Interpretation of Petrophysical Properties in Reservoir Rock Using Capillary Pressure Data of the Mishrif Formation in West Qurna Oilfield, Southern Iraq

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Abstract
In this study, capillary pressure tests for twenty-nine samples acquired from four wells, (Rn-83, WQ-155, WQ286, and WQ-355) were used to estimate pore size distribution, pore-throat sorting, displacement pressure, reservoir grade, oil column, effective porosity, and relative permeability of the Mishrif Formation at West Qurna Oilfield, southern Iraq. Interpretation of capillary pressure data revealed that the formation can be divided into four reservoir facies with different reservoir production performances: very good, good, medium, and poor. The facies with very good performance is characterized by large pore sizes, excellent reservoir grade, low displacement pressure, and high oil saturations. The good facies is characterized by the presence of good pore throat sorting, good reservoir grade, and good porosity. Contrary, Medium-performance reservoir facies are characterized by the presence of medium pore sizes, medium pore throat sorting, and medium reservoir grade. Poorly performing reservoir facies is characterized by small pore size, high displacement pressure, poor throat sorting, and high water saturation levels. Based on the relative permeability calculations some samples are wet with water (water-wet), while others are wet with oil (oil-wet).

Keywords: Capillary pressure; Relative permeability of water; Relative permeability of oil; Reservoir; Permeability

1. Introduction
The capillary pressure is an important parameter in the study of petroleum reservoirs because it can affect the movement of fluids within the reservoir and the recovery of oil and gas. It is defined as the pressure required to move a fluid through a porous material, such as a rock or soil. In the context of petroleum reservoirs, capillary pressure refers to the pressure required to move oil or water through the pores of a reservoir rock (Jenning, 1987). Several techniques can be used to measure capillary pressure in a petroleum reservoir, including the following centrifuge, mercury injection, gas injection, and capillary pressure curves. The mercury injection method is the most commonly used in the petroleum industry and involves injecting mercury into a sample of reservoir rock and measuring the pressure required to push the mercury through the pores of the rock. The obtained data from this method can be
used to study the porous system that controls many petrophysical properties of the rock such as permeability and porosity.

In this study, the capillary pressure test data for 29 core plugs of Mishrif Formation in the West Quran oil field, southern Iraq were mainly used to study the petrophysical properties of this very important oil-producing reservoir. Mishrif Formation (Cenomanian-Early Turonian) represents a super-giant reservoir (Alsharhan, 1995; Aqrawi et al., 1998). The formation makes up about 30% of Iraq’s confirmed reserves and 40% of the Cretaceous oil reserve (Aqrawi et al., 1998).

2. The Study Area

West Quran oil field is located in Basra City, southern Iraq between the latitudes (715–735) East and (3410–3455) North (Fig. 1).

Fig. 1. Location of the study area.
The distance from this oil field to Qurant city, northern Basra is about 14 km and from the center of Basra is about 70 km. The Euphrates River is passing through the study area and divides the oil field into two parts: north and south West Quran oil fields. The most producing oil formation in both oil fields is Mishrif Formation which dates back to the Cretaceous period. About 30% of Iraq’s overall oil reserves and up to 40% of the country’s Cretaceous oil deposits are found in the Mishrif Formation (Mohammed et al., 2020). Due to its economically significant hydrocarbon accumulations, many studies have been done on the Mishrif Formation in southern Iraq (Chafeet et al., 2020; Handhal et al., 2020; Ali et al., 2022, and Ismail et al., 2022).

3. Geological Settings

The oilfield West Qurna is situated in the Mesopotamia foredeep basin on the Arabian Plate's outer platform (Fouad, 2010). This basin was formed by the Mesozoic and Cenozoic orogenic, and it was opened by the Neo-Tethys Ocean. During the Cretaceous period, two events occurred that resulted in a thick association of carbonate deposits: the opening of Southern Neo-Tethys and the closing of Southern Neo-Tethys. The opening occurred during the Tithonian time of the shallow ocean along the Arabian plate's northern and eastern margins and this opening gave rise to distinct microplates or portions of the late continental parts of the Tithonian (Jasim and Goff, 2006), which was dispersed as a result of the formation of the NE dipping into the subduction of the ocean with the southern part of the Neo-Tethys ocean (Aqrawi, 2010). As for the closure, it happened to the microcontinents that separated from the Arabian Plate during the time of the Tithonian, as they approached the trench of the subduction zone within the oceans, which formed the beginning of the development of the structure of the N-S direction in southern Iraq, Saudi Arabia, and Kuwait. The reason for the closure is a result of the trench's fore arch area and these microplates-induced diachronous collisions (Aqrawi, 2010). The oilfield is a portion of a long-axis anticlinal structure. The north part of the structure is characterized by an asymmetrical, elongated anticline. The anticline's trend is north to south; however, The trend changes from northwest to southeast around line 3440. The eastern flank dips by around (1.6°), while the western flank dips by about (2°–3.5°), making the flanks asymmetrical. As compared to the eastern flank, the western flank is steeper. The field West Qurna is fault-free and measures 40 km in length and 17 km in width. The Mishrif Formation was deposited within the Early Cenomanian-Early Turonian cycle, which represents the second sedimentary cycle of the previously named Middle Cretaceous sequence deposited in the Mesopotamian basin in southern and central Iraq. Buday (1980) divided this sequence into two sedimentary cycles. The (Cenomanian-Early Turon) cycle begins with the deposition of the Ahmadi Shale formation during the period of marine progression from the cycle, to be topped by the deposition of the Rumaila Formation consisting of chalk/clay-limestone, which in turn progresses upward to the Mishrif formation during a period of marine retrogression, the (Late Cenomanian-Early Turonian) and graded upward formation of the Khasib Formation containing shales, which is above the Mishrif Formation (Aqrawi et al., 2010). Fig.2 represents a description of the West Qurna Oilfield's stratigraphic column. Where the Mishrif Formation takes its stratigraphic position between the two formations of the Khasib from is top the Rumaila formations at the bottom, where the lower boundary between the two formations is gradual, which leads to difficulty sometimes distinguishing between the two formations. As for the upper boundary between the two formations of Mishrif and Khasib, it is an unconformity (Fig. 2).
Fig. 2. Stratigraphic Column of the West Qurna Oilfield (Aqrawi, 2010).

4. Materials and Methods

Capillary pressure parameters: In a petroleum reservoir, capillary forces are a result of a combination of factors including the wetting characteristics of the system, the pore size and geometry, and the surface and interfacial tensions of the rock and fluids. When the capillary pressure principles are completely accepted and comprehended, techniques for finding and producing oil will be improved by
new insights into reservoir properties. Capillary pressure data is important for extracting a number of parameters for evaluating the performance of the reservoir rocks and determining their ability to produce. Some of these include reservoir grade, oil columns for oil saturations of 50% and 75% oil saturation, and pore-throat sorting (Jennings, 1987).

4.1. Displacement Pressure \((pd)\)

The pressure at which the injected fluid begins to occupy the reservoir is called displacement pressure. The displacement pressure reflects the volumetric average of the dominant porosity throat. The rocks with high-pressure values refer to a fine pore size that requires high pressures to reach the highest injection rate, while rocks that have low values of displacement pressure reflect coarse porosity (Jennings, 1987).

4.2. Pore-Throat Sorting \((PTS)\)

The \((PTS)\) gives the pore geometry measurements and the pore throat's homogeneity for any rock’s porosity ratio (Jennings, 1987). Values for PTS can be easily obtained by using the following equation developed by Trask (1932).

\[
P.T.S = \sqrt{\frac{3d \text{ Quartile pressure}}{1st \text{ Quartile pressure}}} \tag{1}
\]

4.3. Reservoir Grade \((RG)\)

RG may be estimated by showing the data linearly and measuring the area below the curve. RG is the percentage of the linear area integrated under the capillary pressure curve. (Jennings, 1987). It indicates the reservoir quality of rock and ranges from 0 (best quality) to 100 (lowest quality). Measure the degree of the reservoir through the following equation: (Jennings, 1987).

\[
R.G = \left( \frac{\text{area under curve}}{\text{total area}} \right) \times 100 \tag{2}
\]

4.4. Height of Oil Column

The oil column is the height at which the oil accumulates vertically and continuously while containing a free water level at its base, and the water extends with it up to the trap's top (stratigraphic or structural, or both). The oil column can be calculated at 50% and 75% saturation. The values are not arbitrary because 75% oil saturation or above is predicted to produce excellent to good wells, whereas 50% oil saturation or less would typically produce marginal to fair wells. The minimum structural or stratigraphic relief in the trap that is required to achieve a 50% or 75% oil saturation at the top of the trap may be calculated using oil column values (Jennings, 1987). The oil column can be calculated according to Chillinger et al. (1972) using the following equation:

\[
h(\text{ft}) = \frac{P_c}{\Delta \rho} \tag{3}
\]

Where: \(h\) = Oil column height \(h\) (ft), \(\Delta \rho\) = is the difference in density between oil and water \((\text{gm/cc})\), \(P_c\) = capillary pressure at reservoir conditions \((\text{psi})\).
4.5. Pore Throat Radius (R-35)

Winland (1972, 1976) developed the R35 concept to create an empirical relationship between the air-permeability $K_{air}$ (mD), apparent porosity ($\Phi$), and pore throat radius at 35% of the incursion volume (R35). If the radius of the pore throat (R-35) in the porous system is equal to or smaller than the diameter of the throat of the porous system, no flow can occur in them, and instead of that, the rock has a high ability to store (Pittman, 1992). Calculate (R-35) directly from the equation:

$$\log R_{35} = 0.732 + 0.588((\log k_{a}) - 0.864(\log \phi))$$

(4)

Where: $R_{35}$ = Diameter of pore throat at mercury saturation (35%), $K_a$ = air permeability (MD), $\phi$ = Porosity (%).

A specific rock type's R35 value represents its depositional and diagenetic fabric and influences reservoir performance and fluid flow. Coalson et al. (1985) connected the R35 value and the characterization of the pore systems by using the concept of the pore throat type, "Port types," which are quantitative characteristics that might indicate the quality of the reservoir, are used to describe pore systems in reservoir rocks (Martin et al., 1997):

a. Megaport: If R35 is greater than 10 $\mu$m, the rock is referred to as a "Megaport" and is able to produce tens of thousands of bbl/day, b. Macroport: A rock is classified as "Macroport" if R35 is between 2 and 10 $\mu$m and is able to produce hundreds of bbl/day, c. Mesoport: A rock is classified as "Mesoport" if R35 is between 0.1 and 2 $\mu$m and can produce hundreds of bbl/day, d. Microport: The classification of rock is Microport and is regarded to be a non-pay section if R35 is 0.1 $\mu$m, e. nanoport: less than 0.1 $\mu$m R35.

4.6. Effective Porosity ($\Phi_e$ %)

It expresses the pore space occupied by moving fluids, and it is also considered a function of saturation in the non-phase moist. Melas & Friedman (1992) calculate the effective porosity from the equation:

$$\phi_e = \phi \times \frac{S_{Hg}}{100}$$

(5)

Where: $\Phi_e$ = effective porosity, $\Phi$= total porosity, $SHg/100= Hg$ saturation.

4.7. Relative Permeability

Capillary pressure ($pc$), according to Rose and Bruce (1949), is a measurement of the fundamental properties of the formation and may be used to estimate the relative permeabilities.

4.7.1 Relative permeability of water ($K_{rw}$)

Amyx et al. (1960) used Purcell's (1949) used the following equation to calculate relative permeability:
where: $K_{rw}$ = relative permeability of water, $P_c$ = capillary pressure (psi), and $S_w$ = water saturation.

To put it simply, the relative permeability of water can be calculated by calculating the partial and total areas of the curve resulting from drawing $1/Pc^2$ against the mercury saturations for each sample from the equation below according to Jennings (1987) (Fig. 3).

$$K_{rw} = \frac{\int_{S_w} S_w dS}{P_c^2}$$

$$K_{rw} = \frac{1}{A_T}$$

Where: $A_p$: is the partial area of the curve against a given water saturation, and $A_T$: is the total area.

Fig. 3. The relationship between the values of $1/Pc^2$ and the hydrocarbon saturation to extract the area values for the well RN-83 (2255.52).

The pore-geometry factor, $\lambda$, is introduced into the equations used to estimate the relative permeability of oil. The following equation, which was devised, is used to determine the oil relative permeability curve by Standing (1974):

$$K_{ro} = \frac{(2+\lambda)\lambda}{\lambda}$$

$$K_{ro} = [1 - Sw^*] \left[ 1 - (Sw^*) \right]$$
Where: $Sw = \text{Water saturation};\ Swirr = \text{irreducible water saturation};\ Sw^* = \text{effective water saturation}, \text{and } \lambda = \text{pore geometry factor. Or Pore Size Distribution Index “}\lambda\text{”}$

Index of Pore Size Distribution ($\lambda$): The pore size distribution has a considerable impact on the capillary pressure and relative permeability curves, according to Brooks and Corey (1964). To describe the heterogeneity of the porous medium, one parameter that Brooks and Corey created is the pore size distribution index ($\lambda$). The value of the parameter ($\lambda$) indicates the homogeneity of the formation.

(a) There is greater uniformity the higher the value of ($\lambda$).
(b) A lower value shows a higher level of pore size distribution non-uniformity.

The value ($\lambda$) represents the negative inverted slope of a straight line resulting from plotting values ($Sw^*$) against values of (J-Function) extracted from the equation with logarithmic division axes – logarithmic (Fig. 4).

J-Function: The J- function used to calculate $\lambda$ was developed by Leverett (1941) as a method to correlate data on capillary pressure. It is calculated using the equation shown below:

$$J_{function} = \frac{PC}{(\sigma \cos \theta \sqrt{K/\phi})} = \frac{PC}{(368 \sqrt{K/\phi})}$$

Fig. 4. The relationship between J- function and Water saturation and water saturation to extract ($\lambda$) value for the well RN-83 (2255.52).
5. Results and Discussion

The obtained results from the pressure tests are shown in Table 1. The displacement pressure \( (P_d) \) values lie between 8 - 0.248 which reflects a coarse to medium pore system, Fig. 5. The pore-throat sorting is excellent at depths of 2276.68 in the RN-083 well and also at depths of 2278.22 and 2297.85 in the WQ1-268 well. The rest of the wells are either located within pore-medium throat sorting or weak pore-throat sorting. The reason for the difference in the grade of the sorting is the variation in particle size of the pore system. The lower the particle size, the lower the degree of porous sorting, as well as the compression and degree of cementation. More cementation means more hardening of the rock, and a lower degree of porous sorting (Sneider et al., 1977). The importance of pore throat sorting is mostly determined by the rock's ability to absorb oil. As a result, Jennings (1987) observed that "in well-sorted rocks, the oil would rapidly saturate the porosity up to the full capacity once a threshold buoyancy pressure is obtained. In order to obtain the same degree of oil saturation with poorly sorted rocks, pressure must be increased along a much broader variety. Figure 6.a shows the values of pore-throat sorting for the wells of the study area. It was noted that the pore-throat sorting values increased in wells RN-83 and WQ115, and decreased in wells WQ-268 and WQ-355. Low RG values indicate big pore throats, as well as the ability to accommodate oil saturation, is minimal buoyant pressures. For oil saturations to be economically sustainable, pore throat sizes must be lower and buoyancy pressure must be higher, the higher the RG number. A good reservoir evaluation may be obtained by using reservoir grade along with pore-throat sorting. Table 1 shows the values of the reservoir degree for the wells of the study area, where the reservoir degree was found in the range between (Excellent- very good), Figure 6.b shows the values of reservoir grade for the wells of the study area. It was noted that the reservoir grade values increase in wells WQ-355, RN-83, and WQ268, and decreased in wells WQ-115.
### Table 1. Reservoir classification and reservoir coefficients for West Qurna field wells

<table>
<thead>
<tr>
<th>Well</th>
<th>Depth (m)</th>
<th>pd (psi)</th>
<th>P.T.S</th>
<th>Sorting degree</th>
<th>R.G.</th>
<th>reservoir grade</th>
<th>H50 (ft)</th>
<th>H75 (ft)</th>
<th>35 R</th>
<th>pore type</th>
<th>Øe</th>
<th>reserves units</th>
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<td>RN-O83</td>
<td>2276.68</td>
<td>0.968</td>
<td>1.414</td>
<td>Excellent</td>
<td>18.75</td>
<td>good/very good</td>
<td>335.29</td>
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<td>Excellent</td>
<td>8.82</td>
<td>28.23</td>
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<td>Excellent</td>
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<td>0.964</td>
<td>1.87</td>
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<td>7.18</td>
<td>Excellent</td>
<td>42.35</td>
<td>74.11</td>
<td>1.02</td>
<td>Meso</td>
<td>0.23</td>
<td>MB2</td>
</tr>
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<td></td>
<td>2365.19</td>
<td>0.993</td>
<td>1.94</td>
<td>Moderate</td>
<td>12.68</td>
<td>good/very good</td>
<td>63.52</td>
<td>112.94</td>
<td>0.723</td>
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<td>0.152</td>
<td>MB2</td>
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<td>2392.37</td>
<td>0.922</td>
<td>1.62</td>
<td>Moderate</td>
<td>12.6</td>
<td>good/very good</td>
<td>68.82</td>
<td>102.35</td>
<td>0.361</td>
<td>Micro</td>
<td>0.123</td>
<td>MB2</td>
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The values of the thickness of the oil column at saturation of 50% and 75 are shown in Table 1. The increase in the height of the oil column reflects the smoothing of the porous system and the presence of reservoir rocks that are not very productive and require high pressures to reach a saturation state. The decrease in height reflects the roughening of the porous system and the presence of good productivity reservoir rocks. A specific rock type's R35 value represents its depositional and diagenetic fabric and influences reservoir performance and fluid flow. Table 1 shows the results R35 of the wells in the study area, which ranged between (micro-mega). Figure 8 shows the relation between the pore throat radius and the hydrocarbon saturation, it is noticed that the pores range from mesoport to microport. Fig. 7 shows the relationship of porosity to permeability with the R35 values of the well RN-83.
Fig. 7. The relationship of porosity to permeability with the R35 values of the well RN-83.

Fig. 8. The relationship of hydrocarbon saturation with the pore throat radius of a well (RN-83) (2244.53).
From the results of calculating the relative permeability, it was found that the samples are characterized by having a Kro greater than 0.75 and a Krw less than 0.4. The rock’s texture is of granular type, the initial porosity is high, and the oil flow rate is high. Whenever the Kro is low, less than 0.4, and the Krw is high, i.e., 0.6, the rock texture is compacted, meaning the surface area is high, and this rock gives more area for water to flow than oil, (Fig. 9). It also notes that if the intersection point is less than 50%, the wettability towards oil, the Swi is less than 15%, and the Krw end point is greater than 0.5, the rock is (oil-wet). But if the intersection point is more than 50% and Swi is greater than 20-25% and the Krw endpoint is less than 0.3, then the rock is wet with water (water wet) (Fig. 10).

**Fig.9.** The relationship of water saturation with relative permeability was calculated from capillary pressure data by the mercury injection method for well RN-83 (2241.80).
Fig. 10. The relationship of water saturation with relative permeability was calculated from capillary pressure data by the mercury injection method for well RN-83 (2303.71).

Depending on the capillary pressure tests, the rocks were classified as reservoirs in the study area:

- **A very good performance reservoir facies**: These rocks are characterized by the production of free oil, where the height of the oil column is low, the displacement pressure is low, and it has a reservoir grade of less than 15%, and it has coarse porosity, large porous throat, and high oil saturation. These facies was observed in well WQ1-268 in reservoir unit MB2.

- **Good-performing reservoir facies**: These facies is characterized by the production of free oil, the height of the oil column is low, there is low displacement pressure, a porous system with an average sorting range between (1.5-2) and a reservoir grade ranging between (10-20%) and it has coarse porosity and medium porosity throat. These facies was observed in well WQ1-268 in reservoir unit MB1 and the well RN-83 in reservoir unit MB2.

- **Medium-performance reservoir facie**: These facies are characterized by medium reservoir grade, fine granular size, medium sorting degree, and low displacement pressure. These facies was observed in well WQ1-355 in reservoir unit MB2 and well RN-83 in reservoir unit MA.

- **Poorly-performing reservoir facies**: It is characterized by a high displacement pressure, a very high reservoir grade of up to 98%, and a high water saturation of up to 98%, which means that it produces free water, a poor sorting degree, medium porous throat, and an effective porosity equal to 0.363. These facies was observed in well WQ1-115 in reservoir unit MB2.

- **It is noticed through the reservoir facies in the Mishrif formation that the facies with very good performance is located at the reservoir unit MB, then the facies progresses to the good performance below it, then medium-performance until it becomes poor-performing at the bottom of the second reservoir unit. In the upper Mishrif formation (MA), the facies transforms into good to medium-performance reservoir facies.**
4. Conclusions

Depending on the capillary pressure tests, the rocks were classified as reservoirs in the study area into 1-a reservoir unit with very good performance, characterized by a low displacement pressure and a reservoir grade of less than 15%, and with excellent sorting, 2-a well-performing reservoir unit characterized by medium to good porous sorting and porous throat, large to medium, low displacement pressure, and excellent to good reservoir grade. 3-Medium-performance reservoir units, which are characterized by medium porous sorting, medium reservoir grade, and low displacement pressure. Poorly performing reservoir units are characterized by poor reservoir grade, high displacement pressure, and poor sorting. Relative permeability tests showed that if the intersection point is less than 50%, the wettability towards oil, the Swi is less than 15%, and the Krw end point is greater than 0.5, the rock is oil-wet. But if the intersection point is more than 50% and Swi is greater than 20%-25% and the Krw endpoint is less than 0.3, then the rock is wet with water (water wet).

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