Capillary Pressure

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Capillary Pressure

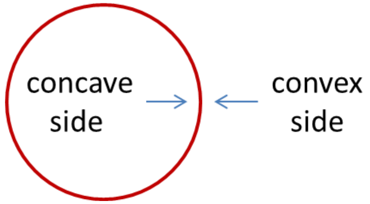
- When two immiscible fluids are in contact, there is a pressure discontinuity between the two fluids which depends upon the curvature of the interface separating the two fluids. This pressure difference or excess pressure is known as the capillary pressure.
- The pressure on the concave side of the interface is higher than that on the convex side of the interface, and the capillary pressure is given by Young-Laplace equation:

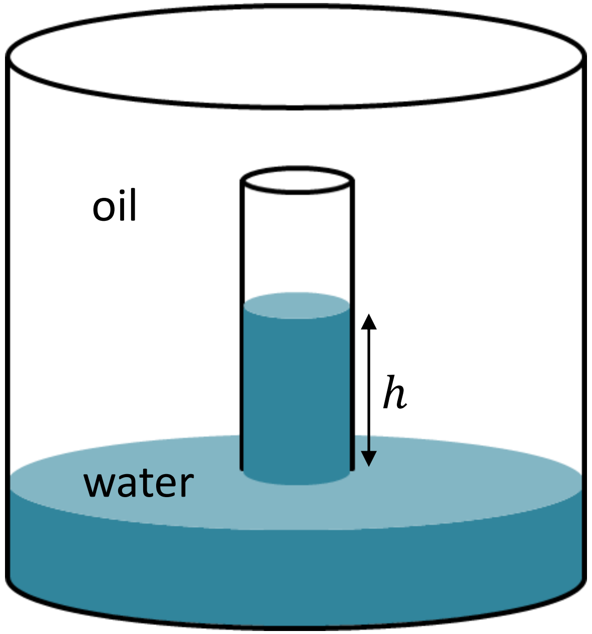
$$P_c = P_2 - P_1 = \sigma\left(\frac{1}{r_1} + \frac{1}{r_2}\right)$$

- Where r_1 and r_2 are referred to as the principal radii of curvature of interface. If the two immiscible fluids are in contact with a solid surface, the interface will intersect the solid at an equilibrium contact angle θ:

$$P_c = \frac{2\sigma\cos\theta}{r}$$

- Laplace equation can be derived by considering the mechanical equilibrium of the interface or by energy considerations.

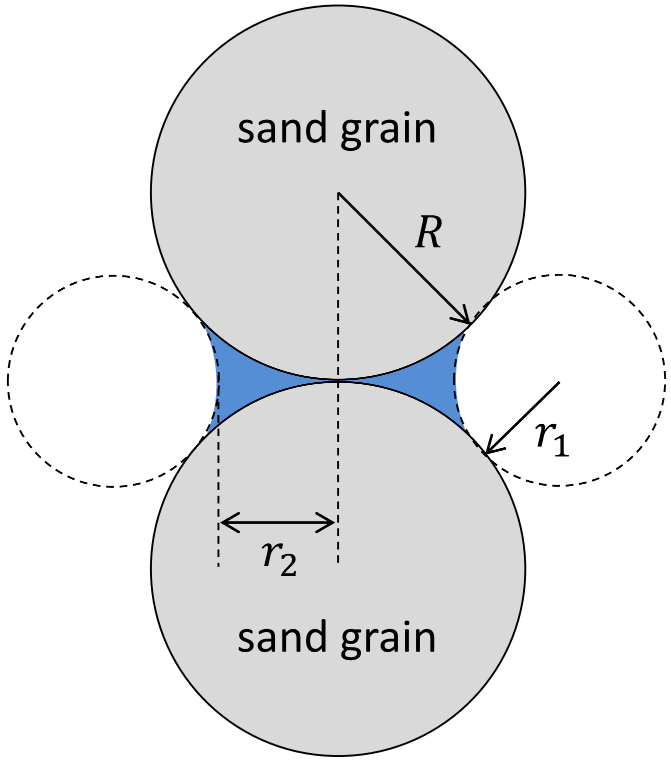




$$h = \frac{2\sigma_{wo}\cos\theta}{r(\rho_w - \rho_o)g}$$

Pendular ring of water between two spheres

- Consider two spherical grains each of radius R in contact with each other.
- A pendular ring of water of volume V that is small compared to the volume of each sphere is associated with the point of contact as shown in the figure to the right.
- Otherwise, spheres are surrounded by air. The contact angle of the water on the material of the spheres is zero.
- Let r_1 and r_2 be the principle radii of curvature of the air-water interface and σ be the interfacial tension between the water and the air.
- Show the relationship between r_1, r_2 and R.
- Given $r_2 = 10\ \mu\mathrm{m}$, $R = 80\ \mu\mathrm{m}$ and $\sigma = 72\ \mathrm{dynes/cm}$, calculate the capillary pressure of the system in psi.
- Calculate the adhesive force holding the grains together.
- Graph the relationship between RP_c/σ vs. r_2/R

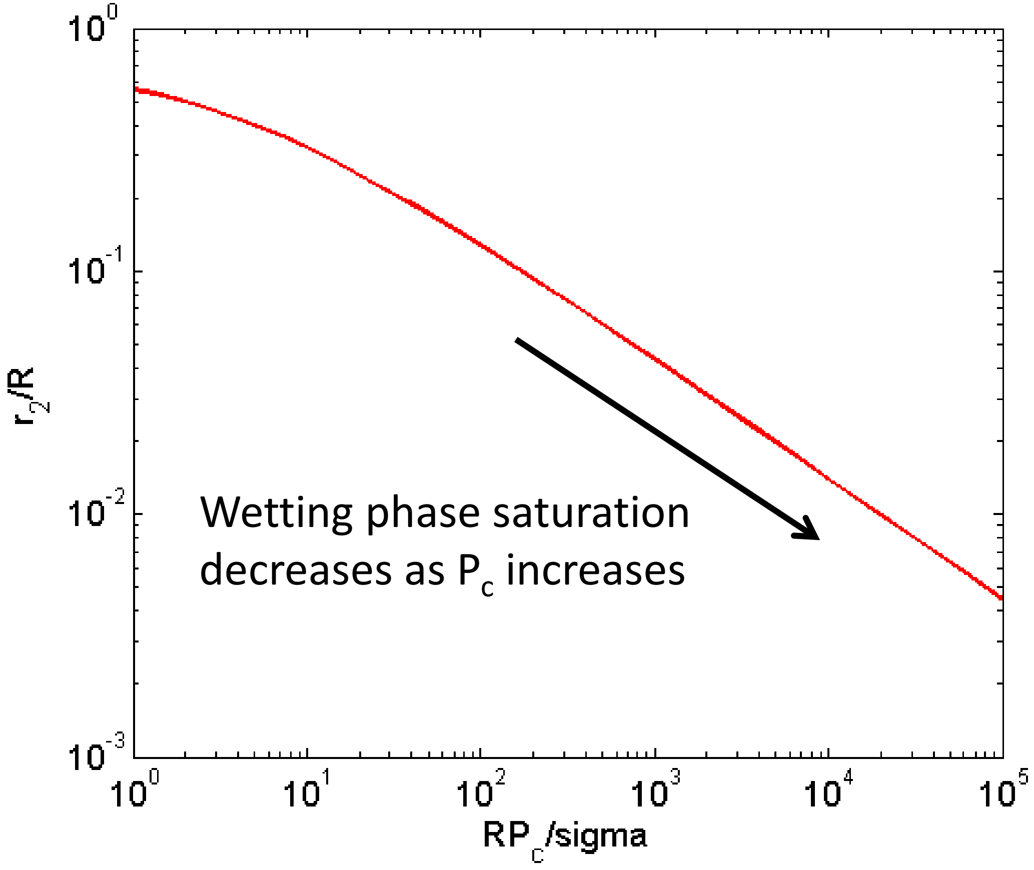


Pendular ring of water between two spheres

- In this example, the principal radii of curvature are on opposite sides of the interface. By sign convention, one radius will be positive and the other will be negative in the Laplace equation:

$$P_c = \sigma \cos\theta \left(\frac{1}{r_1} - \frac{1}{r_2} \right)$$

- If the wetting fluid saturation in the pendular ring is reduced, r_1 and r_2 will be reduced. However, r_1 will be reduced more than r_2 as the wetting phase recedes into the corners of the contact of the grains.
- As a result, the capillary pressure will increase. And vice versa is true for the opposite scenario.
- Low wetting phase saturation corresponds to high capillary pressure and high wetting phase saturation corresponds to low capillary pressure.



Outline

- Capillary pressure vs. saturation relationship
- Drainage capillary pressure curve
- Capillary pressure hysteresis and capillary imbibition
- Capillary end effect in a laboratory core
- Effects of wettability and interfacial tension
- Capillary pressure lab-measurements
- Empirical capillary pressure models
- Capillary trapping in porous media
- Averaging capillary pressure data
- Determination of the initial static reservoir fluid saturations
- Pore size distribution
- Calculation of permeability

Capillary Pressure vs. Saturation Relationship

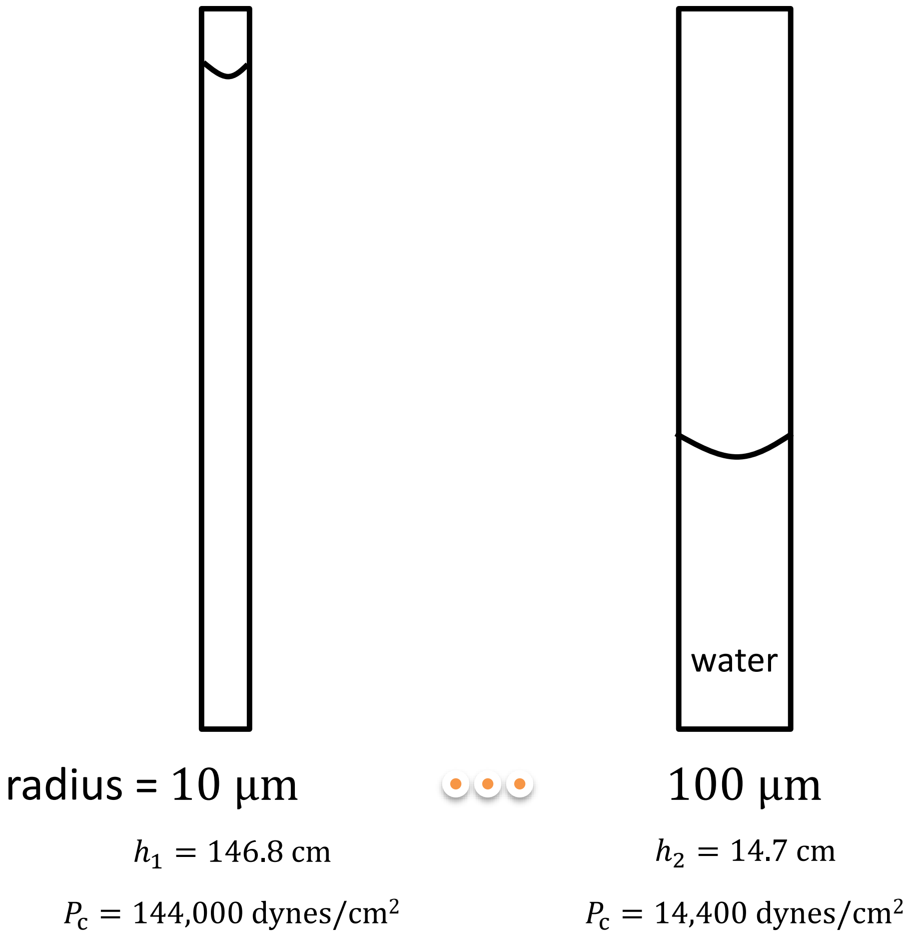
- Before considering the capillary pressure vs. saturation relationship for a porous medium, it is instructive to consider the relationship for an idealized medium consisting of a bundle of capillary tubes of varied radii.
- Let the bundle of capillary tubes medium be dipped into the wetting phase and allowed to attain capillary equilibrium as shown to the right:
  - Wetting phase is water, and air is a non-wetting phase
  - For water rising in glass tubes, we can assume $\theta = 0$
  - The surface tension of water is 72 dynes/cm at 25°C
  - For this scenario, we can calculate the heights as:

$$h = \frac{0.1468}{r}\ \mathrm{cm}^2$$

  - And the capillary pressure as:

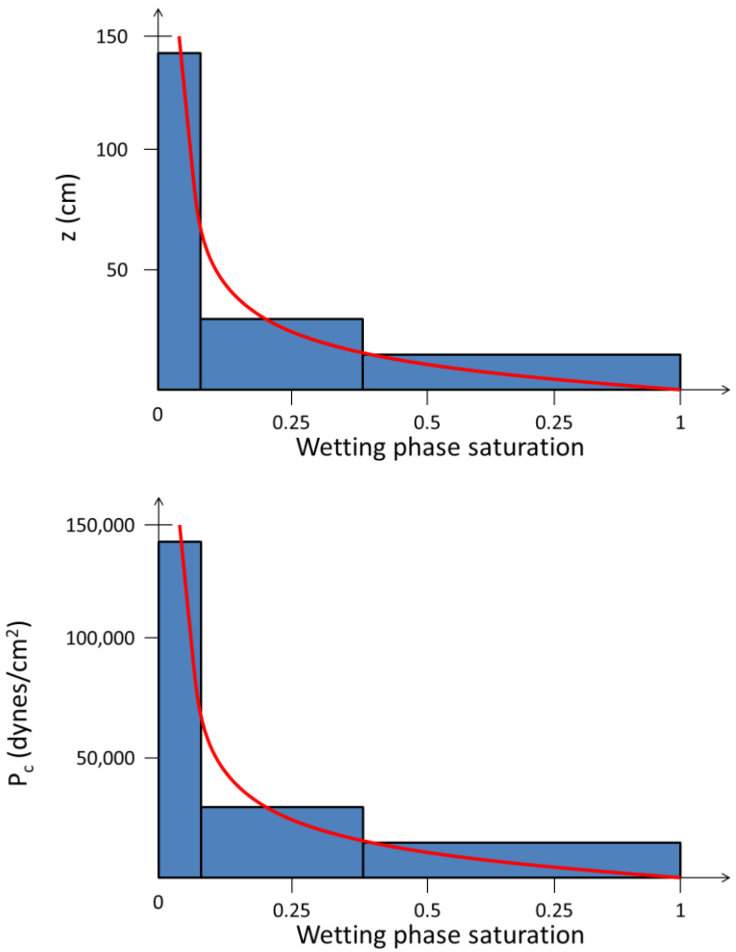
$$P_\mathrm{c} = \frac{144}{r}\ \mathrm{dyne/cm}^2$$

  - The volume of water in the tube can be calculated from the area of tube and the height obtained to calculate the fraction of the total water volume in each tube.
- Let the model consist of ten capillary tubes with the radii changing in between 10 and 100 μm.



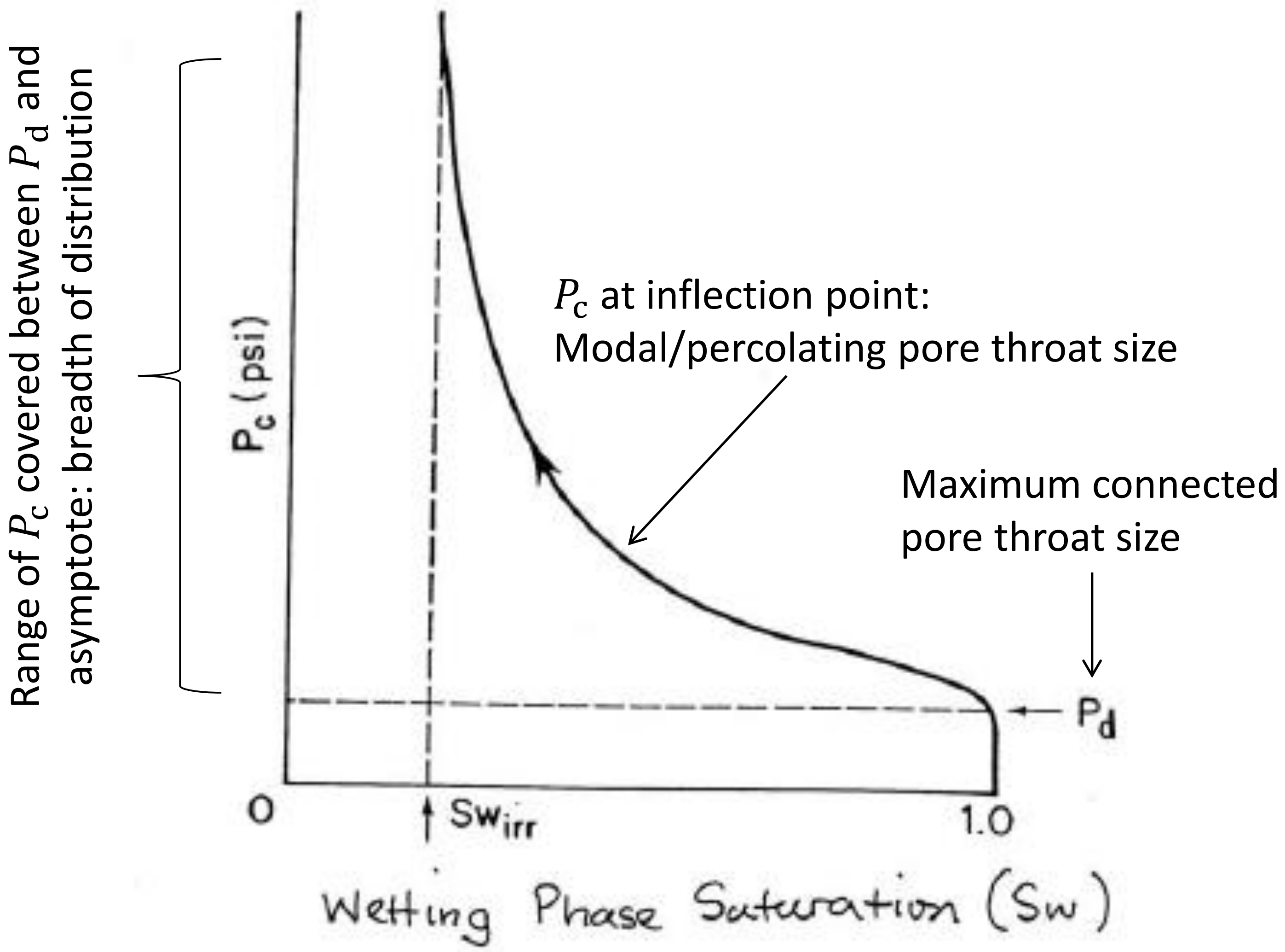
Capillary Pressure vs. Saturation Relationship

- Figures to the right show the capillary pressure vs. wetting phase saturation for the idealized model described above.
- In top figure, the capillary pressure is presented as height above the free water level. This presentation is can be used to determine the water saturation distribution in a petroleum reservoir.
- In bottom figure, the capillary pressure is given in psi. This presentation is useful for calculating pore size distribution.
- The curves have a staircase shape because of the limited number and size of capillary tubes, and it will approach a smooth curve if more tubes are used and the difference in the tube diameters are made small.
- The only limitation of this model is the absence of an irreducible wetting phase saturation. There is no possibility of trapping an irreducible saturation for a model consisting of straight and isolated capillary tubes.



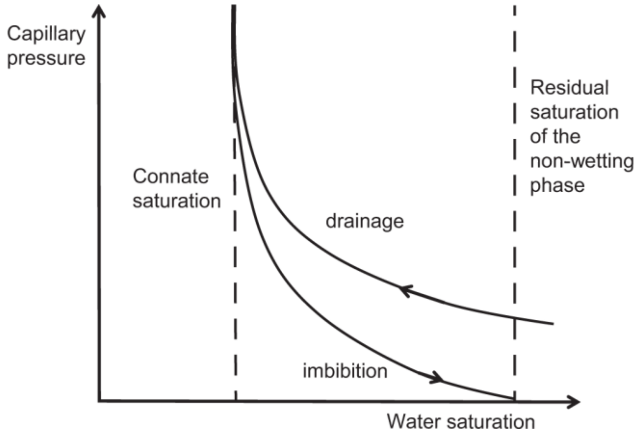
Drainage curves and pore size distributions

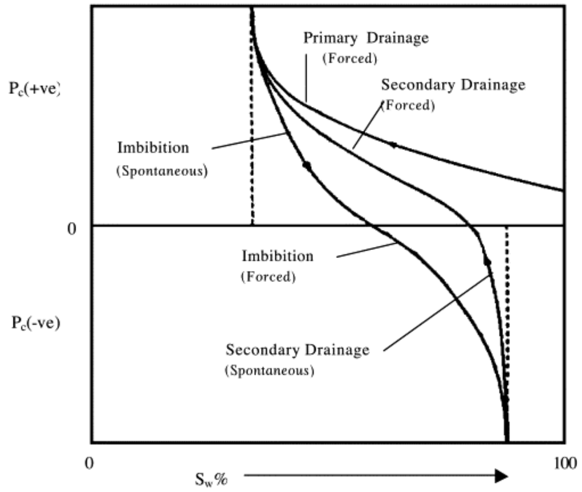
- If the idealized porous medium was replaced by an actual porous medium and the experiment repeated, the drainage capillary pressure curve would look like the one shown to the right.
- The minimum pressure, which is known as the displacement pressure, the threshold pressure or the entry pressure, is determined by the size of the largest pores connected to the surface of the medium. This is the minimum pressure difference required to initiate the drainage.
- At the irreducible wetting phase saturation, the capillary pressure curve becomes nearly vertical. The irreducible wetting phase saturation is a function of the grain-pore size, the wettability of the medium, and the interfacial tension between the wetting and non-wetting fluids.



Capillary pressure hysteresis and capillary imbibition

- Capillary pressure curves show a marked hysteresis depending on whether the curve is determined under a drainage process or an imbibition process. In other words, at any wetting phase saturation, the drainage capillary pressure is higher than the imbibition capillary pressure.
- At a capillary pressure of zero, the spontaneous imbibition curve terminates at a wetting phase saturation that may or may not correspond to the true residual non-wetting phase saturation depending on the wettability of the rock.
- Capillary pressure hysteresis can be explained in a variety of ways. The most intuitive one is the explanation based on pore structure.
- The drainage curve should be used for estimating the initial fluid saturation distribution in the reservoir whereas the imbibition curve should be used for analyzing a water flood performance in a water-wet reservoir.

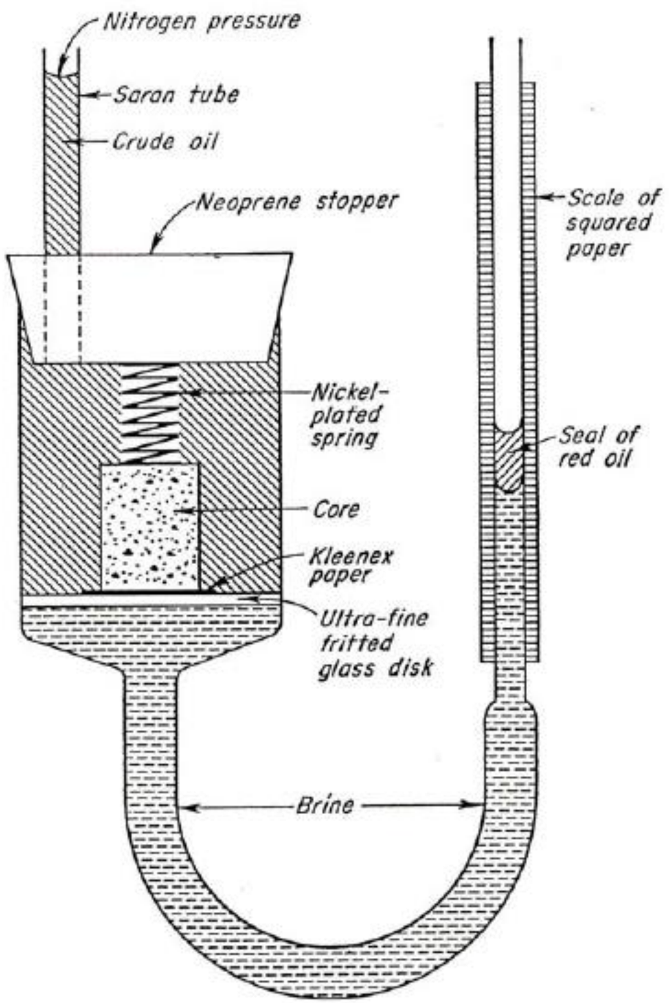




Capillary Pressure Lab-Measurements

Porous Plate Apparatus

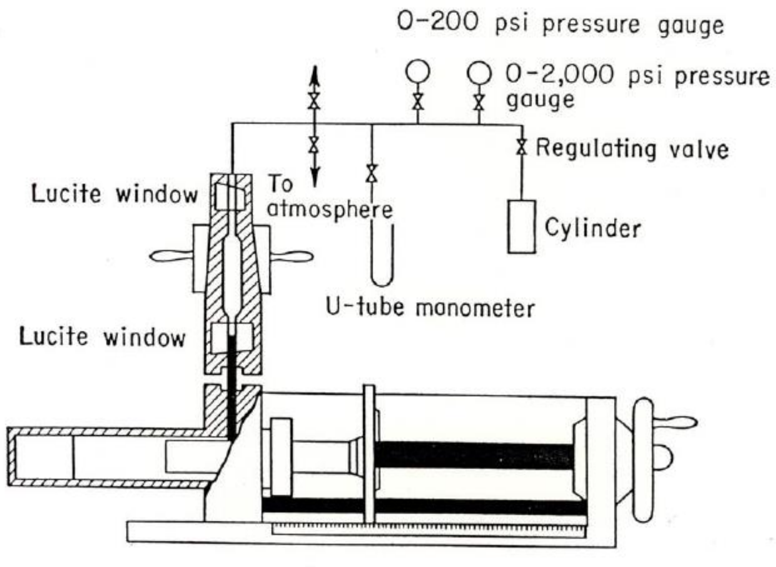
- The bottom of the vessel consists of a semi-permeable plate, which allows the wetting phase displaced from the sample to pass through while blocking the passage of the non-wetting phase.
- Pressure of the non-wetting fluid is increased in steps and the system is allowed to achieve equilibrium after each pressure change.
- The volume of wetting phase displaced at each pressure is measured.
- It takes too long to obtain the entire capillary pressure curve, it is not unusual for the experiment to take several weeks to complete



Capillary Pressure Lab-Measurements

Mercury Injection Method

- Mercury is a non-wetting phase.
- Nitrogen pressure is applied in successive increments and at each step, mercury is injected to maintain the mercury level with the graduation on the capillary.
- The mercury-air capillary pressure versus saturation relationship is calculated from the volume of mercury forced into the sample pore space as a function of applied nitrogen pressure.
- The mercury injection method is very fast. The curves can be obtained in a matter of hours.
- The major disadvantage is that the core can no longer be used for other tests after mercury injection.
- The method also cannot be used to determine the irreducible wetting phase saturation.



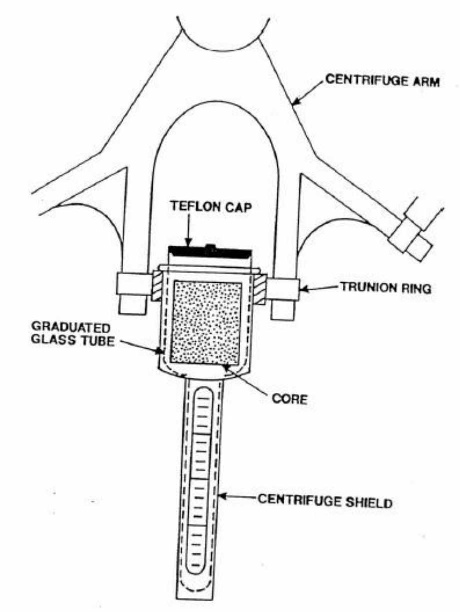
Mercury injection capillary pressure (MICP) apparatus

Capillary Pressure Lab-Measurements

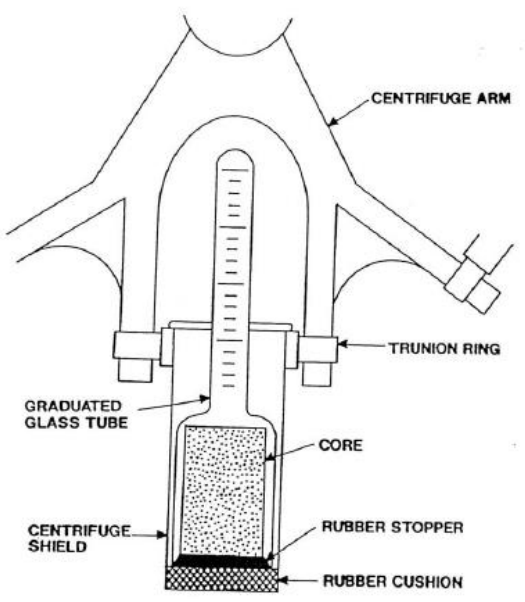
Centrifuge Method

- The sample saturated with a wetting fluid is placed in a centrifuge cup containing the non-wetting fluid.
- It is rotated at a series of constant angular velocities
- The amount of wetting fluid displaced at equilibrium at each velocity is measured with the aid of a stroboscopic light.
- Capillary pressure and saturation is calculated from rotational speed and the volume of wetting fluid displaced, respectively.
- This experiment is fast and allows the capillary pressure measurement to be completed in a day or less.

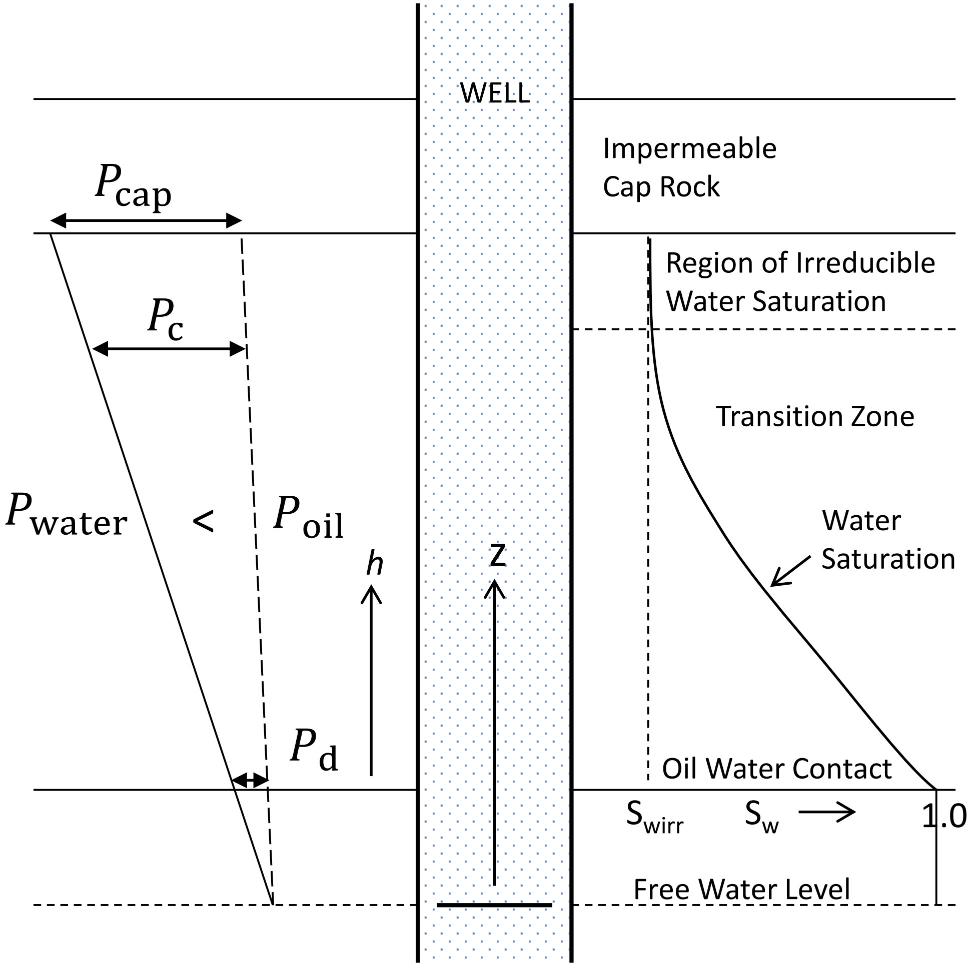
Oil displacing water

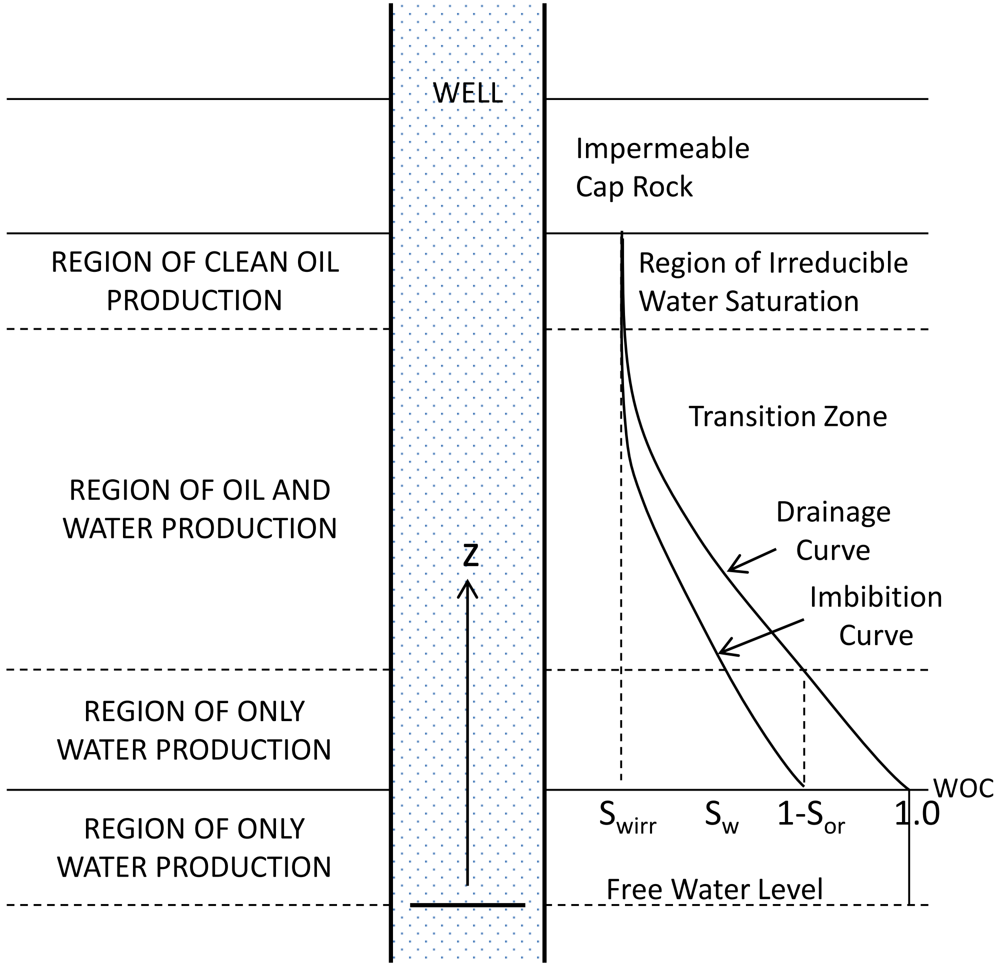


Water displacing oil



Determination of initial fluid saturation





Note: to maintain the integrity of the cap rock, the capillary pressure at the cap rock should be less than the displacement pressure of the cap rock.