Lecture Eleven: Capillary Pressure

11.1. Definition

Capillary pressure is the pressure difference existing across the interface separating two immiscible fluids in capillaries (e.g. porous media).

Denoting the pressure in the wetting fluid by p_w and that in the nonwetting fluid by p_{nw}, the capillary pressure can be expressed as:

Capillary pressure = (pressure of the nonwetting phase) − (pressure of the wetting phase)

$$p_c = p_{nw} - p_w \qquad \text{....... (11-1)}$$

That is, the pressure excess in the nonwetting fluid is the capillary pressure, and this quantity is a function of saturation. This is the defining equation for capillary pressure in a porous medium.

11.2. Capillary pressure in hydrocarbon reservoirs

There are three types of capillary pressure in hydrocarbon reservoirs:

- Water-oil capillary pressure (denoted P_{cwo}).
- Gas-oil capillary pressure (denoted P_{cgo}).
- Gas-water capillary pressure (denoted P_{cgw}).

Gas is always the non-wetting phase in both oil-gas and water-gas systems. Oil is often the non-wetting phase in water-oil systems.

Applying the mathematical definition of the capillary pressure as expressed by Equation (11-1), the three types of capillary pressure can be written as:

$$p_{cwo} = p_o - p_w$$

$$p_{cgo} = p_g - p_o$$

$p_{cgw} = p_g - p_w$

11.3. Capillary pressure equation

The pressure difference across the interface between ***points 1*** and ***2*** as shown in figure (11-1) is essentially the capillary pressure:

$p_c = p_1 - p_2$ ……. (11-2)

The pressure of the water phase at ***point 2*** is equal to the pressure at ***point 4*** minus the head of the water

$p_2 = p_4 - gh\rho_w$ ……. (11-3)

The pressure just above the interface at *point 1* represents the pressure of the air and is given by:

$p_1 = p_3 - gh\rho_{air}$ ……. (11-4)

It should be noted that the pressure at ***point 4*** within the capillary tube is the same as that at ***point 3*** outside the tube. Subtracting Equation (11-3) from (11-4) gives:

$p_c = gh(\rho_w - \rho_{air}) = gh\,\Delta\rho$ ……. (11-5)

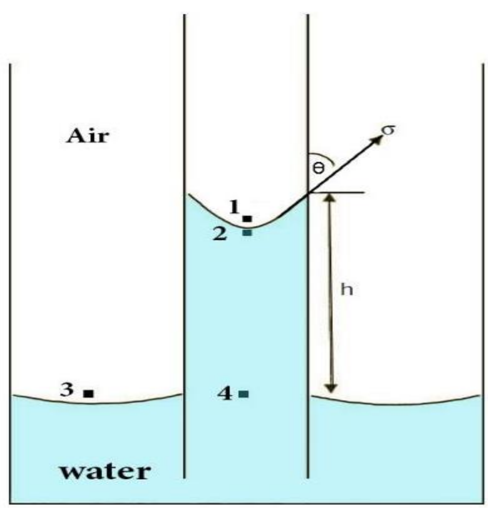

Fig. 11-1 Pressure relations in capillary tubes.

In field units, Equation (11-5) can be expressed as:

$$P_c = \left(\frac{h}{144}\right)\Delta\rho \quad \text{....... (11-6)}$$

where:

p_c = capillary pressure, *psi (lb/in2) = lb/144 ft*^{2}*; 1 ft=12 in.*

h = capillary rise, *ft*.

$\Delta\rho$ = density difference, *lb/ft*^{3}.

The capillary pressure equation can be expressed in terms of the surface and interfacial tension equation (10-5)

$$\sigma = \frac{rh\,\Delta\rho\,g}{2cos\theta} \quad \text{....... (10-5)}$$

By combining interfacial tension equations with Equation (11-5) to give:

1- Gas-Liquid System

$$P_c = \frac{2\,\sigma_{gw}cos\theta}{r} \quad \text{....... (11-7)}$$

$$h = \frac{2\,\sigma_{gw}cos\theta}{r\,g\,(\rho_w - \rho_g)} \quad \text{....... (11-8)}$$

where:

ρ_w = water density, gm/cm^3.

σ_{gw} = gas-water surface tension, dynes/cm.

r = capillary radius, cm.

θ = contact angle.

h = capillary rise, cm.

g = acceleration due to gravity, cm/sec^2.

p_c = capillary pressure, dynes/cm^2.

2-Oil-Water System

$$P_c = \frac{2\,\sigma_{ow} cos\theta}{r} \qquad \text{……. (11-9)}$$

$$h = \frac{2\,\sigma_{ow} cos\theta}{r\,g\,(\rho_w - \rho_o)} \qquad \text{……. (11-10)}$$

where: σow is the water-oil interfacial tension.

Example 1

Calculate the pressure difference, i.e., capillary pressure, and capillary rise in an oil-water system from the following data:

$\theta = 30^\circ$ $\rho_w = 1.0\ gm/cm^3$ $\rho_o = 0.75\ gm/cm^3$

$r = 10^{-4} cm$ $\sigma_{ow} = 25\ dynes/cm$

Solution:

Step 1. Apply Equation (11-9) to give P_c value:

$$P_c = \frac{2\,\sigma_{ow} cos\theta}{r}$$

$$p_c = \frac{(2)(25)(\cos 30^\circ)}{0.0001} = 4.33 \times 10^5\ dynes/cm^2$$

Since $1\ dyne/cm^2 = 1.45 \times 10^{-5}$psi

$$p_c = 6.28\ psi$$

This result indicates that the oil-phase pressure is 6.28 psi higher than the water-phase pressure.

Step 2. Calculate the capillary rise by applying Equation (11-10):

$$h = \frac{2\sigma_{ow}(\cos\theta)}{rg(\rho_w - \rho_o)}$$

$$h = \frac{(2)(25)(\cos 30°)}{(0.0001)(980.7)(1.0 - 0.75)} = 1766\ cm = 75.9\ ft$$

11.4. Dependence of Capillary Pressure on Rock and Fluid Properties

Equations (11-7) and (11-9) show the capillary pressure of an immiscible pair of fluids expressed in terms of **surface or interface forces, wettability, and capillary size**.

A. If the wetting characteristics are the same, that is, the same IFT and contact angle, but the radius of the capillary tube is different; In this case, the capillary pressure is inversely proportional to the capillary tube radius, while the adhesion tension remains constant. It is easily understood from Pc equation that the higher the capillary tube radius, the lower the capillary pressure, or vice versa.

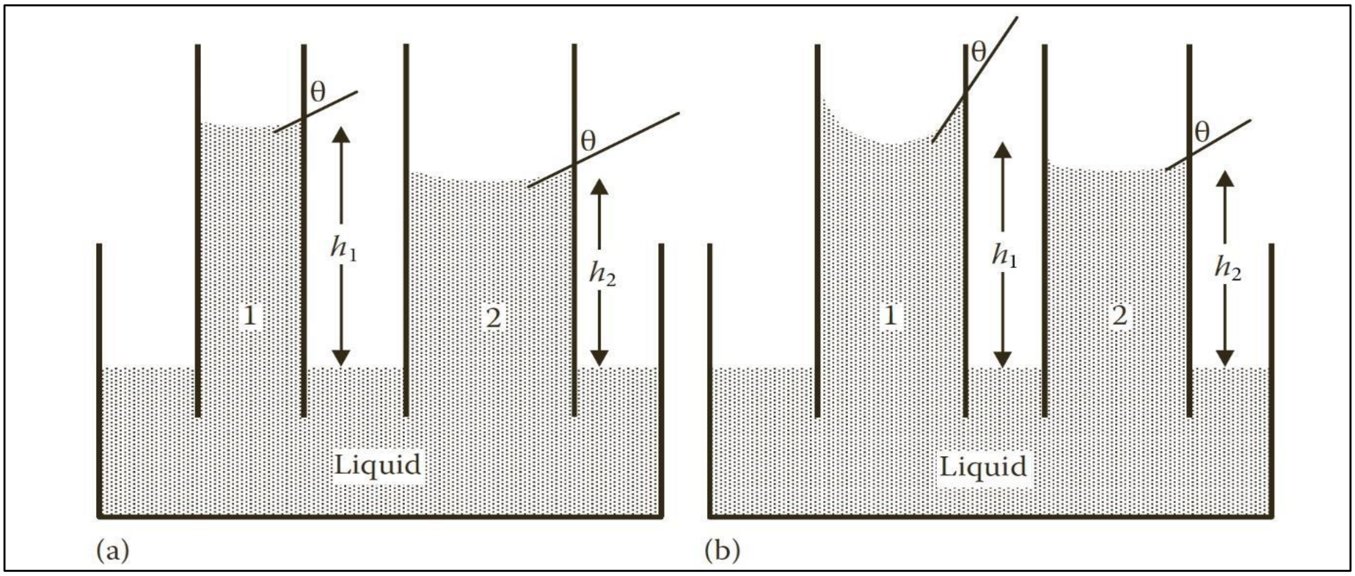

Fig. 11-2 Dependence of capillary pressure on wetting characteristics and pore size (tube radius in this case).

B. On the other hand, when the capillary tubes of same radius but different wetting characteristics are considered, the value of capillary pressure will be directly proportional to the adhesion tension or the wetting characteristics of the system. In this case, the smaller the contact angle, the greater the height of liquid rise and stronger the adhesion tension, leading to higher capillary pressure, whereas the opposite is evident from the other tube having weaker wetting characteristics or adhesion tension that obviously results in lower capillary pressure.

11.5. Relationship between capillary pressure and saturation history

1-Drainage Process

Fluid flow process in which the saturation of the nonwetting phase increases, that is displacing the wetting phase (mostly water) by a nonwetting phase (oil or gas), which primarily establishes the fluid saturations that are found when the reservoir is discovered.

For examples Hydrocarbon (oil or gas) filling the pore space and displacing the original water of deposition in water-wet rock or Water flooding an oil reservoir in which the reservoir is oil wet.

The wetting phase is displaced until reaching some minimum irreducible saturation. This irreducible water saturation is referred to as ***connate water, Swc*.**

2-Imbibition Process

Fluid flow process in which the saturation of the wetting phase increases, involves reversing the drainage process by displacing the nonwetting phase (oil or gas) with the wetting phase, (e.g., water). Mobility of wetting phase increases as wetting phase saturation increases.

For example Accumulation of oil in oil wet reservoir or Water flooding an oil reservoir in which the reservoir is water wet.

Under the assumption that the rocks are water wet, at least prior to hydrocarbon migration, this is accomplished by the drainage process by displacing the wetting phase (water) by a nonwetting phase (oil or gas), which primarily establishes the fluid saturations that are found when the reservoir is discovered. On the other hand, oil production performance (oil as a nonwetting phase) is generally governed by the imbibition process. Therefore, imbibition capillary pressure curves are generally used in such reservoir studies.

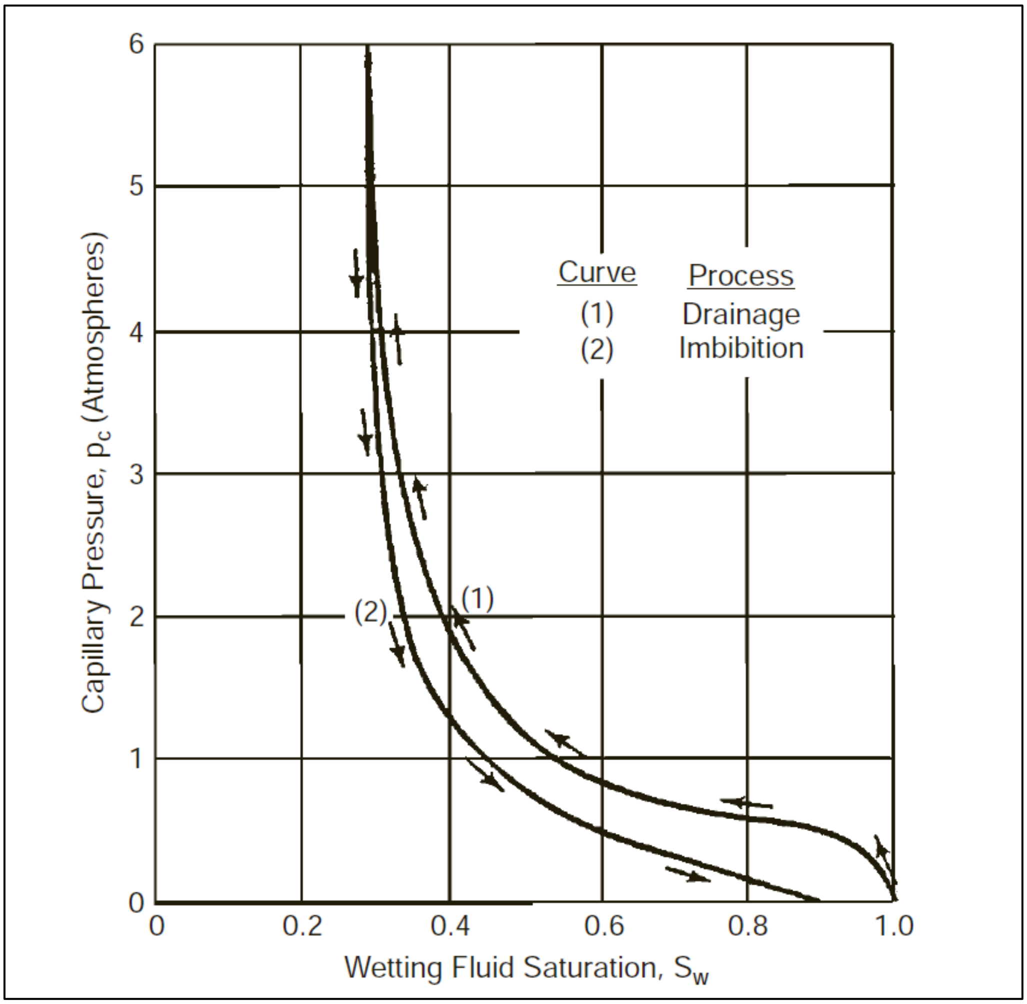

Fig. 11-3 Capillary pressure drainage and imbibition curves.

This difference in the two capillary pressure curves (**Drainage & Imbibition**) is called ***capillary hysteresis.***

The porous diaphragm method is perhaps one of the simplest methods to determine the capillary pressure–saturation relationships for core plug samples. The method is based on the drainage of a core sample initially saturated with a wetting fluid, which is placed inside a chamber filled with a nonwetting fluid (mercury or air mostly).

The core initially 100% saturated with the formation water is subjected to increasing air or mercury pressure which displaces the water from the core, and the test continues until no more water is produced.

The drainage capillary pressure versus wetting-phase saturation curve generated by the porous diaphragm method is schematically shown in Figure (11-4).

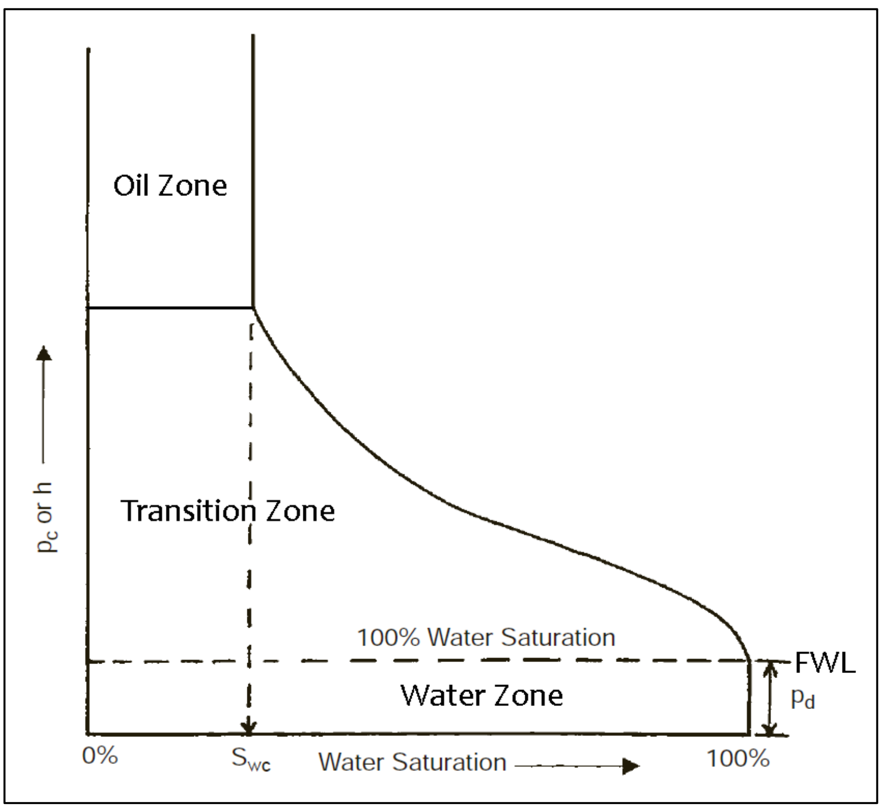

Fig. 11-4 Capillary pressure curve.