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# REAL-GAS EFFECTS IN THE FLOW OF METHANE AND NATURAL GAS THROUGH CRITICAL-FLOW NOZZLES

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# REAL-GAS EFFECTS IN THE FLOW OF METHANE AND NATURAL GAS THROUGH CRITICAL-FLOW NOZZLES

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## INTRODUCTION

When critical-flow nozzles are used for metering the mass flow rate of natural gas, the isentropic flow equations for a perfect gas do not apply. (A critical-flow nozzle is one in which the throat velocity equals the local speed of sound. It has also been called a sonic-flow nozzle or a choked nozzle.) In this paper, a perfect gas is defined as one having an invarient specific heat and a compressibility factor of unity. A perfect gas is to be distinguished from an ideal gas, which has a temperature-dependent specific heat and unity compressibility factor. A nonperfect gas is a real gas. In the absence of dissociation, all real gases approach the ideal-gas condition as the pressure is reduced. 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, natural gas cannot be considered perfect even at pressures less than atmospheric, since natural gas has an appreciable specific-heat variation with temperature. That is, under this condition, natural gas can be considered ideal, but not perfect. At higher pressures, the compressibility factor variation also becomes important.

A number of methods have been used to calculate the isentropic mass flow rate of nonperfect gases. One of these methods is that used in reference 1. In this reference, an isentropic exponent is calculated, and this is then used in the conventional isentropic-flow equations to calculate the flow rates of real gases. Reference 2, using the tabulated data of reference 3, presents tables of compressible-flow functions for the one-dimensional flow of air. Reference 4, using the data of reference 3, presents tables of a critical-flow factor for air, nitrogen, oxygen, normal hydrogen, parahydrogen, and steam that permit the calculation of the isentropic mass flow rate of these gases through critical flow nozzles. Reference 5 presents the critical-flow factor for nitrogen and helium, and, in addition, describes a computer routine for making these real gas computations. In reference 6, a method for calculating both the mass flow rate and the upstream volume flow rate of natural gas through critical-flow nozzles is given. This method requires knowledge of the upstream pressure, temperature, and composition of the natural gas.

In this paper, the results of reference 6 are presented, and, in addition, data for methane are presented which are more accurate than the data in reference 6. These new data are calculated from a state equation given in reference 7. This state equation represents recent methane data and is probably as accurate a representation of the pressure-density-temperature behavior of methane as is presently available. The calculated results in this paper cover a temperature range of 250 to 390 K (450 to 700 R) and pressures up to $69\times10^5$ N/m$^2$ (1000 psia).

This paper will consider only isentropic flow. Actual deviations from isentropic conditions presumably would be embodied in a nozzle discharge coefficient that would be expressible as a function of Reynolds number.

## SYMBOLS

| | |
|---|---|
| $A$ | area |
| $a$ | speed of sound |
| $a_c$ | constant in equation (17) |
| $a_Z$ | constant in equation (18) |
| $b_c$ | constant in equation (17) |
| $b_Z$ | constant in equation (18) |
| $C_D$ | discharge coefficient |
| $c_v$ | specific heat at constant volume |
| $C^*$ | critical flow factor defined in equation (10) |
| $f$ | composition factor defined in equation (16) |
| $H$ | enthalpy |
| $K_H$ | integration constant in equation (5) |
| $K_S$ | integration constant in equation (6) |

| | |
|---|---|
| $M$ | molecular weight |
| $\dot{m}$ | mass flow rate |
| $p$ | pressure |
| $R$ | gas constant |
| $R_m$ | gas constant for calculating mass flow rate (eq. 14) |
| $R_V$ | gas constant for calculating volume flow rate (eq. 15) |
| $S$ | entropy |
| $T$ | temperature |
| $\dot{V}$ | volume flow rate |
| $v$ | velocity |
| $X$ | mole fraction of component in a natural gas mixture |
| $Z$ | compressibility factor |
| $\beta$ | ratio of nozzle throat diameter to inside pipe diameter |
| $\gamma$ | specific heat ratio |
| $\rho$ | density |

Subscripts:

| | |
|---|---|
| 0 | refers to plenum station |
| 1 | refers to nozzle throat station |
| p | refers to a perfect-gas condition |
| i | refers to an ideal-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 assumed to be neither perfect nor ideal and its state equation is given by:

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

where $Z$ is the compressibility factor and is a function 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 density and temperature. The expressions for enthalpy and entropy as developed in reference 8 can be expressed as

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

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

$K_H$ and $K_S$ are constants of integration for the indefinite temperature integrals in equations (5) and (6). As far as equations (2) and (3) are concerned, the values chosen for these constants are immaterial, because they cancel out from both sides of the equations. The expression for the speed of sound, also derivable from reference 8,

$$\frac{a^2}{RT} = Z + \rho \left(\frac{\partial Z}{\partial \rho}\right)_T + \left[Z + T\left(\frac{\partial Z}{\partial T}\right)_{\rho}\right]^2 \Big/ (c_v/R) \tag{7}$$

where

$$\frac{c_v}{R} = \frac{c_{v,i}}{R} - \int_0^{\rho} \left[2T\left(\frac{\partial Z}{\partial T}\right)_{\rho} + T^2\left(\frac{\partial^2 Z}{\partial T^2}\right)_{\rho}\right] \frac{d\rho}{\rho} \tag{8}$$

By substituting equations (5) through (8) in equations (2) through (4), the resulting equations are in terms of density and temperature. Since these equations involve plenum density and temperature rather than the measured plenum pressure and temperature, equation (1) has to be solved for plenum density. The density and temperature equivalents of equations (2) through (5) are then solved for nozzle throat density, temperature, and velocity. The computational procedures for these solutions along with the associated computer program are documented in reference 9. At this point, the mass flow rate of natural gas through a critical-flow nozzle of throat area, $A_1$, can be calculated as follows

$$m = C_D \cdot A_1 \cdot \rho_1 \cdot v_1 \tag{9}$$

In this equation, the discharge coefficient, $C_D$, mainly represents the effects of the nonisentropic and non-one-dimensional flow in the boundary layer of the nozzle. $C_D$ is usually determined by a nozzle calibration and is plotted as a function of Reynolds number. Typical values of $C_D$ are between 0.96 and 1.0 . In these calculations, two equations are used to describe the behavior of natural gas. One is the state equation, (eq. (1)) and the other describes the ideal-gas specific heat. These equations are discussed next.

State equation. Since natural gas is a mixture of many gases, it is desirable to choose a state equation such that the values of its coefficients for a gas mixture can be determined from the coefficients for the individual components of the gas mixture. Such an equation is that developed by Benedict, Webb, and Rubin in references 10 and 11. The form of this equation and the values of the coefficients used for the calculations in this paper are given in reference 9.

Ideal-gas specific heat. This is described by a power series in temperature. The data sources and the power series coefficients for the natural gas components are given in reference 9.

## RESULTS AND DISCUSSION

The results of these calculations are presented in terms of a dimensionless critical-flow factor which is defined as follows:

$$C^* = \frac{(\rho_1 v_1)\sqrt{RT_0}}{p_0} \tag{10}$$

If the gas were perfect, the expression for the critical-flow factor would be constant, would only involve the specific-heat ratio, and would be given by:

$$C_p^* = \left[\gamma\left(\frac{2}{\gamma + 1}\right)^{(\gamma+1)/(\gamma-1)}\right]^{1/2} \tag{11}$$

In terms of the critical-flow factor, the actual mass flow rate of a gas through a critical-flow nozzle is given by

$$\dot{m} = C_D \cdot A_1 \cdot C^* \cdot \frac{p_0}{\sqrt{R_m T_0}} \tag{12}$$

The upstream volume flow rate is then given by

$$\dot{V}_0 = C_D \cdot A_1 \cdot C^* \cdot Z_0 \sqrt{R_V T_0} \tag{13}$$

The specific gas constant in equation (12) is

$$R_m = \frac{48.03}{M} \tag{14}$$

where $M$ is the molecular weight, in order to give $\dot{m}$ in pounds per second $p_0$ is in psia, $A_1$ is in square inches, and $T_0$ is in degrees Rankine.

The specific gas constant for equation (13) is

$$R_V = \frac{2.398}{M} \tag{15}$$

in order to give $\dot{V}_0$ in cubic feet per second, the units of $A_1$ and $T_0$ are the same as those in equation (12).

In equations (12) and (13), the quantities used in determining $\dot{m}$ and $\dot{V}_0$ are the upstream plenum (stagnation) pressure and temperature. In a typical installation, the critical-flow nozzle is installed in a pipe, and the measured pressure is the static pressure that exists at an upstream pipe tap. In order that $\dot{m}$ calculated from this measured pressure shall approximate the $\dot{m}$ calculated from the upstream stagnation pressure, the ratio $\beta$ of the nozzle throat diameter to the upstream, inside pipe diameter should be small. To achieve an error of less than 0.1 percent in $\dot{m}$, $\beta$ should be less than 0.25. The error is on the order of $0.2\ \beta^4$. B. T. Arnberg, in a private communication, recommends that $\beta$ should not exceed 0.25.

If a critical-flow meter is used to prove a volumetric flow meter such as a turbine meter, equation (13) should be used with caution. This equation only applies if the volumetric flow meter is upstream of the critical flow meter, and if the pressure drop between the meters is negligibly small. If this is not true, $\dot{m}$ must be calculated from equation (12), and the density of the gas flowing through the volumetric meter determined separately. By measuring the pressure and the temperature of the gas at the volumetric meter location, this density can be calculated through the use of a state equation (eq. (1)). In measuring the temperature, care should be taken that this temperature will yield the average gas density. This is easy to do if the pipe wall and the gas flowing through the pipe are at the same temperature, which can be achieved if the pipe is insulated, and if time is taken to allow the flowing gas and the pipe to come to thermal equilibrium. Static pressure is usually adequately constant over the pipe cross section, if there is adequate length of straight pipe upstream.

The critical-flow factor was calculated for methane and 19 natural-gas compositions. These compositions were determined from natural-gas samples taken from pipelines throughout the country. The data were supplied in a private communication from Mr. Harry Schroyer of American Meter Company. The range of composition of these gases is given in Table 1. Any alkane in the natural gas having more than 4 carbon atom was ignored. The amount ignored was always less than 0.4 percent by volume; in most cases, it was about 0.1 percent.

Figures 1 and 2 present the critical-flow factor for two typical natural-gas compositions. The dotted portion of the 450 R curve on figure 2 represents a region in the calculation where the partial pressure of one of the components is above the saturation pressure of that component. It is observed that in the limit of zero pressure, a $1\frac{1}{2}$ percent variation in the critical-flow factor exists over the temperature range covered. This is due to the variation of the ideal-gas specific heat with temperature. At a fixed temperature, the variation of the critical-flow factor due to pressure is as much as 20 percent for the pressure range 0 to 1000 psi.

Since the graphical presentation of the data for all 19 natural-gas mixtures would make this paper excessively long, a compact method of presenting these data would be desirable. A method was found that involves a composition factor, f. For methane and the 19 natural-gas mixtures, both the critical-flow factor and the square root of the compressibility factor are linear functions of f. This factor is defined as follows:

$$f = X_{C_2H_6} + X_{CO_2} - \frac{1}{2} X_{N_2} + 2X_{C_3H_8} + 3X_{C_4H_{10}} \qquad (16)$$

where X represents the mole fraction of the component whose chemical symbol appears as a subscript on the X. The accuracy of the critical-flow factor is improved if the correlation is in terms of the product of the critical-flow factor and the square root of the compressibility factor rather than of the critical-flow factor alone. This correlation is as follows:

$$C^* \sqrt{Z_0} = a_c f + b_c \tag{17}$$

where $a_c$ and $b_c$ are functions of plenum pressure and temperature and are determined by means of a least square fit of the data calculated for methane and the 19 natural-gas mixtures. The values of $a_c$ and $b_c$ are listed in Tables 2 and 3. In equation (17), $b_c$ represents the contribution of the methane and $a_c f$ represents the contribution of the other components. (For a perfect-gas mixture with $\gamma = 4/3$, the value of $b_c$ would be 0.6732 and the value of $a_c$ would be 0.)

The coefficients in equation (16) and the form of the equation are entirely empirical. They result from an intuition regarding the contributions of the various components and from several trial-and-error assumptions of numerical values of the coefficients. The values of $C^* \sqrt{Z_0}$ calculated by equation (17) agree with the values of $C^* \sqrt{Z_0}$ used to compute $a_c$ and $b_c$ to within 0.1 percent.

In a similar manner, the square root of the compressibility factor can be represented by

$$\sqrt{Z} = a_Z f + b_Z \tag{18}$$

where $a_Z$ and $b_Z$ are functions of pressure and temperature and are obtained from a least squares fit of the data calculated for methane and the 19 natural-gas mixtures. The values of $a_Z$ and $b_Z$ are listed in Tables 4 and 5. The values of $\sqrt{Z}$ calculated by equation (18) agree with the values calculated by the Benedict-Webb-Rubin state equation to better than 0.5 percent. In most of the cases, the agreement is better than 0.1 percent.

In terms of the factors involved in equations (17) and (18), the expressions for the mass flow rate and volume flow rate become:

$$\dot{m} = C_D A_1 \frac{(a_c f + b_c)}{(a_Z f + b_Z)} \cdot \frac{p_0}{\sqrt{R_m T_0}} \tag{19}$$

and

$$\dot{V}_0 = C_D A_1 (a_c f + b_c)(a_Z f + b_Z) \cdot \sqrt{R_V T_0} \tag{20}$$

Since the coefficients, $a_c$, $b_c$, $a_Z$, and $b_Z$ used in these equations are determined by curve fitting calculated data, the following precautions should be observed in the use of these equations.

1. The mole fractions of the natural-gas components should lie within the range indicated in table 1.

2. The composition factor $f$ should be less than 0.18, which is the maximum value of $f$ calculated for any of the 19 natural gases.

In reference 6, Mr. Hilding Beck, who is one of the discussors in this reference, presents a simplified method of calculating $\dot{m}$ and $V_0$ that is suitable for field use. This method, which uses the data of reference 6, is useful for pressures to 400 psia, and for temperatures from 500 to 560 R.

Although $\dot{m}$ and $\overset{\circ}{V}$ as calculated by equations (19) and (2) are more accurate than if they were calculated using the assumption that natural gas was perfect, errors are still present. The principle sources of these errors are inaccuracies in the Benedict-Webb-Rubin state equation. Recently, Vennix and Kobayashi, in reference 7, presented a state equation for methane that is probably accurate to better than 0.1 percent over the range of pressures and temperatures covered in this paper. In tables 6 and 7 the values of both the critical-flow factor and compressibility factor as calculated by this equation are presented. The details of these calculations are beyond the scope of this paper. In table 8, the values of $C^*$ and $Z_0$ for methane, as calculated by using equations (17) and (18), are compared with the values of $C^*$ and $Z_0$ as tabulated in tables 6 and 7. It is seen that differences of up to 1 percent occur in both $C^*$ and $Z_0$. Over most of the range, the differences are on the order of 1/4 percent. It should be pointed out that while these differences do not exactly apply for natural-gas mixtures, they should apply approximately, since methane is the principal component of natural gas.

## SUMMARY

Equations for the mass flow rate of methane and nineteen natural-gas mixtures through critical flow nozzles have been established, including real-gas effects. For these calculations, the Benedict-Webb-Rubin state equation was used. The data are presented in such a manner, that the mass flow rate can be determined for most natural gases whose composition is known. In addition to the methane calculations based on the Benedict-Webb-Rubin state equations, methane calculations based on a recent

and more accurate state equation are presented. In all cases, the calculations are for pressures to $69 \times 10^5$ N/m$^2$ (1000 psia) and temperatures from 250 to 390 K (450 to 700 R).

TABLE 1. - COMPOSITION RANGE OF 19 NATURAL GASES

| Gas | Mole Fraction |
|---|---|
| Methane | 0.840-0.967 |
| Ethane | 0.003-0.110 |
| Propane | Trace-0.020 |
| 2-Methyl propane | Trace-0.004 |
| Butane | Trace-0.004 |
| Nitrogen | 0.001-0.023 |
| Carbon dioxide | Trace-0.017 |

## REFERENCES

1. W. C. Edminster, "Applied Hydrocarbon Thermodynamics, Part 30. Isentropic Exponents and Critical-Flow Meeting," Hydrocarbon Processing, vol. 46, no. 7, July 1967, pp. 139-143.

2. D. Jordan and M. D. Mintz, Air Tables, McGraw-Hill Book Co. Inc., New York, N. Y., 1965.

3. J. Hilsenrath, et al., Tables of Thermodynamics and Transport Properties, Pergamon Press, New York, N. Y., 1960.

4. R. C. Johnson, "Real-Gas Effects in Critical Flow Through Nozzles and Tabulated Thermodynamic Properties," NASA TN D-2565, 1965.

5. R. C. Johnson, "Real-Gas Effects in Critical Flow Through Nozzles and Thermodynamic Properties of Nitrogen and Helium at Pressures to $300 \times 10^5$ Newtons per Square Meter (Approx. 300 atm)," NASA SP-3046, 1968.

6. R. C. Johnson, "Calculations of the Flow of Natural Gas Through Critical-Flow Nozzles," J. Basic Eng., vol. 92, no. 3, Sept. 1970, pp. 580-590.

7. A. J. Vennix and R. Koboyashi, "An Equation of State for Methane in the Gas and Liquid Phases," AIChE J., vol 15, no. 6, Nov. 1969, pp. 926-931.

8. R. C. Johnson, "Calculations of Real-Gas Effects in Flow Through Critical-Flow Nozzles," *J. Basic Eng.*, vol. 86, no. 3, Sept. 1964, pp. 519-526.

9. R. C. Johnson, "A Set of FORTRAN IV Routines Used to Calculate the Mass Flow Rate of Natural Gas Through Nozzles," NASA TN D-2240, 1971.

10. M. Benedict, G. B. Webb, and L. C. Rubin, "An Empirical Equation for Thermodynamic Properties and Light Hydrocarbons and Their Mixtures," *J. Chem. Phys.*, vol. 8, no. 4, 1940, pp. 334-345.

11. M. Benedict, G. B. Webb, and L. C. Rubin, "An Empirical Equation for Thermodynamic Properties of Light Hydrocarbons and Their Mixtures. Part II - Mixtures of Methane, Ethane, Propane, and n-Butane, "*J. Chem. Phys.*, vol. 10, no. 12, 1942, pp. 747-758.

Table 2

Value of $a_c$

| Plenum temperature, deg R | Plenum pressure, psia | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|
| | 0 | 100 | 200 | 300 | 400 | 500 | 600 | 700 | 800 | 900 | 1000 |
| 450 | -0.0265 | -0.0297 | -0.0330 | -0.0365 | -0.0399 | -0.0430 | -0.0452 | -0.0458 | -0.0435 | -0.0361 | -0.0206 |
| 460 | -0.0272 | -0.0302 | -0.0334 | -0.0366 | -0.0398 | -0.0426 | -0.0448 | -0.0457 | -0.0443 | -0.0394 | -0.0290 |
| 470 | -0.0279 | -0.0308 | -0.0338 | -0.0368 | -0.0398 | -0.0424 | -0.0445 | -0.0455 | -0.0448 | -0.0414 | -0.0343 |
| 480 | -0.0285 | -0.0313 | -0.0342 | -0.0371 | -0.0398 | -0.0423 | -0.0442 | -0.0453 | -0.0451 | -0.0428 | -0.0376 |
| 490 | -0.0292 | -0.0318 | -0.0346 | -0.0373 | -0.0399 | -0.0422 | -0.0441 | -0.0452 | -0.0452 | -0.0437 | -0.0399 |
| 500 | -0.0298 | -0.0324 | -0.0350 | -0.0375 | -0.0400 | -0.0422 | -0.0440 | -0.0451 | -0.0454 | -0.0443 | -0.0416 |
| 510 | -0.0304 | -0.0329 | -0.0353 | -0.0378 | -0.0401 | -0.0422 | -0.0439 | -0.0451 | -0.0455 | -0.0448 | -0.0427 |
| 520 | -0.0310 | -0.0333 | -0.0357 | -0.0380 | -0.0402 | -0.0422 | -0.0439 | -0.0450 | -0.0455 | -0.0451 | -0.0436 |
| 530 | -0.0315 | -0.0338 | -0.0361 | -0.0383 | -0.0404 | -0.0423 | -0.0439 | -0.0450 | -0.0456 | -0.0454 | -0.0443 |
| 540 | -0.0321 | -0.0343 | -0.0365 | -0.0386 | -0.0406 | -0.0424 | -0.0439 | -0.0450 | -0.0456 | -0.0456 | -0.0448 |
| 550 | -0.0326 | -0.0347 | -0.0368 | -0.0388 | -0.0407 | -0.0425 | -0.0439 | -0.0450 | -0.0457 | -0.0458 | -0.0452 |
| 560 | -0.0331 | -0.0351 | -0.0371 | -0.0391 | -0.0409 | -0.0426 | -0.0440 | -0.0451 | -0.0458 | -0.0459 | -0.0455 |
| 570 | -0.0335 | -0.0355 | -0.0375 | -0.0393 | -0.0411 | -0.0427 | -0.0440 | -0.0451 | -0.0458 | -0.0461 | -0.0458 |
| 580 | -0.0340 | -0.0359 | -0.0378 | -0.0396 | -0.0412 | -0.0428 | -0.0441 | -0.0451 | -0.0458 | -0.0462 | -0.0460 |
| 590 | -0.0344 | -0.0362 | -0.0380 | -0.0398 | -0.0414 | -0.0428 | -0.0441 | -0.0451 | -0.0459 | -0.0462 | -0.0462 |
| 600 | -0.0348 | -0.0366 | -0.0383 | -0.0400 | -0.0415 | -0.0429 | -0.0441 | -0.0451 | -0.0459 | -0.0463 | -0.0463 |
| 610 | -0.0351 | -0.0368 | -0.0385 | -0.0401 | -0.0416 | -0.0430 | -0.0442 | -0.0451 | -0.0459 | -0.0463 | -0.0464 |
| 620 | -0.0354 | -0.0371 | -0.0387 | -0.0403 | -0.0417 | -0.0430 | -0.0442 | -0.0451 | -0.0458 | -0.0463 | -0.0464 |
| 630 | -0.0357 | -0.0373 | -0.0389 | -0.0404 | -0.0418 | -0.0430 | -0.0442 | -0.0451 | -0.0458 | -0.0462 | -0.0464 |
| 640 | -0.0360 | -0.0375 | -0.0390 | -0.0405 | -0.0418 | -0.0430 | -0.0441 | -0.0450 | -0.0457 | -0.0462 | -0.0464 |
| 650 | -0.0362 | -0.0377 | -0.0392 | -0.0406 | -0.0418 | -0.0430 | -0.0441 | -0.0449 | -0.0456 | -0.0461 | -0.0463 |
| 660 | -0.0363 | -0.0378 | -0.0392 | -0.0406 | -0.0418 | -0.0430 | -0.0440 | -0.0448 | -0.0455 | -0.0460 | -0.0462 |
| 670 | -0.0365 | -0.0379 | -0.0393 | -0.0406 | -0.0418 | -0.0429 | -0.0439 | -0.0447 | -0.0453 | -0.0458 | -0.0461 |
| 680 | -0.0366 | -0.0380 | -0.0393 | -0.0406 | -0.0417 | -0.0428 | -0.0437 | -0.0445 | -0.0452 | -0.0456 | -0.0459 |
| 690 | -0.0367 | -0.0380 | -0.0393 | -0.0405 | -0.0416 | -0.0427 | -0.0436 | -0.0443 | -0.0450 | -0.0454 | -0.0457 |
| 700 | -0.0367 | -0.0380 | -0.0392 | -0.0404 | -0.0415 | -0.0425 | -0.0434 | -0.0441 | -0.0447 | -0.0452 | -0.0455 |

Table 3

Value of $b_c$

| Plenum temperature, deg R | Plenum pressure, psia | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|
| | 0 | 100 | 200 | 300 | 400 | 500 | 600 | 700 | 800 | 900 | 1000 |
| 450 | 0.6719 | 0.6715 | 0.6713 | 0.6712 | 0.6713 | 0.6717 | 0.6723 | 0.6733 | 0.6747 | 0.6767 | 0.6791 |
| 460 | 0.6717 | 0.6714 | 0.6712 | 0.6712 | 0.6713 | 0.6717 | 0.6724 | 0.6734 | 0.6748 | 0.6766 | 0.6789 |
| 470 | 0.6714 | 0.6712 | 0.6711 | 0.6711 | 0.6714 | 0.6718 | 0.6725 | 0.6734 | 0.6747 | 0.6764 | 0.6786 |
| 480 | 0.6712 | 0.6710 | 0.6710 | 0.6711 | 0.6713 | 0.6718 | 0.6725 | 0.6734 | 0.6747 | 0.6763 | 0.6783 |
| 490 | 0.6709 | 0.6708 | 0.6708 | 0.6709 | 0.6712 | 0.6717 | 0.6724 | 0.6734 | 0.6746 | 0.6761 | 0.6780 |
| 500 | 0.6707 | 0.6706 | 0.6706 | 0.6708 | 0.6711 | 0.6716 | 0.6723 | 0.6733 | 0.6745 | 0.6759 | 0.6777 |
| 510 | 0.6704 | 0.6703 | 0.6704 | 0.6706 | 0.6710 | 0.6715 | 0.6722 | 0.6731 | 0.6743 | 0.6757 | 0.6774 |
| 520 | 0.6701 | 0.6701 | 0.6702 | 0.6704 | 0.6708 | 0.6714 | 0.6721 | 0.6730 | 0.6741 | 0.6755 | 0.6771 |
| 530 | 0.6698 | 0.6698 | 0.6699 | 0.6702 | 0.6706 | 0.6712 | 0.6719 | 0.6728 | 0.6739 | 0.6752 | 0.6767 |
| 540 | 0.6694 | 0.6695 | 0.6697 | 0.6700 | 0.6704 | 0.6709 | 0.6717 | 0.6726 | 0.6736 | 0.6749 | 0.6764 |
| 550 | 0.6691 | 0.6692 | 0.6694 | 0.6697 | 0.6701 | 0.6707 | 0.6714 | 0.6723 | 0.6734 | 0.6746 | 0.6760 |
| 560 | 0.6687 | 0.6689 | 0.6691 | 0.6694 | 0.6699 | 0.6704 | 0.6712 | 0.6720 | 0.6731 | 0.6743 | 0.6756 |
| 570 | 0.6684 | 0.6685 | 0.6687 | 0.6691 | 0.6696 | 0.6701 | 0.6709 | 0.6717 | 0.6727 | 0.6739 | 0.6753 |
| 580 | 0.6680 | 0.6681 | 0.6684 | 0.6688 | 0.6692 | 0.6698 | 0.6706 | 0.6714 | 0.6724 | 0.6735 | 0.6748 |
| 590 | 0.6676 | 0.6678 | 0.6680 | 0.6684 | 0.6689 | 0.6695 | 0.6702 | 0.6711 | 0.6720 | 0.6732 | 0.6744 |
| 600 | 0.6672 | 0.6674 | 0.6677 | 0.6681 | 0.6686 | 0.6692 | 0.6699 | 0.6707 | 0.6717 | 0.6728 | 0.6740 |
| 610 | 0.6668 | 0.6670 | 0.6673 | 0.6677 | 0.6682 | 0.6688 | 0.6695 | 0.6703 | 0.6713 | 0.6723 | 0.6735 |
| 620 | 0.6663 | 0.6666 | 0.6669 | 0.6673 | 0.6678 | 0.6684 | 0.6691 | 0.6699 | 0.6709 | 0.6719 | 0.6731 |
| 630 | 0.6659 | 0.6662 | 0.6665 | 0.6669 | 0.6674 | 0.6680 | 0.6687 | 0.6695 | 0.6705 | 0.6715 | 0.6726 |
| 640 | 0.6655 | 0.6657 | 0.6661 | 0.6665 | 0.6670 | 0.6676 | 0.6683 | 0.6691 | 0.6700 | 0.6710 | 0.6721 |
| 650 | 0.6650 | 0.6653 | 0.6656 | 0.6661 | 0.6666 | 0.6672 | 0.6679 | 0.6687 | 0.6696 | 0.6706 | 0.6717 |
| 660 | 0.6646 | 0.6649 | 0.6652 | 0.6657 | 0.6662 | 0.6668 | 0.6675 | 0.6683 | 0.6691 | 0.6701 | 0.6712 |
| 670 | 0.6641 | 0.6644 | 0.6648 | 0.6652 | 0.6658 | 0.6664 | 0.6671 | 0.6678 | 0.6687 | 0.6696 | 0.6707 |
| 680 | 0.6637 | 0.6640 | 0.6643 | 0.6648 | 0.6653 | 0.6659 | 0.6666 | 0.6674 | 0.6682 | 0.6692 | 0.6702 |
| 690 | 0.6632 | 0.6635 | 0.6639 | 0.6644 | 0.6649 | 0.6655 | 0.6662 | 0.6669 | 0.6678 | 0.6687 | 0.6697 |
| 700 | 0.6627 | 0.6631 | 0.6635 | 0.6639 | 0.6644 | 0.6651 | 0.6657 | 0.6665 | 0.6673 | 0.6682 | 0.6692 |

## Table 4

### Value of $a_z$

| Plenum temperature, deg R | Plenum pressure, psia | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|
| | 0 | 100 | 200 | 300 | 400 | 500 | 600 | 700 | 800 | 900 | 1000 |
| 450 | 0. | -0.0252 | -0.0530 | -0.0837 | -0.1179 | -0.1561 | -0.1988 | -0.2464 | -0.2991 | -0.3564 | -0.4162 |
| 460 | 0. | -0.0234 | -0.0490 | -0.0770 | -0.1078 | -0.1417 | -0.1790 | -0.2199 | -0.2644 | -0.3118 | -0.3610 |
| 470 | 0. | -0.0218 | -0.0454 | -0.0710 | -0.0989 | -0.1293 | -0.1622 | -0.1978 | -0.2360 | -0.2762 | -0.3175 |
| 480 | 0. | -0.0203 | -0.0422 | -0.0657 | -0.0911 | -0.1184 | -0.1478 | -0.1791 | -0.2123 | -0.2469 | -0.2823 |
| 490 | 0. | -0.0190 | -0.0393 | -0.0610 | -0.0842 | -0.1089 | -0.1353 | -0.1631 | -0.1923 | -0.2225 | -0.2532 |
| 500 | 0. | -0.0178 | -0.0366 | -0.0567 | -0.0780 | -0.1005 | -0.1243 | -0.1493 | -0.1752 | -0.2018 | -0.2288 |
| 510 | 0. | -0.0166 | -0.0342 | -0.0528 | -0.0724 | -0.0931 | -0.1147 | -0.1371 | -0.1604 | -0.1841 | -0.2079 |
| 520 | 0. | -0.0156 | -0.0321 | -0.0493 | -0.0675 | -0.0864 | -0.1061 | -0.1265 | -0.1474 | -0.1687 | -0.1900 |
| 530 | 0. | -0.0147 | -0.0301 | -0.0462 | -0.0630 | -0.0804 | -0.0984 | -0.1170 | -0.1360 | -0.1552 | -0.1743 |
| 540 | 0. | -0.0138 | -0.0283 | -0.0433 | -0.0589 | -0.0750 | -0.0916 | -0.1086 | -0.1259 | -0.1433 | -0.1606 |
| 550 | 0. | -0.0130 | -0.0266 | -0.0406 | -0.0551 | -0.0701 | -0.0854 | -0.1010 | -0.1169 | -0.1327 | -0.1485 |
| 560 | 0. | -0.0123 | -0.0251 | -0.0382 | -0.0518 | -0.0656 | -0.0798 | -0.0942 | -0.1088 | -0.1233 | -0.1377 |
| 570 | 0. | -0.0116 | -0.0236 | -0.0360 | -0.0487 | -0.0616 | -0.0748 | -0.0881 | -0.1015 | -0.1149 | -0.1281 |
| 580 | 0. | -0.0110 | -0.0223 | -0.0339 | -0.0458 | -0.0579 | -0.0701 | -0.0825 | -0.0949 | -0.1072 | -0.1194 |
| 590 | 0. | -0.0104 | -0.0211 | -0.0320 | -0.0432 | -0.0545 | -0.0659 | -0.0774 | -0.0889 | -0.1003 | -0.1116 |
| 600 | 0. | -0.0099 | -0.0200 | -0.0303 | -0.0408 | -0.0514 | -0.0621 | -0.0728 | -0.0835 | -0.0941 | -0.1045 |
| 610 | 0. | -0.0094 | -0.0190 | -0.0287 | -0.0385 | -0.0485 | -0.0585 | -0.0685 | -0.0785 | -0.0883 | -0.0980 |
| 620 | 0. | -0.0089 | -0.0180 | -0.0272 | -0.0365 | -0.0458 | -0.0552 | -0.0646 | -0.0739 | -0.0831 | -0.0921 |
| 630 | 0. | -0.0085 | -0.0171 | -0.0258 | -0.0346 | -0.0434 | -0.0522 | -0.0610 | -0.0697 | -0.0783 | -0.0867 |
| 640 | 0. | -0.0081 | -0.0162 | -0.0245 | -0.0328 | -0.0411 | -0.0494 | -0.0577 | -0.0658 | -0.0739 | -0.0818 |
| 650 | 0. | -0.0077 | -0.0154 | -0.0233 | -0.0311 | -0.0390 | -0.0468 | -0.0546 | -0.0623 | -0.0698 | -0.0772 |
| 660 | 0. | -0.0073 | -0.0147 | -0.0221 | -0.0296 | -0.0370 | -0.0444 | -0.0517 | -0.0589 | -0.0660 | -0.0730 |
| 670 | 0. | -0.0070 | -0.0140 | -0.0211 | -0.0281 | -0.0352 | -0.0422 | -0.0491 | -0.0559 | -0.0625 | -0.0691 |
| 680 | 0. | -0.0067 | -0.0134 | -0.0201 | -0.0268 | -0.0334 | -0.0401 | -0.0466 | -0.0530 | -0.0593 | -0.0654 |
| 690 | 0. | -0.0064 | -0.0128 | -0.0192 | -0.0255 | -0.0318 | -0.0381 | -0.0443 | -0.0503 | -0.0563 | -0.0621 |
| 700 | 0. | -0.0061 | -0.0122 | -0.0183 | -0.0243 | -0.0303 | -0.0363 | -0.0421 | -0.0479 | -0.0535 | -0.0589 |

## Table 5

### Value of $b_z$

| Plenum temperature, deg R | Plenum pressure, psia | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|
| | 0 | 100 | 200 | 300 | 400 | 500 | 600 | 700 | 800 | 900 | 1000 |
| 450 | 1.0000 | 0.9891 | 0.9780 | 0.9667 | 0.9552 | 0.9434 | 0.9315 | 0.9195 | 0.9075 | 0.8955 | 0.8837 |
| 460 | 1.0000 | 0.9899 | 0.9796 | 0.9692 | 0.9585 | 0.9478 | 0.9370 | 0.9261 | 0.9152 | 0.9044 | 0.8938 |
| 470 | 1.0000 | 0.9906 | 0.9810 | 0.9714 | 0.9616 | 0.9518 | 0.9419 | 0.9320 | 0.9221 | 0.9124 | 0.9028 |
| 480 | 1.0000 | 0.9912 | 0.9824 | 0.9734 | 0.9644 | 0.9553 | 0.9463 | 0.9373 | 0.9283 | 0.9195 | 0.9109 |
| 490 | 1.0000 | 0.9918 | 0.9836 | 0.9753 | 0.9669 | 0.9586 | 0.9503 | 0.9420 | 0.9339 | 0.9259 | 0.9181 |
| 500 | 1.0000 | 0.9924 | 0.9847 | 0.9770 | 0.9693 | 0.9616 | 0.9539 | 0.9464 | 0.9389 | 0.9316 | 0.9245 |
| 510 | 1.0000 | 0.9929 | 0.9857 | 0.9785 | 0.9714 | 0.9643 | 0.9573 | 0.9503 | 0.9435 | 0.9369 | 0.9304 |
| 520 | 1.0000 | 0.9933 | 0.9866 | 0.9800 | 0.9734 | 0.9668 | 0.9603 | 0.9539 | 0.9477 | 0.9416 | 0.9357 |
| 530 | 1.0000 | 0.9937 | 0.9875 | 0.9813 | 0.9752 | 0.9691 | 0.9631 | 0.9572 | 0.9515 | 0.9459 | 0.9406 |
| 540 | 1.0000 | 0.9941 | 0.9883 | 0.9826 | 0.9768 | 0.9712 | 0.9657 | 0.9603 | 0.9550 | 0.9499 | 0.9450 |
| 550 | 1.0000 | 0.9945 | 0.9891 | 0.9837 | 0.9784 | 0.9732 | 0.9681 | 0.9631 | 0.9582 | 0.9535 | 0.9490 |
| 560 | 1.0000 | 0.9949 | 0.9898 | 0.9848 | 0.9798 | 0.9750 | 0.9702 | 0.9656 | 0.9612 | 0.9569 | 0.9527 |
| 570 | 1.0000 | 0.9952 | 0.9904 | 0.9857 | 0.9811 | 0.9766 | 0.9723 | 0.9680 | 0.9639 | 0.9599 | 0.9562 |
| 580 | 1.0000 | 0.9955 | 0.9910 | 0.9867 | 0.9824 | 0.9782 | 0.9741 | 0.9702 | 0.9664 | 0.9628 | 0.9593 |
| 590 | 1.0000 | 0.9958 | 0.9916 | 0.9875 | 0.9835 | 0.9797 | 0.9759 | 0.9723 | 0.9688 | 0.9654 | 0.9622 |
| 600 | 1.0000 | 0.9960 | 0.9921 | 0.9883 | 0.9846 | 0.9810 | 0.9775 | 0.9741 | 0.9709 | 0.9678 | 0.9649 |
| 610 | 1.0000 | 0.9963 | 0.9926 | 0.9891 | 0.9856 | 0.9823 | 0.9790 | 0.9759 | 0.9729 | 0.9701 | 0.9674 |
| 620 | 1.0000 | 0.9965 | 0.9931 | 0.9898 | 0.9865 | 0.9834 | 0.9804 | 0.9776 | 0.9748 | 0.9722 | 0.9698 |
| 630 | 1.0000 | 0.9967 | 0.9935 | 0.9904 | 0.9874 | 0.9845 | 0.9817 | 0.9791 | 0.9766 | 0.9742 | 0.9719 |
| 640 | 1.0000 | 0.9969 | 0.9939 | 0.9910 | 0.9882 | 0.9856 | 0.9830 | 0.9805 | 0.9782 | 0.9760 | 0.9740 |
| 650 | 1.0000 | 0.9971 | 0.9943 | 0.9916 | 0.9890 | 0.9865 | 0.9841 | 0.9819 | 0.9797 | 0.9777 | 0.9758 |
| 660 | 1.0000 | 0.9973 | 0.9947 | 0.9922 | 0.9897 | 0.9874 | 0.9852 | 0.9831 | 0.9812 | 0.9793 | 0.9776 |
| 670 | 1.0000 | 0.9975 | 0.9950 | 0.9927 | 0.9904 | 0.9883 | 0.9862 | 0.9843 | 0.9825 | 0.9808 | 0.9793 |
| 680 | 1.0000 | 0.9976 | 0.9953 | 0.9931 | 0.9911 | 0.9891 | 0.9872 | 0.9854 | 0.9838 | 0.9822 | 0.9808 |
| 690 | 1.0000 | 0.9978 | 0.9956 | 0.9936 | 0.9917 | 0.9898 | 0.9881 | 0.9865 | 0.9849 | 0.9835 | 0.9823 |
| 700 | 1.0000 | 0.9979 | 0.9959 | 0.9940 | 0.9922 | 0.9905 | 0.9889 | 0.9874 | 0.9861 | 0.9848 | 0.9836 |

## Table 6

## CRITICAL FLOW FACTOR, $C^*$, FOR METHANE

| PLENUM TEMPERATURE DEG R | PLENUM PRESSURE, PSIA 0 | 100 | 200 | 300 | 400 | 500 | 600 | 700 | 800 | 900 | 1000 |
|---|---|---|---|---|---|---|---|---|---|---|---|
| 450 | 0.6717 | 0.6790 | 0.6867 | 0.6951 | 0.7041 | 0.7137 | 0.7242 | 0.7356 | 0.7479 | 0.7613 | 0.7759 |
| 460 | 0.6715 | 0.6784 | 0.6856 | 0.6934 | 0.7017 | 0.7106 | 0.7202 | 0.7304 | 0.7415 | 0.7534 | 0.7661 |
| 470 | 0.6713 | 0.6778 | 0.6846 | 0.6918 | 0.6995 | 0.7077 | 0.7165 | 0.7258 | 0.7358 | 0.7464 | 0.7577 |
| 480 | 0.6711 | 0.6771 | 0.6836 | 0.6903 | 0.6975 | 0.7051 | 0.7131 | 0.7216 | 0.730[illegible] | 0.7402 | 0.7503 |
| 490 | 0.6708 | 0.6765 | 0.6826 | 0.6889 | 0.6956 | 0.7026 | 0.7100 | 0.7178 | 0.7260 | 0.7346 | 0.7437 |
| 500 | 0.6706 | 0.6760 | 0.6816 | 0.6875 | 0.6938 | 0.7003 | 0.7071 | 0.7143 | 0.7218 | 0.7296 | 0.7378 |
| 510 | 0.6703 | 0.6754 | 0.6807 | 0.6862 | 0.6920 | 0.6981 | 0.7044 | 0.7110 | 0.7179 | 0.7250 | 0.7325 |
| 520 | 0.6700 | 0.6748 | 0.6798 | 0.6850 | 0.6904 | 0.6961 | 0.7019 | 0.7080 | 0.7143 | 0.7209 | 0.7276 |
| 530 | 0.6697 | 0.6742 | 0.6789 | 0.6838 | 0.6889 | 0.6941 | 0.6996 | 0.7052 | 0.7110 | 0.7170 | 0.7232 |
| 540 | 0.6693 | 0.6736 | 0.6781 | 0.6827 | 0.6874 | 0.6923 | 0.6974 | 0.7026 | 0.7080 | 0.7135 | 0.7192 |
| 550 | 0.6690 | 0.6730 | 0.6772 | 0.6815 | 0.6860 | 0.6906 | 0.6953 | 0.7002 | 0.7051 | 0.7102 | 0.7155 |
| 560 | 0.6686 | 0.6725 | 0.6764 | 0.6805 | 0.6846 | 0.6889 | 0.6933 | 0.6978 | 0.7025 | 0.7072 | 0.7120 |
| 570 | 0.6682 | 0.6719 | 0.6756 | 0.6794 | 0.6833 | 0.6874 | 0.6915 | 0.6957 | 0.7000 | 0.7043 | 0.7088 |
| 580 | 0.6679 | 0.6713 | 0.6748 | 0.6784 | 0.6821 | 0.6859 | 0.6897 | 0.6936 | 0.6976 | 0.7017 | 0.7058 |
| 590 | 0.6675 | 0.6707 | 0.6740 | 0.6774 | 0.6809 | 0.6844 | 0.6880 | 0.6917 | 0.6954 | 0.6992 | 0.7030 |
| 600 | 0.6671 | 0.6701 | 0.6733 | 0.6765 | 0.6797 | 0.6830 | 0.6864 | 0.6898 | 0.6933 | 0.6968 | 0.7004 |
| 610 | 0.6666 | 0.6695 | 0.6725 | 0.6755 | 0.6786 | 0.6817 | 0.6849 | 0.6881 | 0.6913 | 0.6946 | 0.6979 |
| 620 | 0.6662 | 0.6690 | 0.6718 | 0.6746 | 0.6775 | 0.6804 | 0.6834 | 0.6864 | 0.6894 | 0.6925 | 0.6956 |
| 630 | 0.6658 | 0.6684 | 0.6710 | 0.6737 | 0.6765 | 0.6792 | 0.6820 | 0.6848 | 0.6876 | 0.6905 | 0.6934 |
| 640 | 0.6653 | 0.6678 | 0.6703 | 0.6729 | 0.6754 | 0.6780 | 0.6806 | 0.6833 | 0.6859 | 0.6886 | 0.6913 |
| 650 | 0.6649 | 0.6672 | 0.6696 | 0.6720 | 0.6744 | 0.6769 | 0.6793 | 0.6818 | 0.6843 | 0.6868 | 0.6893 |
| 660 | 0.6645 | 0.6667 | 0.6689 | 0.6712 | 0.6735 | 0.6758 | 0.6781 | 0.6804 | 0.6827 | 0.6851 | 0.6874 |
| 670 | 0.6640 | 0.6661 | 0.6682 | 0.6704 | 0.6725 | 0.6747 | 0.6769 | 0.6791 | 0.6812 | 0.6834 | 0.6856 |
| 680 | 0.6635 | 0.6655 | 0.6675 | 0.6696 | 0.6716 | 0.6736 | 0.6757 | 0.6778 | 0.6798 | 0.6819 | 0.6839 |
| 690 | 0.6631 | 0.6650 | 0.6669 | 0.6688 | 0.6707 | 0.6726 | 0.6746 | 0.6765 | 0.6784 | 0.6804 | 0.6823 |
| 700 | 0.6626 | 0.6644 | 0.6662 | 0.6680 | 0.6698 | 0.6717 | 0.6735 | 0.6753 | 0.6771 | 0.6789 | 0.6808 |

## Table 7

## COMPRESSIBILITY FACTOR, Z, FOR METHANE

| PLENUM TEMPERATURE DEG R | PLENUM PRESSURE, PSIA 0 | 100 | 200 | 300 | 400 | 500 | 600 | 700 | 800 | 900 | 1000 |
|---|---|---|---|---|---|---|---|---|---|---|---|
| 450 | 1.0000 | 0.9780 | 0.9556 | 0.9331 | 0.9103 | 0.8874 | 0.8643 | 0.8412 | 0.8182 | 0.7955 | 0.7732 |
| 460 | 1.0000 | 0.9795 | 0.9588 | 0.9379 | 0.9169 | 0.8959 | 0.8749 | 0.8539 | 0.8331 | 0.8127 | 0.7927 |
| 470 | 1.0000 | 0.9809 | 0.9616 | 0.9423 | 0.9230 | 0.9037 | 0.8844 | 0.8653 | 0.8465 | 0.8280 | 0.8099 |
| 480 | 1.0000 | 0.9821 | 0.9643 | 0.9464 | 0.9285 | 0.9108 | 0.8931 | 0.8757 | 0.8585 | 0.8417 | 0.8254 |
| 490 | 1.0000 | 0.9833 | 0.9667 | 0.9501 | 0.9336 | 0.9172 | 0.9010 | 0.8850 | 0.8694 | 0.8541 | 0.8393 |
| 500 | 1.0000 | 0.9845 | 0.9690 | 0.9536 | 0.9383 | 0.9232 | 0.9083 | 0.8936 | 0.8793 | 0.8653 | 0.8518 |
| 510 | 1.0000 | 0.9855 | 0.9711 | 0.9567 | 0.9426 | 0.9286 | 0.9149 | 0.9014 | 0.8883 | 0.8755 | 0.8632 |
| 520 | 1.0000 | 0.9864 | 0.9730 | 0.9597 | 0.9466 | 0.9337 | 0.9210 | 0.9086 | 0.8965 | 0.8849 | 0.8736 |
| 530 | 1.0000 | 0.9873 | 0.9748 | 0.9624 | 0.9503 | 0.9383 | 0.9266 | 0.9152 | 0.9041 | 0.8934 | 0.8831 |
| 540 | 1.0000 | 0.9882 | 0.9765 | 0.9650 | 0.9537 | 0.9426 | 0.9318 | 0.9213 | 0.9111 | 0.9013 | 0.8918 |
| 550 | 1.0000 | 0.9889 | 0.9780 | 0.9673 | 0.9569 | 0.9466 | 0.9366 | 0.9269 | 0.9175 | 0.9085 | 0.8998 |
| 560 | 1.0000 | 0.9897 | 0.9795 | 0.9696 | 0.9598 | 0.9503 | 0.9411 | 0.9321 | 0.9235 | 0.9152 | 0.9072 |
| 570 | 1.0000 | 0.9903 | 0.9809 | 0.9716 | 0.9626 | 0.9538 | 0.9452 | 0.9370 | 0.9290 | 0.9214 | 0.9141 |
| 580 | 1.0000 | 0.9910 | 0.9821 | 0.9735 | 0.9651 | 0.9570 | 0.9491 | 0.9415 | 0.9341 | 0.9271 | 0.9204 |
| 590 | 1.0000 | 0.9916 | 0.9833 | 0.9753 | 0.9675 | 0.9600 | 0.9527 | 0.9456 | 0.9389 | 0.9324 | 0.9263 |
| 600 | 1.0000 | 0.9921 | 0.9845 | 0.9770 | 0.9698 | 0.9628 | 0.9560 | 0.9495 | 0.9433 | 0.9374 | 0.9318 |
| 610 | 1.0000 | 0.9927 | 0.9855 | 0.9786 | 0.9719 | 0.9654 | 0.9591 | 0.9532 | 0.9474 | 0.9420 | 0.9368 |
| 620 | 1.0000 | 0.9931 | 0.9865 | 0.9801 | 0.9738 | 0.9678 | 0.9621 | 0.9566 | 0.9513 | 0.9463 | 0.9416 |
| 630 | 1.0000 | 0.9936 | 0.9874 | 0.9814 | 0.9757 | 0.9701 | 0.9648 | 0.9597 | 0.9549 | 0.9503 | 0.9460 |
| 640 | 1.0000 | 0.9940 | 0.9883 | 0.9827 | 0.9774 | 0.9723 | 0.9674 | 0.9627 | 0.9583 | 0.9541 | 0.9501 |
| 650 | 1.0000 | 0.9945 | 0.9891 | 0.9840 | 0.9790 | 0.9743 | 0.9698 | 0.9655 | 0.9614 | 0.9576 | 0.9540 |
| 660 | 1.0000 | 0.9948 | 0.9899 | 0.9851 | 0.9805 | 0.9762 | 0.9720 | 0.9681 | 0.9644 | 0.9609 | 0.9576 |
| 670 | 1.0000 | 0.9952 | 0.9906 | 0.9862 | 0.9820 | 0.9780 | 0.9742 | 0.9706 | 0.9672 | 0.9640 | 0.9610 |
| 680 | 1.0000 | 0.9956 | 0.9913 | 0.9872 | 0.9833 | 0.9796 | 0.9762 | 0.9729 | 0.9698 | 0.9669 | 0.9642 |
| 690 | 1.0000 | 0.9959 | 0.9919 | 0.9882 | 0.9846 | 0.9812 | 0.9780 | 0.9750 | 0.9722 | 0.9696 | 0.9672 |
| 700 | 1.0000 | 0.9962 | 0.9925 | 0.9891 | 0.9858 | 0.9827 | 0.9798 | 0.9771 | 0.9745 | 0.9722 | 0.9701 |

# Table 8

## Comparison of Functions for Methane Determined from Tables 3 and 5 with these Same Functions Obtained by Using the Most Accurate State Equation from Reference 11

| $T_o$ R | $p_o$ psia | $\frac{^aZ_o}{^bZ_o} - 1$ | $\frac{^aC*}{^bC*} - 1$ |
|---|---|---|---|
| 450 | 500 | 0.0029 | -0.0024 |
| | 1000 | .0100 | -.0095 |
| 500 | 500 | .0016 | -.0027 |
| | 1000 | .0034 | -.0065 |
| 550 | 500 | .0005 | -.0020 |
| | 1000 | .0009 | -.0045 |
| 600 | 500 | -.0005 | -.0012 |
| | 1000 | -.0008 | -.0027 |
| 650 | 500 | -.0011 | -.0009 |
| | 1000 | -.0019 | -.0013 |
| 700 | 500 | -.0016 | -.0003 |
| | 1000 | -.0027 | -.0006 |

[a] This superscript refers to values determined from tables 3 and 5.

[b] This superscript refers to values obtained by using the state equation in reference 11.

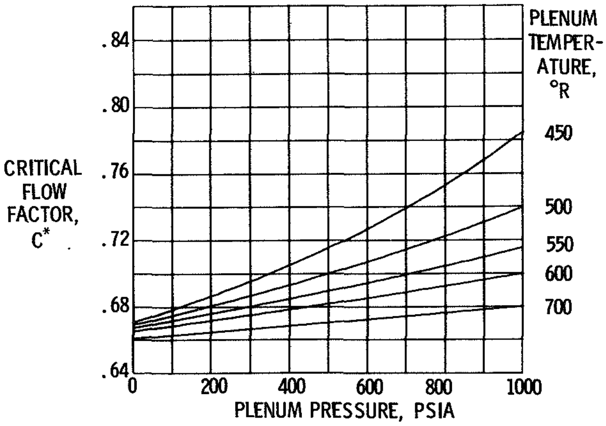

Figure 1. - Critical flow factor for a natural gas. Composition by volume is: 0.9535 methane, 0.0296 ethane, 0.0046 propane, 0.0007 2-methyl propane, 0.0006 butane, 0.0040 nitrogen, and 0.0070 carbon dioxide.

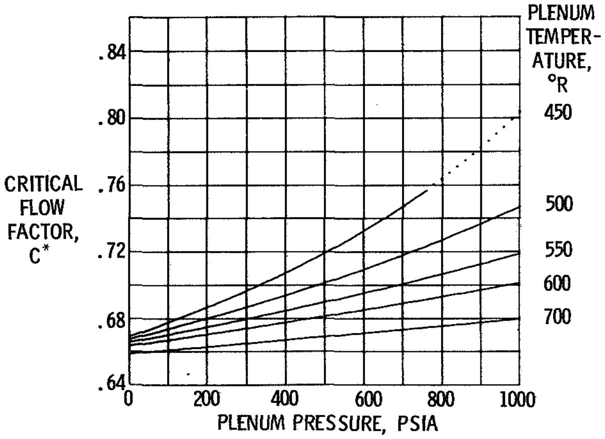

Figure 2. - Critical flow factor for a natural gas. Composition by volume is: 0.8850 methane, 0.0795 ethane, 0.0110 propane, 0.0007 2-methyl propane, 0.0017 butane, 0.0221 nitrogen, and 0 carbon dioxide.