NASA TECHNICAL NOTE

NASA TN D-3098

c. 1

NASA TN D-3098

LOCAL TURBULENT HEAT TRANSFER FOR WATER IN ENTRANCE REGIONS OF TUBES WITH VARIOUS UNHEATED STARTING LENGTHS

by James R. Stone

Lewis Research Center

Cleveland, Ohio

NATIONAL AERONAUTICS AND SPACE ADMINISTRATION • WASHINGTON, D. C. • NOVEMBER 1965

LOCAL TURBULENT HEAT TRANSFER FOR WATER IN ENTRANCE REGIONS OF TUBES WITH VARIOUS UNHEATED STARTING LENGTHS

By James R. Stone

Lewis Research Center
Cleveland, Ohio

NATIONAL AERONAUTICS AND SPACE ADMINISTRATION

For sale by the Clearinghouse for Federal Scientific and Technical Information
Springfield, Virginia 22151 – Price $1.00

LOCAL TURBULENT HEAT TRANSFER FOR WATER IN ENTRANCE REGIONS OF TUBES WITH VARIOUS UNHEATED STARTING LENGTHS

by James R. Stone

Lewis Research Center

SUMMARY

Local heat-transfer coefficients in the entrance region for water in turbulent forced flow through circular tubes of 0.23- and 0.48-inch inside diameters, square-edged entrances, and uniform heat flux were experimentally determined. Data were obtained with several different unheated lengths of tubing immediately upstream of the electrically heated section (unheated length to inside diameter ratios of 0.8, 1.6, 6.0, and 15). The data were taken in the turbulent flow regime with Reynolds numbers from 8000 to 118 000 over a range of liquid bulk temperatures from 66° to 250° F (Prandtl numbers range from 1.45 to 7.25). The mass flow rate, heat flux, test section exit pressure, water bulk temperatures at tube inlet and outlet (with corresponding inlet and outlet Reynolds and Prandtl numbers), and the axial temperature distribution for each run are presented in tabular form. A correlation is presented in terms of local bulk Nusselt, Reynolds, and Prandtl numbers, and geometric parameters valid for Prandtl numbers between 0.7 and 7. That the ratio of local to fully developed Nusselt number in the entrance region is greater than is predicted for a uniform initial velocity profile with a bellmouth inlet is shown. The variation of this Nusselt number ratio with Prandtl number is opposite to what is predicted for a fully developed initial velocity distribution.

INTRODUCTION

The variation of the local heat-transfer coefficient with length has been studied both analytically and experimentally. Some of these studies are listed in table I with the type of study and the ranges of pertinent variables indicated. Very little experimental data have been obtained for tubes with square-edged entrances and relatively short unheated lengths preceding the heated portions. Such configurations are found in many boilers and heat exchangers in which the tube cross-sectional velocity distributions have not

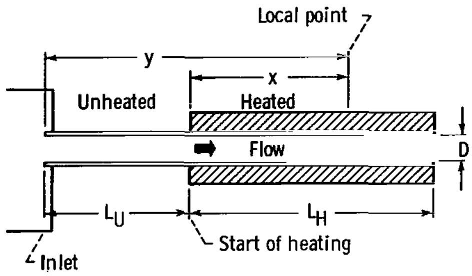


Figure 1. - Diagram of test section with geometric variables indicated.

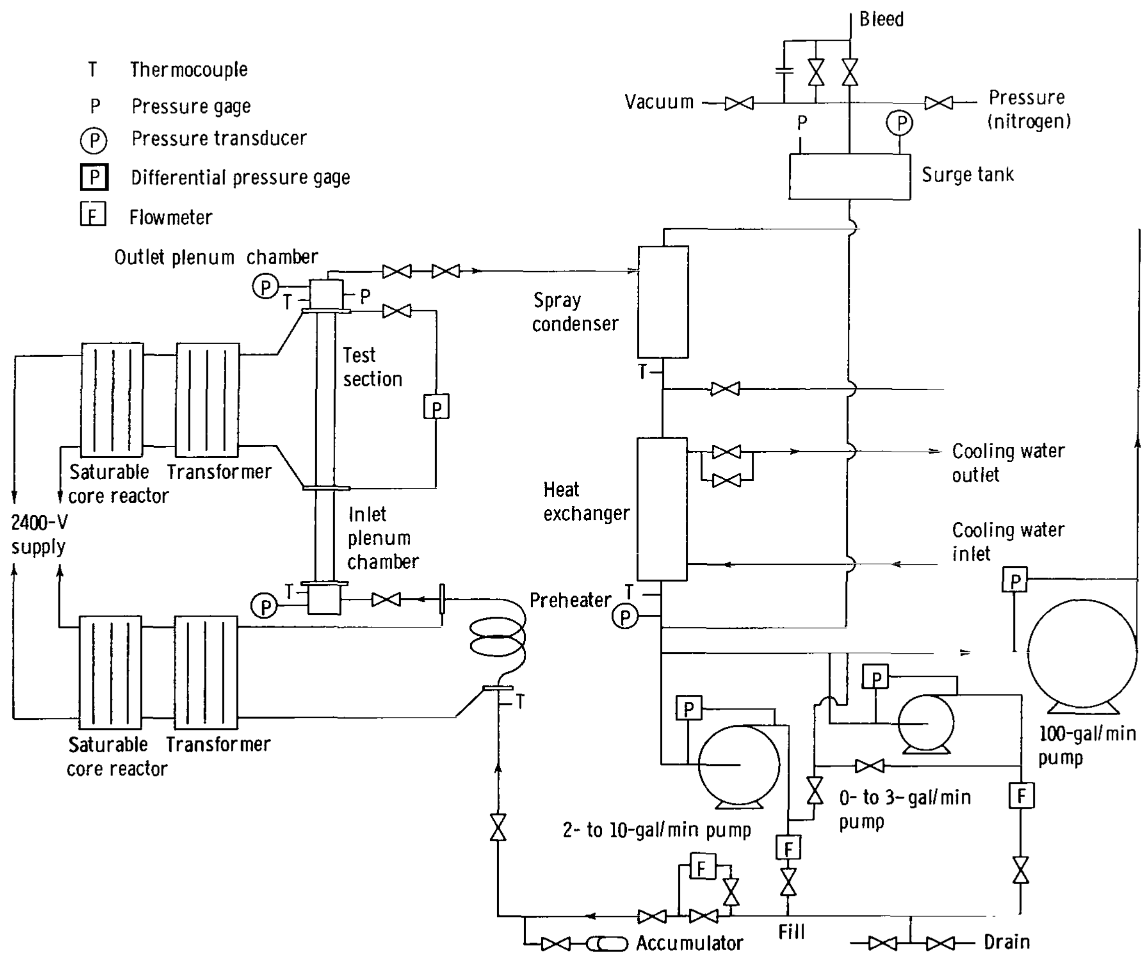


Figure 2. - System flow diagram.

become fully developed at the start of heating. The present investigation was initiated to obtain such data and to correlate it with existing information, both experimental and analytical. The geometric variables considered herein and some of the nomenclature to be used frequently hereafter are shown in figure 1.

Several results from theory are of particular interest in this study. For fully developed velocity and uniform temperature profiles at the start of heating, with uniform wall heat flux, Deissler (ref. 2) predicted that local values of Nu/Nu_{fd} (the ratio of Nu to that obtained for fully developed velocity and temperature profiles at the same Re and Pr) at a given x/D station decrease as Pr increases; variations with Re are small. (Symbols are defined in the appendix.) According to Siegel and Sparrow (ref. 4), for fully developed velocity and uniform temperature profiles at the start of heating, the difference in Nu/Nu_{fd} for cases of uniform heat flux and constant wall temperature is small (on the order of experimental error), with the discrepancy becoming smaller as x/D, Re, and Pr increase. It therefore seems reasonable, hereinafter, to compare directly data for uniform heat flux and constant wall temperature.

The data of Boelter, Young, and Iversen with a bellmouth entrance and one screen obtained for air in tubes (ref. 5) is shown to agree with the analysis for uniform wall temperature and uniform initial velocity and the temperature profiles in reference 1 Without the bellmouth and screen, the coefficients were higher.

The range of conditions investigated in this report is as follows:

Mass flow rate per unit area, G, lb mass/(hr)(sq ft)	0.47×10^6 to 3.46×10^6
Heat flux, q, Btu/(hr)(sq ft)	0 to 1.0×10^6
Local bulk temperature, $T_{B,l}$, ^{o}F	66 to 250
Reynolds number, Re	8000 to 118 000
Prandtl number, Pr	1.45 to 7.25

Four test sections were used in this study: $L_U/D = 1.6$ and 15 for $D = 0.23$ inch and $L_U/D = 0.8$ and 6 for $D = 0.48$ inch. The flow entrance to each test section was square-edged, as shown in figure 1.

No correlation or theory has been found that adequately considers the case of short unheated lengths downstream of square-edged entrances. The only published data for such entrance effects with various unheated lengths are those of reference 5 (air, $Pr = 0.7$). Such a correlation, has been obtained herein, with Nu as a function of Re, Pr, x/D, and y/D. Physical properties were evaluated at local bulk temperature. The data of reference 5 (air), reference 9 (water), and reference 12 (water, fully developed) are also shown to agree with the correlation.

APPARATUS

The experimental data were obtained with the test equipment described in detail in reference 12. The test apparatus, shown schematically in figure 2, consists of a closed loop system in which the water is circulated by one of two gear pumps. The flow is measured by one of three turbine flowmeters having overlapping ranges. The rest of the loop contains a resistance-heated stainless-steel preheater, a resistance-heated Inconel X test section, and a water-cooled heat exchanger. (The spray condenser circuit was not used in the present study.)

Diagrams of a typical test section and the inlet and outlet plenum chambers are shown in figure 3. Inconel X has a nearly constant electrical resistivity over a wide range of temperature, which results in an essentially uniform heat flux along the heated portion of the test section. The power for test section and preheater was provided by two saturable core reactors.

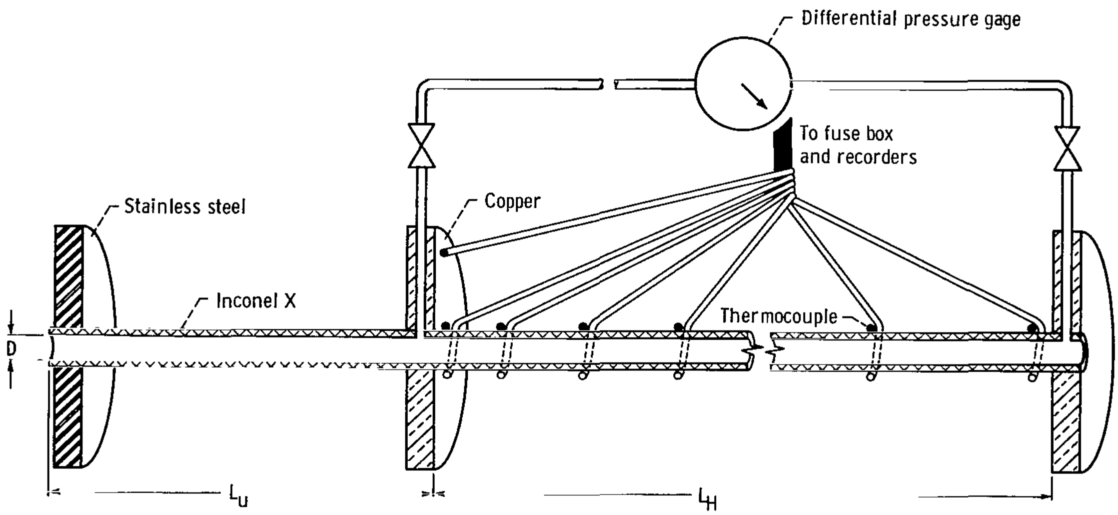
The Chromel-Alumel thermocouples were spotwelded to the outer wall of the test section at the same circumferential position for all axial distances except for one thermocouple located 1/4 inch from the test section exit and spaced 180° from the last thermocouple. These last two thermocouples located 1/4 inch from the exit were used for automatic power shutoff in case of extreme temperatures. Any alternating current voltage picked up by the thermocouples was filtered out before the temperatures were recorded. The liquid bulk temperatures were measured in the plenum chambers. The pressure drop across the test section and the test section exit pressure were measured with gages. Table II summarizes the test section geometries tested.

PROCEDURE

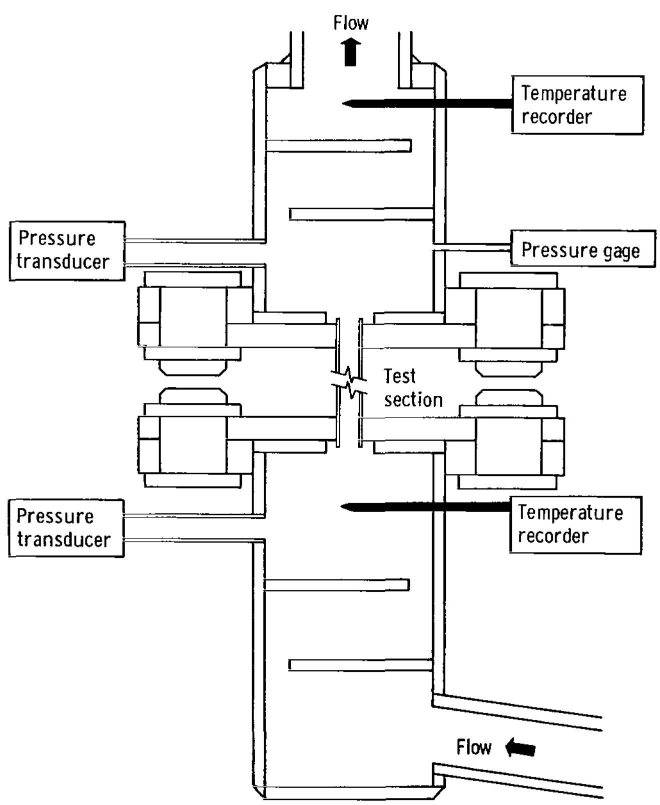
Each day before data were taken, water was circulated and boiled in the test section. Noncondensable gases were removed from the system through a line from the top of the condenser. Dissolved gas content was determined with a gas analyzer and was maintained at less than 3 parts per million by weight based on the average molecular weight of air.

In order to check the thermocouples, runs were made in which no heat was applied in the test section. Since the heat losses were small, the tube outer wall temperatures could then be checked against the water bulk temperatures. The recording instrument was adjusted until bulk and wall temperatures agreed within the scatter of the wall temperature measurement. This was done over the range of bulk temperatures encountered by varying the preheater power.

The desired conditions for each run were established by adjusting the power to the



(a) Heated and unheated sections.



(b) Plenum chambers.

Figure 3. - Test section assembly.

preheater and test section and setting the pump speed and system pressure at selected values. When the inlet and outlet bulk liquid temperatures became constant with time, the data for that run were taken. Temperatures were automatically recorded on strip charts. Flow rate, power, and pressure were read from gages.

Data Reduction

The heat input to the test section was computed from a wattmeter reading by the following equation:

$$Q_E = 3.41\ P \tag{1}$$

The temperature rise of water through the test section was also used to compute the heat input by the equation

$$Q_H = Wc_p(T_{B,O} - T_{B,I}) \tag{2}$$

The comparison between Q_E and Q_H is shown in figure 4, where Q_H is plotted

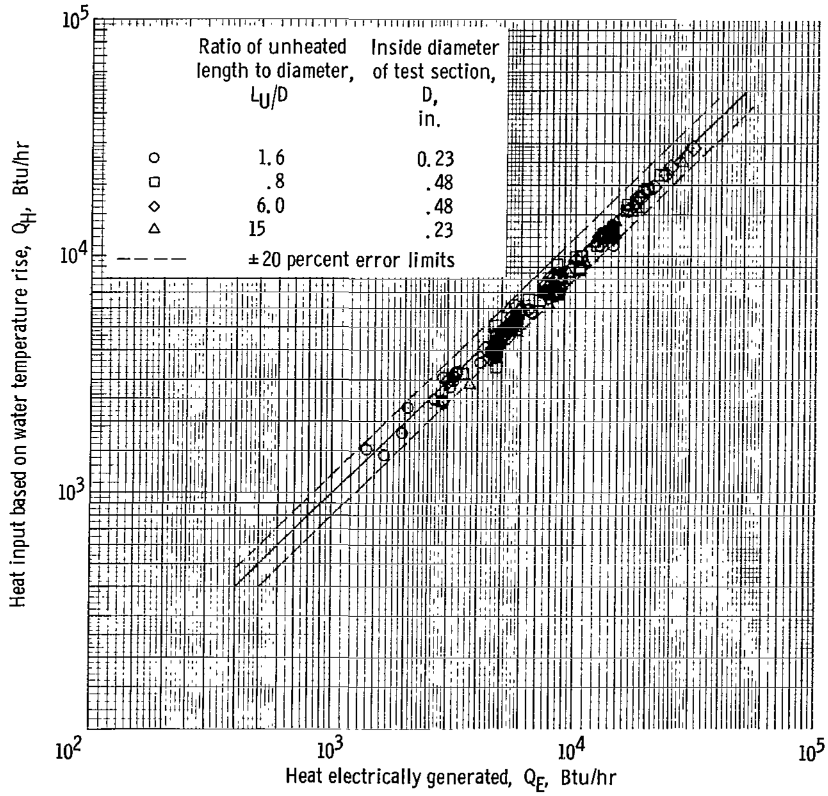


Figure 4. - Comparison of heat input calculated from water bulk temperature rise with the measured electrical heat generation.

against Q_E for each run reported. (Heat losses are discussed in the section Error Considerations.) The heat flux was computed by the following equation from Q_E, which is considered more accurate than Q_H:

$$q = \frac{144\ Q_E}{\pi D L_H} \quad \text{BTU/hr ft}^2 \tag{3}$$

The mass flow rate was computed by

$$G = \frac{(144)(4W)}{\pi D^2} \tag{4}$$

Since the variation of bulk temperature with length was linear because of the constant heat flux, the local bulk temperatures can be obtained by the following equation:

$$T_{B,\ell} = T_{B,I} + (T_{B,O} - T_{B,I}) \frac{x}{L_H} \tag{5}$$

The outside wall temperature was obtained by means of the calibrated emf against temperature curve for Chromel-Alumel thermocouples. The inside wall temperature was computed as in reference 12 by

$$6.4(T_{w,i} - T_{w,o}) + 0.003(T_{w,i}^2 - T_{w,o}^2) = -\frac{qr_i}{r_o^2 - r_i^2}\left[\frac{r_i^2 - r_o^2}{2} + r_o^2 \ln\left(\frac{r_o}{r_i}\right)\right] \tag{6}$$

This equation was derived for the following conditions: no heat loss from the outer surface, no axial heat flow within the wall, constant electrical resistivity, and a linear variation of thermal conductivity with temperature ($k_w = 6.4 + 0.003\ T$ for Inconel X). At most, $(T_{w,o} - T_{w,i})$ is 30 percent of $(T_{w,o} - T_{B,\ell})$, but in most cases is less than 15 percent, even near the start of heating.

Local heat-transfer coefficients based on local bulk temperature were computed by the following equation:

$$h = \frac{q}{T_{w,i} - T_{B,\ell}} \tag{7}$$

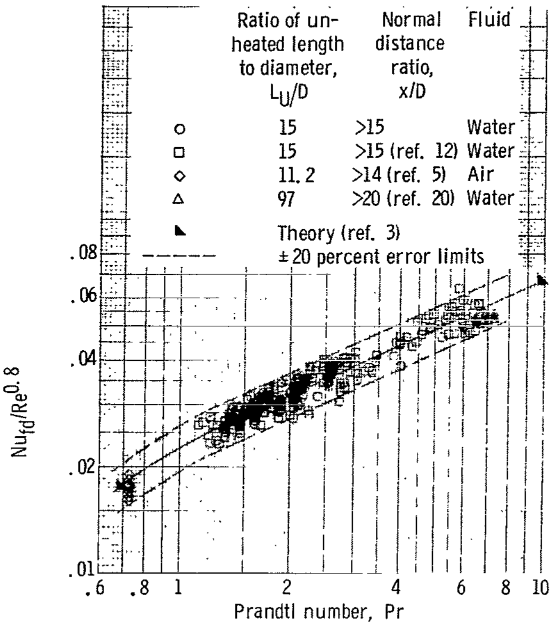


Figure 5. - Nusselt number in fully developed region for Re much greater than 8000.

Local values of Nusselt, Reynolds, and Prandtl numbers were computed based on the physical properties of water evaluated at local bulk temperature. The physical properties of water were obtained from reference 13.

Error Considerations

To estimate the heat loss from the test section, the heat-transfer coefficient to the air was estimated from reference 13 and found to be less than 3 Btu per hour per square foot per $^{\circ}F$ from which convective heat loss from the test section surface was estimated to be less than 1 percent. Axial wall conduction calculations based on measured temperature profiles indicated a maximum heat flux error of approximately 3 percent at the first point on the tube where heat-transfer coefficients were calculated, with error decreasing with length. Since the heat loss from the test section surface was small, end losses and measurement inaccuracies must account for most of the disagreement between Q_E and Q_H shown in figure 4. Therefore, Q_E is considered to give the heat flux more accurately.

In reference 12 the maximum error in $T_{w,i}$ was estimated to be $\pm 3^{\circ}$ F when the maximum deviation in wall thickness, the accuracy of the outer wall temperature, the heat flux measurement, and the validity of the assumptions made in deriving equation (6) were considered. Since the lowest values of $(T_{w,i} - T_{B,l})$ that occurred at the thermocouple nearest the start of heating were about 20° F, the error in h might be as high as 18 percent if a possible error of 1° F in $T_{B,l}$ is assumed. Further downstream, the ΔT would approximately triple, yielding less than a 10 percent error.

RESULTS AND DISCUSSION

Tabulation of Data

The experimental data are presented in table III. For each run the mass flow rate per unit area, the exit pressure, the inlet and outlet temperatures with the corresponding Re and Pr, the wall heat flux, and the axial wall temperature distribution are pre-

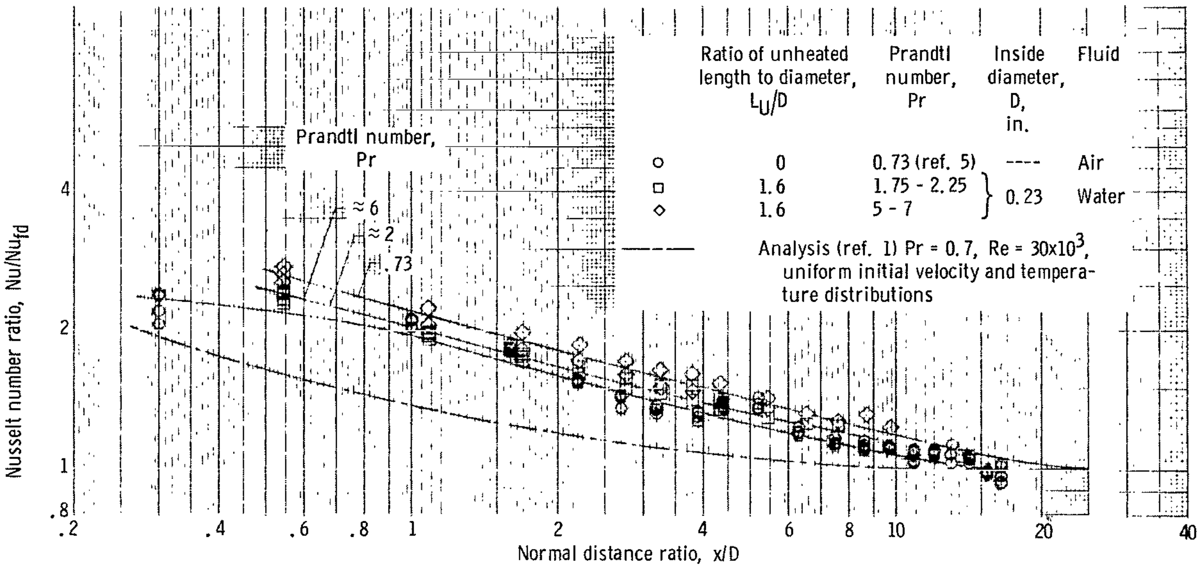


Figure 6. - Variation of Nusselt number ratio with normal distance ratio for various Prandtl numbers (comparison with theory).

sented. Table III contains the data for $L_U/D = 0.8$, 1.6, 6.0, and 15, respectively. For many of the experimental runs, part of the tube was in the subcooled boiling regime. Temperatures that appear to deviate from the nonboiling convection regime are indicated in table III but are not used in this report. Data points were eliminated for which the inner wall temperature $T_{w,i}$ was above saturation temperature and h did not decrease with length.

Fully Developed Region

Entrance region results are commonly presented as Nu/Nu_{fd}, the ratio of the local Nu to the Nu obtained for fully developed velocity and temperature profiles at the same Re and Pr. In order to form this ratio, Nu_{fd} as a function of Re and Pr must be known. The variation of Nu_{fd} with Re has been found to be $Nu_{fd} = c\,Re^{0.8}$, where c is a function of Pr. The parameter $Nu_{fd}/Re^{0.8}$ is plotted against Pr in figure 5 for water and air data and is compared with the analytical results of reference 3 for $Re \geqq 50\,000$. The solid curve faired through the data is used to define Nu_{fd} for all subsequent figures and discussion. When forming the ratio Nu/Nu_{fd}, Nu_{fd} is based on local Re and Pr.

Entrance Region

A plot of Nu/Nu_{fd} against x/D for $L_U/D = 1.6$, $Pr \approx 2$, and $Pr \approx 6$ is given in

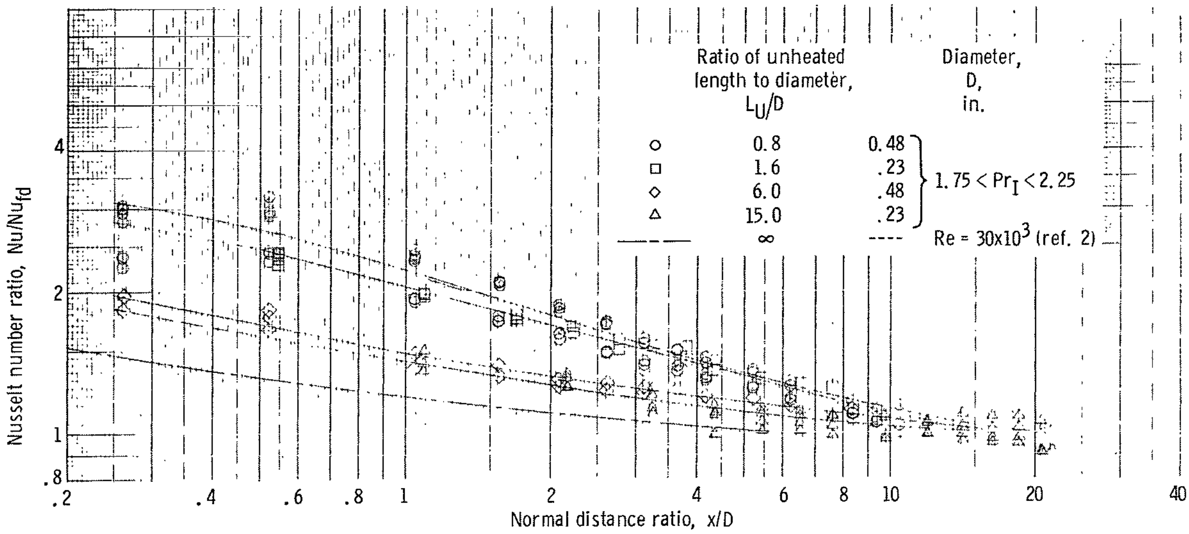


Figure 7. - Variation of Nusselt number ratio with normal distance ratio for various values of the ratio of unheated length to diameter and Prandtl number of 2 (comparison with theory).

figure 6. Comparison is made with the data of reference 5 for $L_U/D = 0$ with a square-edged entrance and $Pr = 0.7$, and also with the theoretical results of reference 1 for uniform initial velocity and temperature distributions, constant wall temperature, $Pr = 0.73$, and $Re = 30\ 000$. (Variation with Re is insignificant.) The data fall considerably higher than predicted for uniform initial velocity and temperature distributions. The increase of Nu/Nu_{fd} with Pr for a given x/D is the opposite of the trend found in reference 2 for uniform initial temperature distribution with fully developed velocity distribution at the start of heating.

A plot of Nu/Nu_{fd} against x/D for $Pr \approx 2$ and various L_U/D are shown in figure 7. The analysis of reference 2 for fully developed initial velocity distribution and constant wall heat flux has been interpolated to $Pr = 2$ for $Re = 30\ 000$ and is shown for comparison. Note that for a given x/D, Nu/Nu_{fd} decreases with increasing L_U/D. A graph of Nu/Nu_{fd} against L_U/D for various Pr is made in figure 8 at a constant x/D of 0.5 to indicate the approach of Nu/Nu_{fd} to that for fully developed initial velocity distribution (refs. 1 and 2) as L_U/D increases. Note that the curves for different Pr must cross at some point to agree with both the experimental data and the analytical results. That the lower Pr data approach the analytical values at a smaller L_U/D than the higher Pr data is evident. (The curves do not approach 1.0 since $x/D = 0.5$ is not sufficient for fully developed heat-transfer results even for $L_U/D = \infty$ over this range of Pr.) For $Pr = 0.7$, data for L_U/D smaller than 5 fall above the prediction for uniform inlet velocity distribution. If the curves for different Pr (uniform inlet velocity distribution) show the same trend as for $L_U/D = \infty$, or even if there is only a slight trend reversal, the L_U/D where the data agree with analysis would increase with Pr.

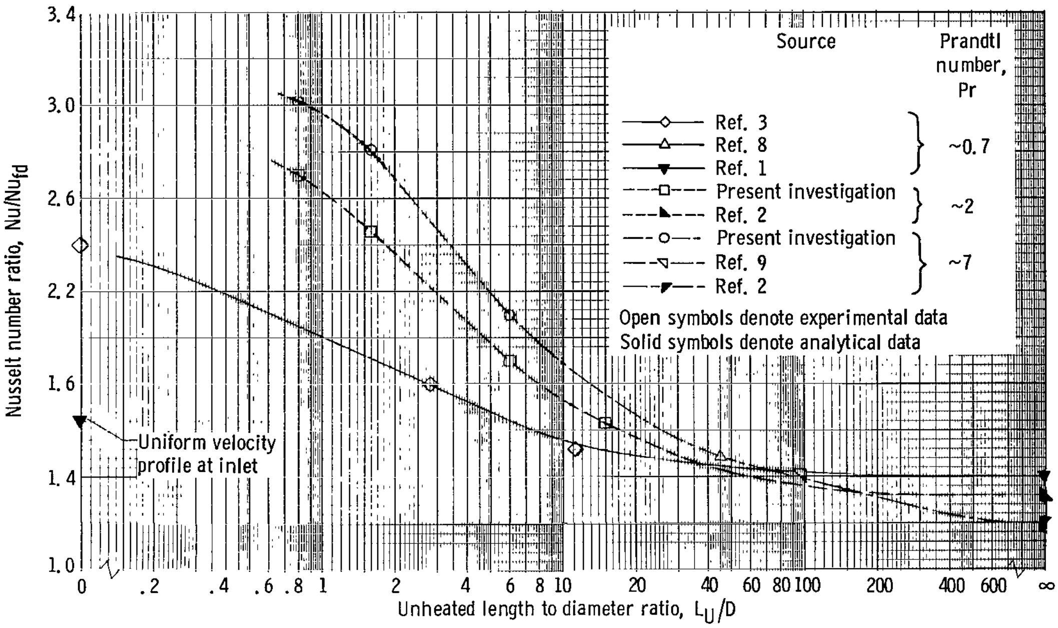


Figure 8. - Ratio of local to fully developed Nusselt number as function of unheated length-to-diameter ratio for various Prandtl numbers, normal distance ratio, 0.5.

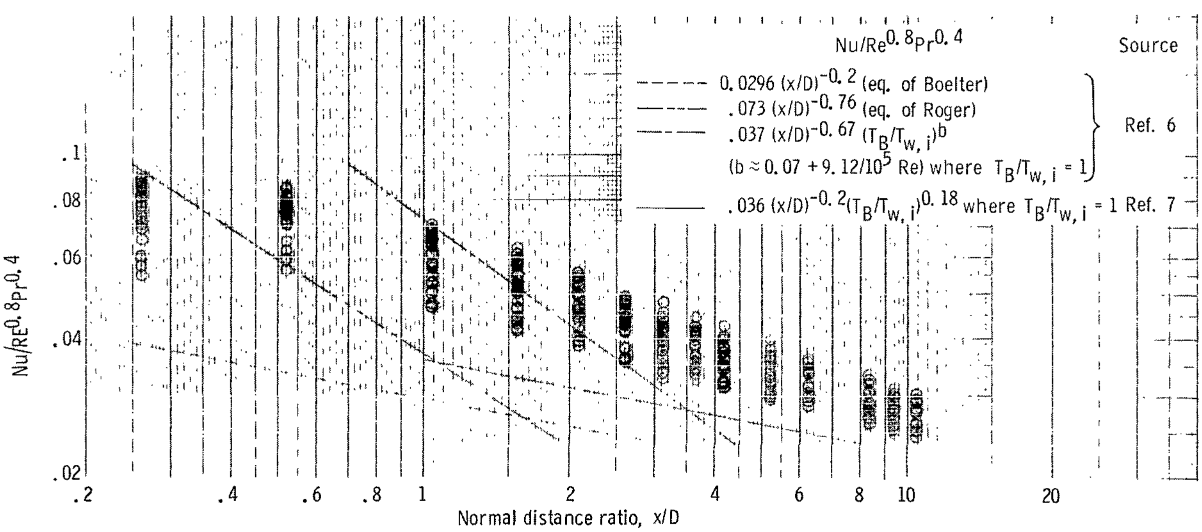


Figure 9. - Comparison of correlations based on gas data with water data, ratio of unheated length to diameter, 0.8.

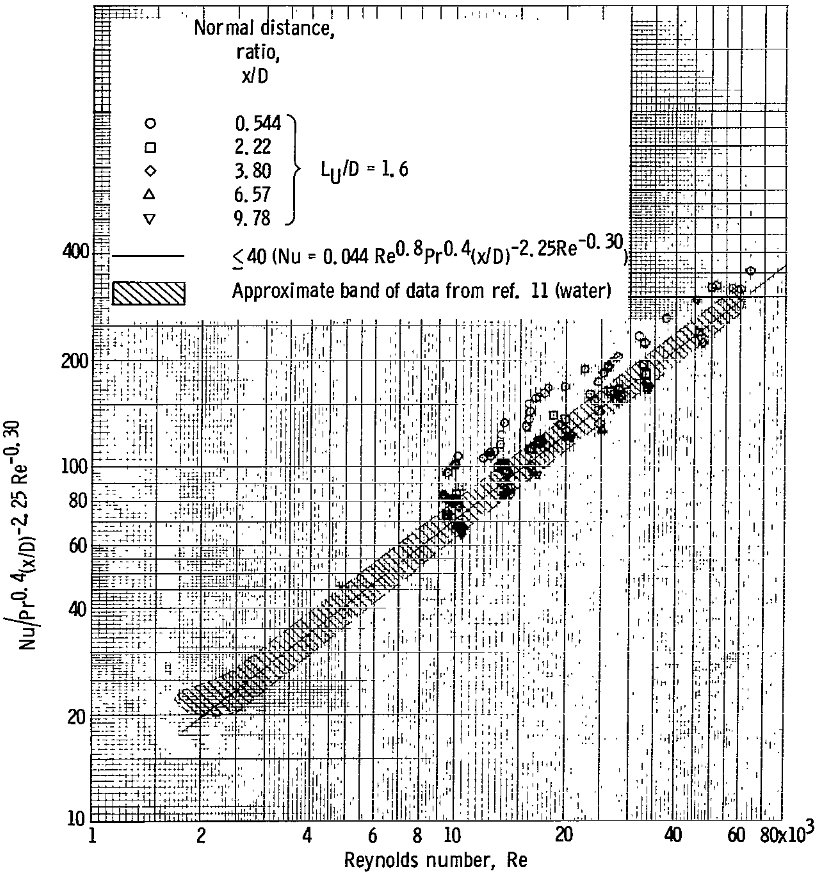
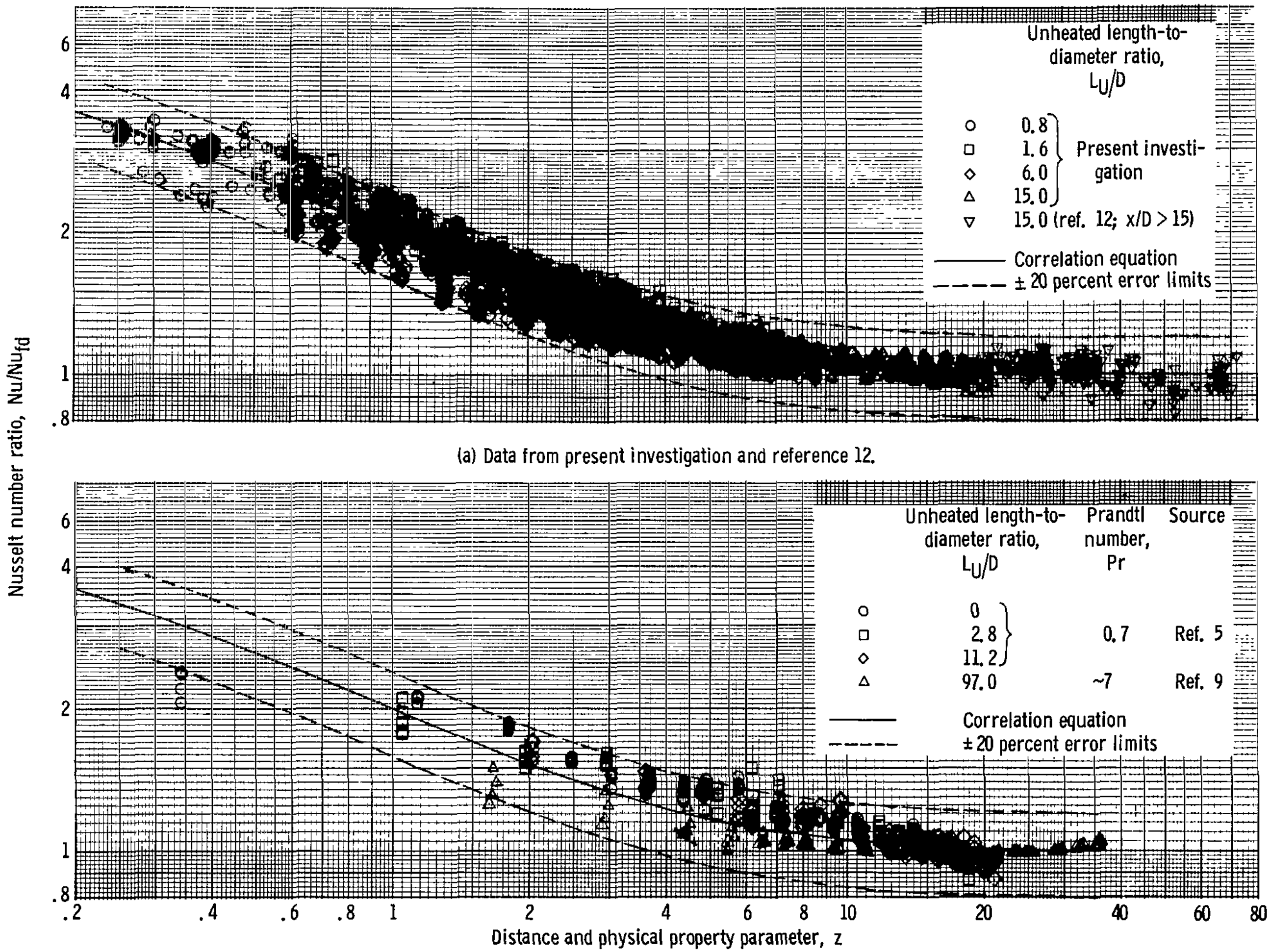


Figure 10. - Comparison of data with correlation of reference 11.

Correlation of Data

No analysis has been found that adequately predicts the experimental Nu in the entrance region for a square-edged entrance with short unheated lengths although theory (refs. 1 to 4) gives results confirmed by data (refs. 9 and 10) for long unheated lengths. Several empirical correlations have been proposed based on data for gases. Agreement of the data of this report with these correlations is shown in figure 9 to be poor. Aladyev's correlation (ref. 11) based on water data is compared with the present data in figure 10. Experimental results are as much as 50 percent greater than the correlation predicts for $x/D \cong 0.5$, $L_U/D = 1.6$ and show a consistent decrease with x/D. To improve on the accuracy of predicting Nu in the entrance region for nonfully developed flows in tubes with an abrupt entrance area change, a correlation of the present data is presented here.

The variation of Nu/Nu_{fd} with Pr at a given x/D, as was shown in figure 6, may



(a) Data from present investigation and reference 12.

(b) Data from references 5 and 9.

Figure 11. - Correlation of Nusselt number ratio in terms of dimensionless distance and physical property parameter z.

be normalized by plotting Nu/Nu_{fd} as a function of $(x/D)/Pr^{0.4}$ for $Re \geq 8\times10^3$. To correlate the effect of L_U/D, it is assumed that the effect of distance may be accounted for by two distance parameters, the heated length x and the total length from the flow inlet y $(y = x + L_U)$. It is further assumed that a correlation of the type $Nu/Nu_{fd} = f_1(x/D, Pr)f_2(y/D, Pr)$ is adequate and that the exponent of Pr in either term is the same, that is, $Nu/Nu_{fd} = f_1(x/D\ Pr^m)f_2(y/D\ Pr^m)$. Since in the limit as $L_U/D \to \infty$ the ratio is independent of L_U/D, $f_2(y/D\ Pr^m)$ is assumed to approach a constant. Thus, a modified x/D parameter z is formed

$$z = \sqrt{\frac{x}{D\ Pr^{0.4}}}\sqrt{\frac{y/D\ Pr^{0.4}}{1 + 0.01\ y/D\ Pr^{0.4}}} = \frac{\sqrt{xy}}{D\ Pr^{0.4}}\sqrt{\frac{1}{1 + 0.01\ y/D\ Pr^{0.4}}} \tag{8}$$

As $L_U/D \to 0$, $z \to x/D\ Pr^{0.4}$ for moderate x/D. Nu/Nu_{fd} is plotted against z for the data of this report and reference 12 in figure 11(a). The following correlation equation is obtained:

$$\frac{Nu}{Nu_{fd}} = 1 + \frac{2.30}{0.5z^2 + z + z^{1/4}} \qquad \text{for } Re \geq 8000 \tag{9}$$

The air data of reference 5 (Pr = 0.73) and the water data of reference 9 (Pr ≈ 7) are shown in figure 11(b). For the data of reference 9, Nu_{fd} is evaluated based on the properties at the outlet (high-temperature end). A correction for physical properties to yield Nu_{fd} based on local properties would yield values of Nu/Nu_{fd} somewhat higher than those shown (the correction being greater the nearer the point is to the start of heating). The data of reference 5 agrees with the correlation fairly well except for the first station (x/D = 0.3) for $L_U/D = 0$.

CONCLUSIONS

From the results of the present investigation the following conclusions can be made:

1. For tubes with unheated length to diameter ratios up to about 5 and square-edged entrances, local Nusselt numbers in the entrance region are significantly greater than those predicted for uniform initial velocity distribution at a Prandtl number of 0.7 and probably are greater for larger unheated length to diameter ratios for higher Prandtl numbers.

2. The Nusselt number ratio increases with increasing Prandtl number in the entrance region. This trend is opposite to that predicted by Deissler for fully developed

velocity distribution at the start of heating.

3. Local heat-transfer data in entrance regions of tubes with square-edged inlets and nonfully developed velocity distributions have been correlated empirically with the ratio of local to fully developed Nusselt number given as a function of Prandtl number and geometric parameters. The equation is valid for a Reynolds number greater than 8000 and Prandtl numbers between 0.7 and 7. Although applicability to other Prandtl numbers has not been established, this correlation does give a more accurate method of predicting the heat transfer in the entrance region of tubes with square-edged inlets than was previously available.

Lewis Research Center,
National Aeronautics and Space Administration,
Cleveland, Ohio, August 9, 1965.

APPENDIX - SYMBOLS

c factor obtained experimentally as $Nu_{fd}/Re^{0.8}$, dimensionless

c_p heat capacity at constant pressure, Btu/(lb mass)($^{\circ}$F)

D inside diameter of test section, in.

G mass flow rate per unit area, lb mass/(hr)(sq ft)

h heat-transfer coefficient, Btu/(hr)(sq ft)($^{\circ}$F)

k thermal conductivity, Btu/(hr)(ft)($^{\circ}$F)

L_H length of heated section, in.

L_U length of unheated starting section, in.

Nu Nusselt number, $hD/12\,k$, dimensionless

P power generated, W

P_e exit pressure, lb force/sq in. abs

Pr Prandtl number, $c_p\mu/k$, dimensionless

Q_E heat electrically generated (eq. (1)), Btu/hr

Q_H heat input based on water temperature rise (eq. (2)), Btu/hr

q heat flux, Btu/(hr)(sq ft)

Re Reynolds number, $DG/12\,\mu$, dimensionless

r radius, ft

T temperature, $^{\circ}$F ($^{\circ}$R when in temperature ratios)

W mass flow, lb mass/hr

x distance from start of heated section to local point, in.

y distance from inlet of unheated section to local point, in.

z distance and physical property parameter defined by eq. (8), dimensionless

μ viscosity, lb mass/(ft)(hr)

Subscripts:

B bulk or evaluated at bulk temperature

fd fully developed region

I inlet

i inner

ℓ local

O outlet

o outer

w wall

REFERENCES

1. Deissler, Robert G.: Analysis of Turbulent Heat Transfer and Flow in the Entrance Regions of Smooth Passages. NACA TN 3016, 1953.

2. Deissler, Robert G.: Analysis of Turbulent Heat Transfer, Mass Transfer, and Friction in Smooth Tubes at High Prandtl and Schmidt Numbers. NACA TR 1210, 1955.

3. Sparrow, E. M.; Hallman, T. M.; and Siegel, R.: Turbulent Heat Transfer in the Thermal Entrance Region of a Pipe with Uniform Heat Flux. Appl. Sci. Res., sec. A, vol. 7, May 1957, pp. 37-52.

4. Siegel, R.; and Sparrow, E. M.: Comparison of Turbulent Heat-Transfer Results for Uniform Wall Heat Flux and Uniform Wall Temperature. J. Heat Transfer (Trans. ASME), ser. C, vol. 82, no. 2, May 1960, pp. 152-153.

5. Boelter, L. M. K.; Young, G.; and Iversen, H. W.: An Investigation of Aircraft Heaters. XXVII - Distribution of Heat-Transfer Rate in the Entrance Region of a Circular Tube. NACA TN 1451, 1948.

6. Pratinidhi, S. V.: An Experimental Method for Measuring Heat Transfer Coefficients in the Thermal Entrance Region of a Circular Tube. M.S. Thesis, McGill Univ., 1956.

7. Davey, T. B.: Entrance Region Heat Transfer Coefficients. Chem. Eng. Prog. Symposium Ser., vol. 59, no. 41, 1963, pp. 47-51.

8. Abbrecht, Peter H.; and Churchill, Stuart W.: Thermal Entrance Region in Fully Developed Turbulent Flow. A.I.Ch.E. J., vol. 6, no. 2, June 1960, pp. 268-273.

9. Hartnett, J. P.: Experimental Determination of Thermal-Entrance Length for the Flow of Water and of Oil in Circular Pipes. Trans. ASME, vol. 77, no. 8, Nov. 1955, pp. 1211-1220.

10. Allen, R. W.; and Eckert, E. R. G.: Friction and Heat-Transfer Measurements to Turbulent Pipe Flow of Water (Pr = 7 and 8) at Uniform Wall Heat Flux. J. Heat Transfer (Trans. ASME) ser. C, vol. 86, no. 3, Aug. 1964, pp. 301-310.

11. Aladyev, I. T.: Experimental Determination of Local and Mean Coefficients of Heat Transfer for Turbulent Flow in Pipes. NACA TM 1356, 1954.

12. Jeglic, Frank A.; Stone, James R.; and Gray, Vernon H.: Experimental Study of Subcooled Nucleate Boiling of Water Flowing in 1/4-Inch-Diameter Tubes at Low Pressures. NASA Tn D-2626, 1965.

13. Kreith, Frank: Principles of Heat Transfer. Int. Textbook Co., 1958.

TABLE I. - ENTRANCE REGION HEAT-TRANSFER STUDIES

Analytical			
Reference	Wall boundary condition	Initial velocity distribution	Prandtl number
1	Uniform heat flux Constant wall temperature Uniform heat flux Uniform heat flux	Uniform Fully developed ↓	0.73 .01
2	Uniform heat flux	Fully developed	1 to 3000
3	Uniform heat flux	Fully developed	0.7 to 100
4	Uniform heat flux Constant wall temperature	Fully developed Fully developed	0.7 to 100
Experimental			
Reference	Mode of heat transfer	Initial conditions	Prandtl number
5	Heated by condensing steam	Various unheated lengths and various types of inlets with no unheated length	0.73
6	Cooled by boiling water	No unheated length	0.73
7	Cooled by boiling water	Area reduction of 4 preceded by 9 diameters of insulated tubing	0.73
8	Heated by condensing steam and by resistance heating	44 diameters unheated length	0.73
9	Resistance heated	97 diameters unheated length	~7 and 50 to 350
10	Resistance heated	96 diameters unheated length	7 to 8
11	Heated by condensing steam	Area reduction of 3.1 preceded by 2.5 diameters of unheated tubing	~2 to 7

TABLE II. - SUMMARY OF TEST SECTION GEOMETRIES TESTED

Inside diameter of test section, D, in.	L_U/D	L_H/D
0.23	15	25
.23	1.6	12.5
.48	6	12.5
.48	.8	12.5

TABLE III. - EXPERIMENTAL DATA

(a) $L_U/D = 0.8$; $L_H/D = 12.5$; inside diameter of test section, 0.48 inch

Mass flow rate, G, lb mass/(hr)(sq ft)	Exit pressure, P_e, lb force/sq in. abs	Inlet bulk temperature, $T_{B,I}$, °F	Outlet bulk temperature, $T_{B,O}$, °F	Inlet Reynolds number, Re_I	Outlet Reynolds number, Re_O	Inlet Prandtl number, Pr_I	Outlet Prandtl number, Pr_O	Heat flux, q, Btu/(hr)(sq ft)	Distance from start of heating section, x, in. 0.125	0.250	0.500	0.750	1.000	1.250	1.500	1.750	2.000	2.500	3.000	4.000	4.500	5.000
									Inner wall temperature, $T_{w,i}$, °F													
0.471×10^6	16.3	114.5	120	13 000	13 800	3.83	3.64	55.4×10^3	135	136	141	145	149	153	159	160	162	165	170	175	179	181
.471		112	120	12 900	13 800	3.93	3.64	74.9	143	147	154	159	164	169	172	176	180	178	186	189	198	202
.471		109	120	12 500	13 800	4.06	3.64	113	154	156	167	178	184	194	200	202	211	220	229	242	247	245
.471		113.5	122.5	13 100	14 200	3.87	3.55	90.1	149	152	159	166	173	181	188	190	192	200	207	217	220	228
.464		140	149	16 300	17 400	2.98	2.78	90.1	173	175	182	191	196	202	208	212	215	221	226	237	238	237
.471		160	169	19 400	20 600	2.51	2.35	91.2	192	193	201	208	213	218	224	228	229	236	242	248	251	242
.471		177.5	186	22 000	23 200	2.19	2.07	91.2	209	210	218	223	229	234	240	242	245	250	256	[a]246	[a]252	[a]242
.471		75.5	92.5	8 580	10 300	6.25	5.05	160	150	152	173	183	196	212	219	223	237	250	251	259	[a]257	[a]252
.805	16.4	82	89	15 900	17 100	5.71	5.24	117	115	119	125	133	137	142	150	153	155	162	167	177	180	183
.805		78	88	15 100	16 800	6.04	5.32	169	126	130	139	148	155	165	172	181	183	190	199	212	216	220
.805		78	90.5	15 100	17 300	6.04	5.17	208	138	146	157	168	175	186	188	197	201	[a]210	224	[a]246	[a]255	[a]246
		78	94.5	15 100	18 100	6.04	4.92	261	155	158	177	186	200	215	[a]226	[a]235	[a]240	[a]251	[a]258	[a]265	[a]259	[a]265
		79	97.5	15 400	18 600	5.94	4.74	303	166	173	188	199	[a]215	[a]231	[a]246	[a]255	[a]259	[a]257	[a]264	[a]264	[a]266	[a]260
.808		75	90.5	14 600	17 300	6.30	5.17	257	155	162	175	184	198	213	224	229	[a]238	[a]251	[a]260	[a]266	[a]266	[a]262
.812		80	96.5	15 600	18 500	5.86	4.80	280	162	168	183	196	208	222	[a]232	[a]238	[a]250	[a]257	[a]264	[a]266	[a]266	[a]260
.805		80.5	99.5	15 600	19 100	5.82	4.63	316	171	181	200	227	[a]227	[a]240	[a]256	[a]256	[a]263	[a]266	[a]261	[a]269	[a]269	[a]263
.805		80	102	15 500	19 600	5.86	4.48	358	186	191	210	227	[a]243	[a]256	[a]263	[a]265	[a]273	[a]267	[a]273	[a]269	[a]272	[a]267
.801		179	183	37 900	38 800	2.17	2.11	74.8	196	195	201	204	207	209	212	213	216	218	220	224	226	226
.805		178	185	37 800	39 500	2.18	2.08	120	205	206	212	217	223	226	230	[a]232	[a]234	[a]237	[a]242	[a]248	[a]250	[a]247
.805		178	187	37 800	40 000	2.18	2.06	166	217	216	226	232	[a]238	[a]245	[a]249	[a]249	[a]255	[a]250	[a]257	[a]259	[a]256	[a]247
.805		178.5	189.5	37 900	48 600	2.17	2.02	196	221	221	[a]231	[a]238	[a]250	[a]250	[a]251	[a]254	[a]256	[a]251	[a]258	[a]258	[a]258	[a]247
.805		99.5	104	19 400	20 300	4.54	4.33	76.0	124	126	131	135	139	142	144	148	149	153	155	162	164	166
.805		119	123	23 600	24 400	3.65	3.52	74.9	142	144	148	152	156	160	162	164	164	168	172	176	178	180
.812		144.5	149.5	29 600	30 700	2.87	2.76	74.9	168	168	172	176	180	183	184	186	188	192	193	198	200	202
.805		166	170	34 700	35 600	2.40	2.32	76.0	187	188	193	196	200	202	205	206	207	210	212	216	219	219
.805		180.5	184.5	38 400	39 400	2.14	2.09	73.8	201	201	206	209	212	214	216	217	219	221	224	229	231	232
.805		188	192	40 400	41 400	2.03	1.98	74.9	210	209	214	216	219	222	224	224	227	229	231	235	237	238
.805		199.5	203	43 500	44 300	1.89	1.85	76.0	220	219	225	228	230	233	236	236	237	239	242	246	248	[a]244
.808	99.8	66	75	12 900	14 500	7.25	6.38	134	107	112	121	129	139	146	153	155	157	168	175	186	188	190
.805	99.9	96	104	18 700	20 200	4.74	4.34	137	134	137	145	153	159	167	170	174	179	185	190	201	201	205
.805	99.8	172	179	36 200	37 900	2.28	2.18	135	204	204	215	221	228	232	235	236	239	244	249	257	259	262

[a]Data in subcooled boiling regime.

TABLE III. - Continued. EXPERIMENTAL DATA

(b) $L_U/D = 1.6$; $L_H/D = 12.5$; inside diameter of test section, 0.23 inch

Mass flow rate, G, lb mass/(hr)(sq ft)	Exit pressure, P_e, lb force/sq in. abs	Inlet bulk temperature, $T_{B,I}$, °F	Outlet bulk temperature, $T_{B,O}$, °F	Inlet Reynolds number, Re_I	Outlet Reynolds number, Re_O	Inlet Prandtl number, Pr_I	Outlet Prandtl number, Pr_O	Heat flux, q, Btu/(hr)(sq ft)	Distance from start of heating section, x, in.												
									0.125	0.250	0.390	0.510	0.635	0.750	0.875	1.000	1.250	1.510	1.750	2.000	2.250
									Inner wall temperature, $T_{w,i}$, °F												
0.714×10^6	16.3	118	125	9 940	10 600	3.69	3.45	113×10^3	150	157	163	166	172	173	175	179	184	190	194	194	200
.714		113	125	9 490	10 600	3.89	3.45	184	166	178	187	192	198	202	207	211	221	229	237	238	243
.727		117	125.5	10 000	10 800	3.73	3.44	135	155	163	171	175	181	183	185	189	194	201	207	206	212
.721		110	125	9 300	10 700	4.02	3.45	220	185	198	207	214	225	229	[a]221	[a]232	[a]241	[a]251	[a]261	[a]261	[a]266
.721		109.5	125	9 250	10 700	4.04	3.45	227	185	201	211	217	225	229	[a]233	[a]240	[a]249	[a]260	[a]260	[a]258	[a]264
0.717		155	162	13 600	14 300	2.62	2.48	113	182	191	195	199	203	204	205	209	213	216	220	219	224
1.06		107	120	13 200	14 900	4.16	3.64	298	174	188	199	205	214	217	221	225	234	[a]243	[a]251	[a]247	[a]246
1.06		103	120	12 700	14 900	4.35	3.64	369	194	211	226	233	[a]244	[a]248	[a]255	[a]261	[a]259	[a]251	[a]253	[a]251	[a]253
1.06		100.5	120	12 300	14 900	4.48	3.64	411	204	223	240	[a]246	[a]258	[a]263	[a]264	[a]264	[a]264	[a]255	[a]256	[a]255	[a]258
1.04		102	120	12 300	14 700	4.40	3.64	397	200	215	[a]234	[a]241	[a]251	[a]258	[a]263	[a]267	[a]265	[a]256	[a]259	[a]259	[a]258
1.05		96.5	119.5	11 800	14 800	4.70	3.66	511	225	243	[a]261	[a]274	[a]281	[a]288	[a]279	[a]281	[a]279	[a]270	[a]271	[a]270	[a]271
1.06		133	140.5	16 800	17 900	3.19	2.98	142	160	165	172	176	179	180	181	184	186	188	194	192	193
1.06		130	140	16 500	17 900	3.28	3.00	199	168	176	185	91	193	196	198	202	207	211	218	216	218
1.06		126	139	15 900	17 600	3.40	3.03	312	190	205	216	226	[a]231	[a]232	[a]237	[a]241	[a]250	[a]257	[a]261	[a]258	[a]259
1.06		124	140	15 500	17 800	3.47	3.00	382	210	228	[a]242	[a]250	[a]256	[a]260	[a]265	[a]270	[a]273	[a]262	[a]263	[a]263	[a]264
1.47		153.5	162	27 600	29 500	2.66	2.48	284	198	208	215	218	223	224	227	[a]232	[a]234	[a]238	[a]242	[a]242	[a]245
1.47		150	160	26 800	29 000	2.74	2.52	326	202	215	224	226	232	234	237	242	246	[a]251	[a]253	[a]252	[a]256
1.47		146	160	26 000	29 000	2.83	2.52	447	219	235	243	248	[a]256	[a]259	[a]261	[a]268	[a]271	[a]275	[a]268	[a]266	[a]271
1.46		146.5	160.5	25 900	29 000	2.82	2.51	461	222	238	247	[a]249	[a]260	[a]261	[a]263	[a]270	[a]274	[a]276	[a]270	[a]267	[a]274
1.47		142	158	25 200	28 500	2.92	2.57	546	234	[a]252	[a]263	[a]270	[a]276	[a]280	[a]276	[a]274	[a]276	[a]272	[a]270	[a]271	[a]269
2.05	16.7	66	88	15 700	20 600	7.25	5.32	964	217	248	[a]270	[a]274	[a]285	[a]285	[a]286	[a]277	[a]282	[a]277	[a]273	----	[a]276
2.05	16.7	73	95	17 300	22 400	6.50	4.85	964	219	[a]251	[a]268	----	[a]285	[a]286	[a]277	[a]281	[a]276	[a]273	----	----	[a]274
.717	99.9	152.5	158	13 300	13 900	2.68	2.56	99.3	179	185	189	192	196	197	199	201	205	208	210	210	212
.714	99.4	120.5	134	10 200	11 400	3.60	3.17	213	178	191	200	207	214	220	224	231	237	244	253	255	260
1.08	99.4	124	132	15 800	17 000	3.47	3.22	199	167	176	184	187	191	196	200	202	207	211	215	218	219
1.08	100.0	179	187	24 400	25 800	2.17	2.05	199	218	227	232	236	241	242	245	248	251	254	256	256	257
2.06	99.6	83	88	19 700	20 900	5.64	5.28	220	116	124	130	132	136	140	141	144	146	148	151	149	153
2.06	100	133	138	32 800	34 200	3.19	3.05	220	163	168	174	176	180	181	182	184	186	188	189	189	191
2.06	99.5	74	96	17 700	22 700	6.40	4.81	979	217	249	270	282	300	309	315	325	342	[a]346	[a]345	[a]342	[a]342
2.06	99.6	94	116.5	22 200	29 000	4.86	3.78	979	231	260	280	288	302	309	315	327	337	[a]346	[a]343	[a]342	[a]345
2.05	100.0	129.5	151.5	31 600	37 600	3.30	2.72	979	256	283	300	305	319	323	328	339	[a]346	[a]347	[a]345	[a]344	[a]346
	100.2	150	171	37 400	43 600	2.74	2.31	964	267	294	309	316	329	332	338	[a]347	[a]351	[a]349	[a]348	[a]345	[a]347
	100.1	175	197	45 100	52 000	2.23	1.92	979	286	268	330	337	348	353	358	368	[a]354	[a]354	[a]355	[a]353	[a]356
	99.9	189	210.5	49 600	56 400	2.02	1.77	979	297	322	337	[a]344	[a]357	[a]358	[a]359	[a]355	[a]355	[a]355	[a]354	[a]353	[a]355
	99.9	194	216	51 300	58 100	1.95	1.72	993	303	326	[a]341	[a]347	[a]361	[a]362	[a]352	[a]354	[a]353	[a]356	[a]353	[a]352	[a]356
	99.9	188.5	210	57 000	63 200	2.03	1.78	993	300	324	[a]341	[a]348	[a]358	[a]357	[a]356	[a]362	[a]362	[a]362	[a]362	[a]358	[a]360
	99.9	199	220.5	52 900	59 500	1.89	1.67	993	313	333	[a]348	[a]353	[a]365	[a]359	[a]358	[a]363	[a]363	[a]364	[a]363	[a]362	[a]364
	99.7	212	233	57 200	63 500	1.75	1.57	993	317	[a]344	[a]357	[a]363	[a]364	[a]364	[a]364	[a]366	[a]365	[a]367	[a]367	[a]364	[a]365

[a]Data in subcooled boiling regime.

TABLE III. - Continued. EXPERIMENTAL DATA

(c) $L_U/D = 6$; $L_H/D = 12.5$; inside diameter of test section, 0.48 inch

Mass flow rate, G, lb mass/(hr)(sq ft)	Exit pressure, P_e, lb force/sq in. abs	Inlet bulk temperature, $T_{B,I}$, °F	Outlet bulk temperature, $T_{B,O}$, °F	Inlet Reynolds number, Re_I	Outlet Reynolds number, Re_O	Inlet Prandtl number, Pr_I	Outlet Prandtl number, Pr_O	Heat flux, q, Btu/(hr)(sq ft)	Distance from start of heating section, x, in.													
									0.125	0.250	0.500	0.750	1.000	1.250	1.500	1.750	2.000	2.500	3.000	4.000	4.500	5.000
									Inner wall temperature, $T_{w,i}$, °F													
0.471×10^6	16.3	155	160	18 600	19 300	2.62	2.52	47.8×10^3	182	186	195	198	200	201	202	204	204	205	208	209	211	212
.467		150.5	159	17 800	19 000	2.72	2.55	84.7	199	207	218	224	231	233	234	238	239	242	246	[a]247	[a]238	[a]238
.464		150	159.5	17 700	18 900	2.74	2.54	93.3	202	212	225	229	234	238	239	[a]240	[a]234	[a]237	[a]238	[a]240	[a]240	[a]239
.471		146	160	17 400	19 200	2.83	2.52	137	223	234	240	[a]241	[a]240	[a]240	[a]241	[a]240	[a]240	[a]239	[a]241	[a]241	[a]241	[a]241
.474		112.5	120.5	13 100	14 000	3.91	3.62	82.5	162	171	181	189	193	197	200	204	206	207	209	217	220	219
0.471		106.5	120	12 200	13 800	4.17	3.63	132	187	204	222	232	240	[a]243	[a]243	[a]242	[a]243	[a]242	[a]244	[a]242	[a]244	[a]242
.805		116	120	23 000	23 700	3.77	3.63	68.4	145	150	158	160	162	163	164	164	164	167	168	170	170	171
.805		114	120	22 500	23 700	3.85	3.63	91.2	150	161	169	172	175	176	179	179	180	182	184	187	188	188
.805		112	120	22 100	23 700	3.93	3.63	134	172	181	193	198	201	204	209	209	211	212	215	218	222	222
.805		108.5	120.5	21 400	23 700	4.08	3.62	205	198	212	230	237	244	248	253	[a]252	[a]252	[a]253	[a]255	[a]255	[a]255	[a]254
0.805		80	85.5	15 500	16 400	5.88	5.48	87.9	120	128	137	140	143	146	147	148	151	152	155	156	158	158
.805		79	87	15 300	16 700	5.96	5.38	127	139	148	163	168	175	177	179	182	184	188	190	195	196	197
.805		79.5	89	15 400	17 000	5.92	5.25	160	154	164	182	185	194	200	203	206	208	213	218	222	223	226
.808		79.5	90.5	15 500	17 400	5.92	5.15	197	172	184	201	213	222	226	232	234	240	244	247	258	[a]255	[a]254
.808		80	95.5	15 600	18 400	5.86	4.85	261	200	217	240	249	261	[a]261	[a]263	[a]262	[a]262	[a]261	[a]264	[a]263	[a]264	[a]263
0.805		78.5	96	15 200	18 400	5.99	4.83	287	209	227	253	[a]261	[a]264	[a]265	[a]267	[a]264	[a]265	[a]264	[a]267	[a]268	[a]268	[a]265
.995	16.4	117	120	28 700	29 400	3.73	3.63	71.6	142	146	151	153	155	156	157	157	157	158	159	160	161	161
.735	99.9	80	88	14 200	15 400	5.88	5.31	124	138	146	160	165	170	174	177	179	181	184	188	194	195	197
.805	100.0	80	87.5	15 500	16 800	5.88	5.34	121	133	142	155	162	165	166	172	172	175	177	179	185	187	187
.805	99.8	79.5	91.5	15 400	17 600	5.91	5.09	202	169	181	199	211	217	224	230	233	235	242	248	253	253	261
0.805	99.9	79.5	99	15 400	18 900	5.90	4.66	332	225	241	271	288	300	307	318	327	337	[a]338	[a]337	[a]338	[a]338	[a]340
	99.8	78	101.5	15 200	19 400	6.02	4.54	391	249	272	308	307	320	336	345	[a]346	[a]346	[a]345	[a]345	[a]345	[a]350	[a]349
	99.8	78	106.5	15 200	20 400	6.02	4.30	482	285	312	[a]352	[a]352	[a]353	[a]352	[a]353	[a]353	[a]352	[a]352	[a]353	[a]358	[a]357	[a]355
	99.8	179.5	192	38 200	41 200	2.16	1.99	221	261	269	288	293	299	302	303	302	307	309	313	318	319	321
	99.8	178	195.5	37 800	42 000	2.18	1.95	296	279	289	314	322	328	333	339	341	[a]340	[a]344	[a]343	[a]346	[a]345	[a]344
0.810	99.8	178	200	37 700	42 900	2.18	1.90	378	307	323	[a]349	[a]348	[a]349	[a]350	[a]350	[a]349	[a]349	[a]348	[a]352	[a]355	[a]354	[a]354
.805	99.8	72	80	13 900	15 300	6.60	5.95	137	127	136	151	155	162	165	169	175	175	181	185	191	193	192
.805	99.8	101	109	19 700	21 300	4.58	4.10	130	155	162	175	180	185	189	191	192	195	196	200	204	204	204
.805	99.9	138	145	27 900	29 300	3.04	2.87	134	184	190	203	208	211	214	217	219	220	222	224	228	228	230
.805	99.9	183.5	190.5	39 200	49 000	2.10	2.00	130	224	229	243	247	249	251	252	253	254	256	260	264	264	266

[a]Data in subcooled boiling regime.

TABLE III. - Concluded. EXPERIMENTAL DATA

(d) $L_U/D = 15$; $L_H/D = 25$; inside diameter of test section, 0.23 inch

Mass flow rate, G, lb mass/(hr)(sq ft)	Exit pressure, P_e, lb force/sq in. abs	Inlet bulk temperature, $T_{B,I}$, °F	Outlet bulk temperature, $T_{B,O}$, °F	Inlet Reynolds number, Re_I	Outlet Reynolds number, Re_O	Inlet Prandtl number, Pr_I	Outlet Prandtl number, Pr_O	Heat flux, q, Btu/(hr)(sq ft)	Distance from start of heating section, x, in.														
									0.250	0.500	0.750	1.000	1.250	1.500	1.750	2.250	2.750	3.250	3.750	4.250	4.750	5.000
									Inner wall temperature, $T_{w,i}$, °F													
2.08×10^6	16.5	148.5	160	38 200	41 200	2.77	2.53	259×10^3	204	211	216	221	221	222	223	225	228	229	230	233	233	235
2.06	16.5	138	160	34 900	41 000	3.04	2.53	458	237	251	261	[a]268	[a]268	[a]268	[a]270	[a]273	[a]275	[a]279	[a]278	[a]277	[a]277	[a]278
3.46	16.6	152	160	65 600	68 900	2.68	2.53	304	194	199	204	208	209	209	210	211	213	214	214	215	216	---
3.48		148	160	64 100	69 100	2.78	2.53	436	210	217	222	226	226	226	228	230	231	233	235	236	240	240
3.46		168	180	73 500	79 200	2.34	2.34	436	225	231	237	241	242	242	245	248	250	251	252	254	257	257
3.48	↓	194	200	86 400	90 300	1.97	1.94	184	218	220	224	227	227	227	228	229	229	230	231	231	233	---
1.04	99.9	152	189.5	19 700	25 300	2.65	2.01	412	288	309	326	335	337	339	341	343	[a]343	[a]345	[a]345	[a]347	[a]347	[a]349
1.04	99.8	220	229.5	31 000	32 100	1.67	1.60	122	256	262	264	271	273	274	275	278	279	280	281	283	286	286
1.04	99.8	202	230	27 500	32 200	1.84	1.59	322	297	311	322	330	333	334	339	342	345	344	346	348	351	350
2.06	99.9	178	190	47 000	50 700	2.16	2.01	269	230	237	243	245	246	247	248	249	252	254	256	256	258	258
2.04	99.9	164	190	42 500	48 800	2.40	2.01	587	275	292	302	307	309	311	313	317	319	325	328	329	333	336
2.04	99.8	219.5	230	60 100	63 000	1.68	1.59	269	266	275	277	279	281	281	282	283	286	287	288	290	293	293
3.46	99.6	165	190	72 000	84 000	2.39	2.03	937	288	302	312	319	320	321	323	325	---	327	336	337	344	345
3.46	99.8	220.5	230	104 000	105 000	1.66	1.59	376	266	271	275	278	279	278	280	281	284	286	286	289	291	291
3.44	99.8	214	230	97 000	106 000	1.72	1.59	617	285	295	302	303	307	308	308	312	314	316	---	321	325	326
3.46	99.8	236	250	110 000	118 000	1.54	1.44	510	300	306	312	315	317	317	319	321	323	326	---	328	331	331

[a]Data in subcooled boiling regime.

3 | 12 ? 5 06

"The aeronautical and space activities of the United States shall be conducted so as to contribute . . . to the expansion of human knowledge of phenomena in the atmosphere and space. The Administration shall provide for the widest practicable and appropriate dissemination of information concerning its activities and the results thereof."

—NATIONAL AERONAUTICS AND SPACE ACT OF 1958

NASA SCIENTIFIC AND TECHNICAL PUBLICATIONS

TECHNICAL REPORTS: Scientific and technical information considered important, complete, and a lasting contribution to existing knowledge.

TECHNICAL NOTES: Information less broad in scope but nevertheless of importance as a contribution to existing knowledge.

TECHNICAL MEMORANDUMS: Information receiving limited distribution because of preliminary data, security classification, or other reasons.

CONTRACTOR REPORTS: Technical information generated in connection with a NASA contract or grant and released under NASA auspices.

TECHNICAL TRANSLATIONS: Information published in a foreign language considered to merit NASA distribution in English.

TECHNICAL REPRINTS: Information derived from NASA activities and initially published in the form of journal articles.

SPECIAL PUBLICATIONS: Information derived from or of value to NASA activities but not necessarily reporting the results of individual NASA-programmed scientific efforts. Publications include conference proceedings, monographs, data compilations, handbooks, sourcebooks, and special bibliographies.

Details on the availability of these publications may be obtained from:

SCIENTIFIC AND TECHNICAL INFORMATION DIVISION

NATIONAL AERONAUTICS AND SPACE ADMINISTRATION

Washington, D.C. 20546