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CORRELATION OF FRICTION COEFFICIENTS FOR LAMINAR AND TURBULENT FLOW WITH RATIOS OF SURFACE TO BULK TEMPERATURE FROM 0.35 TO 7.35

by Maynard F. Taylor

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SUMMARY

The existing conventional methods of correlating and predicting friction coefficients for laminar and turbulent flow, where the physical properties and density do not vary greatly, are shown to give friction coefficients that are in poor agreement with the measured values when there are large variations in the physical properties, that is, large ratios of surface to fluid-bulk temperature.

The local and average friction coefficients used were measured by seven investigators for laminar and turbulent flow of helium, hydrogen, nitrogen, carbon dioxide, and air through smooth tubes. Inside diameters varied from 0.115 to 0.569 inches (0.292 to 1.445 cm); ratios of surface to fluid-bulk temperature ranged from 0.35 to 7.35; and modified surface Reynolds numbers ranged from 170 to 550 000. These data were used to determine the best methods of correlating and predicting local friction coefficients for ratios of distance from entrance of test section to inside diameter of test section (x/D) from 16 to 113 and average friction coefficients for ratios of length to diameter (L/D) from 21 to 200.

The recommended correlation equation for modified surface Reynolds numbers less than 3000 is $f/2 = 8/Re_s$, where $f/2$ is half friction coefficient and Re_s is the modified surface Reynolds number. For modified surface Reynolds numbers of 3000 or greater, the recommended correlation is $f/2 = (0.0007 + 0.0625/Re_s^{0.32})(T_b/T_s)^{0.5}$, where T_b and T_s are the bulk and surface temperatures, respectively. The foregoing smooth tube relations also correlated laminar and turbulent friction coefficients for flow between parallel plates.

INTRODUCTION

There has long been a need for a means of correlating both laminar and turbulent friction coefficients for gases, with large variations in the physical properties, flowing through smooth tubes. Probably the most widely used method of correlating and predicting friction coefficients for turbulent flow is that of Kármán-Nikuradse, in which the friction coefficient and Reynolds number are evaluated at the film temperature T_f, as postulated by Humble, Lowdermilk, and Desmon (ref. 1):

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

All symbols are defined in appendix A

This method worked well for Reynolds numbers greater than 20 000, for surface to fluid-bulk temperature ratios T_s/T_b less than 2.5, and for a length to diameter ratio of 60. Recent experiments present friction coefficients that cannot be correlated by equation (1). In these experiments, Taylor (refs. 2 and 3) measured average friction coefficients for helium and hydrogen with wall temperatures up to 5600° R (3110° K) and T_s/T_b from 1.0 to 4.1, and Perkins and Worsoe-Schmidt (ref. 4) measured local friction coefficients for nitrogen with T_s/T_b from 1.4 to 7.35. Figure 1 shows that the measured friction coefficient can be as much as three times the value predicted by equation (1). Perkins, et al. found that some of their average friction data ($T_s/T_b < 2.46$) could be correlated with T_s/T_b raised to the 0.6 power.

Dalle-Donne (ref. 5) stated that the bulk friction coefficient can be predicted by the use of the modified surface Reynolds number, for both laminar and turbulent flow, for $1 < T_s/T_b \leq 2.2$. When the correlation method of reference 5 was extended to T_s/T_b as great as 7.35, the experimental data fell as much as 70 percent below the Kármán-Nikuradse line, as shown in figure 2.

Other experimental data are now available. Davenport (ref. 6) presented heating data for helium and nitrogen in the laminar region. For turbulent flow, McEligot (ref. 7) and Magee (ref. 8) give heating data for helium and air, Wolf (ref. 9) gives both heating and cooling data for air and carbon dioxide, and McCarthy and Wolf (ref. 10) give heating data for helium and hydrogen. The data of reference 10 were not used in the present investigation because the magnitude of the momentum pressure drops approached (and sometimes exceeded) that of the total pressure drop (see appendix B). The range of conditions covered by the various investigators is shown in table I.

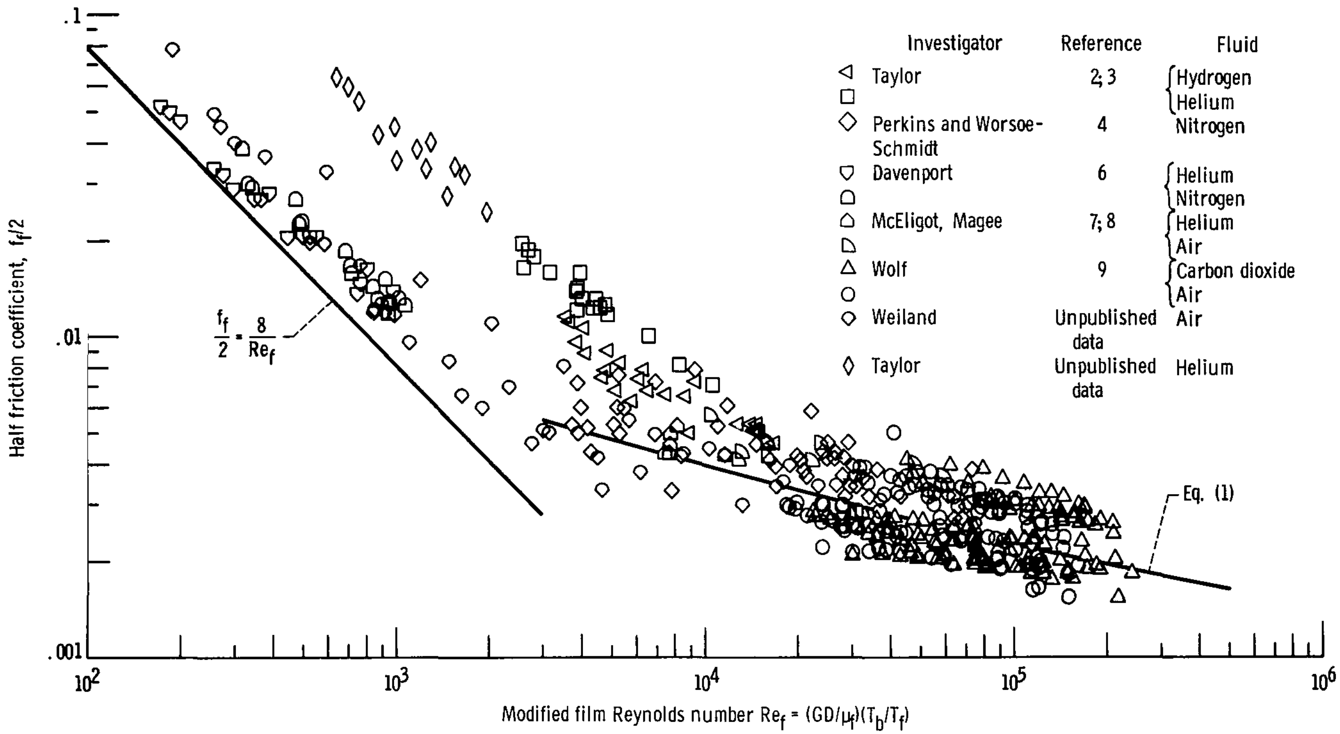

Figure 1. - Variation of local and average friction coefficients with modified film Reynolds number. Viscosity, and density evaluated at film temperature.

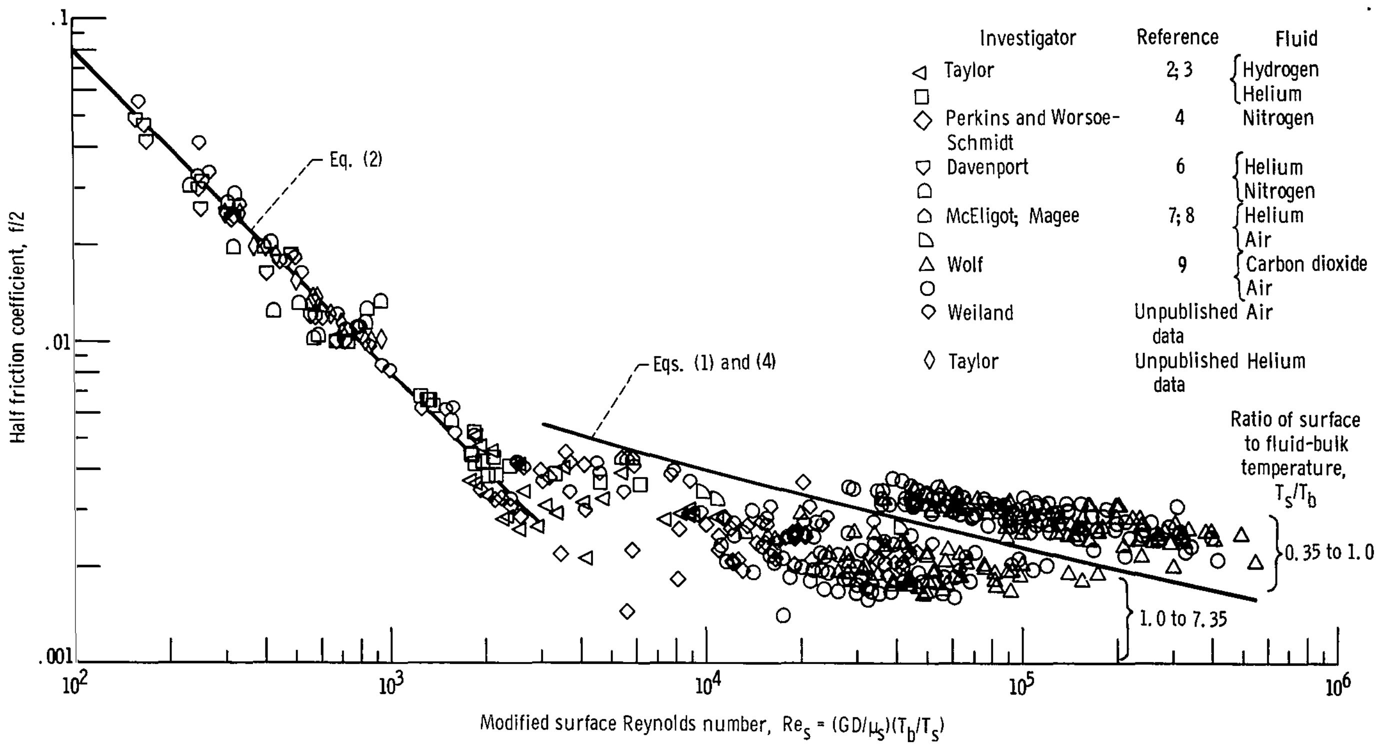

Figure 2. - Variation of local and average friction coefficients with modified surface Reynolds number. Density in friction coefficient evaluated at bulk temperature; viscosity in Reynolds number evaluated at surface temperature.

Presented herein are methods of correlating both local and average friction coefficients for laminar and turbulent flow of gases through smooth tubes with ratios of surface to fluid-bulk temperature from 0.35 to 7.35. These friction coefficients were obtained for helium, hydrogen, nitrogen, air, and carbon dioxide and represent the work of seven investigators.

The equations used in this investigation to correlate the friction data can easily be used to predict friction coefficients for designers working within the range of test conditions presented in table I.

METHOD OF CORRELATION

Dalle-Donne was able to correlate friction coefficients for both laminar and turbulent flow of air and helium with small variations in the physical properties ($1 < T_s/T_b < 2.2$) by using the bulk friction coefficient and a modified surface Reynolds number. In this report, their correlation method is compared with data for extreme variations in physical properties due to either heating ($T_s/T_b > 1$) or cooling ($T_s/T_b < 1$).

The equations presented herein were also compared with the data for laminar and turbulent friction coefficients for flow between parallel plates reported by Slaby, Maag, and Siegel (ref. 11).

The relation recommended by Dalle-Donne for laminar flow with $1 < T_s/T_b < 2.2$ is

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

Equation (2) was used in this investigation to correlate friction data for helium, hydrogen, nitrogen, and air with $1 < T_s/T_b < 4.1$ with good results for modified surface Reynolds numbers up to 3000 (bulk Reynolds numbers up to 22 000), as shown in figure 2.

Dalle-Donne also found that the use of the bulk friction coefficient and the modified surface Reynolds number correlated their friction data for turbulent flow with $1 < T_s/T_b < 2.2$ to the Kármán-Nikuradse line with good results. In the present investigation, the Koo, Drew, and McAdams relation (ref. 12) was used because of its simplicity and its close agreement with the Kármán-Nikuradse relation. The Koo, Drew, and McAdams relation for bulk Reynolds numbers from 3000 to 3 000 000 is given as

$$\frac{f}{2} = 0.0007 + \frac{0.0625}{Re_b^{0.32}} \tag{3}$$

In the present investigation, a modified surface Reynolds number was used in place of the bulk Reynolds number and gives the following relation:

$$\frac{f}{2} = 0.0007 + \frac{0.0625}{Re_s^{0.32}} \tag{4}$$

When equation (4) was used to predict friction coefficients for $0.35 < T_s/T_b < 7.35$ and for modified surface Reynolds numbers from 3000 to 550 000, the measured values deviated from the predicted values by as much as -70 percent for the runs with heat addition ($1.0 < T_s/T_b < 7.35$) and by as much as 70 percent for the runs with heat removal ($0.35 < T_s/T_b < 1.0$), as shown in figure 2. Since the deviation appeared to be a function of T_s/T_b, the ratio of the friction coefficient calculated by equation (4) to the measured friction coefficient was plotted as a function of T_s/T_b (fig. 3). The slope of the line drawn through the data points is 0.5 and passes through $(f/2)_{calc}/(f/2)_{exp} = 1$ at $T_s/T_b = 1$, as it should since equation (3) is equal to equation (4) at a $T_s/T_b = 1$. Figure 3 indicates that equation (4) should be modified with the square root of T_s/T_b as follows:

$$\frac{f}{2} = \left(0.0007 + \frac{0.0625}{Re_s^{0.32}}\right)\left(\frac{T_b}{T_s}\right)^{0.5} \tag{5}$$

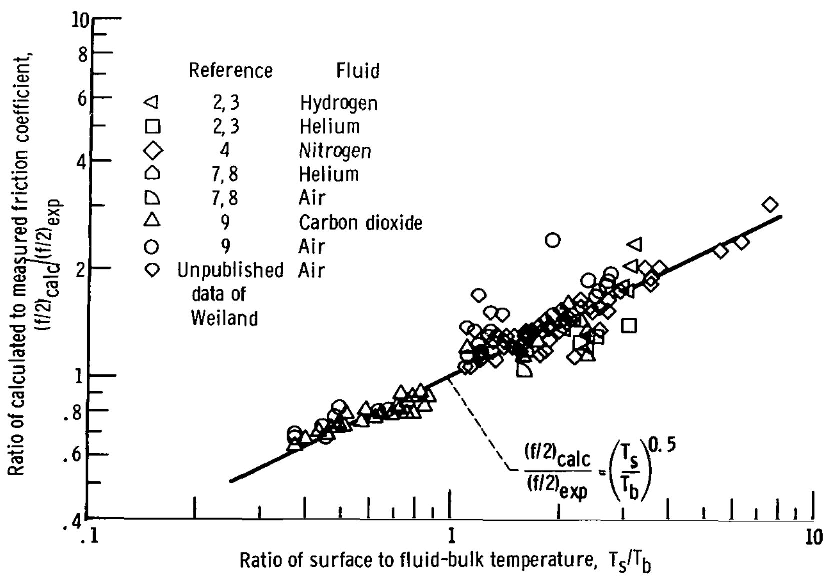

Figure 3. - Variation of ratio of friction coefficient calculated by equation (4) to measured local and average friction coefficient with ratio of surface to fluid-bulk temperature for modified surface Reynolds numbers of 3000 and greater.

Equation (5) predicts friction coefficients within ±10 percent for both heating and cooling of gases with modified surface Reynolds numbers from 3000 to 550 000 (bulk Reynolds numbers from about 5400 to 187 000, the limit of the experimental data).

Since figure 3 shows an effect of T_s/T_b on the friction coefficient for modified surface Reynolds numbers of 3000 and greater, a similar plot was made for modified surface Reynolds numbers less than 3000. Figure 4 shows the ratio of the friction coefficient calculated by equation (2) to the measured friction coefficient as a function of T_s/T_b for a modified surface Reynolds number less than 3000. It appears from figure 4 that there is no discernable effect of T_s/T_b on the friction coefficient for a modified surface Reynolds number less than 3000.

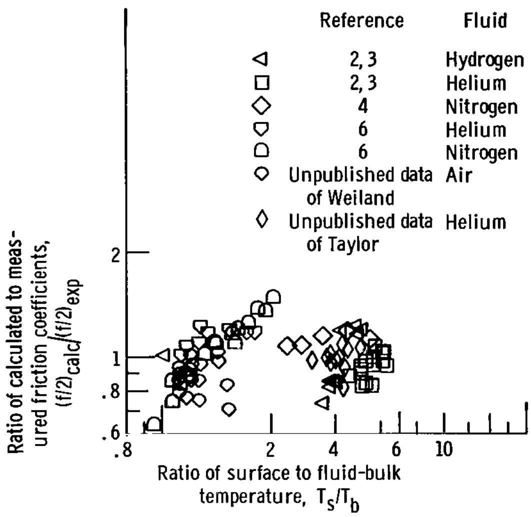

Figure 4. - Variation of ratio of friction coefficient calculated by equation (2) to measured local and average friction coefficient with ratio of surface to fluid-bulk temperature for modified surface Reynolds numbers less than 3000.

DISCUSSION OF RESULTS

The relations shown in equations (2) and (5) correlate local friction coefficients for x/D from 16 to 113 and average friction coefficients for L/D from 21 to 200 (with $0.35 < T_s/T_b < 7.35$ and modified surface Reynolds numbers from 170 to 550 000) for both vertical and horizontal smooth tubes. The tube inside diameters range from 0.115 to 0.569 inch (0.292 to 1.445 cm).

In figure 5 the experimental friction coefficients are shown as a function of the modified surface Reynolds number for low Reynolds number flow ($Re_s < 3000$). Of the 109 experimental points shown, 84 percent of them fall within ±20 percent of the correlation line represented by equation (2).

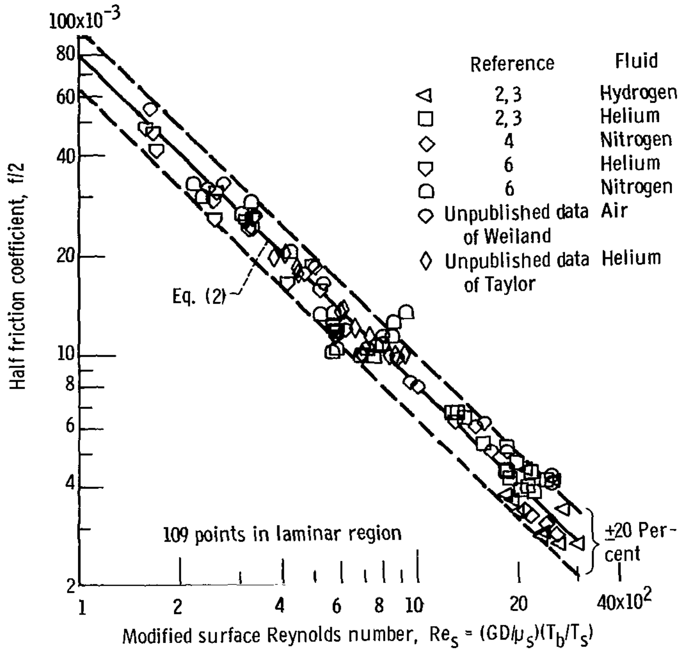

Figure 5. - Correlation of local and average friction coefficients for modified surface Reynolds number less than 3000. Density in friction coefficient evaluated at bulk temperature; viscosity in Reynolds number evaluated at surface temperature.

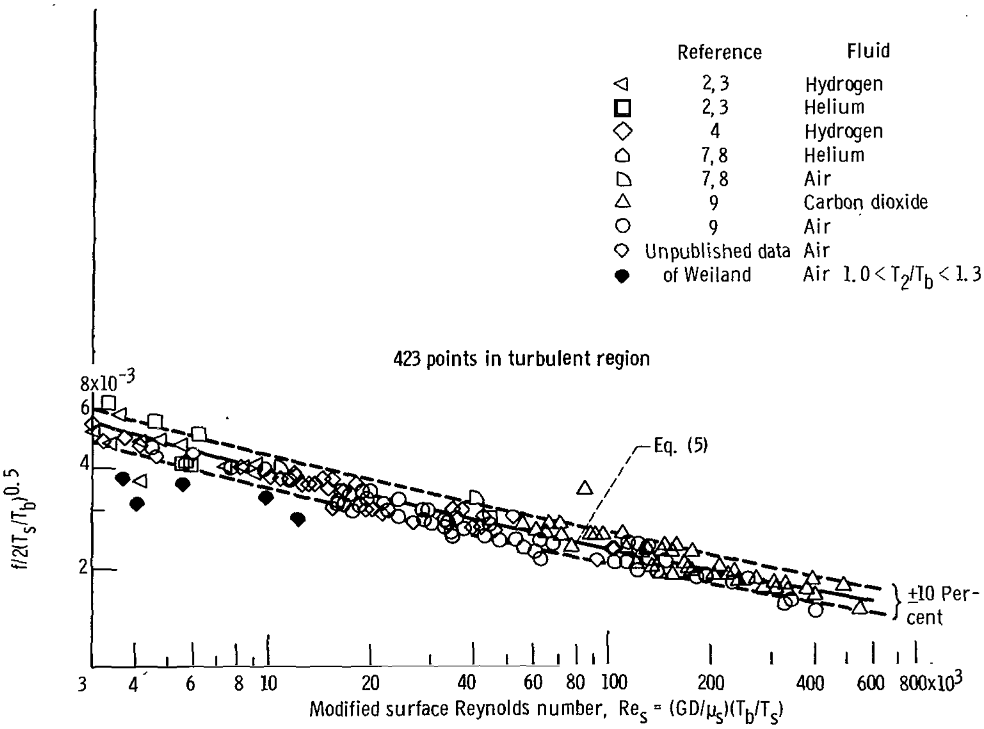

Figure 6. - Correlation of local and average friction coefficients for modified surface Reynolds numbers of 3000 and greater. Density in friction coefficients evaluated at bulk temperature; viscosity in Reynolds number evaluated at surface temperature.

Figure 6 shows the experimental friction coefficients as a function of the modified surface Reynolds number for turbulent flow (Re_s of 3000 and greater). There are 423 experimental data points for both heating and cooling of the gas; 97 percent of the data points are within ±15 percent, and 90 percent fall within ±10 percent of the correlation line defined by equation (5).

The data in figure 5 indicate a lack of a transition region, except for the few points with a $T_s/T_b < 1.3$ that fall below the correlation line. Thus, it appears that the large variation in the physical properties and density tends to make the flow turbulent at a modified surface Reynolds number of 3000 or more.

Slaby, Maag, and Siegel (ref. 11) measured laminar and turbulent friction coefficients for flow between parallel plates and attempted to correlate the data by the generally accepted method of evaluating physical properties and density at a film temperature. The results are shown in figure 7. The agreement between measured and predicted friction coefficients is poor for modified film Reynolds numbers below 3500. The agreement is better at higher Reynolds numbers. Better agreement between measured and predicted friction coefficients occurs when equations (2) and (5) are used. Figure 8 shows the correlation of measured parallel-plate friction coefficients using equations (2) and (5).

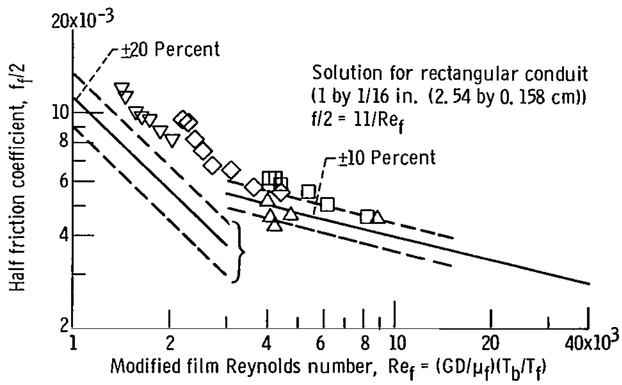

Figure 7. - Correlation of average friction coefficients for laminar and turbulent flow between parallel plates with physical properties and density evaluated at film temperature. Experimental data from reference 11.

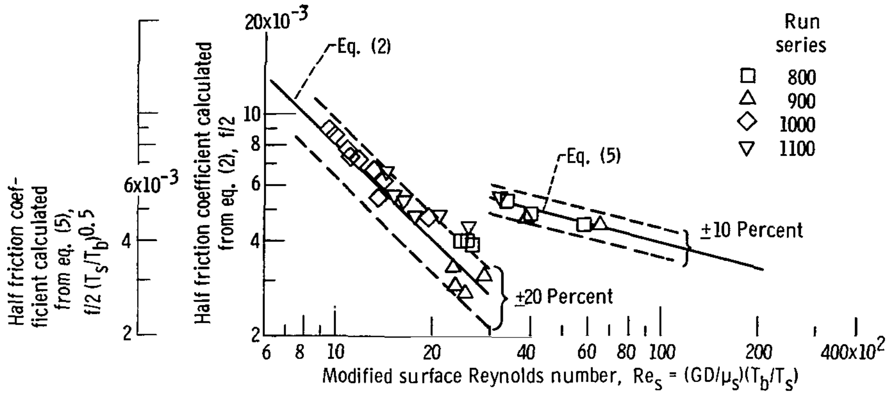

Figure 8. - Correlation of average friction coefficients for laminar and turbulent flow between parallel plates with use of equations (2) and (5). Experimental data from reference 11.

CONCLUSIONS

For ratios of surface to fluid-bulk temperature of 0.35 to 7.35, modified surface Reynolds numbers from 170 to 550 000, and ratios of length to diameter from 21 to 200, the following conclusions may be made for flow through smooth circular tubes. These conclusions also appear to apply to flow between parallel plates.

1. For modified surface Reynolds numbers below 3000, both local and average friction coefficients for ratios of surface to fluid-bulk temperature of 1.0 to 4.1 can be predicted within ±20 percent by the Dalle-Donne relation $f/2 = 8/Re_s$ where $f/2$ is the half friction coefficient and Re_s is the modified surface Reynolds number.

2. For modified surface Reynolds numbers of 3000 and greater, the flow appears to be fully turbulent. Both local and average friction coefficients for ratios of surface to fluid-bulk temperature from 0.35 to 7.35 can be predicted within ±10 percent by the relation $f/2 = (0.0007 + 0.0625/Re_s^{0.32})(T_b/T_s)^{0.5}$, where $f/2$ is the half friction coefficient, Re_s is the modified surface Reynolds number, and T_b and T_s are the bulk and surface temperatures, respectively.

3. For ratios of surface to fluid-bulk temperature greater than approximately 1.3, there appears to be no transition region for friction coefficients.

4. The modified surface Reynolds number determines if the laminar flow equation or the turbulent flow equation should be used to predict friction coefficients.

5. For large ratios of surface to fluid-bulk temperature, the use of the reference-temperature concept (evaluating physical properties and density in both the friction coefficient and Reynolds number at some reference temperature $[T_X \equiv X(T_s - T_b) + T_b]$ is not applicable to friction coefficients for flow through smooth tubes or flow between parallel plates.

Lewis Research Center,
National Aeronautics and Space Administration,
Cleveland, Ohio, April 25, 1967,
122-28-02-16-22.

APPENDIX A

SYMBOLS

D	inside diameter of test section, ft; m
dp/dx	pressure gradient in axial direction, $(N/m^2)/m$
$f/2$	half friction coefficient, $g_c \rho_{bav} \Delta p_{fr}/4(L/D)G^2$
$f_f/2$	half film friction coefficient, $(f/2)(T_f/T_b)$
G	mass flow per unit cross-sectional area, lb/(hr)(ft^2); kg/(sec)(m^2)
g_c	conversion factor, 4.17×10^8 (lb mass)(ft)/(lb force)(sec^2); 9.8 (kg)(m)/(N)(sec^2)
L	test section length, ft; m
p	static pressure, lb/ft^2; N/m^2
Δp	static pressure drop across test section, lb/ft^2; N/m^2
R	specific gas constant
Re_b	bulk Reynolds number, GD/μ_b
Re_f	modified film Reynolds number, $(GD/\mu_f)(T_b/T_f)$
Re_s	modified surface Reynolds number, $(GD/\mu_s)(T_b/T_s)$
T_b	bulk temperature, ^oR; ^oK
T_f	film temperature, $(T_s + T_b)/2$, ^oR; ^oK
T_s	surface temperature, ^oR, ^oK
T_X	reference temperature, ^oR; ^oK
t	static temperature, ^oR; ^oK
V	velocity, ft/hr; m/sec
X	parameter used in reference temperature equation
x	distance from entrance of test section, ft; m
μ_b	absolute viscosity of gas at T_b, lb/(hr)(ft); (N)(sec)/m^2
μ_f	absolute viscosity of gas at T_f, lb/(hr)(ft); (N)(sec)/m^2
μ_s	absolute viscosity of gas at T_s, lb/(hr)(ft); (N)(sec)/m^2
ρ_{av}	average density of gas (eq. (B5))
ρ_{bav}	average bulk density of gas based on average static pressure and average static bulk temperature (eq. (B4)), lb/ft^3; kg/m^3

τ_w shear stress at wall, lb/ft^2; N/m^2

Subscripts:

calc calculated value

exp measured value

fr friction

mom momentum

1 inlet

2 outlet

APPENDIX B

CALCULATION OF FRICTION COEFFICIENTS

Average Friction Coefficients

The experimentally determined average friction coefficients for smooth tubes presented by Taylor (refs. 2 and 3), Wolf (ref. 9), McCarthy and Wolf (ref. 10), and unpublished data by Weiland and Taylor were used in the present investigation. The average friction coefficient is calculated from the equation

$$\frac{f}{2} = \frac{g_c \rho_{bav} \Delta p_{fr}}{4\frac{L}{D}G^2} \tag{B1}$$

The friction pressure drop is obtained by measuring the total pressure drop and subtracting the momentum drop,

$$\Delta p_{fr} = \Delta p - \Delta p_{mom} \tag{B2}$$

where

$$\Delta p_{mom} = \frac{GR}{g_c}\left(\frac{t_2}{p_2} - \frac{t_1}{p_1}\right) \tag{B3}$$

The average bulk density in the friction coefficient is evaluated at the average static pressure and the average static bulk temperature:

$$\rho_{bav} = \frac{1}{R}\left(\frac{p_1 + p_2}{t_1 + t_2}\right) \tag{B4}$$

Equation (B4) does not give the average density, which is

$$\rho_{av} = \frac{1}{R}\left(\frac{p_1}{t_1} + \frac{p_2}{t_2}\right) \tag{B5}$$

Equation (B4) is usually used to calculate the density that is used in equation (B1).

Equation (B2) can be written as

$$\Delta p = \Delta p_{mom} + \Delta p_{fr} \tag{B6}$$

from which it can be seen that the accuracy of Δp_{fr} is not only dependent on the accuracy of measuring Δp but on the magnitude of Δp_{mom} compared with Δp_{fr}. Table II presents the various investigators and the maximum ratio of momentum to friction pressure drop $\Delta p_{mom}/\Delta p_{fr}$.

The large ratios of Δp_{mom} to Δp_{fr} (in ref. 10) resulted in an inaccurate Δp_{fr} and correspondingly inaccurate friction coefficients. In some cases, the Δp_{mom} appeared larger than the total pressure drop across the test section, which resulted in negative friction coefficients. Because of these inaccuracies, the friction coefficients presented in reference 10 were not included in this investigation.

Local Friction Coefficients

The local friction coefficients presented by Perkins and Worsoe-Schmidt (ref. 4), Davenport (ref. 6), McEligot (ref. 7), and Magee (ref. 8) were calculated by the equation

$$\frac{f}{2} \equiv \frac{\tau_w}{\frac{\rho_b V^2}{2g_c}} \tag{B7}$$

where

$$\tau_w = -\frac{D}{4}\frac{dp}{dx} + \rho\frac{V^2}{2g_c} \tag{B8}$$

All local friction coefficients seemed to have an acceptable degree of accuracy.

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TABLE I. - TEST CONDITIONS FOR VARIOUS SOURCES OF DATA

Investigator	Reference	Fluid	Ratio of surface temperature to bulk temperature, T_s/T_b	Friction coefficient type	Length to diameter ratio, L/D or x/D	Bulk temperature, T_b		Surface temperature, T_s		Modified surface Reynolds number, Re_s	Tube orientation	Tube inside diameter, D	
						^{o}R	^{o}K	^{o}R	^{o}K			in.	cm
Taylor	2	H_2 and He	1.0 to 3.7	Average	80	829 to 1643	460 to 913	1559 to 4749	866 to 2638	1.9×10^3 to 10.9×10^3	Vertical	0.115	0.292
Taylor	3	H_2 and He	1.0 to 4.1	Average	80	501 to 1243	278 to 691	1803 to 4600	1000 to 2555	1.3×10^3 to 4.2×10^3	Vertical	.115	.292
Perkins and Worsoe-Schmidt	4	N_2	1.4 to 7.4	Local	16, 53, 73, 93, 113	210 to 1091	117 to 606	371 to 2003	206 to 1127	1.9×10^3 to 45.6×10^3	Vertical	.124	.315
Davenport	6	N_2 and He	1.1 to 2.2	Local	25, 44, 68	721 to 2226	401 to 1236	1084 to 2460	602 to 1366	$.17\times10^3$ to $.94\times10^3$	Vertical	.125	.318
McEligot	7	He and Air	1.4 to 2.5	Local	16, 18, 27, 34, 46, 63	541 to 1022	300 to 568	844 to 1705	468 to 948	5.1×10^3 to 40.9×10^3	Vertical	.123 .250	.313 .635
Magee	8	He and Air	1.4 to 2.5	Local	16, 18, 27, 34, 46, 63	541 to 1022	300 to 568	844 to 1705	468 to 948	5.1×10^3 to 40.9×10^3	Vertical	.123 .250	.313 .635
Wolf	9	Air CO_2	.35 to 2.7	Average	21, 40, 60	545 to 1941	303 to 1079	544 to 1782	302 to 990	11.3×10^3 to 550×10^3	Horizontal	.384 .569	.976 1.445
Weiland	(a)	Air	1.0 to 1.5	Average	200	592 to 1324	329 to 736	711 to 1896	395 to 1048	$.17\times10^3$ to 91.6×10^3	Horizontal	.184	.468
Taylor	(a)	He	1.0 to 3.4	Average	80	1045 to 1589	581 to 883	3112 to 5400	1730 to 3000	$.37\times10^3$ to 1.3×10^3	Vertical	.115	.292

[a]Unpublished data, Lewis Research Center.

TABLE II. - MAXIMUM RATIO OF MOMENTUM TO FRICTION

PRESSURE DROP FOR EACH INVESTIGATOR

Investigator	Reference	Data	Fluid	Maximum ratio of momentum to friction pressure drop, $\Delta p_{mom}/\Delta p_{fr}$
Taylor	2	Heating	He	2.3
	2		H_2	2.8
	3		He	2.7
	3		H_2	3.6
Wolf	9		Air	Not given
	9		CO_2	Not given
	9	Cooling	Air	.1
	9	Cooling	CO_2	.09
McCarthy and Wolf	10	Heating	He	20
	10		H_2	19
Weiland	(a)		Air	1.2
Taylor	(a)		He	.66

[a]Unpublished data, Lewis Research Center.

NASA-Langley, 1967 —— 12 E-3669

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