

Reservoir Engineering II

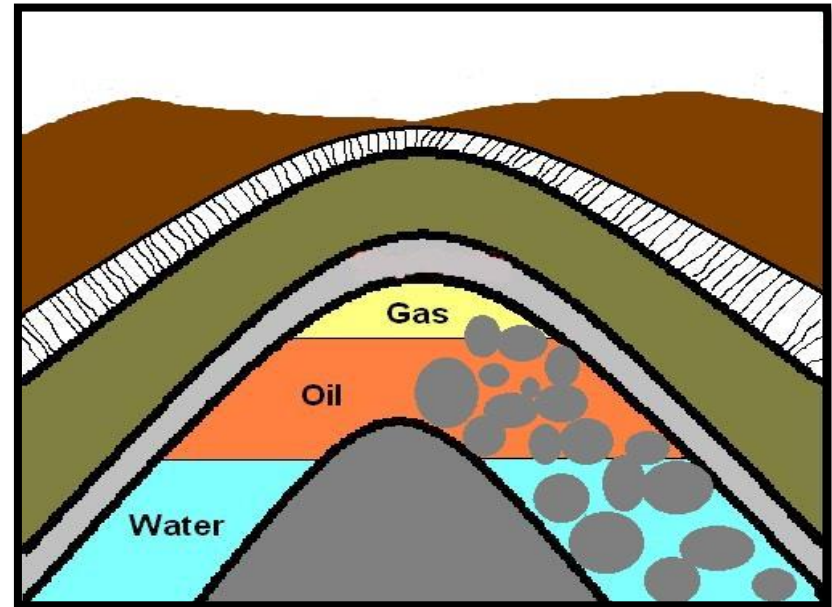
Reservoir fluid properties

By

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Introduction

- Reservoir-fluid properties play a key role in the design and optimization of injection/production strategies and surface facilities for efficient reservoir management.
- Inaccurate fluid characterization often leads to high uncertainties in in-place-volume estimates and recovery predictions.



Properties Of Natural Gases

- **the natural gas is a mixture of hydrocarbon and nonhydrocarbon gases.**
- **The hydrocarbon gases that are normally found in a natural gas are methanes, ethanes, propanes, butanes, pentanes.**
- **The nonhydrocarbon gases (i.e., impurities) include carbon dioxide, hydrogen sulfide, and nitrogen.**

Properties Of Natural Gases

- **Density, ρ_g**
- **Apparent molecular weight, M_a**
- **Specific volume, v**
- **Specific gravity, γ_g**
- **Compressibility factor, z**
- **Isothermal gas compressibility coefficient, c_g**
- **Gas formation volume factor, B_g**
- **Gas expansion factor, E_g**
- **Viscosity, μ_g**

Behavior Of Ideal Gases

- **The ideal gas is a hypothetical gas, but it serves as a useful tool to explain the more complex real gas behavior. Moreover, the equation for the ideal gas is also the basis of developing other equations for real gases.**
- **The physical properties of a gas is controlled by three variables and these are**
 - 1. Pressure exerted by the gas,**
 - 2. Volume occupied by the gas and**
 - 3. Temperature of the gas.**

Behavior Of Ideal Gases

- **An ideal gas has the following properties:**
 - 1. The volume occupied by gas molecules is negligible compared with the volume occupied by the gas;**
 - 2. There is no attractive or repulsive forces among the molecules or between the gas molecules and the wall of the container except during collisions;**
 - 3. All collisions between the gas molecules are purely elastic, implying no internal energy loss on collision.**

Laws Of Ideal Gas

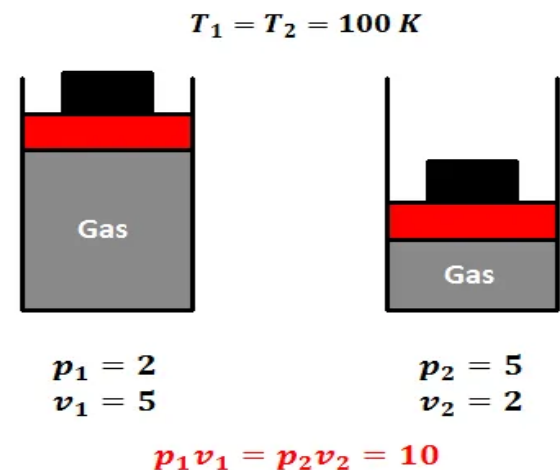
- Boyle's Law

- It states that under constant temperature, the absolute pressure of a given mass of an ideal gas varies inversely as its volume.

$$p \propto \frac{1}{v}$$
$$pv = \text{Constant}$$

From the above result we can write this equation as

$$p_1v_1 = p_2v_2 = p_3v_3 = \dots = \text{Constant}$$



Laws Of Ideal Gas

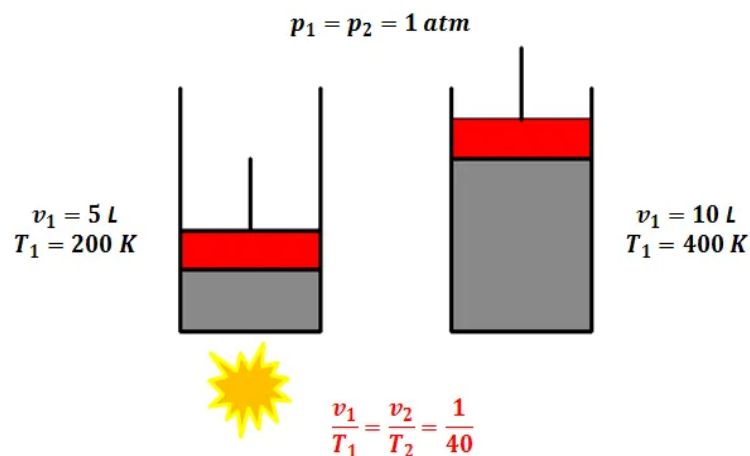
- Charles's Law

- **At constant absolute pressure, the volume of a given mass of an ideal gas varies directly to its temperature.**

$$v \propto T$$
$$\frac{v}{T} = \text{Constant}$$

If we take different sets of condition than the above equation can be written as

$$\frac{v_1}{T_1} = \frac{v_2}{T_2} = \frac{v_3}{T_3} = \text{Constant}$$



Laws Of Ideal Gas

- Avogadro's Law

- Under constant temperature and pressure, equal volumes of all the gases contains equal number of molecules.

$$V \propto n$$

$$\frac{V}{n} = k$$

$$\frac{V_1}{n_1} = \frac{V_2}{n_2}$$

- $k =$ constant which is equals to RT/P , where R is the universal gas constant

Laws Of Ideal Gas

- **General Gas Equation or Ideal Gas Law**
- **Ideal gas law or general gas equation is the combined form of boyle's law, Charles's law and Avogadro law. The ideal gas equation is written as:**

$$PV=nRT.....(1)$$

Laws Of Ideal Gas

- **General Gas Equation or Ideal Gas Law**
- **P = pressure of the gas, psia**
- **V = Volume of the gas, ft³**
- **n = Amount of substance of gas (in moles)**
- **R= Universal gas constant)= 10.730 psia ft³/lb-mole °R**
- **T = Absolute temperature of the gas, °R**

Laws Of Ideal Gas

- **At low pressures, most real gases almost behave like an ideal gas.**
- **For simplifying engineering calculation, a natural gas may be considered as an ideal gas under low pressures (less than 0.4 Mpa ~ 58 psi).**
- **In reservoirs (high pressure), however, a natural gas behaves far from an ideal gas does.**

Apparent Molecular Weight

- **There is no fixed molecular formula for any natural gas. Therefore, it is impossible to calculate the molecular weight of a natural gas in terms of its molecular formula like a pure substance.**
- **It represents the average molecular weight of all molecules in a natural gas.**
- **Numerically, the molecular weight of a natural gas is estimated in terms of the composition of a gas. Gas composition measured in the laboratory is customarily reported in mole fraction (y_i).**

Apparent Molecular Weight

- The apparent molecular weight of the gas can be estimated using a mixing rule such as

$$M_a = \sum_{i=1}^n y_i M_i \dots (5)$$

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

- The density of gas mixture is

$$\rho_g = \frac{m}{V} = \frac{PM_a}{RT} \dots \dots (6)$$

Apparent Molecular Weight

Example :- Calculate the molecular weight of a natural gas according to its mole composition given in Table (1-3) .

Solution

According to the mole composition of the gas, the values of $y_i M_i$ for each component are first calculated, which are listed in the last column of Table . The molecular weight of the gas is then determined by Eq.(5) :

Table (1-3) Mole compositions of a natural gas

Components	Mole fraction, y_i	Molecular weight, M_i	$y_i M_i$
Methane	0.85	16.0	13.60
Ethane	0.09	30.1	7.71
Propane	0.04	44.1	1.76
Butane	0.02	58.1	1.16
Sum	1.00		$M = 19.23$

$$M_a = \sum_{i=1}^N y_i M_i = 13.6 + 7.71 + 1.76 + 1.16 = 19.23$$

Gas Density

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

$$n = \frac{m}{M} \dots(2)$$

where m = weight of gas, lb

M = molecular weight, lb/lb-mol

$$PV = \frac{m}{M} RT \dots(3)$$

$$\rho_g = \frac{m}{V} = \frac{PM}{RT} \dots(4)$$

where ρ_g = density of the gas, lb/ft³

Gas Density

Example

Three pounds of n-butane are placed in a vessel at 120°F and 60 psia. Calculate the volume of the gas assuming an ideal gas behavior.

Solution

Step 1. Determine the molecular weight of n-butane from Table 1-1 to give:

$$M = 58.123$$

Step 2. Solve Equation 1.3 for the volume of gas:

$$V = \left(\frac{m}{M}\right) \frac{RT}{p}$$
$$V = \left(\frac{3}{58.123}\right) \frac{(10.73)(120 + 460)}{60} = 5.35 \text{ ft}^3$$

- $T(R) = T(F) + 460$

Gas Density

Table 1-1 Physical properties of hydrocarbon gases

Gases	Molecular formula	Molecular weight	Boiling point (0.1 MPa) (°C)	Critical pressure, p_{ci} (MPa)	Critical temperature, T_{ci} (K)	Acentric factor
Methane	CH ₄	16.043	-161.50	4.6408	190.67	0.0115
Ethane	C ₂ H ₆	30.070	-88.61	4.8835	303.50	0.098
Propane	C ₃ H ₈	44.097	-42.06	4.2568	370.00	0.1454
Isobutane	<i>i</i> C ₄ H ₁₀	58.124	-11.72	3.6480	408.11	0.1756
Normalbutane	<i>n</i> C ₄ H ₁₀	58.124	-0.50	3.7928	425.39	0.1928
Isopentane	<i>i</i> C ₅ H ₁₂	72.151	27.83	3.3336	460.89	0.2273
Normalpentane	<i>n</i> C ₅ H ₁₂	72.151	36.06	3.3770	470.11	0.2510

Gas Density

Table 1-2 Physical properties of nonhydrocarbon gases

Gases	Molecular formula	Molecular weight	Boiling point (0.1 MPa) (°C)	Critical pressure, p_{ci} (MPa)	Critical temperature, T_{ci} (K)	Acentric factor, ω
Carbon dioxide	CO ₂	44.010	-78.51	7.3787	304.17	0.2250
Helium	He	4.003	-268.93	0.2289	5.278	
Hydrogen	H ₂	2.016	-252.87	1.3031	33.22	-0.2234
Hydrogensulfide	H ₂ S	34.076	-60.31	9.0080	373.56	0.0949
Nitrogen	N ₂	28.013	-195.80	3.3936	126.11	0.0355
Oxygen	O ₂	31.999	-182.96	5.0807	154.78	0.0196
Aqueous vapor	H ₂ O	18.015	100	22.1286	647.33	0.3210

Standard Volume

- The standard volume is defined as the volume of gas occupied by 1 lb-mol of gas at standard conditions.
- The standard conditions are usually 14.7 psia and 60°F.
- $$V_{sc} = \frac{(1) R T_{sc}}{P_{sc}} = \frac{1 \times 10.73 \times 520}{14.7} \dots\dots(6)$$
- $V_{sc} = 379.4$ scf/lb-mol

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

scf = standard cubic feet

T_{sc} = standard temperature, °R

P_{sc} = standard pressure, psia

Specific Volume

- The specific volume is defined as the volume occupied by a unit mass of the gas.

- $$v = \frac{V}{m} = \frac{RT}{PM} = \frac{1}{\rho_g} \quad \dots(7)$$

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.**

Specific Gravity

$$\gamma_g = \frac{\rho_g}{\rho_{air}} \dots\dots(8)$$

$$\gamma_g = \frac{\frac{P_{sc} M_a}{R T_{sc}}}{\frac{P_{sc} M_{air}}{R T_{sc}}} \dots\dots(9)$$

$$\gamma_g = \frac{M_a}{M_{air}} \dots\dots(10)$$

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

Gas Mixture Density

Example

A gas well is producing a natural gas with the following composition:

Assuming an ideal gas behavior, calculate:

- Apparent molecular weight
- Specific gravity
- Gas density at 2,000 psia and 150°F
- Specific volume at 2,000 psia and 150°F

Solution

Component	y_i	M_i	$y_i \cdot M_i$
CO ₂	0.05	44.01	2.200
C ₁	0.90	16.04	14.436
C ₂	0.03	30.07	0.902
C ₃	0.02	44.11	0.882

$$M_a = 18.42$$

Gas Mixture Density

a. Apply Equation (5) to calculate the apparent molecular weight:

$$M_a = 18.42$$

b. Calculate the specific gravity

$$\gamma_g = M_a/28.96 = 18.42/28.96 = 0.636$$

c. Solve for the density

$$\rho_g = \frac{PM_a}{RT} = \frac{(2000)(18.42)}{(10.73)(610)} = 5.628 \text{ lb/ft}^3$$

d. Determine the specific volume

$$v = \frac{1}{\rho} = \frac{1}{5.628} = 0.178 \text{ ft}^3/\text{lb}$$

Behavior Of Real Gases

- In most cases, the deviation from ideal behavior of real gases can be modified by a correction factor; and the results can satisfy the accuracy in engineering application.
- The correction factor called the gas compressibility factor, gas deviation factor, or simply the z-factor.
- The compressibility equation of state for real gases is developed as

$$PV=znRT.....(11)$$

Behavior Of Real Gases

- **General Gas Equation of Real Gas**
- **P = pressure of the gas, psia**
- **V = Volume of the gas, ft³**
- **n = Amount of substance of gas (in moles)**
- **R= Universal gas constant)= 10.730 psia ft³/lb-mole °R**
- **T = Absolute temperature of the gas, °R**
- **z= The gas compressibility factor, dimensionless**

Gas Compressibility Factor

- The gas compressibility factor z is a dimensionless quantity.
- It 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 .

$$z = \frac{V_{actual}}{V_{ideal}} = \frac{V}{(nRT)/P} \quad \dots(12)$$

Gas Compressibility Factor Calculation

- pseudo-critical properties, i.e., P_{pc} and T_{pc} , calculation.

$$P_{pc} = \sum_{i=1}^n y_i P_{ci} \dots(13)$$

$$T_{pc} = \sum_{i=1}^n y_i T_{ci} \dots(14)$$

- Dimensionless terms, Pseudo-reduced pressure and Pseudo-reduce temperature calculation .

$$P_{pr} = \frac{P}{P_{pc}} \dots(15)$$

$$T_{pr} = \frac{T}{T_{pc}} \dots(16)$$

Gas Compressibility Factor Calculation

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

Gas Compressibility Factor

Table A-1
Physical Constants

*See the Table of Notes and References

Number	Compound	Formula	A		B		C		D				
			Molar mass (molecular weight)	Boiling point, °F 14.696 psia	Boiling point, °F 14.696 psia	Freezing point, °F 14.696 psia	Refractive index, n_D 60°F	Critical constants					
									Pressure, psia	Temperature, °F	Volume, ft ³ /lbm	Z_c	Number
1	Hydrogen chloride	HCl	36.46	-109.1	-109.1	-112.2	1.0418	1013.2	239.8	1013.2	172.0	0.076	1
2	Hydrogen fluoride	HF	20.01	-84.1	-84.1	-128.0	1.0303	1013.2	293.0	1013.2	130.0	0.076	2
3	Hydrogen cyanide	HCN	26.04	-78.0	-78.0	-132.0	1.0290	1013.2	308.0	1013.2	120.0	0.076	3
4	Hydrogen sulfide	H ₂ S	34.08	-107.9	-107.9	-129.0	1.0306	1013.2	207.3	1013.2	149.0	0.076	4
5	Hydrogen peroxide	H ₂ O ₂	34.02	-31.1	-31.1	-112.0	1.0306	1013.2	489.3	1013.2	130.0	0.076	5
6	Hydrogen bromide	HBr	80.91	-182.7	-182.7	-169.0	1.0308	1013.2	238.0	1013.2	130.0	0.076	6
7	Hydrogen iodide	HI	127.91	-224.0	-224.0	-181.0	1.0308	1013.2	238.0	1013.2	130.0	0.076	7
8	Hydrogen selenide	H ₂ Se	77.08	-175.0	-175.0	-150.0	1.0308	1013.2	238.0	1013.2	130.0	0.076	8
9	Hydrogen telluride	H ₂ Te	127.6	-181.0	-181.0	-150.0	1.0308	1013.2	238.0	1013.2	130.0	0.076	9
10	Hydrogen phosphide	H ₃ P	33.97	-188.0	-188.0	-150.0	1.0308	1013.2	238.0	1013.2	130.0	0.076	10
11	Hydrogen arsenide	H ₃ As	75.94	-185.0	-185.0	-150.0	1.0308	1013.2	238.0	1013.2	130.0	0.076	11
12	Hydrogen stibide	H ₃ Sb	124.9	-185.0	-185.0	-150.0	1.0308	1013.2	238.0	1013.2	130.0	0.076	12
13	Hydrogen selenide	H ₂ Se	77.08	-175.0	-175.0	-150.0	1.0308	1013.2	238.0	1013.2	130.0	0.076	13
14	Hydrogen telluride	H ₂ Te	127.6	-181.0	-181.0	-150.0	1.0308	1013.2	238.0	1013.2	130.0	0.076	14
15	Hydrogen phosphide	H ₃ P	33.97	-188.0	-188.0	-150.0	1.0308	1013.2	238.0	1013.2	130.0	0.076	15
16	Hydrogen arsenide	H ₃ As	75.94	-185.0	-185.0	-150.0	1.0308	1013.2	238.0	1013.2	130.0	0.076	16
17	Hydrogen stibide	H ₃ Sb	124.9	-185.0	-185.0	-150.0	1.0308	1013.2	238.0	1013.2	130.0	0.076	17
18	Hydrogen selenide	H ₂ Se	77.08	-175.0	-175.0	-150.0	1.0308	1013.2	238.0	1013.2	130.0	0.076	18
19	Hydrogen telluride	H ₂ Te	127.6	-181.0	-181.0	-150.0	1.0308	1013.2	238.0	1013.2	130.0	0.076	19
20	Hydrogen phosphide	H ₃ P	33.97	-188.0	-188.0	-150.0	1.0308	1013.2	238.0	1013.2	130.0	0.076	20
21	Hydrogen arsenide	H ₃ As	75.94	-185.0	-185.0	-150.0	1.0308	1013.2	238.0	1013.2	130.0	0.076	21
22	Hydrogen stibide	H ₃ Sb	124.9	-185.0	-185.0	-150.0	1.0308	1013.2	238.0	1013.2	130.0	0.076	22
23	Hydrogen selenide	H ₂ Se	77.08	-175.0	-175.0	-150.0	1.0308	1013.2	238.0	1013.2	130.0	0.076	23
24	Hydrogen telluride	H ₂ Te	127.6	-181.0	-181.0	-150.0	1.0308	1013.2	238.0	1013.2	130.0	0.076	24
25	Hydrogen phosphide	H ₃ P	33.97	-188.0	-188.0	-150.0	1.0308	1013.2	238.0	1013.2	130.0	0.076	25
26	Hydrogen arsenide	H ₃ As	75.94	-185.0	-185.0	-150.0	1.0308	1013.2	238.0	1013.2	130.0	0.076	26
27	Hydrogen stibide	H ₃ Sb	124.9	-185.0	-185.0	-150.0	1.0308	1013.2	238.0	1013.2	130.0	0.076	27
28	Hydrogen selenide	H ₂ Se	77.08	-175.0	-175.0	-150.0	1.0308	1013.2	238.0	1013.2	130.0	0.076	28
29	Hydrogen telluride	H ₂ Te	127.6	-181.0	-181.0	-150.0	1.0308	1013.2	238.0	1013.2	130.0	0.076	29
30	Hydrogen phosphide	H ₃ P	33.97	-188.0	-188.0	-150.0	1.0308	1013.2	238.0	1013.2	130.0	0.076	30
31	Hydrogen arsenide	H ₃ As	75.94	-185.0	-185.0	-150.0	1.0308	1013.2	238.0	1013.2	130.0	0.076	31
32	Hydrogen stibide	H ₃ Sb	124.9	-185.0	-185.0	-150.0	1.0308	1013.2	238.0	1013.2	130.0	0.076	32
33	Hydrogen selenide	H ₂ Se	77.08	-175.0	-175.0	-150.0	1.0308	1013.2	238.0	1013.2	130.0	0.076	33
34	Hydrogen telluride	H ₂ Te	127.6	-181.0	-181.0	-150.0	1.0308	1013.2	238.0	1013.2	130.0	0.076	34
35	Hydrogen phosphide	H ₃ P	33.97	-188.0	-188.0	-150.0	1.0308	1013.2	238.0	1013.2	130.0	0.076	35
36	Hydrogen arsenide	H ₃ As	75.94	-185.0	-185.0	-150.0	1.0308	1013.2	238.0	1013.2	130.0	0.076	36
37	Hydrogen stibide	H ₃ Sb	124.9	-185.0	-185.0	-150.0	1.0308	1013.2	238.0	1013.2	130.0	0.076	37
38	Hydrogen selenide	H ₂ Se	77.08	-175.0	-175.0	-150.0	1.0308	1013.2	238.0	1013.2	130.0	0.076	38
39	Hydrogen telluride	H ₂ Te	127.6	-181.0	-181.0	-150.0	1.0308	1013.2	238.0	1013.2	130.0	0.076	39
40	Hydrogen phosphide	H ₃ P	33.97	-188.0	-188.0	-150.0	1.0308	1013.2	238.0	1013.2	130.0	0.076	40
41	Hydrogen arsenide	H ₃ As	75.94	-185.0	-185.0	-150.0	1.0308	1013.2	238.0	1013.2	130.0	0.076	41
42	Hydrogen stibide	H ₃ Sb	124.9	-185.0	-185.0	-150.0	1.0308	1013.2	238.0	1013.2	130.0	0.076	42
43	Hydrogen selenide	H ₂ Se	77.08	-175.0	-175.0	-150.0	1.0308	1013.2	238.0	1013.2	130.0	0.076	43
44	Hydrogen telluride	H ₂ Te	127.6	-181.0	-181.0	-150.0	1.0308	1013.2	238.0	1013.2	130.0	0.076	44
45	Hydrogen phosphide	H ₃ P	33.97	-188.0	-188.0	-150.0	1.0308	1013.2	238.0	1013.2	130.0	0.076	45
46	Hydrogen arsenide	H ₃ As	75.94	-185.0	-185.0	-150.0	1.0308	1013.2	238.0	1013.2	130.0	0.076	46
47	Hydrogen stibide	H ₃ Sb	124.9	-185.0	-185.0	-150.0	1.0308	1013.2	238.0	1013.2	130.0	0.076	47
48	Hydrogen selenide	H ₂ Se	77.08	-175.0	-175.0	-150.0	1.0308	1013.2	238.0	1013.2	130.0	0.076	48
49	Hydrogen telluride	H ₂ Te	127.6	-181.0	-181.0	-150.0	1.0308	1013.2	238.0	1013.2	130.0	0.076	49
50	Hydrogen phosphide	H ₃ P	33.97	-188.0	-188.0	-150.0	1.0308	1013.2	238.0	1013.2	130.0	0.076	50

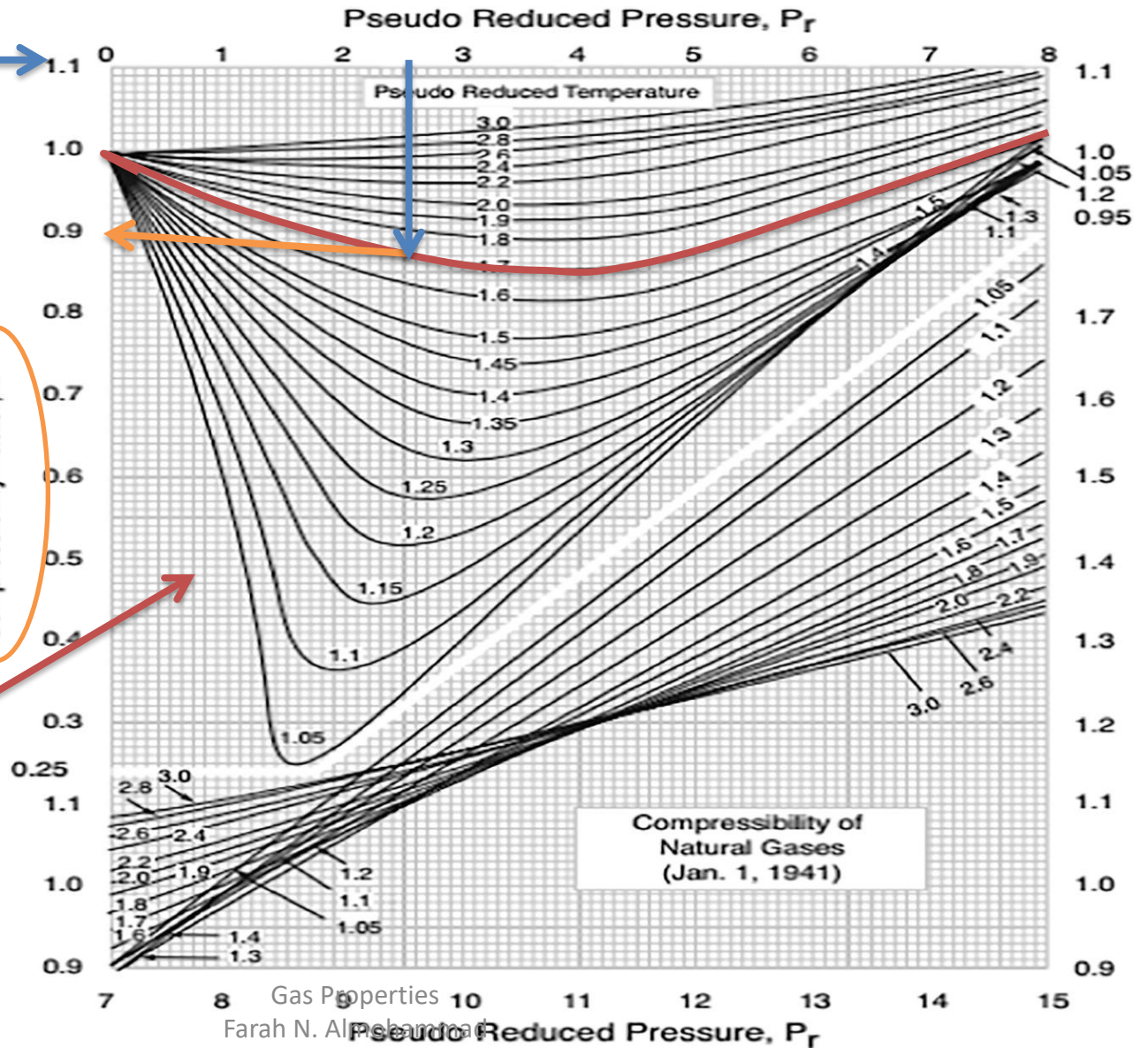
NOTE: Numbers in this table do not have accuracies greater than 1 part in 1000; in some cases extra digits have been added to calculated values to achieve consistency or to permit recalculation of experimental values.

Standing And Katz Compressibility Factor Chart

P_{pr} value

T_{pr} value

Compressibility Factor, z



Gas Compressibility Factor

Example

A gas reservoir has the following gas composition: the initial reservoir pressure and temperature are 3,000 psia and 180°F, respectively.

Component	y_i
CO ₂	0.02
N ₂	0.01
C ₁	0.85
C ₂	0.04
C ₃	0.03
i - C ₄	0.03
n - C ₄	0.02

Calculate the gas compressibility factor under initial reservoir conditions.

Gas Compressibility Factor

Solution

Component	y_i	$T_{ci} \text{ } ^\circ\text{R}$	$y_i T_{ci}$	P_{ci}	$y_i P_{ci}$
CO ₂	0.02	547.91	10.96	1071	21.42
N ₂	0.01	227.49	2.27	493.1	4.93
C ₁	0.85	343.33	291.83	666.4	566.44
C ₂	0.04	549.92	22.00	706.5	28.26
C ₃	0.03	666.06	19.98	616.4	18.48
i - C ₄	0.03	734.46	22.03	527.9	15.84
n - C ₄	0.02	765.62	15.31	550.6	11.01

$T_{pc} = 383.38$ $P_{pc} = 666.38$

Step 1. Determine the pseudo-critical pressure from Equation 13

$$P_{pc} = 666.18$$

Step 2. Calculate the pseudo-critical temperature from Equation 14

$$T_{pc} = 383.38$$

Step 3. Calculate the pseudo-reduced pressure and temperature by applying Equations 15 and 16, respectively:

$$P_{pr} = \frac{3000}{666.38} = 4.50$$

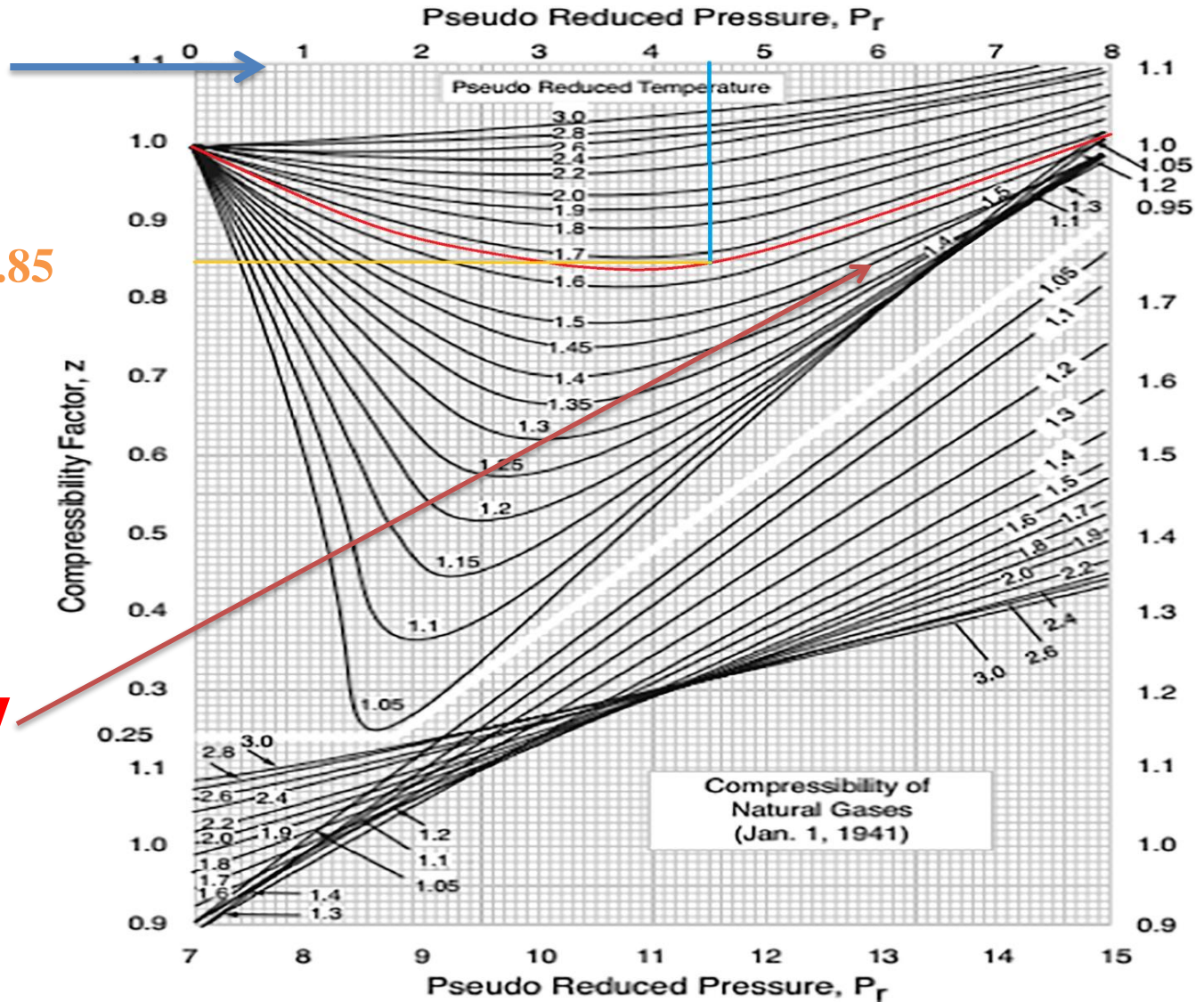
$$T_{pr} = \frac{640}{383.38} = 1.67$$

Standing And Katz Compressibility Factor Chart

$P_{pr} = 4.5$

$Z = 0.85$

$T_{pr} = 1.67$



Gas Compressibility Factor

Step 4. Determine the z-factor

$$z = 0.85$$

Equation 11 can be written in terms of the apparent molecular weight M_a and the weight of the gas m :

$$pV = z \left(\frac{m}{M_a} \right) RT$$

Solving the above relationship for the gas specific volume and density, give:

$$v = \frac{V}{m} = \frac{zRT}{pM_a}$$

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

where v = specific volume, ft^3/lb

ρ_g = density, lb/ft^3

Gas Compressibility Factor

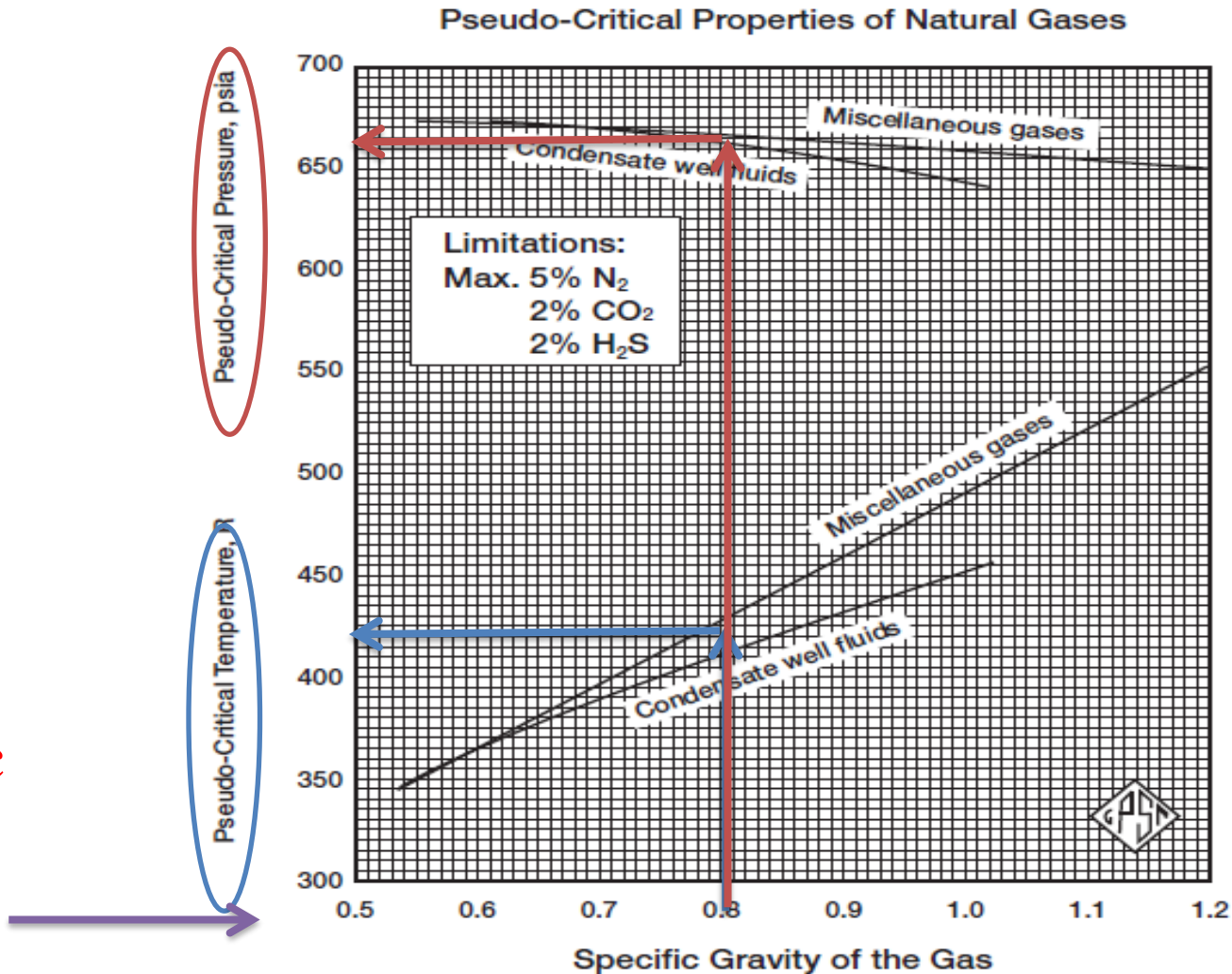
- In cases where the composition of a natural gas is not available, the pseudo-critical properties, i.e., p_{pc} and T_{pc} , can be predicted solely from the specific gravity of the gas.
- This can be done either by Pseudo-critical properties of natural gases chart or by using the following equations.
- Case : Natural Gas Systems

$$T_{pc} = 168 + 325 \gamma_g - 12.5 \gamma_g^2 \quad \dots(17)$$

$$P_{pc} = 677 + 15.0 \gamma_g - 37.5 \gamma_g^2 \quad \dots\dots(18)$$

Gas Compressibility Factor

Gas
specific
gravity
value



Adjustment of The Z-factor

- **Higher contents of nonhydrocarbons in natural gases result in large deviations in the pseudoreduced properties of natural gases by Kay's rule. Therefore, the correction to the Z-factor from a chart is necessary.**
- **Besides the hydrogen sulfide and carbon dioxide, nitrogen is common in natural gases. Generally, the presence of nitrogen does not greatly affect the accuracy of a Z-factor from a generalized chart; Z-factor increases by about 1 % for each 5 % of nitrogen in the gas.**
- **However, the presence of hydrogen sulfide and carbon dioxide in natural gases may cause large errors in Z-factors from a generalized chart.**

Adjustment of The Z-factor

The equations used for the adjustment by The Wichert-Aziz Correction Method are:

$$T'_{pc} = T_{pc} - \epsilon \quad \text{.....(19)}$$

$$P'_{pc} = \frac{P_{pc} T'_{pc}}{T_{pc} + B(1 - B)\epsilon} \quad \text{.....(20)}$$

where T_{pc} = pseudo-critical temperature, °R

P_{pc} = pseudo-critical pressure, psia

T'_{pc} = corrected pseudo-critical temperature, °R

P'_{pc} = corrected pseudo-critical pressure, psia

B = mole fraction of H_2S in the gas mixture

ϵ = pseudo-critical temperature adjustment factor and is defined mathematically by the following expression

$$\epsilon = 120 [A^{0.9} - A^{1.6}] + 15 (B^{0.5} - B^{4.0}) \quad \text{.....(21)}$$

where the coefficient A is the sum of the mole fraction H_2S and CO_2 in the gas mixture,

Adjustment of The Z-factor

Example

A sour natural gas has a specific gravity of 0.7. The compositional analysis of the gas shows that it contains 5% CO₂ and 10% H₂S. Calculate the density of the gas at 3,500 psia and 160°F.

Solution

Step 1. Calculate the uncorrected pseudo-critical properties of the gas from Equations 17 and 18

$$T_{pc} = 168 + 325 (0.7) - 12.5 (0.7)^2 = 389.38^\circ\text{R}$$

$$p_{pc} = 677 + 15 (0.7) - 37.5 (0.7)^2 = 669.1 \text{ psia}$$

Step 2. Calculate the pseudo-critical temperature adjustment factor from Equation 21 :

$$\epsilon = 120 (0.15^{0.9} - 0.15^{1.6}) + 15 (0.1^{0.5} - 0.1^4) = 20.735$$

Step 3. Calculate the corrected pseudo-critical temperature by applying Equation 19

$$T'_{pc} = 389.38 - 20.735 = 368.64$$

Adjustment of The Z-factor

Step 4. Adjust the pseudo-critical pressure p_{pc} by applying Equation 20

$$P'_{pc} = \frac{(669.1)(368.64)}{389.38 + 0.1(1 - 0.1)(20.635)}$$

Step 5. Calculate p_{pr} and T_{pr} :

$$P_{pr} = \frac{3500}{630.44} = 5.55$$
$$T_{pr} = \frac{160 + 460}{368.64} = 1.68$$

Step 6. Determine the z-factor

$$z = 0.89$$

Step 7. Calculate the apparent molecular weight of the gas from Equation 10

$$M_a = (28.96)(0.7) = 20.27$$

Step 8. Solve for gas density:

$$\rho_g = \frac{(3500)(20.27)}{(0.89)(10.73)(620)} = 11.98 \text{ lb/ft}^3$$

Compressibility Of Natural Gases

- **Gas isothermal compressibility is a measure of a change in the volume of a gas with respect to a change in reservoir pressure. Since reservoir temperature is always constant during gas production, the isothermal gas compressibility is extensively used in determining the compressible properties of gas reservoirs.**
- **In general, the compressibility of natural gas is significantly higher than that of crude oil and interstitial water in reservoirs, typically by two orders of magnitude. The gas compressibility is about in the order of $720 \times 10^{-4} \text{ MPa}^{-1}$, whereas typical water and oil compressibilities are about 6×10^{-4} and $15 \times 10^{-4} \text{ MPa}^{-1}$, respectively**

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

where c_g = isothermal gas compressibility, 1/psi.

Compressibility Of Natural Gases

- Care should be taken so that one is not confused with the two concepts: C_g and Z because they both use the word “compressibility”, and both are related to the effect of pressure on gas volume.
- C_g (gas compressibility) means the ability of the gas being compressed at constant temperature; whereas Z (compressibility factor or Z -factor) denotes the deviation from ideality of a gas.
- C_g is used for the calculation of the elastic energy of a gas reservoir, but Z -factor is used for the calculation of gas behavior in the equation of states.

Compressibility Of Natural Gases

From the real gas equation-of-state:

$$V = \frac{nRTz}{p}$$

Differentiating the above equation with respect to pressure at constant temperature T gives:

$$\left(\frac{\partial V}{\partial p}\right)_T = nRT \left[\frac{1}{p} \left(\frac{\partial z}{\partial p}\right) - \frac{z}{p^2} \right]$$

Substituting into Equation 2-44 produces the following generalized relationship:

$$c_g = \frac{1}{p} - \frac{1}{z} \left(\frac{\partial z}{\partial p}\right)_T \quad \dots(22)$$

For an ideal gas, $z = 1$ and $(\partial z/\partial p)_T = 0$, therefore:

$$c_g = \frac{1}{p} \quad \dots(23)$$

Equation (22) can be conveniently expressed in terms of the pseudo-reduced pressure and temperature by simply replacing p with $(p_{pc} p_{pr})$, or:

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

Multiplying the above equation by p_{pc} yields:

$$c_g p_{pc} = c_{pr} = \frac{1}{p_{pr}} - \frac{1}{z} \left[\frac{\partial z}{\partial p_{pr}} \right]_{T_{pr}} \quad \dots(24)$$

The term c_{pr} is called the isothermal pseudo-reduced compressibility and is defined by the relationship:

$$c_{pr} = c_g p_{pc} \quad \dots(25)$$

Compressibility Of Natural Gases

where c_{pr} = isothermal pseudo-reduced compressibility

c_g = isothermal gas compressibility, psi^{-1}

p_{pr} = pseudo-reduced pressure, psi

- Values of $(\partial z / \partial p_{pr})_{T_{pr}}$ can be calculated from the slope of the T_{pr} isotherm on the Standing and Katz z-factor chart

Compressibility Of Natural Gases

Example

A hydrocarbon gas mixture has a specific gravity of 0.72. Calculate the isothermal gas compressibility coefficient at 2,000 psia and 140°F by assuming:

- An ideal gas behavior
- A real gas behavior

Solution

- Assuming an ideal gas behavior, determine c_g by applying

$$c_g = \frac{1}{2000} = 500 \times 10^{-6} \text{ psi}^{-1}$$

- Assuming a real gas behavior

Step 1. Calculate T_{pc} and p_{pc} by applying Equations 17 and 18

$$T_{pc} = 168 + 325 (0.72) - 12.5 (0.72)^2 = 395.5 \text{ }^\circ\text{R}$$

$$p_{pc} = 677 + 15 (0.72) - 37.5 (0.72)^2 = 668.4 \text{ psia}$$

Step 2. Compute p_{pr} and T_{pr} from Equations 15 and 16

$$p_{pr} = \frac{2000}{668.4} = 2.99$$

$$T_{pr} = \frac{600}{395.5} = 1.52$$

Compressibility Of Natural Gases

Calculated $P_{pr} = 2.99$ at $T_{pr} = 1.52$

For these pseudo conditions $z = 0.78$

To find $\left(\frac{\partial z}{\partial P_{pr}}\right)_{T_{pr}}$:

Let $P_{pr} = 2.5$ at constant $T_{pr} = 1.52$

For these pseudo conditions $z = 0.792$

$$\left(\frac{\partial z}{\partial P_{pr}}\right)_{T_{pr}} = \frac{z_1 - z_2}{P_{pr1} - P_{pr2}}$$

Compressibility Of Natural Gases

Step 3. Determine the z-factor .

$$z = 0.78$$

Step 4. Calculate the slope $[\partial z/\partial p_{pr}]_{T_{pr} = 1.52}$:

$$\left[\frac{\partial z}{\partial P_{pr}} \right]_{T_{pr}} = -0.022$$

Step 5. Solve for c_{pr} by applying Equation 24

$$c_{pr} = \frac{1}{2.99} - \frac{1}{0.78} [-0.022] = 0.3627$$

Step 6. Calculate c_g from Equation 25

$$c_g = \frac{0.327}{668.4} = 543 \times 10^{-6} \text{ psi}^{-1}$$

Gas Formation Volume Factor

- **Gas formation volume factor is defined as the volume of free gas, measured at reservoir conditions, required to produce unit volume of the gas at surface standard conditions. Thus**

$$B_g = \frac{V_R}{V_{sc}} \dots\dots(26)$$

where B_g = gas formation volume factor, ft³/scf

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

V_{sc} = volume of gas at standard conditions, scf

- **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.**

Gas Formation Volume Factor

Applying the real gas equation-of-state,

$$B_g = \frac{\frac{zn RT}{P}}{\frac{z_{sc} n R T_{sc}}{P_{sc}}} = \frac{P_{sc}}{T_{sc}} \frac{zT}{P}$$

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

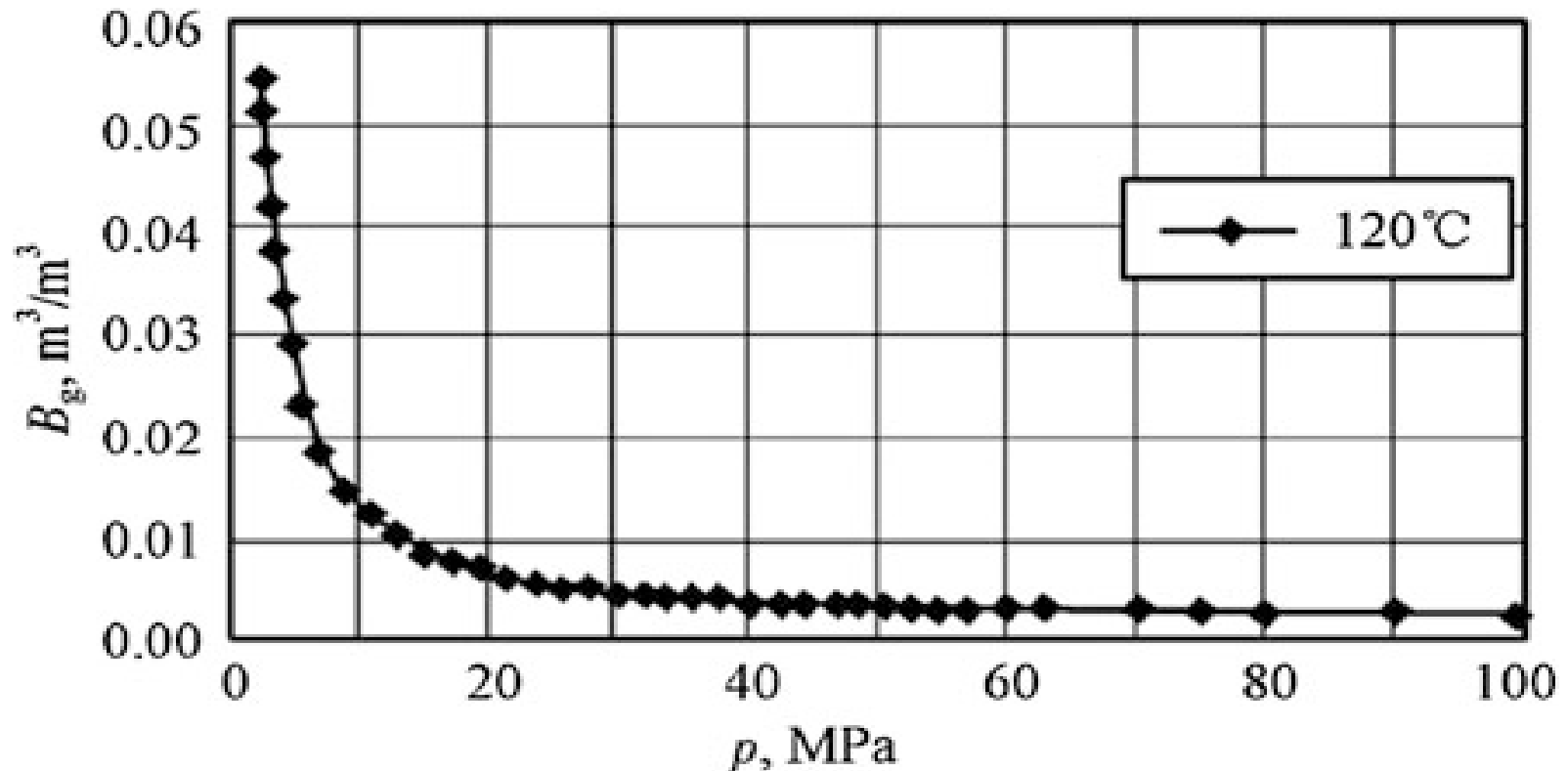
$$B_g = 0.02827 \frac{zT}{P} \quad \text{.....(26)}$$

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

$$B_g = 0.005035 \frac{zT}{P} \quad \text{.....(27)}$$

Gas Formation Volume Factor

A typical curve of gas formation volume factor as a function of pressure at reservoir temperature



Gas Expansion Factor

- The reciprocal of the formation value of the factor sometimes is called gas expansion factor.

$$E_g = 35.37 \frac{P}{zT}; \quad \text{scf/ft}^3$$

or in terms of the gas density ρ_g :

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

In other units:

$$E_g = 198.6 \frac{P}{zT}; \quad \text{scf/bbl}$$