3. Rock properties

- Rock properties are essential for reservoir engineering calculation as they directly affect both the quantity and the distribution of hydrocarbons and when combined with fluid properties.
- Rock properties are controlling the flow of the existing phases (gas, oil, water) within the reservoir.
- Rock properties are determined by performing laboratory analysis on cores from the reservoir to be evaluated.
- The most important rock properties are **porosity**, **permeability**, **saturation** and **capillary pressure**.

3.1. Porosity (Φ)

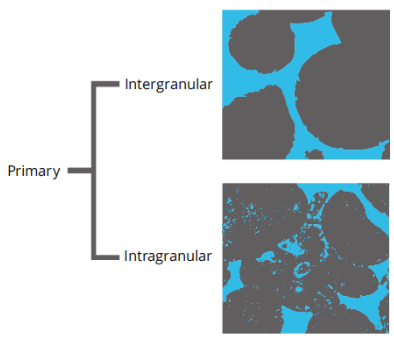
- Porosity is the rocks fluid storage capacity or is the ability of the rock to store fluids.
- Porosity is the ratio of void volume in a porous medium to the total volume of that medium.
- Porosity has two types of classifications: **geological** and **engineering**.

3.1.1. Geological classification of Porosity

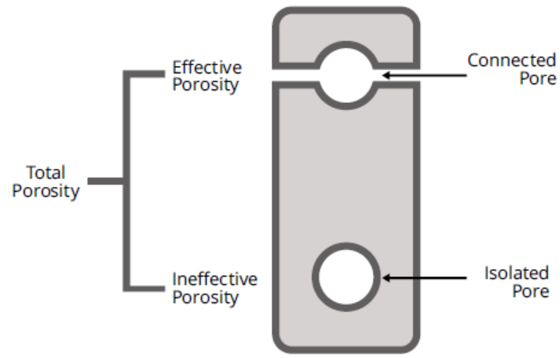
- In terms of geological classification, porosity is classified into two subdivisions: **primary** and **secondary**.
- **Primary porosity** is the original porosity that develops during the deposition of the material.
- **Primary porosity** can be either **intergranular** or **intragranular**.
- **Intergranular porosity** is the porosity between grains, while **intragranular porosity** is the porosity within the grain itself.
- **Intergranular porosity** forms the majority of the porosity of the rock.
- **Secondary (induced) porosity** is developed after deposition by geological processes which result in vugs and fractures.

3.1.2. Engineering Classification of Porosity

- ❖ In terms of engineering classification, porosity can be subdivided into two categories: **total and effective porosity**.
- ❖ **Total porosity (Φ_t)** is the total pore volume of the rock divided by the bulk volume.
- ❖ **Effective porosity** (Φ_e) is the interconnected pore volume divided by the bulk volume.
- ❖ **Ineffective porosity** is the isolated pore volume divided by the bulk volume.
- ❖ As petroleum engineers we are mainly interested in the effective porosity since hydrocarbons can only flow through connected pores.



Schematic showing the difference between intergranular and intragranular porosities.



Schematic showing the difference between porosity subdivisions: total, effective, and ineffective.

3.1.3 Calculation of Porosity

1. **Absolute or total porosity (Φ_a)**: is the ratio of all the pore spaces in a rock to the bulk volume.

$$\Phi_a = \frac{\text{pore volume}}{\text{Bulk volume}} = \frac{v_p}{v_b}$$

Pore volume (V_p) = bulk volume – grain volume

2. **Effective porosity (Φ_e)**: is the ratio of the interconnected pore spaces in a rock to the bulk volume.

$$\Phi_e = \frac{\text{interconnected pore spaces volume}}{\text{Bulk volume}}$$

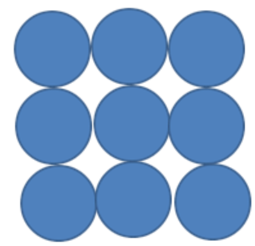
(0-5%) negligible, (5-10%) poor or low, (10-20%) good & (≥ 20%) very good.

3. **Residual porosity (Φ_r)**: It is the unconnected (isolated) porosity in which fluids can't collects.

$\Phi_r = \Phi_a - \Phi_e$

Ex} If we consider a cubic packing of spheres (ideal situation) and look at a cube section as shown in Figure below, the length of the cube is $2r$, where r is the radius of the sphere.

Cubic packing



Cubic volume = (Length of the side)^3

Length of the side = 2r + 2r + 2r = 6r

V_b (bulk volume) $= (6r)^3$

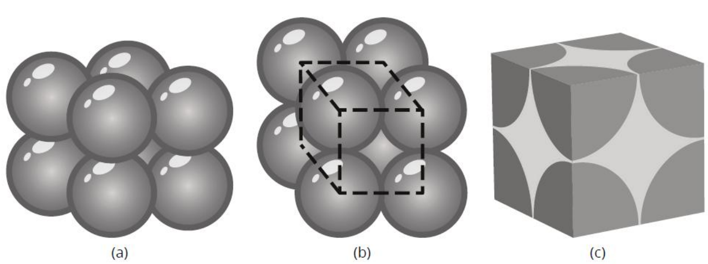
Since the grain is spherical:

Ball volume $= \frac{4}{3}\pi r^3$

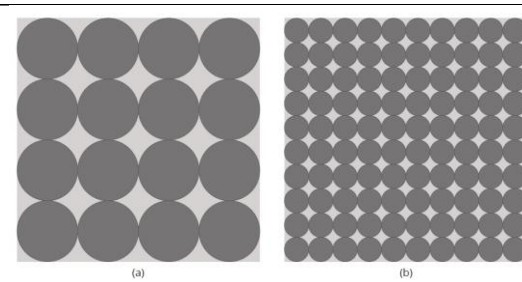
V_G (volume of grain) $= 27\left(\frac{4}{3}\pi r^3\right)$

$\Phi = \frac{V_b - V_G}{V_b} = \frac{(6r)^3 - (27)\left(\frac{4}{3}\pi r^3\right)}{(6r)^3} * 100\% = 47.6\% \approx 48\%$

We can conclude that the grain size does not affect the porosity of the rock (as all the radii in the equation cancel out). In other words, having large spheres or small spheres will lead to the same porosity as long as they are all of the same size and have the same packing. A value of 0.476 is the highest achievable porosity, and naturally you will always come across a porosity value less than this.



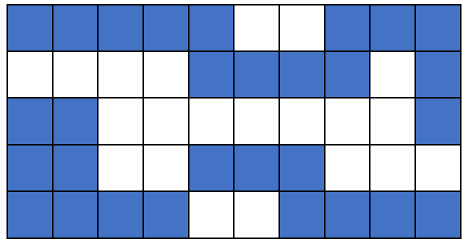
Schematic showing (a) a cubic packing of spheres from which (b) a subset cube is selected and then (c) analyzed



Schematic showing (a) the large particle size and (b) the small particle size.

Ex} Calculate the effective porosity, total porosity and residual porosity of a 2- dimensional hypothetical porous medium shown below:

Note: Blue grids represent the grain and white grids represent the pores.



Answer:

Total volume= 5x10= 50 Connected pores volume= 17

Unconnected pores volume= 4

Total pores volume= **Connected pores volume+ Unconnected pores volume**

=17+4=21

Total porosity (Φ_T) = $\frac{\text{Total pores volume}}{\text{Total volume}} = \frac{v_p}{v_b} = \frac{21}{50}$ = 0. 42 or 42%

Effective porosity (Φ_e) = $\frac{\text{Connected pores volume}}{\text{Total volume}} = \frac{17}{50}$ = 0.34 or 34%

Residual porosity (Φ_r) = $\frac{\text{UnConnected pores volume}}{\text{Total volume}} = \frac{4}{50}$ = 0.08 or 8%.

To check our answer (Φ_e) + (Φ_r)= (Φ_T).

3.1.4. Measuring Porosity

There are usually two methods of measuring porosity. We either measure it using laboratory measurements at the centimeter scale or using wireline logging at the meter scale.

1. Direct method or laboratory measurement or core analysis: This method depends on taking a rock core from the formation, and samples are usually taken for some depths of the formation, and not taken for all depths of the formation, because it requires a very high cost. This is the best method for calculating porosity and permeability. But it is not sufficient alone because the models taken are for some depths and not for all depth of composition.

2. In direct methods: such as Well logging and Well testing.

3.1.5. Laboratory measurements of porosity

There are Several methods which involve only determination of two out of three basic parameters (V_p, V_G and V_b). To measure bulk volume in laboratory, must prevent fluid penetration into the pore sample

Measuring Pore volume by fluid displacement: **Fluid Displacement**

In this technique, we weigh a dry core and measure the dimensions, specifically the diameter and length of the core. Then, we vacuum saturate the core with water or brine (salt water), for instance, to make sure that the water has filled all the pore spaces and no air is trapped in the core. The core is then weighed to find the saturated weight. Subtracting the saturated weight from the dry weight, we obtain the weight of the water in the pore spaces. By dividing the weight of the water by the density of the water, we obtain the pore volume:

$$V_p = \frac{w_{sat} - w_{dry}}{\rho_{liq}}$$

where W_{sat} is the weight of the core saturated with fluid [g], W_{dry} is the dry weight of the core [g], and ρ_{Liq} is the density of the fluid [g/cm^3]; since the fluid in this case is water, the density is 1 g/cm^3.

Ex} A cylindrical core sample has a length of 5 cm and a diameter of 2 cm. The dry weight of the sample is 56.5 g, and the weight of the sample saturated with water is 60.3 g. Given that the density of water is 1 g/cm^3. Determine V_b, V_p and the porosity. What kind of porosity value was determined from this experiment?

Answer:

We find the total volume of the core sample (bulk volume):

$V_b = \pi r^2 L = \pi (2/2)^2 (5) = 15.71$ cm^3

We find the weight of water in the sample: $W_w = w_{sat} - w_{dry} = 60.3$ g - 56.5 g = 3.8 g.

We find the pore volume of the sample: $V_p = \frac{w_{sat} - w_{dry}}{\rho_{liq}} = \frac{60.3\text{ g} - 56.5\text{ g}}{1\ g/cm^3}$ =3.8 g/cm^3

find the porosity: Porosity (Φ)= $\frac{v_p}{v_b} = \frac{3.8}{15.71}$= 0.242 = 24.2%

The porosity it calculated is **effective porosity** because only connected pore space could have been saturated by water.

Note: From the displacement method, we can also find the **bulk volume of irregular shapes.** Let us consider a rock with an irregular shape. In order to measure the volume, we need to coat the surface of the rock with an insulating material such as paraffin (ρ= 0.9 g/cm^3) to prevent the fluid we are using to enter the pores. However, before that we need to measure the dry weight of the rock sample and the weight of the core with the paraffin. The difference between the two weights divided by the density of paraffin is the volume of the added paraffin. This volume will then be subtracted from the final volume calculation. After performing all these steps, we can find the volume of the rock using two methods:

1) We can record the initial volume of water in the graduated cylinder, and then record the new volume of water after submerging the rock. The difference between the new volume and the initial volume is the volume of the rock. However, we also need to subtract the volume of the paraffin to obtain the actual bulk volume of the rock.

2) We can also use the Archimedes' principle to find the bulk volume of the rock:

$$W_{df} = W_r - W_a$$

where W_{df} is the weight of the displaced fluid [g], Wr is the dry weight of the core or the weight of the core at the initial conditions before submerging (real weight) [g], and Wa is the weight of the core after submerging it in the fluid (apparent weight) [g]. Finally, in order to measure the bulk volume, we need to use the following equation:

$$V_b = \frac{W_{df}}{\rho} - V_{coat}$$

where ρ is the density of the fluid in which the core is submerged [g/cm^3], which in this case is water, and V_{coat} is the volume of coat used, usually paraffin [cm^3].

Note that V_{coat} can be measured by subtracting the weight of the sample with the coat from the weight of the sample without the coat and divide the product by the density of coat used, i.e., paraffin.

Ex} The dry weight of a sample is 330 g, and its weight when saturated with water is 360 g. The apparent weight of this sample in water is recorded as 225 g. Given that the density of water is 1 g/cm^3, find the porosity of the sample. Assuming the sample is coated with a material of negligible weight.

Sol) find the pore volume of the sample: $V_p = \frac{w_{sat} - w_{dry}}{\rho_{liq}} = \frac{360\text{ g} - 330\text{g}}{1\ g/cm^3}$ =30 g/cm^3

find the weight of the displaced fluid: $W_{df} = W_r - W_a$ = 330-225 = 105 g.

find the bulk volume: $V_b = \frac{W_{df}}{\rho} - V_{coat} = \frac{105}{1} - 0 = 105$ cm^3.

find the porosity: Porosity (Φ)= $\frac{v_p}{v_b} = \frac{30}{105}$= 0.286 = 28.6%

3.1.6. Average of porosity (Φ_{avg})

Reservoir rocks are characterized by the presence of variation in their petrophysical characteristics, whether in the vertical or horizontal direction. The vertical variation is greater than the horizontal one due to compaction. The porosity average in the reservoir can be calculated in several ways:

1. Arithmetic average: $\Phi_{\mathbf{avg}} = \frac{\sum_{i=1}^{n} \Phi i}{n}$
2. Thickness weighted average: $\Phi_{\mathbf{avg}} = \frac{\sum_{i=1}^{n} \Phi i\ hi}{\sum_{i=1}^{n} hi}$
3. Areal weighted average: $\Phi_{\mathbf{avg}} = \frac{\sum_{i=1}^{n} \Phi i\ Ai}{\sum_{i=1}^{n} Ai}$
4. Volumetric weighted average: $\Phi_{\mathbf{avg}} = \frac{\sum_{i=1}^{n} \Phi i\ Vi}{\sum_{i=1}^{n} Vi}$

Where :

n: total number of samples. Φ_i: porosity of the sample (i)

h_i: thickness of the sample (i) A_i: area of the sample (i)

V_i: volume of the sample (i)

Note: The most accurate method is **volumetric weighted** then **Areal weighted** and the least accurate **Arithmetic average**.

Ex} calculate the arithmetic average and thickness-weighted average porosity from the following laboratory measurement.

Sample	Thickness, ft	Porosity %
1	1	10
2	1.5	12
3	1	11
4	2	13
5	2.1	14
6	1.1	10

Answer:

Arithmetic average $\Phi = \frac{10+12+11+13+14+10}{6} = 11.67\%$

Thickness- weighted average $\Phi = \frac{(1*10)+(1.5*12)+(1*11)+(2*13)+(2.1*14)+(1.1*10)}{1+1.5+1+2+2.1+1.1} = 12.11\%$

3.2. Permeability

- Permeability is a property of the porous medium that measures the capacity and ability of the formation to transmit fluids.
- The rock permeability, k, is a very important rock property because it controls the directional movement and the flow rate of the reservoir fluids in the formation.
- The equation that defines permeability in terms of measurable quantities is called Darcy's Law.

$q = \frac{K\ A\ (p_2 - p_1)}{\mu L}$ & $k = \frac{q \mu L}{A\ (p_2 - p_1)}$

Where

k = proportionality constant, or permeability, Darcys

μ =viscosity of the flowing fluid, centipoise (cp).

q = flow rate through the porous medium, cm /sec

A = cross-sectional area across which flow occurs, cm^2

L = length of core, cm

One Darcy is a relatively high permeability as the permeabilities of most reservoir rocks are less than one Darcy. The term millidarcy (md) is used. 1 Darcy = 1000 md

Ex} Brine is used to measure the absolute permeability of a core plug. The rock sample is 4 cm long and 3 cm in cross section. The brine has a viscosity of 1.0 cp and is flowing a constant rate of 0.5 cm^3/sec under a 2.0 atm pressure differential. Calculate the absolute permeability.

Solution: Applying Darcy's equation gives:

$$k = \frac{q\mu L}{A\,(p_2 - p_1)} = \frac{0.5\,(1)(4)}{(4*3)(2)} \qquad k = 0.083 \text{ Darcys}$$

Ex} Rework the above example assuming that an oil of 2.0 cp is used to measure the permeability. Under the same differential pressure, the flow rate is 0.25 cm^3/sec

Solution: Applying Darcy's equation yields:

$$k = \frac{q\mu L}{A\,(p_2 - p_1)} = \frac{0.25\,(2)(4)}{(4*3)(2)} \qquad k = 0.083 \text{ Darcys}$$

Ex} In an experiment designed to measure the permeability of a core sample using brine, the cylindrical core was saturated with brine, and then water was injected at a rate of 0.07 cm^3/s. The pressure differential was measured to be 2.925 atm while the outlet was open to atmospheric pressure. Knowing that the core length is 9 cm, the core diameter is 3.75 cm, and the brine viscosity is 1 cP, calculate the permeability of the core.

Solution) $k = \frac{q\mu L}{A\,(p_2 - p_1)}$, $A = \pi r^2 = \pi\,(3.75/2)^2 = 11.04\ cm^2$

$$k = \frac{0.07*1*9}{11.04*2.925} = 19.51 \text{ Darcys}$$

Ex} Find the effective permeability from the following data:

Volume of oil = 1000 cm^3, duration of test = 500 sec. Upstream pressure = 1.45 atm.

Downstream pressure = 1 atm. Cross suction area (A)= 2 cm^2, L = 2 cm, μ=1 cp.

Ans.) q= Volume/ time = 1000 cm^3 / 500 sec = 2 cm^3/sec

$\Delta P= (P_2-P_1)= 1.45-1= 0.45$ atm

$k = \frac{q\mu L}{A\,(p_2-p_1)} = \frac{2*1*2}{2*0.45} = 4.44$ Darcys.

3.2.1. Classification of permeability

1. **Absolute permeability (K_a):** permeability of a rock saturated 100% with flowing fluid.
2. **Effective permeability (K_e):** permeability of a rock saturated less than 100% of flowing fluid.

k_g = effective gas permeability, k_o = effective oil permeability, k_w = effective water permeability.

3. **Relative permeability (K_r):** Relative permeability (K_r) is the ratio of K_e to K_a. When two or more fluids flow at the same time, the relative permeability of each phase at a specific saturation is the ratio of the effective permeability of the phase to the absolute permeability.

$K_r = K_e/K_a$ $K_{r\,o}= K_o/K_a$ $K_{r\,w}= K_w/K_a$ $K_{r\,g}= K_g/K_a$

Where:

$K_{r\,o}$: oil Relative permeability. $K_{r\,w}$: water Relative permeability.

$K_{r\,g}$: gas Relative permeability. K_o: effective permeability of oil.

K_w: effective permeability of water. K_g: effective permeability of gas.

When are K_e equal K_a? **Ans.)** When the rock is saturated 100% with the flowing fluid.

When are K_e less than K_a? **Ans.)** If saturation is less than 100%

For example, if the absolute permeability (k_a) of a rock is 200 md and the effective permeability k_o of the rock at an oil saturation of 80 percent is 60 md, the relative permeability k_{ro} is 0.30 at $S_o = 0.80$.

Since the effective permeabilities may range from zero to k, the relative permeabilities may have any value between zero and one, or:

$0 =< k_{r\,w}, k_{r\,o}, k_{r\,g} =< 1.0$

Note: permeability of the petroleum reservoir rocks may range from 0.1 to 1000 md.

The quality of permeability may be:

1- Poor if $k < 1$ md 2- Fair if $1 < k < 10$ md

3- Moderate if $10 < k < 50$ md 4- Good if $50 < k < 250$ md

5- Very good if $k > 250$ md