Tishk International University
Engineering Faculty
Petroleum and Mining Engineering Department

Petroleum Reservoir Engineering II

Lecture 4: Fundamentals of Rock Properties (Capillary Pressure)

Third Grade- Spring Semester 2020-2021

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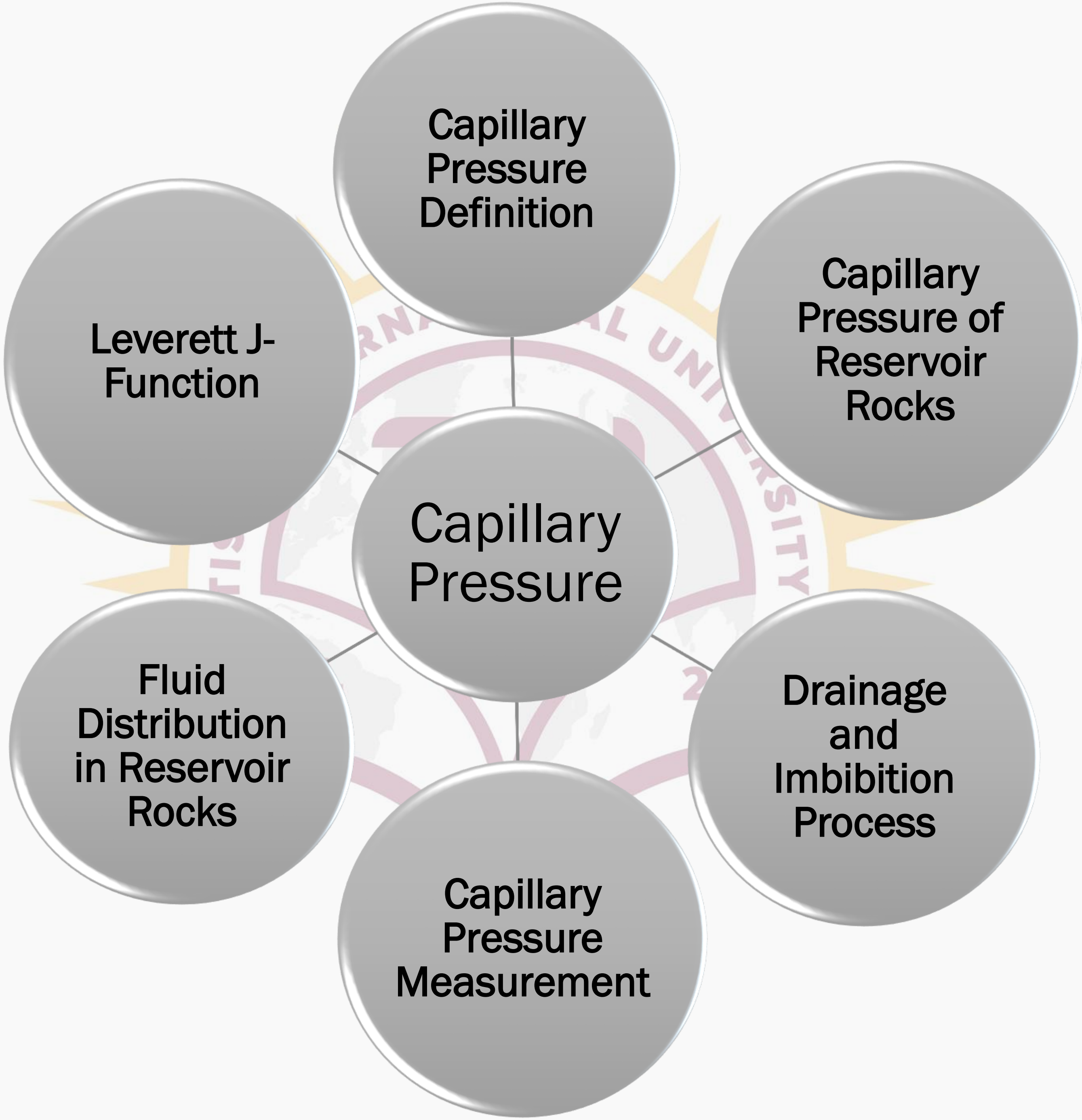
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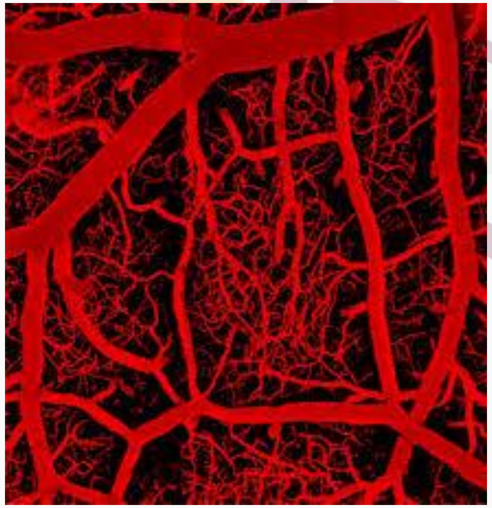
Capillary Pressure:

- **Capillary:** a very thin tube, especially one of the smaller tubes that carry blood around the body.
- **Capillary Tube:** a glass tube with a fine bore and thick walls, used in thermometers, etc.



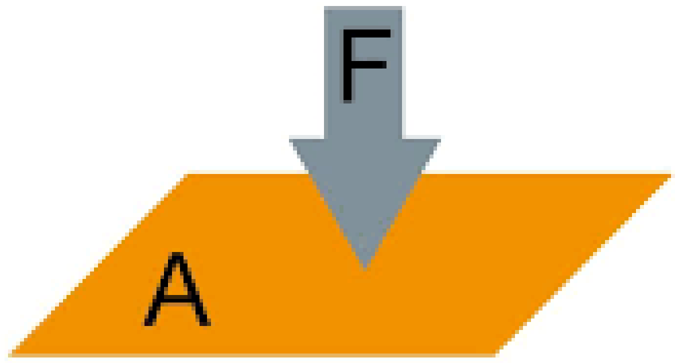
Capillary

Capillary Tube

Capillary Pressure:

- **Pressure:** is the perpendicular force per unit area.

$$Pressure\ (p) = \frac{Force\ (F_n)}{Area(A)}$$



Capillary Pressure:

- The capillary forces in a petroleum reservoir are the result of the combined effect of:

- The surface and interfacial tensions of the rock and fluids
- The pore size and geometry
- The wetting characteristics of the system

Capillary Pressure:

- Any curved surface between two immiscible fluids has the tendency to contract into the smallest possible area per unit volume.
- When two immiscible fluids are in contact, a discontinuity in pressure exists between the two fluids, and the pressure difference is called the capillary pressure, and it is referred to by p_c.

Capillary Pressure:

- The displacement of one fluid by another in the pores of a porous medium is either aided or opposed by the surface forces of capillary pressure.
- Consequently, in order to maintain a porous medium partially saturated with nonwetting fluid and while the medium is also exposed to wetting fluid, it is necessary to maintain the pressure of the nonwetting fluid at a value greater than that in the wetting fluid.

Capillary Pressure:

- 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:

$$\text{capillary pressure} = (\text{pressure of the nonwetting phase}) - (\text{pressure of the wetting phase})$$

$$\mathrm{p_c = p_{nw} - p_w} \text{ ---(1)}$$

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.

Capillary Pressure:

- There are three types of capillary pressure:

1. water-oil capillary pressure (denoted as p_{cwo})
2. Gas-oil capillary pressure (denoted as p_{cgo})
3. Gas-water capillary pressure (denoted as p_{cgw})

Capillary Pressure:

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

- water-oil capillary pressure (denoted as p_{cwo}):

$$p_{cwo} = p_o - p_w --- (2)$$

- Gas-oil capillary pressure (denoted as p_{cgo}):

$$p_{cgo} = p_g - p_o --- (3)$$

- Gas-water capillary pressure (denoted as p_{cgw}):

$$p_{cgw} = p_g - p_w --- (4)$$

Capillary Pressure:

- If all three phases are continuous, then:

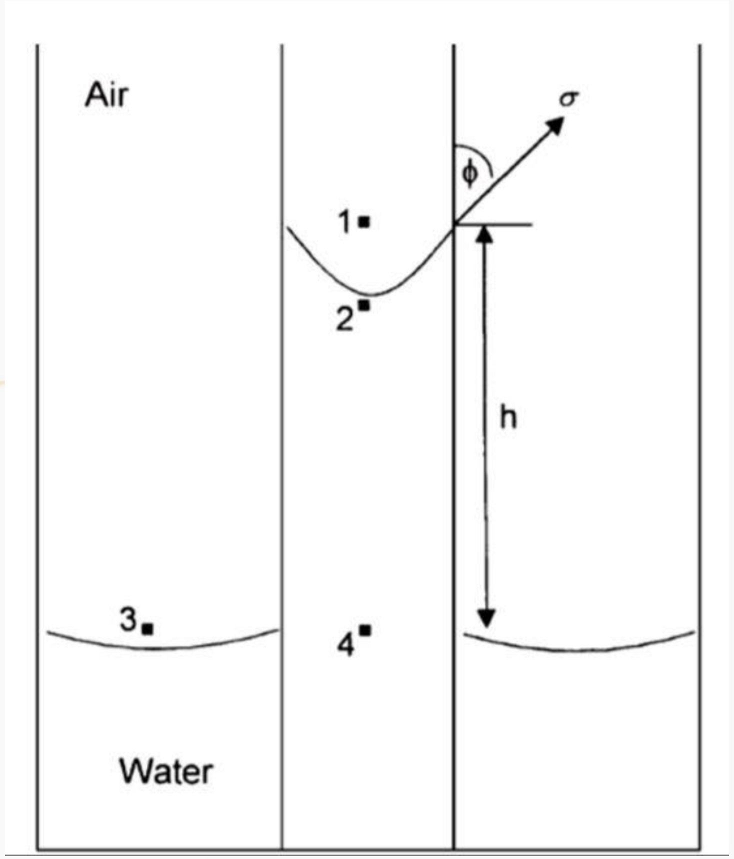
$$p_{cgw} = p_{cgo} + p_{cwo} --- (5)$$

- The pressure difference across the interface between points 1 and 2 is essentially the capillary pressure:

$$p_c = p_1 - p_2 --- (6)$$

- The pressure of the water phase at point 2 is equal to the Pressure at point 4 minus the head of the water or:

$$p_2 = p_4 - gh\rho_w --- (7)$$



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

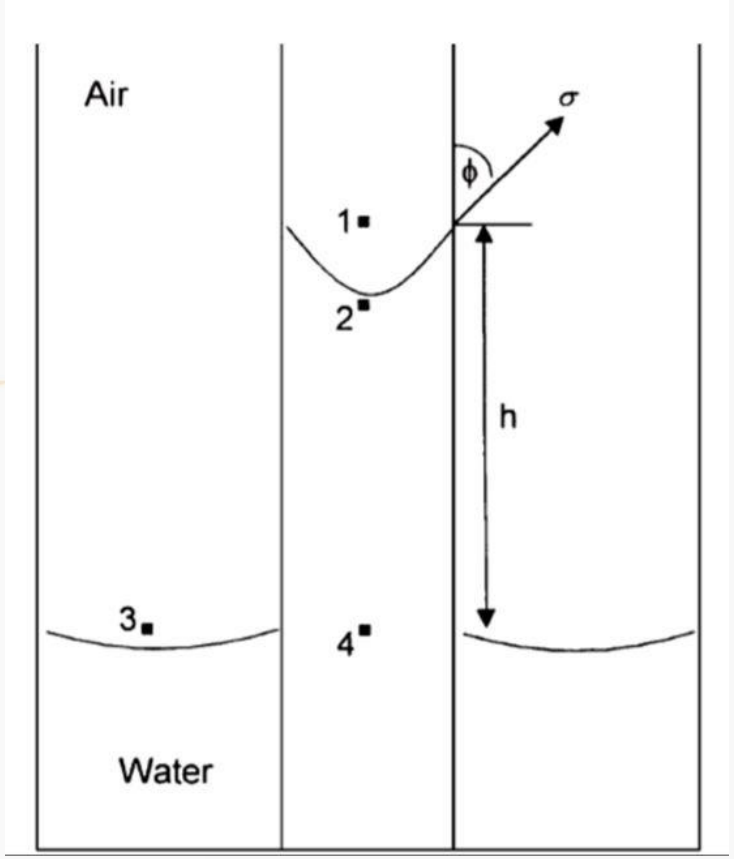
$$p_1 = p_3 - gh\rho_{air} --- (8)$$

Capillary Pressure:

- 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 (7) from equation (8) gives:

$$p_c = gh(\rho_w - \rho_{air}) = gh\Delta\rho ---(9)$$

Where $\Delta\rho$ is the density difference between the wetting and nonwetting phase.

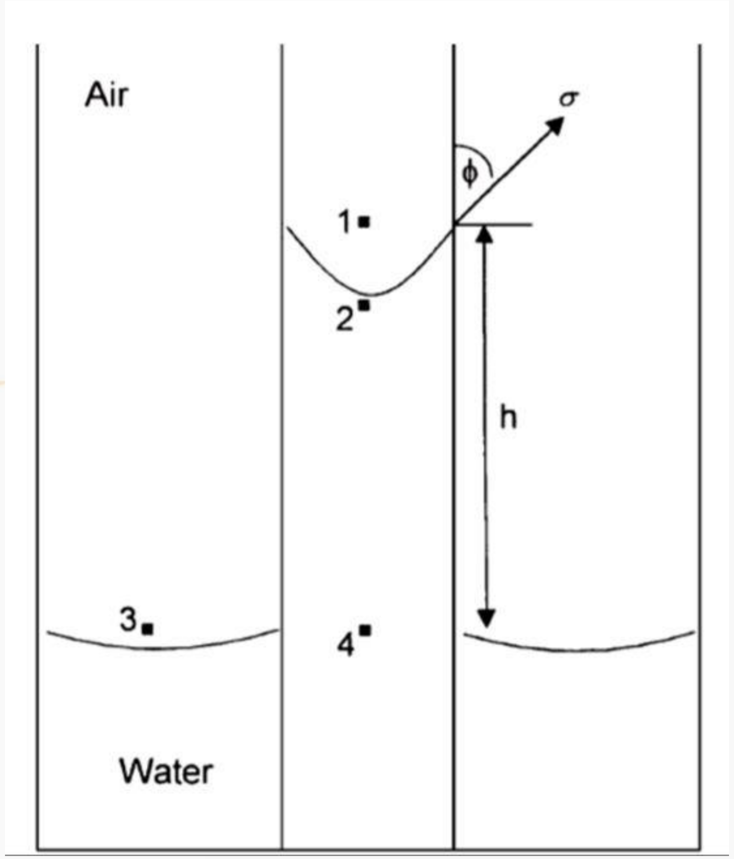


The density of the air (gas) is negligible in comparison with the water density.

Capillary Pressure:

- In practical units, equation (9) can be expressed as:

$$p_c = \left(\frac{h}{144}\right)\Delta\rho \text{ --- } (10)$$



Where p_c= capillary pressure, psi

h= capillary rise, ft

$\Delta\rho$= density difference, lb/ft^3

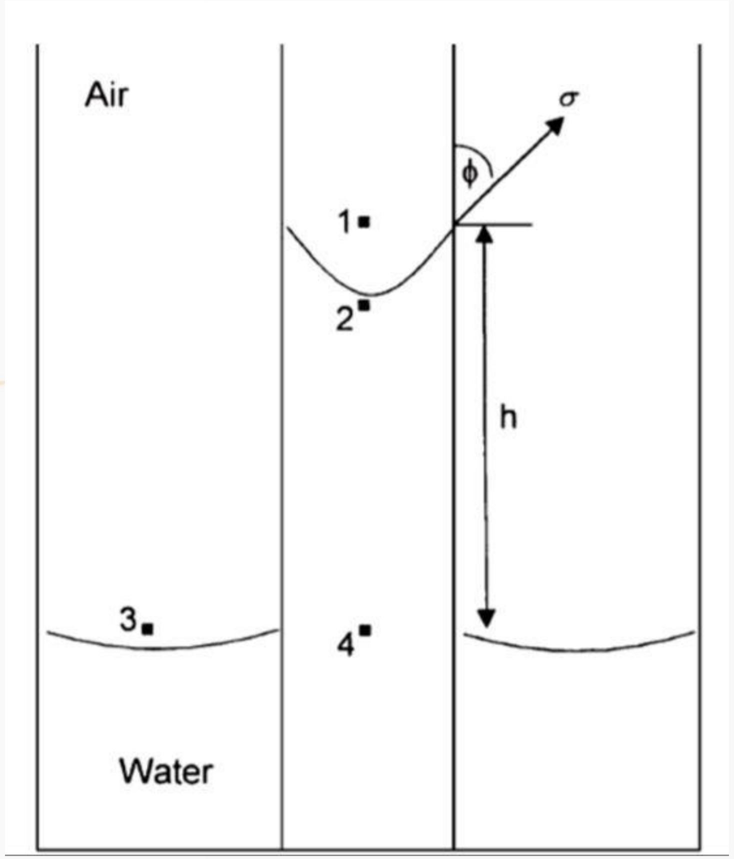
Capillary Pressure:

- In case of an oil-water system, equation (9) can be written as:

$$p_c = gh(\rho_w - \rho_o) = gh\Delta\rho ---(11)$$

And in practical units:

$$\mathrm{p_c} = \left(\frac{\mathrm{h}}{144}\right)(\rho_\mathrm{w} - \rho_\mathrm{o}) ---(12)$$



Capillary Pressure:

- The capillary pressure equation can be expressed in terms of the surface and interfacial tension.
- Recalling surface and interfacial tension equations from previous lecture:

$$\sigma_{ow} = \frac{rhg(\rho_w - \rho_o)}{2cos\theta} --- (13)$$

$$\sigma_{gw} = \frac{rh\rho_w g}{2cos\theta} --- (14)$$

Capillary Pressure:

- ❑ Combining equations (11) and (12) with equations (13) and (14) gives:
- **Gas-Liquid System:**

$$p_c = \frac{2\sigma_{gw}(\cos\theta)}{r} - - -(15)$$

And

$$h = \frac{2\sigma_{gw}(\cos\theta)}{rg(\rho_w - \rho_{gas})} - - -(16)$$

Where ρ_w=water density, gm/cm^3

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

r= capillary radius, cm

Θ= contact angel

h= capillary rise, cm

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

p_c= capillary pressure, dynes/ cm^2

Capillary Pressure:

- Combining equations (11) and (12) with equations (13) and (14) gives:

- **Oil-water System:**

$$p_c = \frac{2\sigma_{ow}(\cos\theta)}{r} --- (17)$$

And

$$h = \frac{2\sigma_{wo}(\cos\theta)}{rg(\rho_w - \rho_o)} --- (18)$$

Where

σ_{wo} is the water-oil interfacial tension.

Capillary Pressure:

Example: Calculate the capillary pressure in Psi, and capillary rise in an oil-water system from the following data:

θ= 30° , ρ_w= 1.0 $\mathrm{gm/cm^3}$, ρ_o= 0.75 $\mathrm{gm/cm^3}$, r=10^{-4}cm , σ_{wo}=25 dynes/cm

Capillary Pressure:

Solution:

step 1. apply equation (17) to calculate capillary pressure:

$$p_c = \frac{2\sigma_{ow}(\cos\theta)}{r} = \frac{(2)(25)\ (\cos 30°)}{0.0001} = 4.33 * 10^5 \text{dynes/cm}^2$$

Since $1\,\frac{\text{dynes}}{\text{cm}^2} = 1.45 * 10^{-5}\text{psi}$, then:

$$p_c = 6.28\ \text{psi}$$

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

Capillary Pressure:

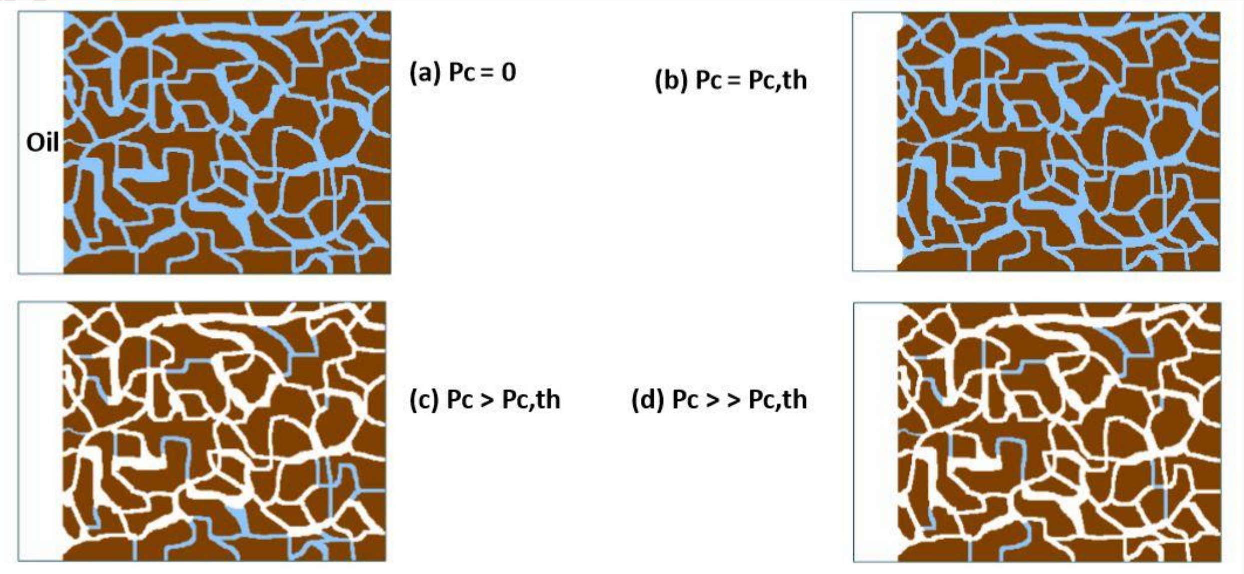
Solution:

step 2. Calculate the capillary rise by applying equation (18):

$$h = \frac{2\sigma_{wo}(\cos\theta)}{rg(\rho_w - \rho_o)} = \frac{(2)(25)\ (\cos 30^\circ)}{(0.0001)(980.7)(1.0 - 0.75)} = 1766 \text{ cm} = 57.9 \text{ ft}$$

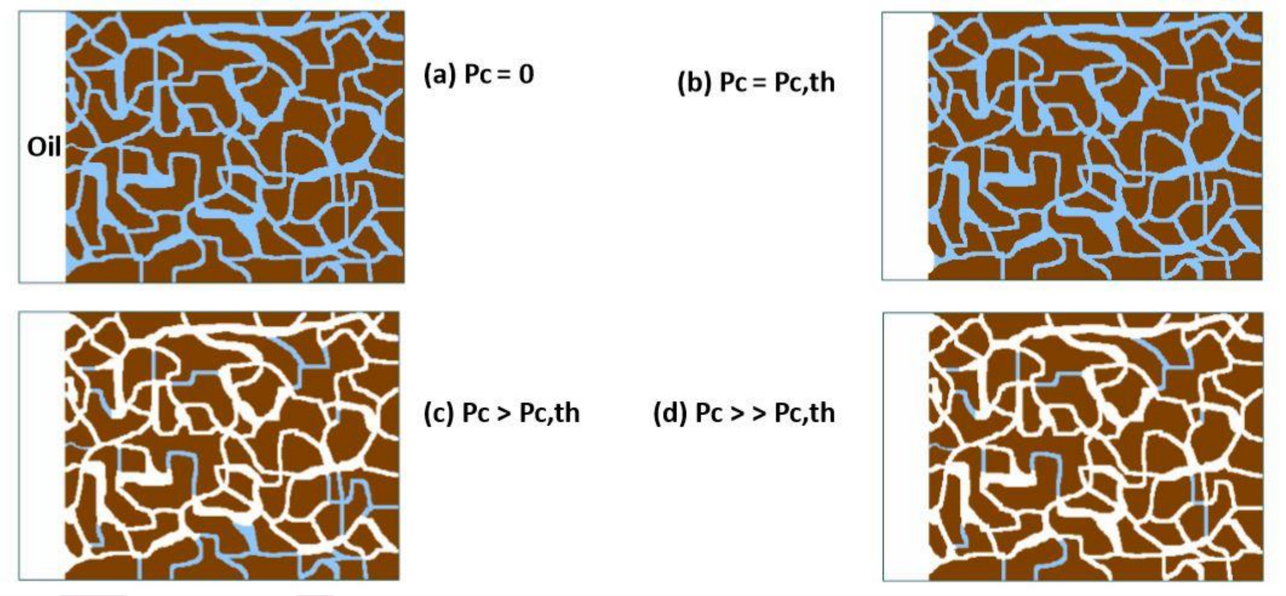
Capillary Pressure of Reservoir Rocks:

- Due to the nature of inter-granular pore space, throats- are usually smaller in diameter than the pore itself.
- This fact plays a crucial role in distribution of fluids within the pore space.
- When two or more fluids share the pore space of a rock, the wetting fluid will readily coat the walls of the pores, and a capillary pressure will exist at the interface between them.
- In porous media, water filling all the pores and oil is just coating the inlet face of the core.



Capillary Pressure of Reservoir Rocks:

- An increase in the oil pressure would cause the oil to enter the core displacing water inwards.
- To start the displacement, the oil-water pressure difference, ΔP, would be just above the minimum P_c,th and this will first take place in large size pores (small P_c).
- Increase the P_c, will displace more oil specially in small pores, and this means reducing water saturation.



Drainage and Imbibition Process:

- **Drainage:** fluid flow process in which the saturation of the nonwetting phase increases.
- capillary pressure increases steadily with decrease in water saturation.
- Maximum capillary pressure is reached at minimum water saturation value called (irreducible water saturation) at which water saturation can not be reduced.
- Mobility of nonwetting fluid phase increases as nonwetting phase saturation increases.
- This process of displacing wetting phase by non-wetting phase is called drainage process.

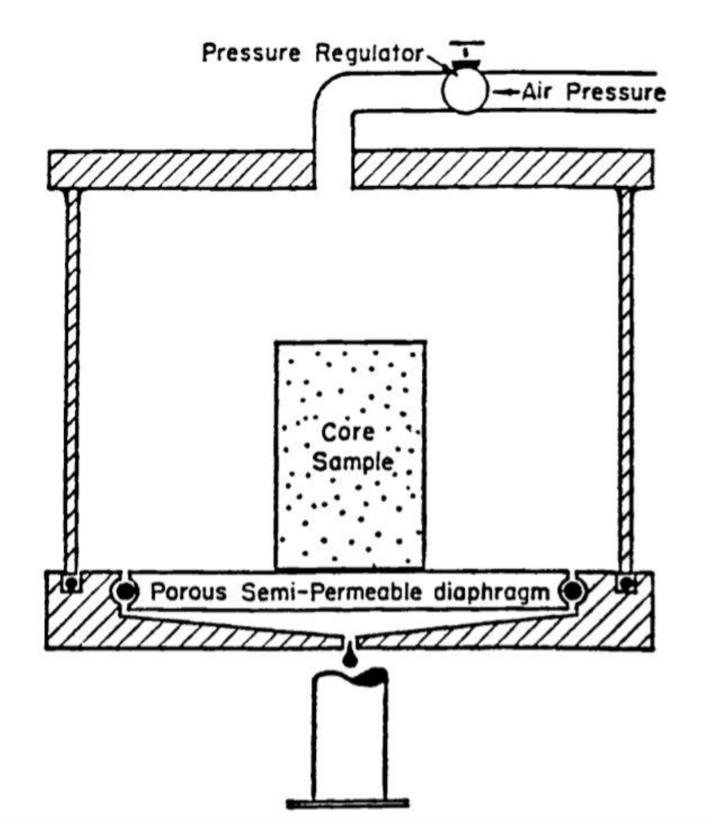
Drainage and Imbibition Process:

- **Imbibition:** is a fluid flow process in which the saturation of the wetting phase increases and the nonwetting phase saturation decreases.
- This process results in reducing the capillary pressure as the water (wetting phase) saturation increases.
- Mobility of wetting phase increases as wetting phase saturation increases.
- This process continues to a certain water saturation (maximum value) at which no more oil can be displaced. This point is called residual oil saturation.

Capillary Pressure Measurement:

- Laboratory experiments have been developed to simulate the displacing forces in a reservoir in order to determine the magnitude of the capillary forces in a reservoir and, thereby, determine the fluid saturation distributions and connate water saturation.

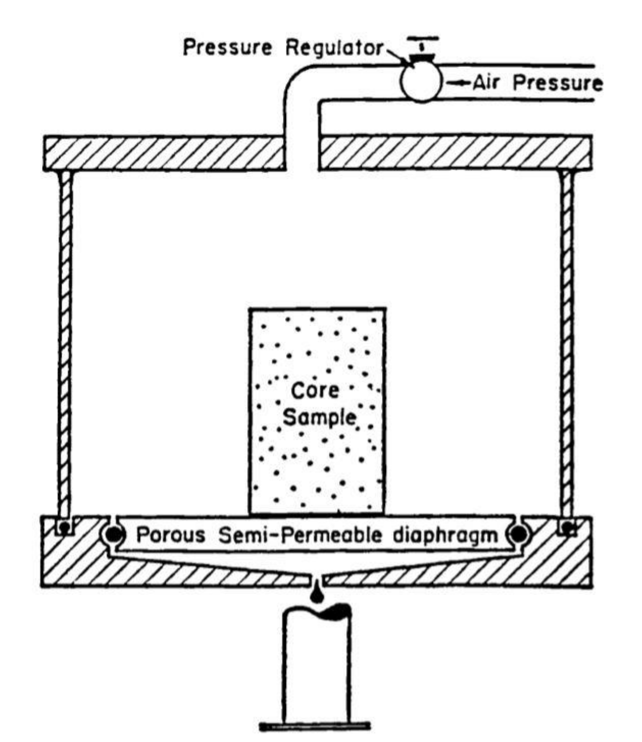
- One such experiment is called the restored capillary pressure technique, which was developed primarily to determine the magnitude of the connate water saturation.



Capillary Pressure Measurement:

Procedure:

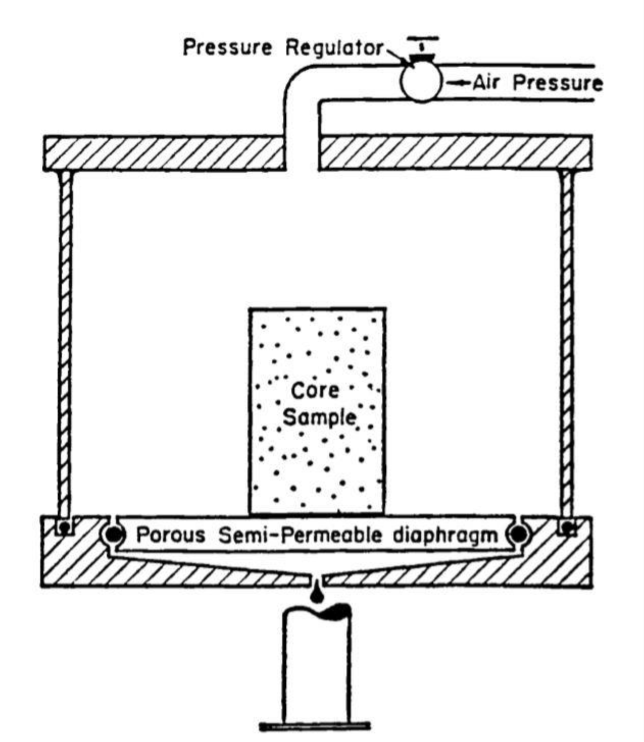
- Saturating a core 100% with the reservoir water.
- Placing the core on a porous membrane, which is saturated 100% with water and is permeable to the water only, under the pressure drops imposed during the experiment.
- Air is then admitted into the core chamber and the pressure is increased until a small amount of water is displaced through the porous, semi-permeable membrane into the graduated cylinder.



Capillary Pressure Measurement:

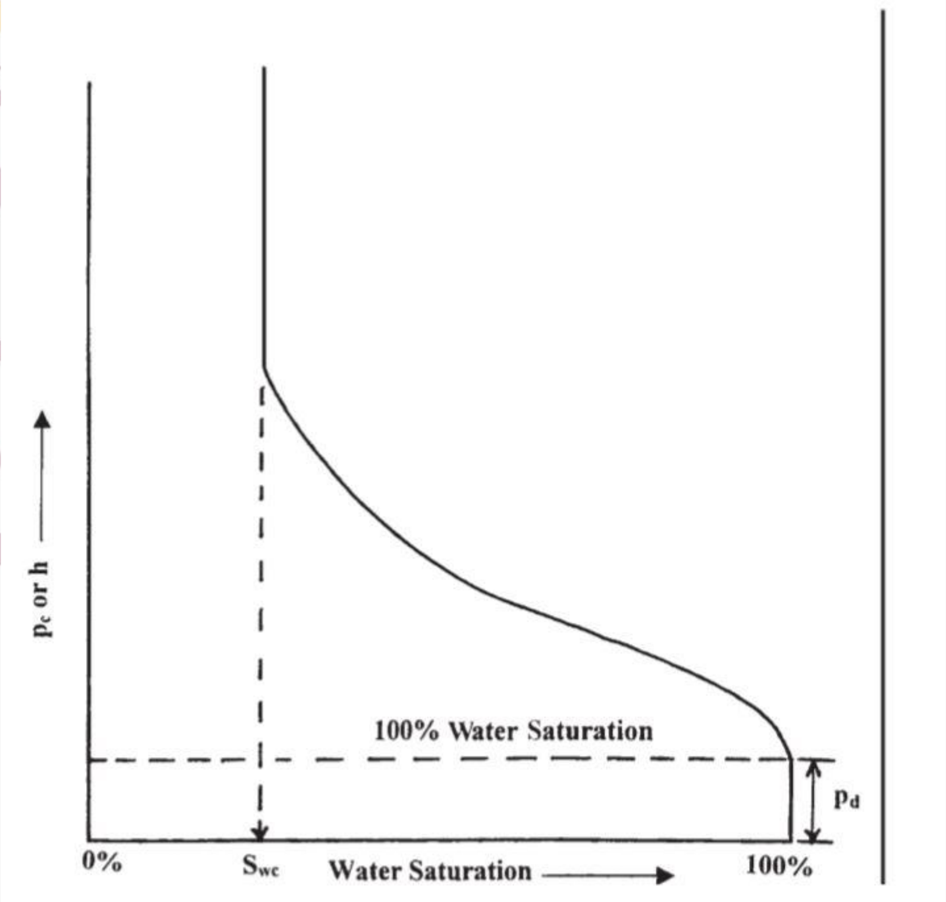
Procedure:

- Pressure is held constant until no more water is displaced which may require several days or even several weeks, after which the core is removed from the apparatus and the water saturation is determined by weighing.
- The core is then replaced in the apparatus, the pressure is increased, and the procedure is repeated until the water saturation is reduced to a minimum.



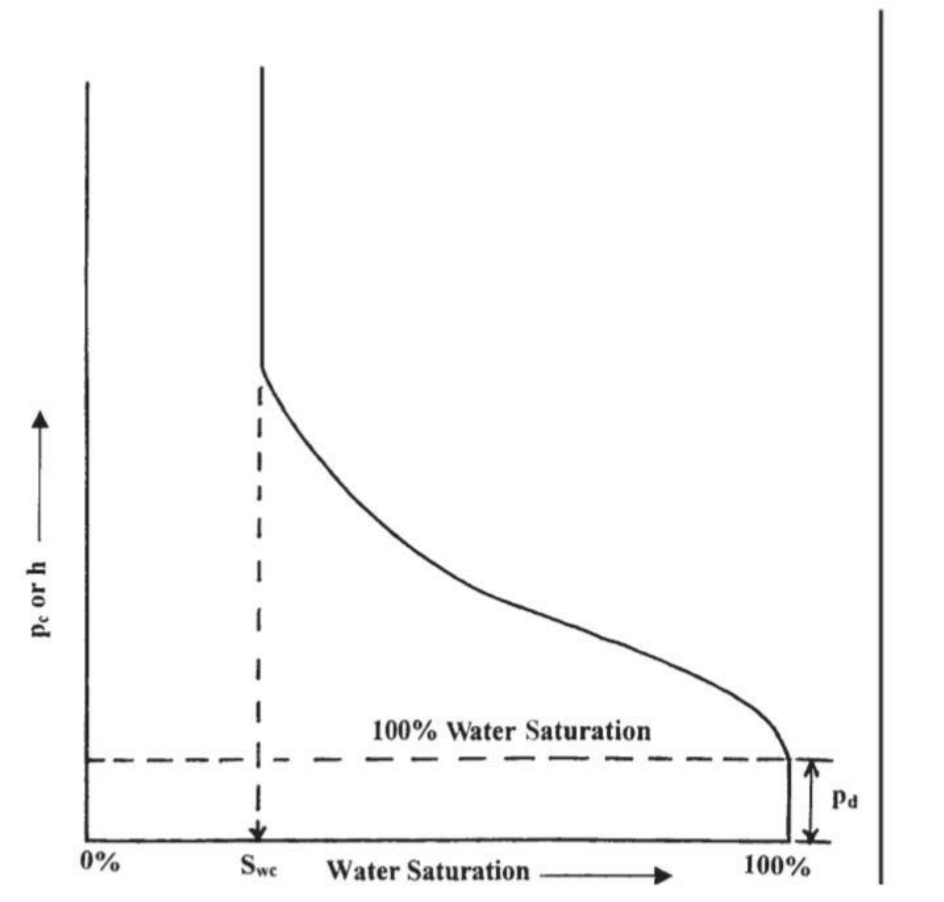
Capillary Pressure Measurement:

- This figure shows the experiment data.
- **Displacement pressure, P_d:** there is a finite capillary pressure at 100% water saturation that is necessary to force the nonwetting phase into a capillary filled with the wetting phase. This minimum capillary pressure is known as the displacement pressure.



Capillary Pressure Measurement:

- This figure shows the experiment data.
- **Connate water saturation, S_{wc}:** as the wetting phase is displaced, the second phenomenon of any immiscible displacement process is encountered, that is, the reaching of some finite minimum reducible saturation. This irreducible water saturation is referred to as connate water.



Fluid Distribution in Reservoir Rocks:

- An important application of the concept of capillary pressures pertains to the fluid distribution in a reservoir prior to exploitation.
- The capillary pressure-saturation data can be converted into height-saturation data (19):

$$h = \frac{144 p_c}{\Delta\rho} --- (19)$$

Where p_c= capillary pressure, psia

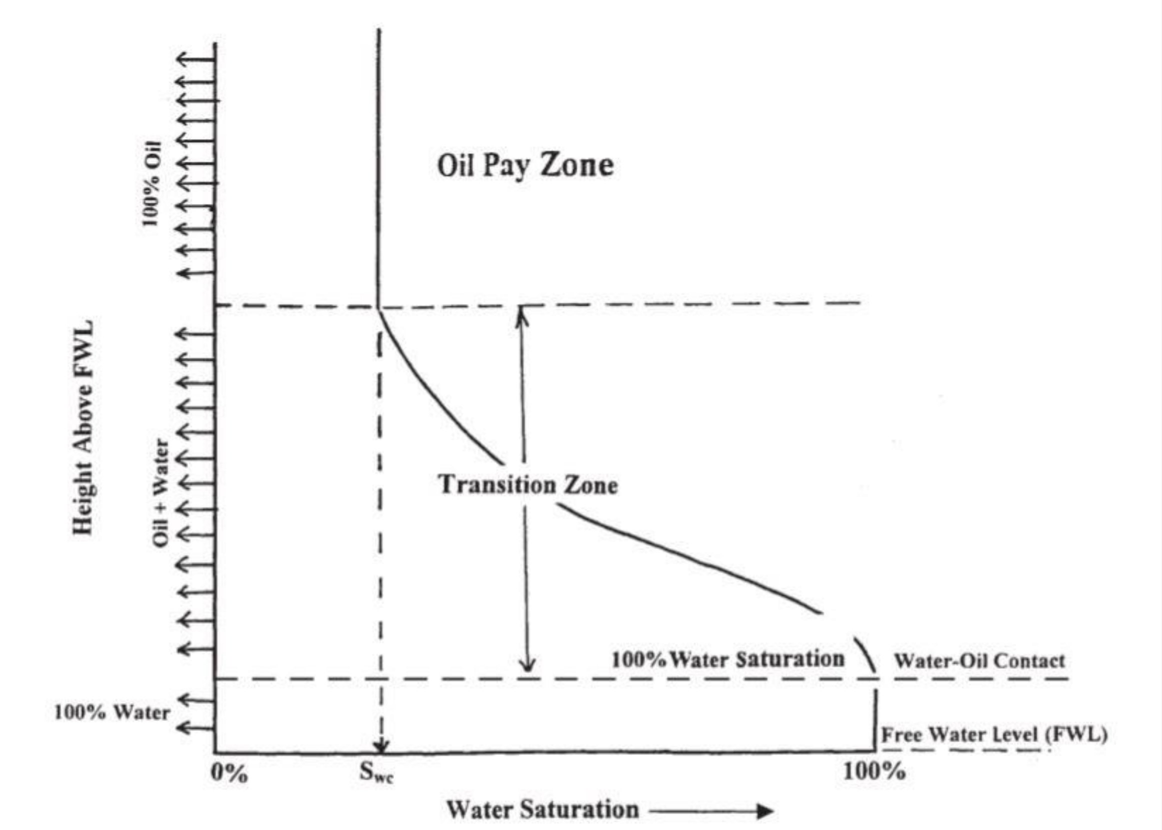
$\Delta\rho$= density difference between the wetting and nonwetting phase, lb/ft^3

h= height above the free-water level, ft.

Fluid Distribution in Reservoir Rocks:

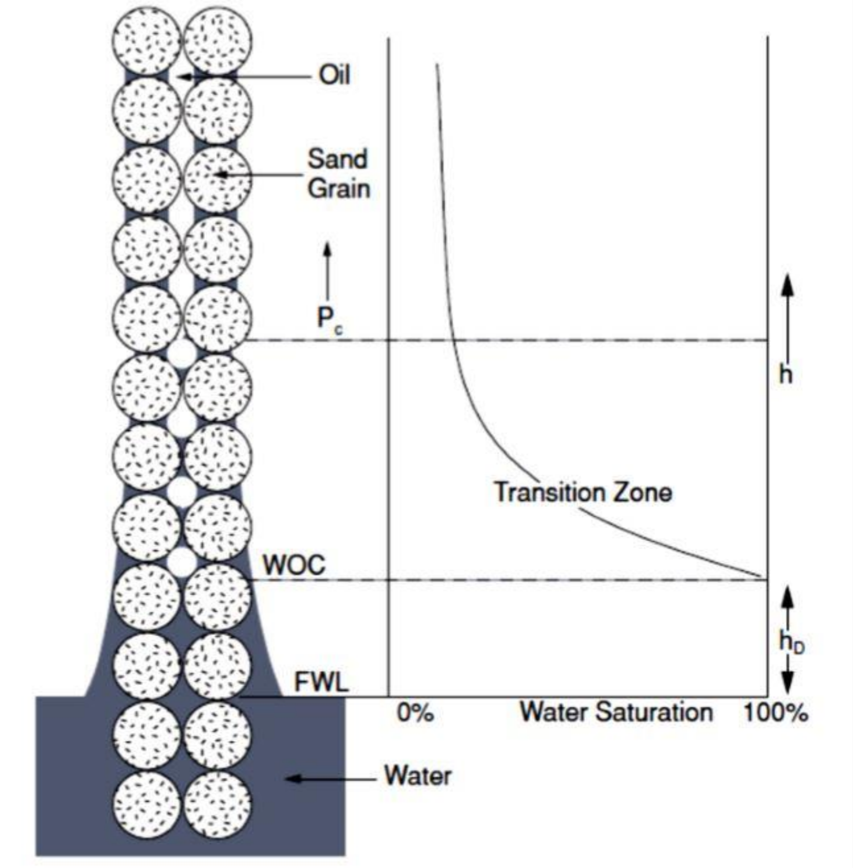
- ❑ The water saturation profile figure shows the water saturation distribution as a function of distance from the free-water level in an oil-water system.
- ❑ In is essential at this point to introduce and define four important concepts:

- Transition zone
- Water-oil contact (WOC)
- Free water level (FWL)



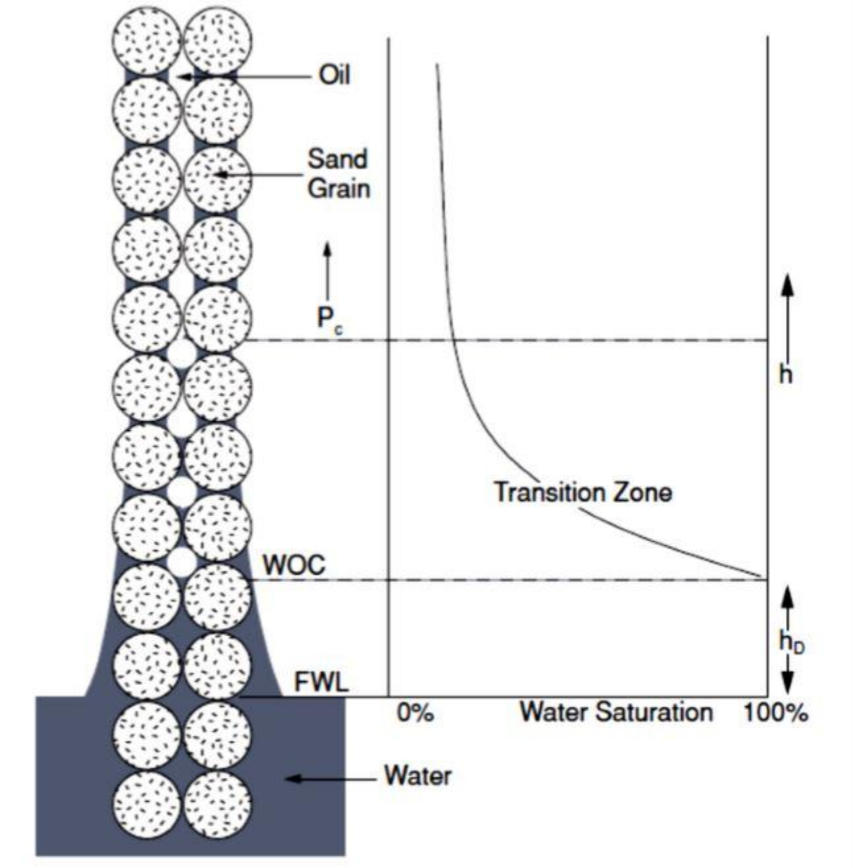
Fluid Distribution in Reservoir Rocks:

- ❑ Water is retained by capillary forces in reservoirs and referred as Connate water.
- ❑ In water wet rocks, water coats rock surfaces and occupies the smallest pores, whereas hydrocarbons occupy the center of the larger pores.
- ❑ At the base of the reservoir, there will usually be a zone of 100% water saturated rock. The upper limit of this is referred to as the water table or water oil contact (WOC).
- ❑ water saturation reduces with increased height above the hydrocarbon-water contact.
- ❑ There is a non identifiable level, the free water level representing the position of zero capillary pressure.



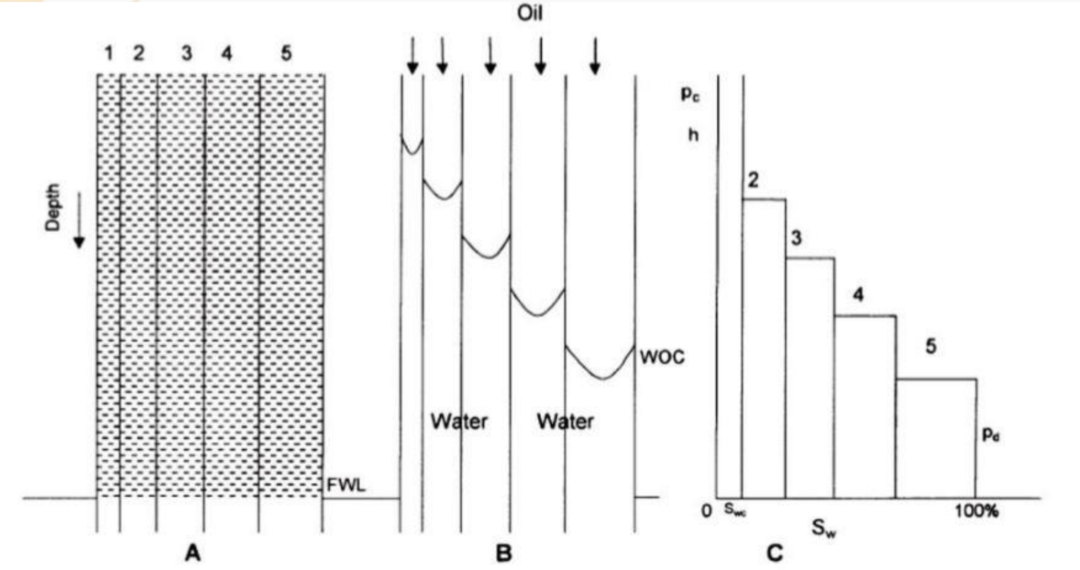
Fluid Distribution in Reservoir Rocks:

- ❑ The 100% water saturation continues some distance above the free water level corresponding to the largest pores of the rock.
- ❑ Above this level both the oil and water are present and the reservoir water saturation decreases with increased height above the hydrocarbon water contact, since the larger pores can no longer support the water by capillary action.
- ❑ This zone is referred to as transition zone at which the water saturation falls between the 100% WOC and the irreducible saturation.



Fluid Distribution in Reservoir Rocks:

- The figure shows a schematic illustration of a core that is represented by five different pore sizes and completely saturated with water (wetting phase).
- Assume that we subject the core to oil (the nonwetting phase) with increasing pressure until some water is displaced from the core, i.e., displacement pressure, Pd.
- This water displacement will occur from the largest pore size.
- The oil pressure will have to increase to displace the water in the second largest pore. This sequential process is shown in section B and C of the figure.



Fluid Distribution in Reservoir Rocks:

- It should be noted that there is a difference between the free water level (FWL) and the depth at which 100% water saturation exists.
- From a reservoir engineering standpoint, the free water level is defined by zero capillary pressure.
- Obviously, if the largest pore is so large that there is no capillary rise in this size pore, then the free water level and 100% water saturation level, i.e., WOC, will be the same.
- This concept can be expressed mathematically by the following:

$$\mathrm{FWL} = \mathrm{WOC} + \frac{144 p_d}{\Delta\rho} --- (20)$$

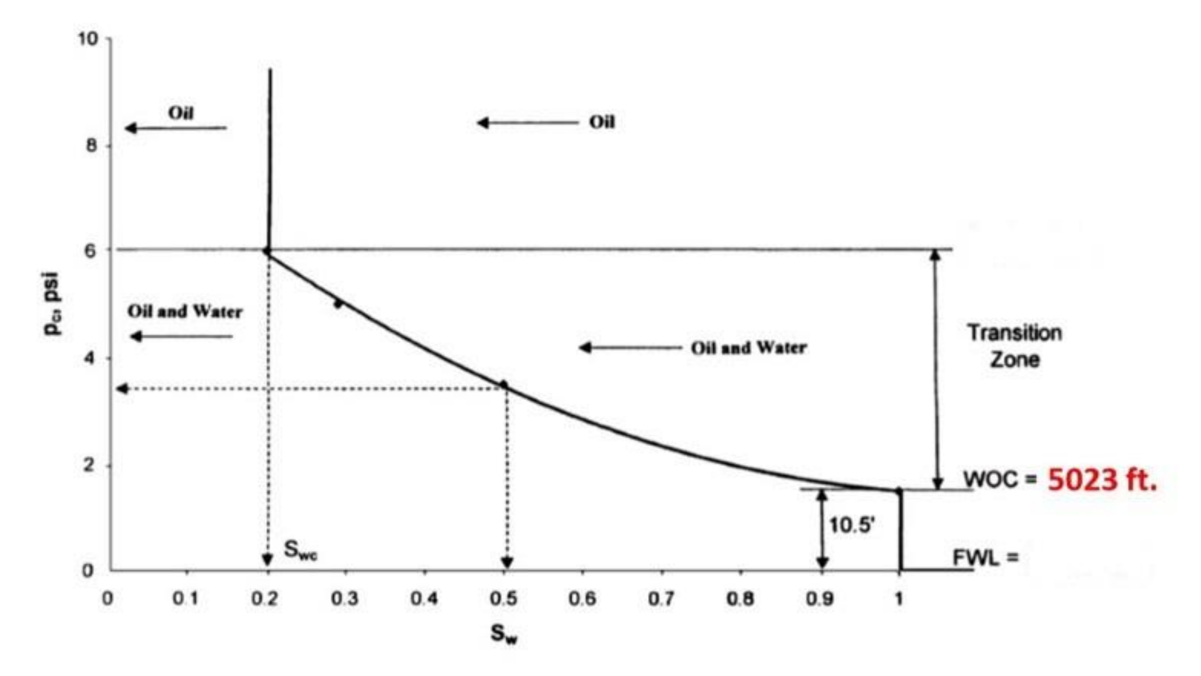
Fluid Distribution in Reservoir Rocks:

Example: The reservoir capillary pressure-saturation data of the Big Oil reservoir is shown graphically in below figure. Geophysical log interpretations and core analysis establish the WOC at 5,023 ft. The following additional data are available.

- Oil density = 43.5 lb/ft^3 and water density = 64.1 lb/ft^3
- Interfacial tension= 50 dynes/cm
- S_{wc}= 0.2

Calculate:

- Depth to FWL and thickness of the transition zone
- Depth to reach 50% water saturation



Fluid Distribution in Reservoir Rocks:

Solution:

a) FWL

$$\mathrm{FWL} = \mathrm{WOC} + \frac{144 p_d}{\Delta\rho}$$

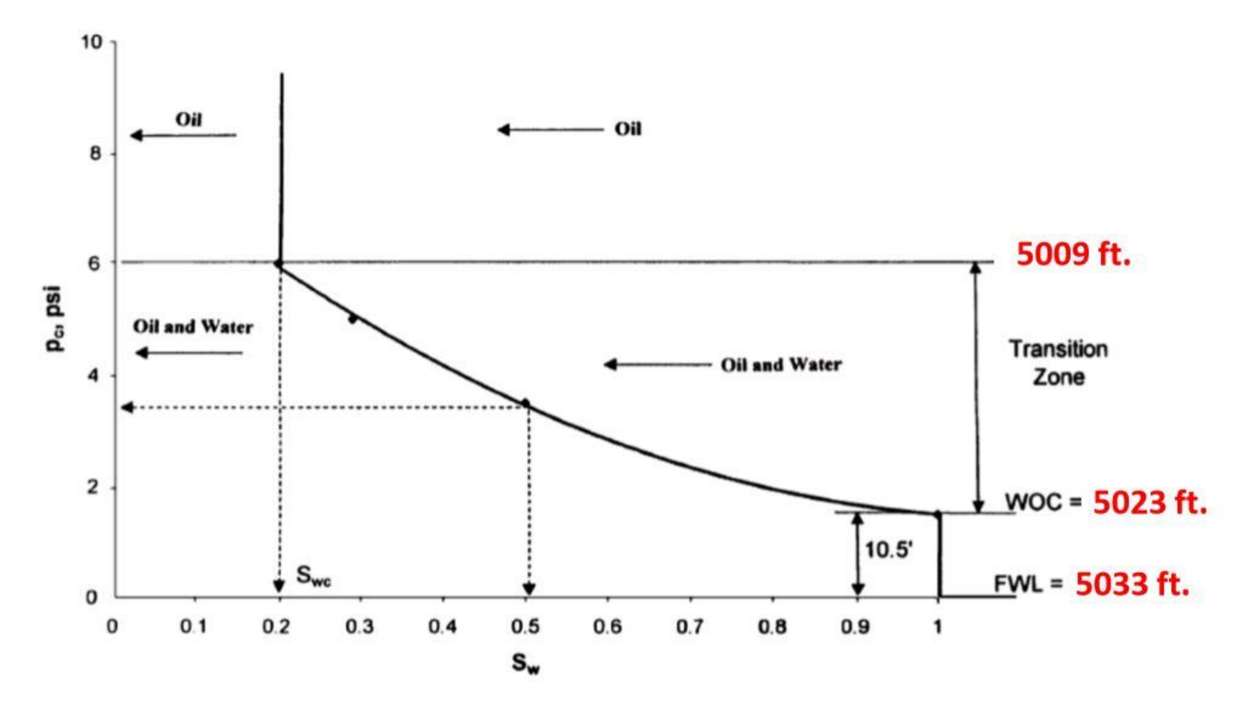
$$= 5023 + \frac{(144)(1.5)}{(64.1 - 43.5)} = 5033.5 \text{ ft}$$

b) Thickness of transition zone

$$\frac{144(6.0 - 1.5)}{(64.1 - 43.5)} = 31.5 \text{ ft}$$

c) At $\mathbf{S_w}$= 0.5, $\mathbf{P}_c$= 3.5 psi

Equivalent height above the FWL=(144)(3.5)/(64.1-432.5)=24.5 ft



Leverett J-Function:

- Capillary pressure data are obtained on small core samples that represent an extremely small part of the reservoir.
- Therefore, it is necessary to combine all capillary data to classify a particular reservoir.
- The fact that the capillary pressure-saturation curves of nearly all naturally porous materials have many features and many attempts have been presented to describe that.
- Leverett (1941) approaches the problem from the standpoint of dimensional analysis.
- He realized that capillary pressure should depend on the porosity, interfacial tension, and mean pore radius.

Leverett J-Function:

- Leverett defined the dimensionless function of saturation, which he called the J-function, as:

$$J(S_w) = 0.21645 \frac{p_c}{\sigma} \sqrt{\frac{k}{\varphi}} --- -(21)$$

Where $J(S_w)$= Leverett J-function

p_c= capillary pressure, psi

σ= interfacial tension, dynes/cm

k= permeability, md

Φ= fractional porosity

Leverett J-Function:

Example: A laboratory capillary pressure test was conducted on a core sample taken from a certain field. The core has a porosity and permeability of 16% and 80md, respectively. The capillary pressure-saturation data are given as follows:

S_w	p_c, psi
1.0	0.50
0.8	0.60
0.6	0.75
0.4	1.05
0.2	1.75

The interfacial tension is measured at 50 dynes/cm. Further reservoir engineering analysis indicated:

Porosity= 19% and permeability = 120 md.

Generate the capillary pressure data for the reservoir.

Leverett J-Function:

Solution:

Step 1. Calculate the J-function using the measured capillary pressure data.

$$J(S_w) = 0.21645\left(\frac{p_c}{50}\right)\sqrt{80/0.16} = 0.096799p_c$$

S_w	p_c, psi	$J(S_w) = 0.096799\,(p_c)$
1.0	0.50	0.048
0.8	0.60	0.058
0.6	0.75	0.073
0.4	1.05	0.102
0.2	1.75	0.169

Leverett J-Function:

Solution:

Step 2. Using the new porosity and permeability values and determine the capillary pressure p_c.

$$p_c = J(S_w)\sigma/[0.21645\sqrt{\frac{k}{\varphi}}] = 9.192\ J(S_w)$$

S_w	$J(S_w)$	$p_c = 9.192\ J(S_w)$
1.0	0.048	0.441
0.8	0.058	0.533
0.6	0.073	0.671
0.4	0.102	0.938
0.2	0.169	1.553