

Reservoir Engineering II

Reservoir fluid properties

By

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Properties Of Crude Oil

Physical properties of primary interest in petroleum engineering studies include:

- Fluid gravity
- Bubble-point pressure
- Gas solubility
- Oil formation volume factor
- Isothermal compressibility coefficient of undersaturated crude oils
- Oil density
- Total formation volume factor
- Crude oil viscosity

Oil Gravity

The specific gravity of a crude oil is defined as the ratio of the density of the oil to that of water. Both densities are measured at 60°F and atmospheric pressure:

$$\gamma_{oil} = \frac{\rho_o}{\rho_w} = \frac{\rho_o}{62.4} \dots(1)$$

γ_o = specific gravity of the oil

ρ_o = density of the crude oil, lb/ft³

ρ_w = density of the water, lb/ft³ = 62.4 lb/ft³

Oil Gravity

- It should be pointed out that the liquid specific gravity is dimensionless, but traditionally is given the units $60^{\circ}/60^{\circ}$ to emphasize the fact that both densities are measured at standard conditions.
- Generally, the specific gravity of crude oil varies between 0.8 and 0.97 in most instances.

The API Gravity Of Crude Oil

- API (American Petroleum Institute) gravity, expressed in degrees, is more prevalent in petroleum industry.
- API gravity is also a measure of oil density, and is related to specific gravity by the following equation
- $$API = \frac{141.5}{\gamma_o} - 131.5 \dots (2)$$

The API Gravity Of Crude Oil

- The API gravity of a crude oil is inversely proportional to its specific gravity.
- The API gravities of crude oils usually range from 47° API for the lighter crude oils to 10° API for the heavier asphaltic crude oils.
- Normally, the price of the crude oil depends on its gravity, the less dense (higher API) being the most valuable.

The API Gravity Of Crude Oil

Example

Calculate the specific gravity and the API gravity of a crude oil system with a measured density of 53 lb/ft^3 at standard conditions.

Solution

Step 1. Calculate the specific gravity from Equation 1

$$\gamma_o = \frac{53}{62.4} = 0.849$$

Step 2. Solve for the API gravity:

$$\text{API} = \frac{141.5}{0.849} - 131.5 = 35.2^\circ \text{ API}$$

Bubble-Point Pressure

- The bubble-point pressure p_b of a hydrocarbon system is defined as the highest pressure at which a bubble of gas is first liberated from the oil.
- This important property can be measured experimentally for a crude oil system by conducting a constant-composition expansion test.
- In the absence of the experimentally measured bubble-point pressure, It should be estimated by correlations.
- correlations are essentially based on the assumption that the bubble-point pressure is a strong function of gas solubility R_s , gas gravity γ_g , oil gravity API, and temperature T, or:
- $P_b = f(R_s, \gamma_g, \text{API}, T)$

Bubble-Point Pressure

- **Standing's Correlation**

Standing's correlation should be used with caution if nonhydrocarbon components are known to be present in the system.

$$p_b = 18.2 [(R_s/\gamma_g)^{0.83} (10)^a - 1.4] \quad \dots\dots(3)$$

with

$$a = 0.00091 (T - 460) - 0.0125 (\text{API}) \quad \dots\dots(4)$$

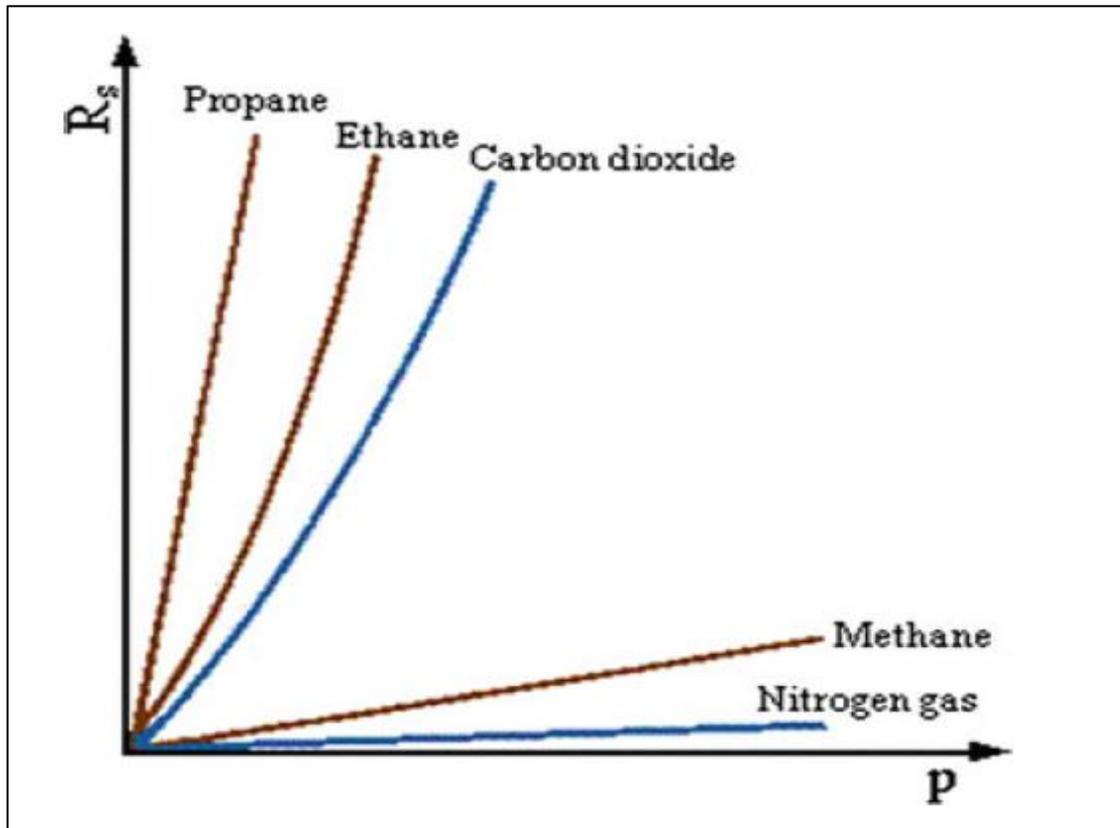
where p_b = bubble-point pressure, psia
 T = system temperature, °R

Gas Solubility

- Gas solubility means the amount of a gas that dissolves in a unit liquid at certain temperature and pressure. Gas solubility varies with temperature and pressure.
- The solubility of a natural gas in a crude oil is a strong function of the pressure, temperature, API gravity, and gas gravity.
- Solubility factor relates with both gas and liquid properties. At given temperature, the solubility factor of a gas in a given liquid depends on the properties of the gas.
- Figure 1 shows several solubility curves of pure gases. It can be seen that the gases with large molecular weights have large solubility factor, and thus dissolve more easily in a liquid.

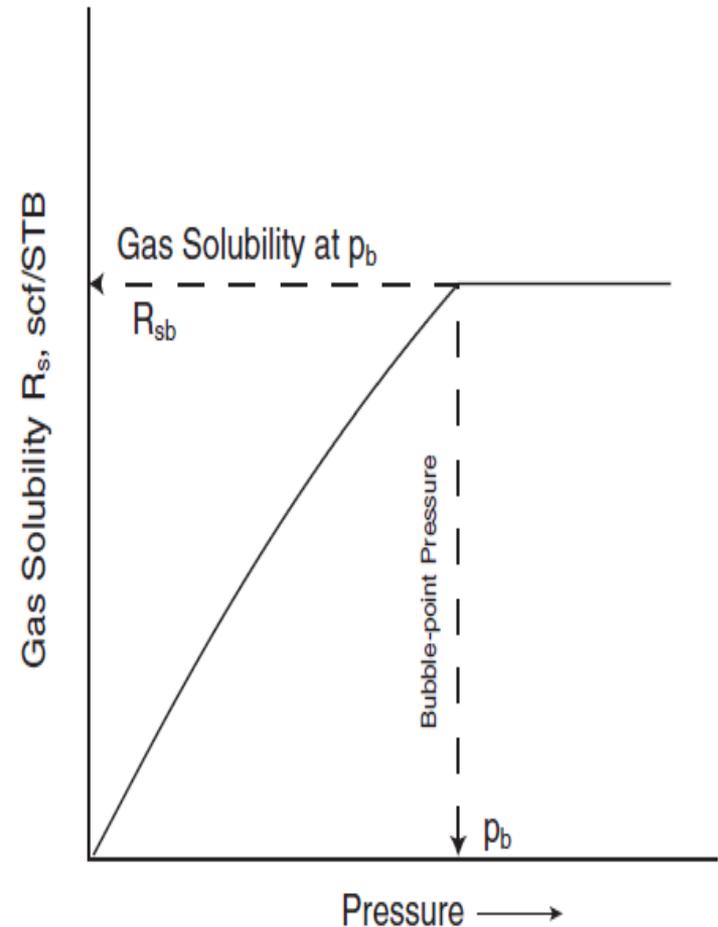
Gas Solubility

- **Figure 1 Solubility curves of pure gases**



Gas Solubility

- For a particular gas and crude oil to exist at a constant temperature, the solubility increases with pressure until the saturation pressure is reached.
- At the saturation pressure (bubble-point pressure) all the available gases are dissolved in the oil and the gas solubility reaches its maximum value.
- As the pressure is reduced from the initial reservoir pressure p_i to the bubble-point pressure p_b , no gas evolves from the oil and consequently the gas solubility remains constant at its maximum value of R_{sb}



Oil Formation Volume Factor

- The oil formation volume factor, B_o , is defined as the ratio of the volume of oil (plus the gas in solution) at the prevailing reservoir temperature and pressure to the volume of oil at standard conditions.
- B_o is always greater than or equal to unity.
- The oil formation volume factor can be expressed mathematically as:

- $$B_o = \frac{(V_o)_{P,T}}{(V_o)_{sc}}$$

Oil Formation Volume Factor

where B_o = oil formation volume factor, bbl/STB

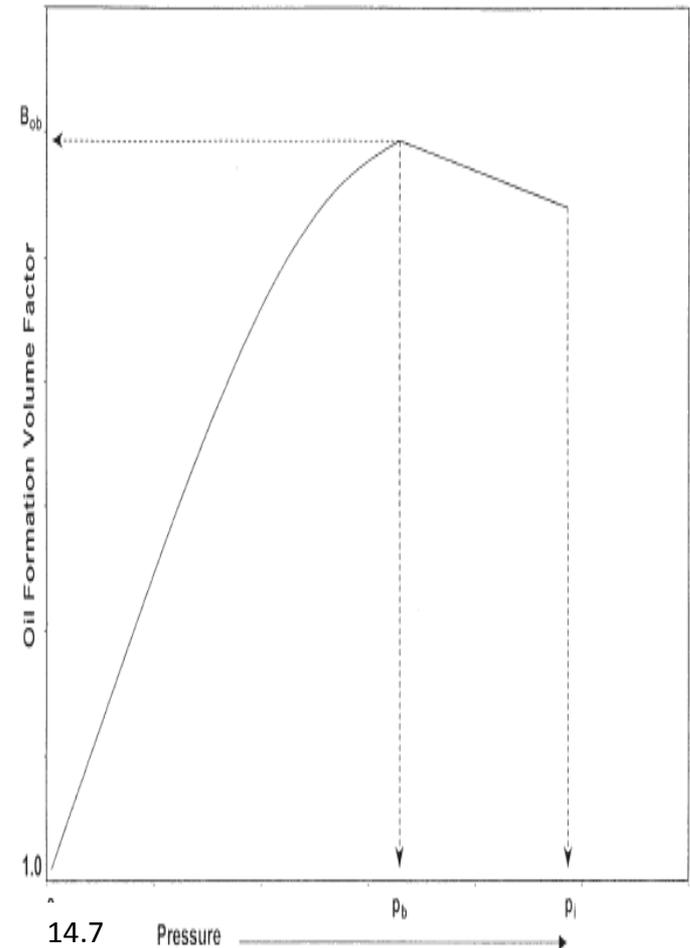
$(V_o)_{p,T}$ = volume of oil under reservoir pressure p and temperature T , bbl

$(V_o)_{sc}$ = volume of oil is measured under standard conditions, STB

$$B_o = \frac{62.4 \gamma_o + 0.0136 \gamma_g R_s}{\rho_o}$$

Oil Formation Volume Factor

- As the pressure is reduced below the initial reservoir pressure p_i , the oil volume increases due to the oil expansion. This behavior results in an increase in the oil formation volume factor and will continue until the bubble-point pressure is reached
- At p_b , the oil reaches its maximum expansion and consequently attains a maximum value of B_{ob} for the oil formation volume factor.
- As the pressure is reduced below p_b , volume of the oil and B_o are decreased as the solution gas is liberated.
- When the pressure is reduced to atmospheric pressure and the temperature to 60°F , the value of B_o is equal to one.



Isothermal Compressibility

- Oil, gas and water are the fluids produced from petroleum reservoirs. These fluids can be classified as incompressible, slightly compressible, or compressible, depending on how they behave when subjected to external pressure.
- An incompressible fluid, as the name implies, has zero compressibility, a slightly compressible fluid has a small but constant compressibility that usually ranges from 10^{-5} to 10^{-6} psi^{-1} .
- A compressible fluid has a higher compressibility than a slightly compressible fluid, usually approximately 10^{-4} to 10^{-3} psi^{-1} .

Isothermal Compressibility

- For a crude oil system, the isothermal compressibility coefficient of the oil phase c_o is defined for pressures above the bubble-point by one of the following equivalent expressions

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

$$c_o = - \frac{1}{B_o} \left(\frac{\partial B_o}{\partial p} \right)_T$$

where c_o = isothermal compressibility, psi⁻¹

ρ_o = oil density lb/ft³

B_o = oil formation volume factor, bbl/STB

- At pressures below the bubble-point pressure, the oil compressibility is defined as:

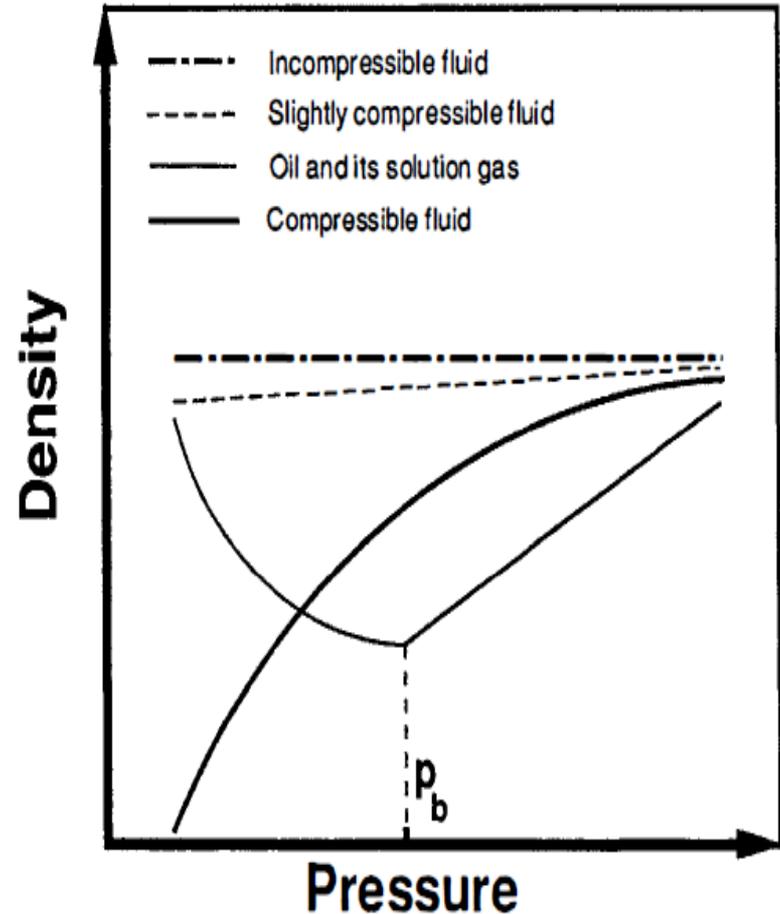
$$c_o = - \frac{1}{B_o} \frac{\partial B_o}{\partial p} + \frac{B_g}{B_o} \frac{\partial R_s}{\partial p}$$

Crude Oil Density

- An incompressible fluid has zero compressibility therefore, it has constant density regardless of pressure. This type of fluid is an idealization for gas-free (or dead) oil and water.
- Under reservoir conditions, dead oil, undersaturated oil, and water behave as slightly compressible fluids.
- The density of a compressible fluid increases as pressure increases but tends to level off at high pressures.
- At reservoir pressures and temperatures, gas is a good example of a compressible fluid.

Crude Oil Density

- Oil and its solution gas are treated as slightly compressible when reservoir pressure is higher than the oil bubble point pressure.
- As the pressure gradually decreases below bubble point pressure the soluble gas in the oil phase is liberated, which causes an increase in oil density.



Total Formation Volume Factor

- To describe the pressure-volume relationship of hydrocarbon systems below their bubble-point pressure, it is convenient to express this relationship in terms of the total formation volume factor as a function of pressure.
- This property defines the total volume of a system regardless of the number of phases present. The total formation volume factor, denoted B_t , is defined as the ratio of the total volume of the hydrocarbon mixture (i.e., oil and gas, if present), at the prevailing pressure and temperature per unit volume of the stock-tank oil.
- Because naturally occurring hydrocarbon systems usually exist in either one or two phases, the term two-phase formation volume factor has become synonymous with the total formation volume.

Total Formation Volume Factor

$$B_t = \frac{(V_o)_{p,T} + (V_g)_{p,T}}{(V_o)_{sc}}$$

where B_t = total formation volume factor, bbl/STB

$(V_o)_{p,T}$ = volume of the oil at p and T , bbl

$(V_g)_{p,T}$ = volume of the liberated gas at p and T , bbl

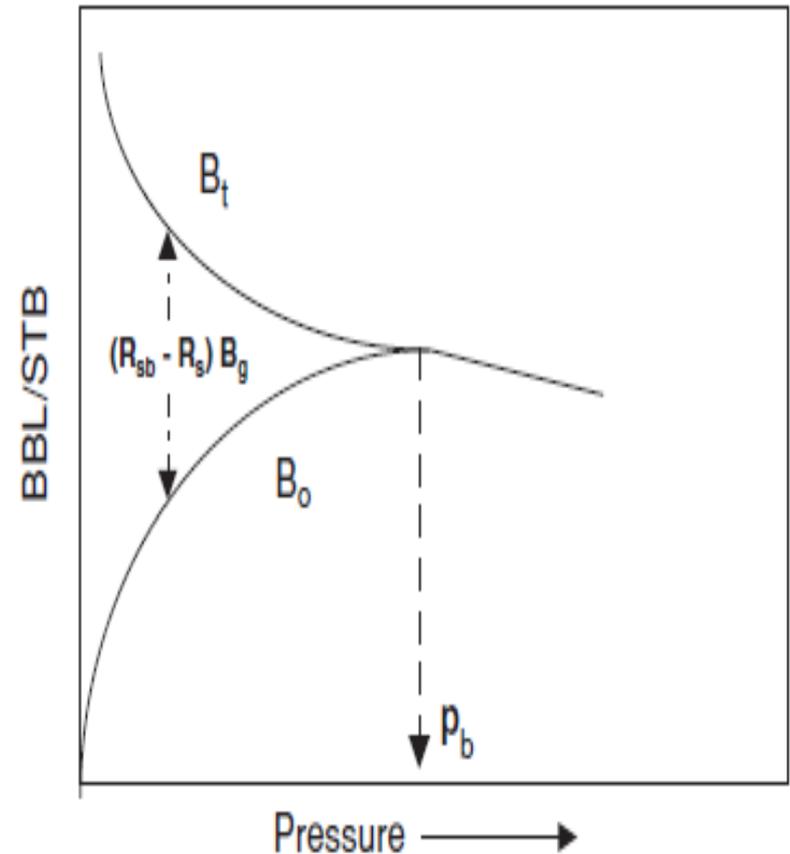
$(V_o)_{sc}$ = volume of the oil at standard conditions, STB

- above the bubble point pressure, no free gas exists and the expression is reduced to the equation that describes the oil formation volume factor, that is:

$$B_t = \frac{(V_o)_{p,T} + 0}{(V_o)_{sc}} = \frac{(V_o)_{p,T}}{(V_o)_{sc}} = B_o$$

Total Formation Volume Factor

- B_o and B_t are identical at pressures above or equal to the bubble-point pressure because only one phase, the oil phase, exists at these pressures. It should also be noted that at pressures below the bubble-point pressure, the difference in the values of the two oil properties represents the volume of the evolved solution gas as measured at system conditions per stock-tank barrel of oil.



Total Formation Volume Factor

From the definition of the two-phase formation volume factor

$$B_t = B_o + (R_{sb} - R_s)B_g$$

where R_{sb} = gas solubility at the bubble-point pressure, scf/STB

R_s = gas solubility at any pressure, scf/STB

B_o = oil formation volume factor at any pressure, bbl/STB

B_g = gas formation volume factor, bbl/scf

- the term $(R_{sb} - R_s)$ represents the volume of the free gas as measured in scf per stock-tank barrel of oil

Total Formation Volume Factor

Example

Given the following PVT data:

$$p_b = 2,744 \text{ psia}$$

$$T = 600^\circ\text{R}$$

$$\gamma_g = 0.6744$$

$$R_s = 444 \text{ scf/STB}$$

$$R_{sb} = 603 \text{ scf/STB}$$

$$\gamma_o = 0.843 \text{ } 60^\circ/60^\circ$$

$$p = 2,000 \text{ psia}$$

$$B_o = 1.1752 \text{ bbl/STB}$$

calculate B_t at 2,000 psia

Total Formation Volume Factor

Solution by Using Definition of B_t

Step 1. Calculate T_{pc} and p_{pc} of the solution gas from its specific gravity

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

$$T_{pc} = 168 + 325 (0.6744) - 12.5(0.6744)^2 = 381.49 \text{ } ^\circ\text{R}$$

$$p_{pc} = 677 + 15 \gamma_g - 37.5(\gamma_g)^2 = 670.06 \text{ psia}$$

Step 2. Calculate p_{pr} and T_{pr} :

$$p_{pr} = \frac{2000}{670.00} = 2.986$$

$$T_{pr} = \frac{600}{381.49} = 1.57$$

Step 3. Determine the gas compressibility factor from Figure $\rightarrow Z = 0.81$

Step 4. Calculate B_g

$$B_g = 0.00504 \frac{(0.81)(600)}{2000} = 0.001225 \text{ bbl/scf}$$

Step 5. Solve for B_t from:

$$B_t = B_o + (R_{sb} - R_s) B_g$$

$$B_t = 1.1752 + 0.0001225 (603 - 444) = 1.195 \text{ bbl/STB}$$

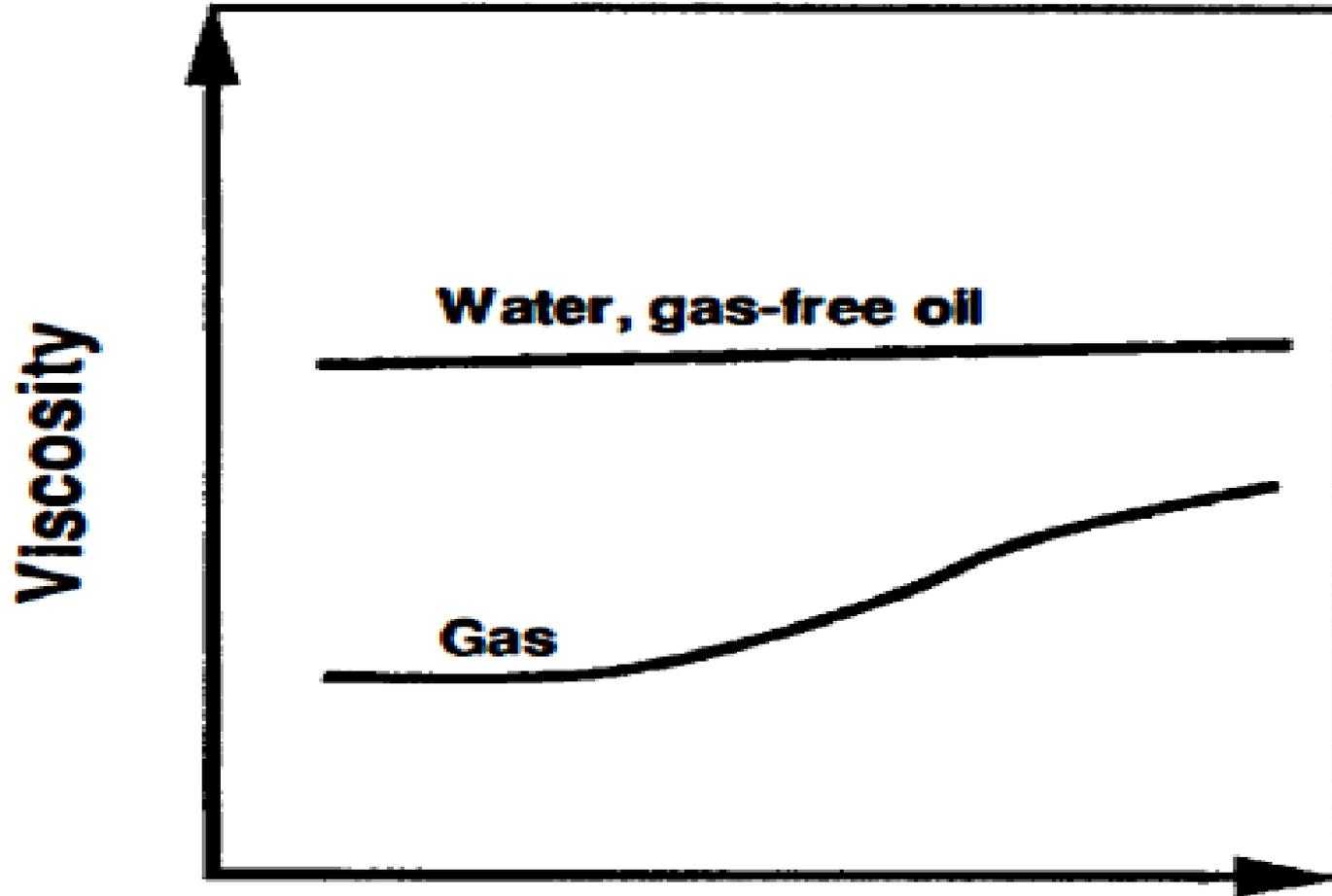
Oil viscosity

- Fluid viscosity is a measure of the ease with which the fluid flows as a result of an applied pressure gradient.
- For a gaseous fluid, the molecules are far apart and offer low resistance to flow.
- In contrast, a dense fluid offers high resistance to flow because the fluid molecules are close to each other and their random motions retard flow.
- Fluid viscosity is a function of both pressure and temperature; however, we are only interested in the pressure dependence of viscosity in isothermal reservoirs.

Oil viscosity

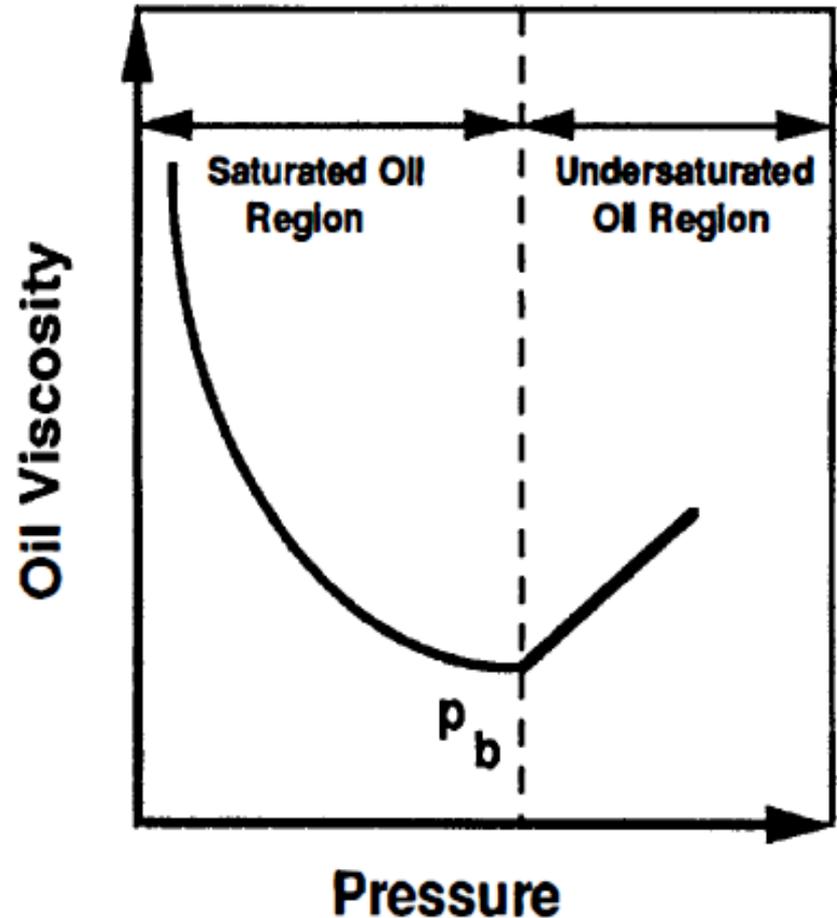
- One can analyze the variation of water and gas viscosities with pressure by considering the effect of pressure on their densities.
- Water is slightly compressible at reservoir conditions; therefore, as pressure increases, water viscosity increases slightly or remains almost constant.
- Gas is a compressible fluid, and its viscosity is low at low pressures. Gas viscosity increases as pressure increases but tends to level off at high pressures because gas under high pressure begins to behave as if it is a liquid.

Oil viscosity



Oil viscosity

- The pressure/viscosity relationship for gas-free (dead) oil is analogous to that of water.
- Pressure effects on oil-phase density and solution-gas/oil ratio on oil-phase dilution.
- In the undersaturated oil region ($p > P_b$), oil dilution remains unchanged because R_s is constant.
- Only the oil density decreases as pressure decreases from P_i to P_b . As a result, the oil-phase viscosity in this region decreases as pressure decreases.



Oil viscosity

- In the saturated oil region ($p \leq P_b$) both oil-phase dilution and density change in response to pressure changes.
- As pressure decreases, gas evolves from the oil phase, leaving it less diluted by gas; more dense.
- On the other hand, the oil component and the associated solution gas expand as pressure drops; less dense.
- The effect of gas liberation on viscosity dominates the effect of oil expansion; therefore, the oil phase becomes more viscous as the reservoir pressure drops.

