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PREDICTION OF FRICTION AND HEAT-TRANSFER COEFFICIENTS WITH LARGE VARIATIONS IN FLUID PROPERTIES

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16. Abstract

The conventional methods of predicting single-phase turbulent heat-transfer and friction coefficients often give values that are in poor agreement with measured values when large variations in the fluid properties are present. Heat-transfer and friction data for hydrogen, helium, nitrogen, air, and carbon dioxide were used to determine the best available relation for correlating friction and heat-transfer coefficients for heat addition to, and heat extraction from, gases flowing subsonically through a smooth tube.

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PREDICTION OF FRICTION AND HEAT-TRANSFER COEFFICIENTS WITH LARGE VARIATIONS IN FLUID PROPERTIES

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SUMMARY

The conventional methods of predicting single-phase turbulent heat-transfer and friction coefficients often give values that are in poor agreement with measured values when large variations in the fluid properties are present. Heat-transfer and friction coefficients calculated by recently reported prediction equations were compared with measured values for hydrogen, helium, nitrogen, air, and carbon dioxide from several different investigations.

For the case of heat extraction from a gas the heat-transfer coefficient can be accurately predicted with the relation

$$Nu_b = 0.023\ Re_b^{0.8} Pr_b^{0.4}$$

and for the case of heat addition with the relation

$$Nu_b = 0.023\ Re_b^{0.8} Pr_b^{0.4} \left(\frac{T_s}{T_b}\right)^{-C_2}$$

where Nu_b is the bulk Nusselt number, Re_b is the bulk Reynolds number, Pr_b is the bulk Prandtl number, T_s is the surface temperature, and T_b is the bulk temperature.

For both heat extraction and heat addition to a gas the friction coefficient can be accurately predicted by the relation

$$\frac{f}{2} = \left(0.0007 + \frac{0.0625}{Re_s^{0.32}}\right)\left(\frac{T_s}{T_b}\right)^{-C_2}$$

where f is the friction coefficient, Re_s is the modified surface Reynolds number, T_s is the surface temperature, and T_b is the bulk temperature.

For both friction and heat transfer the exponent of the temperature ratio T_s/T_b is

$$C_2 = 0.57 - \frac{1.59}{x/D}$$

where x is the distance from the entrance of the test section and D is the inside diameter of the test section. These prediction equations are applicable to gases flowing subsonically through a smooth tube.

INTRODUCTION

Large variations in the physical properties of gases flowing turbulently through tubes have been found to greatly affect the heat-transfer and friction coefficients. The conventional "reference temperature" methods (i.e., evaluating the properties and density at a reference temperature $T_X = X(T_s - T_b) + T_b$) can predict coefficients that are greatly in error. For example, figure 1 shows that the measured friction coefficient

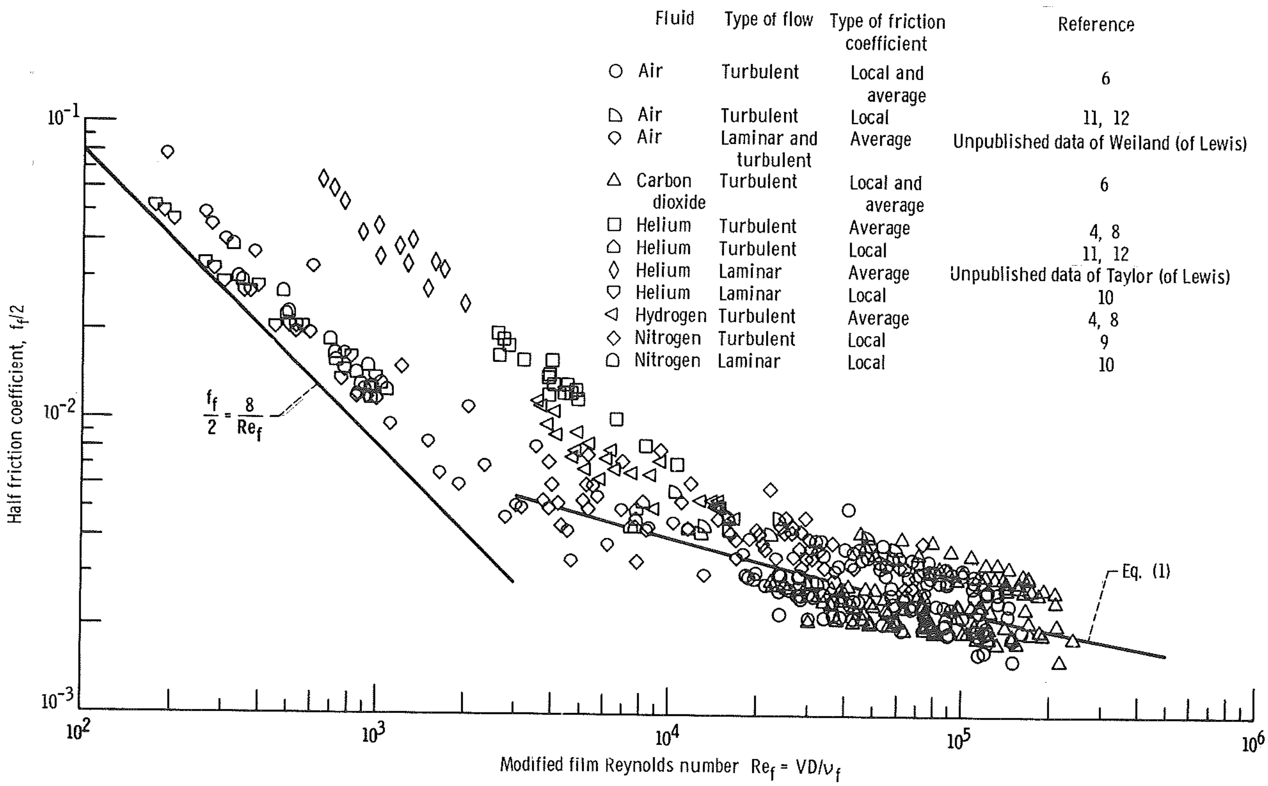

Figure 1. - Variation of local and average friction coefficients with modified film Reynolds number. Viscosity and density evaluated at film temperature.

can be as much as three times the value predicted by the Kármán-Nikuradse equation with the physical properties evaluated at the film temperature $T_f = (T_s + T_b)/2$:

$$\frac{1}{\sqrt{8\frac{f_f}{2}}} = 2 \log Re_f \sqrt{8\frac{f_f}{2}} - 0.8 \tag{1}$$

Errors of the same magnitude are found when measured heat-transfer coefficients are compared with those calculated by

$$Nu_f = 0.021\, Re_f^{0.8} Pr_f^{0.4} \tag{2}$$

Equations (1) and (2) are applicable only for developed flow.

The use of the ratio of surface to fluid-bulk temperatures T_s/T_b raised to a power has been very successful in correlating both friction coefficients (ref. 1) and heat-transfer coefficients (ref. 2) with large variations in the fluid properties. The study of available friction data (ref. 1) resulted in the recommendation that the modified surface Reynolds number $Re_s = VD/\nu_s$ be used in correlating the friction coefficients. It appeared that a modified surface Reynolds number of 3000 was critical, and the following correlation equations were recommended:

For $Re_s < 3000$:

$$\frac{f}{2} = \frac{8}{Re_s} \tag{3}$$

For $Re_s \geq 3000$:

$$\frac{f}{2} = \left(0.0007 + \frac{0.0625}{Re_s^{0.32}}\right)\left(\frac{T_s}{T_b}\right)^{-0.5} \tag{4}$$

The recommended correlation equation for heat addition $(T_s/T_b > 1.0)$ to hydrogen, helium, and nitrogen (ref. 2) is

$$Nu_b = 0.023\, Re_b^{0.8} Pr_b^{0.4} \left(\frac{T_s}{T_b}\right)^{-C_2} \tag{5}$$

where

$$C_2 = 0.57 - \frac{1.59}{\frac{x}{D}}$$

Because of the great interest in hydrogen as a propellant for both nuclear and advanced chemical rockets, a large amount of heat-transfer data has been reported. These data cover a wide range of conditions, including surface to fluid-bulk temperature ratios to 23 and heat flux to 46 megawatts per square meter (28 Btu/sec-in.^{2}).

Even though equations (3) to (5) predict friction and heat-transfer coefficients with much greater accuracy than has been possible heretofore, some interesting questions have been prompted by combining the friction and heat-transfer studies. One concerns the possibility of inserting the most recent exponent of T_s/T_b from the heat-transfer correlation equation (5) into the prior friction correlation equation (4) to make it applicable to smaller values of x/D. Another point of importance is that the friction equation (4) appears to apply to both heat addition ($T_s/T_b > 1.0$) and heat extraction ($T_s/T_b < 1.0$), but the heat-transfer equation (5) has been tested only for $T_s/T_b > 1.0$. The question of the applicability of equation (5) to heat extraction ($T_s/T_b < 1.0$) is certainly of interest. This investigation explored and answered these two questions.

SYMBOLS

C_1	constant used in eq. (6)
C_2	exponent of T_s/T_b
c_p	specific heat at constant pressure
D	inside diameter of test section
f/2	half bulk friction coefficient
$f_f/2$	half film friction coefficient
G	mass flow rate per unit cross-sectional area
h	local heat-transfer coefficient
k	thermal conductivity of gas
L	length of test section
Nu	Nusselt number, hD/k
Re	Reynolds number, VD/ν
Pr	Prandtl number, $c_p\mu/k$
T	temperature
V	velocity
X	parameter used in reference temperature equation
x	distance from entrance of test section
μ	absolute viscosity of gas
ν	kinematic viscosity of gas, μ/ρ
ρ	density of gas

Subscripts:

b fluid bulk (denotes evaluation at fluid bulk temperature, T_b)

cal calculated

ex experimental

f film (denotes evaluation at film temperature, $T_f = (T_s + T_b)/2$)

s surface (denotes evaluation at surface temperature, T_s)

CORRELATION EQUATIONS

Heat-Transfer Coefficients

Several investigators have used the same basic equation

$$Nu_b = C_1 Re_b^{0.8} Pr_b^{0.4} \left(\frac{T_s}{T_b}\right)^{-C_2} \tag{6}$$

(with C_1 varying from 0.021 to 0.024 and C_2 varying with x/D as shown in fig. 2) to

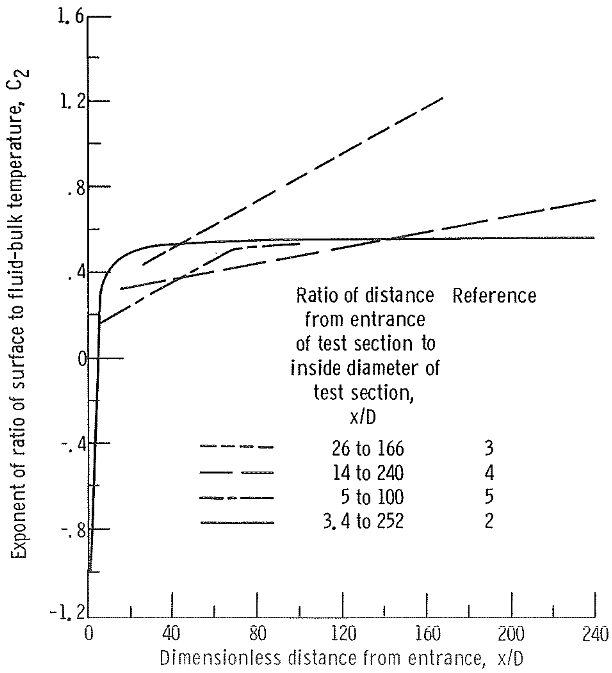

Figure 2. - Variation of exponent of ratio of surface to fluid-bulk temperatures with axial distance from entrance of test section.

correlate heat-transfer coefficients for helium and air (ref. 3), hydrogen and helium (ref. 4), and nitrogen (ref. 5) for T_s/T_b to 8.0. The availability of hydrogen heat-transfer data taken over a wide range of conditions led to a thorough study of both the data and the many proposed correlation equations (ref. 2). The study recommended the use of the correlation equation

$$Nu_b = 0.023\ Re_b^{0.8} Pr_b^{0.4} \left(\frac{T_s}{T_b}\right)^{-C_2} \tag{5}$$

where

$$C_2 = 0.57 - \frac{1.59}{\frac{x}{D}}$$

for all single-phase flow outside the near-critical region and for $2 < x/D < 252$. Equation (5) was used to calculate more then 3600 heat-transfer coefficients for hydrogen, and 87 percent deviated less than ±25 percent from the measured coefficients. In addition to the hydrogen data, 88 nitrogen gas and 359 helium gas heat-transfer coefficients were predicted with equation (5), and 98 percent deviated less than ±25 percent from the measured coefficients. All the data used in reference 2 involved heat addition to the gas ($T_s/T_b > 1$), and equation (5) was not tested on data with heat extracted from the gas ($T_s/T_b < 1$).

In the present investigation, heat-transfer coefficients for heat extraction from air and carbon dioxide (ref. 6) and air (ref. 7) were used to test equation (5) for its applicability in the range $0.25 < T_s/T_b < 1.0$. Predicted heat-transfer coefficients using equation (5) are as much as twice the measured coefficients. These results suggest that the term $\left(T_s/T_b\right)^{-C_2}$ does not apply to $T_s/T_b < 1.0$. To determine the effect of $T_s/T_b < 1.0$ on the heat-transfer coefficients, the term $\left(T_s/T_b\right)^{-C_2}$ was omitted from equation (5) to give

$$Nu_b = 0.023\ Re_b^{0.8} Pr_b^{0.4} \tag{7}$$

Heat-transfer coefficients predicted using equation (7) are in good agreement with the measured data, 81 percent of the calculated coefficients deviating less than ±15 percent from the measured values. No effect of T_s/T_b appears to be present.

Reference 6 also reported heat-transfer coefficients for heat addition to air and carbon dioxide. Where equation (5) was used to predict these heat-transfer coefficients, 93 percent of the calculated coefficients deviated less than ±25 percent from the measured values.

Friction Coefficients

The study of friction coefficients (ref. 1) which recommended the following equation for modified surface Reynolds numbers of 3000 or greater

$$\frac{f}{2} = \left(0.0007 + \frac{0.0625}{Re_s^{0.32}}\right)\left(\frac{T_s}{T_b}\right)^{-0.5} \tag{4}$$

used both local and average friction data for both heat addition and extraction (refs. 4, 6, and 8 to 12). Equation (4) correlated local friction coefficients for x/D from 16 to 113. Because equation (5) correlates heat-transfer coefficients for an x/D as low as 2, an obvious step is to use the exponent of T_s/T_b from the heat-transfer equation (5) in the friction equation (4), which gives

$$\frac{f}{2} = \left(0.0007 + \frac{0.0625}{Re_s^{0.32}}\right)\left(\frac{T_s}{T_b}\right)^{-C_2} \tag{8}$$

where

$$C_2 = 0.57 - \frac{1.59}{\frac{x}{D}}$$

Local friction coefficients for heat extraction from air and carbon dioxide (ref. 6) were compared with coefficients predicted using equation (8), and the agreement was very good for $5 < x/D < 57$ (the limit of the experimental data with the exception of the first data point which was at an $x/D = 1.57$). Equation (8) predicts local friction coefficients which are in good agreement with measured values for both heat extraction ($0.3 < T_s/T_b < 1.0$) and heat addition ($1.0 < T_s/T_b < 7.35$) for x/D from 5 to 113.

DISCUSSION OF RESULTS

Heat-Transfer Coefficients

The relation shown in equation (7) was used to calculate heat-transfer coefficients for heat extraction from air and carbon dioxide (ref. 6) and air (ref. 7). The coefficients for air and carbon dioxide (ref. 6) were calculated using equation (7), with 80 percent of them deviating less than ±15 percent from the measured coefficients for x/D from 5 to 52. Air data (ref. 7) measured only in the entrance section of a tube at x/D of 1.5, 4, 7, and 10 were also calculated using equation (7), with 86 percent of the calculated values deviating less than ±15 percent from the measured values for x/D of 4, 7, and 10. The calculated coefficients at x/D of 1.5 ran 15 to 30 percent lower than measured values.

The additional data for heat added to air and carbon dioxide (ref. 6) were local heat-transfer coefficients for x/D from 0.22 to 59 and T_s/T_b to 2.8. Using equation (5), 98 percent of the calculated heat-transfer coefficients for air deviated less than ±15 percent for x/D from about 2 to 59. The calculated values for carbon dioxide for the same x/D did not agree as well as the air data, with 88 percent deviating less than ±25 percent. Table I summarizes the results of both the present investigation and reference 2.

TABLE I. - PERCENT OF PREDICTED LOCAL HEAT-TRANSFER COEFFICIENTS THAT DEVIATE LESS THAN ±25 PERCENT FROM EXPERIMENTAL COEFFICIENTS FOR VARIOUS GASES

Gas	Number of data points	Percent of h_{cal} that deviate less than ±25 percent from h_{ex}
Heat added to gas, $1.0 < T_s/T_b < 23$; calculations used eq. (5)		
Hydrogen	3674	87
Helium	359	98
Nitrogen	88	97
Air	370	97
Carbon dioxide	370	88
Heat extracted from gas, $0.25 < T_s/T_b < 1.0$; calculations used eq. (7)		
Air	641	86
Carbon dioxide	550	94

Friction Coefficients

The relation shown in equation (8) was used to calculate 1100 friction coefficients for heat extraction from air and carbon dioxide (ref. 6) for $0.3 < T_s/T_b < 1.0$ and $5 < x/D < 52$. Of the 1100 friction coefficients calculated, 94 percent deviated less than ±15 percent and 88 percent deviated less than ±10 percent from the measured values.

Figure 3 shows the product of the friction coefficient and the temperature ratio correction factor as a function of the modified surface Reynolds number. A total of 1523

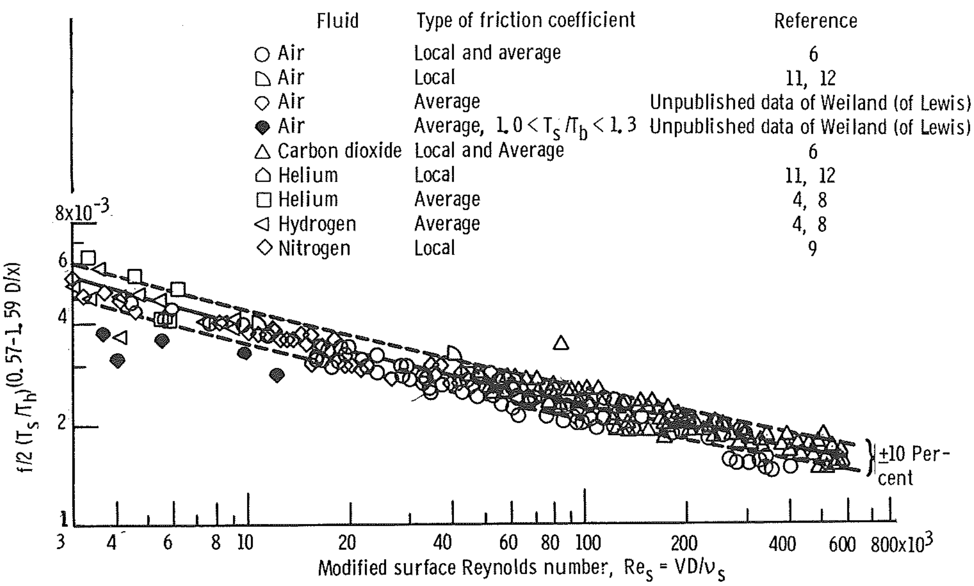

Figure 3. - Correlation of local and average friction coefficients for modified surface Reynolds numbers of 3000 and greater. Density in friction coefficients evaluated at bulk temperature; viscosity in Reynolds number evaluated at surface temperature; 1523 data points in turbulent region. In ordinate D/x applies to local coefficients, D/L should be used for average coefficients.

friction coefficients for both the heating and cooling of gases were calculated using equation (9); 95 percent of the data are within ±15 percent and 89 percent fall within ±10 percent of the correlation line. The data in figure 3 indicate a lack of a transition region, except for the few points for air with a $T_s/T_b < 1.3$ that fall below the correlation line. Thus, it appears that the large variations in the fluid properties tend to make the flow turbulent at modified surface Reynolds numbers of 3000 or more.

CONCLUSIONS

Single-phase heat-transfer and friction coefficients for hydrogen, helium, nitrogen, air, and carbon dioxide with large variations in the physical properties have been studied. The coefficients were measured over a wide range of conditions outside the near-critical region for subsonic flow through smooth straight tubes. For the conditions stated, the following conclusions may be made:

1. For heat extraction from air and carbon dioxide with $0.25 < T_s/T_b < 1.0$ and $4 < x/D < 52$, there appears to be no discernable effect of either x/D or T_s/T_b on the heat-transfer coefficient and the equation

$$Nu_b = 0.023\, Re_b^{0.8} Pr_b^{0.4}$$

where Nu_b is the bulk Nusselt number, Re_b is the bulk Reynolds number VD/ν_b, and Pr_b is the bulk Prandtl number, is recommended to predict heat-transfer coefficients. Using this equation, 80 percent of the calculated heat-transfer coefficients deviated less than ±15 percent and 90 percent deviated less than ±25 percent.

2. For heat addition to hydrogen, helium, nitrogen, air, and carbon dioxide with $1.0 < T_s/T_b < 23$ and $2 < x/D$ 252, there is a strong effect of both x/D and T_s/T_b. A total of 4900 heat-transfer coefficients were calculated with the relation

$$Nu_b = 0.023\, Re_b^{0.8} Pr_b^{0.4} \left(\frac{T_s}{T_b}\right)^{-C_2}$$

where

$$C_2 = 0.57 - \frac{1.59}{\frac{x}{D}}$$

and Nu_b, Re_b, and Pr_b are the bulk Nusselt, Reynolds, and Prandtl numbers, respectively, T_s is the surface temperature, T_b is the fluid-bulk temperature, x is the axial distance from the entrance, and D is the inside diameter of the tube. Ninety percent of the calculated coefficients deviated less than ±25 percent from the measured values.

3. Friction coefficients for heat addition to hydrogen, helium, nitrogen, air, and carbon dioxide with T_s/T_b to 7.35 and $5 < x/D < 200$ and heat extraction from air

and carbon dioxide with T_s/T_b as low as 0.30 and $5 < x/D < 57$ all show an effect of both x/D and T_s/T_b and have been accurately predicted by the relation

$$\frac{f}{2} = \left(0.0007 + \frac{0.0625}{Re_s^{0.32}}\right)\left(\frac{T_s}{T_b}\right)^{-C_2}$$

$$C_2 = 0.57 - \frac{1.59}{\frac{x}{D}}$$

where Re_s is the modified surface Reynolds number VD/ν_s, T_s is the surface temperature, T_b is the fluid-bulk temperature, x is the axial distance from the entrance, and D is the inside diameter of the tube. Of the 1100 friction coefficients calculated, 88 percent deviated less than ±10 percent and 94 percent deviated less than ±15 percent from the measured values.

Lewis Research Center,
National Aeronautics and Space Administration,
Cleveland, Ohio, December 30, 1970,
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