N71-18633

NASA TECHNICAL MEMORANDUM

NASA TM X-52965

NASA TM X-52965

REAL-GAS EFFECTS IN FLOW METERING

by Robert C. Johnson
Lewis Research Center
Cleveland, Ohio

TECHNICAL PAPER proposed for presentation at
Symposium on Flow - Its Measurement and Control
in Science and Industry
Pittsburgh, Pennsylvania, May 10-14, 1971

E-6167

Real-Gas Effects in Flow Metering

Robert C. Johnson

National Aeronautics and Space Administration
Lewis Research Center
Cleveland, Ohio 44135

Methods of computing the mass-flow rate of nonperfect gases are discussed. Data for computing mass-flow rate through a sonic-flow nozzle are given for air, nitrogen, oxygen, normal and para-hydrogen, argon, helium, steam, methane, and natural gas. The pressure ranges to 100×10^5 N/m^2 ($\sim$ 100 atm). For steam, the temperature range is from 550 to 800 K. For the other gases, the temperature range is from 250 to 400 K.

INTRODUCTION

When flow meters are used for measuring the mass-flow rate of gases, errors may arise if the flow relations that are used in data reduction involve the assumption that the gas is perfect. For this report, a <u>perfect gas</u> is defined as one having an invariant specific heat and a compressibility factor of unity. A perfect gas is to be distinguished from an <u>ideal gas</u>, which has a temperature-dependent specific heat and unity compressibility factor. A nonperfect gas is a <u>real gas</u>. The assumption that the gas is perfect is sufficiently accurate for computing the flow of such gases as air and nitrogen at atmospheric pressure and room temperature. However, for gases at high pressure or low temperatures, significant errors will result if the perfect-gas flow relations are used.

There are a number of cases where the real-gas corrections are simple to apply. For these cases, the changes in pressure and temperature of the gas as it flows through the meter are much smaller than the respective absolute levels of pressure and temperature; the flow can then be considered incompressible. It is then only necessary to know the gas density, which can be determined from the pressure and temperature. In references [1, 2, and 3] the densities or compressibility factors of some common gases are tabulated as functions of pressure and temperature. For these cases, the real-gas correction consists of using an accurate value of density rather than a value that would result from assuming the gas to be perfect. The correct density can be calculated from an equation of state, or else obtained from a tabulation, such as references [1, 2, or 3], of density or compressibility factor as a function of pressure and temperature. Two examples where incompressible flow may be assumed are:

1. A volumetric flowmeter such as a turbine-type meter where the pressure drop across the meter is much smaller than the absolute level of pressure.
2. A head-type meter such as a nozzle or orifice operating at a high pressure level where the pressure drop across the meter is much smaller than the absolute level of pressure.

The material presented in this report applies to head-type flowmeters through which the flow can be considered one-dimensional and isentropic.

Two such flowmeters are the nozzle and the venturi. In both of these meters, the flow from the upstream plenum to the flowmeter throat can be considered one-dimensional and isentropic to a good approximation. Actual deviations from these conditions can be handled by applying a multiplying factor (the discharge coefficient) that is almost unity, and is a function of Reynolds number. The flow through an orifice is neither one-dimensional nor isentropic to a sufficient degree to permit rigorous application of the data developed here.

While the conventional isentropic flow equations apply to a perfect gas, a number of investigators have considered the isentropic flow of nonperfect gases. References [4 and 5] develop equations for calculating the isentropic flow of gases described by the Van der Waals equation of state. A method of calculating the flow of nonperfect diatomic gases using Berthelot's state equation is described in reference [6]. In references [7, 8, and 9], the authors consider the flow of gases described by the Beattie-Bridgeman equation of state. In addition, reference [9] presents tables of functions that aid in the one-dimensional flow calculations of real air. References [10 and 11] present methods of estimating isentropic exponents to be used for calculating the flow of imperfect gases through sonic-flow nozzles. (A <u>sonic-flow nozzle</u> is one in which the throat velocity equals the local speed of sound. A sonic-flow nozzle has also been called a <u>choked nozzle</u> or a <u>critical-flow nozzle</u>.) Reference [12], using the tabulated data of reference [1], presents a graphical method for computing the isentropic mass flow rate of imperfect gases. In reference [13], the author reviews the sonic-flow meter and suggests methods for correcting for gaseous imperfections. In reference [14], a computer program for calculating the one-dimensional flow of imperfect gases is given. The program involves the interpolation of sets of thermodynamic-property data that are stored in the computer. These same authors have published a set of tables (ref. [15]), for calculating the one-dimensional flow properties of real air. The thermodynamic data for air that are involved in reference [15] are the data tabulated in reference [1]. Sonic-flow functions for steam are given in reference [16]. Reference [17] presents a set of graphs that permit the mass-flow rate of air, N_2, O_2, n-H_2, A, He, and H_2O through sonic-flow nozzles to be calculated. Information is also given on how to make the mass-flow rate calculation when the nozzle is operated subsonically. In reference [2], the air, N_2, O_2, n-H_2, and H_2O data of reference [17] are presented in tabular form; p-H_2 data are also presented. Reference [3] has tabulated data that permit calculating the mass-flow rate of N_2 and He through sonic-flow nozzles. Reference [3] differs from references [2 and 17] in that the pressure and temperature ranges in reference [3] are greater than the ranges in references [2 and 17]. References [2 and 3] also contain tables of such thermodynamic properties as compressibility factor, specific heat, and speed of sound. In addition, reference [3] contains the computer programs used in making the calculations. In reference [18], data for calculating the flow of natural gas through sonic-flow nozzles are presented; the computer program for calculating these data is given in reference [19].

In this report, the sonic flow data for various gases, as presented in references [2, 3, 17, and 18], are summarized. Since these references were published, more exact calculations for argon and methane have been made.

The more exact argon data replaces that in reference [17], and the more exact methane data replaces that in reference [18]. These data are presented in terms of a sonic-flow factor. The use of this factor permits the mass flow rate of these gases through sonic-flow nozzles to be calculated. In addition, the empirical method, given in reference [17], of calculating the mass-flow rate of these gases through subsonic nozzles, is presented. For all gases except steam, the calculations are for temperatures from 250 to 400 K, and pressures to 100×10^5 N/m^2. For steam, the temperatures are from 500 to 800 K, and the pressures to 100×10^5 N/m^2. S.I. 1960 units are used throughout this report.

SYMBOLS

A	area, m^2
a	speed of sound, m/sec
c_p	specific heat at constant pressure, m^2/(sec^2 K)
c_v	specific heat at constant volume, m^2/(sec^2 K)
G	mass flow rate per unit area, kg/(m^2 sec)
H	enthalpy, m^2/sec^2
K_H, K'_H	integration constants for enthalpy, K
K_S, K'_S	integration constants for entropy
$\dot{m}$	mass flow rate, kg/sec
p	pressure, N/m^2
R	gas constant, m^2/(sec^2 K)
S	entropy, m^2/(sec^2 K)
T	temperature, K

v velocity, m/sec

Z compressibility factor

γ specific-heat ratio

ϕ sonic-flow factor defined implicitly by equation 12, (sec $K^{\frac{1}{2}}$)/m

Subscripts

0 refers to plenum station

1 refers to nozzle throat station

i refers to ideal-gas condition

P refers to perfect-gas condition

ANALYSIS

The conditions assumed in this analysis are as follows: The gas is at rest in a plenum and accelerates one-dimensionally and isentropically to the throat of a nozzle where its speed is sonic. The measured quantities are the plenum pressure and temperature. The gas is not assumed to be perfect, and its state equation is given by

$$p = Z\rho RT \tag{1}$$

where Z is the compressibility factor and may be expressed as a function of pressure and temperature or of density and temperature. The assumption that the flow is one-dimensional and starts from rest is represented by

$$H_0 = H_1 + \frac{1}{2} v_1^2 \tag{2}$$

The assumption that the flow is isentropic is represented by

$$S_0 = S_1 \tag{3}$$

and the fact that the flow is sonic is represented by

$$v_1 = a_1 \tag{4}$$

In order to solve equations (1) through (4), it is necessary to express enthalpy, entropy, and the speed of sound in terms of either pressure and temperature, or density and temperature, depending on the form of the state equation.

Case I. $Z = Z(p,T)$

The expressions for enthalpy and entropy are integrated forms of Eqs. (4) and (5) in reference [17].

$$\frac{H}{R} = \int \left(\frac{c_{p,i}}{R}\right) dT - T \int_0^p \left[T\left(\frac{\partial Z}{\partial T}\right)_p\right] \frac{dp}{p} + K_H \tag{5}$$

$$\frac{S}{R} = \int \left(\frac{c_{p,i}}{R}\right) \frac{dT}{T} - \ln p - \int_0^p \left[Z - 1 + T\left(\frac{\partial Z}{\partial T}\right)_p\right] \frac{dp}{p} + K_S \tag{6}$$

The temperature integrals in Eqs. (5) and (6) are indefinite integrals whose constants of integration are included in K_H and K_S. The values of K_H and K_S depend on the choice of the gas reference state. Equations (5) and (6) also involve the ideal-gas specific heat. The term ideal-gas refers to a gas whose compressibility factor is invariant, with a value of unity; however, unlike a perfect gas, the specific heat is a function of temperature. This condition is approached as the pressure of the gas approaches zero, providing dissociation does not occur. The expression for the speed of sound is found in reference [17]. The value of a is obtained from

$$Z^2RT/a^2 = Z - p\left(\frac{\partial Z}{\partial p}\right)_T - \left[Z + T\left(\frac{\partial Z}{\partial T}\right)_p\right]^2 / (c_p/R) \tag{7}$$

where

$$\frac{c_p}{R} = \frac{c_{p,i}}{R} - \int_0^p \left[2T\left(\frac{\partial Z}{\partial T}\right)_p + T^2\left(\frac{\partial^2 Z}{\partial T^2}\right)_p \right] \frac{dp}{p} \tag{8}$$

If these expressions for enthalpy, entropy, and speed of sound are substituted in Eqs. (2), (3), and (4), and the iteration procedures given in reference [17] are then applied, solutions can be obtained for the velocity, pressure, and temperature at the nozzle throat. Knowing the pressure and temperature at the nozzle throat, the corresponding density is determined through Eq. (1). The mass flow rate per unit area through the sonic-flow nozzle then becomes

$$G_1 = \rho_1 v_1 \tag{9}$$

Case II. $Z = Z(\rho,T)$

The expressions for enthalpy and entropy are given in reference [3] and are:

$$\frac{H}{R} = \int \frac{c_{v,i}}{R}\, dT + T\left[Z - \int_0^\rho T\left(\frac{\partial Z}{\partial T}\right)_\rho \frac{d\rho}{\rho} \right] + K'_H \tag{10}$$

$$\frac{S}{R} = \int \frac{c_{v,i}}{R} \frac{dT}{T} - \ln \rho - \int_0^\rho \left[Z - 1 + T\left(\frac{\partial Z}{\partial T}\right)_\rho \right] \frac{d\rho}{\rho} + K'_S \tag{11}$$

The expression for the speed of sound is found in reference [17]. The value of a is obtainable from

$$a^2/RT = Z + \rho\left(\frac{\partial Z}{\partial \rho}\right)_T + \left[Z + T\left(\frac{\partial Z}{\partial T}\right)_\rho \right]^2 / (c_v/R) \tag{12}$$

where

$$\frac{c_v}{R} = \frac{c_{v,i}}{R} - \int_0^\rho \left[2T\left(\frac{\partial Z}{\partial T}\right)_\rho + T^2\left(\frac{\partial^2 Z}{\partial T^2}\right)_\rho \right] \frac{d\rho}{\rho} \tag{13}$$

These expressions for enthalpy, entropy, and speed of sound are substituted in Eqs. (2), (3), and (4). Equations (1) through (4) are then solved for plenum density, and for density, temperature, and velocity at the nozzle throat. The iteration procedures involved in this solution are found in reference [3]. The expression for the mass-flow rate per unit area through the sonic-flow nozzle is again given by equation (9).

RESULTS AND DISCUSSION

The Sonic-Flow Factor

The mass flow rate of gases through sonic flow nozzles can be expressed in terms of a sonic-flow factor, ϕ, as follows:

$$\dot{m} = A_1 \cdot \phi \cdot (p_0/T_0^{\frac{1}{2}}) \tag{14}$$

For a perfect gas, the value ϕ_P of this sonic-flow factor is independent of pressure and temperature and is given by

$$\phi_P^2 = \frac{\gamma_P}{R} \cdot \left(\frac{2}{\gamma_P+1}\right)^{(\gamma_P+1)/(\gamma_P-1)} \tag{15}$$

where γ_P is chosen to be 7/5 for air, nitrogen, oxygen, normal hydrogen, and para-hydrogen; 5/3 for argon and helium; and 4/3 for steam, methane, and natural gas.

For an ideal gas, the sonic-flow factor has a value ϕ_i that is a function of temperature and is given by

$$\phi_i = \lim_{p \to 0} \phi \tag{16}$$

The results of the real-gas calculations are presented graphically in Figs. (1) to (3). Instead of plotting the sonic-flow factor as a function of pressure and temperature the ratio of the real-gas sonic-flow factor to the ideal-gas sonic-flow factor is plotted. The reason for this is that, if the sonic-flow factor itself were plotted, the families of curves would cross each other for some of the gases, making the graphs difficult to read. In terms of the ordinates in Figs. (1) to (3), the expression for the sonic mass-flow rate is

$$\dot{m} = A_1 \left(\frac{\phi}{\phi_i}\right) \cdot \phi_i \cdot \frac{p_o}{T_0^{\frac{1}{2}}} \tag{17}$$

where the values of ϕ_i are given on the figures to which they apply.

In the event that it is desired to use nozzles or venturies subsonically, but the velocities are such that the flow has to be considered compressible, the following equation, derived from Eq. (27) in reference [17], applies

$$\dot{m} = \frac{\dot{m}_P}{Z_0^{\frac{1}{2}}} \left\{ 1 + 2 \left(\frac{p_0 - p_1}{p_0}\right) \left[\left(\frac{\phi}{\phi_i}\right) \left(\frac{\phi_i}{\phi_P}\right) Z_0^{\frac{1}{2}} - 1 \right] \right\} \tag{18}$$

Equation (18) is not based on theory, but is an approximation to actual subsonic calculations. For the pressure and temperature ranges involved, Eq. (18) reproduces the subsonic calculations to within $\frac{1}{4}$ percent for the gases considered in this report. The values (ϕ_i/ϕ_P) are given on the figures to which they apply. The values of the compressibility factor are given graphically in Figs. (4) to (6) for the gases considered in this report. The perfect-gas mass-flow rate $\dot{m}_P$ is given by

$$(\dot{m}_P/A_1)^2 = \frac{2\gamma_P}{\gamma_P - 1} \cdot \frac{p_0^2}{RT_0} \cdot \left(\frac{p_1}{p_0}\right)^{2/\gamma_P} \cdot \left[1 - \left(\frac{p_1}{p_0}\right)^{(\gamma_P - 1)/\gamma_P}\right] \tag{19}$$

In Figs. (1) to (3), (ϕ/ϕ_i) is plotted as a function of P and T for air, N_2, O_2, n-H_2, p-H_2, A, He, H_2O, CH_4, and natural gas. One of the interesting results in Fig. (2a) is that even though the sonic-flow factors for n-H_2 and p-H_2 are different, the ratio (ϕ/ϕ_i) is the same; further, over the range of pressures and temperatures considered, this ratio is independent of temperature.

The natural gas data in Fig. (3b) are for a particular composition. Therefore, this data would not apply strictly to a natural gas of a different composition. However, since methane is usually the principal component of natural gas, the sonic-flow factors of natural gases approximate those of methane.

Table I lists the sources of the data presented in Figs. (1) to (3), as well as the references for the compressibility-factor and ideal-gas specific-heat data that were used in the calculations.

The pressure and temperature ranges covered by some of the references exceed the ranges covered in this report. Table II lists the actual ranges covered in references [2, 3, 17, and 18].

Compressibility-Factor Data

In order to use Eq. (18), it is necessary to have compressibility-factor data. To this end, Figs. (4) to (6) are presented. Pressure and temperature ranges are the same as in the sonic-flow ratio figures (Figs. (1) to (3)).

[1]J. Hilsenrath, et al., Tables of Thermodynamics and Transport Properties of Air, Argon, Carbon Dioxide, Carbon Monoxide, Hydrogen, Nitrogen, Oxygen, and Steam (Pergamon Press, New York, 1960).

[2]R. C. Johnson, Real-Gas Effects in Critical Flow Through Nozzles and Tabulated Thermodynamic Properties, NASA TN D-2565 (1965).

[3]R. C. Johnson, Real-Gas Effects in Critical Flow Through Nozzles and Thermodynamic Properties of Nitrogen and Helium at Pressures to $300X10^5$ Newtons per Square Meters (Approx 300 atm), NASA SP-3046 (1968).

[4]H.-S. Tsien, One Dimensional Flows of a Gas Characterized by Van der Waal's Equation of State, J. Math Phys. 25, 301 (1947).

[5]C. duP. Donalson, Note on the Importance of Imperfect-Gas Effects and Variation of Heat Capacities on the Isentropic Flow of Gases. NACA RM L8J14 (1948).

[6]A. J. Eggers, Jr., One-Dimensional Flows of an Imperfect Diatomic Gas, NACA TN 1861 (1949).

[7]J. C. Crown, Flow of a Gas Characterized by the Beattie-Bridgeman Equation of State and Variable Specific Heats; Part I - Isentropic Relations, Naval Ordnance Laboratory Memo 9619 (Apr. 22, 1949).

[8]R. E. Randall, Thermodynamics Properties of Gases: Equations Derived from the Beattie-Bridgeman Equation of State Assuming Variable Specific Heats, Arnold Engineering Development Center TR-57-10, AD-135332 (Aug. 1957).

[9]R. E. Randall, Thermodynamics Properties of Air: Tables and Graphs Derived from the Beattie-Bridgeman Equation of State Assuming Variable Specific Heats, Arnold Engineering Development Center TR-57-8, AD-135331, (Aug. 1957).

[10]A. S. Iberall, The Effective 'Gamma' for Isentropic Expansion of Real Gases, J. Appl. Phys. 19, 997 (1948).

[11]W. C. Edminster, Applied Hydrocarbon Thermodynamics, Part 30 - Isentropic Exponents and Critical-Flow Metering, Hydrocarbon Processing 46, 139 (1967).

[12]R. M. Reimer, Computation of the Critical-Flow Function Pressure Ratio, and Temperature Ratios for Real Air, J. Basic Eng. 86, 169 (1964).

[13]B. T. Arnberg, Review of the Critical-Flow Meter for Gas Flow Measurements, J. Basic Eng. 84, 447 (1962).

[14]M. D. Mintz and D. P. Jordan, Procedure for Digital Computer Analysis of One-Dimensional Fluid-Flow Processes Involving Real Gases, Lawrence Radiation Laboratory Report UCRL-7530 (Jan. 1964).

[15]D. P. Jordan and M. D. Mintz, Air Tables (McGraw-Hill Book Co., Inc., New York, 1965).

[16]J. W. Murdock and J. M. Bauman, The Critical Flow Function for Superheated Steam, J. Basic Eng., 86, 507 (1964).

[17]R. C. Johnson, Calculations of Real-Gas Effects in Flow Through Critical-Flow Nozzles, J. Basic Eng., 86, 519 (1964).

[18]R. C. Johnson, Calculations of the Flow of Natural Gas Through Critical Flow Nozzles, J. Basic Eng. 92, 580 (1970).

[19]R. C. Johnson, A Set of FORTRAN IV Routines used to Calculate the Mass Flow Rate of Natural Gas Through Nozzles, NASA TM X-2240 (1971).

[20]H. W. Woolley, R. B. Scott and F. G. Brickwedde, Computation of Thermal Properties of Hydrogen in Its Various Isotopic and Ortho-Para Modifications, J. Res. Nat. Bur. Std. (U.S.) 41, 379 (1948).

[21]A. L. Gosman, R. D. McCarty and J. G. Hust, Thermodynamic Properties of Argon From the Triple Point to 300 K at Pressures to 1000 Atmospheres, National Bureau of Standards NSRDS-NBS-27 (1969).

[22]D. B. Mann, The Thermodynamic Properties of Helium from 3 to 300 K Between 0.5 and 100 Atmospheres, National Bureau of Standards Tech. Note 154 (1962).

[23]F. G. Keyes, The Consistency of the Thermodynamic Data for Water Substance Vapor Phase to 550° C, part VII, J. Chem. Phys. 17, 923 (1949).

[24]A. J. Vennix and R. Kobayashi, An Equation of State for Methane in the Gas and Liquid Phases, AIChE J. 15, 926 (1969).

[25]R. S. McDowell and F. H. Kruse, Thermodynamic Functions of Methane, J. Chem. Eng. Data 8, 547 (1963).

[26]M. Benedict, G. B. Webb and L. C. Rubin, An Empirical Equation for Thermodynamic Properties of Light Hydrocarbons and Their Mixtures - Constants for Twelve Hydrocarbons, Chem. Eng. Progr. 47, 419 (1951).

[27]C. T. Sciance, C. P. Colver and C. M. Sliepcevich, Bring Your C_1-C_4 Data up to Date, Hydrocarbon Processing 46, 173 (1967).

[28]Anon., Technical Data Book - Petroleum Refining (American Petroleum Institute, New York, 1966).

Table I. Data References

Gas	Sonic-Flow Factor	Compressibility Factor	Ideal-Gas Specific Heat
Air	2,17	1	1
N_2	2,17	1	1
O_2	2,17	1	1
n-H_2	2,17	20	20
p-H_2	2	20	20
A	(a)	21	21
He	3	22	22
H_2O	2,17	23	1
CH_4	(a)	24	25
Nat. Gas	18,19	18,19,26	1,25,27,28

(a) These data are presented in this report for the first time.

Table II. Pressure and Temperature Ranges Covered in References. Pressures in 10^5 N/m^2 (~ atm); Temperatures in K.

Gas	Ref. 2 (Tables)	Ref. 3 (Tables)	Ref. 17 (Graphs)	Ref. 18 (Tables)
Air	$p_0 \leq 100$ $220 \leq T_0 \leq 390$	---	$p_0 \leq 100$ $220 \leq T_0 \leq 390$	---
N_2	$p_0 \leq 100$ $220 \leq T_0 \leq 390$	$p_0 \leq 300$ $100 \leq T_0 \leq 400$	$p_0 \leq 100$ $220 \leq T_0 \leq 390$	---
O_2	$p_0 \leq 100$ $220 \leq T_0 \leq 390$	---	$p_0 \leq 100$ $220 \leq T_0 \leq 390$	---
n-H_2	$p_0 \leq 100$ $100 \leq T_0 \leq 390$	---	$p_0 \leq 100$ $220 \leq T_0 \leq 390$	---
p-H_2	$p_0 \leq 100$ $100 \leq T_0 \leq 390$	---	---	---
A	---	---	$p_0 \leq 100$ $220 \leq T_0 \leq 390$	---
He	---	$p_0 \leq 300$ $15 \leq T_0 \leq 400$	$p_0 \leq 100$ $220 \leq T_0 \leq 390$	---
H_2O	$p_0 \leq 300$ $400 \leq T_0 \leq 830$	---	$p_0 \leq 300$ $440 \leq T_0 \leq 830$	---
CH_4	---	---	---	$p_0 \leq 69$ $250 \leq T_0 \leq 390$
Nat. gas	---	---	---	$p_0 \leq 69$ $250 \leq T_0 \leq 390$

FIGURE LEGENDS

(a) Air.

(b) Nitrogen.

(c) Oxygen.

Figure 1. - Ratio of the real-gas sonic-flow factor to the ideal-gas sonic-flow factor for various gases.

(a) Hydrogen.

(b) Argon.

(c) Helium.

Figure 2. - Ratio of the real-gas sonic-flow factor to the ideal-gas sonic-flow factor for various gases.

(a) Methane.

(b) Natural gas (fractional composition by volume, CH_4-0.9272, C_2H_6-0.0361, C_3H_8-0.0055, iC_4H_{10}-0.0007, nC_4H_{10}-0.0010, N_2-0.0218, CO_2-0.0077).

Figure 3. - Ratio of the real-gas sonic-flow factor to the ideal-gas sonic-flow factor for various gases.

(a) Air.

(b) Nitrogen.

(c) Oxygen.

Figure 4. - Compressibility factor for various gases.

(a) Normal and para hydrogen.

(b) Argon.

(c) Helium.

(d) Steam.

Figure 5. - Compressibility factor for various gases.

(a) Methane.

(b) Natural gas- (composition is the same as in fig. 3(b)).

Figure 6. - Compressibility factor for various gases.

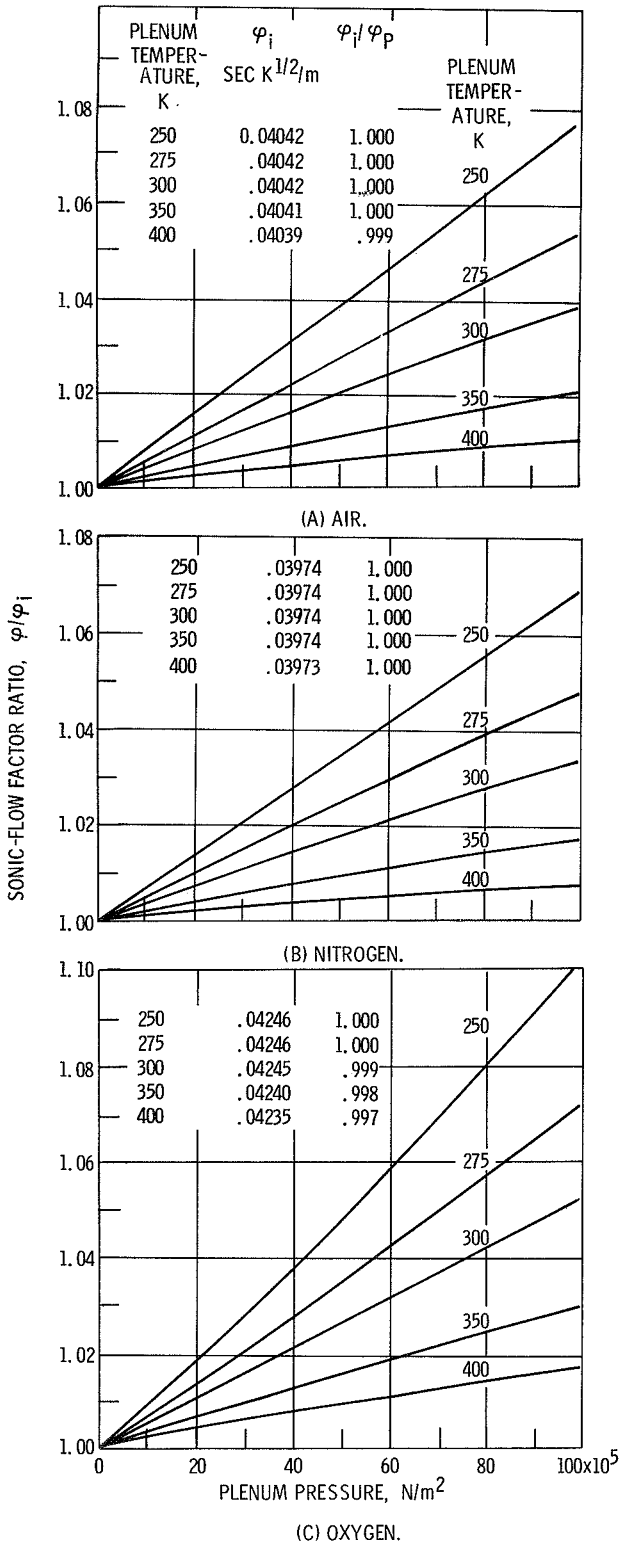


Figure 1

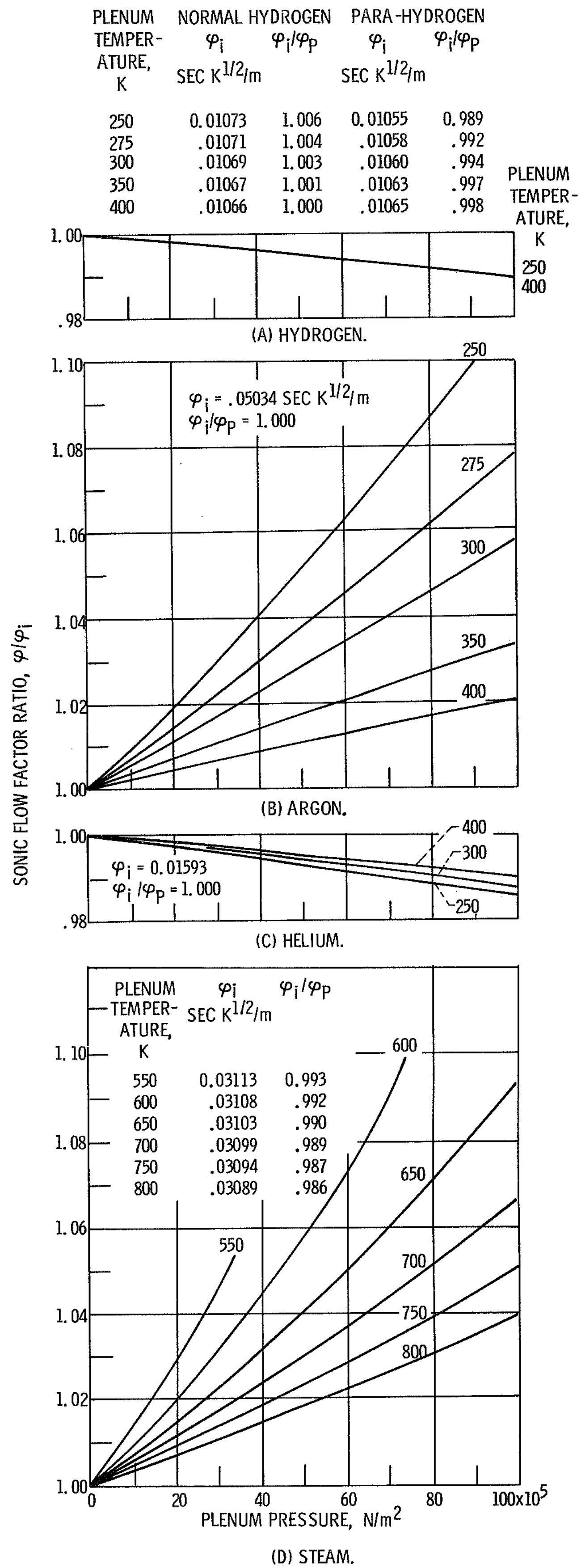
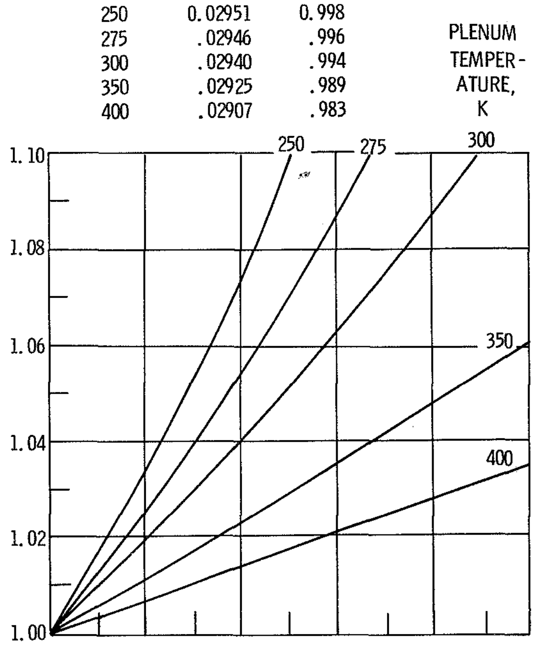


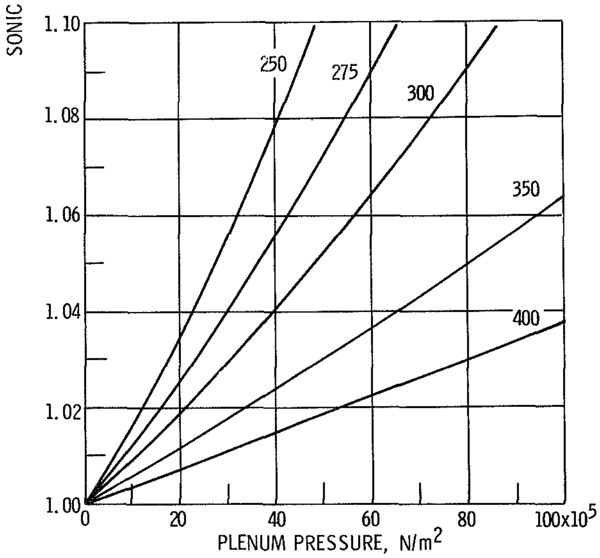
Figure 2

PLENUM TEMPERATURE, K	φ_i SEC $K^{1/2}$/m	φ_i/φ_P
250	0.02951	0.998
275	.02946	.996
300	.02940	.994
350	.02925	.989
400	.02907	.983



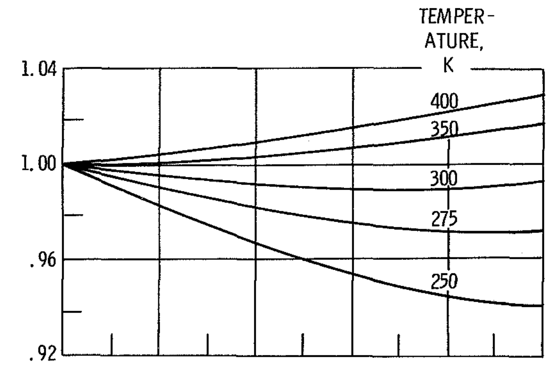
(A) METHANE.

250	.03054	.996
275	.03049	.994
300	.03042	.992
350	.03025	.986
400	.03006	.980

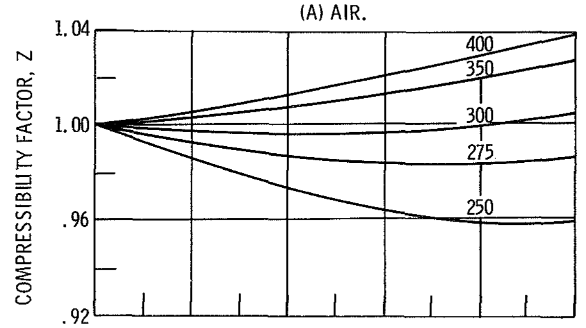


(B) NATURAL GAS (FRACTIONAL COMPOSITION BY VOLUME, CH_4-0.9272, C_2H_6-0.0361, C_3H_8-0.0055, iC_4H_{10}-0.0007, nC_4H_{10}-0.0010, N_2-0.0218, CO_2-0.0077).

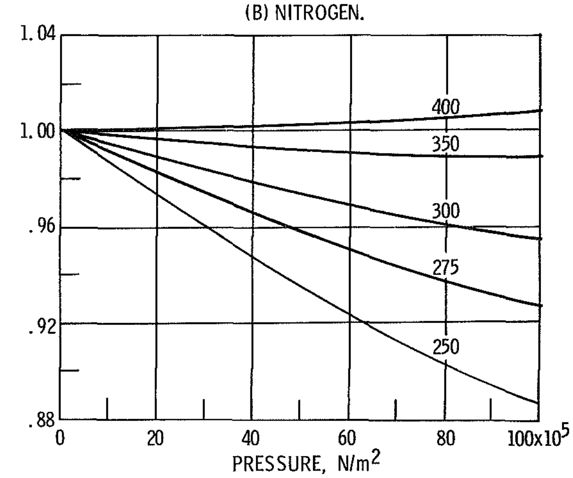
Figure 3



(A) AIR.

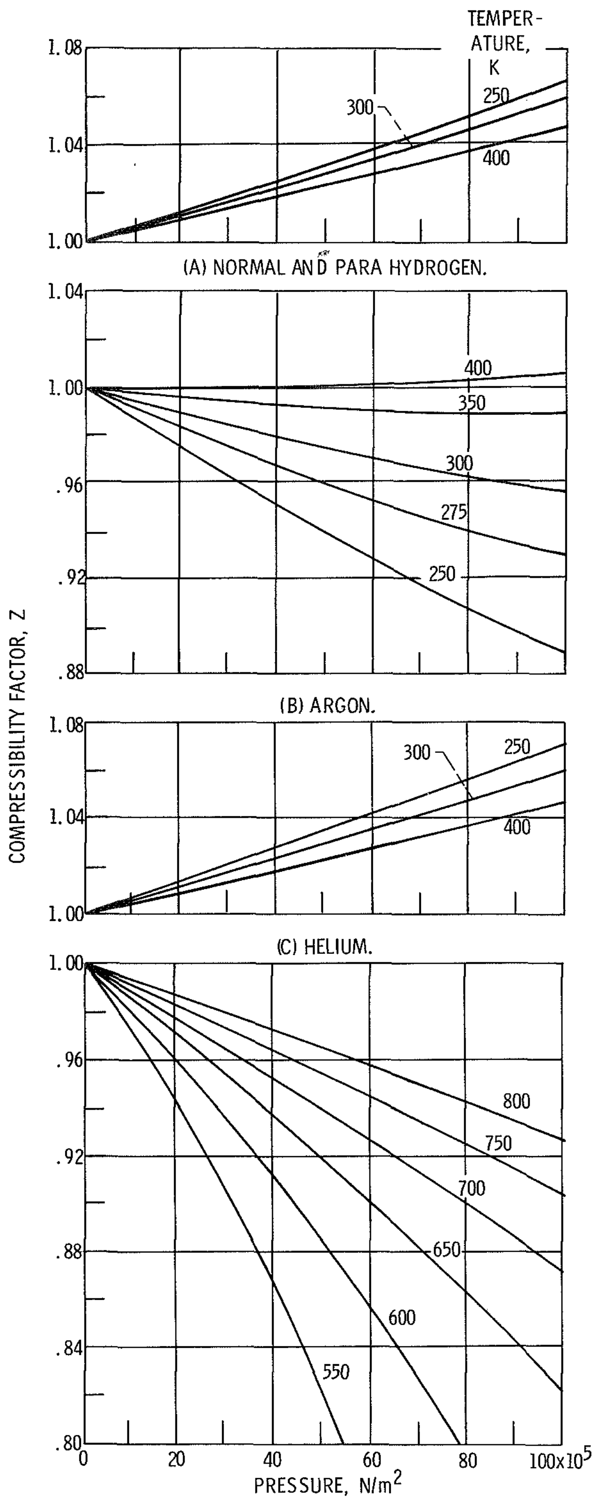


(B) NITROGEN.



(C) OXYGEN.

Figure 4



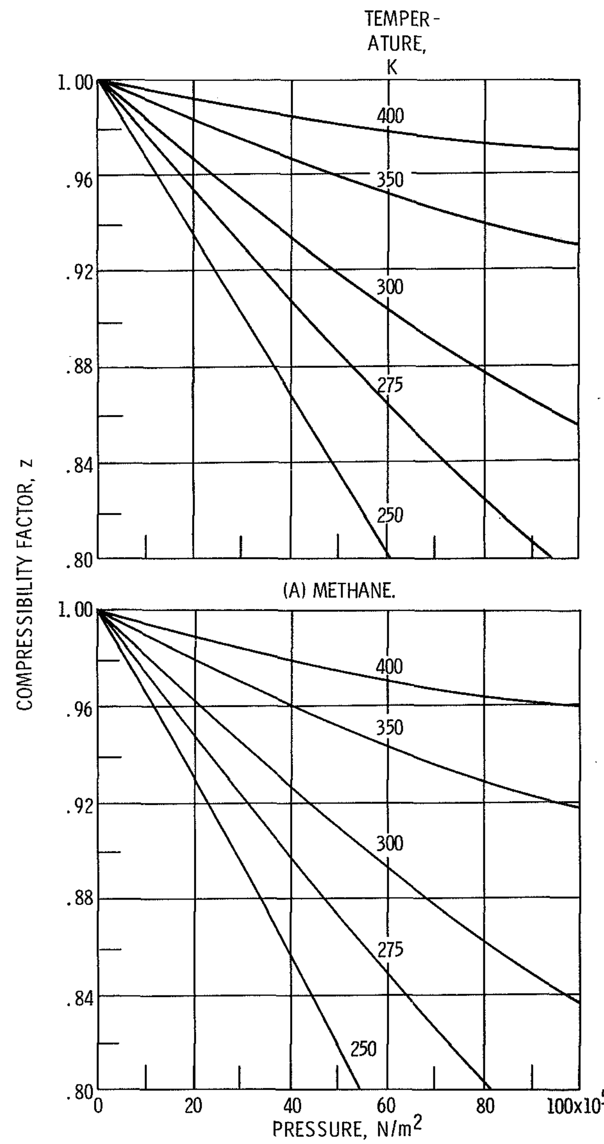
(A) NORMAL AND PARA HYDROGEN.

(B) ARGON.

(C) HELIUM.

(D) STEAM.

Figure 5



(A) METHANE.

(B) NATURAL GAS - (COMPOSITION IS THE SAME AS IN FIG. 3(B)).

Figure 6