Hydraulic - Electrical Flow Units and Water Saturation Calculation: Dam Formation, South Western Qatar, Arabian Gulf

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Abstract. Hydraulic-electric flow units represent two different concepts with different measuring units. They are frequently used to confirm each other’s for distinguishing the different reservoir flow zones but sometimes give undesirable results. 60 limestone samples were collected from the upper part of the Dam Formation exposed in the Al-Nakhsh area, Southwestern Qatar Peninsula. These samples represent the Upper Dam sediments which are considered as an important aquifer for underground water in its subsurface occurrences in Qatar and nearby areas. Porosity, gas permeability and electrical resistivity were laboratory measured for the collected samples. Saturation exponent (n), cementation exponent(m) and pore throat radius (r35) were calculated for each sample. The vertical profile of gas permeability and pore throat radius (R35) is accomplished. Also, gas-permeability versus porosity is performed. Numerous useful and applicable relationships have been found. The obtained reservoir flow units which are distinguished according to hydraulic flow indicators (RQI and Øz) are only three units. However, the hydraulic-electric cross-plots (i.e. n-R35 and n-FZI) indicate three and four reservoir flow units respectively. In conclusion, the obtained number of reservoir flow units in the study area ranges from 3-4. It means that the hybrid hydraulic-electric combination sometimes shows flow units in concordance with the single type parameter, but occasionally give dissimilar results. An innovative nomograph is constructed according to an empirical equation related to the Dam Formation [1] to estimate the water saturation (S_W) in oolitic carbonate facies. The present nomograph is verified by carbonate facies, deltaic distributary channel and barrier bar sandstone. The obtained values of water saturation from the proposed model are acceptable in case of both resistivity ratio (Rt/Rw) and porosity (Ø) are available.

1. Introduction
The Miocene sediments in Qatar are characterized by several regression cycles followed by continental erosions. The Miocene Dam Formation consists of shallow marine and lacustrine deposits and reaches a thickness of 80 m. The Miocene oolitic facies belong to the Upper part of the Dam Formation. [2] studied the possible causes of the Archie’s saturation exponent (n) anomalies. The Dam Formation covers some part of the Southwest Qatar Peninsula [3]. It is exposed in some places (e.g. Al-Nakhsh formation, near Karana and Al Kharrarah area) and has subsurface occurrences in the nearby areas. It is underlined by Oligocene Dolomite and overlain by the Hofuf sandstones. The Hofuf Formation consists of fluvial sediments and is ~18 m thick. The deposits consist of coarse sand and sandstone with pebbles of various rocks, mostly derived from the Arabian shield and the Arabian shelf.
and transported by large river systems [4]. The Hofuf deposits are overlain by the Quaternary sediments consisting of sabkha deposits, sand dunes and calcareous sand. The Miocene (Dam Formation is subdivided into seven members [5]. Among them is the Al Nakhsh section. It is subdivided into three members as;

a. The Lower Al Nakhsh Member encompasses three fully-developed coarsening- or shallowing-upward sequences, named Al Nakhsh 1 through Al Nakhsh 3, each starting off with bioclastic calcareous rocks and ending up with stromatolites.

b. The Middle Al Nakhsh Member takes on an outward appearance which closely resembles that of the Upper Al Nakhsh Member. Fully developed cycles may be denominated as brining-upward cycles reflecting a shallowing-upward trend in a supratidal-dominated regime.

c. The Upper Al Nakhsh deposits are likely to have formed under the influence of a fluctuating water table rather than by pure pedogenic processes under aquatic conditions.

The studied samples are belonging to the Al -Nakhsh section. The prime objective of this paper is to study the hydraulic flow units presented in the Dam Formation sediments and to verify the nature of the link between them and the electric flow units. In addition, a novel chart is proposed to calculate water saturation from porosity and resistivity ratio (Rt/Rw).

2. Materials and Methods

A total of 60 carbonate core samples were tested for porosity, permeability and electrical resistivity properties. Selected samples were dried at low temperature for several days in an oven. Porosity was measured by both of mercury pump universal porosimeter (model 101-1A) for bulk volume determination (Vb) and Helium porosimeter (model 7542-005) for grain volume estimation. The gas permeability was measured using Core Lab-.Permeameter [6]. The electrical resistivity (Rc) was measured three times; when samples were fully saturated by brine with water resistivity (Rw = 4.82;0.451 and 0.071 ohm.m) using of Core Lab Inc A.C. bridge (Model 100A). The measuring technique was outlined by [7]. Electrical resistance (r) of the samples was measured along the axis of cylindrical plug. Then, resistivity (R) was calculated from the measured resistance (r) using the cross-sectional area of the core (A) and the length of the core (L). Formation factor was obtained as a ratio of rock resistivity (Ro) to brine resistivity (Rw) as:

\[ F = \frac{R_o}{R_w} \]  

(1)

34 core samples were selected for resistivity index (I_R)- water saturation (S_w) measurements at water resistivity (R_w = 0.45 ohm.m). The selected samples were not only varying in porosity (Ø ranged from 12.9% up to 45.5%) but also, they cover all textural characteristics that were outlined by [2]. The water saturation (S_w) of samples under investigation was step by step and gradually reduced using high speed centrifuge technique [8]. The resistivity of the rock sample partially saturated with water (R_t) is calculated at each step of re-watering and then the resistivity index (I_R) is calculated at each step by:

\[ I_R = \frac{R_t}{R_o} \]  

(2)

An innovative nomograph has been built according to an empirical equation [1] related to the Dam Formation to estimate the water saturation (S_w) in oolitic carbonate facies. The used empirical equation is:

\[ \frac{R_t}{R_w} = \left( \frac{3.6}{\Omega^{1.77}} \right) \times \left( 1.19/ S_w^{2.57} \right) \]  

(3)

Ooids forming this lithofacies were spherical to ellipsoidal with a mean diameter of 1.5-2.0 mm. In general, oolitic grainstones had 12-45% porosity and from 4.0 to > 10,000–mD permeability. The samples of smooth ooid surfaces exhibit higher permeability than those with rough grained surfaces.
Grains were often coated by an isopachous calcite cement up to 0.20 mm in thickness and sometimes exhibits pore linings and/or pore fillings [2]. Uniform and well-sorted to moderately sorted grain size is a typical characteristic of these facies.

3. Results and Discussions

The measured laboratory data such as porosity, permeability and resistivity parameters are used to establish and recognize hydraulic, electric and hybrid flow units using different cross plots.

3.1. Hydraulic Flow Units (Theoretical Background):

Several authors have various definitions of flow units, which are resultant of the depositional environment and diagenetic process. [9] defined the hydraulic (pore geometrical) unit as the representative elementary volume of the total reservoir rock within which the geological and petrophysical properties of the rock volume are the same. Flow unit is a powerful concept that helps to define optimum layering in a reservoir simulation study [10]. Winland (published by [11]) developed the following empirical equation that has proved most valuable as a cutoff criterion to delineate commercial hydrocarbon reservoirs in stratigraphic traps:

\[ R_{35} = 5.395 \left( \frac{K}{\phi} \right)^{0.588} / \phi^{0.864} \]  

(4)

where \( R_{35} \) is the calculated pore throat radius (μm) at 35% mercury saturation from a mercury-injection capillary pressure test. [12] developed the following equation for calculating pore-throat radius at 35% mercury saturation:

\[ R_{35} = 2.665 \left( \frac{K}{\phi} \right)^{0.45} \]  

(5)

where permeability is in mD and porosity is a percentage.

Amaefule et al. [13] introduced the concept of reservoir quality index (RQI) as:

\[ \text{RQI} = 0.0314 \sqrt{K/\phi} \]  

(6)

where RQI is expressed in micrometers or μm.

The flow zone indicator (FZI) is a unique parameter that includes the geological attributes of the texture and mineralogy in the structure of distinct pore geometrical facies. It is related to RQI as:

\[ \log(\text{RQI}) = \log(\phi) + \log(\text{FZI}) \]  

(7)

where \( \phi \) is the ratio of pore volume to grain volume:

\[ \phi_z = \phi / (1 - \phi) \]  

(8)

Tiab flow unit characterization factor HT clearly combines all the petrophysical and geological Properties and it is related to FZI as:

\[ \text{HT} = \left( \frac{1.0}{\text{FZI}^2} \right) \]  

(9)

The hydraulic tortuosity can be estimated from:

\[ T = \phi^{1-m} \]  

(10)

where \( m \) is the Archie’s cementation exponent.
Rock and fluid volumetric properties, such as porosity, saturation, and mineral volumes, are generally estimated from petrophysical measurements such as density, resistivity, neutron porosity and gamma ray, through petrophysical equations [15], [16].

3.2. Permeability- Porosity Relation
Permeability-porosity relation (figure 1) shows slightly scattered data points with good coefficient of correlation ($R^2 = 0.608$). At porosity equals 20% you can find permeability ranged from 0.01μm$^2$ to approximately 1.0μm$^2$. It means that there are more than one lithologic population in the studied Al Nakhsh section. The calculated permeability–porosity regression equation is:

$$K = 1E^{-0.70}Ω^{4.931}$$

where $K =$ permeability, μm$^2$, $Ω =$ Porosity, %

(11)

Permeability decreases when porosity reach more than 40%. This explain that pores and/or vugs are not completely connected and pointing to dead ending cavities are present.

3.3. Vertical Profile of Permeability and R35
Both permeability and R35 are drawn vertically (figure 2). They show a great harmony along the whole Al Nakhsh section. They increase in the following intervals above sea level is (8-12m, 18-20m, 22-24m, 27-34m and >35m). It means that there are more than one lithologic population of different physical properties.

**Figure 1.** Permeability–Porosity Relation

**Figure 2.** Vertical Profile of Both Permeability and R35
3.4. Reservoir Quality Index – Void Ratio Relation

The reservoir quality index (RQI) – void ratio (Øz) relation (figure 3) indicates that Al Nakhsh section represents three hydraulic units. Each of which is characterized by a reliable coefficient of correlation. They range from $R^2 = 0.88.4$ up to 0.98. The void ratio of each hydraulic unit can be outlined using the calculated equations:

\[
\begin{align*}
\text{RQI} & = 35.16 \; \text{Øz}^{1.92} \quad R^2 = 0.88 \quad (12) \\
\text{RQI} & = 21.60 \; \text{Øz}^{2.4} \quad R^2 = 0.93 \quad (13) \\
\text{RQI} & = 4.97 \; \text{Øz}^{2.9} \quad R^2 = 0.98 \quad (14)
\end{align*}
\]

The calculated fluid zone indicator (FZI) for each hydraulic unit is ranged from 5 $\mu$ for the lower one, and 23$\mu$ for the middle up to 35$\mu$ for the upper unit. Therefore, the best hydraulic reservoir unit is the upper one represented by equation (12).

![Figure 3. Reservoir Quality Index Versus Pore Ratio](image)

3.5. Pore Throat Radius (R35) – Saturation Exponent Relation(n)

Although the relation between (R35) and (n) is a hybrid hydraulic-electrical combination, it displays three reservoir units (Figure 4) confirming the hydraulic RQI-Øz relation clearly shown in figure-3. The calculated coefficients of correlation for the regression equations of the obtained three units are ranged from 0.76 to 0.98. They are controlled by:

\[
\begin{align*}
n & = 2.24 \; e^{0.0118 \; \text{R35}} \quad R^2 = 0.76 \quad (15) \\
n & = 1.77 \; e^{0.0111 \; \text{R35}} \quad R^2 = 0.87 \quad (16) \\
n & = 3 \; E-05 \; \text{R35}^2 + 0.0366 \; \text{R35} + 0.3412 \quad R^2 = 0.976 \quad (17)
\end{align*}
\]

By using the above equations, the saturation exponent (n) can be beneficial in delineation of the R35 which is regularly estimated from mercury capillary pressure measurements.
The hybrid hydraulic-electrical combination of flow zone indicator and saturation exponent displays four reservoir units in contrary of the obtained number in previous plots. Each obtained unit is characterized by a regression line equation as:

\[ n = 0.01 \text{FZI}^2 + 0.0031 \text{FZI} + 0.389 \quad R^2 = 0.987 \] (18)

\[ n = 0.0082 \text{FZI}^2 + 0.0698 \text{FZI} + 0.7085 \quad R^2 = 0.9757 \] (19)

\[ n = 1.562 e^{0.0643 \text{FZI}} \quad R^2 = 0.935 \] (20)

\[ n = 2.1011 e^{0.0613 \text{FZI}} \quad R^2 = 0.7061 \] (21)

The calculated coefficients of correlation for these equations are ranged from 0.71 up to 0.99 allowing FZI estimation from the saturation exponent.

3.7. New Nomograph

An innovative nomograph has been built according to an empirical equation [1] related to the Dam Formation (equation-3) to estimate the water saturation ($S_w$) in oolitic carbonate facies (figure 6). In the present chart the needed data are: 1. Porosity and 2. $R_t/R_w$. Porosity could be either laboratory measured or estimated from porosity logs such as Sonic, Neutron, Density and NMR logs. The resistivity ratio could be obtained from: 1. Deep Resistivity logs to get $R_t$ and 2. Spontaneous potential or RFT log to get $R_w$. 

![Figure 4. Pore Throat Radius (R35) Versus Saturation Exponent (n)](image-url)
Figure 5. Flow Zone Indicator Versus Saturation Exponent

\[ y = 1.5623e^{0.0634x} \quad R^2 = 0.935 \]

\[ y = 0.0082x^2 + 0.0698x + 0.7085 \quad R^2 = 0.9757 \]

\[ y = 2.1011e^{0.0613x} \quad R^2 = 0.7061 \]

\[ y = 0.01x^2 + 0.0031x + 0.3859 \quad R^2 = 0.9871 \]

Figure 6. Rt/Rw Ratio Versus Water Saturation Chart

\[ \theta = 5\% \quad \theta = 10\% \quad \theta = 20\% \quad \theta = 30\% \quad \theta = 40\% \quad \theta = 50\% \]

\[ \bar{u} (\theta = 5\%) \quad \bar{u} (\theta = 10\%) \quad \bar{u} (\theta = 20\%) \quad \bar{u} (\theta = 30\%) \quad \bar{u} (\theta = 40\%) \quad \bar{u} (\theta = 50\%) \]
The present nomograph is verified by measured data of both carbonate and sandstone facies collected from different geologic basins (Qatar, Saudi Arabia, Iran, North Sea and Hungary [1&7]. The water saturation data collected (Sw-c) are correlated with the data calculated using the present model (Sw-m) as shown in figure 7. It displays data of carbonates (blue), sandstone of deltaic distributary channel rock type (green) and barrier bar sandstone (red). The distribution of the data points is adjusted by 100% fixed line. The carbonate data points lying above 100% line indicating that (Sw-m) are underestimated. It is may be due to that not all the collected carbonates are of oolitic facies. The Barrier bar data points are closely fitted to the 100% agreement line. It is may be due to the coarseness of the sand grains like the oolitic-pelletic carbonate of the studied section. The data of the distributary channel sandstone rock type are distributed under and above the 100% agreement line. Each data points are characterized by polynomial equations (2^2, 2^3 and 2^4 for respectively; for Carbonates, for Barrier Bar Sandstone and for Distributary Channel Sandstone):

Sw-c = -0.0153 (Sw-m)^2 + 2.5373 Sw-m - 3.035 \quad R^2 = 0.9498 \quad (22)

Sw-c = -0.0044(Sw-m)^2 + 1.2313 (Sw-m) + 2.3546 \quad R^2 = 0.84 \quad (23)

Sw-c = -0.0046(Sw-m)^2 + 1.1218 (Sw-m) + 10.762 \quad R^2 = 0.76 \quad (24)

The calculated coefficients of correlations for the above listed equations are ranged from (R^2 = 0.76 up to 0.95) and reliable for estimate water saturation.

4. Conclusions
Permeability -porosity relation displays slightly scattered data points with good coefficient of correlation (R^2=0.608). Both permeability and R35 vertical profiles demonstration an excessive harmony along the whole Al Nakhsh section. The reservoir quality index (RQI – void ratio (Ωz) relation indicate that Al Naksh section represents three hydraulic units, where each of which is characterized by a reliable coefficient of correlation (equation :12-14). The calculated fluid zone indicator (FZI) for each hydraulic unit is ranged from (5 μ) for the lower one, and (23μ) for the middle up to(35μ ) for the upper unit. Therefore, the best hydraulic reservoir unit is the upper one represented by equation (12). Although the relation between (R35) and saturation exponent (n) is a hybrid hydraulic-electrical combination, it displays three reservoir units, approving the hydraulic RQI-Ωz relation. The hybrid hydraulic-electrical combination of flow zone indicator and saturation exponent
(n) displays four reservoir units in contrary of the obtained number in previous plots. The obtained number of reservoir flow units in the study area ranges from 3-4. It means that the hydraulic-electric flow units sometimes give different results. On the other hand, an innovative nomograph has been constructed according to an empirical equation related to the Dam Formation [1] to estimate the water saturation (Sw) in oolitic carbonate facies. The present nomograph is verified by carbonate facies, deltaic distributary channel and barrier bar sandstone collected from different geographic locations.

Acknowledgements

Authors acknowledge all efforts of the colleagues who helped in sampling and field trips. Also, the fund offered by the University of Qatar is highly appreciated. The facilities introduced in the laboratory measurements of Ain Shams university (petrophysical Research Unit) was supportive.

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