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MEASUREMENTS OF FRICTION COEFFICIENTS IN A PIPE FOR SUBSONIC AND SUPERSONIC FLOW OF AIR

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NATIONAL ADVISORY COMMITTEE FOR AERONAUTICS

ADVANCE RESTRICTED REPORT

MEASUREMENTS OF FRICTION COEFFICIENTS IN A PIPE FOR SUBSONIC AND SUPERSONIC FLOW OF AIR

By Joseph H. Keenan and Ernest P. Neumann

SUMMARY

Tests of the flow of air through brass tubes show that, for subsonic flow, the friction coefficient is the same function of Reynolds number as for incompressible flow but that, for supersonic flow, the apparent friction coefficient is less than for incompressible flow at the same value of the Reynolds number and decreases with increase in Mach number. The analytical relation between friction coefficient, tube length, and Mach number is shown for flow without shock and the conditions for flow with and without shock are delimited. The method of analysis is given.

INTRODUCTION

The effect of friction on the flow of compressible fluids in pipes of uniform cross-sectional area was investigated analytically by Grashof (reference 1) and Zeuner (reference 2), who arrived at a relationship between velocity and friction coefficient for ideal gases. Stodola (reference 3) showed that the curves of Fanno permit a general graphical treatment for any law of friction. Frössel (reference 4) presented the first extensive measurements of friction coefficients for air flow through a smooth tube with velocities above and below the velocity of sound. Frössel's measured coefficients for compressible flow were in excellent agreement, at corresponding Reynolds numbers, with coefficients measured for incompressible flow. Egli (reference 5) expressed in dimensionless form the equations for flow of an ideal gas through a channel and used these equations to deduce friction coefficients from measurements of flow through channels varying in width from 0.0025 to 0.010 inch.

Previous experiments (Frössel (reference 4) and Keenan (reference 6)) with compressible fluids at subsonic velocities indicate that variation in the Mach number between zero and 1 - that is, for subsonic velocities - has no appreciable effect on the coefficient of friction. For the flow of air in smooth brass pipes, Frössel reports the same relation between Reynolds number and friction coefficient as was obtained by many experimenters (notably Stanton and Panell) for incompressible fluids.

For compressible fluids at Mach numbers greater than 1 - that is, at supersonic velocities, Frössel reports the same relation between friction coefficient and Reynolds number as that obtained at Mach numbers less than 1 - that is, at subsonic velocities. Previous measurements made in the laboratory of Mechanical Engineering at the Massachusetts Institute of Technology indicated friction coefficients in supersonic flow considerably different from the coefficients reported by Frössel.

The definition of the friction coefficient and the means of computing it are described in appendix A. This material is largely drawn from reference 6, but since it is necessary to an understanding of the computed results of the present tests it is restated briefly here.

The object of the present investigation is to measure the coefficient of friction in a smooth tube with compressible flow of air and, in particular, with supersonic flow.

TEST APPARATUS

The arrangement of the test apparatus is shown in figure 1. Air is supplied by a two-stage steam-driven air compressor running at constant speed. At the discharge from the compressor is a receiver to smooth out fluctuations in flow. After leaving the receiver, the air passes through a cooling coil, where a portion of the moisture, contained in the air leaving the compressor, is condensed and drawn off. The saturated air leaving the cooling coil is then passed through a heating coil in order to superheat the water vapor contained in the air and thereby to prevent formation of waterdrops in the approach pipe

that precedes the test length. The cooling and heating coils were used only for tests 9 and 10, all other tests having been completed before the coils were installed.

The air stream is introduced into the test pipe through a rounded-entrance nozzle of circular cross section. Details of the nozzles used in different tests are shown in figures 2 to 4. The test pipe is of standard drawn-brass tubing of 0.4375-inch inside diameter for supersonic data and of 0.375-inch inside diameter for subsonic data. The pressure measurements, from which the friction coefficients are calculated, were made at 0.020-inch-diameter holes drilled in the tube wall at intervals of 2 inches for the supersonic tests (with additional holes for some tests) and at intervals of 12 inches, with an additional tap located 3 inches from the tube end, for the subsonic tests. Additional pressure taps were later drilled in the pipe, 180° from the first row of taps at 3, 4, 5, 7, 9, and 11 inches from the tube entrance to obtain additional pressure measurements for the supersonic tube. In order that there should be no burr at the pressure tap, the inside of the test pipe was carefully polished with fine emery cloth. Connections between the pressure taps, manifolds, and manometers are made with $\frac{1}{4}$-inch copper tubing.

With the exception of the initial pressure for the supersonic runs, all pressures were measured by simple U-tube manometers. Small pressure differences were measured in centimeters of water and larger pressure differences, in centimeters of mercury. With the aid of a sliding marker on the manometer scales, pressure differences could be read to 0.01 centimeter. For the supersonic data, initial pressures were measured with a calibrated Bourdon gage.

The temperature of the air stream in front of the nozzle could be measured by either a copper-constantan thermocouple or a mercury-in-glass thermometer. Readings were usually made with the thermometer.

The discharge coefficient of each nozzle was determined by calibrating against a gasometer. The rate of flow of air in each test was then found from the state of the air in front of the nozzle (and in subsonic tests, the pressure after) and the discharge coefficient.

METHOD OF TESTING

The air compressor was started and sufficient time was allowed to elapse to obtain steady-state conditions before any readings were taken. Temperature readings were taken at definite intervals of time. Pressure differences between a given pair of taps were measured on either a mercury or a water manometer, depending upon the magnitude of the difference to be measured. In order to establish a continual check against possible leakage from either of the two manifolds used, pressure differences were recorded for each pair of taps with the higher pressure first in one manifold and then in the other. As a check against possible leakage from the connections between the pressure taps and the manifold, a soap-and-water solution was applied at each connection. For the supersonic runs, in which the pressures measured were below atmospheric pressure, the manometer system was tested by subjecting it to a pressure higher than atmospheric before starting a test.

SYMBOLS

λ friction coefficient

L length of test section (ft)

D diameter of test section (ft)

x distance along test section (ft)

p pressure (lb/sq ft. abs.)

N_M Mach number

N_R Reynolds number

T temperature (°F abs.)

V mean velocity of fluid stream (ft/sec)

a cross-sectional area of test section (sq ft)

v specific volume (cu ft/lb)

g acceleration given to unit mass by unit force

ρ mass density $\left(\frac{1}{vg.}\right)$

F wall friction force (lb)

τ friction force per unit of wall surface (lb/sq ft)

w mass rate of flow (lb/sec)

G mass rate of flow per unit area (lb/sq ft sec)

h enthalpy (ft-lb/lb)

k ratio of specific heats

Subscripts:

i refers to the initial state of the fluid stream

1 and 2 any arbitrary datum points along the test section

Constants used in making calculations:

k ratio of specific heats, 1.400

C_p specific heat at constant pressure, 0.240 $\frac{\text{Btu}}{^{\circ}\text{F lb}}$

RESULTS OF TESTS

Subsonic Flow

The results for the subsonic tests are presented in tables I to IV. The variation in pressure along the length of the test pipe is shown in figure 5. For tests 1 and 2 the pressure in the exhaust space behind the end of the pipe was below the sound pressure - that is, the pressure at the state of maximum entropy; consequently, the flow through the pipe was the maximum flow corresponding to the initial condition of the air stream. For tests 2 and 4 the air stream was throttled behind and in front of the pipe, respectively, to produce pressures at the pipe exit in excess of the sound pressure, which resulted in a flow less than the maximum flow for the existing initial conditions.

The friction coefficients corresponding to the intervals of pipe length between pressure taps are given in tables I to IV. In figure 6 the arithmetic mean of these values of the friction coefficient for each test is plotted against the arithmetic mean of the Reynolds number for that test. The length interval from 0 to 1 foot was omitted from the calculation of the mean because the velocity profile was doubtless changing greatly in this interval. The last 3 inches of length were also omitted because of the effect on velocity and pressure distribution of the abrupt discharge into the exhaust space.

The von Kármán-Nikuradse relation between friction coefficient and Reynolds number for incompressible flow is shown by the curve in figure 6. The greatest discrepancy between the present results and this curve is of the order of 3 percent, which is approximately the degree of uncertainty in the present measurements.

Figures 7 and 8 show the variation along the length of the tube of friction coefficient, mean temperature, and Mach number for tests 1 and 2. The values of friction coefficient for incompressible flow corresponding to the Reynolds number at each point along the length of the pipe are shown by the dash curve of figure 7. In test 1 the Mach number ranges from 0.32 to 1 and in test 2 from 0.3 to 0.47. In both tests, however, the agreement between the measured friction coefficients and those for incompressible flow is consistently good. This agreement confirms the conclusion reached by Keenan and by Frössel that for subsonic velocities the friction coefficient is a function of the Reynolds number and is not appreciably affected by change in the Mach number.

Supersonic Flow

The length of the test pipe for supersonic tests is limited by the divergence ratio of the nozzle that feeds the pipe. For a given divergence ratio and a given nozzle efficiency, a maximum length of test pipe exists for which a pressure shock*

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*The terms "shock" and "pressure shock" are used in this report to denote a transverse shock unless otherwise indicated.

will not appear in a pipe. For greater lengths the shock moves closer to the nozzle. Since the velocity of the stream on the downstream side of the shock is always subsonic, the maximum length of supersonic flow is attained in the longest pipe without a pressure shock. Considerations which govern the length of subsonic and supersonic flow are presented in appendix B.

With nozzle B, which has a divergence ratio of 6.7, it was possible to use a tube 50 diameters in length without having a shock in the tube. Four tests, namely tests 5, 6, 7, and 8, were made with this combination of nozzle and tube. The variation of absolute pressure with distance along the tube is shown in figure 9.

In these four tests the test points show departures from a smooth curve which decrease in magnitude with increasing distance from the nozzle. Tests 5 and 6 were separated by a time interval of 24 hours but were otherwise identical. Figure 9 shows that test 6 reproduces test 5, even to the departures from smoothness, with high fidelity.

Between tests 6 and 7 the tube and the nozzle were removed separately from the apparatus and the tube was repolished with fine emery. Between tests 7 and 8 the tube was removed again and two more pressure taps were added. Test 8 shows departures from smoothness similar to tests 5 and 6. Test 7 shows marked differences from the others in departures from smoothness. The faired curves through the test points of 7 and 8 are in agreement, but both differ appreciably from the smoothed curves of tests 5 and 6.

It appears probable that the departures from smoothness are the result of oblique shock waves in the tube, which are set up by the transition between the nozzle and the tube and which are reflected down the tube. The departures are reproducible as long as the relation between nozzle and tube is undisturbed. Between tests 6 and 7 not only was this relation disturbed but the polishing operation apparently altered slightly the character of flow in the tube. Measurements made on the tube inlet after polishing showed a slight change in diameter.

In an attempt to reduce the amplitude of the oblique shock waves, nozzle C was made (fig. 4). Here the transition from the nozzle cone to the cylindrical wall was made with a curve of large radius. Tests 9 and 10 were made with this nozzle and figure 10 shows the measured pressure variation. It appears

little reduction in the pressure fluctuations was realized; moreover, owing to an accidental increase in throat diameter, the transverse pressure shock moved into the tube and reduced the length of supersonic flow.

Further efforts should be made to reduce these fluctuations in pressure by modifying the nozzle profile and by improving the junction between nozzle and tube. It should be noted, however, that the amplitude of the fluctuations is of the order of 30 centimeters of water or 1/2 pound per square inch, which is about 1/4 percent of the pressure drop through the nozzle. Complete elimination of such small disturbances may prove to be difficult.

In the present state of the data it appears prudent to reject that portion of the test curve where the fluctuations are severe. The friction coefficients calculated from the remainder of the data will be almost unaffected by oblique shocks; however, the length of supersonic flow is so limited that accelerations are large and some change in velocity profile is probably occurring. In view of the uncertainty as regards the effect of this change, the friction coefficients calculated for supersonic flow will be called apparent friction coefficients.

Figures 11 and 12 show the apparent friction coefficient plotted against Mach number and distance along the tube, respectively. The various tests are in agreement within about 5 percent. The curves for tests 5 and 6, which were run before the tube was repolished, lie lower than the others. In tests 5, 6, 7, and 8 moisture was condensing in the approach pipe and was being carried through the nozzle in varying concentrations in the course of the tests. In tests 9 and 10 the air was dried by cooling and reheating it before it reached the nozzle. The data show no change resulting from these precautions.

In figures 11 and 12 are shown the friction coefficients for incompressible flow for Reynolds numbers corresponding to the test conditions. The supersonic values appear to be lower by as much as 25 percent. In figure 11 it appears that, for a Mach number of 1, the curves for supersonic flow and incompressible flow may meet. The friction coefficient for the interval between the last two taps is not included in these charts, because the final tap was in a short piece of tubing which was butted against the end of the test pipe. The factors calculated for this interval are not in accord with the others. The supersonic data are too meager, however, to justify any conclusion concerning Mach numbers near 1.

Figure 13 shows the variation along the length of the tube of mean temperature and Mach number for tests 5 and 6.

The conclusion reached by Frössel to the effect that the friction coefficient is the same at all values of the Mach number for a given value of the Reynolds number has not been confirmed. The published data of Frössel (reference 4) were inadequate to determine the validity of his conclusion; moreover, Frössel's method of computing the friction coefficient from a derivative of a curve of pressure variation left a wide range within which his results could be interpreted.

CONCLUSIONS

For subsonic flow the friction coefficient is the same function of Reynolds number as that given by the von Kármán-Nikuradse equation for incompressible flow and is essentially independent of Mach number. This finding is in accord with the results obtained by Frössel and by Keenan.

The apparent friction coefficient is less for supersonic flow than for incompressible flow for the same Reynolds number. The difference reaches magnitudes of the order of 25 percent. This finding is not in accord with the results obtained by Frössel. It appears that for a given Reynolds number the coefficient of friction increases with decrease in Mach number.

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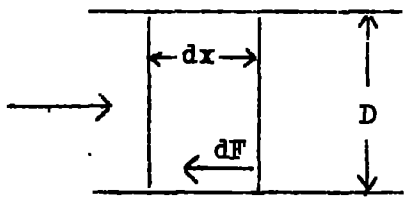
APPENDIX A

METHOD OF ANALYSIS

The analysis that follows, except for certain minor changes to follow the notation of this paper, has been taken verbatim from the appendix of reference 6.

Dynamic Equation for Flow in Pipe of Constant Cross-Sectional Area

Consider an element of fluid which is bounded by two parallel planes transverse to the direction of flow and a distance dx apart. The forces acting on this element may be classified.



as normal forces corresponding to hydrostatic pressures and shearing forces corresponding to wall friction. It can be shown that Newton's Second Law becomes for steady flow

$$-a\,dp - dF = (w/g)\ dV \qquad (1)$$

where a denotes the cross-sectional area of the passage, dp the increase in hydrostatic pressure of the fluid across distance dx, dF the wall friction force applied to the stream between the two planes, w the mass rate of flow, g the acceleration given to unit mass by unit force, and dV the increase in the mean velocity of the stream across dx.

The wall-friction force dF may be expressed in terms of a friction coefficient which is commonly defined by the relation.

$$\lambda = \frac{\tau}{\frac{1}{2}\rho\ V^2}$$

where λ denotes the friction coefficient, τ the friction force per unit of wall surface, and ρ a mass density of the fluid which is otherwise $1/vg$. Then we may write

$$dF = \tau\pi D dx = \lambda V^2 \pi D dx/2vg$$

where D is the pipe diameter and dx is an element of length along the pipe. Substituting this expression for dF in equation (1) dividing through by av and rearranging, we get

$$\frac{dp}{v} + \frac{G}{gv}\, dV + \frac{\lambda}{2}\left(\frac{V}{v}\right)^2 \frac{\pi D}{ag}\, dx = 0$$

where G is w/a. Since G for steady flow is constant along the length of the pipe and equal to V/v, the last equation may be written in the form

$$\frac{dp}{v} + \frac{G^2}{g}\frac{dv}{v} + \frac{2\lambda G^2}{Dg}\, dx = 0 \qquad (2)$$

This is the dynamic equation of flow through a pipe. It may be used to determine the mean friction coefficient between two cross sections as follows:

Assume λ to be constant between sections 1 and 2. Then equation (2) integrates to the expression

$$\int_1^2 \frac{dp}{v} + \frac{G^2}{g}\ln\frac{v_2}{v_1} + \frac{2\lambda G^2}{Dg}(x_2 - x_1) = 0 \qquad (3)$$

which may be solved for λ. In an actual case λ may be interpreted as the mean coefficient of friction. For a numerical solution it is necessary to know not only the dimensions of the pipe and the rate of fluid flow but also the relationship between pressure and specific volume along the path of flow.

The Pressure-Volume Relationship

Let us consider first the adiabatic case, that is, the case in which heat flow to or from the fluid stream is negligible. Then from the first law of thermodynamics we know that for

any section a along the pipe length the sum of the enthalpy and kinetic energy per unit mass of fluid crossing that section is constant and is equal to the enthalpy at a preceding section i, where the cross-sectional area is very large and the kinetic energy is negligible: Thus

$$h + V^2/2g = h_i \tag{4}$$

where h_i denotes the enthalpy at section i and the symbols without subscript denote quantities corresponding to section a. Substituting Gv for V in equation (4) we get

$$h + \frac{G^2 v^2}{2g} = h_i \tag{5}$$

Equation (5) yields a series of relationships between h and v.

Having determined by measurements the initial state i and the mass rate of flow per unit area G of a stream flowing through the pipe, we may determine by equation (5) the h-v relationship.

For a perfect gas

$$h = \frac{k}{k - 1} pv = Bpv \tag{6}$$

where k is the ratio of the specific heats and B is a constant defined by equation (6).

Substituting equation (6) into the Fanno-line equation (5) we got

$$h_i = \frac{G^2 v^2}{2g} + Bpv \tag{7}$$

which, for given values of h_i and G, is a pure pressure-volume relation. Solving equation (7) for p, differentiating, and dividing through by v we get for the first term of equation (2)

$$\frac{dp}{v} = - \frac{G}{2gB} \frac{dv}{v} - \frac{h_i}{B} \frac{dv}{v^3}$$

Friction Coefficient

Substituting the last expression into equation (3) and integrating between sections 1 and 2, we get

$$\frac{G^2}{g}\left(1 - \frac{1}{2B}\right) \ln \frac{v_2}{v_1} + \frac{h_i}{2B}\left(\frac{1}{v_2^2} - \frac{1}{v_1^2}\right) + \frac{2G^2\lambda(x_2 - x_1)}{gD} = 0$$

or

$$\lambda = \frac{gD}{2G^2(x_2 - x_1)}\left[\frac{c_pT_i}{2k}\frac{(k-1)}{}\left(\frac{1}{v_1^2} - \frac{1}{v_2^2}\right) - \frac{G^2}{g}\frac{(k+1)}{2k}\ln\frac{v_2}{v_1}\right] \quad (8)$$

If measurements are made of the initial state, the rate of flow and the pressures at 1 and 2, the values of v_1 and v_2 can be found by solving the quadratic equation (7). The friction coefficient may then be computed from equation (8).

This analysis is oversimplified in that a single velocity V is associated with a given cross section of the stream and this velocity is assumed to be identical with the mean velocity of flow Gv, where v denotes the mean specific volume. It is probable that the friction coefficient so derived may be used to calculate wall friction whenever the section is sufficiently far from the entrance to the tube that variation in that distance will not appreciably alter the pattern of flow if velocity, pressure, and other factors remain unchanged. In subsonic flow such conditions are doubtless attained except in very short tubes; however, in supersonic flow these conditions may not be attained at all because of the rapid change in pressure and velocity along the tubes of even the greatest possible lengths. The friction coefficient so calculated may be called the apparent friction coefficient.

In the present state of knowledge of supersonic flow it is uncertain how closely the product of λ and $\frac{1}{2}(\rho V^2)$ approximates the shear stress τ at the wall of the pipe. It appears probable, however, that, with some exceptions, the apparent friction coefficient will prove adequate for design of passages in supersonic flow. The apparent friction coefficient is at least the analogue of the friction coefficient for incompressible flow and as such its variation with the usual parameters is of interest. The apparent friction coefficient also permits a direct

comparison of the variation of static pressure along the path of flow for various tests. Frössel's tests were reported in terms of this apparent friction coefficient.

The value of the viscosity employed in calculating the Reynolds number N_R and that of the velocity of sound in the Mach number N_M correspond to the mean state of the fluid at any cross section. This mean state is determined from the measured pressure and the specific volume as found by solving equation (7). The viscosity was in turn found from Sutherland's formula, namely, viscosity

$$\text{(in centipoises)} = 0.01709 \; \frac{491.6 + 205.2}{T + 205.2} \left(\frac{T}{491.6}\right)^{3/2}$$

APPENDIX B

ANALYTICAL RELATIONS

Possible Ranges of Subsonic and Supersonic Flow

The relation between length of flow, pressure change, and mean friction coefficient for a stable velocity distribution is shown in figure 14. The curves shown were computed from the relations derived in appendix A.

The region in figure 14 lying below curve C represents conditions of subsonic flow throughout the tube. The region lying above curve A represents conditions of supersonic flow throughout the tube.

Within each of these regions are shown lines of constant ratio of the pressure at the exit of an interval of tube length to the pressure at the entrance. If the Mach number at entrance, the tube diameter, and the tube length between two measured pressures are known, the friction coefficient λ may be found from figure 14. Conversely, for a given value of λ the pressure distribution along the length of a tube may be found for any value of the Mach number at the entrance. The curves of constant pressure ratio in the supersonic region are valid only if no shock occurs in the length of tube to which they are applied.

Curve A shows the maximum length of tube for supersonic flow for each value of the Mach number at the entrance, and curve C shows the corresponding length for subsonic flow. Along each of these curves the Mach number at the tube exit is 1. In the tube corresponding to curve A the Mach number decreases in the direction of flow, whereas in the tube corresponding to curve B the Mach number increases.

Curve A indicates that the length of supersonic flow in a tube may be increased by increasing the Mach number at entrance, which is accomplished by increasing the divergence ratio of the nozzle that feeds the tube. The steepness of the curve at higher Mach numbers shows, however, that in this region large increases in Mach number result in only small increases in the length of flow. A Mach number of infinity at the entrance, which requires an infinite divergence ratio, gives a finite value of $\lambda L/D$, namely, 0.206. If it is assumed from inspection of figure 11 that the mean value of λ is of the order of 0.0025, then the maximum possible value of L/D is 82.2. Only if λ approaches zero as the Mach number approaches infinity will it be possible to obtain infinite or even very large lengths in supersonic flow.

Flow with Shock

The region to the left of curve A may include a shock in the course of flow provided that the pressure in the exhaust space is great enough; on the other hand, the region between curves A and B must include a shock. Along curve B the Mach number, which is less than 1 following the shock, has attained 1 at the exit. Between curves A and B the Mach number is less than 1 at the exit and greater than 1 at the entrance. An interval of length corresponding to this interval may be subdivided into a supersonic interval corresponding to the region above curve A, a subsonic interval corresponding to the region below curve C, and an interval within which the shock occurs. The velocity distribution will not always be stable enough to make the curves of constant pressure ratio applicable.

The region between curves B and C is an imaginary region in which flow with a stable velocity distribution with or without a shock cannot exist.

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TABLE I

TEST 1

[Nozzle A; nozzle throat diam., 0.375 in.; tube diam., 0.375 in.; inlet temperature, 126° F; inlet pressure, 16,179 lb/sq ft abs.; tube length, 10 ft; flow per unit area, 188.2 lb/sec sq ft]

x (ft)	p (lb/sq ft abs.)	$\bar{\lambda}$ (a)	N_M	N_R (b)	T (°F abs.)	V (fps)
-----	[c]4,527.3	-------	----	-------	-----	------
10	4,288	-------	[c]1.00	[c]5.14×10^5	[c]488.3	[c]1083.4
9.75	5,652	0.00313	.824	4.91	516	917.0
9	7,448	.00326	.640	4.74	541	730.4
8	8,879	.00322	.543	4.75	553	625.9
7	9,956	.00323	.485	4.62	560	564.4
6	10,866	.00327	.447	4.58	563	520.8
5	11,682	.00327	.417	4.57	565	486.9
4	12,420	.00328	.392	4.55	569	459.7
3	13,102	.00333	.372	4.54	570	437.2
2	13,751	.00321	.356	4.54	571	417.4
1	14,336	.00386	.342	4.53	572	401.2
0	15,004	------	.326	4.52	574	384.1

[a]Average λ, from x = 1 ft to x = 9.75 ft = 0.003224.
[b]Average N_R from x = 1 ft to x = 9.75 ft. = 4.63×10^5.
[c]From calculated pressure at state of maximum entropy.

TABLE II

TEST 2

[Nozzle A; nozzle throat diam., 0.375 in.; tube diam., 0.375 in.; inlet temperature, 125° F; inlet pressure, 17,607 lb/sq ft abs.; tube length, 10 ft; flow per unit area, 188.0 lb/sec sq ft]

x (ft)	p (lb/sq ft abs.)	$\bar{\lambda}$ (a)	N_M	N_R (b)	T (°F abs.)	V (fps)
10	------	-------	-----	---------	---	-----
9.75	10,355	0.00318	0.466	4.61×10^5	560	543.1
9	10,998	.00326	.440	4.61	562	513.6
8	11,789	.00314	.414	4.61	564	481.8
7	12,491	.00316	.390	4.56	566	455.8
6	13,143	.00322	.370	4.56	567	433.8
5	13,764	.00326	.354	4.56	568	414.9
4	14,352	.00328	.341	4.54	571	399.0
3	14,917	.00326	.328	4.54	572	384.6
2	15,452	.00325	.317	4.54	572+	371.7
1	15,964	.00386	.307	4.52	573	360.3
0	16,546	-------	.296	4.52	574	348.1

[a]Average λ, from $x = 1$ ft to $x = 9.75$ ft $= 0.00322$.

[b]Average N_R from $x = 1$ ft to $x = 9.75$ ft. $= 4.55 \times 10^5$.

TABLE III

TEST 3

[Nozzle A; nozzle throat diam., 0.375 in.; tube diam., 0.375 in.; inlet temperature, 126° F; inlet pressure, 7,422.1 lb/sq ft abs.; tube length, 10 ft; flow per unit area, 82.77 lb/sec sq ft]

x (ft)	p (lb/sq ft abs.)	$\bar{\lambda}$ (a)	N_M	N_R (b)	T (°F abs.)	V (fps)
10	2008.1	-------	-----	---------	431	1057.1
9.75	2561.3	0.00386	0.790	2.19×10^5	506	873.5
9	3391.1	.00386	.790	2.11	530	690.6
8	4052.2	.00384	.790	2.11	542	589.8
7	4558.4	.00380	.790	2.11	547	529.7
6	4987.1	.00385	.790	2.11	550	487.4
5	5368.4	.00387	.393	2.05	552	454.8
4	5717.3	.00389	.393	2.05	554	428.5
3	6040.9	.00392	.393	2.05	555	406.8
2	6342.4	.00385	.393	2.05	557	388.3
1	6624.6	.00448	.393	2.03	559	372.4
0	6934.3	-------	.307	2.03	559.4	356.4

[a]Average λ, from $x = 1$ ft to $x = 9.75$ ft $= 0.00386$.

[b]Average N_R from $x = 1$ ft to $x = 9.75$ ft $= 2.069 \times 10^5$.

TABLE IV

TEST 4

[Nozzle A; nozzle throat diam., 0.375 in.; tube diam., 0.375 in.; inlet temperature, 126° F; inlet pressure, 4,146.5 lb/sq ft abs.; tube length, 10 ft; flow per unit area, 42.01 lb/sec sq ft]

x (ft)	p (lb/sq ft abs.)	$\bar{\lambda}$ (a)	N_M	N_R (b)	T (°F abs.)	V (fps)
10	------	-------	------	----------	---	------
9.75	2150.3	--------	0.485	1.082×10^5	523	545.4
9	2357.3	0.00456	.485	1.082	523	501.2
8	2595.5	.00455	.485	1.082	523	458.2
7	2807.4	.00459	.485	1.082	523	425.4
6	2999.3	.00459	.485	1.082	523	399.7
5	3176.3	.00459	.333	1.067	536	378.2
4	3341.2	.00459	.333	1.067	536	360.6
3	3493.7	.0049	.333	1.067	536	345.3
2	3640.0	.00459	.333	1.067	536	331.9
1	3778.2	.00451	.333	1.067	536	320.2
0	3930.1	.00515	.269	1.061	540	308.0

[a]Average λ, from $x = 1$ ft to $x = 9.75$ ft. = 0.00456.

[b]Average N_R from $x = 1$ ft to $x = 9.75$ ft. = 1.067×10^5.

TABLE V

SUPERSONIC DATA

Throat diam. of nozzle B, 0.169 in.; throat diam. of nozzle C, 0.175 in.; tube diam., 0.4375 in.

Run	Inlet pressure (lb/sq in. abs.)	Inlet temp. (°F)	Nozzle	Flow per unit area (lb/sec sq ft)
[a]5	200.9	135	B	93.3
6	200.9	135	B	93.3
[b]7	201.2	130	B	93.9
8	200.0	126	B	
[c]9	194.3	87	C	100.9
10	194.1	88	C	

[a]Runs 5 and 6 were combined. Calculations were made based on pressure-distance curves, fig. 9. Mean friction coefficients were calculated for 2-inch lengths.

[b]Same calculation procedure as runs 5 and 6. See pressure-distance curve, fig. 9.

[c]Same calculation procedure as runs 5 and 6. See pressure-distance curve, fig. 10. Between compressor and nozzle the air is first cooled and then heated. Additional pressure taps were added for run 10.

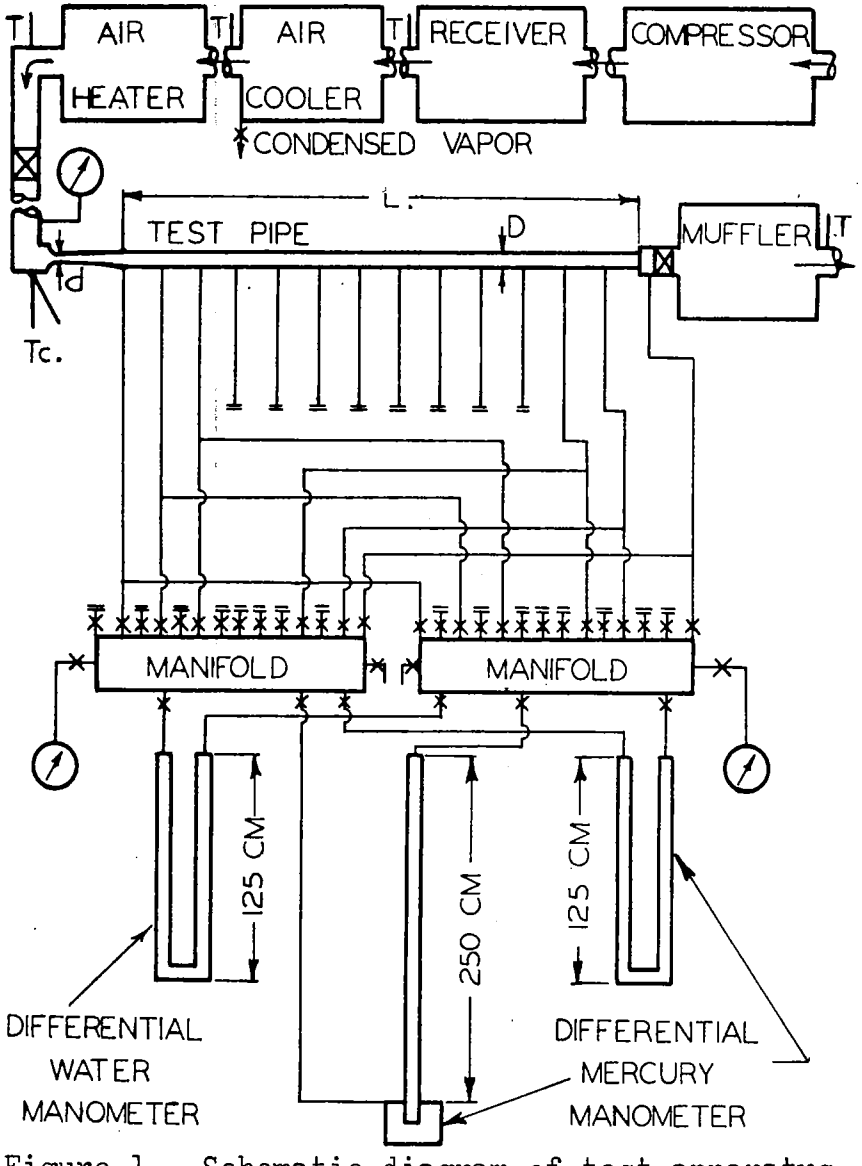

Figure 1.- Schematic diagram of test apparatus.

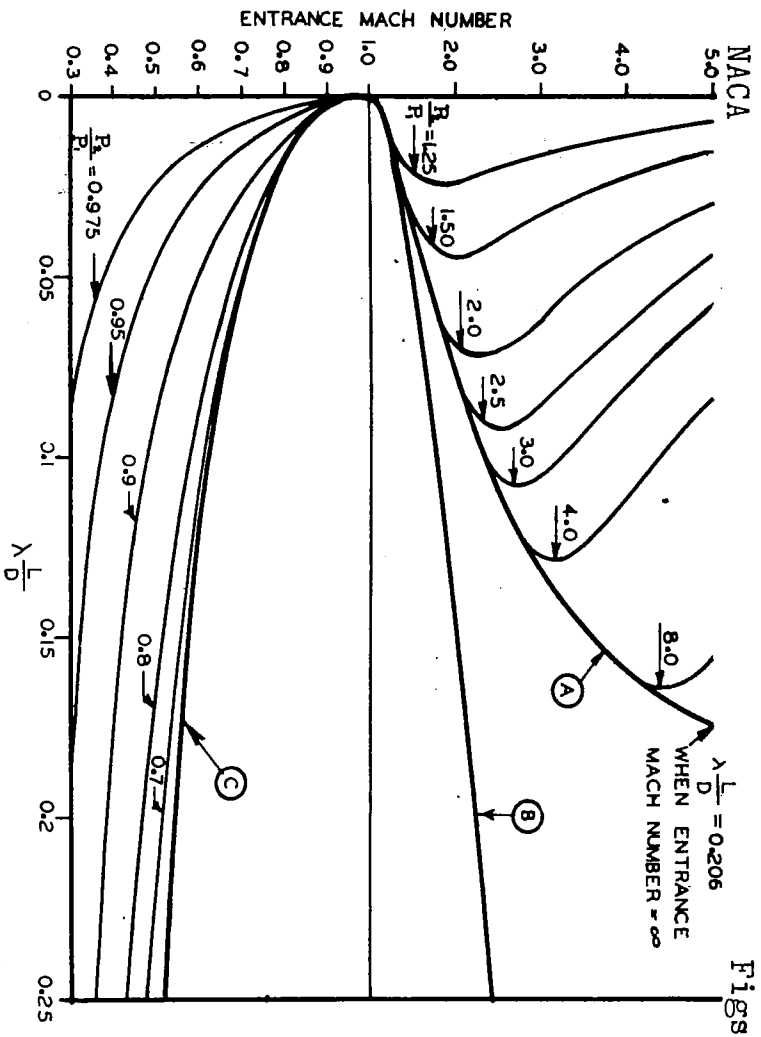

Figure 14.- Entrance Mach number against λL/D.

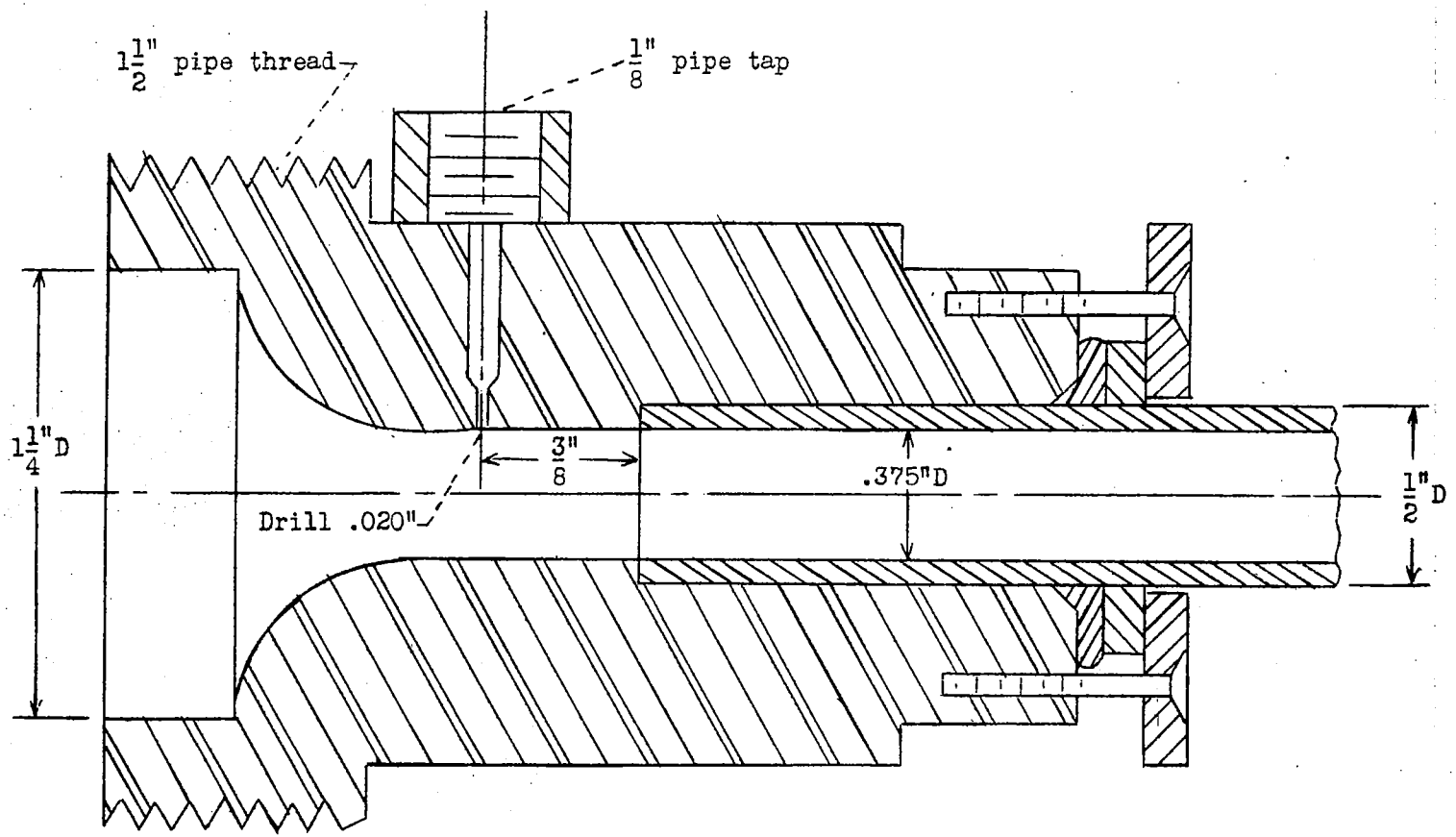

Figure 2.- Inlet to test pipe, nozzle A.

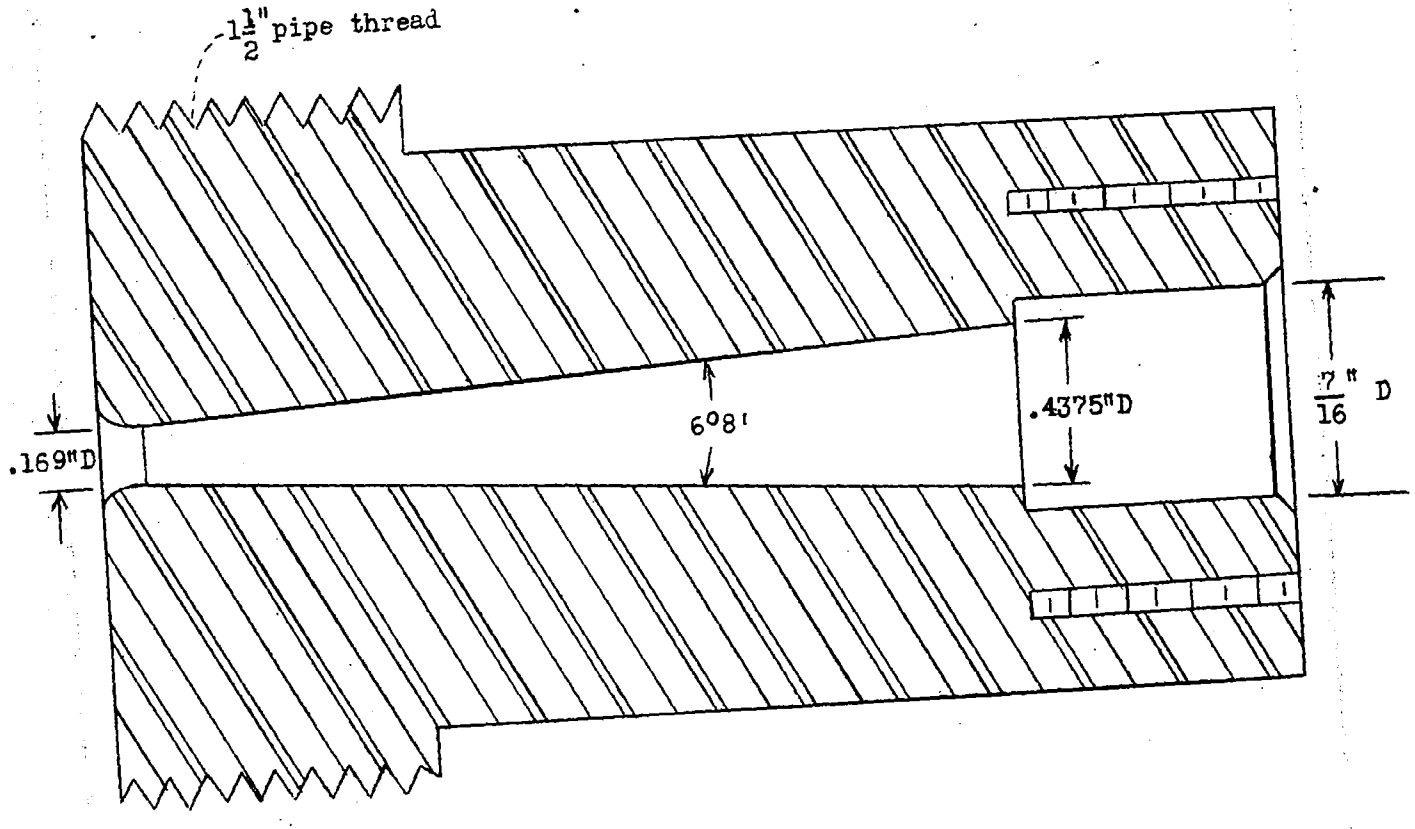

Figure 3.- Inlet to test pipe, nozzle B.

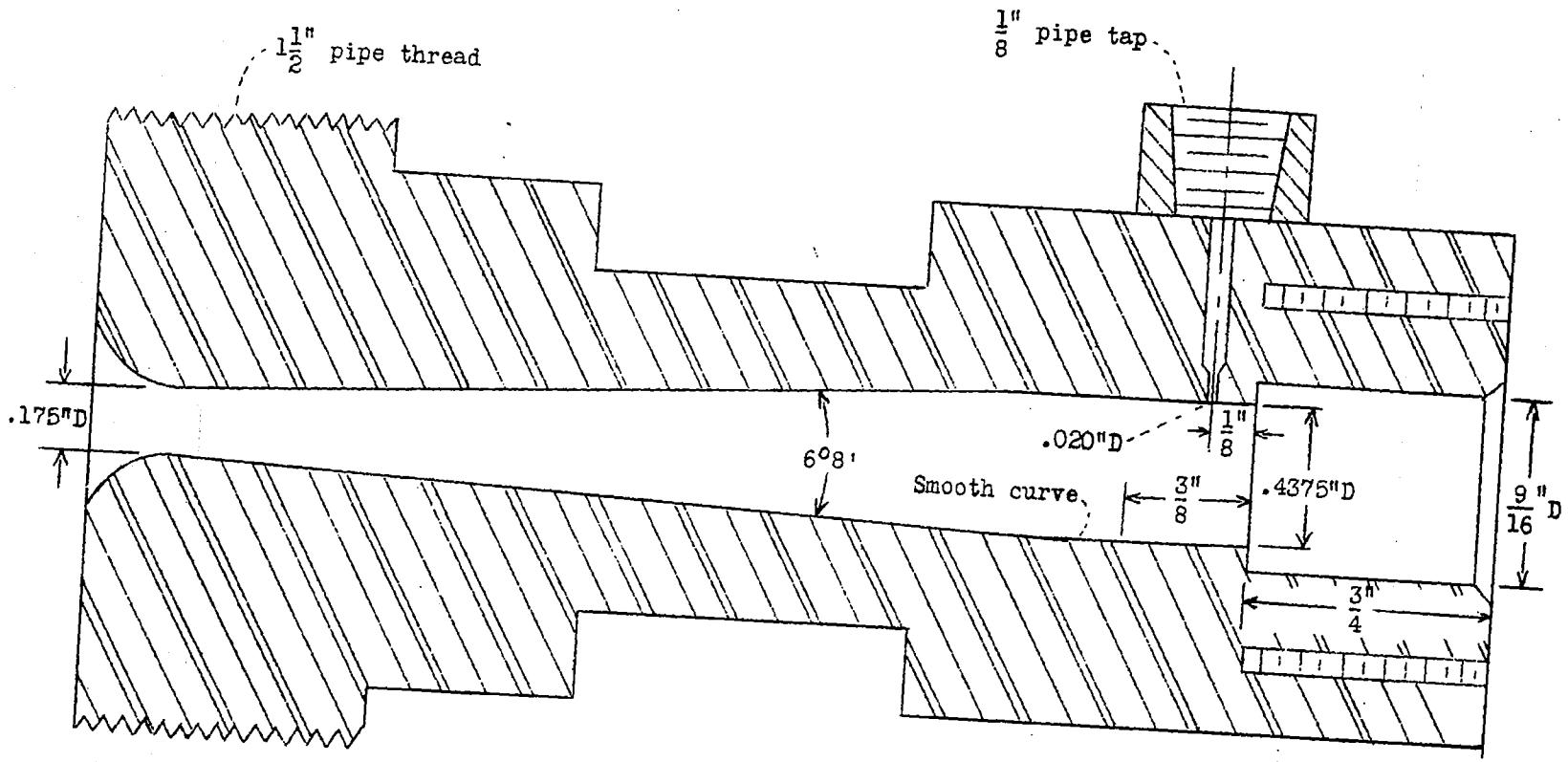

Figure 4.- Inlet to test pipe, nozzle C.

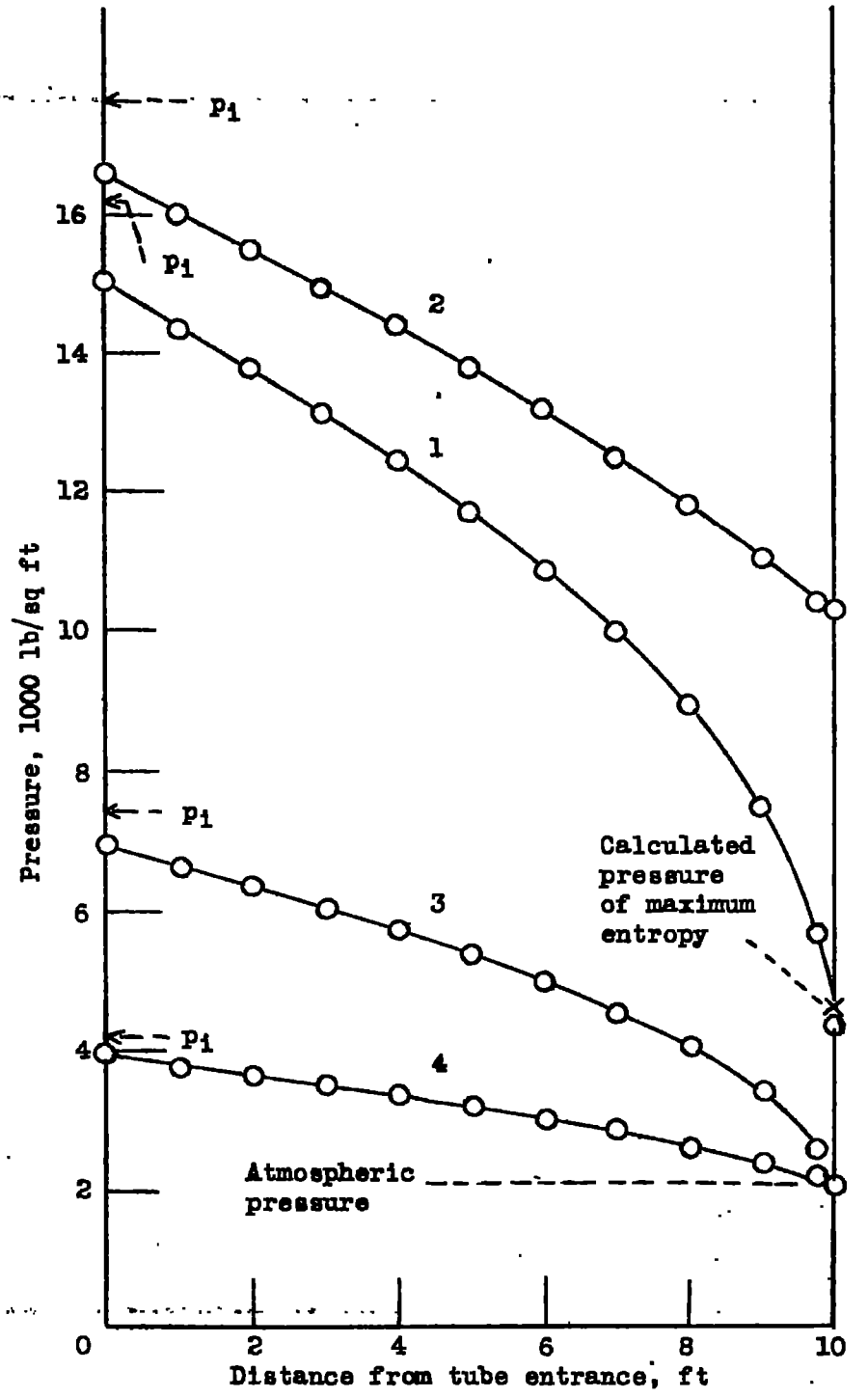

Figure 5.- Pressure distribution along the test pipe for subsonic flow.

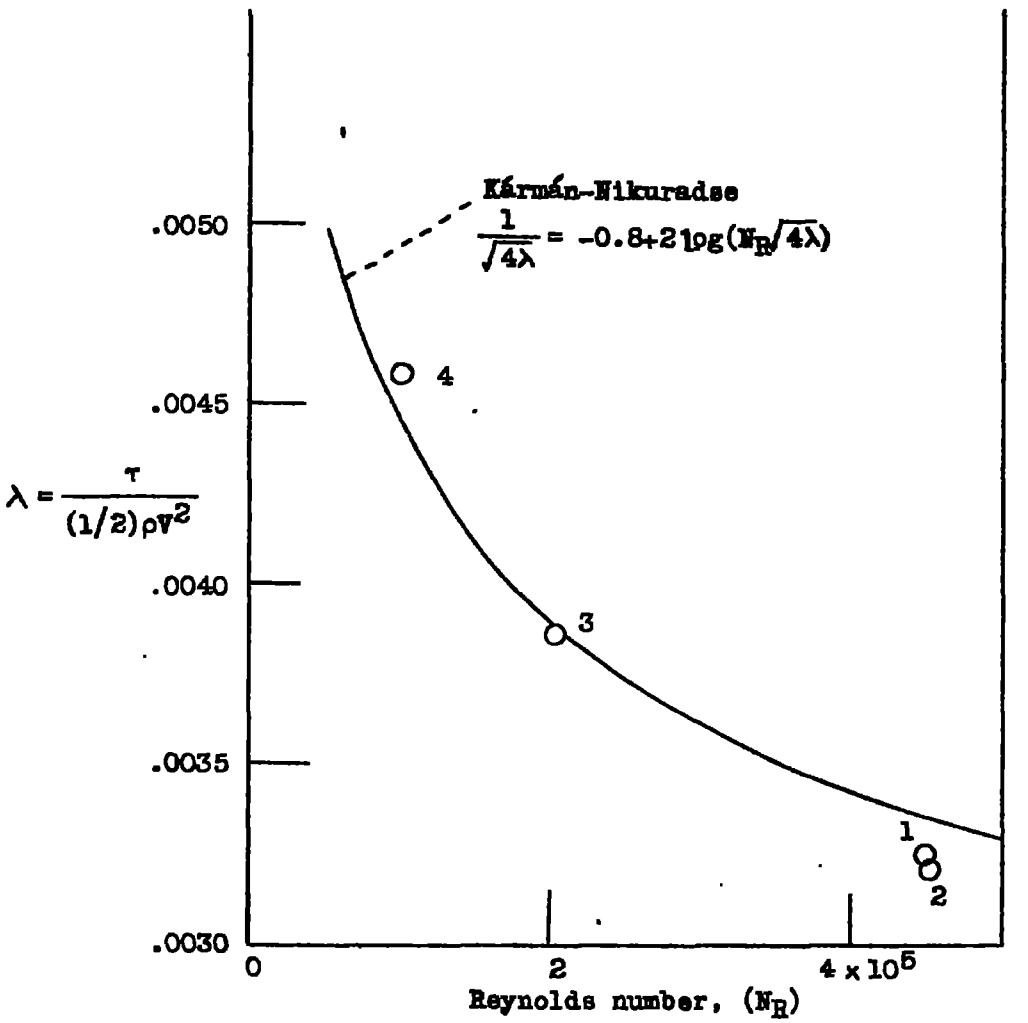

Figure 6.- Friction coefficients for subsonic flow compared with those for incompressible flow. τ = friction force per unit of wall surface; ρ = mass density.

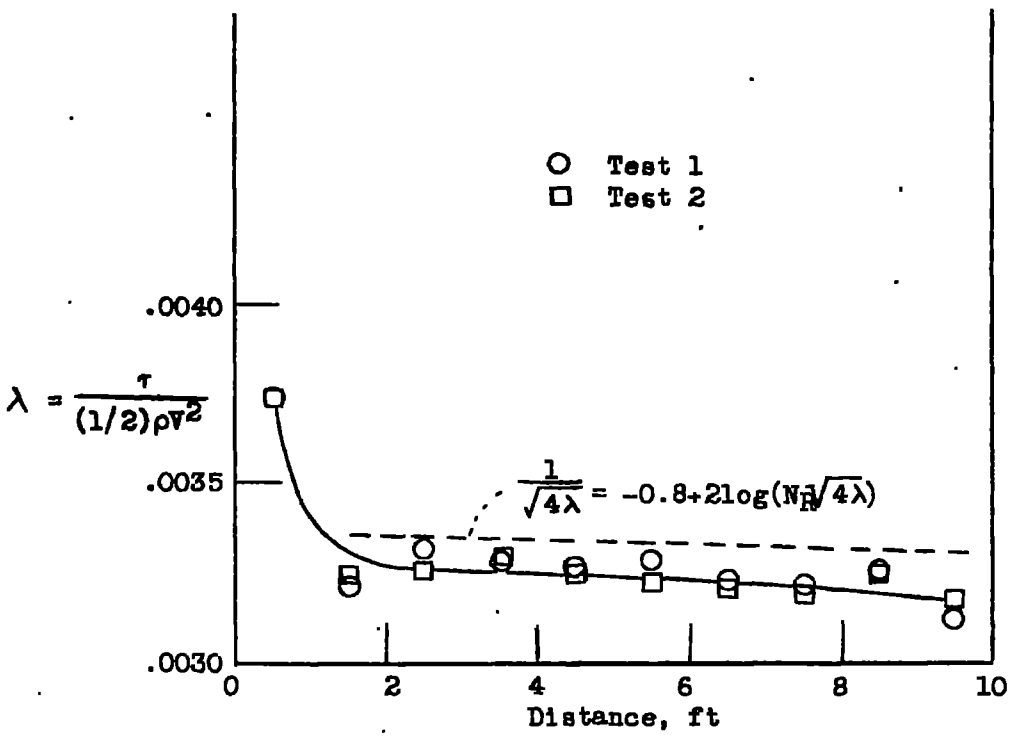

Figure 7.- Friction coefficient against distance along pipe for subsonic flow.

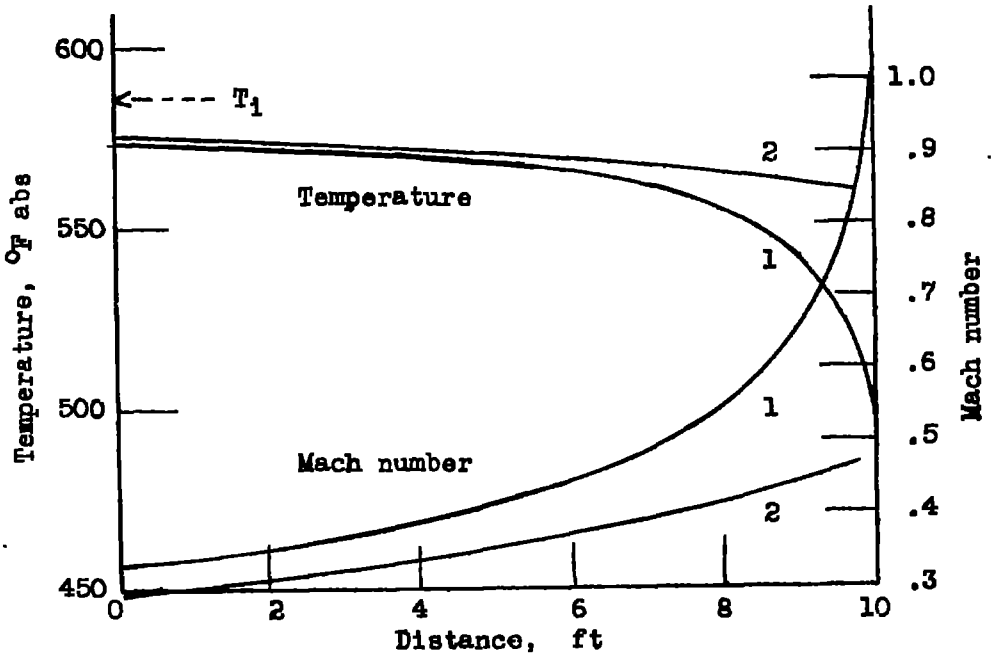

Figure 8.- Temperature and Mach number against distance along pipe for subsonic flow.

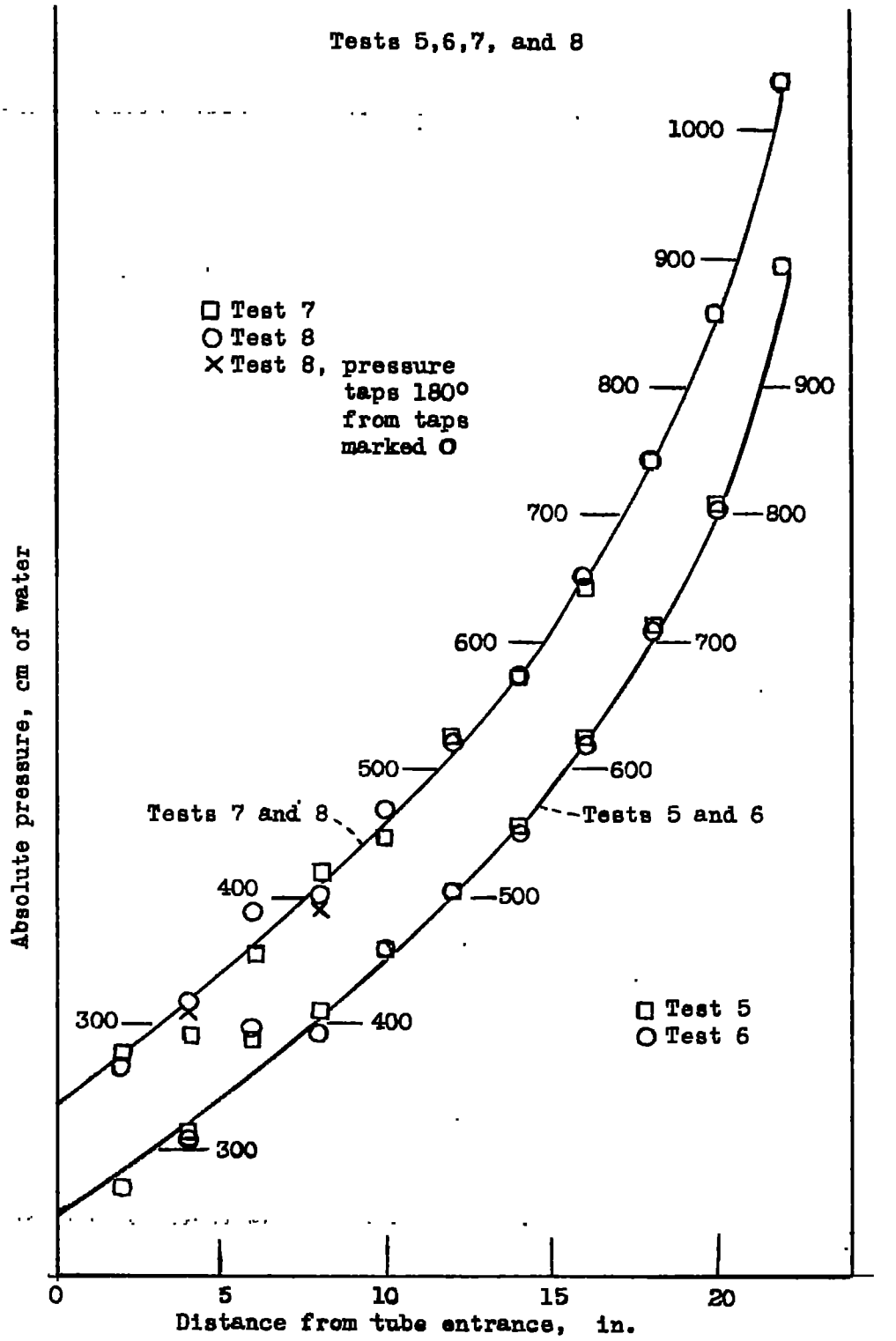

Figure 9.- Pressure against distance along pipe for supersonic flow.

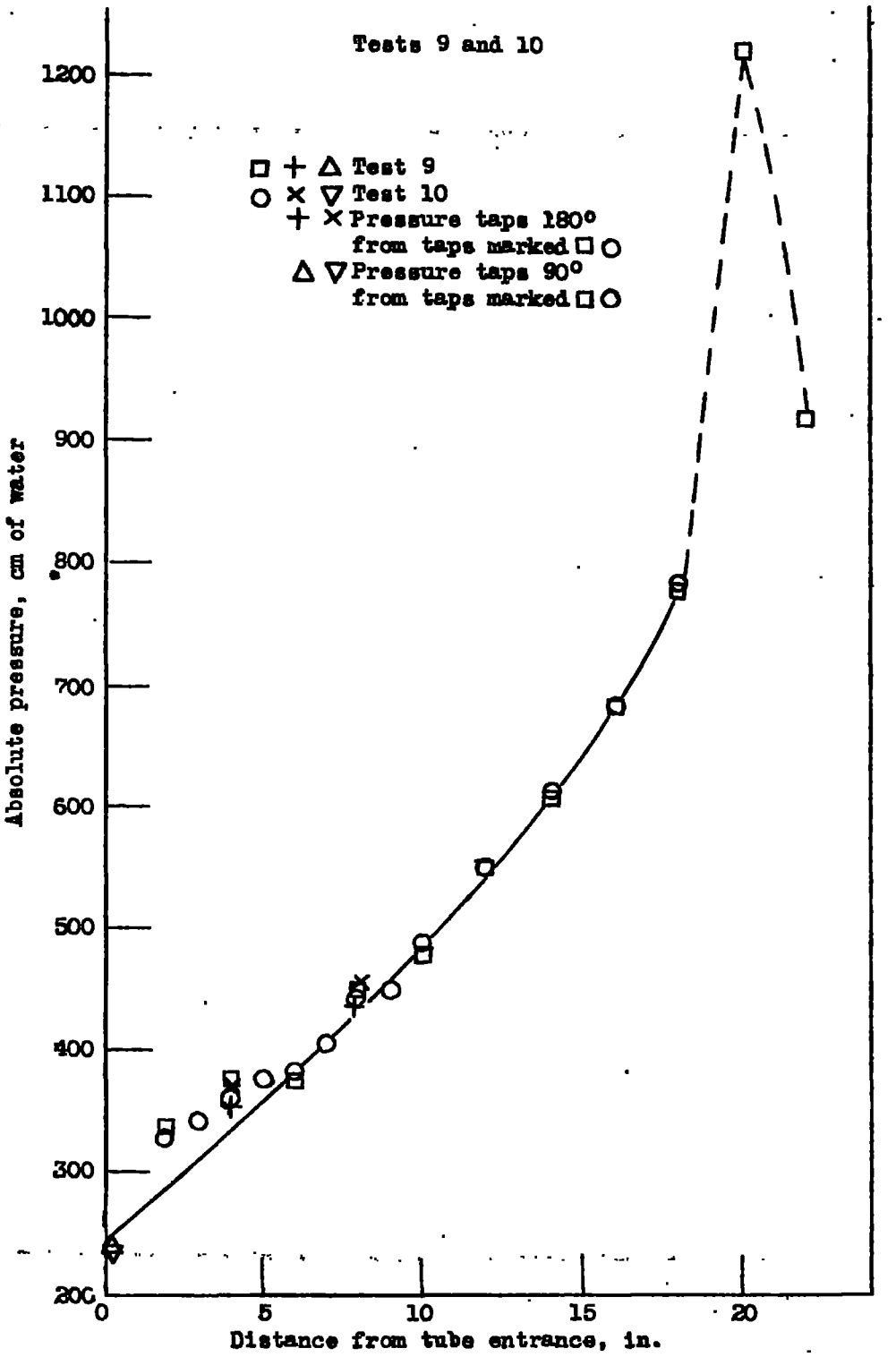

Figure 10.- Pressure against distance along pipe for supersonic flow.

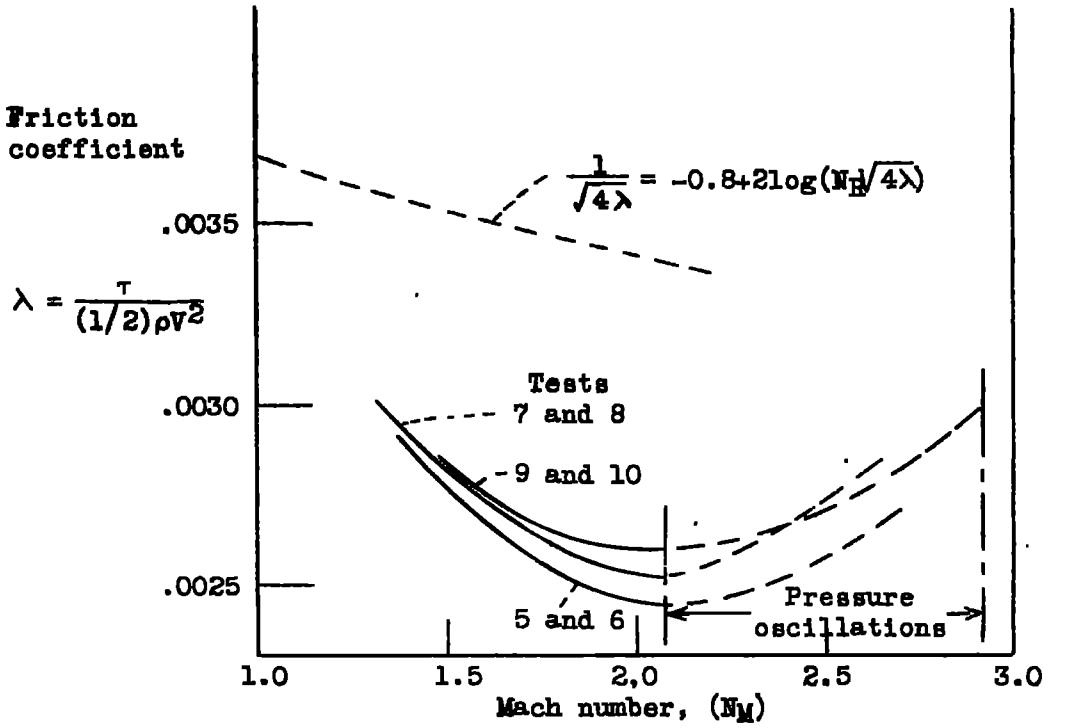

Figure 11.- Friction coefficients for supersonic flow against Mach number.

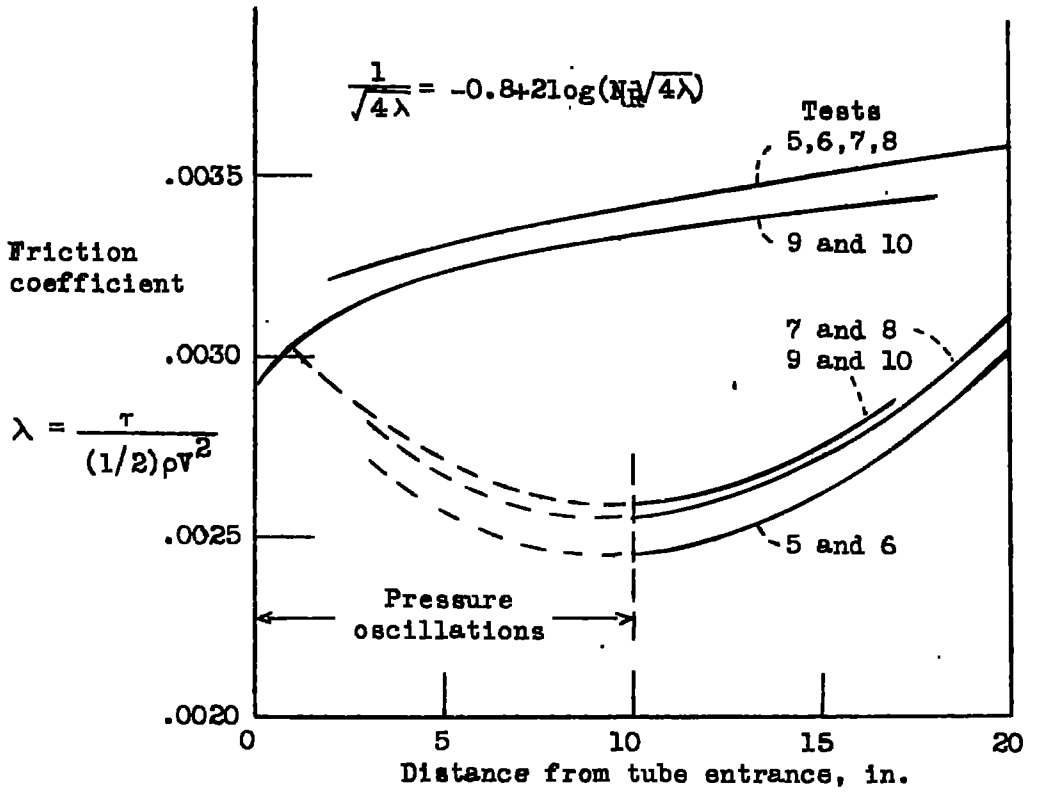

Figure 12.- Friction coefficients for supersonic flow against distance along pipe.

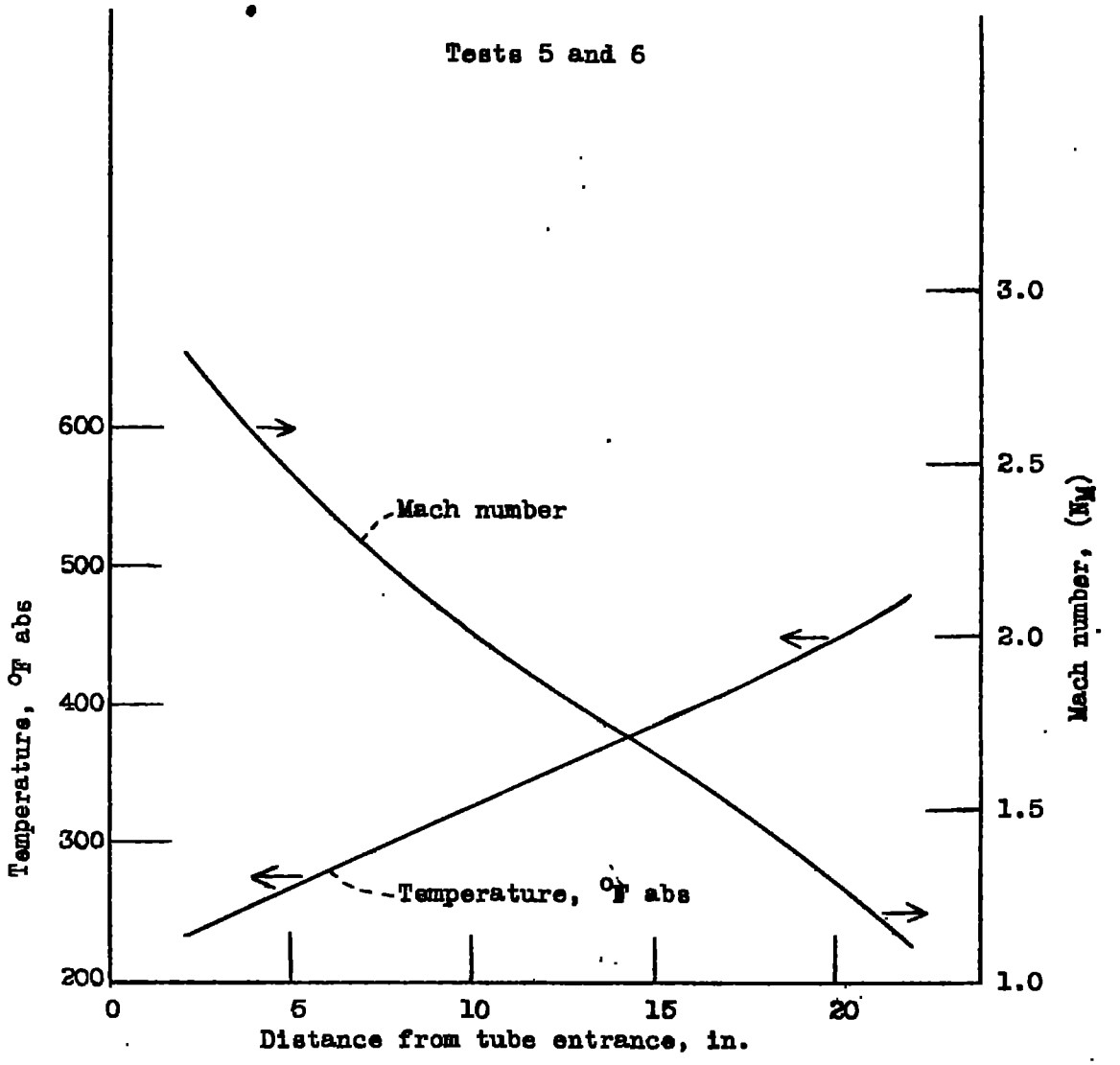

Figure 13.- Temperature and Mach number against distance along pipe for supersonic flow.

TITLE: Measurements of Friction Coefficients in a Pipe for Subsonic and Supersonic Flow of Air

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Supersonic Flow P1/3
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