REAL-GAS EFFECTS IN FLOW METERING

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Real-Gas Effects in Flow Metering

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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 $100 \times 10^5$ N/m$^2$ (~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 perfect gas is defined as one having an invariant 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. 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 **sonic-flow nozzle** is one in which the throat velocity equals the local speed of sound. A sonic-flow nozzle has also been called a **choked nozzle** or a **critical-flow nozzle**.) 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 thermo-
dynamic 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 \(100 \times 10^5\) N/m\(^2\). For steam, the temperatures are from 500 to 800 K, and the pressures to \(100 \times 10^5\) 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
- \(m\) 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
**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

\[ p = Z \rho RT \]  \hspace{1cm} (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

\[ H_0 = H_1 + \frac{1}{2} v_1^2 \]  \hspace{1cm} (2)

The assumption that the flow is isentropic is represented by

\[ S_0 = S_1 \]  \hspace{1cm} (3)

and the fact that the flow is sonic is represented by

\[ v_1 = a_1 \]  \hspace{1cm} (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].

\[
\frac{H}{R} = \int \left( \frac{C_p}{R} \right) \frac{dT}{T} - T \int P \left( \frac{\partial Z}{\partial T} \right)_P \frac{dp}{p} + K_H \tag{5}
\]

\[
\frac{S}{R} = \int \left( \frac{C_p}{R} \right) \frac{dT}{T} - \ln P - \int P \left( \frac{\partial Z}{\partial T} \right)_P \frac{dp}{p} + K_S \tag{6}
\]

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

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

where
\[ \frac{c_P}{R} = \frac{c_{P,i}}{R} - \int_0^p \left[ 2T \left( \frac{\partial Z}{\partial T} \right)_p + T^2 \left( \frac{\partial^2 Z}{\partial T^2} \right)_p \right] \frac{dp}{p} \]  

(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

\[ G_1 = \rho_1 v_1 \]  

(9)

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

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

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

(10)

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

(11)

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

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

(12)

where
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, \( \phi \), as follows:

\[
\dot{m} = A_1 \cdot \phi \cdot \left( \frac{p_0}{T_0^2} \right)
\]

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

\[
\phi_p^2 = \frac{\gamma_p}{R} \cdot \left( \frac{2}{\gamma_p+1} \right)^{(\gamma_p+1)/(\gamma_p-1)}
\]

where \( \gamma_p \) 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 \( \phi_i \) that is a function of temperature and is given by

\[
\frac{c_v}{R} = \frac{c_{v,i}}{R} - \int_0^\rho \left[ 2T \left( \frac{\partial Z}{\partial T} \right)_p + T^2 \left( \frac{\partial^2 Z}{\partial T^2} \right)_p \right] \frac{dp}{\rho}
\]
\[ \phi_1 = \lim_{p \to 0} \phi \]  

(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

\[ \dot{m} = A_1 \left( \frac{\phi}{\phi_1} \right) \cdot \frac{P_0}{T_0^2} \]  

(17)

where the values of \( \phi_1 \) 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

\[ \dot{m} = \dot{m}_P \left\{ 1 + 2 \left( \frac{P_0 - P_1}{P_0} \right) \left[ \left( \frac{\phi}{\phi_1} \right) \left( \frac{\phi_1}{\phi_P} \right) \frac{Z_0^2}{Z_0^2} - 1 \right] \right\} \]  

(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 \( \frac{1}{2} \) percent for the gases considered in this report. The values \( \phi_1/\phi_P \) 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

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

(19)

In Figs. (1) to (3), $(\phi/\phi_1)$ is plotted as a function of $P$ and $T$ for air, $N_2$, $O_2$, n-H$_2$, p-H$_2$, A, He, H$_2$O, 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 $(\phi/\phi_1)$ 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)).


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).

Table I. Data References

<table>
<thead>
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<th>Sonic-Flow Factor</th>
<th>Compressibility Factor</th>
<th>Ideal-Gas Specific Heat</th>
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<td>20</td>
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<td>22</td>
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(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.

<table>
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<td>$250 \leq T \leq 390$</td>
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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, CH4-0.9272, C2H6-0.0361, C3H8-0.0055, IC4H10-0.0007, nC4H10-0.0010, N2-0.0218, CO2-0.0077).

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

(A) AIR.

(B) NITROGEN.

(C) OXYGEN.

(D) STEAM.

Figure 2

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<th>( \Phi_1/\Phi_P )</th>
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<td>0.03089</td>
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<td>0.03099</td>
<td>0.986</td>
</tr>
</tbody>
</table>

\( \Phi_1 = 0.5034 \text{ SEC } K^{1/2} \text{ m} \)

\( \Phi_1/\Phi_P = 1.000 \)
PLENUM PRESSURE, N/m²

<table>
<thead>
<tr>
<th>TEMPERATURE, K</th>
<th>(\Phi_i)</th>
<th>(\Phi_i/\Phi_p)</th>
</tr>
</thead>
<tbody>
<tr>
<td>250</td>
<td>0.02951</td>
<td>0.998</td>
</tr>
<tr>
<td>275</td>
<td>0.02946</td>
<td>0.996</td>
</tr>
<tr>
<td>300</td>
<td>0.02940</td>
<td>0.994</td>
</tr>
<tr>
<td>350</td>
<td>0.02925</td>
<td>0.989</td>
</tr>
<tr>
<td>400</td>
<td>0.02907</td>
<td>0.983</td>
</tr>
</tbody>
</table>

Figure 3

(A) METHANE.

(B) NATURAL GAS (FRACTIONAL COMPOSITION BY VOLUME, CH₄-0.9272, C₂H₆-0.0361, C₃H₈-0.0055, iC₄H₁₀-0.007, nC₄H₁₀-0.0010, N₂-0.0218, CO₂-0.0077).

Figure 4

(A) AIR.

(B) NITROGEN.

(C) OXYGEN.
Figure 5

(A) NORMAL AND PARA HYDROGEN.

(B) ARGON.

(C) HELIUM.

(D) STEAM.

Figure 6

(A) METHANE.

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