Wettability can be defined as the ability of a fluid phase to preferentially wet a solid surface in the presence of a second immiscible phase.

Microscopic fluid saturation distribution in a water-wet and oil-wet rock.
Wettability

(1) water wet; contact angle $\theta < 90^\circ$
(2) neutral wettability, $\theta = 90^\circ$
(3) oil wet, $\theta > 90^\circ$

**Fractional wettability** – heterogeneous wetting; i.e., portions of the rock are strongly oil wet, whereas other portions are strongly water wet. Occurs due to variation in minerals with different surface chemical properties.

**Mixed wettability** – refers to small pores occupied by water and are water-wet, while larger pores are oil-wet and continuous.
Wettability

The **contact angle** is a measure of the wettability of the rock-fluid system, and is related to the interfacial energies by Young’s equation,

\[
\sigma_{os} - \sigma_{ws} = \sigma_{ow} \cos \theta
\]

where:

- \( \sigma_{os} \) = interfacial energy between oil and solid, dyne/cm;
- \( \sigma_{ws} \) = interfacial energy between water and solid, dyne/cm;
- \( \sigma_{ow} \) = interfacial energy, or interfacial tension, between oil and water, dyne/cm;
- \( \theta \) = contact angle at oil-water-solid interface measured through the water phase,
Wettability

Sessile drop method of measuring contact angles for water-oil systems
Wettability

USBM method of determining wettability for a water wet sample

\[ I_w = \log \left( \frac{A_1}{A_2} \right) \]

- Increasing positive values indicate a preference to water wet; i.e., \( A_1 \) progressively becomes greater than \( A_2 \). Negative values of the index indicate an oil-wet preference (\( A_2 > A_1 \))
Wettability

**Combined USBM-Amott Wettability Test**

1. Sample is 100% water saturated,
2. Oil displaces water to $S_{wi}$ (drainage cycle)
3. spontaneous imbibition of brine, $V_{osp}$
4. Water displaces oil to $S_{or}$ (imbibition cycle)
5. spontaneous imbibition of oil, $V_{wsp}$
6. final displacement of water by oil (2nd drainage cycle).

\[
I_w = \frac{V_{osp}}{V_{ot}} - \frac{V_{wsp}}{V_{wt}} = \delta_o - \delta_w
\]

Amott Index

+1 Strongly water wet
-1 Strongly oil wet
Capillary Pressure

force up = force down
force up = \(2\pi r \sigma \cos \theta\)
force down = \(\pi r^2 h \Delta \gamma\)

\[P_c = \text{force up} / (\pi r^2) = \text{force down} / (\pi r^2)\]
\[P_c = \frac{2\sigma \cos \theta}{r}\]

\[P_c = \frac{\pi r}{2} gh \left(\rho_w - \rho_{air}\right) = \Delta \rho \, gh\]
Capillary Pressure

In reservoirs, capillary pressure is the difference between the nonwetting phase pressure \( (P_{nw}) \) and the wetting-phase pressure \( (P_w) \).

\[
P_c = P_{nw} - P_w
\]
Capillary Pressure

Conversion of lab to reservoir conditions

\[ P_{c(res)} = P_{c(lab)} \frac{(\sigma \cos \theta)_{res}}{(\sigma \cos \theta)_{lab}} \]

Example:

Laboratory \( \sigma \) (air-water) = 72 dyne/cm
\( \theta \) (air-water) = 0°
Reservoir \( \sigma \) (oil-water) = 24 dyne/cm
\( \theta \) (oil-water) = 30°
\( \rho_w = 65 \text{ lb/cu ft} \)
\( \rho_o = 53 \text{ lb/cu ft.} \)

\[ P_{c(res)} = P_{c(lab)} \frac{24 \cos 30^\circ}{72 \cos 0} = 0.289 P_{c(lab)} \]

\[ h = \frac{P_c}{\Delta \rho} = \frac{P \times 144}{65 - 53} = 12.0 \times P_{c(res)} \]
Capillary Pressure

Entry Pressure

Drainage/Imbibition
Capillary Pressure

- Entry pressure
- Irreducible water saturation
- Slope of transition zone curve
- Grain size distribution
- Grain and pore size

Permeability effect
Capillary Pressure Measurement

Mercury injection

Schematic of mercury injection apparatus

Example mercury-air capillary pressure curves
Capillary Pressure Measurement

Porous Diaphragm

Schematic of a Ruska diaphragm pressure cell

Example of capillary pressure curve for a water-wet system
Capillary Pressure Measurement

Centrifuge

Capillary pressure measurement by centrifuge

Example capillary pressure curves from centrifugal data.
Curves 2 and 4 are estimated because they typically cannot be determined by centrifuge.
Capillary Pressure Measurement

Centrifuge

Schematic illustrating the variation of pressure and water saturation as a function of core length.

Hyperbolic least squares fit

\[
(P_c)_i = \frac{A + B\overline{S}}{1 + C\overline{S}}
\]

\[
\frac{d(P_c)_i}{d\overline{S}} = \frac{B - AC}{(1 + C\overline{S})^2}
\]
## Capillary Pressure Measurement

### Comparison

<table>
<thead>
<tr>
<th></th>
<th>Equilibrium</th>
<th>Air/Hg</th>
<th>Centrifuge</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Duration</strong></td>
<td>5 weeks</td>
<td>1 day</td>
<td>3 days/run</td>
</tr>
<tr>
<td><strong>Max Height (m gas/oil)</strong></td>
<td>30/60</td>
<td>7000/14500</td>
<td>80/160</td>
</tr>
<tr>
<td><strong>At stress?</strong></td>
<td>Yes</td>
<td>Yes</td>
<td>No</td>
</tr>
<tr>
<td><strong>On cuttings?</strong></td>
<td>No</td>
<td>Yes</td>
<td>No</td>
</tr>
<tr>
<td><strong>Sample damaged?</strong></td>
<td>No</td>
<td>Yes</td>
<td>Weak only</td>
</tr>
<tr>
<td><strong>Unconsolidated</strong></td>
<td>Yes</td>
<td>Yes</td>
<td>Yes?</td>
</tr>
<tr>
<td><strong>Equilibrium reached?</strong></td>
<td>Yes</td>
<td>Yes</td>
<td>Nearly</td>
</tr>
<tr>
<td><strong>Clay correction required</strong></td>
<td>No</td>
<td>Yes</td>
<td>No</td>
</tr>
<tr>
<td><strong>Costs</strong></td>
<td>Expensive</td>
<td>Cheap</td>
<td>Medium</td>
</tr>
<tr>
<td><strong>Additional Information</strong></td>
<td>Imbibition RI</td>
<td>Imbibition</td>
<td>Imbibition Wettability</td>
</tr>
</tbody>
</table>
Capillary Pressure

• Importance in defining:
  – the height of the transition zone
  – the initial distribution of reservoir fluids
  – the retention of the wetting phase in the reservoir

• Assign based on:
  – rock types
  – flow process
Averaging Capillary Pressure Data

Methods to fit a laboratory measured capillary pressure curve for the purpose to produce a saturation-height function.

1. Averaging curve fit parameters (e.g. $a$, $b$, $\lambda$ vs. $\phi$)
   Of these the **lambda-fit** normally works best. It fits the wetting saturation $S_w$ to the capillary pressure $P_c$ using three fit constants, $a$, $b$ and $\lambda$, according to: $S_w = aP_c^{-\lambda} + b$

2. Interpolation within data set

3. Leverett-J

4. Neural networks

5. Regression (linear, non-linear, multi-variate)
Averaging Capillary Pressure Data

Leverett J Function

calculate $J(S_w)$ for each capillary pressure point using:

$$J(S_w) = \frac{P_c}{\sigma \cos \theta \sqrt{\phi}}$$

plot $J(S_w)$ versus $S_w$ and draw a smooth curve through the points,

calculate $h$ for each $S_w$, for any set of $k$ and $\phi$;

$$h = \frac{J(S_w)(\sigma \cos \theta)_{res}}{\left(\rho_w - \rho_o\right)\sqrt{k/\phi}_{res}}$$

plot $h$ versus $S_w$. 
Averaging Capillary Pressure Data

Set of capillary pressure curves for the D sands

J-function relates rock type ($\phi$ and $k$) to $P_c$ and normalizes data for application at different locations in a reservoir

Resulting J-function curve for the D-sands
Capillary Pressure

saturation-height as a function of rock type
Causes of errors in capillary pressure curves are:
- Alteration of wettability by invasion of drilling mud filtrate
- Biased sampling
- Sample integrity
- Effect of core cleaning on wettability
- Laboratory measurement and appropriate corrections for temperature, stress, and clays
- Averaging

Causes of errors in log calculations are:
- Tool calibrations and quality control
- Invasion, thin bed and borehole effects
- Application of the correct interpretation model
- Assumptions or validity of m, n, or a

Also, the difference in “scale” will impact the degree of agreement between core-derived and log-derived saturation-height curves.
Capillary Pressure - PSD

Purcell Method

The concept is based on analogy with Carmen-Kozeny’s equation. Recall from the Carmen-Kozeny, \( k = f(\text{porosity, PSD}) \). Capillary pressure, \( P_c = f(\text{wettability, saturation}) \), where saturation is a function of pore geometry. Thus a \( P_c – S_w \) curve relates the pore size penetrated by the non-wetting fluid at a given capillary pressure.

\[
k = 10.24(\sigma \cos \theta)^2 \phi \lambda \bullet \int_{S=0}^{S=1} \frac{dS}{P_c^2}
\]

Where \( \lambda \) is a lithology factor \( \sim 0.216 \)

Compare with CK equation,

\[
S_{pv} = \frac{1}{(\sigma \cos \theta)^2 \bullet \int_{S=0}^{S=1} \frac{dS}{P_c^2}}
\]

\[
k_z = 1/\lambda = 4.63
\]
Capillary Pressure

Burdine Method

Define a distribution function, \( D(r_i) \), The area under the curve at a particular radius represents the fraction of the volume with pores larger than the given radius.

\[
k = \frac{100\phi V}{p \Delta S \cdot \bar{r}_i^4} \sum_{i=1}^{n} \frac{\Delta S \cdot \bar{r}_i^4}{x_i \cdot \bar{r}_i^2}
\]

Where \( x_i \) is a dividing factor to account for the complex geometry of porous media.
Procedure to develop Pc curve for centrifuge measurement and estimate k from Pc curve

Step-by-step procedure

1. Measured data: N, rpms and volume of water displaced, Vdis, cc.

2. Calculate average water saturation:

\[ S_w = 1 - \frac{V_{\text{dis}}}{V_p} \]

3. Calculate inlet Pc:

\[ (P_c)_i = 1.096 \times 10^{-6} \Delta \rho N^2 \left( r_e - \frac{L}{2} \right) L \text{ in Kpa} \]

\[ \times 0.14507 \text{ in psi} \]

4. Assume values of average water saturation

5. Calculate inlet Pc from a hyperbolic regression fit of Pcinlet=f(Save)

\[ (P_c)_i = \frac{A + BS}{1 + CS} \]

6. Calculate the derivative

\[ \frac{d(P_c)_i}{dS} = \frac{B - AC}{(1 + CS)^2} \]

7. Calculate the inlet water saturation

\[ S_i = \bar{S} + (P_c)_i \times \frac{dS}{d(P_c)_i} \]
Capillary Pressure

Procedure to develop Pc curve for centrifuge measurement and estimate k from Pc curve

8. Calculate inlet Pc from regression fit of Pcinlet=f(Sinlet)

\[ P_{ci} = 0.5594S_i^{-1.9843} \]

9. Calculate the derivative

\[ \frac{dP_{ci}}{dS_i} = -1.11S_i^{-2.9843} \]

10. Calculate the pore entry radius, \( r_i \)

\[ r_i = \frac{2\sigma \cos \theta}{P_{ci}} \]

6895 Pa = psi

10,000 microns = cm
dyne/cm² = .1 Pa

11. Calculate the distribution function from inlet properties

\[ D_{(ri)} = P_c \frac{V_p}{r} \left( \frac{dS_o}{dP_c} \right)_{inlet} \]

Note: derivative is based on displacing fluid

12. Calculate and graph, Sw vs 1/Pc²

13. Develop a regression fit to the data and integrate

14. Calculate permeability from Purcell's method

\[ k = 10.24(\sigma \cos \theta)^2 \phi \lambda \cdot \int_{S=0}^{S=1} \frac{dS}{P_c^2} \]

\[ \lambda = 0.216 \]
Capillary Pressure

Procedure to develop Pc curve for centrifuge measurement and estimate k from Pc curve

15. Calculate permeability using Burdine's method
   
   \[ k = \frac{100\phi V_p}{8(9.87 \times 10^{-7})} \sum_{i=1}^{n} \Delta S \cdot \bar{r}_i^{4} \]
   
   a. Summation term approximation
   
   \[ \bar{r}_i = \frac{r_i (j-1) + r_i \cdot j}{2} \]
   
   \[ Term = \Delta S_{air} \cdot \bar{r}_i^{2} \]

   b. Numerical - Composite Simpson's rule