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AN EXTENSION OF ESTIMATED HYPERSONIC FLOW PARAMETERS FOR HELIUM AS A REAL GAS

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SUMMARY

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The various hypersonic flow parameters for helium have been estimated by use of the Beattie-Bridgeman equation of state for helium at stagnation pressures up to 50,000 lb/sq in. abs and stagnation temperatures up to 10,000° F. Calculations were limited to densities below the critical density. The results were obtained to establish reasonable estimates of the departure from ideal-gas behavior over a broad practical range of stagnation pressure and temperature at Mach numbers up to 100. The results are presented as correction factors which are to be applied to ideal-gas parameters for a specific-heat ratio of 5/3.

INTRODUCTION

Hypersonic helium tunnels have been used to study fluid dynamic problems for a number of years. Most of this work has been carried out at Mach numbers in the neighborhood of 20 with stagnation temperatures not much different from room temperature and stagnation pressures up to about 3,000 lb/sq in. abs. For these stagnation conditions, there can be appreciable errors in the determination of the various flow parameters when based on the ideal-gas parameters for a specific-heat ratio of 5/3 because of deviations from ideal-gas behavior at the higher densities. For example, results of calculations presented in reference 1, which are based on the thermodynamic properties of helium reported in reference 2, indicate that the free-stream temperature, pressure, and density are approximately 5, 9, and 15 percent greater, respectively, than the ideal-gas values for a specific-heat ratio of 5/3 when the stagnation temperature is 80° F and the stagnation pressure is 3,000 lb/sq in. abs. At the same temperature but higher stagnation pressures, the errors are even greater.

Reference 1 presents the results of calculations as correction factors which must be applied to the tabulated ideal-gas parameters for a specific-heat ratio of 5/3. The ideal-gas parameters for helium which must be used in conjunction with these correction terms are presented in reference 3 for Mach numbers up to 40 and in reference 4 for Mach numbers from 40 to 100.

The thermodynamic data for helium presented in reference 2, which were used in calculating the correction factors in reference 1, are limited to the pressure range of 14.7 to 6,000 lb/sq in. abs and temperatures up to 600° F. Likewise, the correction terms of reference 1 are limited to stagnation pressures up to 6,000 lb/sq in. abs and temperatures up to 600° F.

It appears possible to operate a hotshot-type tunnel, with an appropriate arc chamber, with helium as the test gas at Mach numbers of 60 or so at stagnation pressures as high as 50,000 lb/sq in. abs over a broad range of stagnation temperatures. In addition to this approach to obtaining higher Mach number flows in helium, work at the Langley Research Center is in progress to develop a conventional Mach 40 helium blowdown tunnel capable of operating at stagnation pressures up to 15,000 lb/sq in. abs with a stagnation temperature of about 600° F.

Because of the limited pressure and temperature ranges of the available thermodynamic properties of helium, the correction terms presented in reference 1 fall short of the stagnation conditions for operating the previously mentioned facilities. It is the purpose of this present work to obtain reasonable estimates of the correction terms for the hypersonic flow parameters for helium at stagnation temperatures up to 10,000° F and pressures up to 50,000 lb/sq in. abs at Mach numbers up to 100 or that limited by equilibrium condensation of helium.

SYMBOLS

a velocity of sound

a', A_o, b, B_o, C constants in equation (1)

c_p specific heat at constant pressure

c_v specific heat at constant volume

c_v^* specific heat at constant volume for ideal-gas conditions

F correction factor (The correction factor is a particular flow parameter calculated by dividing the real-gas value by the ideal-gas value for $\gamma = 5/3$ at the same M_1. For example, $F_{p,1} = p_1/p_{1,i}$ where both p_1 and $p_{1,i}$ are evaluated at the same M_1.)

h specific enthalpy

M Mach number

p pressure

q dynamic pressure

R gas constant

s	specific entropy
T	temperature
V	velocity
W	limiting velocity ratio
Z	compressibility factor
γ	ratio of specific heats
ρ	density

Subscripts:

c	conditions for equilibrium condensation
i	based on ideal gas and $\gamma = 5/3$
t,1	stagnation conditions upstream of shock
t,2	stagnation conditions downstream of shock
1	free-stream conditions upstream of shock
2	free-stream conditions just downstream of shock

THERMODYNAMIC RELATIONS

Equation of State

The thermodynamic properties of helium presented in reference 2 include pressures up to 6,000 lb/sq in. abs and temperatures up to 600° F. For the most part, these data are based on the Beattie-Bridgeman equation of state. In order to calculate the desired flow parameters for stagnation conditions beyond this limited range, the thermodynamic properties of helium must be extended. In the present work the Beattie-Bridgeman equation with appropriate constants for helium was assumed to be an adequate representation of the equation of state for helium. It should be emphasized that results obtained by the employment of this equation are to be treated only as first-order estimates since the constants of the equation are determined for a rather limited range. This equation is not reliable above the critical density so it was necessary to restrict the use of it to densities below the critical density. The critical density of helium is 4.3 lb/cu ft. The Beattie-Bridgeman equation is

$$p = RT(1 - e)(1 + B\rho)\rho - A\rho^2 \tag{1}$$

where $A = A_o(1 - a'\rho)$; $B = B_o(1 - b\rho)$; $e = C\rho/T^3$. The value of the constant b

for helium is zero so that equation (1) can be rewritten in terms of the constants a', A_o, B_o, and C. Thus,

$$p = A_o\rho^2(a'\rho - 1) + R\rho(B_o\rho + 1)T - RC\rho^2(B_o\rho + 1)\frac{1}{T^2} \tag{2}$$

This equation is used in conjunction with various thermodynamic relations to find the expressions for enthalpy, entropy, and velocity of sound, each as a function of density and temperature.

Enthalpy

The expression for enthalpy is found by beginning with the relation,

$$dh = \left(\frac{\partial h}{\partial T}\right)_\rho dT + \left(\frac{\partial h}{\partial \rho}\right)_T d\rho \tag{3}$$

From the definition of enthalpy and c_v, the first term on the right-hand side of this equation can be written as

$$\left(\frac{\partial h}{\partial T}\right)_\rho = c_v + \frac{1}{\rho}\left(\frac{\partial p}{\partial T}\right)_\rho \tag{4}$$

The second term of equation (3) can be written as a function of T, p, and ρ by introducing the equation,

$$dh = T\ ds + \frac{1}{\rho}\ dp \tag{5}$$

which can be rewritten as

$$\left(\frac{\partial h}{\partial \rho}\right)_T = T\left(\frac{\partial s}{\partial \rho}\right)_T + \frac{1}{\rho}\left(\frac{\partial p}{\partial \rho}\right)_T \tag{6}$$

and by using the Maxwell relation,

$$\left(\frac{\partial s}{\partial \rho}\right)_T = \frac{-1}{\rho^2}\left(\frac{\partial p}{\partial T}\right)_\rho \tag{7}$$

Thus,

$$\left(\frac{\partial h}{\partial \rho}\right)_T = \frac{-T}{\rho^2}\left(\frac{\partial p}{\partial T}\right)_\rho + \frac{1}{\rho}\left(\frac{\partial p}{\partial \rho}\right)_T \tag{8}$$

Since h is a point function, equation (3) may be integrated over a two-step path by first holding ρ constant and integrating with respect to T and then by holding T constant and integrating with respect to ρ. Before this integration is performed, p is eliminated from equations (4) and (8) by use of equation (2). By direct differentiation of equation (2),

$$\left(\frac{\partial p}{\partial T}\right)_\rho = R\rho\left(B_o\rho + 1\right) + 2RC\rho^2\left(B_o\rho + 1\right)\frac{1}{T^3} \tag{9}$$

and

$$\left(\frac{\partial p}{\partial \rho}\right)_T = RT + 2\left(RB_oT - \frac{RC}{T^2} - A_o\right)\rho + 3\left(A_oa' - \frac{RB_oC}{T^2}\right)\rho^2 \tag{10}$$

These two equations are then used in equations (4) and (8). The density level chosen for the integration along the constant density path from a reference temperature to a desired temperature can be made as small as desired so that c_v in equation (4) can be replaced by c_v^*, which is the value of c_v as $\rho \to 0$ and is equal to a constant of $(3/2)R$. The second integration is carried out along the path of constant desired temperature from this very low reference density up to the desired density. Since the reference value of the enthalpy is an arbitrary constant, it can be set equal to zero at the reference conditions. Upon integration, the expression for enthalpy as a function of ρ and T becomes,

$$h = \left(c_v^* + R\right)T - \left(2A_o - RB_oT + 4\frac{RC}{T^2}\right)\rho - \frac{1}{2}\left(5\frac{RB_oC}{T^2} - 3A_oa'\right)\rho^2 \tag{11}$$

Entropy

The expression for entropy as a function of T and ρ is found by beginning with the relation,

$$ds = \left(\frac{\partial s}{\partial T}\right)_\rho dT + \left(\frac{\partial s}{\partial \rho}\right)_T d\rho \tag{12}$$

The first term on the right-hand side of this equation can be written as

$$\left(\frac{\partial s}{\partial T}\right)_\rho = \frac{c_v}{T} \tag{13}$$

and the second term is given by equation (7). Upon substitution of equations (7) and (13) into equation (12) and integrating over the same two paths for which the enthalpy was determined and setting the value of entropy equal to zero at the reference conditions, the expression for entropy as a function of T and ρ is

$$s = c_v^* \log_e T - R\left[\log_e \rho + \left(B_o + \frac{2C}{T^3}\right)\rho + \frac{B_oC}{T^3}\rho^2\right] \tag{14}$$

Velocity of Sound

The expression for the velocity of sound is found by beginning with the relations,

$$a^2 = \left(\frac{\partial p}{\partial \rho}\right)_s = \gamma\left(\frac{\partial p}{\partial \rho}\right)_T \tag{15}$$

$$c_p - c_v = \frac{-T}{\rho^2}\left(\frac{\partial p}{\partial T}\right)_\rho\left(\frac{\partial \rho}{\partial T}\right)_p \tag{16}$$

and

$$\left(\frac{\partial p}{\partial \rho}\right)_T = -\left(\frac{\partial p}{\partial T}\right)_\rho\left(\frac{\partial T}{\partial \rho}\right)_p \tag{17}$$

Equation (16) is divided by c_v and multiplied by the quantity $\left(\frac{\partial p}{\partial \rho}\right)_T$ according to equation (17). Then to this resulting equation, the quantity $\left(\frac{\partial p}{\partial \rho}\right)_T$ is added to give the desired equivalent of equation (15),

$$a^2 = \left(\frac{\partial p}{\partial \rho}\right)_T + \frac{T}{\rho^2 c_v}\left(\frac{\partial p}{\partial T}\right)_\rho^{2} \tag{18}$$

The two quantities, $\left(\frac{\partial p}{\partial T}\right)_\rho$ and $\left(\frac{\partial p}{\partial \rho}\right)_T$, are given by equations (9) and (10), respectively. The expression for c_v at a given temperature can be determined at a desired density ρ from the equation,

$$c_v = c_v{*} + \int_0^\rho \left(\frac{\partial c_v}{\partial \rho}\right)_T d\rho \tag{19}$$

where $c_v{*}$ is the heat capacity at constant volume for the condition of $\rho \to 0$. The integrand of equation (19) is replaced by the relation,

$$\left(\frac{\partial c_v}{\partial \rho}\right)_T = -\frac{T}{\rho^2}\left(\frac{\partial^2 p}{\partial T^2}\right)_\rho \tag{20}$$

and by differentiation of equation (9),

$$\left(\frac{\partial^2 p}{\partial T^2}\right)_\rho = -6RC_\rho{}^2\left(B_o\rho + 1\right)\frac{1}{T^4} \tag{21}$$

The integration of equation (19) with the substitution of equation (21) yields

$$c_v = c_v{}^* + 3\frac{RC}{T^3}\rho\left(B_o\rho + 2\right) \tag{22}$$

which is used to evaluate c_v in equation (18). As shown in the next section, these thermodynamic relations are used to determine the various flow parameters for helium for a number of stagnation conditions and Mach numbers.

CALCULATION OF FLOW PARAMETERS

The foregoing derived relations for enthalpy, entropy, and velocity of sound, along with the equation of state, are used to calculate the various flow parameters. The numerical results for a range of stagnation conditions and Mach numbers were obtained with an IBM 7090 electronic data processing system. In this section the method of computation is discussed.

The first step of the calculation scheme is to establish the stagnation conditions by specifying the stagnation temperature $T_{t,1}$ and stagnation density $\rho_{t,1}$. The stagnation pressure $p_{t,1}$, stagnation enthalpy $h_{t,1}$, and stagnation entropy $s_{t,1}$ are then calculated by application of equations (2), (11), and (14), respectively.

Free-Stream Conditions

Various free-stream conditions are determined for an arbitrary set of stagnation conditions by choosing a series of free-stream temperatures T_1, which are successively less than $T_{t,1}$. For each value of T_1, the value of the free-stream density ρ_1 is determined for an isentropic expansion from the stagnation condition by setting s in equation (14) equal to $s_{t,1}$ and T equal to T_1 and iterating for ρ_1. After ρ_1 is determined for a given value of T_1, equations (2) and (11) can be used to find p_1 and h_1. The corresponding velocity of sound is determined from equation (18) with use of equations (9), (10), and (22). The free-stream velocity is then determined from the energy equation,

$$V_1 = \sqrt{2\left(h_{t,1} - h_1\right)} \tag{23}$$

and the free-stream Mach number M_1 is simply found by dividing V_1 by a_1. To this point, for a specific stagnation condition, T_1, p_1, ρ_1, V_1, and M_1 are determined. A number of values for T_1 can be taken to find these same parameters for a range of M_1.

Conditions Just Downstream of Normal Shock

The conservation relations for mass, momentum, and energy are

$$\rho_1 V_1 = \rho_2 V_2 \tag{24}$$

$$p_1 + \rho_1 V_1^2 = p_2 + \rho_2 V_2^2 \tag{25}$$

and

$$h_{t,1} = h_1 + \frac{1}{2} V_1^2 = h_2 + \frac{1}{2} V_2^2 \tag{26}$$

and are used in conjunction with equations (2) and (11) to determine the conditions just downstream of the normal shock. This determination is accomplished by eliminating V_2 from equations (24) to (26) and replacing p_2 by equation (2) and h_2 by equation (11) followed by a double iteration for ρ_2 and T_2. Once ρ_2 and T_2 are determined, p_2 is calculated from equation (2), h_2 from equation (11), s_2 from equation (14), V_2 from equation (23), and a_2 from equation (18).

Stagnation Conditions Downstream of Normal Shock

The stagnation conditions downstream of a normal shock must satisfy two conditions, $s_{t,2} = s_2$ and $h_{t,2} = h_{t,1}$. Since s_2 and $h_{t,1}$ have been calculated for a given stagnation condition and free-stream condition, $s_{t,2}$ and $h_{t,2}$ are known. The simultaneous solution of equations (11) and (14) by double iteration determined $\rho_{t,2}$ and $T_{t,2}$. The value of $p_{t,2}$ is then determined from equation (2).

The various flow parameters are therefore determined for a number of combinations of stagnation conditions and Mach numbers based on the Beattie-Bridgeman equation for helium. The constants used in this work which appear in the Beattie-Bridgeman equation, according to reference 2, are

$$a' = 0.23963 \frac{ft^3}{lb_m}$$

$$A_o = 5.0906 \left(\frac{ft^3}{lb_m}\right)^2 \frac{lb_f}{in.^2}$$

$$B_o = 0.056063 \frac{ft^3}{lb_m}$$

$$C = 934.17 \frac{ft^3}{lb_m} \, {}^oR^3$$

$$R = 2.6829 \frac{\left(ft^3/lb_m\right)\left(lb_f/in.^2\right)}{{}^oR}$$

where the subscripts m and f indicate mass and force, respectively.

In these calculations the various parameters were made nondimensional by dividing by an appropriate reference condition. The following parameters were obtained for a number of stagnation conditions and various values of M_1: $T_1/T_{t,1}$, $p_1/p_{t,1}$, $\rho_1/\rho_{t,1}$, $q_1/p_{t,1}$, W_1, T_2/T_1, p_2/p_1, ρ_2/ρ_1, M_2, $T_{t,2}/T_{t,1}$, $p_{t,2}/p_{t,1}$, and $\rho_{t,2}/\rho_{t,1}$. For ease of presentation, these parameters were divided by the corresponding ideal-gas parameter with $\gamma = 5/3$ for the same value of M_1 to give the correction factors. For example, the correction factor for the free-stream temperature, $F_{T,1}$, is $\left(T_1/T_{t,1}\right)/\left(T_1/T_{t,1}\right)_i$ or $T_1/T_{1,i}$ for a given value of M_1.

Vapor-Pressure Curve for Helium

In order to calculate the maximum Mach number which can be obtained from an equilibrium isentropic expansion in helium without helium condensation, the vapor-pressure relation presented in reference 5 is used. For $T_c > 3.942^o$ R

$$\log_{10} p_c = -\frac{5.4432}{T_c} + 2.208 \log_{10} T_c - 0.06027 \tag{27a}$$

and for $T_c < 3.942^o$ R

$$\log_{10} p_c = -\frac{6.9462}{T_c} + 0.922 \log_{10} T_c + 1.0860 \tag{27b}$$

where T_c is the temperature at which helium just condenses when the pressure for equilibrium conditions is p_c. This relation is applied to find the Mach number at which helium condensation just occurs for equilibrium flow for a given set of stagnation conditions by first calculating the free-stream pressure p_1 and Mach number M_1 for a particular value of the free-stream temperature T_1. This value of T_1 is used in conjunction with equation (27a) or (27b) to find the pressure at which equilibrium condensation could occur. If this calculated pressure p_c is greater than the free-stream pressure p_1, condensation will not occur. On the other hand, if p_c is less than p_1, condensation will occur for equilibrium flow. The state such that $p_1 = p_c$ at the same time $T_1 = T_c$ is the condition for maximum Mach number without condensation. The value of Mach number at which helium condensation will just occur for a given stagnation condition was determined by an iterative procedure and was the maximum value used in these calculations.

RESULTS AND DISCUSSION

The results of the calculations for helium based on the Beattie-Bridgeman equation of state are presented in figures 1 to 8 as correction factors to be used in conjunction with the ideal-gas parameters for helium presented in references 3 and 4. A comparison between the values of the correction factors for hypersonic flow parameters in helium presented in reference 1 and those calculated in the present work shows an agreement that is always better than 3 percent even when the effect of Mach number is considered. As was noted previously, the work of reference 1 was based on the assumption of ideal-gas behavior below 1 atmosphere, which would cause the various correction factors to become independent of Mach number so long as the expansion was carried below 1 atmosphere. In the present work the Beattie-Bridgeman equation was applied over the entire flow process and, as a result, a small dependency on Mach number was noted even for expansions carried below 1 atmosphere. This small difference between the results of reference 1 and the present work is attributed to the slightly different methods of calculation.

The correction factors for W_1, p_2/p_1, ρ_2/ρ_1, and M_2 are not presented since they were all within 1 percent of unity for the entire range of calculation.

The results presented in reference 1 were limited to stagnation pressures up to 6,000 lb/sq in. abs and temperatures up to 600° F, whereas the present work is for stagnation pressures up to 50,000 lb/sq in. abs and temperatures up to 10,000° F with the restriction that the calculations are limited to densities below the critical density. Because of the broad range of conditions considered, the results presented herein are to be considered simply as reasonable estimates of the correction factors for the various hypersonic flow parameters for helium.

The use of the correction factors presented in figures 1 to 8 is easily shown by an example. Let us assume that a hypersonic helium tunnel operates with a stagnation temperature of 600° F and a stagnation pressure of 10,000 lb/sq in. abs at a ratio of pitot pressure to stagnation pressure of 3.50×10^{-4}. For these stagnation conditions, the correction factor $F_{p,t,2}$ is approximately 1.185

(see fig. 7) with some uncertainty due to Mach number. The ideal-gas value for $p_{t,2}/p_{t,1}$ is therefore $\left(3.50 \times 10^{-4}\right)/1.185$, or 2.95×10^{-4}. The actual Mach number for these conditions is then found from reference 4 to be approximately 42.60. Since there was initially a question as to which Mach number to use in reading figure 7, the value of $F_{p,t,2}$ should be read again with the added knowledge that M_1 is very close to 42.60. Now by considering the small effect of Mach number in figure 7, the value of $F_{p,t,2}$ is 1.181, which gives an ideal-gas value for $p_{t,2}/p_{t,1}$ of 2.96×10^{-4}, so that the Mach number is 42.55.

Now that the value of M_1 is determined, the various ideal-gas parameters can be found for $M_1 = 42.55$ from reference 4 and the corresponding correction factors obtained from figures 1 to 8. For example, the actual value of $T_1/T_{t,1}$ is determined by multiplying the ideal-gas value of 1.65×10^{-3} found in reference 4 for $M_1 = 42.55$ by a correction factor of 1.102 found from figure 1 for a stagnation temperature of 600° F and a stagnation pressure of 10,000 lb/sq in. abs which gives $1.102\left(1.65 \times 10^{-3}\right)$, or 1.82×10^{-3}. The other flow parameters are determined in the same manner.

Figure 9 shows the maximum Mach number that can be attained by the isentropic expansion from various combinations of stagnation temperatures and pressures for equilibrium conditions. The values presented in this figure are also to be considered simply as reasonable estimates.

Finally, figure 10 shows the compressibility factor Z plotted as a function of pressure for a number of temperatures as calculated from equation (2). For a given temperature and pressure, the density can be found from the relation

$$p = Z\rho RT \tag{28}$$

and figure 10.

CONCLUDING REMARKS

The various hypersonic flow parameters for helium have been estimated by use of the Beattie-Bridgeman equation of state for helium for stagnation pressures up to 50,000 lb/sq in. abs and stagnation temperatures up to 10,000° F. Calculations were made for Mach numbers up to 100 or the Mach number corresponding to the point of equilibrium helium condensation, whichever was smaller. These calculations were restricted to densities below the critical density and are considered to be only reasonable estimates of the flow parameters for helium. The results are presented as simple correction factors which can be used in conjunction with the tabulated ideal-gas parameters presented in NACA TN 4063 and NASA TN D-1252 for a specific-heat ratio of 5/3. This work extends the stagnation pressure and temperature range considered in NASA TN D-462.

Langley Research Center,
National Aeronautics and Space Administration,
Langley Station, Hampton, Va., January 21, 1963.

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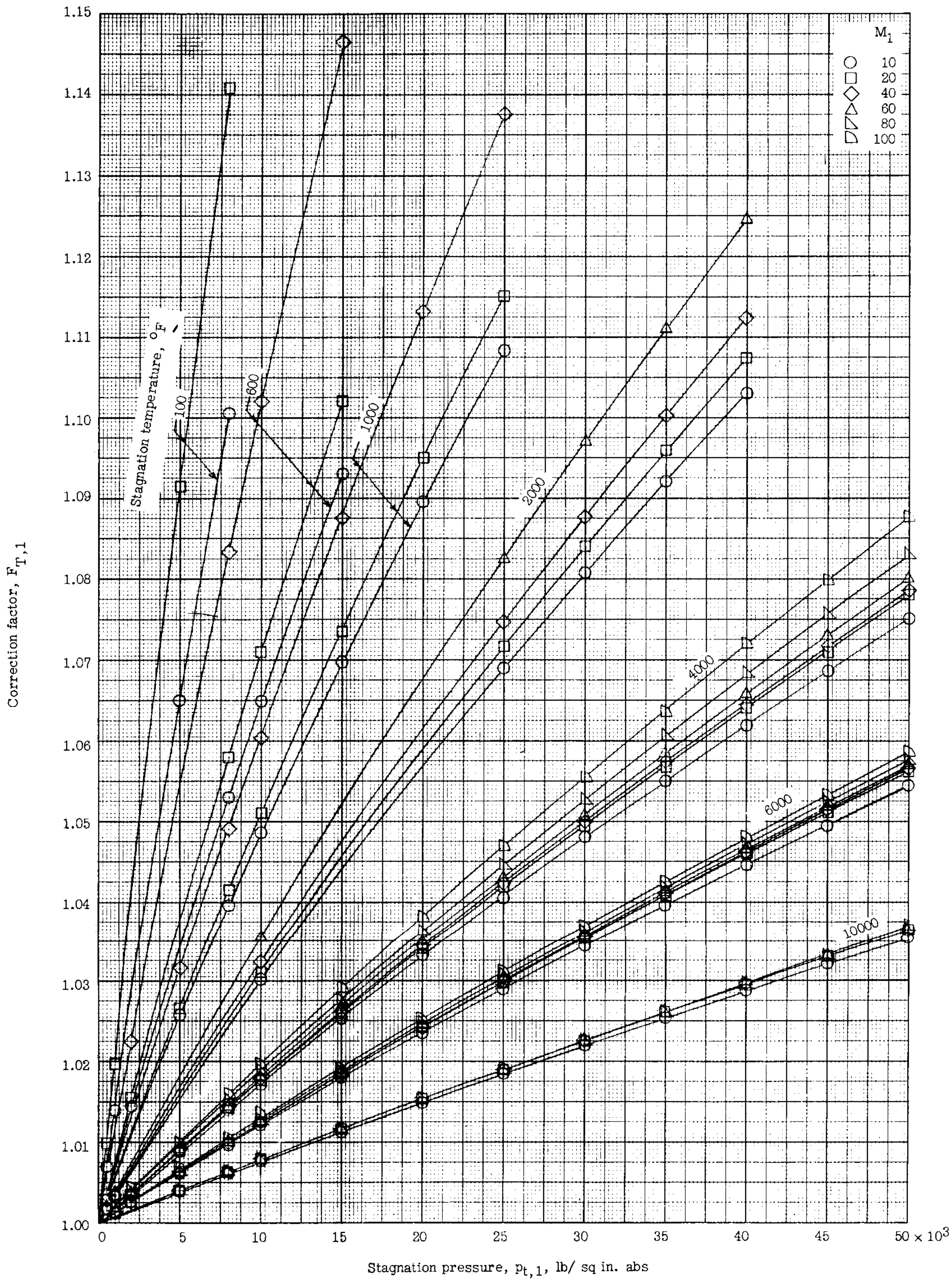

Figure 1.- Correction factor $F_{T,1}$ as a function of stagnation pressure for various stagnation temperatures and Mach numbers.

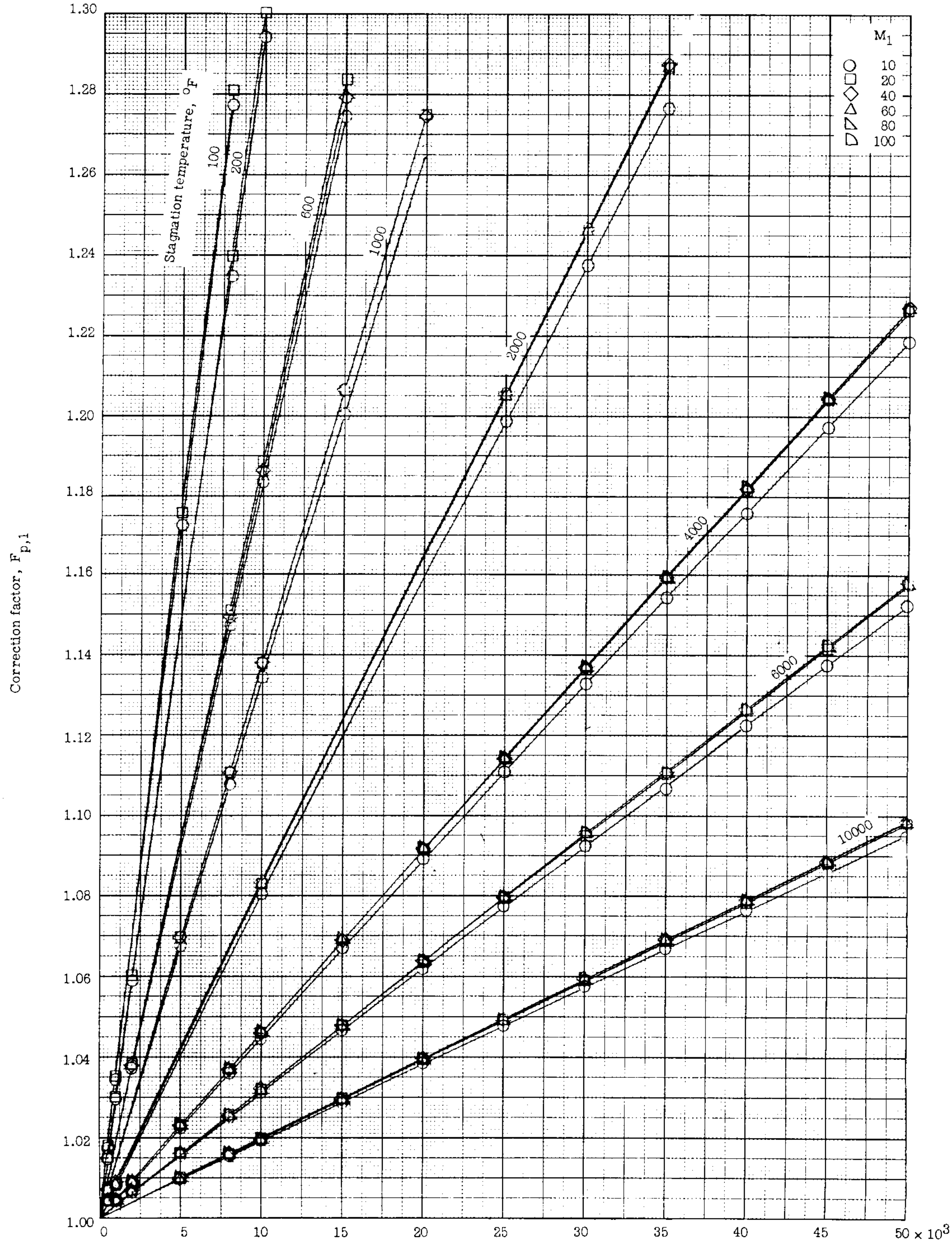

Figure 2.- Correction factor $F_{p,1}$ as a function of stagnation pressure for various stagnation temperatures and Mach numbers.

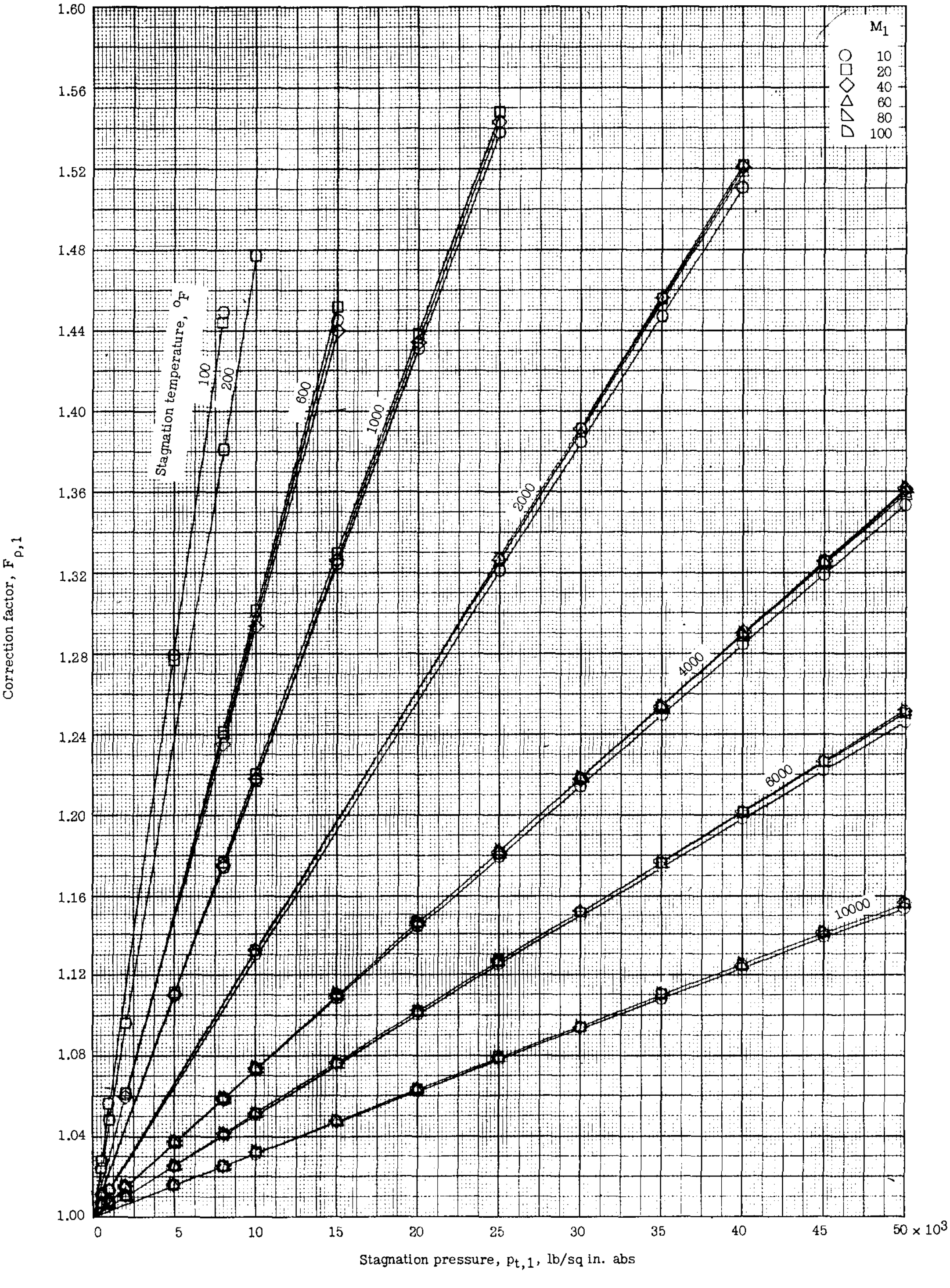

Figure 3.- Correction factor $F_{\rho,1}$ as a function of stagnation pressure for various stagnation temperatures and Mach numbers.

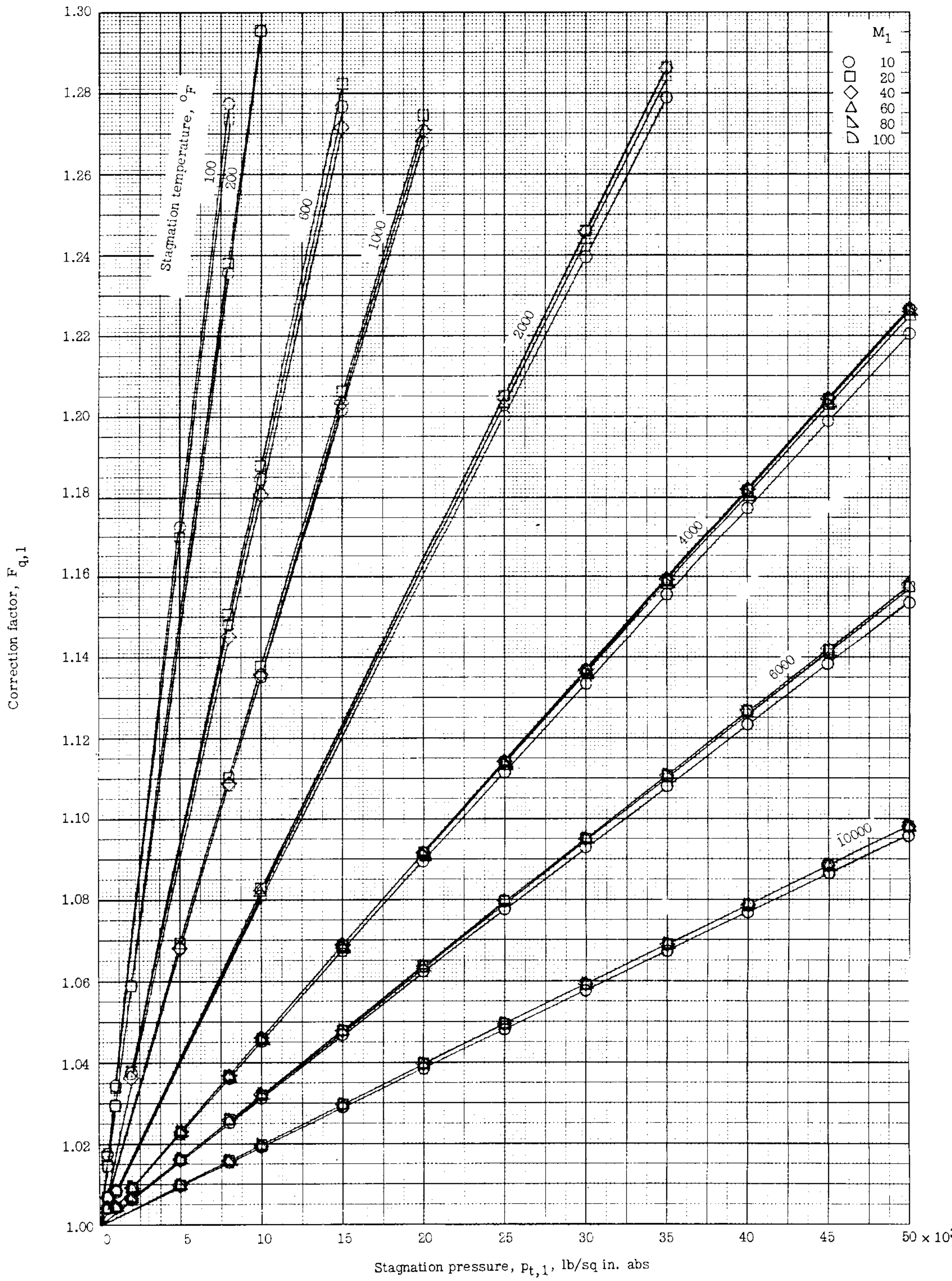

Figure 4.- Correction factor $F_{q,1}$ as a function of stagnation pressure for various stagnation temperatures and Mach numbers.

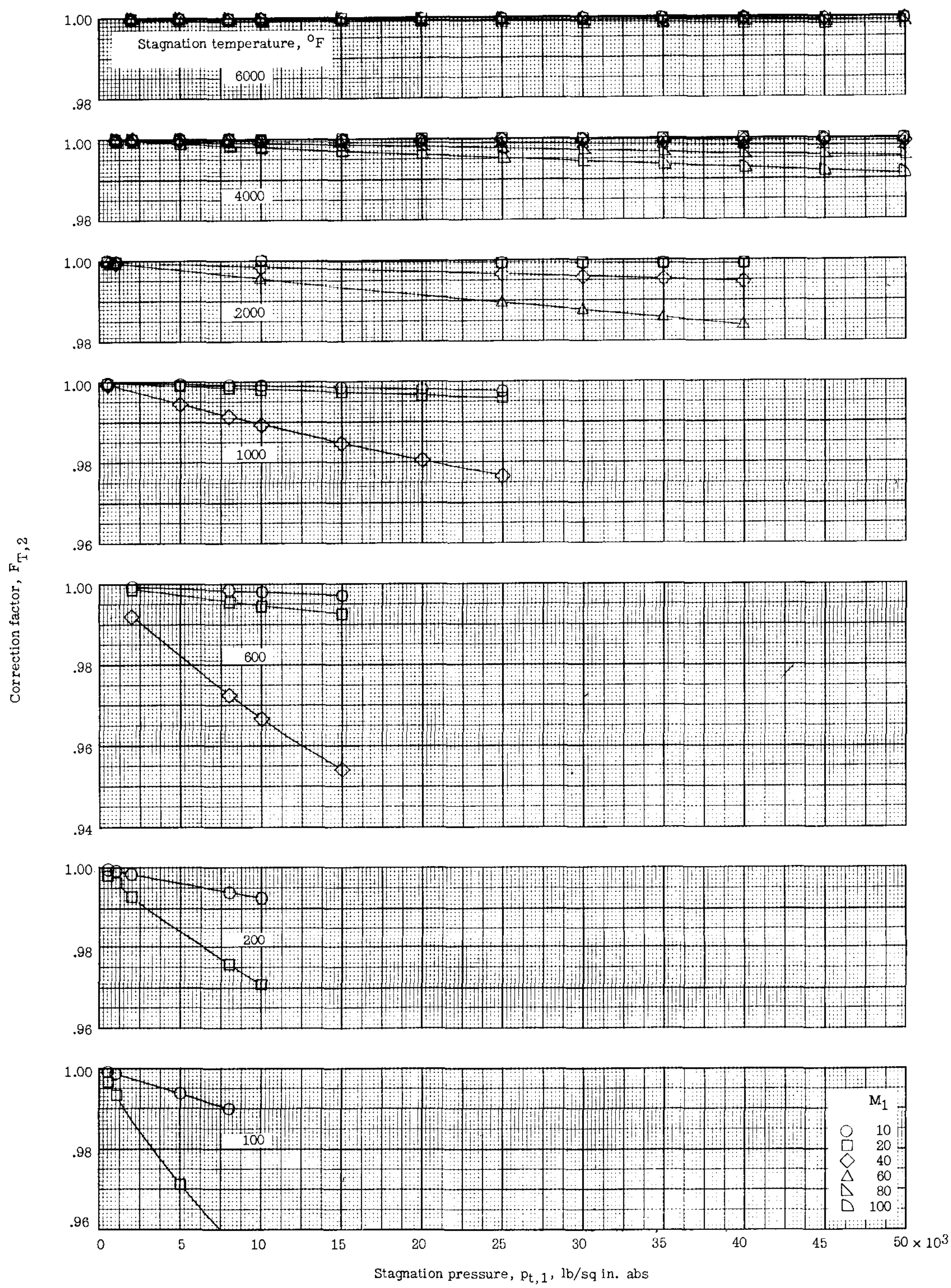

Figure 5.- Correction factor $F_{T,2}$ as a function of stagnation pressure for various stagnation temperatures and Mach numbers.

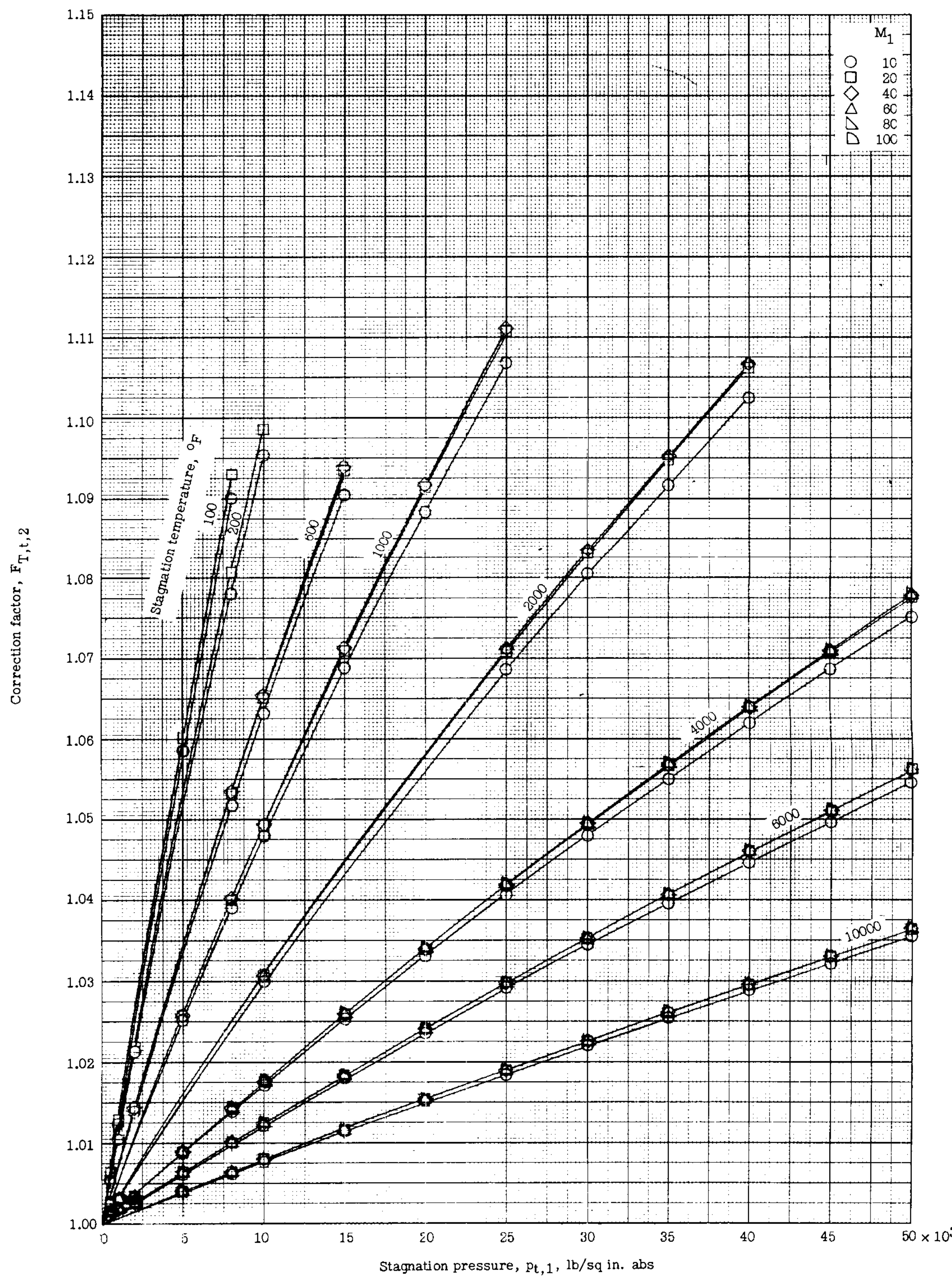

Figure 6.- Correction factor $F_{T,t,2}$ as a function of stagnation pressure for various stagnation temperatures and Mach numbers.

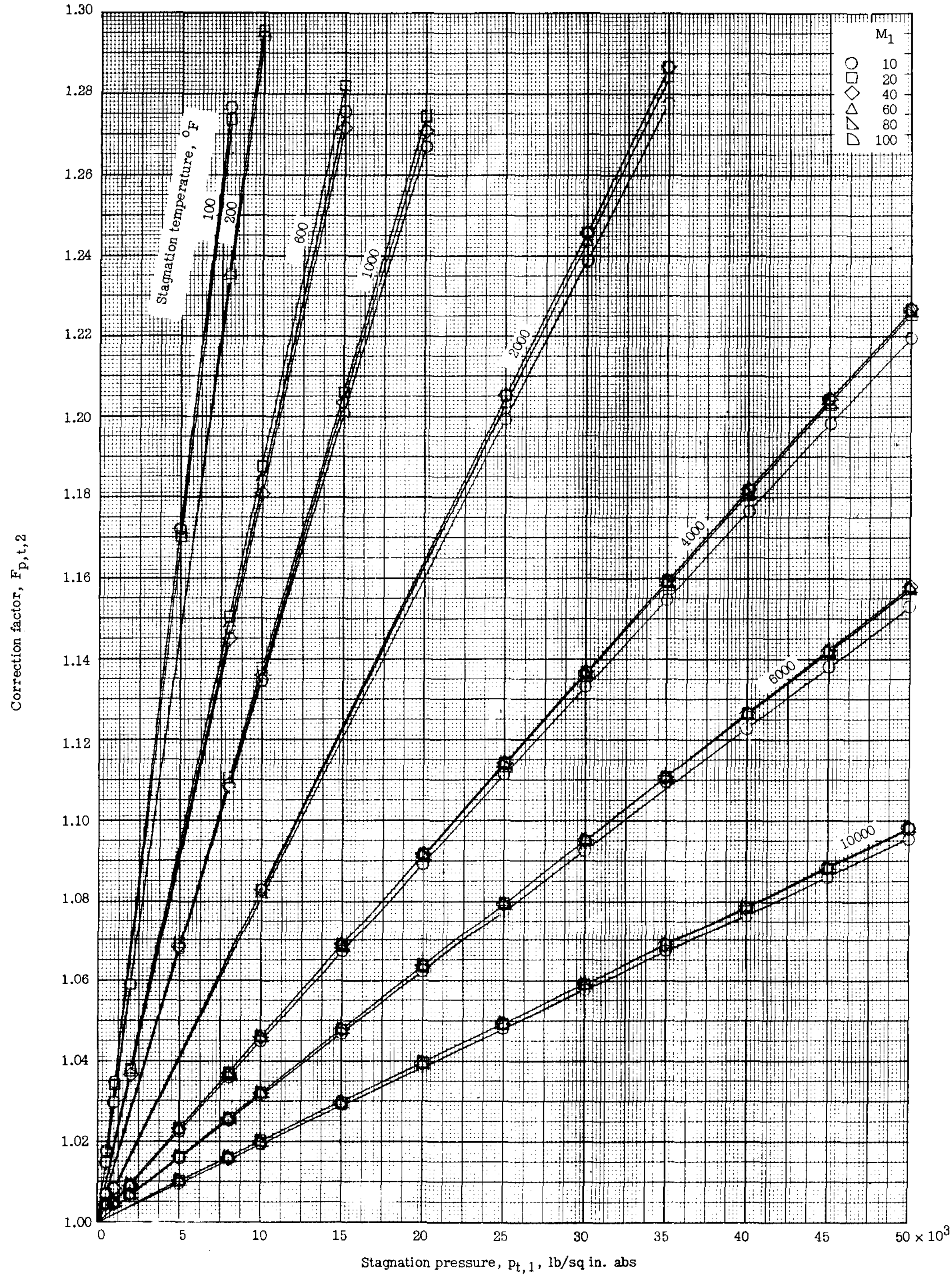

Figure 7.- Correction factor $F_{p,t,2}$ as a function of stagnation pressure for various stagnation temperatures and Mach numbers.

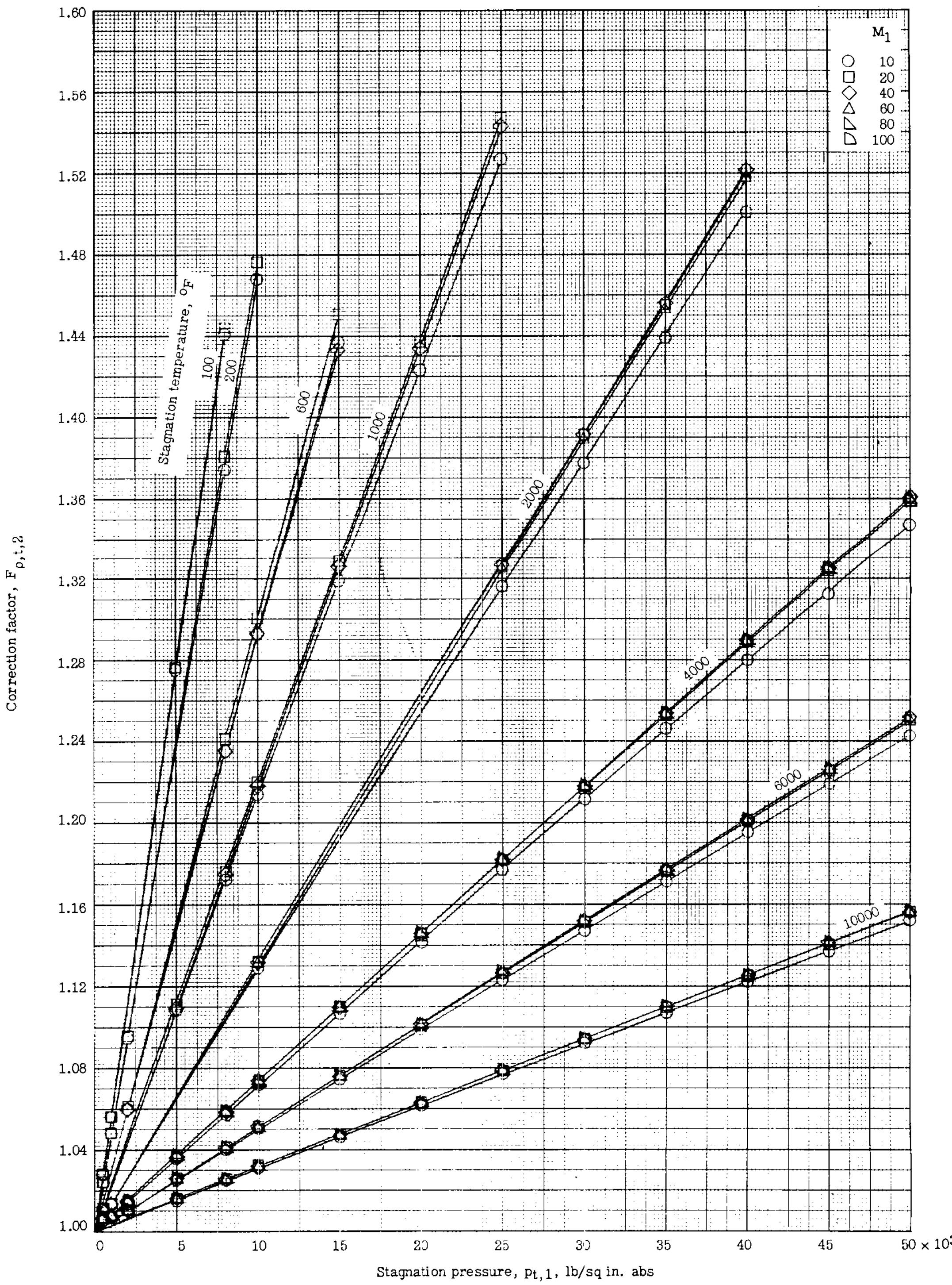

Figure 8.- Correction factor $F_{\rho,t,2}$ as a function of stagnation pressure for various stagnation temperatures and Mach numbers.

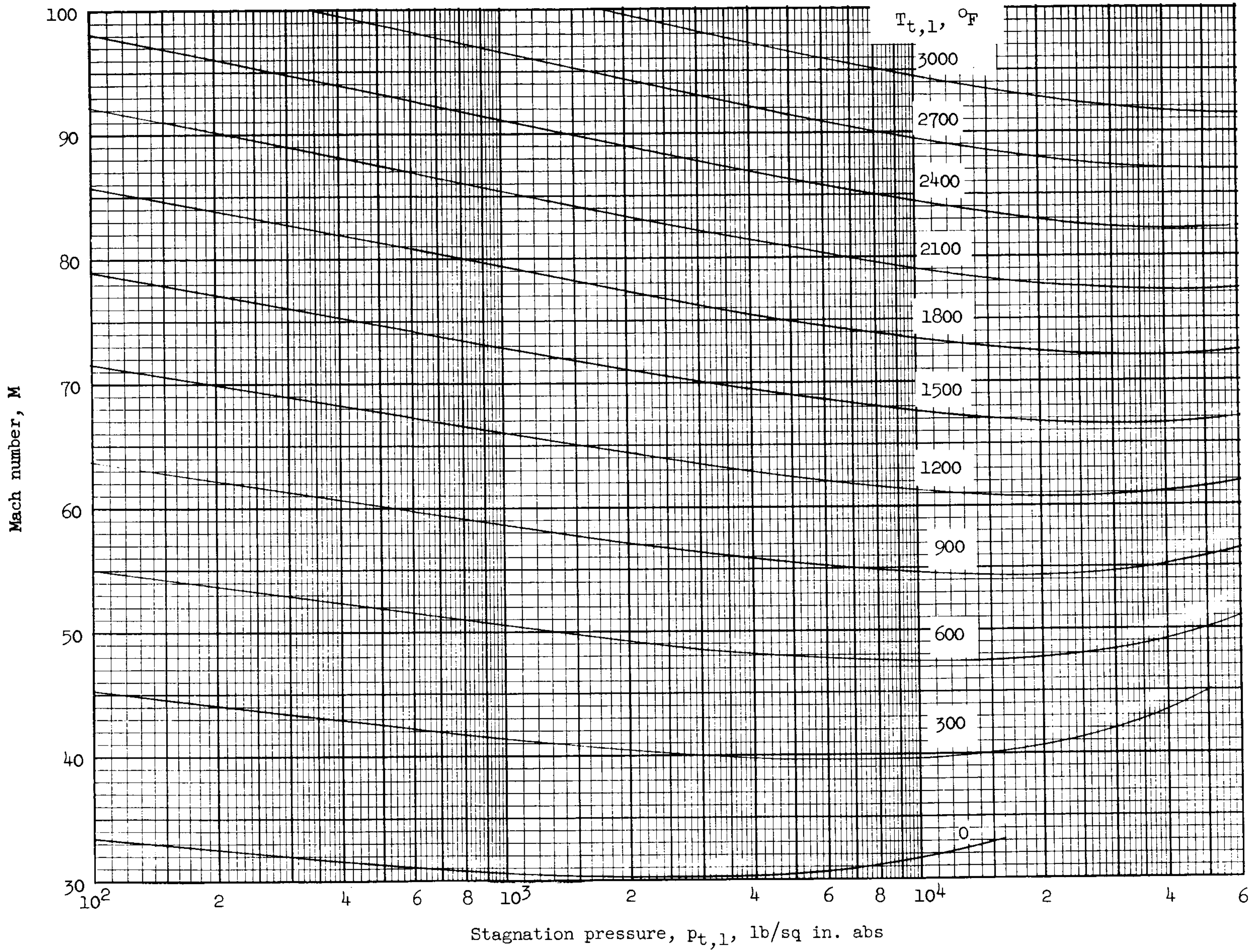

Figure 9.- Mach number at which condensation just occurs for equilibrium conditions as a function of stagnation pressure for various stagnation temperatures.

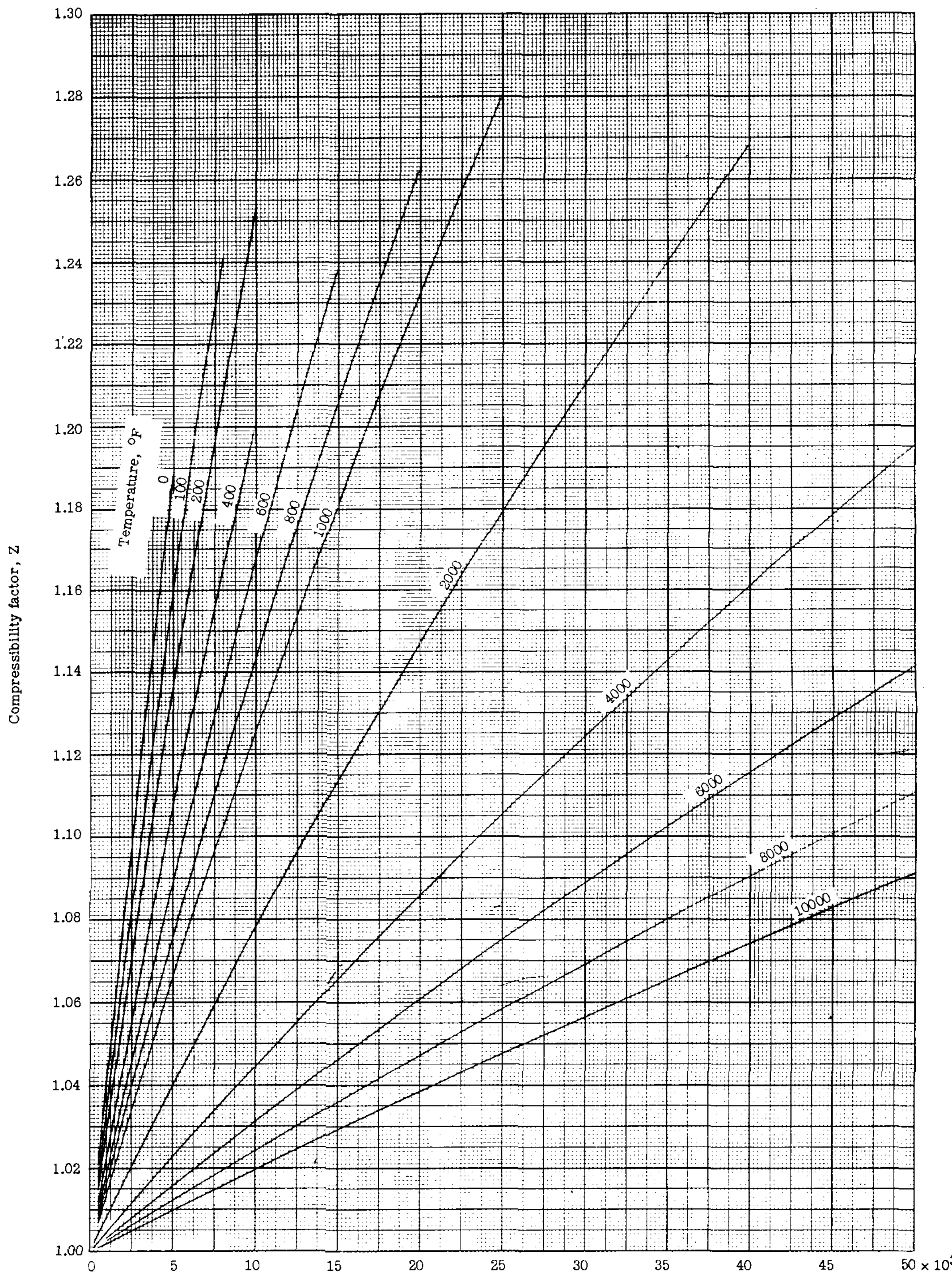

Figure 10.- Compressibility factor Z as a function of pressure at various temperatures.

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