Experimental Investigating of Compaction Effect on Porosity Measurement for Carbonate Rocks

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Abstract

Oil and natural gas may be found in commercial reservoirs, porous and easily permeable rocks. Porosity is an essential characteristic of reservoirs. This research focuses on comparing laboratory-measured porosity to log porosity. A comparison of the porosity values determined in the lab using the liquid saturation technique, density method, an ultrasonic method, and the porosity computed from wireline logs such as sonic, density, and neutron logs. Compaction is the decrease in volume caused by an external force. A discrepancy exists between the laboratory and log porosities because of the rock compaction. It is important to note that porosity may be broken down into two categories: total and effective. After calculating the bulk and grain volumes, the total porosity is determined by averaging the results of several techniques, such as gas density logs, density logs, and neutron logs. The porosity is estimated using ultrasonic equipment in the lab and compared to sonic logs. Sonic tests show a higher porosity in the lab than in the log due to the formation's rocks being compacted. An excellent correlation exists between density log porosity and density porosity from the lab, with a determination coefficient of 0.79.

Keywords: Total porosity; Effective porosity; Liquid saturation method; Density porosity; Sonic porosity

1. Introduction

There are often discrepancies between laboratory-derived porosity estimates and those obtained from wireline logs. Direct measurements of physical characteristics on tiny reservoir samples using the approach of indirect measurements, which provide average physical values, account for some of these differences. According to Fig 1 (Chatzis et al., 1983), several of these distinctions may be seen. Changes in porosity, water saturation, and fluid volume are all related to petrophysical heterogeneity in the Mishrif Formation units. According to reservoir characteristics, the Mishrif Formation was subdivided into five units using CPI and separated by barrier beds (seal rock) (porosity and saturation). High porosity and low water saturation with variable quality reservoir units are separated by tight muddy limestone layers with high water saturation and poor porosity. (Abbas and Mahdi, 2020)

The porosity of a rock, as a measure of the empty space available for the storage of hydrocarbons, is critical in reservoir engineering.

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In geological time, the developed void spaces got segregated from the other void spaces by excessive cementation; hence, many of the void spaces are linked while the others are not.

Absolute and effective porosity are the two types of porosity.

The absolute porosity ($\phi_a$) calculated using this ratio: the entire pore space in a rock divided by its bulk volume.

The rock may have a high absolute porosity, but it lacks fluid conductivity due to the absence of pore connections. The absolute porosity ($\phi_a$) may be expressed quantitatively using the following equation:

$$\phi_a = \frac{\text{pore volume}}{\text{bulk volume}} \quad \ldots \ldots (1)$$

$$\phi_a = \frac{V_B - V_G}{V_B} \quad \ldots \ldots (2)$$

The concept of effective porosity is defined as the percentage of interconnected pore space with respect to the bulk volume, or

$$\phi_e = \frac{V_P_{\text{interconnected}}}{V_B} \quad \ldots \ldots (3)$$

Where $\phi_e$=effective porosity

In the reservoir engineering calculations, the effective porosity ($\phi_e$) can be used because it represents the interconnected pore space that contains the recoverable hydrocarbon fluids. Mainly connected pores control the transportation of fluids. For intergranular materials, poorly to moderately well cemented, the total porosity is approximately equal to effective porosity. For more cemented materials and some carbonates, a significant difference in total porosity and effective porosity values may occur. As the pore space is filled with cementing material during the cementation process in consolidated rocks, a considerable drop in porosity may occur.

Porosity will change with depth because compaction pressures vary with depth, notably in clays and shales. According to Krumbein and Sloss (1951), as depth increases from 0 to 2000 meters, sandstone porosity decreases from 52 to 41% and shale porosity decreases from 60 to 6%. The inelastic, so irreversible, effects of intergranular migration account for the majority of pore shrinkage. Reservoir rocks can have a lot of porosity variation vertically, but not so much porosity variation parallel to the bedding planes.
2. Pore Types

Data from the core description, petrography for thin section, SEM, and tests for capillary pressure may be used to identify the pore types of sandstone and carbonate. These analysis reveal that the pore types of clastic and carbonate pore types vary significantly.

2.1. Sandstone Pore Systems

In the sandstone, there are four forms of porosity: intergranular (primary), microporosity (secondary), and fracture (Fig. 2). Phosphorus is found between detrital grains in intergranular spaces. In the microporosity, pores smaller than 2 μm were included. Dissolution porosity is the pore space created when framework grains and/or cement are partially or completely dissolved. In the void space around natural cracks, fracture porosity occurred (Pittman, 1979).

Fig. 2. Types of porosity in sandstone rocks

2.2. Pore Types in Carbonate Rocks

Carbonate rocks have a wide range of pore types. As illustrated in Fig.3, pore systems may be divided into three categories based on whether they are fabric-specific, non-fabric-specific, or both. Interparticle, intranasal, intercrystal, melodic and fenestral porosity are all forms of carbonate rock porosity (Choquette and Pray, 1970).

Fig. 3. Idealized carbonate porosity system
3. Location of the Study Area

West Qurna is a supergiant oil field in the southeast of Iraq; it is around 70 kilometres north-west of Basra. The field is considered one of the giant’s reservoir of world oil field as indicated it’s coordinated in Fig.4.

![Location map of West Qurna-1 Oilfield Southern of Iraq](image)

Fig. 4. Location map of West Qurna-1 Oilfield Southern of Iraq(Naser and Farman, 2021)

4. Geology of the Study Area

A heterogeneous carbonate reservoir has formed in the West Qurna-1 oil field, known as Mishrif. An important reservoir not just in the West Qurna-1 area but also across southern Iraq is the Mishrif formation. Above and below, as seen in Fig.5, the Khasib Formation and Rumaila Formation separate this formation(Abdullah and Al-Shahwan, 2021). The anticlinal fold with moderate dips is what makes up the Mishrif formation. At well (WQ-110), the Mishrif formation is located at a depth of (2207 m) and a width of about 16.5 kilometres from the centre of the region with thickness 202 m. West Qurna oil field include the Mishrif Formation units Caprock I, Upper Mishrif and Cap Rock II, and Lower Mishrif (Abdulzahra and AL-Jawad, 2011).
Fig. 5. Stratigraphic column for the southern region of Iraq (Al-Khadhimi et al., 1996)

5. Materials and Methods

5.1. Sample Preparation

To find porosity in the lab the hydrocarbon content in the plugs must be removed. The type of hydrocarbon present in the plug affects the cleaning of plugs. The factors that affect the washing plugs include the mineralogy of the rocks, the presence of salts in the plugs and the type of hydrocarbon. Different solvents are used to remove salt content and hydrocarbons. The most effective solvent to remove liquid hydrocarbons is toluene. If the hydrocarbons are not removed with toluene other solvents such as methanol, methylene chloride may be used. Salts can be removed by using methanol. To wash the rocks that contain smectite, the temperature of the soxhlet device set is low to overcome the removal
of structural and bound water (Keelan, 1972). To find the porosity in the laboratory the plugs must be dry. The temperature of the oven is set to 100° C to dry the freest clay in the plugs

5.2. Porosity by Gas

The principle of this method is by using Helium Porosimeter as shown in Fig. 6. The basic principle of "Helium Porosimeter" is Boyle's law \((P_1V_1 = P_2V_2)\). After the plugs has been dried, the air inside the porous media is evacuated by using vacuum machine. From grain volume \((V_g)\) data if an accurate bulk volume \((V_b)\) measurement of the core sample is available (by using Vernier caliper), the pore volume can be calculated by subtracting the \(V_g\) from \(V_b\), The porosity can be determined from the equations (1,2 and 3).

Where: \(P_1\) and \(P_2\) initial and final pressure in the cell
\(V_1\) and \(V_2\) initial and final volume of the gas in the cell

\[
P_fV_f = P_x(V_f + V_s - V_g)
\]

**Fig.6. Helium Porosimeter**

| Plug no | 1   | 2   | 3   | 4   | 5   | 6   | 7   | 8   | 9   |
|---------|-----|-----|-----|-----|-----|-----|-----|-----|-----|
| Phi Gas | 0.218| 0.236| 0.21| 0.306| 0.292| 0.258| 0.297| 0.236| 0.249 |

5.3. Porosity Determination by Liquid Saturating Method

The purpose of this method is to find the effective porosity by liquid saturation for the porous media. The following procedure for this method:

- Clean the plugs with a soxhlet device by using toluene.
- Dry the plugs in the oven at 100 °C for 4 to 6 hours and weigh it \((W_{dry})\).
- Saturate the plugs with brine in the vacuum container and run for 4 hours where the plugs remain undersaturation for more than one week and calculate the saturated weight \((W_{sat})\).
- Find the pore volume \((V_p)\) from the difference between saturated and dried weights divided by the density of the saturated brine as shown in equation 6:

\[
V_p = \frac{(W_s - W_d)}{\rho_{sat}}
\]  

\[(6)\]

where
\(W_s\) = weight of the saturated plug
Wd = weight of the dry plug  
ρs = density of brine saturated the plug  

find the porosity by dividing the pore volume and bulk volume.

\[ \phi_{sat} = \frac{V_p}{V_b} \]  

(7)

The calculation results are as in table 2. The advantages of this method it can be considered accurate, the plugs can be used in another testing and the time of saturation is dependent on the permeability.

5.3.1. Bulk volume measurement

The plugs shape as cylinders so that the bulk volume can be calculated from the formula

\[ V_B = \pi * r^2 * L \]  

(8)

VB=bulk volume  
r =plug radius  
L=length of the plug  
The bulk volume calculations as in the following table 2.

| Plug no | Depth (m) | Length (cm) | VB (cc) | Wd (gram) | Ws (gram) | VP (cc) | phi saturation |
|---------|-----------|-------------|---------|-----------|-----------|--------|----------------|
| 1       | 2354.49   | 7.2         | 79.554  | 177.26    | 189.83    | 11.031 | 0.1374         |
| 2       | 2364.36   | 7           | 77.344  | 159.05    | 170.43    | 9.9868 | 0.1291         |
| 3       | 2384.43   | 7.35        | 81.211  | 177.59    | 190.93    | 11.707 | 0.1478         |
| 4       | 2390.11   | 7.5         | 80.658  | 169.28    | 188.81    | 17.139 | 0.2124         |
| 5       | 2394.1    | 7.3         | 80.658  | 161.44    | 175.47    | 12.312 | 0.2319         |
| 6       | 2442.58   | 7.25        | 80.658  | 166.07    | 181.3     | 13.366 | 0.2063         |
| 7       | 2446.71   | 7.3         | 80.658  | 158.5     | 176.14    | 15.48  | 0.2241         |
| 8       | 2453.98   | 7.6         | 83.973  | 178.79    | 192.96    | 12.435 | 0.1672         |
| 9       | 2462.27   | 7           | 77.344  | 169.84    | 184.18    | 12.584 | 0.1726         |

5.4. Porosity by Density Measurement

A density log is a porosity log that measures the electron density of a formation. The formation bulk density (ρb) is a function of matrix density, porosity, and density of the fluid in the pores (Asquith and Gibson, 1982).

\[ \phi_D = \frac{\rho_{ma} - \rho_b}{\rho_{ma} - \rho_f} \]  

(9)

Presence of hydrocarbon affecting density log as shown in the following equation;

\[ \rho_{b_{cor, hyd.}} = \rho_b + \left( \phi * S_{hr} * \left( \rho_{mf} - \rho_h \right) \right) \]  

(10)

The presence of shale can be corrected by the following equation;

\[ \rho_{b_{corr}} = \rho_b + V_{sh} * \left( \rho_{matrix} - \rho_{clean} \right) \]  

(11)

The calculated values of porosity from density in lab and log are shown in table 3.
Table 3. Density porosity from lab and log

| Plug no | Depth (Ma) | RHOB dry | RHOB wet | RHOB LOG | phi density log | phi density lab |
|---------|------------|----------|----------|----------|----------------|----------------|
| 1       | 2354.49    | 2.228    | 2.3862   | 2.414    | 0.18848        | 0.20333        |
| 2       | 2364.36    | 2.056    | 2.2035   | 2.3398   | 0.23572        | 0.28142        |
| 3       | 2384.43    | 2.187    | 2.351    | 2.42     | 0.18465        | 0.20711        |
| 4       | 2390.11    | 2.099    | 2.3409   | 2.41     | 0.19102        | 0.2599         |
| 5       | 2394.1     | 2.002    | 2.1755   | 2.31     | 0.2547         | 0.30357        |
| 6       | 2442.58    | 2.059    | 2.2477   | 2.34     | 0.23559        | 0.26138        |
| 7       | 2446.71    | 1.965    | 2.1838   | 2.2867   | 0.26953        | 0.3084         |
| 8       | 2453.98    | 2.129    | 2.2979   | 2.342    | 0.23432        | 0.2449         |
| 9       | 2462.27    | 2.196    | 2.3813   | 2.42     | 0.18465        | 0.20523        |

5.5. Neutron Porosity

The neutron log is a porosity log that largely reacts to the formation's hydrogen content (Pirson, 1963). When water or oil fills the pores in a clean formation, the neutron log shows the level of porosity. Neutron porosity decreases when pores are filled with gas. This is due to a decrease in hydrogen content in the gas. Table 4 shows the neutron porosity of the plugs.

Table 4. Neutron porosity for the plugs

| Plug no | NHPI | 1   | 2   | 3   | 4   | 5   | 6   | 7   | 8   | 9   |
|---------|------|-----|-----|-----|-----|-----|-----|-----|-----|-----|
|         |      | 0.195 | 0.229 | 0.129 | 0.175 | 0.233 | 0.238 | 0.273 | 0.247 | 0.222 |

5.6. Sonic Porosity

The interval transit time $\Delta t$ of a compressional sound wave travelling through one foot of a formation is measured using a sonic log (Asquith and Gibson, 1982). Because the sonic log only captures matrix porosity, rather than vuggy or fracture porosity, readings for sonic porosities of carbonates having vuggy or fracture porosity will be excessively low. The formula for calculating porosity from sonic log

$$\Phi_{sonic} = \frac{\Delta t_{log}-\Delta t_{ma}}{\Delta t_{f}-\Delta t_{ma}}$$

(12)

Where $\Delta t_{f}=189$ usec/ft
$\Delta t_{ma}=47.5$ usec/ft

The porosity calculated from the ultrasonic device in the lab and log is shown in table 5 where $vp_{lab}$ and $vp_{log}$ is compressional wave velocity that is measured in usec/ft.

Table 5. Porosity from sonic in lab and log

| Plug no | Vp lab (usec/ft) | Vp log (usec/ft) | phi sonic lab | phi sonic log |
|---------|------------------|------------------|----------------|---------------|
| 1       | 90.833           | 73.328           | 0.306          | 0.185         |
| 2       | 94.948           | 81.02            | 0.335          | 0.239         |
| 4       | 85.48            | 70.801           | 0.268          | 0.167         |
| 5       | 108.59           | 85.205           | 0.432          | 0.269         |
| 6       | 99.243           | 82               | 0.366          | 0.246         |
| 7       | 100.37           | 83.6             | 0.374          | 0.257         |
| 8       | 104.99           | 84.571           | 0.406          | 0.264         |
| 9       | 89.468           | 75.8             | 0.297          | 0.202         |
5.7. Absolute Porosity

The absolute porosity is calculated by taking small samples that remain from the samples after cutting them. Find the weighted samples and use equation (13) to get the grain volume, bulk volume, matrix density, and absolute porosity; the porosity values calculated using this method are displayed in table 6.

\[
\varphi = \frac{V_B - V_G}{V_B} \quad (13)
\]

\[
\rho_{matrix} = \frac{\text{weight}}{V_B} \quad (14)
\]

| Plug no | Absolute porosity | Matrix density |
|---------|-------------------|---------------|
| 1       | 0.31              | 2.68          |
| 2       | 0.18              | 2.674         |
| 3       | 0.219             | 2.68          |
| 4       | 0.36              | 2.674         |
| 5       | 0.325             | 2.7           |
| 6       | 0.273             | 2.68          |
| 7       | 0.36              | 2.705         |
| 8       | 0.304             | 2.682         |
| 9       | 0.27              | 2.69          |

5.8. The Relationship between Porosity Values

5.8.1. The Relationship between porosity by gas and liquid saturation

Porosity by gas is plotted with porosity by liquid saturation where the porosity by gas represent total porosity and the porosity by liquid saturation represent effective porosity where the determination coefficient $R^2$ is equal to 0.8339 as in Fig.7 with the following relationship:

\[
\Phi_{\text{gas}} = 0.9922 \times \Phi_{\text{saturation}} + 0.0671 \quad (15)
\]

![Fig. 7. The relationship between $\Phi_{\text{sat}}$ saturation and $\Phi_{\text{gas}}$](image)

Gas porosity is greater than porosity by liquid saturation because gas porosity represents total porosity and the porosity by liquid saturation represents effective porosity.

5.8.2. The Relationship between porosity by density from lab and log

Density porosity in the lab is calculated by weighting the saturated plugs, divided by bulk volume of the plug. The density porosity calculated using equation (9) where the matrix density 2.71 gm/cc.
RHOB (ρb) for log is used from well logs in the same depths for the plugs. Density porosity for lab and log is plotted as in Fig.8 where density porosity for the lab is greater than density porosity for log because of the compaction. The determination coefficient $R^2$ between $\Phi_{\text{density log}}$ and lab is equal to 0.79 and the relation between them is as follows;

$$\Phi_{\text{density log}}=0.7153\Phi_{\text{density lab}}+0.039$$  \hspace{1cm} (16)

![Fig. 8. The relationship between $\phi$ density lab and $\phi$ density log](image)

After finding the porosity by neutron, density and sonic, the secondary porosity can be found by the difference between them.

5.8.3. The relation between porosity by sonic from lab and log

Compressional wave velocity ($V_p$) was measured in the lab by using an ultrasonic device and sonic porosity was calculated and compared with sonic porosity from the log as shown in Fig.9 with equation (12) and the relationship between them is as follows;

$$\Phi_{\text{sonic log}}=0.647\Phi_{\text{sonic lab}}+0.0035$$  \hspace{1cm} (17)

![Fig. 9. The relationship between $\phi$ sonic log and lab](image)

5.8.4. The Relationship between porosity by Neutron and density from lab and log

The porosity from neutron is plotted with density porosity from log and lab as shown in Fig.10 where lab density porosity greater than density porosity from the log and some values approach with neutron porosity for the plugs 8 and 9.
The relationship between $\phi_n$ and $\phi_d$ from lab and log

5.8.5. The relationship between absolute porosity and liquid saturation method

The absolute porosity is calculated from grinded small samples and calculate the grain and bulk volumes.

The absolute porosity, which represent total porosity is plotted against liquid saturation porosity as shown in Fig.11 where the determination coefficient $R^2$ equal to 0.53 with the following relationship:

$$\Phi_{\text{absolute}} = 1.1413\phi_{\text{saturation}} + 0.0825$$ (18)

Fig.11. The relation between $\phi$ absolute and $\phi$ by liquid saturation method

6. Results and Discussion

To understand the effect of compaction on porosity values for Mishrif formation in West-Qurna-1 different methods were used to calculate the porosity. Porosity by gas gives the total porosity plotted with porosity by liquid saturated where the values of porosity by gas are found greater than the porosity by saturation with a good determination coefficient ($R^2$) equal to 0.8339. Density porosity from lab plotted with density porosity from the log where the values found from log less than from lab because of the rock density in the formation is affected by the rock compaction and the determination coefficient equal to 0.79. The neutron tool measures $\phi$ only under rare circumstances. The neutron tool is usually run in conjunction with the density tool where the neutron porosity is used to moderate the density porosity. The sonic porosity was calculated from the lab is larger than the sonic porosity from the log because it affected by the shale and the rock compaction. The absolute porosity calculated by grinded small samples from the same plugs when plotted with liquid saturation porosity he relationship between
them is weak with $R^2 = 0.53$. The values of porosities calculated from the laboratory which include sonic lab, density lab, liquid saturation method and absolute porosity with porosity values calculated from logs which include sonic, density and neutron are plotted as shown in Fig.12. From Fig.12, we notice that the porosity calculated by the liquid saturation method is less than from all the other values, which represent the effective porosity that can be used in the initial oil in place calculation. From Fig.12, we notice that porosity calculated by sonic in lab more than absolute porosity that calculated by grinding the samples because of sonic porosity needed to be corrected to the shale.

![Fig. 12. Porosity values for all plugs](image-url)

**7. Conclusions**

- The porosity calculated by gas is more than the value from the liquid saturation method because it is affected by the Klinkenberg effect.
- The porosity calculated by density and neutron gives the total porosity.
- The porosity calculated by the liquid saturation method gives the effective porosity and the porosity calculated by neutron and density gives the total porosity.
- The matrix density calculated by the grain of the small samples from the same plug gives a value approach to 2.7, which is limestone matrix density.
- The sonic porosity is less than the density porosity because it gives the primary porosity.
- Calculating the secondary porosity came from the difference between the density and neutron porosity and sonic porosity.

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