Lecture Three: Natural Gas Properties

3.1 Introduction

To understand and predict the volumetric behavior of oil and gas reservoirs as a function of pressure, knowledge of the physical properties of reservoir fluids must be gained. These fluid properties are usually determined by laboratory experiments performed on samples of actual reservoir fluids. In the absence of experimentally measured properties, it is necessary for the petroleum engineer to determine the properties from empirically derived correlations. The objective of this lecture is to present several of the well-established physical property correlations for the Natural gases.

3.2 Properties of Natural Gas

A gas is defined as a homogeneous fluid of low viscosity and density that has no definite volume but expands to completely fill the vessel in which it is placed. Generally, the natural gas is a mixture of hydrocarbon and non-hydrocarbon gases. The hydrocarbon gases that are normally found in a natural gas are methane, ethane, propane, butanes, pentanes, and small amounts of hexanes and heavier. The non-hydrocarbon gases (i.e., impurities) include carbon dioxide, hydrogen sulfide, and nitrogen. Knowledge of pressure-volume-temperature (PVT) relationships and other physical and chemical properties of gases are essential for solving problems in natural gas reservoir engineering. These properties include:

- Apparent molecular weight, M_a
- Specific gravity, γ_g
- Compressibility factor, Z
- Density, ρ_g
- Specific volume, V
- Isothermal gas compressibility coefficient, C_g
- Gas formation volume factor, B_g
- Gas expansion factor, E_g
- Viscosity, μ_g

3.2.1 Behavior of Ideal Gas

The kinetic theory of gases postulates that gases are composed of a very large number of particles called molecules. For an ideal gas, the volume of these molecules is insignificant compared with the total volume occupied by the gas. It is also assumed that these molecules have no attractive or repulsive forces between them, and that all collisions of molecules are perfectly elastic. Based on the above kinetic theory of gases, a mathematical equation called **equation-of-state** can be derived to express the relationship existing between pressure P, volume V, and temperature T for a given quantity of moles of gas n. This relationship for perfect gases is called the ideal gas law and is expressed mathematically by the following equation:

$$\mathbf{PV = nRT} \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots \text{(3-1)}$$

Where:

P = absolute pressure, psia

V = volume, ft3

T = absolute temperature, R°

n = number of moles of gas, lb-mole

R = the universal gas constant, which, for the above units, has the value 10.730 psia ft3/lb-mole R°

The number of pound-moles of gas, i.e., n, is defined as the weight of the gas m divided by the molecular weight M, or:

$$\mathbf{n = m / M} \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots \text{(3-2)}$$

Combining Equation 2-1 with 2-2 gives:

$$\mathbf{PV = (m / M)\, RT} \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots \text{(3-3)}$$

Where:

m = weight of gas, lb

M = molecular weight, lb/lb-mol

Since the density is defined as the mass per unit volume of the substance, Equation 3-3 can be rearranged to estimate the gas density at any pressure and temperature:

$$\boldsymbol{\rho_g} \mathbf{= m / V = PM / RT} \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots \text{(3-4)}$$

Where

ρ_g = density of the gas, lb/ft3

It should be pointed out that lb refers to lbs mass in any of the subsequent discussions of density in this text.

Apparent Molecular Weight

One of the main gas properties that are frequently of interest to engineers is the apparent molecular weight. If Y_i represents the mole fraction of the i^{th} component in a gas mixture, the apparent molecular weight is defined mathematically by the following equation:

$$\mathbf{Ma} = \sum_{i=1}^{n} \mathbf{Yi\ Mi} \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots \text{(3-5)}$$

Where:

M_a = apparent molecular weight of a gas mixture

M_i = molecular weight of the i^{th} component in the mixture

Y_i = mole fraction of component i in the mixture

Standard Volume

In many natural gas engineering calculations, it is convenient to measure the volume occupied by l lb-mole of gas at a reference pressure and temperature. These reference conditions are usually 14.7 psia and 60°F, and are commonly referred to as standard conditions. The standard volume is then defined as the volume of gas occupied by 1 lb-mol of gas at standard conditions. Applying the above conditions to Equation 3-1 and solving for the volume, i.e., the standard volume, gives:

$$Vsc = \frac{n\ R\ Tsc}{Psc} = \frac{1 * 10.73 * 520}{14.7}$$

Or

$$\mathbf{V_{sc} = 379.4\ scf/lb\_mol} \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots \text{(3-6)}$$

Where:

V_{sc} = standard volume, scf/lb-mol

scf =standard cubic feet

T_{sc} = standard temperature, °R

P_{sc} = standard pressure, psia

Density

The density of an ideal gas mixture is calculated by simply replacing the molecular weight of the pure component in Equation 3-4 with the apparent molecular weight of the gas mixture to give:

$$\boldsymbol{\rho_g = PM_a / RT} \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots \text{(3-7)}$$

Where:

ρ_g = density of the gas mixture, lb/ft3

Ma = apparent molecular weight.

Specific Volume

The specific volume is defined as the volume occupied by a unit mass of the gas. For an ideal gas, this property can be calculated by applying Equation 3-3:

$$\mathbf{v} = \frac{\mathbf{V}}{\mathbf{m}} = \frac{\mathbf{RT}}{\mathbf{PMa}} = \frac{\mathbf{1}}{\boldsymbol{\rho}\mathbf{g}} \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ (3\text{-}8)$$

Where:

V = specific volume, ft3/lb

ρ_g = gas density, lb/ft3

Specific Gravity

The specific gravity is defined as the ratio of the gas density to that of the air. Both densities are measured or expressed at the same pressure and temperature. Commonly, the standard pressure P_{sc} and standard temperature T_{sc} are used in defining the gas specific gravity:

$$\gamma_g = \rho_g \,/\, \rho_{air} \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ (3\text{-}9)$$

Assuming that the behavior of both the gas mixture and the air is described by the ideal gas equation, the specific gravity can then be expressed as:

$$\gamma_g = \frac{\dfrac{Psc\,Ma}{R\,Tsc}}{\dfrac{Psc\,Mair}{R\,Tsc}}$$

Or

$$\gamma g = \frac{Ma}{Mair} = \frac{Ma}{28.96} \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ (3\text{-}10)$$

Where:

γ_g = gas specific gravity

ρ_{air} = density of the air

M_{air} = apparent molecular weight of the air = 28.96

M_a = apparent molecular weight of the gas

P_{sc} = standard pressure, psia

T_{sc} = standard temperature, °R

2.2.2 Behavior of real gases

In dealing with gases at a very low pressure, the ideal gas relationship is a convenient and generally satisfactory tool. At higher pressures, the use of the ideal gas equation-of-state may lead to errors as great as 500%, as compared to errors of 2–3% at atmospheric pressure.

Basically, the magnitude of deviations of real gases from the conditions of the ideal gas law increases with increasing pressure and temperature and varies widely with the composition of the gas. Real gases behave differently than ideal gases. The reason for this is that the perfect gas law was derived under the assumption that the volume of molecules is insignificant and that no molecular attraction or repulsion exists between them. This is not the case for real gases.

Numerous equations-of-state have been developed in the attempt to correlate the pressure-volume-temperature variables for real gases with experimental data. In order to express a more exact relationship between the variables P, V, and T, a correction factor called **the gas compressibility factor, gas deviation factor, or simply the z-factor**, must be introduced into Equation 3-1 to account for the departure of gases from ideality. The equation has the following form:

$$\mathbf{PV = ZnRT} \qquad \text{(3-11)}$$

Where the gas compressibility factor Z is a dimensionless quantity and is defined as the ratio of the actual volume of n-moles of gas at T and P to the ideal volume of the same number of moles at the same T and P:

$$\mathbf{Z = \frac{V_{actual}}{V_{ideal}} = \frac{V_{actual}}{nRT/P}}$$

Studies of the gas compressibility factors for natural gases of various compositions have shown that compressibility factors can be generalized with sufficient accuracies for most engineering purposes when they are expressed in terms of the following two dimensionless properties:

- Pseudo-reduced pressure
- Pseudo-reduced temperature

These dimensionless terms are defined by the following expressions:

$$\mathbf{P_{pr} = P / P_{pc}} \qquad \text{(3-12)}$$

$$\mathbf{T_{pr} = T / T_{pc}} \qquad \text{(3-13)}$$

Where:

P = system pressure, psia

P_{pr} = pseudo-reduced pressure, dimensionless

T = system temperature, °R

T_{pr} = pseudo-reduced temperature, dimensionless

P_{pc}, T_{pc} = pseudo-critical pressure and temperature, respectively, and defined by the following relationships:

$$\mathbf{Ppc = \sum_{i=0}^{n} Yi\ Pci} \qquad \text{(3-14)}$$

$$\mathbf{Tpc = \sum_{i=0}^{n} Yi\ Tci} \qquad \text{(3-15)}$$

It should be pointed out that these pseudo-critical properties, i.e., Ppc and Tpc, do not represent the actual critical properties of the gas mixture. These pseudo properties are used as correlating parameters in generating gas properties.

Based on the concept of pseudo-reduced properties, Standing and Katz (1942) presented a generalized gas compressibility factor chart as shown in Figure 3-1. The chart represents compressibility factors of sweet natural gas as a function of P_{pr} and T_{pr}. This chart is generally reliable for natural gas with minor amount of non-hydrocarbons. It is one of the most widely accepted correlations in the oil and gas industry.

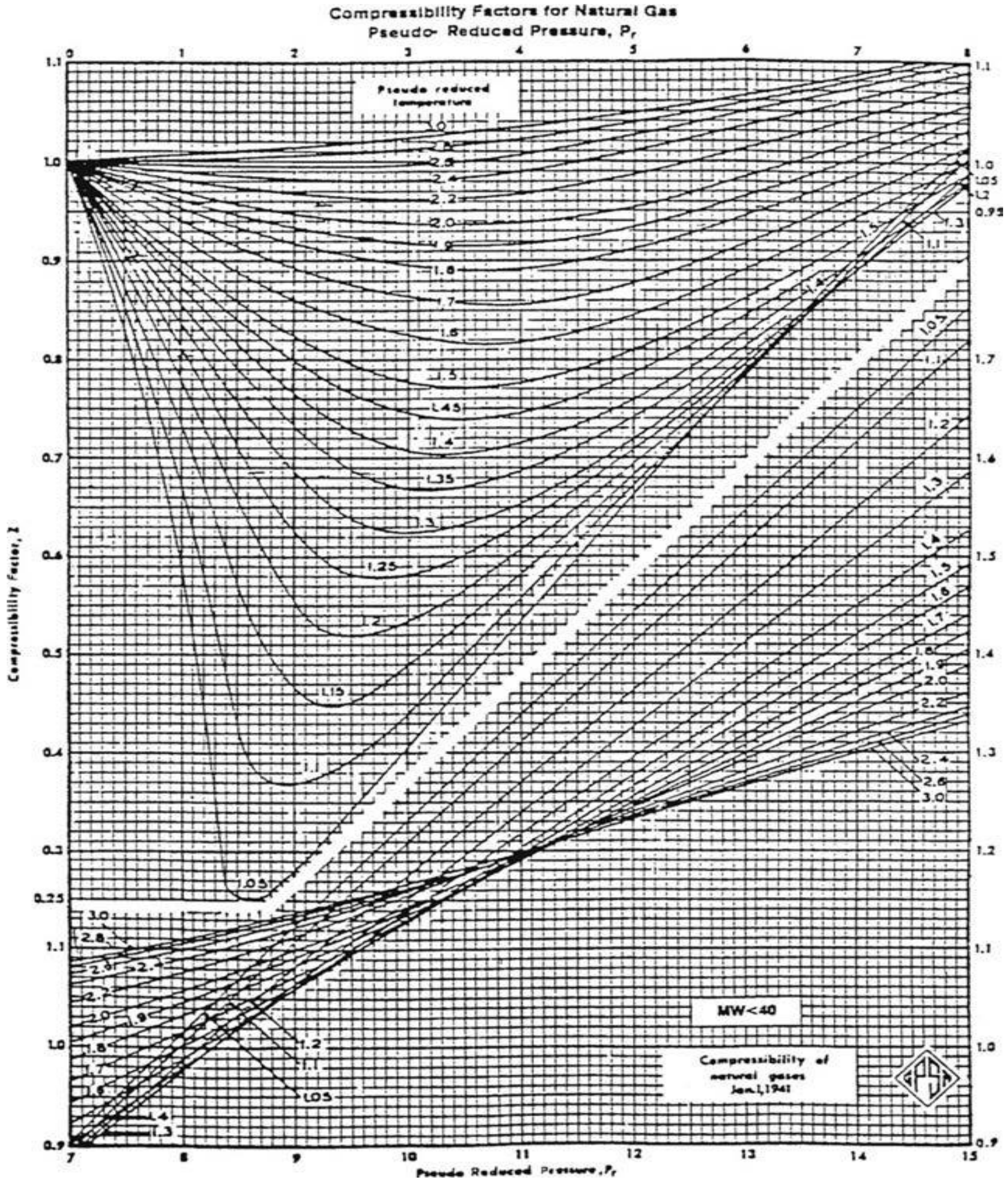

Figure 3-1: Standing and Katz compressibility factors chart. (Courtesy of GPSA and GPA Engineering Data Book, EO Edition, 1987).

In cases where the composition of a natural gas is not available, the pseudo-critical properties, i.e., Ppc and Tpc, can be predicted solely from the specific gravity of the gas. Brown et al. (1948) presented a graphical method for a convenient approximation of the pseudo-critical pressure and pseudo-critical temperature of gases when only the specific gravity of the gas is available. The correlation is presented in Figure 3.2. Standing (1977) expressed this graphical correlation in the following mathematical forms:

Case 1: Natural Gas Systems

$T_{pc} = 168 + 325\ \gamma_g - 12.5\ \gamma_g^{\ 2}$ …………………… (3-16)

$P_{pc} = 667 + 15.0\ \gamma g - 37.5\ \gamma_g^{\ 2}$ ……………………. (3-17)

Case 2: Gas-Condensate Systems

$Tpc = 187 + 330\ \gamma_g - 71.5\ \gamma_g^{\ 2}$ …………………… (3-18)

$Ppc = 706 + 51.7\ \gamma_g - 11.1\ \gamma_g^{\ 2}$ …………………….(3-19)

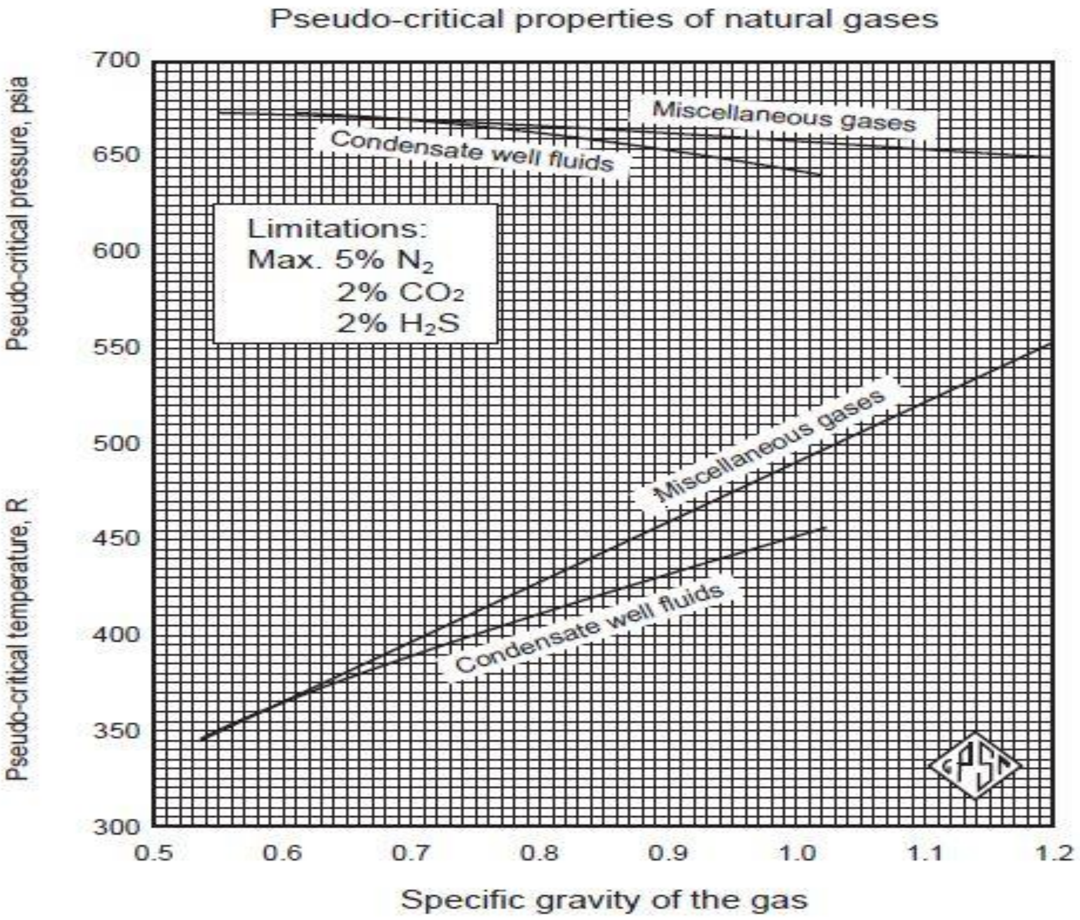

Figure 3-2: Pseudo-critical properties of natural gases. (Courtesy of GPSA and GPA Engineering Data Book, 10th Edition, 1987).

Effect of non-hydrocarbon components on the Z-factor

Natural gases frequently contain materials other than hydrocarbon components, such as nitrogen, carbon dioxide, and hydrogen sulfide. Hydrocarbon gases are classified as sweet or sour depending on the hydrogen sulfide content. Both sweet and sour gases may contain nitrogen, carbon dioxide, or both. A hydrocarbon gas is termed a sour gas if it contains one grain of H2S per 100 cubic feet.

The common occurrence of small percentages of nitrogen and carbon dioxide is, in part, considered in the correlations previously cited. Con-centrations of up to 5 percent of these non-hydrocarbon components will not seriously affect accuracy. Errors in compressibility factor calculations as large as 10 percent may occur in higher concentrations of non-hydrocarbon components in gas mixtures.

Non-hydrocarbon Adjustment Methods

There are two methods that were developed to adjust the pseudo-critical properties of the gases to account for the presence of the non-hydrocarbon components.

These two methods are the:

- Wichert-Aziz correction method
- Carr-Kobayashi-Burrows correction method

Direct calculation of compressibility factor

After four decades of existence, the Standing-Katz z-factor chart is still widely used as a practical source of natural gas compressibility factors. As a result, there has been an apparent need for a simple mathematical description of that chart. Several empirical correlations for calculating z-factors have been developed over the years. The following three empirical correlations are described below:

- Hall-Yarborough
- Dranchuk-Abu-Kassem
- Dranchuk-Purvis-Robinson

Compressibility of Natural Gases

Knowledge of the variability of fluid compressibility with pressure and temperature is essential in performing many reservoir engineering calculations. For a liquid phase, the compressibility is small and usually assumed to be constant. For a gas phase, the compressibility is neither small nor constant.

By definition, the isothermal gas compressibility is the change in volume per unit volume for a unit change in pressure or, in equation form:

$$Cg = -\frac{1}{V}\left(\frac{\partial V}{\partial P}\right)_T \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots \quad (3\text{-}20)$$

Where: C_g = isothermal gas compressibility, 1/psi.

Gas Formation Volume Factor

The gas formation volume factor is used to relate the volume of gas, as measured at reservoir conditions, to the volume of the gas as measured at standard conditions, i.e., 60°F and 14.7 psia. This gas property is then defined as the actual volume occupied by a certain amount of gas at a specified pressure and temperature, divided by the volume occupied by the same amount of gas at standard conditions. In an equation form, the relationship is expressed as

$$\mathbf{B_g = V_{p,T} / V_{sc}} \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots \quad (3\text{-}21)$$

Where:

B_g = gas formation volume factor, ft3/scf

Vp,T = volume of gas at pressure p and temperature, T, ft3

Vsc =volume of gas at standard conditions, scf

Applying the real gas equation-of-state, i.e., Equation 3-11, and substituting for the volume V, gives:

$$B_g = \frac{\dfrac{znRT}{p}}{\dfrac{z_{sc}nRT_{sc}}{p_{sc}}} = \frac{p_{sc}}{T_{sc}}\frac{zT}{p}$$

Where:

Z_{sc} = z-factor at standard conditions = 1.0

P_{sc}, T_{sc} = standard pressure and temperature

Assuming that the standard conditions are represented by Psc =14.7 psia and Tsc = 520, the above expression can be reduced to the following relationship:

$$B_g = 0.02827\frac{zT}{p} \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots \quad (3\text{-}22)$$

Where:

B_g = gas formation volume factor, ft3/scf

z = gas compressibility factor

T = temperature, °R

Equation 3-22 can be expressed in terms of the gas density ρ_g if combined with following Equation

$$\rho_g = \frac{1}{v} = \frac{pM_a}{zRT}$$

To give:

$$B_g = 0.02827\frac{M_a}{R\rho_g} = 0.002635\frac{M_a}{\rho_g}; ft^3/scf$$

Where:

ρ_g = gas density, lb/ft3

M_a = apparent molecular weight of gas

In other field units, the gas formation volume factor can be expressed in bbl/scf, to give:

$$B_g = 0.005035\frac{zT}{p} \quad \text{………………………… (3.23)}$$

Similarly, Equation 2-23 can be expressed in terms of the gas density ρ_g by:

$$Bg = 0.00504\frac{Ma}{R\rho g} = 0.000469\frac{Ma}{\rho g}$$

The reciprocal of the gas formation volume factor is called the gas expansion factor and is designated by the symbol E_g, or:

$$E_g = 35.37\frac{p}{zT}, scf/ft^3 \quad \text{………………………… (3-24)}$$

Or in terms of the gas density ρ_g:

$$E_g = 35.37\frac{R\rho_g}{M_a} = 379.52\frac{\rho_g}{M_a}; \ scf/ft^3$$

In other units:

$$E_g = 198.6\frac{p}{ZT}, scf/bbl \quad \text{…………………… (3-25)}$$

Or:

$$E_g = 198.6\frac{R\rho_g}{M_a} = 2131.0\frac{\rho_g}{M_a}; \ scf/bbl$$

Gas Viscosity

The viscosity of a fluid is a measure of the internal fluid friction (resistance) to flow. If the friction between layers of the fluid is small, i.e., low viscosity, an applied shearing force will result in a large velocity gradient. As the viscosity increases, each fluid layer exerts a larger frictional drag on the adjacent layers and velocity gradient decreases.

The viscosity of a fluid is generally defined as the ratio of the shear force per unit area to the local velocity gradient. Viscosities are expressed in terms of poises, centipoise, or micropoises. One poise equals a viscosity of 1 dynesec/ cm2 and can be converted to other field units by the following relationships:

$$
\begin{aligned}
\mathbf{1poise} &= \mathbf{100\ centipoise} \\
&= \mathbf{1*10^{6}\ micropoises} \\
&= \mathbf{6.72 * 10^{-2}\ lbmass/ft\_\ sec} \\
&= \mathbf{2.09 * 10^{-3}\ lb\_\ sec/ft^{2}}
\end{aligned}
$$

The gas viscosity is not commonly measured in the laboratory because it can be estimated precisely from empirical correlations. Like all intensive properties, viscosity of a natural gas is completely described by the following function:

$$\mu_g = (P, T, Yi)$$

Where μ_g = the viscosity of the gas phase. The above relationship simply states that the viscosity is a function of pressure, temperature, and composition. Many of the widely used gas viscosity correlations may be viewed as modifications of that expression.

Methods of calculating the viscosity of natural gases

Two popular methods that are commonly used in the petroleum industry are the:

- Carr-Kobayashi-Burrows Correlation Method
- Lee-Gonzalez-Eakin Method

The Carr-Kobayashi-Burrows Correlation Method

Carr, Kobayashi, and Burrows (1954) developed graphical correlations for estimating the viscosity of natural gas as a function of temperature, pressure, and gas gravity. The computational procedure of applying the proposed correlations is summarized in the following steps:

Step 1: Calculate the pseudo-critical pressure, pseudo-critical temperature, and apparent molecular weight from the specific gravity or the composition of the natural gas. Corrections to these pseudo-critical properties for the presence of the non-hydrocarbon gases (CO_2, N_2, and H_2S) should be made if they are present in concentrations greater than 5 mole percent.

Step 2: Obtain the viscosity of the natural gas at one atmosphere and the temperature of interest from Figure 3-3. This viscosity, as denoted by μ1, must be corrected for the presence of non-hydrocarbon components by using the inserts of Figure 3-3. The non-hydrocarbon fractions tend to increase the viscosity of the gas phase. The effect of non-hydrocarbon components on the viscosity of the natural gas can be expressed mathematically by the following relationships:

$$\mu_1 = (\mu_1)_{uncorrected} + (\Delta\mu)_{N_2} + (\Delta\mu)_{CO_2} + (\Delta\mu)_{H_2S} \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots \text{(3-26)}$$

Where:

μ_1 = “corrected” gas viscosity at 1 atm and reservoir temperature, cp
$(\Delta\mu)_{N2}$ = viscosity corrections due to the presence of N_2
$(\Delta\mu)_{CO2}$ = viscosity corrections due to the presence of $_{CO2}$
$(\Delta\mu)_{H2S}$ = viscosity corrections due to the presence of H_2S
$(\mu 1)_{uncorrected}$ = uncorrected gas viscosity, c_p

Step 3: Calculate the pseudo-reduced pressure and temperature.

Step 4: From the pseudo-reduced temperature and pressure, obtain the viscosity ratio (μ_g/μ_1) from Figure 3.4. The term μ_g represents the viscosity of the gas at the required conditions.

Step 5: The gas viscosity, μ_g, at the pressure and temperature of interest is calculated by multiplying the viscosity at one atmosphere and system temperature, μ_1, by the viscosity ratio.

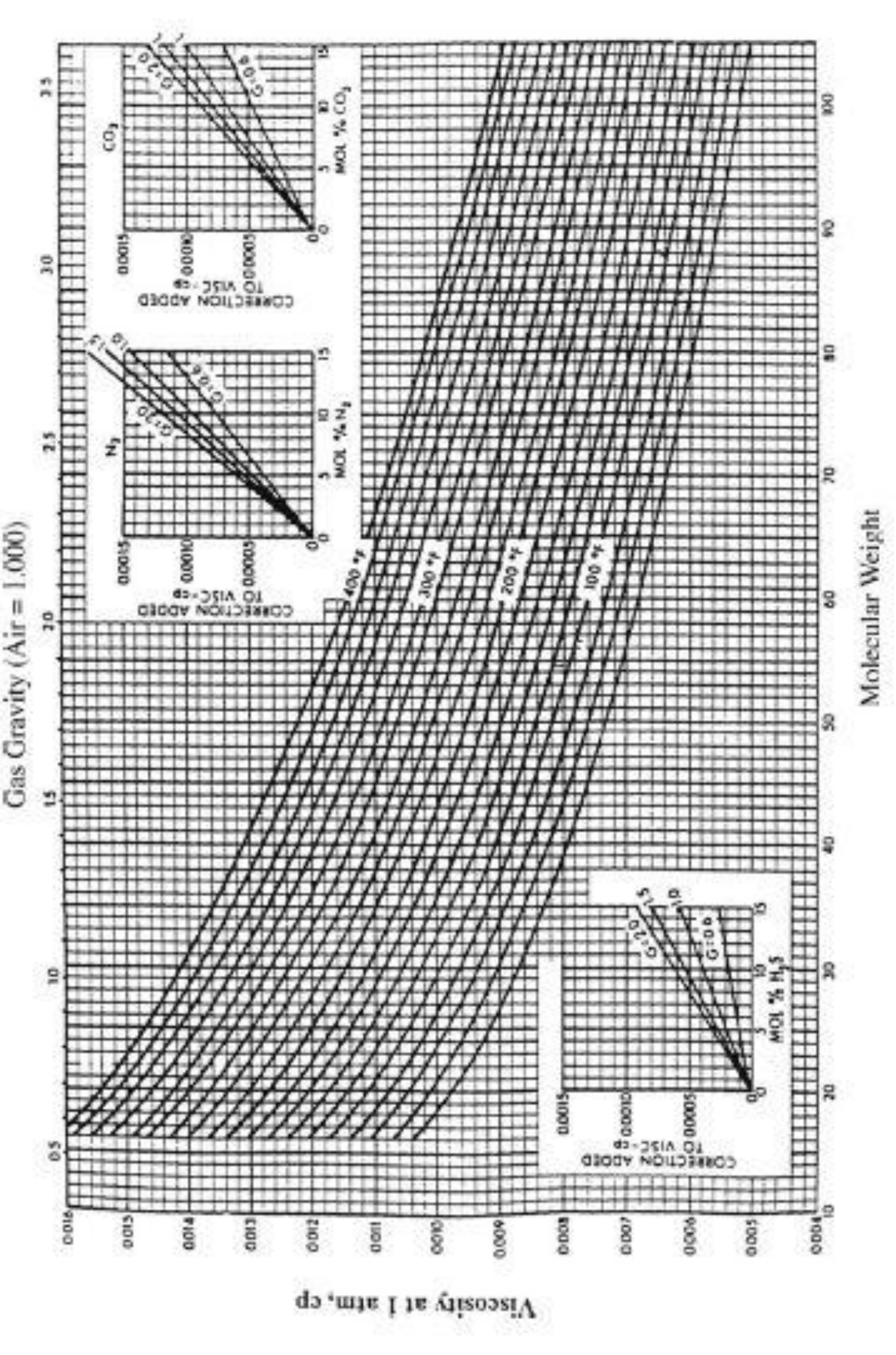

Figure 3-3: Carr's atmospheric gas viscosity correlation. (Permission to publish by the Society of Petroleum Engineers of AIME. Copyright SPE-AIME).

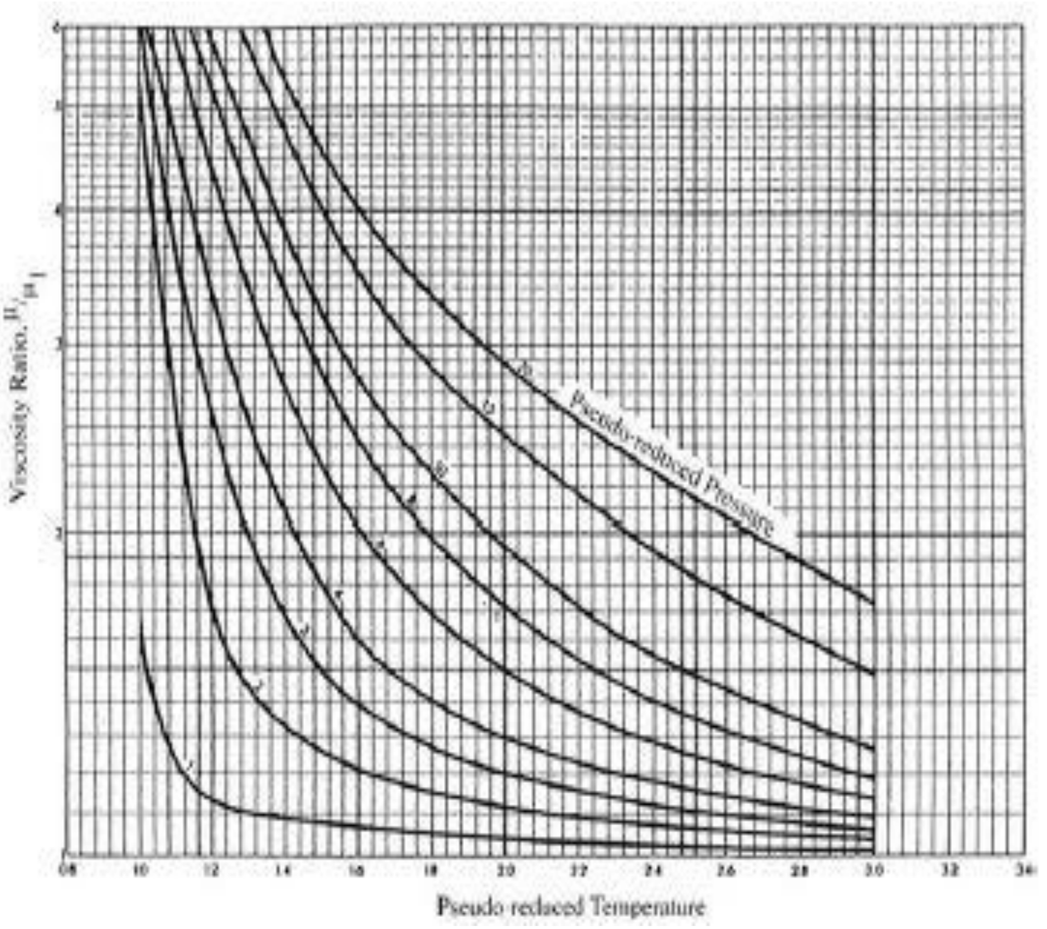

Figure 3-4: Carr's viscosity ratio correlation. (Permission to publish by the Society of Petroleum Engineers of AIME. Copyright SPE-AIME).