Petroleum System

A petroleum system is defined as a natural system that encompasses of active source rock and all related oil and gas and which includes all the geologic elements and processes that are essential if a hydrocarbon accumulation is to exist.

Definition of Petroleum

Petroleum is a complex mixture of hydrocarbons and other constituents that can be in the form of either natural gas or liquid depending on composition, condition of pressure and temperature, reservoir rock depth, and type. The mixture of hydrocarbons is comprised of:

a. Natural gas
b. Crude oil
c. Condensate
d. Other constituants including:
l Nitrogen (N2)
l Carbon dioxide (CO2)
l Hydrogen-sulphide H2S or sulphur

1.1 Reservoir Fluid Properties

1.1.1 Natural gas properties

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 chapter is to present several of the well-established physical property correlations for the following reservoir fluids:

- Natural gases
- Crude oil systems
- Reservoir water systems

Gas is defined as a homogeneous fluid of low viscosity and density, which 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 normally found in a natural gas are methane, ethane (light components as gases), propane, butanes, pentanes, and small amounts of hexanes (medium components) and

heavier components (heptane, octane, ...etc).The medium and heavy components are normally liquids. The non-hydrocarbon gases, that is, impurities, include carbon dioxide CO2, hydrogen sulfide H_2S, and nitrogen N.
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. The properties of interest include:

- • Isothermal gas compressibility coefficient, c_g.
- • Gas formation volume factor, Bg.
- • Gas expansion factor, Eg.
- • Gas viscosity, μ_g
- • Apparent molecular weight, Ma.
- • Gas density, ρg.
- • Specific gravity, ɣg.
- • Specific volume ,v.
- • Compressibility factor, Z.

The mathematical expressions define these properties are:

1 Apparent Molecular Weight (Ma) and Mole Fraction (yi)

$$M_a = \sum_{i=1} y_i M_i \qquad eq.(1.1)$$

where:
M_a = apparent molecular weight of a gas mixture.
M_i = molecular weight of the ith component in the mixture.

y_i = mole fraction of component i in the mixture.

$$y_i = \frac{n_i}{n} = \frac{n_i}{\sum_i n_i} \qquad eq.(1.2)$$

$$n = \frac{wi.}{\mu i}$$

w_i = weight fraction

where:
n = number of moles of gas, *lb-mole.*
ni = number of moles of component i.

= mole fraction.

$$w_i = \frac{m_i}{m} = \frac{m_i}{\sum_i m_i} \qquad eq. (1.3)$$

where:
= weight fraction.
= weight of component i in the mixture, lb/lb-mol.
= total weight.

$$v_i = \frac{V_i}{V} = \frac{V_i}{\sum_i V_i} \qquad eq. (1.4)$$

where:
= the volume fraction of a particular component.
=volume of component i in 1 lb-mol of the mixture.
= total volume.

$$y_i = \frac{n_i}{n} = \frac{n_i}{1} = n_i \qquad (At\ n = 1)$$

$$m_i = n_i M_i = y_i M_i$$

$$w_i = \frac{m_i}{m} = \frac{m_i}{\sum_i m_i} = \frac{y_i M_i}{\sum_i y_i M_i} = \frac{y_i M_i}{M_a}$$

$$y_i = \frac{w_i / M_i}{\sum_i w_i / M_i} \qquad eq. (1.5)$$

The kinetic theory of gases postulates that gases are composed of a very large number of particles called molecules.

Table 2.1 Physical Properties of the Paraffin Hydrocarbons and Other Compounds (after *Eilerts*[12])

Compound	Molecular weight	Boiling point at 14.7 psia °F	Critical constants		Liquid density 60°F, 14.7 psia		Est. part. volume at 60°F, 14.7 psia, gal per M SCF	Est. part. volume at 60° F, 14.4 psia, gal per lb-mole
			Pressure, p_c, psia	Temperature T_c, °R	G (grams) per cc	lb per gal		
Methane	16.04	–258.7	673.1	343.2	[a]0.348	2.90	14.6	5.53
Ethane	30.07	–127.5	708.3	549.9	[a]0.485	4.04	19.6	7.44
Propane	44.09	–43.7	617.4	666.0	[b]0.5077	4.233	27.46	10.417
Isobutane	58.12	10.9	529.1	734.6	[b]0.5631	4.695	32.64	12.380
n-Butane	58.12	31.1	550.1	765.7	[b]0.5844	4.872	31.44	11.929
Isopentane	72.15	82.1	483.5	829.6	0.6248	5.209	36.50	13.851
n-Pentane	72.15	96.9	489.8	846.2	0.6312	5.262	36.14	13.710
n-Hexane	86.17	155.7	440.1	914.2	0.6641	5.536	41.03	15.565
n-Heptane	100.2	209.2	395.9	972.4	0.6882	5.738	46.03	17.463
n-Octane	114.2	258.2	362.2	1024.9	0.7068	5.892	51.09	19.385
n-Nonane	128.3	303.4	334	1073	0.7217	6.017	56.19	21.314
n-Decane	142.3	345.4	312	1115	0.7341	6.121	61.27	23.245
Air	28.97	–317.7	547	239				
Carbon dioxide	44.01	–109.3	1070.2	547.5				
Helium	4.003	–452.1	33.2	9.5				
Hydrogen	2.106	–423.0	189.0	59.8				
Hydrogen sulfide	34.08	–76.6	1306.5	672.4				
Nitrogen	28.02	–320.4	492.2	227.0				
Oxygen	32.00	–297.4	736.9	278.6				
Water	18.0	2212.0	3209.5	1165.2	0.9990	8.337		

[a] Basis partial volume in solution.
[b] At bubble-point pressure and 60°F.

2 Gas Density (ρg)

The density is defined as the mass per unit volume of the substance.

$$\rho_g = \frac{m}{v}$$

$$\rho_g = \frac{pM_a}{RT} \qquad eq.(1.6)$$

$$\rho_g = \frac{1}{v} = \frac{pM_a}{zRT} \qquad (2\text{-}17)$$

where v = specific volume, ft^3/lb
ρ_g = density, lb/ft^3

3 Specific Gravity, γg

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.
If $\gamma g < 1.0$ (lighter than air)

If $\gamma g > 1.0$ (higher than air)

$$\gamma_g = \frac{gas\ density\ @\ 14.7\ and\ 60°}{air\ density\ @\ 14.7\ and\ 60°} = \frac{\rho_g}{\rho_{air}} \qquad eq.(1.7)$$

$$\gamma_g = \frac{\frac{p_{sc}M_a}{RT_{sc}}}{\frac{p_{sc}M_{air}}{RT_{sc}}}$$

Or

$$\gamma_g = \frac{M_a}{M_{air}} = \frac{M_a}{28.96} \qquad eq.(1.8)$$

where:

γ_g = gas specific gravity, 60°/60°

ρ_{air} = density of the air.

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

M_a = apparent molecular weight of the gas.

p_{sc}= standard pressure, psia.

T_{sc}= standard temperature, °R.

4 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.

$$\nu = \frac{V}{m} = \frac{RT}{PM_a} = \frac{1}{\rho} \qquad eq.(1.9)$$

Where:
ρ_g = density of the gas mixture, lb/ft3

M_a = apparent molecular weight.

Determination of Z-factor Value

Z factor (compressibility factor= deviation factor)

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, dimensionless quantity.
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.

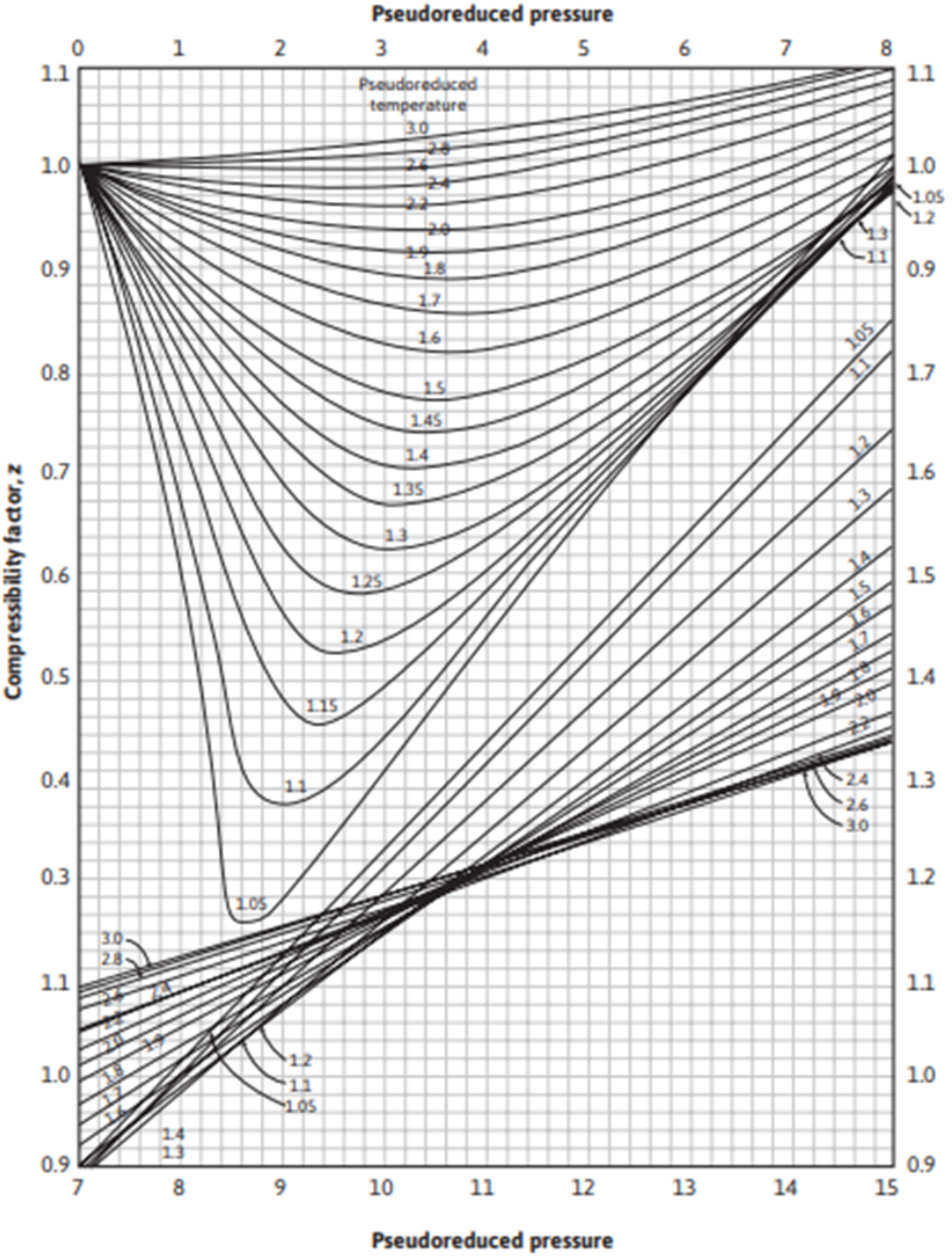
$\frac{1}{Z}$ **super compressibility**

$$z = \frac{V_{actual}}{V_{ideal}} = \frac{V}{(nRT)/p}$$

$$Z = \frac{p\left(V_{gas}\right)_{p,T}}{T} \frac{T_{sc}}{p_{sc}\left(V_{gas}\right)_{sc}} = \frac{V_R p_R T_{sc}}{V_{sc} p_{sc} T_R} \qquad eq.(1.10)$$

The derivation start with

$$\frac{Z_{act}}{Z_{ideal}} = \frac{Z_{act}}{1}$$



Compressibility factors for natural gases (*after* Standing and Katz, *trans.* AIME).[9]

5 Isothermal Gas Compressibility, cg

Type of systems

1. Adiabatic
2. Isothermal (under constant temp.)
3. Isobaric (constant pressure)

4. Isochoric (constant volume)

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:

$$c_g = -\frac{1}{V}\left(\frac{\partial V}{\partial p}\right)_T \qquad eq.(1.11)$$

Where
Cg = isothermal gas compressibility, 1/psi.

1- Isothermal compressibility factor for **ideal gas** given by deriving the ideal gas law at constant temperature:

$$pV = nRT; \qquad T = constant$$

$$p\partial V + V\partial p = 0$$

$$p\partial V = -V\partial p \implies \frac{\partial V}{\partial p} = \frac{-V}{p} \qquad eq.(1.12)$$

by substituting into Eq. (1.11):

$$c_g = \frac{-1}{V}\left(\frac{-V}{p}\right) \implies c_g = \frac{1}{p}\ (psi^{-1}) \qquad eq.(1.13)$$

You could find more explanations

2- Isothermal compressibility factor for **real gas** given by deriving the real gas law at constant temperature:

$$pV = ZnRT; \qquad T = constant$$

$$p\partial V + V\partial p = nRT\partial Z$$

by dividing the equation above by (   ):

$$p\frac{\partial V}{\partial p} + V\cancel{\frac{\partial p}{\partial p}} = nRT\frac{\partial Z}{\partial p}$$

$$p\frac{\partial V}{\partial p} = nRT\frac{\partial Z}{\partial p} - V$$

$$\frac{\partial V}{\partial p} = \frac{nRT}{p}\frac{\partial Z}{\partial p} - \frac{V}{p} \qquad eq. (1.14)$$

by substituting (*V=ZnRT/p*) from real gas law and Eq. (1.14) into Eq. (1.11):

$$c_g = \frac{ZnRT}{pZnRT} - \frac{1}{Z}\frac{\partial Z}{\partial p}$$

$$c_g = \frac{1}{p} - \frac{1}{Z}\left(\frac{\partial Z}{\partial p}\right)_T \qquad eq. (1.15)$$

For an ideal gas $z = 1.00$ and $dz/dp = 0$;

If the gas composition data are not available, we can calculate an approximate value of the pseudo critical temperature and pseudo critical
pressure of the gas.

Equation (1.15) is the isothermal compressibility factor for real gas. From the law of corresponding state, we know that:

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$$p_{pr} = \frac{p}{p_{pc}} \Rightarrow p = p_{pr} p_{pc}$$

By substituting = from the law of corresponding state into Eq. (1.15):

$$c_g = \frac{1}{p_{pr} p_{pc}} - \frac{1}{z}\left[\frac{\partial Z}{\partial\left(p_{pr} p_{pc}\right)}\right]_{T_{pr}}$$

Multiplying this equation by p_{pc} yields:

$$c_g p_{pc} = c_{pr} = \frac{1}{p_{pr}} - \frac{1}{Z}\left[\frac{\partial Z}{\partial p_{pr}}\right]_{T_{pr}} \qquad eq.(1.16)$$

The term c_{pr} is called the isothermal pseudoreduced compressibility, de-fined by the relationship:

$$c_{pr} = c_g p_{pc} \qquad eq.(1.17)$$

where:
c_{pr} = isothermal pseudoreduced compressibility.
c_g = isothermal gas compressibility, psi-1.
p_{pc} = pseudoreduced pressure, psi.

6 Gas Formation Volume Factor, Bg

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.

The value of Bg is always less than one

ابسط تعريف لمعامل التكوين الحجمي للغاز هو حجم الغاز المحسوب عند الظروف المكمنية و المطلوب لإنتاج قدم مكعب قياسي واحد عند السطح.

$$B_g = \frac{(V)_{p,T}}{V_{sc}} \qquad eq.(1.18)$$

Where:
Bg = gas formation volume factor, ft3/scf

$V_{p,T}$= volume of gas at pressure p and temperature, T, ft3
V_{sc} = volume of gas at standard conditions, scf

Applying the real gas equation of state, (pV=ZnRT) and substituting for the volume V, gives:

$$B_g = \frac{\frac{ZnRT}{p}}{\frac{Z_{sc}nRT_{sc}}{p_{sc}}} = \frac{p_{sc}ZT}{T_{sc}p}$$

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 p_{sc} =14.7 psia
and T_{sc} = 520, the above expression can be reduced to the following
relationship:

$$B_g = 0.02827\frac{ZT}{p}\ (ft^3/scf) \qquad eq.(1.19)$$

where:
B_g = gas formation volume factor, ft3/scf.
Z = gas compressibility factor.
T = temperature, °R.
In other field units, the gas formation volume factor can be expressed in bbl/scf, by dividing it on 5.614 ft3 / bbl to give:

$$B_g = 0.005035\frac{ZT}{p}\ (bbl/scf) \qquad eq.(1.20)$$

And also

$$c_g = \frac{-1}{B_g}\left(\frac{\partial B_g}{\partial p}\right)_T \qquad eq.(1.21)$$

7 Gas Expansion Factor, Eg

$$E_g = \frac{1}{B_g}$$

In terms of *scf/ft3*, the gas expansion factor is:

$$E_g = 35.37\frac{p}{ZT}, scf/ft^3 \qquad eq. (1.22)$$

In other units:

$$E_g = 198.6\frac{p}{ZT}, scf/bbl \qquad eq. (1.23)$$

8 Gas Viscosity, μg

It is a function of three variables

1. **Composition**
2. **Temperature**
3. **Pressure**

The viscosity of a fluid is a measure of the internal fluid friction (resistance) to flow. Viscosities are expressed in terms of poises, centipoise, or micropoises. One poise equals a viscosity of 1 dyne sec/cm^2. Viscosity of a natural gas is completely described by the following function:

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

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.

METHODS OF CALCULATING THE VISCOSITY OF NATURAL GASES

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

1 Carr-Kobayashi-Burrows Correlation Method

$$\mu_1 = (\mu_1)_{uncorrected} + (\Delta\mu)_{N_2} + (\Delta\mu)_{CO_2} + (\Delta\mu)_{H_2S} \qquad eq. (1.24)$$

where:
μ_1 = “corrected” gas viscosity at 1 atm and reservoir temperature, cp. (Δ) 2 = viscosity corrections due to the presence of N_2.
(Δ) 2= viscosity corrections due to the presence of CO_2.
(Δ) 2 = viscosity corrections due to the presence of H_2S.
$(\mu_1)_{uncorrected}$ = uncorrected gas viscosity, cp.

2 Lee-Gonzalez-Eakin Method

$$\mu_g = 10^{-4} K exp\left[X\left(\frac{\rho_g}{62.4}\right)^Y\right] \qquad eq. (1.25)$$

$$K = \frac{(9.4 + 0.02M_a)T^{1.5}}{209 + 19M_a + T} \qquad eq. (1.26)$$

$$X = 3.5 + \frac{986}{T} + 0.01M_a \qquad eq. (1.27)$$

$$Y = 2.4 - 0.2X \qquad eq. (1.28)$$

Where:
ρ = gas density at reservoir pressure and temperature, lb/ft^3.
T = reservoir temperature, °R.
M_a = apparent molecular weight of the gas mixture.