.984	64.54	-12.50	-14.81	-10.43	-.02	750.95
TC 9	10.979	88.75	12.50	10.22	-8.92	.04	749.37
TC10	14.597	118.00	36.50	34.25	-7.08	-.10	747.68
TC11	17.736	143.38	70.00	67.81	-1.44	.34	741.60

RUN 131

	TC	TH, STAG F	V FT/SEC	TH, STAT F	TW, AW F	QPP, GAS BTU/HRFT2	FILM CCEFF BTU/FHRFT2
	1	-270.68	53.405	-270.93	-270.69	16528.2	275.49
	2	-269.08	54.025	-269.33	-269.10	19649.9	204.00
	3	-266.04	55.221	-266.28	-266.05	21403.4	165.95
	4	-260.71	57.281	-260.95	-260.72	23172.2	158.35
	5	-252.89	60.020	-253.16	-252.91	23202.2	144.98
	6	-238.59	64.978	-238.91	-238.61	23615.3	146.52
	7	-214.68	73.105	-215.09	-214.71	23832.3	134.44
	8	-178.83	85.067	-179.40	-178.88	23188.6	141.33
	9	-143.25	97.080	-144.00	-143.32	23139.8	150.71
	10	-99.98	111.714	-100.97	-100.07	23087.4	171.89
	11	-82.43	124.562	-63.66	-62.55	22899.7	175.67

PARAMETERS BASED ON BLK TEMPERATURE

	TC	NU, B	RE, B	PR, B	TW/TR	T1/2	PARAMETER 1
	1	501.35	146498.3	.8749	1.319	1.214	642.02
	2	368.26	145307.3	.8707	1.507	1.333	518.72
	3	295.04	143095.5	.8627	1.668	1.431	447.80
	4	274.29	139382.3	.8495	1.737	1.472	431.00
	5	242.04	134290.4	.8370	1.776	1.495	388.51
	6	229.46	126051.4	.8176	1.731	1.469	365.23
	7	190.86	114768.6	.7958	1.726	1.465	306.45
	8	176.27	101837.4	.7758	1.587	1.382	269.60
	9	167.95	91675.5	.7622	1.499	1.321	247.34
	10	169.98	81607.5	.7548	1.377	1.251	237.96
	11	158.67	75248.0	.7455	1.332	1.222	218.09

RUN131 PARAMETERS BASED ON WALL TEMPERATURE

	T,W(DEGF)	NU,w	RE,w	PR,w	NU/PR0.4
TC 1	-210.70	384.46	85555.6	.7918	422.092
TC 2	-172.77	248.85	66203.0	.7727	275.879
TC 3	-137.08	181.24	53891.5	.7610	202.163
TC 4	-114.39	162.29	48636.1	.7571	181.401
TC 5	-92.87	140.47	45108.6	.7529	157.361
TC 6	-77.44	136.71	44742.0	.7490	153.460
TC 7	-37.44	114.53	41373.4	.7393	129.241
TC 8	-14.81	114.89	43176.4	.7344	129.983
TC 9	10.22	116.62	44075.0	.7291	132.324
TC10	34.25	127.27	45868.7	.7242	144.801
TC11	67.81	122.81	45106.7	.7185	140.170

AVERAGE HEAT TRANSFER RESULTS, BULK

T_{B,AV} = -156.50 F, T_{w,AV} = -7.30 F, T_w/T_{B,AV} = 1.4921, H = 151.139 BTU/HRFTF
 RE_{AV} = 95066.2, NU_{AV} = 174.92, PR_{AV} = .7651, NU/PR_{0.4} = 194.694

FRICTION FACTOR RESULTS

PROPERTIES AND INTERPOLATED HEAT TRANSFER RESULTS AT PRESSURE TAPS

	X IN	X/D	T, STAT F	P, STAT PSIA	PHI PSIA	NU	NU/PR.4	TW/TB	MACH	RE,B
PT 1	.743	6.002	-264.08	85.73600	86.57173	286.46	304.67	1.697	.08377	141536.8
PT 2	1.985	16.044	-250.06	85.53590	86.44567	239.30	257.47	1.766	.08729	132366.8
PT 3	6.492	52.481	-197.17	84.97708	86.15266	183.53	202.12	1.656	.09915	107797.9
PT 4	8.962	72.450	-167.83	84.62124	85.94222	173.55	192.54	1.555	.10536	98301.1
PT 5	11.469	92.712	-138.17	84.18860	85.65822	168.23	187.63	1.473	.11137	90169.7
PT 6	13.955	112.817	-108.60	83.79202	85.40953	169.62	189.69	1.397	.11708	83228.5
PT 7	16.427	132.795	-79.23	83.31612	85.08211	163.39	183.37	1.351	.12275	77765.0

RUN131

LOCAL FRICTION FACTORS, BASED ON BULK

TAU,W F/2,B BETA
PSI

RT 1

RT 2 J0028944 .003182 .C2491

PT 3 .0024135 .002053 .C2549

PT 4 J0030658 .002321 .C2185

PT 5 J0032974 .002244 .C2063

PT 6 J0035960 .002223 .C1943

AVERAGE FRICTION FACTOR, BULK, PER HUMBLE ET AL

PTS	T,STAT,AV F	P,STAT,AV PSIA	RE,AV	F/2,AV
1 TO 7	-171.65	84.53	99441.6	.002215
2 TO 6	-179.33	84.66	101815.6	.002077

NITROGEN

RUN 140, DATE 21264, TEST SECTION 1, ID = .12370 IN, WALL THICKNESS = .021600 IN

E = 13.400 VOLTS/16.647 IN, I = 185.60 AMPS, QP,GEN = 6118.76 BTU/HRFT

TG,IN = -285.00 F, TC, OLT = 1059.00 F, T,LE = -298.00 F

CRIFICE = 0.159 IN DIA

P,ATM = 30.00 IN HG = 14.74 PSIA, P,DP = 90.91 PSIA, T,DP = 42.0 DEG F

DELTA P,DP = 18.50 IN HG SCALE = 50.68 IN H2O, GAS FLOW = 34.084 LBM/HR

	LOCATION IN	X/D	TW,O F	TW,I F	QP,RADIAL BTU/HRFT	QP,AXIAL BTU/HRFT	QP,GAS BTU/HRFT
TC 1	1.153	1.24	104.50	96.11	1338.21	441.89	4338.66
TC 2	1.307	2.48	158.00	348.98	1386.78	126.75	4605.23
TC 3	1.566	4.58	717.00	706.44	783.48	169.92	5165.36
TC 4	1.802	8.10	1059.00	1048.31	641.23	45.98	5431.56
TC 5	1.725	12.94	1468.00	1458.26	630.40	35.88	5452.47
TC 6	3.012	24.35	1717.00	1707.80	646.78	22.31	5449.66
TC 7	5.057	40.88	1333.00	1321.64	326.56	-8.70	5800.90
TC 8	8.092	65.41	1293.00	1281.40	283.53	-1.14	5836.37
TC 9	11.125	89.94	1337.00	1325.69	326.99	-.05	5791.81
TC10	14.792	119.58	1355.00	1384.03	378.40	-.57	5740.92
TC11	17.975	145.31	1494.00	1483.38	407.07	-.70	5712.39

RUN 140

	TB,STAG F	V FT/SEC	TB,STAT F	TW,AW F	QPP,GAS BTU/HRFT2	FILM CCEFF BTU/FHRFT2
TC 1	-280.90	81.423	-281.44	-280.91	133973.1	355.35
TC 2	-274.30	85.612	-274.55	-274.33	142204.4	228.14
TC 3	-260.88	94.228	-261.52	-260.91	159500.6	164.88
TC 4	-240.27	106.114	-241.14	-240.33	167720.5	130.15
TC 5	-203.42	126.895	-204.68	-203.52	168366.5	101.32
TC 6	-136.22	164.557	-138.36	-136.41	168279.7	91.25
TC 7	-24.58	228.310	-28.74	-24.98	179125.5	133.02
TC 8	148.22	333.196	139.39	147.26	180220.7	158.91
TC 9	320.60	452.407	304.31	318.71	178844.9	177.61
TC10	525.34	624.954	494.79	521.71	177273.5	205.58
TC11	698.89	820.616	647.26	692.81	176392.3	223.12

PARAMETERS BASED ON BLK TEMPERATURE

	NU,B	RE,B	PR,B	TW/TB	T1/2	PARAMETER 1
TC 1	683.08	255749.2	.9070	3.118	2.217	1574.48
TC 2	423.83	247316.0	.8854	4.377	2.811	1250.76
TC 3	286.39	231110.0	.8504	5.884	3.458	1056.59
TC 4	205.81	210352.1	.8196	6.900	3.865	861.40
TC 5	138.21	182761.4	.7876	7.521	4.106	624.31
TC 6	100.03	149174.7	.7612	6.745	3.805	424.44
TC 7	111.26	116209.1	.7374	4.133	2.700	339.38
TC 8	99.55	90337.5	.7074	2.906	2.110	241.27
TC 9	90.91	75923.4	.6900	2.337	1.812	191.04
TC10	88.27	65041.9	.6844	1.932	1.585	162.86
TC11	85.61	58852.2	.6865	1.755	1.483	147.55

RUN140 PARAMETERS BASED ON WALL TEMPERATURE

	T _w (DEGF)	NU _w	RE _w	PR _w	NU/PR ^{0.4}
TC 1	96.11	237.34	30613.0	.7141	271.563
TC 2	348.98	111.57	16668.6	.6875	129.611
TC 3	706.44	60.86	9670.3	.6875	70.698
TC 4	1048.31	39.94	7026.2	.6987	46.101
TC 5	1458.26	26.39	5570.7	.7157	30.166
TC 6	1707.80	21.93	5781.5	.7241	24.949
TC 7	1921.64	36.40	10592.2	.7105	41.737
TC 8	1281.40	44.17	15273.4	.7088	50.686
TC 9	1325.69	48.53	18709.8	.7107	55.635
TC10	1384.03	54.98	22204.8	.7129	62.943
TC11	1483.38	57.61	23685.3	.7166	65.825

AVERAGE HEAT TRANSFER RESULTS, BULK

T_{B,AV} = 387.00 F, T_{w,AV} = 1358.19 F, T_w/T_{B,AV} = 2.1470, H = 221.451 BTU/HRFTF
 RE_{AV} = 70659.8, NU_{AV} = 104.41, PR_{AV} = .6860, NU/PR^{0.4} = 121.398

FRICTION FACTOR RESULTS

PROPERTIES AND INTERPOLATED HEAT TRANSFER RESULTS AT PRESSURE TAPS

	X IN	X/D	T _{STAT} F	P _{STAT} PSIA	PHI PSIA	NU	NU/PR ^{0.4}	T _w /T _B	MACH	RE _B
PT 1	1.746	6.034	-253.09	85.73600	88.09364	253.08	271.66	6.304	.14294	221982.6
PT 2	2.005	16.208	-190.24	84.75214	87.86837	129.90	143.33	7.352	.16664	174267.8
PT 3	6.1580	53.197	55.66	80.19019	86.69698	105.38	120.02	3.517	.24684	101114.1
PT 4	9.083	73.425	193.27	76.81278	85.44069	96.73	111.45	2.720	.29080	84832.6
PT 5	11.622	93.951	330.10	72.67667	83.69550	90.56	105.09	2.282	.33869	74181.9
PT 6	14.142	114.322	461.01	68.06577	81.75951	88.74	103.21	2.004	.39267	66687.3
PT 7	16.647	134.576	583.65	61.95706	78.95200	86.72	100.85	1.829	.45959	61190.1

RUN140
 LOCAL FRICTION FACTORS, BASED ON BLK,
 TAU,W F/2,B BETA
 PSI

PT 1			
PT 2	.0060455	.001940	.05167
PT 3	.0127648	.001962	.04170
PT 4	.0182979	.002121	.03567
PT 5	.0224960	.002042	.03246
PT 6	.0288520	.002107	.02906

AVERAGE FRICTION FACTOR, BLK, PER HUMBLE ET AL

PTS	T, STAT, AV F	P, STAT, AV PSIA	RE, AV	F/2, AV
1 TO 7	165.28	73.85	87584.0	.001974
2 TO 6	135.38	76.41	90786.8	.001878

DISTRIBUTION

N.Grossman, Chief (10 copies) Engineering Development Branch Division of Reactor Development U.S. Atomic Energy Commission Washington 25, D. C.	Francis Jackson, Director Laboratories for Research and Development The Franklin Institute Philadelphia 3, Pennsylvania
W.D.Manly, Director(4 copies) Gas-Cooled Reactor Program Oak Ridge National Laboratory P.O. Box X Oak Ridge, Tennessee	Theodore Jarvis, Manager Nuclear Development Division Ford Instrument Company 31-10 Thomson Avenue Long Island City 1, New York
John H. Russell (4 copies) Los Alamos Scientific Laboratory Los Alamos, New Mexico	O. E. Dwyer, Director Chemical Engineering Division Brookhaven National Laboratory Upton, Long Island, New York
Director, Contracts Division (3 copies) San Francisco Operations Office U.S.Atomic Energy Commission 2111 Bancroft Way Berkeley 4, California	James P. McGee Branch of Coal Gasification Bureau of Mines P.O. Box 880 Morgantown, West Virginia
F. W. Simpson Technical Information Services General Atomic Division General Dynamics Corporation P.O. Box 608 San Diego 12, California	Erich Soehngen Fluid Dynamics Research Branch Aeronautical Research Laboratory Wright Air Development Center Wright-Patterson Air Force Base, Ohio
James M. McCampbell Scientific and Nuclear Development Bechtel Corporation 220 Bush Street San Francisco 4, California	Manager, Compressor Department Allis-Chalmers Manufacturing Company P.O. Box 512 Milwaukee, Wisconsin
D. C. Schluderberg Physics and Mathematics Department Babcock & Wilcox Company Atomic Energy Division P.O. Box 1260 Lynchburg, Virginia	Argonne National Laboratory Technical Information Section 9700 South Cass Avenue Argonne, Illinois
Raymond E. Vener The M. W. Kellogg Company 711 Third Avenue New York 17, New York	Manager, EGCR Project Allis-Chalmers Manufacturing Company 508 Kennedy Street, N.W. Washington 11, D. C.
	Aerojet-General Nucleonics P.O. Box 77 San Ramon, California
	Rutgers University College of Engineering New Brunswick, New Jersey Attn: R. L. Peskin