The Fundamentals Of Gas Volume & Flow Measurement

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ABSTRACT

The application of correct methods for determining the effect of pressure and temperature on the behavior of natural gas is essential in projects involving gas measurement. The gas compressibility factor may be neglected in gas calculations only at low pressures and high temperatures. This paper presents the basic equations, with example solutions, for determining the gas compressibility factor, the volumes occupied by a gas at different pressures and temperatures, and the flow of gas through pipelines as measured with an orifice meter.

INTRODUCTION

Early investigators of the behavior of gases provided several fundamental relationships that have since become the basis of natural gas calculations. Of these, Boyle's and Charles' Laws are of particular importance in that they express the effects of pressure and temperature on the volume of a gas. Avogadro introduced the idea that, at the same temperature and pressure, equal volumes of different gases contain the same number of molecules, thus introducing the mole, or more exactly, the pound mole as a unit of gas volume containing 2.733×10^{26} molecules.

A mole of gas is a quantity of gas whose weight in pounds is numerically equal to its molecular weight. For example, 2.016 pounds of hydrogen (H_2), 32.000 pounds of oxygen (O_2), or 16.04 pounds of methane all individually constitute one mole, contain the same number of molecules and occupy the same volume at the same pressure and temperature when considered as ideal gases. In effect, the above merely states that the number of moles represented by a quantity of gas is equal to the weight of the gas in pounds divided by its molecular weight.

Many other fundamental laws may be cited from the literature; taken collectively, they provide the petroleum industry with a sound technical background for computing natural gas volumes and flow rates. Most of these early investigations dealt with the so-called ideal gas, or one where the relationships between pressure and volume and temperature and volume are straight line or linear functions. That is to say, if the pressure of a given quantity of an ideal gas is doubled at constant temperature the volume is reduced to one-half its original value (Boyle's Law), or if the absolute temperature of a given quantity of an ideal gas is doubled at constant pressure, the volume is increased to twice its original value (Charles' Law).

Most gases approach ideal behavior at low pressures and high temperatures, but within the normal range of pressure and temperature at which natural gases are handled in the field there is a deviation from the ideal behavior; hence, the gases are referred to as real gases. If the pressure of a given quantity of a real gas is doubled at constant temperature the volume is usually reduced to less than one-half its original volume. A compressibility factor (sometimes designated as the gas deviation factor or supercompressibility factor) has been incorporated into the basic ideal gas laws to compensate for the real or non-ideal behavior.

THE GAS LAW

The gas law, which is a combination of Boyle's and Charles' Laws, for an ideal gas is

$$PV = nRT \tag{1}$$

and for a real gas, the following law applies

$$PV = ZnRT \tag{2}$$

where,

P = the absolute pressure of the gas (psia) = gage pressure (psig) + atmospheric pressure.
V = the volume of gas (cubic feet) at P and T.
n = the number of moles of gas (pound moles).
T = the absolute temperature of the gas in degrees Rankine (°R) = the temperature in degrees Fahrenheit plus 460, or °R = °F + 460.
R = the universal gas constant (10.732).
Z = the compressibility or gas deviation factor (unitless).

The compressibility factor (Z) in equation (2) is defined as the ratio of the volume of a given number of moles of an actual or real gas at a specific pressure and temperature to the volume of the same number of moles of an ideal gas at the same pressure and temperature.

Equation (2) is more commonly used in the following form to convert the volume of a gas at one pressure and temperature to the volume at some other pressure and temperature.

$$\frac{P_1 V_1}{Z_1 T_1} = \frac{P_2 V_2}{Z_2 T_2} \tag{3}$$

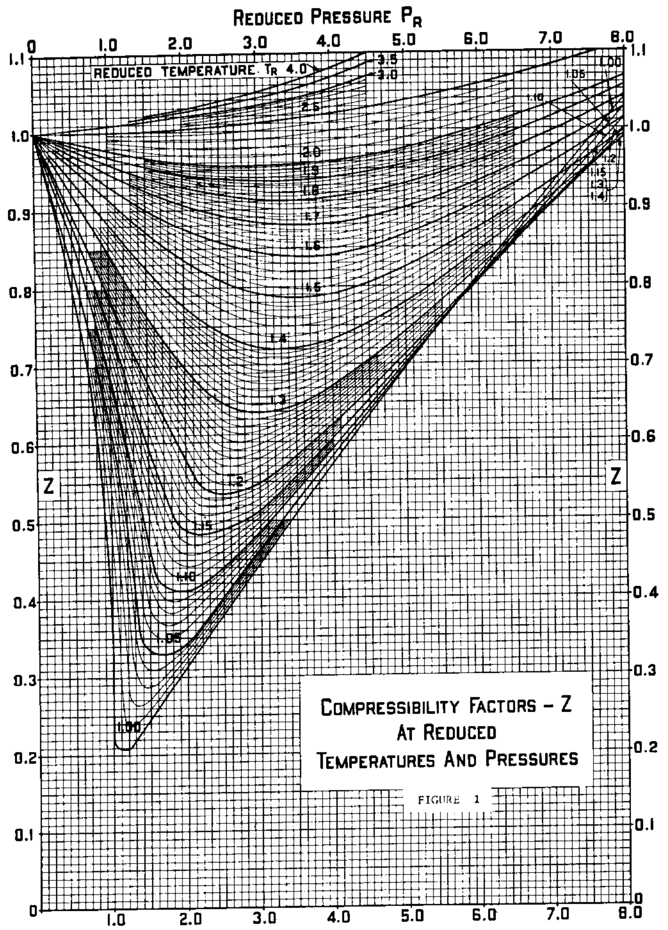
Equation (3) is obtained by writing equation (2) at the two conditions of pressure and temperature (designated by the subscripts 1 and 2) and equating the products of the number of moles and the gas constant at each condition. This is the form of the equation used to convert gas volumes measured at some pressure and temperature in the field to standard cubic feet, the volume at base condition.

Determining the Compressibility Factor (Z)

The compressibility factors for single component or pure gases can usually be found in the literature. Natural gas, however, is a mixture of components, the composition of which varies from field to field and over the producing life of a particular field. It is impractical to expect laboratory measurements of the compressibility of each natural gas encountered in the field.

Laboratory investigations have yielded a correlation chart (Fig. 1) relating gas compressibility factor to reduced pressure and temperature for mixtures of hydrocarbon gases containing less than 5 per cent impurities (nitrogen, carbon dioxide, and hydrogen sulfide) and at least 50 per cent methane by volume.

The use of Fig. 1 requires knowledge of the reduced



Compressibility Factors - Z At Reduced Temperatures And Pressures

FIGURE 1

pressure and temperature of the gas which is obtained from the following

$$P_R = P/pP_c \text{ and } T_R = T/pT_c \qquad (4)$$

where pP_c and pT_c are the pseudo critical pressure and pseudo critical temperature of the gas, respectively, and P and T are the pressure and temperature at which the compressibility factor of the gas is desired. Again, all of these terms must be in absolute units as defined for equation (2).

A system is said to exist at the critical state when its pressure and temperature are the critical values. At this state, the intensive properties of the vapor and liquid phases become equal. An intensive property is one which is completely independent of the amount of material; for example, pressure, temperature, density, composition and viscosity. The pseudo critical values used in correlating the PVT behavior of a gas mixture are not the actual critical values of the mixture; however, these fictitious or pseudo values are necessary to afford a sound basis of correlation.

TWO METHODS

The pseudo critical constants for a gas mixture may be determined by several techniques, two of which will be presented here. The first method requires knowledge of the composition of the gas and the second the specific gravity of the gas.

Composition Method

If the composition of a gas is known, the pseudo critical constants of the mixture may be calculated by summing the products of the mole fraction and critical constants of each component. Table I lists the physical properties of the Alkane series hydrocarbons and other components normally found in natural gases. The composition of a west Texas natural gas (Canyon Reef reservoir gas sample) is shown in Table II with an example solution for the pseudo critical constants of the gas. The calculated pseudo critical pressure is 650.1 psia and the pseudo critical temperature is 474.73 °R. If the compressibility factor of this gas at 1000 psig (gage pressure) and 75°F were desired, the following calculations would be required.

1. Using equation (4) and assuming an atmospheric pressure of 14.4 psi, the reduced pressure and temperature are

$$P_R = P/pP_c = \frac{1000 + 14.4}{650.1} \quad 1.56,$$

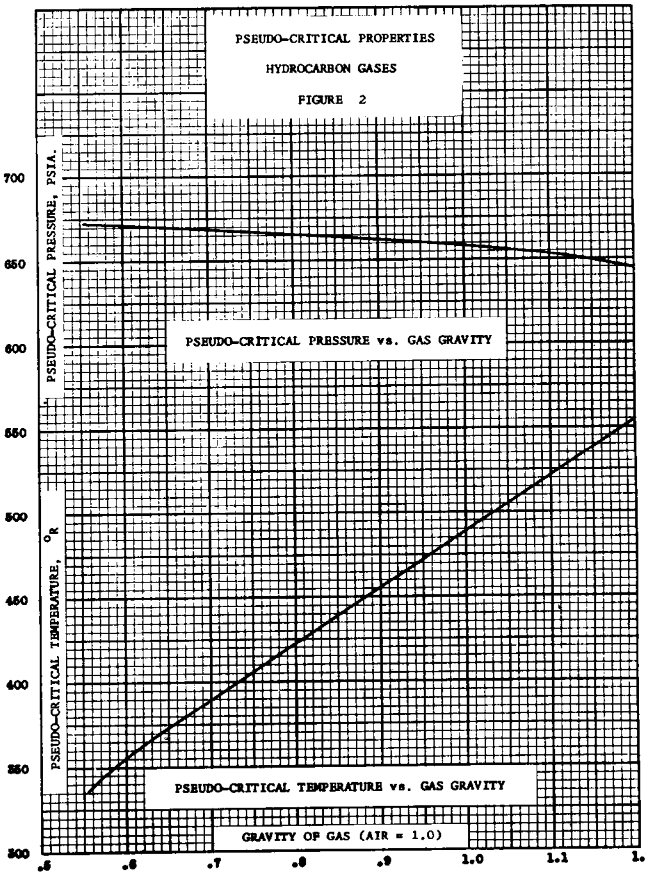
$$T_R = T/pT_c = \frac{460 + 75}{474.73} \quad 1.13$$

2. From Fig. 1, the compressibility factor, (Z), corresponding to a reduced pressure of 1.56 and a reduced temperature of 1.13 is 0.54.

The Specific Gravity Method

In many instances the composition of a natural gas has not been determined or is not readily available; however, the specific gravity (G) usually is known or can easily be measured with little expense. Several authors have presented, in the literature, correlations between gas gravity and the pseudo critical constants. The C. N. G. A. data expressing pseudo critical pressure and pseudo critical temperature as a function of gas gravity are presented in Fig. 2.

These data were accumulated for hydrocarbon gases containing little or no impurities, and therefore must be



PSEUDO-CRITICAL PROPERTIES
HYDROCARBON GASES
FIGURE 2

TABLE I

Physical Properties of Some Natural Gas Components

Component	Molecular Weight	Critical Temperature °R	Critical Pressure psia
Methane	16.04	344	673
Ethane	30.07	549	712
Propane	44.09	666	617
n-Butane	58.12	766	551
iso-Butane	58.12	732	544
n-Pentane	72.15	846	485
iso-Pentane	72.15	829	483
n-Hexane	86.17	914	435
n-Heptane	100.20	972	397
n-Octane	114.22	1024	362
n-Nonane	128.30	1073	334
n-Decane	142.30	1115	316
Air	28.97	239	547
Carbon Dioxide	44.01	548	1070
Helium	4.003	9.5	33
Hydrogen	2.016	59.8	189
Hydrogen Sulfide	34.08	672	1306
Nitrogen	28.02	227	492
Oxygen	32.00	279	737
Water	18.02	1165	3210

TABLE II

Determining Pseudo Critical Constants from Gas Composition

Component	Mole %	Critical Pressure psia	Critical Temperature °R	$\frac{\text{Mole \% x } P_c}{100}$	$\frac{\text{Mole \% x } T_c}{100}$
N_2	4.5	492	227	22.1	10.21
C_1	49.55	673	344	333	170
C_2	18.59	712	549	132	102
C_3	18.42	617	666	114	123
iC_4	1.94	544	732	10.6	14.2
nC_4	4.50	551	766	24.8	34.5
iC_5	0.61	483	829	2.95	5.06
nC_5	1.00	485	846	4.85	8.46
C_6	0.14	435	914	0.61	1.28
C_7+	0.40	362*	1024*	1.45	4.10
CO_2	0.35	1070	548	3.74	1.92
Totals	100.00			pP_c= 650.10	pT_c=474.73

* C_8 values used for C_7+.

corrected for nitrogen, carbon dioxide, and hydrogen sulfide content. Carr, Kobayashi, and Burrows (A.I.M.E. Trans., 1954) presented the following corrections for nonhydrocarbon constituents.

Component	Corrections* per mole per cent to be applied to the pseudo critical constants	
	pP_c, psi	pT_c, °R
N_2	-1.7	-2.4
CO_2	+4.4	-0.84
H_2S	+5.9	+1.3

*The correction constants were taken from straight line graphical presentations of the original data and represent a specific gravity range of 0.6 to 1.5 and mole percentages from 0 to 15.

These corrections, being hypothetical in nature, assume that the hydrocarbon distribution is unaffected by the presence of the nonhydrocarbons. Nonetheless, the corrections have been found to yield values within reasonable limits of accuracy.

Referring to the sample problem in Table II, the compressibility factor of the gas at 1000 psig and 75°F is determined by the specific gravity method as follows.

1. The specific gravity of the gas was reported as 0.98. From Fig. 2, the pseudo critical pressure is 659 psia and the pseudo critical temperature is 482°R.
2. Correction for nitrogen content:

$$pP_c = 659 - 4.5(1.7) = 651.4,$$

$$pT_c = 482 - 4.5(2.4) = 471.2$$

3. Correction for carbon dioxide content:

$$pP_c = 651.4 + 0.35(4.4) = 652.9,$$

$$pT_c = 471.2 - 0.35(0.84) = 470.9$$

4. From equation (4), the reduced pressure and temperature are:

$$P_R = \frac{1000 + 14.4}{652.9} = 1.55$$

$$T_R = \frac{460 + 75}{470.9} = 1.14$$

5. From Fig. 1, the compressibility factor is 0.56.

The above value compares favorably with the compressibility factor of 0.54 as determined by the composition method.

Ducker (Principles of Natural Gas Engineering, Course Syllabus, Department of Petroleum Engineering, Texas Technological College) applied the method of least squares to the data of Fig. 2 and presented the following equations relating the pseudo critical constants to specific gravity:

$$\left.\begin{aligned} pP_c &= 690 - 31\ G \\ pT_c &= 158 + 1000\ G/3 \end{aligned}\right. \qquad (5)$$

for gas gravities from 0.55 to 1.00. Using these equations instead of Fig. 2 in the above example problem

$$pP_c = 690 - 31(0.98) = 659.6$$

and

$$pT_c = 158 + 1000(0.98)/3 = 484.7$$

These uncorrected values are very close to those used in step 2 above and, after correction for nitrogen and carbon dioxide, will yield approximately the same value for compressibility factor.

SOME APPLICATIONS OF GAS COMPRESSIBILITY FACTOR

The use of the gas compressibility factor is illustrated by the following routine gas calculations:

Illustration I: Again referring to the Canyon Reef reservoir gas in Table II, how many standard cubic feet (base conditions of 14.65 psia and 60°F) are represented by 1000 cubic feet of the gas measured at 1000 psig and 75° F?

The (Z) factor at 1000 psig and 75 °F is 0.54 as previously calculated by the composition method. The compressibility factor at the base conditions is essentially equal to 1.00. In equation 3, setting the subscript 1 representative of base conditions and the subscript 2 as the conditions stated above and solving for V_1

$$V_1 = \frac{P_2 V_2 Z_1 T_1}{Z_2 T_2 P_1} = \frac{1014.4(1000)1.00(460 + 60)}{0.54(460 + 75)14.65}$$

$= 124{,}600$ SCF

This is approximately twice the number of standard cubic feet that would have been present had the gas been considered an ideal gas.

Illustration 2: What volume would 300 pounds of the above gas occupy at 1000 psig and 75°F? Referring to the gas law (equation 2)

$$P\ V = Z\ n\ R\ T$$

where n, the number of moles of gas has been defined as the weight in pounds divided by the molecular weight. The molecular weight of a gas is equal to the specific gravity of the gas times the molecular weight of air, which is equal to 28.97. Substituting weight (W) over molecular weight ($\overline{MW}$) and $\overline{MW} = 28.97\ G$ in the above equation

$$P\ V = \frac{Z\ W\ R\ T}{28.97\ G}$$

and solving for V

$$V = \frac{Z\ W\ R\ T}{28.97\ G P}$$

Thus, 300 pounds of the gas would occupy

$$V = \frac{0.54(300)10.732(460+75)}{28.97(0.98)1014.4} = 32.3 \text{ cubic feet}$$

ORIFICE METERING OF NATURAL GAS

The general orifice flow equation can be written as

$$Q = C \times \frac{14.65}{P_b} \times \frac{460 + T_b}{520} \times \sqrt{\frac{0.60}{G}} \times \sqrt{\frac{520}{460+T_f}} \times \sqrt{\frac{1}{Z}} \times \sqrt{h\ P} \qquad (6)$$

where,

Q = the flow rate in standard cubic feet per day.

C = the basic orifice factor, a function of the orifice diameter, pipe diameter, and the type pressure taps. It can be obtained from a natural gas reference book or handbook. Table III lists these factors for flange taps as reported by the Railroad Commission of Texas (Pamphlet for Gas-Oil Ratio Determination) and the American Gas Association.

P_b = the base pressure, psia

T_b = the base temperature, °F

G = the gas gravity

T_f = the flowing temperature, °F

h = the differential pressure across the orifice, inches of water

P = the static line pressure, psia

The above terms are often grouped as a series of correction factors as follows:

$$Q = C \times f_{pb} \times f_{tb} \times f_g \times f_{tf} \times f_{pv} \times \sqrt{h\ P}$$

where the correction factors are referred to as the base pressure correction, base temperature correction, gravity correction, flowing temperature correction, and supercompressibility correction, respectively. Three other factors — the Reynolds' Number factor, expansion factor, and manometer factor — may be included but are usually neglected, except in certain cases where extremely accurate measurement is required.

Of the above correction factors, the compressibility factor correction is probably the largest and most significant one often neglected. The correction in many instances is negligible; however, the particular conditions at hand should be examined to determine whether or not the disregarding of the factor is justified. Illustration 3:

A portable orifice recorder is used to measure the daily gas input to a well on continuous gas lift. The average extension ($\sqrt{h\ P}$) is 103 for a 24 hour well test. The following data are known:

$T_f = 70$°F, $P = 650$ psig, $G = 0.65$, Orifice dia. $= 0.750$ in.,

Pipe diameter (meter run) $= 2.067$ in. I. D. (2 in. nominal).

Determine the number of standard cubic feet of gas per day (base conditions of 14.65 psia and 60 °F) input and the effect of gas compressibility on the measurement. Assume an atmospheric pressure of 14.4 psi.

1. From Fig. 2, assuming the CO_2 and N_2 content of the gas to be negligible, $pT_c = 373$ °R and $pP_c = 670$ psia. Using equation (4),

   $$T_R = \frac{460+70}{373} = 1.421 \text{ and } P_R = \frac{650+14.4}{670} = 0.992$$

2. From Fig. 1, $(Z) = 0.893$
3. From Table III, $C = 3586.59$
4. Using equation (6),

$$Q = 3586.59 \times \frac{14.65}{14.65} \times \frac{460+60}{520} \times \sqrt{\frac{0.60}{0.65}} \times \sqrt{\frac{520}{530}} \times \sqrt{\frac{1.000}{0.893}} \times 103$$

$$Q = 3586.59 \times 1.000 \times 1.000 \times 0.9608 \times 0.9905 \times 1.058 \times 103$$

Q 372,000 SCF or 372 MCF

TABLE III

Orifice Coefficients - Flange Taps
Cubic Feet per Day; Pressure Base, 14.65 psia
$G = 0.60$; Base and Flowing Temperature, 60°F

Orifice Diameter, Inches	Nominal Pipe Size, Inches 2 (2.067)	3 (3.068)	4 (4.026)
0.250	395.97	395.78	395.11
0.375	885.57	883.96	882.84
0.500	1573.87	1566.68	1564.61
0.625	2470.72	2449.31	2442.97
0.750	3586.59	3537.56	3522.63
0.875	4936.93	4833.08	4805.97
1.000	6548.87	6340.86	6292.44
1.125	8464.13	8069.44	7985.39
1.250	10751.54	10031.91	9889.08
1.375	13504.60	12245.62	12009.60
1.500	16893.23	14733.73	14354.57

5. If (Z) had been neglected, the daily gas input would have been calculated as 351,600 SCF, which at first seems small; however, the difference, 20,400 SCF/day would be reported as produced formation gas on a well test and could easily result in an unwarranted well allowable penalty, the magnitude of which would depend on the daily oil production and produced formation GOR of the well. For example, if the well in this problem has an allowable of 50 bbls/day and a producing formation GOR of 2000/1, with a maximum permissible GOR of 2000/1, neglecting the compressibility factor in the gas measurement results in an allowable penalty of approximately 8 bbls/producing day.

SUMMARY

Simplified methods of computing gas compressibility factor and its incorporation in gas volume and flow calculations have been presented. These methods are designed for field use where a minimum of data are available. More elaborate techniques, requiring in general more basic data, are presented in the various gas handbooks, gas association publications, and technical literature. Gas compressibility factors should not be neglected in routine field calculations without preliminary investigation of its effect.