6.15 Physical Properties of Gases and Fluids

Synopsis: **The Bulk modulus** (K) of a fluid or a gas is defined as

$$K = \frac{1}{\beta} = -\frac{dP}{(dV/V)} = \rho\,\frac{dP}{d\rho}$$

where β is compressibility, P is pressure, and V is volume. For small pressure variations (typical for wave propagation), the pressure variation is related to the density variation through the acoustic velocity c_o (which is 1500 m/s for water at room conditions):

$$dP = c_o^2\,d\rho.$$

Therefore,

$$K = \rho\,c_o^2.$$

BRINE. The **density of brine** ρ_B of salinity S of sodium chloride is

$$\rho_B = \rho_w + S\{0.668 + 0.44S + 10^{-6}[300P - 2400PS + T(80 + 3T - 3300S - 13P + 47PS)]\}$$

where the **density of pure water** (ρ_w) is

$$\rho_w = 1 + 10^{-6}(-80T - 3.3T^2 + 0.00175T^3 + 489P - 2TP + 0.016T^2P - 1.3\times10^{-5}T^3P - 0.333P^2 - 0.002TP^2)$$

In these formulas pressure P is in MPa, temperature T is in degrees Centigrade, salinity S is in fractions of one (parts per million divided by 10^6), and density (ρ_B and ρ_w) is in g/cm^3.

The **acoustic velocity in brine** V_B in m/s is

$$V_B = V_w + S(1170 - 9.6T + 0.055\,T^2 - 8.5\times10^{-5}T^3 + 2.6P - 0.0029TP - 0.0476P^2) + S^{1.5}(780 - 10P + 0.16P^2) - 1820S^2$$

where the **acoustic velocity in pure water** V_w in m/s is

$$V_w = \sum_{i=0}^{4}\sum_{j=0}^{3} w_{ij}T^iP^j$$

and coefficients w_{ij} are

$w_{00} = 1402.85$	$w_{02} = 3.437\times10^{-3}$
$w_{10} = 4.871$	$w_{12} = 1.739\times10^{-4}$
$w_{20} = -0.04783$	$w_{22} = -2.135\times10^{-6}$
$w_{30} = 1.487\times10^{-4}$	$w_{32} = -1.455\times10^{-8}$
$w_{40} = -2.197\times10^{-7}$	$w_{42} = 5.230\times10^{-11}$

$w_{01} = 1.524$	$w_{03} = -1.197\text{x}10^{-5}$
$w_{11} = -0.0111$	$w_{13} = -1.628\text{x}10^{-6}$
$w_{21} = 2.747\text{x}10^{-4}$	$w_{23} = 1.237\text{x}10^{-8}$
$w_{31} = -6.503\text{x}10^{-7}$	$w_{33} = 1.327\text{x}10^{-10}$
$w_{41} = 7.987\text{x}10^{-10}$	$w_{43} = -4.614\text{x}10^{-13}$

We define **gas-water ratio** R_G as the ratio of the volume of dissolved gas at standard conditions to the volume of brine. Then for temperatures below 250°C, the maximum amount of methane that can go into solution in brine is

$$\begin{aligned}\text{Log}_{10}(R_G) = \text{Log}_{10}\{0.712P|T - 76.71|^{1.5} + 3676P^{0.64}\} \\ - 4 - 7.786S(T + 17.78)^{-0.306}\end{aligned}$$

If K_B is the bulk modulus of the gas-free brine, and K_G is that of brine with gas-water ratio R_G, then

$$\frac{K_B}{K_G} = 1 + 0.0494R_G$$

i.e., bulk modulus decreases linearly with increasing gas content. As far as the density of the brine is concerned, experimental data is sparse, but the consensus is that it is almost independent of the amount of dissolved gas.

The **viscosity of brine** η in cPs for temperatures below 250°C is

$$\eta = 0.1 + 0.333S + (1.65 + 91.9S^3)e^{-[0.42(S^{0.8} - 0.17)^2 + 0.045]T^{0.8}}$$

Gas. Natural gas is characterized by its gravity G which is the ratio of gas density to air density at 15.6°C and atmospheric pressure. The gravity of methane is 0.56. It may be as large as 1.8 for heavier natural gases. Algorithms for calculating **gas density** and **bulk modulus** follow.

Step 1: Calculate absolute temperature T_a as

$$T_a = T + 273.15$$

where T is in degrees Centigrade.

Step 2: Calculate pseudo pressure P_r and pseudo temperature T_r as

$$P_r = \frac{P}{4.892 - 0.4048G}\,, \quad T_r = \frac{T_a}{94.72 + 170.75G}$$

where pressure is in MPa.

Step 3: Calculate **density** ρ_G in g/cm^3 as

$$\rho_G \approx \frac{28.8GP}{ZRT_a}$$

$$Z = aP_r + b + E\,, \quad E = cd$$

$$d = \exp\{-[0.45 + 8(0.56 - \frac{1}{T_r})^2]\frac{P_r^{1.2}}{T_r}\}$$

$$c = 0.109(3.85 - T_r)^2 , \quad b = 0.642T_r - 0.007T_r^4 - 0.52$$

$$a = 0.03 + 0.00527(3.5 - T_r)^3$$

$$R = 8.31441 \text{ J/g–mole deg} \quad \text{(gas constant)}$$

Step 4: Calculate the adiabatic **bulk modulus** K_G in MPa as

$$K_G \approx \frac{P\gamma}{1 - \frac{P_r}{Z}f} , \quad \gamma = 0.85 + \frac{5.6}{P_r + 2} + \frac{27.1}{(P_r + 3.5)^2} - 8.7e^{-0.65(P_r + 1)}$$

$$f = cdm + a , \quad m = 1.2\left\{ - [0.45 + 8(0.56 - \frac{1}{T_r})^2]\frac{P_r^{0.2}}{T_r} \right\}$$

The above approximate expressions for ρ_G and K_G are valid as long as P_r and T_r are not both within 0.1 of unity.

Oil. Oil density under room conditions may vary from under 0.5 to 1 g/cm^3, with most produced oils in the 0.7 to 0.8 g/cm^3 range. A reference (standard) density that can be used to characterize an oil ρ_0 is measured at 15.6^{o}C and atmospheric pressure. A widely used classification of crude oil is the American Petroleum Institute oil gravity (API gravity). It is defined as

$$API = \frac{141.5}{\rho_0} - 131.5$$

where density is in g/cm^3. API gravity may be about 5 for very heavy oils and about 100 for light condensates.

Acoustic velocity in oil V_P may generally vary with temperature T and **molecular weight** M:

$$V_P(T, M) = V_0 - b\,\Delta T - a_m\left(\frac{1}{M} - \frac{1}{M_0}\right)$$

$$b = 0.306 - 7.6 / M$$

In this formula, V_0 is the velocity of oil of molecular weight M_0 at temperature T_0; a_m is a positive function of temperature and so oil velocity increases with molecular weight. When components are mixed, velocity can be approximately calculated as a fractional average of the end components.

For **dead oil** (oil with no dissolved gas), the effects of pressure and temperature on **density** are largely independent. The pressure dependence is

$$\rho_P = \rho_0 + (0.00277P - 1.71\times10^{-7}P^3)(\rho_0 - 1.15)^2 + 3.49\times10^{-4}\,P$$

where ρ_P is the density in g/cm^3 at pressure P in MPa. Temperature dependence of density at given pressure P is

$$\rho = \rho_P / [0.972 + 3.81 \times 10^{-4}\,(T + 17.78)^{1.175}]$$

where temperature is in degrees Centigrade.

Acoustic velocity in **dead oil** depends on pressure and temperature as

$$V_P\,(\text{m/s}) = 2096\,\left(\frac{\rho_0}{2.6-\rho_0}\right)^{1/2} - 3.7\,T + 4.64\,P$$
$$+\,0.0115\,[4.12\,(1.08\,\rho_0^{-1} - 1)^{1/2} - 1]\,T\,P$$

or, in terms of API gravity:

$$V_P\,(\text{ft/s}) = 15450\,(77.1 + \text{API})^{-1/2} - 3.7\,T + 4.64\,P$$
$$+\,0.0115\,[0.36\,\text{API}^{1/2} - 1]\,T\,P$$

Live oil. Large amounts of **gas can be dissolved in an oil**. The original fluid in situ is usually characterized by R_G, the volume ratio of liberated gas to remaining oil at atmospheric pressure and 15.6 ^oC. The maximum amount of gas that can be dissolved in an oil is a function of pressure, temperature, and composition of both the gas and the oil:

$$R_G^{(max)} = 0.02123\,G\,\left[P\,\exp\left(\frac{4.072}{\rho_0} - 0.00377\,T\right)\right]^{1.205}$$

or, in terms of API gravity:

$$R_G^{(max)} = 2.03\,G\,[P\,\exp\left(0.02878\,\text{API} - 0.00377\,T\right)]^{1.205}$$

where R_G is in liters/liter (1 L/L = 5.615 cu ft/ BBL) and G is the gas gravity. Temperature is in degrees Centigrade, and pressure is in MPa.

Velocities in oils with dissolved gas can still be calculated versus pressure and temperature using the above formulas with a pseudo density ρ' used instead of ρ_0:

$$\rho' = \frac{\rho_0}{B_0}\,(1 + 0.001\,R_G)^{-1}$$

$$B_0 = 0.972 + 0.00038\,\left[2.4\,R_G\,\left(\frac{G}{\rho_0}\right)^{1/2} + T + 1.78\right]^{1.175}$$

The true **density of oil with gas** (in g/cm^3) can be calculated as

$$\rho_G = (\rho_0 + 0.0012\,G\,R_G)\,/\,B_0$$

Viscosity of dead oil (η) decreases rapidly with increasing temperature. At room pressure for a gas-free oil we have

$$\log_{10}(\eta + 1) = 0.505\,y\,(17.8 + T)^{-1.163}$$
$$\log_{10}(y) = 5.693 - 2.863/\rho_0$$

Pressure has a smaller influence on viscosity. It can be estimated independent of the temperature influence – if oil viscosity is η_0 at a given temperature and room pressure, its viscosity at pressure P and the same temperature is

$$\eta = \eta_0 + 0.145\,PI$$
$$\log_{10}(I) = 18.6\,[0.1\log_{10}(\eta_0) + (\log_{10}(\eta_0) + 2)^{-0.1} - 0.985]$$

Viscosity in these formulas is in centipoise, temperature in degrees Centigrade, and pressure in MPa.

Uses: To calculate velocities and densities of pore fluids.

Assumptions/ Limitations: Mostly, the formulas are based on empirical measurements, summarized by Batzle and Wang, 1992.

References:

Batzle, M. and Wang, Z., 1992, Seismic properties of pore fluids, *Geophysics*, 57, 1396 - 1408.