GRAPHICAL CORRELATION OF PRESSURE DROP IN ADIABATIC FLOW OF COMPRESSIBLE FLUIDS IN PIPES

BY

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ABSTRACT

Analytic equations for the flow of compressible fluids in conduits with friction are awkward to solve, since the variables involved usually necessitate trial and error solution. A study of the situation indicated that a series of graphs for different values of the specific heat ratio would eliminate the trial and error solution.

The purpose of this paper is to present in graphical form a solution of the equations relating the ratios of the pressure and temperatures in adiabatic flow of compressible fluids to the friction and velocity.

The equations for adiabatic flow of compressible fluids in horizontal ducts of constant cross section have been employed to calculate a series of values of the pressure ratio and the friction at each of several Mach numbers for each of three specific heat ratios. The temperature ratio has also been calculated for each of several mach numbers for each of the three specific heat ratios.

The graphs make it possible to calculate the pressure drop and temperature drop of compressible fluids, in adiabatic flow in horizontal ducts of constant cross section with friction, without resorting to trial and error solution.

The results are presented graphically on pages 9 to 11.

INTRODUCTION

Where the flow is isothermal, general methods of calculation, both algebraic and graphical, have been developed. (2, 4, 5, 6, 7, 8) Equations have been developed for conditions of adiabatic flow, (1, 2, 8) but these are so complex that for most design purposes their use involves lengthy and tedious graphical solutions. There is also available a general method of calculation based on the Thermodynamic properties of the fluid which involves the Fanno lines (3). This method also involves lengthy calculations before any solution can be obtained.

Mechanical Engineering texts have plots relating the pressure ration in adiabatic flow of compressible fluids for several initial Mach numbers - to the friction and velocity (4). The plots appearing in Advance Fluid Dynamics and Fluid Machinery by Binder are representative, but only 4 Mach numbers have been plotted for only one specific heat ration. These graphs cannot be read with any degree of accuracy.

It is the purpose of this paper to present in graphical form a solution of the equations relating the ratios of the pressures and temperatures in adiabatic flow of compressible fluids to the friction and velocity and to offer a simplified method of determining the performance of horizontal ducts handling compressible fluids at high pressure drops. Lapple has studied adiabatic flow of compressible fluids and has devised a graphical method for finding the rate of discharge from a storage tank through a pipe line. Lapple's graphs are not well adapted to the calculation of the pressure drop between two sections in a line. It is possible to calculate the pressure drop between two sections of a line by means of Lapple's graphs, but a trial and error solution must be used, whereas the graphical method developed here requires no trial.

DISCUSSION

Binder (4) has plotted graphs relating the pressure ratio to the friction and velocity in horizontal ducts of constant cross section for both isothermal and adiabatic flow for several initial Mach numbers for a specific heat ratio of 1.4. The only Mach numbers plotted were M = 0.05, M = 0.10, M = 0.125 and M = 0.20. These graphs were plotted for adiabatic flow using the following equations:

$$\beta = (k-1) M_1^2 \left[2 + (k-1) M_1^2\right] \qquad (1)$$

$$\frac{f'L}{D} = \frac{k-1}{k\beta}\left[1-\left(\frac{P_2}{P_1}\right)^2 - \frac{P_2}{P_1}\sqrt{\left(\frac{P_2}{P_1}\right)^2 + \beta} + \sqrt{1+\beta}\right] + \frac{k+1}{k}\log_e\left[\frac{\frac{P_2}{P_1} + \sqrt{\left(\frac{P_2}{P_1}\right)^2 + \beta}}{1+\sqrt{1+\beta}}\right] \qquad (2)$$

Binder's graph (4) relating the pressure ratio to friction and velocity for adiabatic flow of compressible fluids in horizontal ducts for several Mach numbers indicates that it is possible to construct a series of graphs for different values for the specific heat ratio which would be extremely useful in solving problems of design for compressible fluids. When Binder has related the pressure ratio to the friction factor and velocity, the friction factor (f^1) is the Mechanical Engineering friction factor which is four times the friction factor commonly used by Chemical Engineers. No attempt has been made by Binder to include the temperature ratio on the graph relating the pressure ratio to the friction and velocity.

It was felt that it would be advantageous to include the temperature ratio on a graph where the pressure ratio is related to the friction and velocity. For this reason, the following equations have been chosen to construct graphs for specific heat ratios of K = 1.1, K = 1.4 and K = 1.67. For cases met in practice the specific heat ratio would fail in the chosen range.

If the initial acoustic velocity $C_1 = \sqrt{K g_c R T_1 / M}$

Then
$$\frac{fL}{D} = \frac{-2.30\,(K+1)}{K} \log_{10} \frac{V_2}{V_1} + \frac{1}{K}\left[\frac{C_1^2}{V_1^2} + \frac{(K-1)}{2}\right]\left(1 - \frac{V_1^2}{V_2^2}\right) \quad (3)$$

$$\frac{P_2}{P_1} = \frac{V_1}{V_2}\left[1 + \frac{(K-1)V_1^2}{2C_1^2}\left(1 - \frac{V_2^2}{V_1^2}\right)\right] \quad (4)$$

$$\frac{T_1}{T_2} = \left(\frac{P_1}{P_2}\right)\left(\frac{V_2}{V_1}\right) \quad (5)$$

Where $\frac{V_1}{C_1} = M_1$ and $R_H = \frac{D}{4}$ for circular cross section

These formulas relating the pressure ratio to the friction and velocity for adiabatic flow of compressible fluids are shown in the Chemical Engineers' Handbook (2).

Sufficient data were calculated to relate both the pressure and temperature ratios to the friction and velocity. Since V_2 and V_1 always appear as a ratio $\left(\frac{V_2}{V_1}\right)$ or its reciprocal, except where the initial velocity (V_1) appears as a ratio with the initial acoustic velocity (C_1) it becomes simple to establish the temperature ratio $\left(\frac{T_2}{T_1}\right)$, since the temperature ratio is equal to the pressure ratio multiplied by the velocity ratio.

A curved line for each initial Mach number relating the pressure ratio to the friction can be plotted by solving Equations 3 and 4 simultaneously for a series of values of the velocity ratio from 1.25 to 8.00. Curved lines can be constructed for each temperature ratio by carrying the calculation one step further and multiplying the pressure ratios by velocity ratios for each Mach number in accordance with Equation 5.

SAMPLE CALCULATIONS

The graphs for specific heat ratios of K = 1.1, K = 1.4 and K = 1.67 were constructed by keeping the specific heat ratio constant and solving Equations 3 and 4 simultaneously for a series of values of the velocity ratio from 1.25 to 8.00 for each Mach number. The temperature ratio was then calculated by multiplying the pressure ratio by the velocity ratio for each Mach number:

When $k = 1.4$ and $R_H = \frac{D}{4}$ for ducts of circular cross section

Assume $M_1 = \frac{V_1}{C_1} = 0.150$ and $\frac{V_2}{V_1} = 2.00$

substituting in Equation 3.

$$\frac{4fL}{D} = -\frac{2.30\,(1.4+1)}{1.4}\log_{10}(2.00) + \frac{1}{1.4}\left[\frac{1}{(.15)^2} + \frac{(1.4-1)}{2}\right]\left(1 - \frac{1}{(2)^2}\right)$$

$$\frac{4fL}{D} = 22.729$$

$$\frac{fL}{D} = 5.682$$

substituting in Equation 4.

$$\frac{P_2}{P_1} = \frac{1}{2}\left[1 + \frac{(1.4-1)(0.15)^2}{2}\left(1 - 2^2\right)\right]$$

$$\frac{P_2}{P_1} = 0.49325$$

Substituting the assumed value of the velocity ratio and the calculated value of the pressure ratio in Equation 5, the temperature ration can be calculated

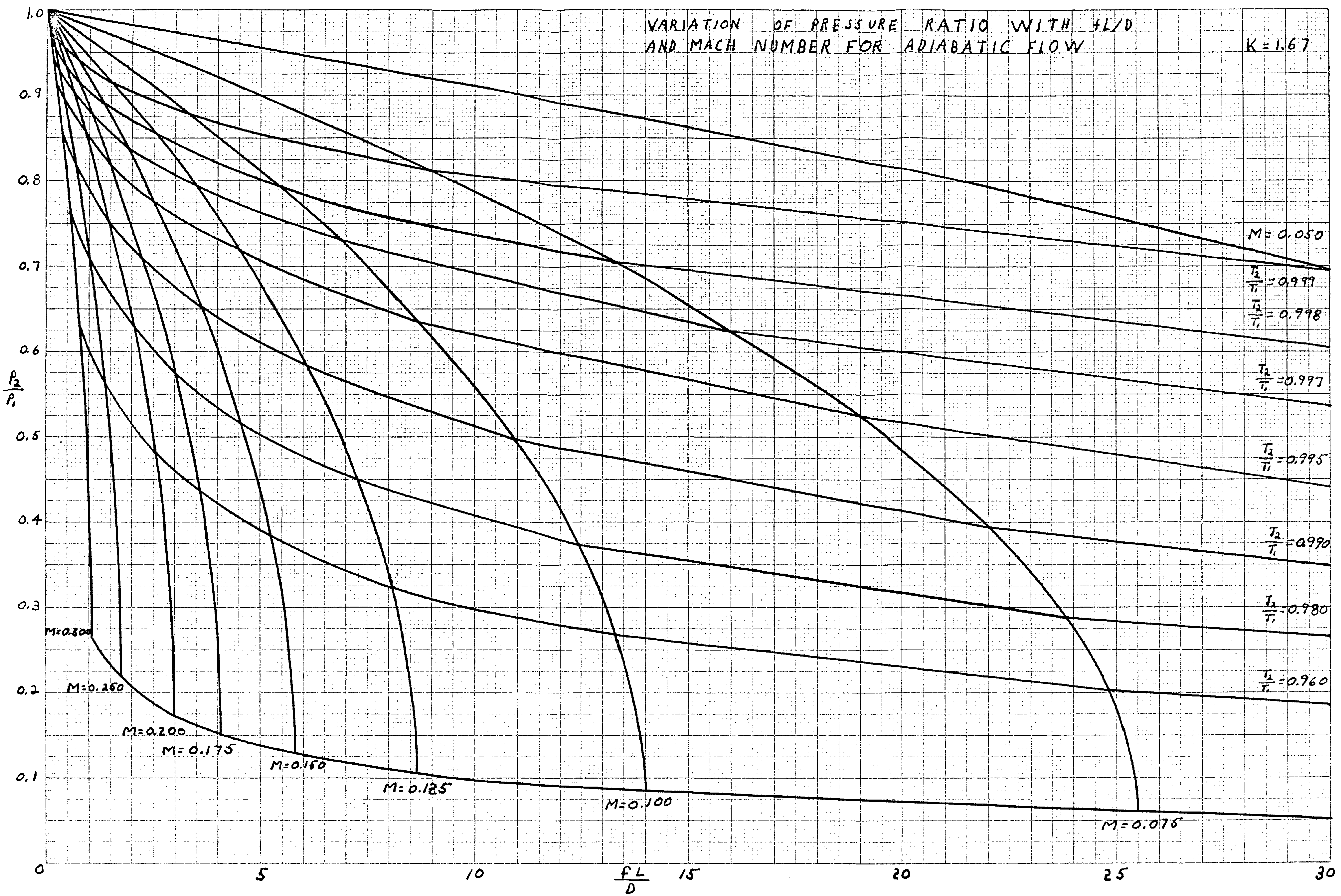
$$\frac{T_2}{T_1} = 0.49325 \times 2.00 = 0.9865$$

RESULTS

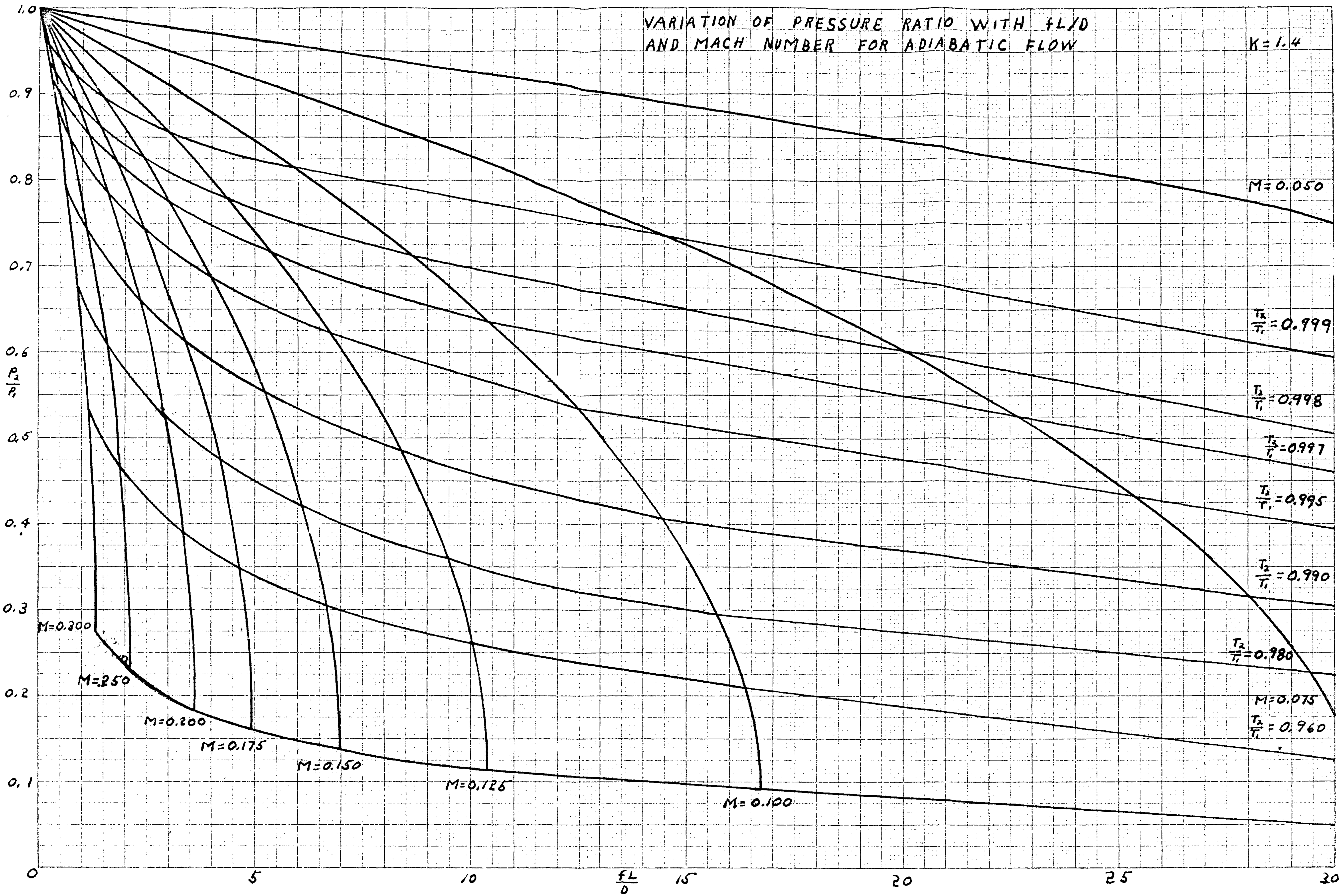
The results are presented by graphs I, II and III on the next three pages where both the pressure ratio and the temperature ratio are related to the friction and velocity.

The limiting conditions of maximum flow are calculated from

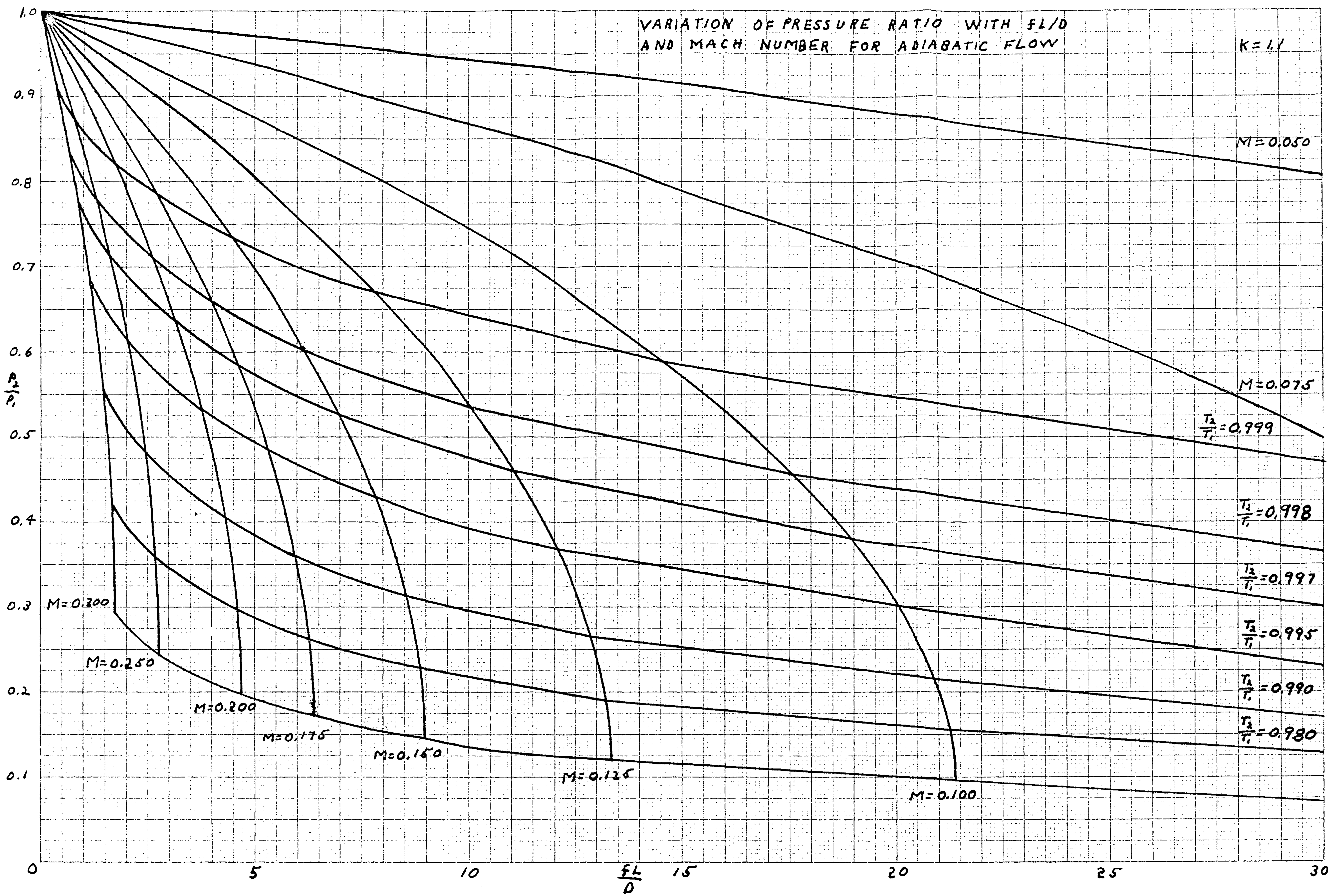
$$\frac{P_2}{P_1} = M^2 \left\{ \left(\frac{k-1}{k+1}\right)\left[1 + \frac{2}{(k-1)M^2}\right]\right\}^{\frac{1}{2}}$$



VARIATION OF PRESSURE RATIO WITH 4L/D
AND MACH NUMBER FOR ADIABATIC FLOW
K = 1.67
M = 0.050
T2/T1 = 0.999
T2/T1 = 0.998
T2/T1 = 0.997
T2/T1 = 0.995
T2/T1 = 0.990
T2/T1 = 0.980
T2/T1 = 0.960
M=0.300
M=0.250
M=0.200
M=0.175
M=0.150
M=0.125
M=0.100
M=0.075
P2/P1
1.0
0.9
0.8
0.7
0.6
0.5
0.4
0.3
0.2
0.1
0
5
10
fL/D
15
20
25
30



VARIATION OF PRESSURE RATIO WITH fL/D
AND MACH NUMBER FOR ADIABATIC FLOW
K = 1.4
1.0
0.9
0.8
0.7
0.6
0.5
0.4
0.3
0.2
0.1
0
P2/P1
5
10
15
20
25
30
fL/D
M=0.050
T2/T1 = 0.999
T2/T1 = 0.998
T2/T1 = 0.997
T2/T1 = 0.995
T2/T1 = 0.990
T2/T1 = 0.980
M=0.075
T2/T1 = 0.960
M=0.300
M=.250
M=0.200
M=0.175
M=0.150
M=0.126
M=0.100



VARIATION OF PRESSURE RATIO WITH fL/D AND MACH NUMBER FOR ADIABATIC FLOW
K = 1.1
M = 0.050
M = 0.075
$\frac{T_2}{T_1} = 0.999$
$\frac{T_2}{T_1} = 0.998$
$\frac{T_2}{T_1} = 0.997$
$\frac{T_2}{T_1} = 0.995$
$\frac{T_2}{T_1} = 0.990$
$\frac{T_2}{T_1} = 0.980$
M = 0.300
M = 0.250
M = 0.200
M = 0.175
M = 0.150
M = 0.125
M = 0.100
$\frac{P_2}{P_1}$
$\frac{fL}{D}$
1.0
0.9
0.8
0.7
0.6
0.5
0.4
0.3
0.2
0.1
0
5
10
15
20
25
30

SAMPLE PROBLEM

For purposes of comparison, a sample problem has been solved by several methods, including the method developed by the writer.

Air enters a steel pipe 6 inches in diameter at a rate of 2000 ft.^{3}/ minute at 70° F. and 18 psia. Determine the discharge conditions at a point 500 feet from the entrance of the pipe.

I. Method involving trial-and-error solution by means of simultaneous equations.

Using ρ = .0916 and u = 000672 X .018 $\frac{\text{lb. mass}}{\text{ft. sec.}}$ the Reynolds number at the entrance will be

$$R_e = \frac{DV\rho}{\mu} = \frac{2000}{60}\;\frac{16}{2\pi}\;\frac{.0916}{.000672 \times .018} = 6.4 \times 10^5$$

from the Chemical Engineers Handbook (2), f = .0045, K = 1.4,

$$C_1 = \sqrt{Kg_c R T_1/M} = \sqrt{\frac{1.4 \times 32.17 \times 1546 \times 530}{29}} = 1128.13$$

The inlet velocity is $V_1 = \frac{2000}{60} \Big/ \frac{\pi}{16} = 169.7$

The initial Mach number is

$$M_1 = \frac{V_1}{C_1} = \frac{169.7}{1128.13} = 0.150$$

then

$$\frac{fL}{D} = \frac{.0045 \times 500}{0.5} = 4.5$$

Using the formulas given in the Chemical Engineers Handbook (2) to solve the sample problem

$$\frac{fL}{R_H} = \frac{-2.3(k+1)}{k}\log_{10}\frac{V_2}{V_1} + \frac{1}{k}\left[\frac{c_1^2}{V_1^2} + \frac{(k-1)}{2}\right]\left(1 - \frac{V_1^2}{V_2^2}\right) \quad (3)$$

$$\frac{P_2}{P_1} = \frac{V_1}{V_2}\left[1 + \frac{(k-1)V_1^2}{2C_1^2}\left(1 - \frac{V_2^2}{V_1^2}\right)\right] \quad (4)$$

Assume $\frac{V_2}{V_1}$ 1.500 and substitute in Equation 3

$$\frac{fL}{R_H} = \frac{-2.3(1.4+1)}{1.4}\log_{10} 1.5 + \frac{1}{1.4}\left[\frac{1}{(1.5)^2} + \frac{(1.4-1)}{2}\right]\left(1 - \frac{1}{(1.5)^2}\right)$$

$$\frac{fL}{R_H} = 17.024 \qquad \frac{fL}{D} = 4.256$$

Adjusting $\frac{V_2}{V_1} = 1.564$

From the equation, we obtain:

$$\frac{fL}{R_H} = 18.04 \qquad \frac{fL}{D} = 4.51$$

This checks the value 4.5 given above.

Then substituting $\frac{V_2}{V_1} = 1.564$ in Equation 4

$$\frac{P_2}{P_1} = \frac{1}{1.564}\left[1 + \frac{(1.4-1)(1.5)^2}{2}\left(1 - (1.564)^2\right)\right]$$

$$\frac{P_2}{P_1} = 0.635$$

$$P_2 = 0.635\,P_1 = 0.635 \times 18 = 11.43 \text{ psia}$$

$$\frac{T_2}{T_1} = \left(\frac{P_2}{P_1}\right)\left(\frac{V_2}{V_1}\right) = .635 \times 1.564 = 0.993$$

$$T_2 = 0.993 \times T_1 = 0.993 \times 530 = 526.3^\circ R$$

II. Writer's Method

By means of the graphs presented in this paper, the solution is obtained much more simply.

From the previous calculation, we know that

$f = .0045$ $\qquad M_1 = 0.150$ $\qquad K = 1.4$

and $\frac{fL}{D} = 4.5$

Using the graph, Figure 2, for a specific heat ratio of $K = 1.4$, we can read directly the pressure ratio and temperature ratio corresponding to $M_1 = 0.150$ and $\frac{fL}{D} = 4.5$

Reading directly from the graph, we obtain the following values:

$\frac{P_2}{P_1} = 0.635$, $\frac{T_2}{T_1} = 0.993$

Therefore - $P_2 = .635 \times 18 = 11.43$ psia

$T_2 = .993 \times 530 = 526.3°R$

III. Lapple's Method

Working the sample problem presented previously by Lapple's graphical method (5) we must assume that the air enters the pipe from a chamber through a frictionless nozzle. This means of solving the problem must be done by trial-and-error solution

From previous calculations we know that $V_1 = 169.7$ ft/sec.

then

$$G_1 = V_1 \rho = 169.7 \times .0916 = 15.54 \text{ lb/ft}^2 \text{ sec.}$$

$$P_1 = 18 \times 144 = 2592 \text{ lb/ft}^2$$

$$N = \frac{fL}{R_H} = \frac{4fL}{D} = 4.5 \times 4 = 18.0$$

From the Chemical Engineers Handbook (2)

$$G_{ci} = P_o \sqrt{\frac{g_c M}{2.718 R T_o}} = P_o \sqrt{\frac{32.17 \times 29}{2.718 \times 1545\, T_o}}$$

reading from Lapple's graph for K = 1.4 for adiabatic flow, assume

$$\frac{P_1}{P_o} = 0.96 \quad , \quad N = 0$$

We find $\frac{G_1}{G_{ci}} = 0.40$, $\frac{T_1}{T_o} = .9905$

therefore $G_{ci} = \frac{15.54}{.4} = 38.85$, $T_o = \frac{530}{.9905} = 535\,°R$

Substituting these values in the formula

$$P_o = \frac{G_{ci}}{\sqrt{\frac{g_c M}{2.718 R T_o}}} = \frac{38.85}{\sqrt{\frac{32.17 \times 29}{2.718 \times 1545 \times 535}}}$$

$$P_o = 1913 \text{ lb/ft}^2$$

then $\frac{P_1}{P_o} = \frac{2592}{1913} = 1.35$

This does not check the assumed value of $\frac{P_1}{P_o} = 0.96$

Adjusting $\frac{P_1}{P_0} = 0.975$, $N = 0$

Therefore $\frac{G_1}{G_{ci}} = 0.288$, $\frac{T_1}{T_0} = 0.9935$

$$G_{ci} = \frac{15.54}{0.288} = 53.95 \qquad T_0 = \frac{530}{.9935} = 533$$

Substituting in the formula

$$P_0 = \frac{G_{ci}}{\sqrt{\frac{g_0 M}{2.718 R T_0}}}$$

We obtain $P_0 = 2657$

then $\frac{P_1}{P_0} = \frac{2592}{2657} = 0.975$

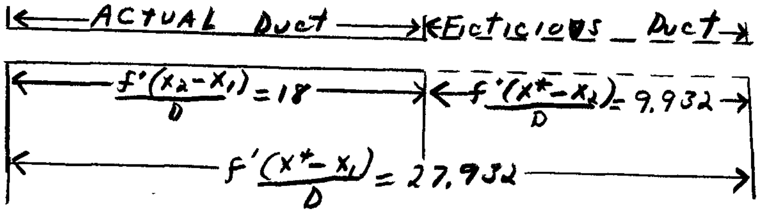
This checks the assumed value for $\frac{P_1}{P_0} = 0.975$

for $N = 18$, $\frac{P_2}{P_0} = 0.62$, $\frac{T_2}{T_0} = 0.988$

then $P_2 = \frac{\frac{P_2}{P_0}}{\frac{P_1}{P_0}} \times P_1 = \frac{0.62}{0.975} \times 18 = 11.45$ psia.

and $T_2 = \frac{\frac{T_2}{T_0}}{\frac{T_1}{T_0}} \times T_1 = \frac{0.988}{0.9935} \times 530 = 527°R$

IV. Method Based on Fanno Tables



solving the sample problem by means of the Fanno Tables (3):

$$f' = 4f = 4 \times 0.0045 = 0.018$$

The friction length is

$$f'\frac{(x_2-x_1)}{D} = 0.018 \times \frac{500}{1/2} = 18$$

The inlet velocity is $V_1 = \frac{2000}{60} \Big/ \frac{\pi}{16} = 169.7$

at the inlet

$$M_1 = \frac{V}{a} = \frac{169.7}{49.03\sqrt{530}} = 0.150$$

The Fanno Tables have a column headed $\frac{fL}{D}$ from which we read the value for $f'\frac{(x^*-x_1)}{D}$ at $M = 0.150$ of 27.932

By reference to the figure above we know that

$$f'\frac{(x^*-x_1)}{D} - f'\frac{(x_2-x_1)}{D} = f'\frac{(x^*-x_2)}{D}$$

or

$$27.932 - 18 = 9.932$$

For the value of $f'\frac{(x^*-x_2)}{D} = 9.932$ we find from the Fanno Tables that $M_2 = .2347$.

The Fanno Tables have columns headed $\frac{P}{P^*}$ and $\frac{T}{T^*}$ corresponding to various values of M. Therefore, for M_1 and M_2 we can read

$\frac{P_2}{P^*} = 4.6441$ $\qquad$ $\frac{P_1}{P^*} = 7.2866$

$\frac{T_2}{T^*} = 1.1869$ $\qquad$ $\frac{T_1}{T^*} = 1.1946$

The exit conditions are then found:

$$P_2 = P_1 \times \frac{P_2}{P^*} \times \frac{P^*}{P_1} = \frac{18 \times 4.6441}{7.2866} = 11.47 \text{ psia}$$

$$T_2 = T_1 \times \frac{T_2}{T^*} \times \frac{T^*}{T_1} = \frac{530 \times 1.1869}{1.1946} = 526.5 \text{ °R}$$

This method does not involve trial-and-error, but requires the use of a special set of tables.

CONCLUSIONS

There should be little doubt that certain design problems concerning fluid flow of compressible fluids can be solved more simply through the use of the three graphs presented in this paper relating the pressure ratio and temperature ratio to the friction and velocity. While it is possible to interpolate between graphs for specific heat ratios other than those presented in this paper (K = 1.1, K = 1.4 and K = 1.67), valuable additions could be made to this problem by constructing graphs for specific heat ratios of 1.2, 1.3, 1.5 and 1.6.

With the graphs presented in this paper the maximum velocity limitation is about 340 feet per second for air at 70°F. At greater velocities the Mach number would exceed 0.300. A further contribution could be made by constructing graphs for Mach numbers in excess of 0.300. Graphs with Mach numbers higher than 0.300 would increase the possible maximum velocity range.

TABLE OF NOMENCLATURE

D = diameter, ft.

f = friction factor

f^1 = $4f$

g_c = 32.1740 (lb. mass) (ft.)/ (lb. force) (sec.^{2})

G = $V\rho = V/v$ mass velocity, lb. mass/(sec.) (sq. ft.)

G_{ci} = $\sqrt{g_c P_0 / 2.718 v_0} = P_0 \sqrt{g_c M / 2.718 R T_0}$

K = C_p/c_v, ratio of specific heat at constant pressure to that a constant volume

L = Length, ft.

M = Molecular weight, lb. mass/lb. mole

= viscosity, lb. mass/ (ft.) (sec.)

N = $\frac{fL}{R_H}$ = frictional resistance in velocity heads

P_1, P_2 = pressure at inlet and outlet, respectively. $\frac{\text{lb. force}}{\text{sq. inch}}$

R = gas constant 1546 ft. -lb. force/ (lb. -mole) (°R)

T_1, T_2 = absolute temperature at inlet and outlet, respectively, °R

V_1, V_2 = linear velocity at inlet and outlet, respectively, ft./sec.

M_1 = $\frac{V_1}{C_1}$ initial Mach number

M_2 = outlet Mach number

C_1 = initial acoustic velocity

ρ = density of fluid, lb. mass/cu. ft.

P_0 = pressure in theoretical chamber, lb./sq. ft.

T_0 = temperature in theoretical chamber, °R

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APPENDIX

CALCULATED DATA

K = 1.1 M = 0.05

$\frac{V_2}{V_1}$	$\frac{fL}{D}$	$\frac{P_2}{P_1}$	$\frac{T_2}{T_1}$
1.10	15.734	0.90907	0.9999
1.25	32.625	0.79994	0.9999
1.50	50.318	0.66656	0.9998
1.75	60.965	0.57128	0.9998
2.00	67.861	0.49981	0.9996
2.25	72.574	0.44421	0.9995
2.50	75.937	0.39973	0.9992
2.75	78.416	0.36333	0.9991
3.00	80.294	0.33300	0.9990
3.25	81.751	0.30732	0.9987
3.50	82.901	0.28531	0.9986
3.75	83.825	0.26623	0.9983
4.00	84.578	0.24953	0.9981
4.25	85.197	0.23479	0.9979
4.50	85.964	0.22168	
4.75	86.148	0.20995	
5.00	86.517	0.19940	
5.25	86.831	0.18984	
5.50	87.103	0.18115	
5.75	87.337	0.17321	
6.00	87.541	0.16593	
8.00	88.508	0.12402	

$M\sqrt{K} = 0.052$

K = 1.1 M = 0.075

$\frac{V_2}{V_1}$	$\frac{fL}{D}$	$\frac{P_2}{P_1}$	$\frac{T_2}{T_1}$
1.10	6.969	0.90904	0.9999
1.25	14.443	0.79987	0.9999
1.50	22.260	0.66643	0.9996
1.75	26.952	0.57109	0.9993
2.00	29.981	0.49957	0.9991
2.25	32.045	0.44393	0.9988
2.50	33.512	0.39940	0.9985
2.75	34.589	0.36296	0.9983
3.00	35.401	0.33258	0.9977
3.25	36.027	0.30686	0.9974
3.50	36.519	0.28481	0.9968
3.75	36.911	0.26568	0.9964
4.00	37.229	0.24894	0.9958
4.25	37.488	0.23416	0.9954
4.50	37.703	0.22101	0.9945
4.75	37.881	0.20924	0.9937
5.00	38.032	0.19865	0.9933
5.25	38.159	0.18905	0.9928
5.50	38.267	0.18032	0.9917
5.75	38.359	0.17234	0.9907
6.00	38.439	0.16502	0.9901
8.00	38.793	0.12279	0.9823

$M\sqrt{K}$ = 0.07866

$K = 1.1$ $M = 0.100$

$\frac{V_2}{V_1}$	$\frac{fL}{D}$	$\frac{P_2}{P_1}$	$\frac{T_2}{T_1}$
1.10	3.651	0.90899	0.9999
1.25	8.080	0.79977	0.9998
1.50	12.439	0.66625	0.9995
1.75	15.047	0.57083	0.9989
2.00	16.724	0.49925	0.9985
2.25	17.860	0.44354	0.9979
2.50	18.664	0.39895	0.9975
2.75	19.250	0.36244	0.9966
3.00	19.688	0.33200	0.9960
3.25	20.024	0.30622	0.9952
3.50	20.285	0.28410	0.9944
3.75	20.492	0.26492	0.9934
4.00	20.657	0.24812	0.9925
4.25	20.790	0.23328	0.9914
4.50	20.899	0.22008	0.9904
4.75	20.988	0.20825	0.9892
5.00	21.062	0.19760	0.9880
5.25	21.123	0.18794	0.9867
5.50	21.174	0.17915	0.9853
5.75	21.217	0.17112	0.9839
6.00	21.253	0.16375	0.9825
8.00	21.392	0.12106	0.9685

$M\sqrt{K} = 0.10488$

K = 1.1 M = 0.125

$\frac{V_2}{V_1}$	$\frac{fL}{D}$	$\frac{P_2}{P_1}$	$\frac{T_2}{T_1}$
1.10	2.481	0.90894	0.9998
1.25	5.134	0.79964	0.9995
1.50	7.894	0.66601	0.9990
1.75	9.537	0.57050	0.9984
2.00	10.587	0.49882	0.9976
2.25	11.295	0.44303	0.9968
2.50	11.791	0.39835	0.9958
2.75	12.150	0.36177	0.9949
3.00	12.417	0.33125	0.9937
3.25	12.617	0.30539	0.9925
3.50	12.771	0.28320	0.9912
3.75	12.892	0.26394	0.9898
4.00	12.986	0.24707	0.9883
4.25	13.061	0.23215	0.9866
4.50	13.121	0.21888	0.9850
4.75	13.169	0.20697	0.9831
5.00	13.207	0.19625	0.9813
5.25	13.238	0.18652	0.9792
5.50	13.263	0.17766	
5.75	13.283	0.16955	
6.00	13.298	0.16210	
7.00	13.332	0.13750	

$M\sqrt{K} = 0.1311$

$K = 1.1$ $M = 0.150$

$\frac{V_2}{V_1}$	$\frac{fL}{D}$	$\frac{P_2}{P_1}$	$\frac{T_2}{T_1}$
1.10	1.710	0.90886	0.9998
1.25	3.534	0.79949	0.9994
1.50	5.425	0.66572	0.9986
1.75	6.544	0.57010	0.9977
2.00	7.254	0.49831	0.9966
2.25	7.728	0.44241	0.9954
2.50	8.058	0.39763	0.9940
2.75	8.293	0.36095	0.9926
3.00	8.465	0.33033	0.9910
3.25	8.593	0.30438	0.9892
3.50	8.690	0.28209	0.9873
3.75	8.763	0.26274	0.9853
4.00	8.845	0.24578	0.9831
4.25	8.863	0.23077	0.9808
4.50	8.896	0.21740	0.9783
4.75	8.921	0.20541	
5.00	8.941	0.19460	
5.25	8.955	0.18478	
5.50	8.965	0.17583	
5.75	8.975	0.16763	
6.00	8.977	0.16010	

$M\sqrt{K} = 0.15732$

$K = 1.1$ $M = 0.175$

$\frac{V_2}{V_1}$	$\frac{fL}{D}$	$\frac{P_2}{P_1}$	$\frac{T_2}{T_1}$
1.10	1.245	0.90060	0.9997
1.25	2.569	0.79931	0.9991
1.50	3.936	0.66539	0.9981
1.75	4.739	0.56962	0.9968
2.00	5.244	0.49770	0.9954
2.25	5.578	0.44167	0.9938
2.50	5.807	0.39678	0.9920
2.75	5.970	0.35998	0.9900
3.00	6.083	0.32925	0.9878
3.25	6.142	0.30318	0.9854
3.50	6.229	0.28079	0.9828
3.75	6.274	0.26133	0.9798
4.00	6.307	0.24425	
4.25	6.331	0.22914	
4.50	6.348	0.21567	
4.75	6.360	0.20357	
5.00	6.363	0.19265	

$M\sqrt{K} = 0.18354$

K = 1.1 M = 0.200

$\frac{V_2}{V_1}$	$\frac{fL}{D}$	$\frac{P_2}{P_1}$	$\frac{T_2}{T_1}$
1.10	0.943	0.90871	0.9996
1.25	1.943	0.79910	0.9988
1.50	2.970	0.66500	0.9975
1.75	3.567	0.56907	0.9959
2.00	3.939	0.49700	0.9940
2.25	4.182	0.44083	0.9918
2.50	4.345	0.39580	0.9895
2.75	4.458	0.35886	0.9870
3.00	4.537	0.32800	0.9840
3.25	4.592	0.30180	0.9809
3.50	4.631	0.27928	0.9776
3.75	4.658	0.25970	
4.00	4.676	0.24250	
4.25	4.688	0.22726	
4.50	4.695	0.21366	

$M\sqrt{K} = 0.20976$

$K = 1.1$ $M = 0.225$

$\frac{V_2}{V_1}$	$\frac{fL}{D}$	$\frac{P_2}{P_1}$	$\frac{T_2}{T_1}$
1.10	0.736	0.90801	0.9994
1.25	1.514	0.79886	0.9986
1.50	2.307	0.66455	0.9969
1.75	2.764	0.56844	0.9947
2.00	3.045	0.49620	0.9924
2.25	3.225	0.43987	0.9898
2.50	3.344	0.39468	0.9868
2.75	3.423	0.35759	0.9834
3.00	3.477	0.32658	0.9798
3.25	3.513	0.30024	
3.50	3.536	0.27757	
3.75	3.551	0.25784	
4.00	3.559	0.24050	

$M\sqrt{K} = 0.23598$

K = 1.1 M = 0.250

$\frac{V_2}{V_1}$	$\frac{fL}{D}$	$\frac{P_2}{P_1}$	$\frac{T_2}{T_1}$
1.10	0.588	0.90849	0.9994
1.25	1.207	0.79859	0.9983
1.50	1.833	0.66406	0.9962
1.75	2.190	0.56776	0.9937
2.00	2.405	0.49531	0.9906
2.25	2.541	0.43880	0.9873
2.50	2.627	0.39343	0.9835
2.75	2.683	0.35617	0.9796
3.00	2.719	0.32500	
3.25	2.740	0.29849	
3.50	2.753	0.27566	

$M\sqrt{K}$ 0.26220

K = 1.1 M = 0.275

$\frac{V_2}{V_1}$	$\frac{fL}{D}$	$\frac{P_2}{P_1}$	$\frac{T_2}{T_1}$
1.10	0.476	0.90838	0.9992
1.25	0.980	0.79829	0.9979
1.50	1.483	0.66351	0.9953
1.75	1.765	0.56697	0.9923
2.00	1.932	0.49432	0.9886
2.25	2.034	0.43761	0.9846
2.50	2.097	0.39205	0.9803
2.75	2.135	0.35461	0.9752
3.00	2.158	0.32325	
3.25	2.194	0.29656	

$M\sqrt{K}$ = 0.28842

K = 1.1 M = 0.300

$\frac{V_2}{V_1}$	$\frac{fL}{D}$	$\frac{P_2}{P_1}$	$\frac{T_2}{T_1}$
1.10	0.395	0.90823	0.9990
1.25	0.807	0.79797	0.9975
1.50	1.216	0.66291	0.9944
1.75	1.442	0.56612	0.9907
2.00	1.572	0.49325	0.9865
2.25	1.649	0.43631	0.9817
2.50	1.694	0.39055	0.9765
2.75	1.719	0.35289	
3.00	1.731	0.32133	

$M\sqrt{K}$ = 0.31464

$K = 1.4$ $M = 0.050$

$\frac{V_2}{V_1}$	$\frac{fL}{D}$	$\frac{P_2}{P_1}$	$\frac{T_2}{T_1}$
1.10	12.362	0.90899	0.9999
1.25	25.636	0.79977	0.9998
1.50	39.535	0.66625	0.9995
1.75	47.896	0.57083	0.9989
2.00	53.310	0.49925	0.9985
2.25	57.009	0.44354	0.9979
2.50	59.647	0.39895	0.9975
2.75	61.591	0.36244	0.9966
3.00	63.063	0.33200	0.9960
3.25	64.204	0.30622	0.9952
3.50	65.104	0.28410	0.9944
3/75	65.827	0.26492	0.9934
4.00	66.415	0.24812	0.9925
4.25	66.899	0.23328	0.9915
4.50	67.302	0.22008	0.9905
4.75	67/640	0.20825	0.9894
5.00	67.928	0.19760	0.9880
5.25	68.172	0.18794	0.9865
5.50	68.383	0.17915	0.9856
5.75	68.565	0.17112	0.9838
6.00	68.723	0.16375	0.9825
8.00	69.457	0.12063	0.9648

$M\sqrt{K} = 0.05916$

$K = 1.4$ $M = 0.075$

$\frac{V_2}{V_1}$	$\frac{fL}{D}$	$\frac{P_2}{P_1}$	$\frac{T_2}{T_1}$
1.10	5.475	0.90887	0.9998
1.25	11.348	0.79949	0.9994
1.50	17.486	0.66572	0.9986
1.75	21.168	0.57010	0.9977
2.00	23.543	0.49831	0.9966
2.25	25.161	0.44241	0.9954
2.50	26.309	0.39763	0.9940
2.75	27.150	0.36095	0.9928
3.00	27.784	0.33033	0.9910
3.25	28.273	0.30438	0.9893
3.50	28.655	0.28209	0.9874
3.75	28.960	0.26274	0.9851
4.00	29.207	0.24578	0.9831
4.25	29.407	0.23077	0.9809
4.50	29.573	0.21740	0.9783
4.75	29.711	0.20541	
5.00	29.826	0.19460	
5.25	29.923	0.18478	
5.50	30.006	0.17583	
5.75	30.077	0.16763	
6.00	30.137	0.16010	
8.00	30.395	0.11614	

$M\sqrt{K} = 0.08874$

K = 1.4 M = 0.100

$\frac{V_2}{V_1}$	$\frac{fL}{D}$	$\frac{P_2}{P_1}$	$\frac{T_2}{T_1}$
1.10	3.065	0.90870	0.9996
1.25	6.347	0.79910	0.9989
1.50	9.768	0.66500	0.9975
1.75	11.812	0.56907	0.9959
2.00	13.125	0.49700	0.9940
2.25	14.013	0.44083	0.9918
2.50	14.640	0.39580	0.9895
2.75	15.096	0.35886	0.9870
3.00	15.437	0.32800	0.9840
3.25	15.697	0.30180	0.9809
3.50	15.898	0.27928	0.9776
3.75	16.057	0.25970	0.9739
4.00	16.184	0.24250	0.9700
4.25	16.285	0.22726	0.9658
4.50	16.368	0.21366	0.9615
4.75	16.435	0.20144	0.9568
5.00	16.491	0.19040	
5.25	16.536	0.18035	
5.50	16.574	0.17118	
5.75	16.606	0.16276	
6.00	16.632	0.15500	
7.00	16.695	0.12915	

$M\sqrt{K} = 0.11832$

K = 1.4 M = 0.125

$\frac{V_2}{V_1}$	$\frac{fL}{D}$	$\frac{P_2}{P_1}$	$\frac{T_2}{T_1}$
1.10	1.949	0.90849	0.9993
1.25	4.032	0.79859	0.9983
1.50	6.196	0.66406	0.9962
1.75	7.482	0.56774	0.9935
2.00	8.303	0.49531	0.9906
2.25	8.854	0.43880	0.9873
2.50	9.239	0.39343	0.9835
2.75	9.517	0.35617	0.9796
3.00	9.720	0.32500	0.9750
3.25	9.876	0.29849	0.9701
3.50	9.994	0.27566	0.9648
3.75	10.085	0.25578	0.9592
4.00	10.156	0.23828	
4.25	10.212	0.22274	
4.50	10.256	0.20885	
4.75	10.291	0.19634	
5.00	10.319	0.18500	
5.25	10.340	0.17466	
5.50	10.357	0.16519	
5.75	10.371	0.15648	
6.00	10.381	0.14843	

MVK = 0.14790

$K = 1.4$ $M = 0.150$

$\frac{V_2}{V_1}$	$\frac{fL}{D}$	$\frac{P_2}{P_1}$	$\frac{T_2}{T_1}$
1.10	1.343	0.90823	0.9991
1.25	2.775	0.79797	0.9975
1.50	4.256	0.66291	0.9944
1.75	5.130	0.56612	0.9907
2.00	5.682	0.49325	0.9865
2.25	6.051	0.43631	0.9817
2.50	6.305	0.39055	0.9765
2.75	6.486	0.35289	0.9704
3.00	6.617	0.32133	0.9640
3.25	6.714	0.29445	0.9569
3.50	6.786	0.27125	
3.75	6.841	0.25099	
4.00	6.882	0.23312	
4.25	6.913	0.21722	
4.50	6.936	0.20297	
4.75	6.953	0.19009	
5.00	6.966	0.17840	

$M\sqrt{K} = 0.17748$

K = 1.4 M = 0.175

$\frac{V_2}{V_1}$	$\frac{fL}{D}$	$\frac{P_2}{P_1}$	$\frac{T_2}{T_1}$
1.10	0.977	0.90792	0.9987
1.25	2.017	0.79724	0.9965
1.50	3.086	0.66156	0.9924
1.75	3.711	0.56420	0.9874
2.00	4.104	0.49081	0.9816
2.25	4.361	0.43338	0.9752
2.50	4.536	0.38713	0.9678
2.75	4.659	0.34901	0.9598
3.00	4.745	0.31700	
3.25	4.807	0.28967	
3.50	4.852	0.26602	
3.75	4.884	0.24533	
4.00	4.907	0.22703	
4.25	4.923	0.21070	

$M\sqrt{K}$ = 0.20706

$K = 1.4$ $M = 0.200$

$\frac{V_2}{V_1}$	$\frac{fL}{D}$	$\frac{P_2}{P_1}$	$\frac{T_2}{T_1}$
1.10	0.740	0.90756	0.9983
1.25	1.525	0.79640	0.9955
1.50	2.327	0.66000	0.9900
1.75	2.791	0.56200	0.9835
2.00	3.078	0.48800	0.9760
2.25	3.266	0.43000	0.9675
2.50	3.388	0.38320	0.9580
2.75	3.473	0.34454	
3.00	3.530	0.31200	
3.25	3.570	0.28415	
3.50	3.597	0.26000	
3.75	3.615	0.23880	

$M\sqrt{K} = 0.23664$

K = 1.4 M = 0.225

$\frac{V_2}{V_1}$	$\frac{fL}{D}$	$\frac{P_2}{P_1}$	$\frac{T_2}{T_1}$
1.10	0.578	0.90715	0.9979
1.25	1.187	0.79544	0.9943
1.50	1.806	0.65822	0.9873
1.75	2.160	0.55949	0.9791
2.00	2.376	0.48481	
2.25	2.513	0.42616	
2.50	2.601	0.37873	
2.75	2.659	0.33947	
3.00	2.697	0.30633	
3.25	2.722	0.27790	

$M\sqrt{K} = 0.26622$

K = 1.4 M = 0.250

$\frac{V_2}{V_1}$	$\frac{fL}{D}$	$\frac{P_2}{P_1}$	$\frac{T_2}{T_1}$
1.10	0.461	0.90670	0.9974
1.25	0.946	0.79437	0.9930
1.50	1.434	0.65625	0.9845
1.75	1.709	0.55669	0.9742
2.00	1.873	0.48125	0.9625
2.25	1.975	0.42187	0.9492
2.50	2.038	0.37375	
2.75	2.078	0.33380	
3.00	2.101	0.30000	

$M\sqrt{K} = 0.29580$

K = 1.4 M = 0.275

$\frac{V_2}{V_1}$	$\frac{fL}{D}$	$\frac{P_2}{P_1}$	$\frac{T_2}{T_1}$
1.10	0.375	0.90620	0.9968
1.25	0.768	0.79319	0.9915
1.50	1.158	0.65406	0.9812
1.75	1.375	0.55360	0.9688
2.00	1.501	0.47731	
2.25	1.577	0.41713	
2.50	1.622	0.36823	
2.75	1.647	0.32754	

$M\sqrt{K} = 0.32538$

K = 1.4 M = 0.300

1.02		0.97968	0.9993
1.05		0.95062	0.9982
1.10	0.366	0.90565	0.9962
1.25	0.632	0.79190	0.9899
1.50	0.949	0.65166	0.9776
1.75	1.121	0.55021	0.9629
2.00	1.218	0.47300	0.9460
2.25	1.274	0.41194	
2.50	1.305	0.36220	

$M\sqrt{K} = 0.35496$

$K = 1.67$ $M = 0.050$

$\frac{V_2}{V_1}$	$\frac{fL}{D}$	$\frac{P_2}{P_1}$	$\frac{T_2}{T_1}$
1.10	10.363	0.90893	0.9998
1.25	21.486	0.79962	0.9995
1.50	33.132	0.66592	0.9989
1.75	40.137	0.57044	0.9982
2.00	44.671	0.49874	0.9975
2.25	47.768	0.44293	0.9965
2.50	50.026	0.39824	0.9955
2.75	51.601	0.36163	0.9944
3.00	52.882	0.33110	0.9933
3.25	53.785	0.30522	0.9919
3.50	54.537	0.28302	0.9905
3.75	55.140	0.26374	0.9888
4.00	55.631	0.24685	0.9874
4.25	56.034	0.23193	0.9856
4.50	56.370	0.21863	0.9837
4.75	56.651	0.20672	0.9818
5.00	56.890	0.19598	0.9799
5.25	57.093	0.18623	0.9775
5.50	57.268	0.17736	0.9757
5.75	57.419	0.16924	
6.00	57.550	0.16178	
8.00	58.164	0.11841	

$M\sqrt{K} = 0.06462$

$K = 1.67$ $M = 0.075$

$\frac{V_2}{V_1}$	$\frac{fL}{D}$	$\frac{P_2}{P_1}$	$\frac{T_2}{T_1}$
1.10	4.589	0.90873	0.9996
1.25	9.510	0.79915	0.9989
1.50	14.651	0.66509	0.9976
1.75	17.733	0.56920	0.9961
2.00	19.721	0.49717	0.9943
2.25	21.073	0.44104	0.9923
2.50	22.031	0.39604	0.9901
2.75	22.734	0.35913	0.9876
3.00	23.262	0.32830	0.9849
3.25	23.668	0.30214	0.9819
3.50	23.987	0.27965	0.9788
3.75	24.239	0.26010	0.9754
4.00	24.444	0.24293	0.9717
4.25	24.609	0.22772	0.9678
4.50	24.746	0.21416	0.9637
4.75	24.859	0.20197	0.9594
5.00	24.954	0.19095	
5.25	25.034	0.18094	
5.50	25.101	0.17179	
5.75	25.159	0.16340	
6.00	25.207	0.15567	
8.00	25.417	0.11016	

$M\sqrt{K} = 0.09692$

K = 1.67 M = 0.100

$\frac{V_2}{V_1}$	$\frac{fL}{D}$	$\frac{P_2}{P_1}$	$\frac{T_2}{T_1}$
1.10	2.569	0.90845	0.9993
1.25	5.318	0.79849	0.9981
1.50	8.183	0.66387	0.9958
1.75	9.892	0.56748	0.9931
2.00	10.988	0.49497	0.9899
2.25	11.729	0.43839	0.9864
2.50	12.251	0.39296	0.9824
2.75	12.630	0.35564	0.9780
3.00	12.912	0.32440	0.9732
3.25	13.127	0.29783	0.9679
3.50	13.294	0.27494	0.9623
3.75	13.424	0.25499	0.9562
4.00	13.528	0.23743	
4.25	13.611	0.22184	
4.50	13.678	0.20789	
4.75	13.732	0.19531	
5.00	13.777	0.18392	
5.25	13.813	0.17352	
5.50	13.843	0.16400	
5.75	13.867	0.15523	
6.00	13.888	0.14712	

MVK = 0.12923

K = 1.67   M = 0.125

$\frac{V_2}{V_1}$	$\frac{fL}{D}$	$\frac{P_2}{P_1}$	$\frac{T_2}{T_1}$
1.10	1.633	0.90809	0.9989
1.25	3.378	0.79764	0.9970
1.50	5.189	0.66230	0.9935
1.75	6.263	0.56525	0.9892
2.00	6.946	0.49214	0.9843
2.25	7.405	0.43499	0.9787
2.50	7.724	0.38900	0.9725
2.75	7.953	0.35114	0.9656
3.00	8.122	0.31937	0.9581
3.25	8.249	0.29229	
3.50	8.345	0.26888	
3.75	8.418	0.24843	
4.00	8.476	0.23037	
4.25	8.520	0.21427	
4.50	8.555	0.19983	
4.75	8.581	0.18676	
5.00	8.603	0.17487	
5.25	8.619	0.16399	

$M\sqrt{K}$ = 0.16154

$K = 1.67$ $M = 0.150$

$\frac{V_2}{V_1}$	$\frac{fL}{D}$	$\frac{P_2}{P_1}$	$\frac{T_2}{T_1}$
1.05		0.95164	0.9992
1.10	1.125	0.90764	0.9984
1.25	2.324	0.79660	0.9958
1.50	3.562	0.66038	0.9906
1.75	4.291	0.56254	0.9844
2.00	4.751	0.48869	0.9774
2.25	5.056	0.43083	0.9694
2.50	5.265	0.38417	0.9604
2.75	5.413	0.34564	0.9505
3.00	5.520	0.31323	
3.25	5.598	0.28551	
3.50	5.656	0.26148	
3.75	5.699	0.24041	
4.00	5.731	0.22173	
4.25	5.755	0.20503	

$M\sqrt{K} = 0.19385$

$K = 1.67$ $M = 0.175$

$\frac{V_2}{V_1}$	$\frac{fL}{D}$	$\frac{P_2}{P_1}$	$\frac{T_2}{T_1}$
1.05		0.95138	0.9989
1.10	0.819	0.90714	0.9979
1.25	1.689	0.79538	0.9942
1.50	2.582	0.65811	0.9872
1.75	3.102	0.55933	0.9788
2.00	3.427	0.48461	0.9692
2.25	3.639	0.42592	0.9583
2.50	3.782	0.37845	
2.75	3.881	0.33915	
3.00	3.951	0.30597	
3.25	4.000	0.27750	
3.50	4.035	0.25273	
3.75	4.059	0.23092	

$M\sqrt{K} = 0.22615$

K = 1.67 M = 0.200

$\frac{V_2}{V_1}$	$\frac{fL}{D}$	$\frac{P_2}{P_1}$	$\frac{T_2}{T_1}$
1.10	0.620	0.90654	0.9972
1.25	1.276	0.79397	0.9925
1.50	1.945	0.65550	0.9833
1.75	2.331	0.55563	0.9724
2.00	2.568	0.47990	0.9598
2.25	2.720	0.42025	
2.50	2.820	0.37186	
2.75	2.887	0.33165	
3.00	2.933	0.29760	
3.25	2.963	0.26826	

$M\sqrt{K}$ = 0.25846

K = 1.67 M = 0.225

$\frac{V_2}{V_1}$	$\frac{fL}{D}$	$\frac{P_2}{P_1}$	$\frac{T_2}{T_1}$
1.10	0.484	0.90585	0.9965
1.25	0.993	0.79236	0.9905
1.50	1.509	0.65253	0.9788
1.75	1.802	0.55144	
2.00	1.979	0.47456	
2.25	2.089	0.41382	
2.50	2.160	0.36438	
2.75	2.206	0.32316	

$M\sqrt{K}$ = 0.29077

K = 1.67 M = 0.250

$\frac{V_2}{V_1}$	$\frac{fL}{D}$	$\frac{P_2}{P_1}$	$\frac{T_2}{T_1}$
1.05		0.95033	0.9978
1.10	0.386	0.90510	0.9956
1.25	1.791	0.79057	0.9882
1.50	1.197	0.64921	0.9738
1.75	1.423	0.54675	0.9568
2.00	1.557	0.46859	
2.25	1.639	0.40664	
2.50	1.688	0.35603	

$M\sqrt{K} = 0.32308$

K = 1.67 M = 0.275

1.10	0.304	0.90425	0.9947
1.25	0.642	0.78859	0.9858
1.50	0.966	0.64555	0.9684
1.75	1.163	0.54157	
2.00	1.246	0.46199	
2.25	1.305	0.39870	

$M\sqrt{K} = 0.35538$

$K = 1.67$ $M = 0.300$

$\frac{V_2}{V_1}$	$\frac{fL}{D}$	$\frac{P_2}{P_1}$	$\frac{T_2}{T_1}$
1.01		0.98950	0.9994
1.02		0.97919	0.9988
1.10	0.259	0.90334	0.9937
1.25	0.528	0.78643	0.9830
1.50	0.790	0.64154	0.9623
1.75	0.931	0.53589	0.9378
2.00	1.008	0.45477	
2.25	1.051	0.39000	

$M\sqrt{K} = 0.38769$