Improvement of Water Saturation and Formation Factor Parameters in a Clastic Reservoir, Zagros Basin, SW Iran

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Abstract

Water saturation (*Sw*) is one of the most important petro-physical parameter for evaluating the clastic horizons of hydrocarbon reservoir, which can be calculated using Archie's equation. The Archie's parameters (*m, a*) are the major source of uncertainty in the calculation of Sw. In order to obtain Archie's parameters, a total number of 117 sandstone samples, having resistivity measurements from Asmari Formation were studied. Due to scattered data points on the Log-Log plot of F versus Ø and to obtain reliable values for m and *a* parameters, the data were classified based on current zone indicator (*CZI*) into 6 classes of electrical flow unit (*EFU*). The values of parameters *m* and *a* obtained from *F-Ø* cross plots with excellent correlation coefficient. To avoid from data diversity and to make data applicable, the average values of *m* and *a* were obtained with considering the number of samples in each class. To assess the validation of the calculated *F* based on proposed values of *m* and *a*, the measured values of *F* versus calculated one's using Archie, Tixier and Humble formulas and proposed values were compared. The plot shows that the calculated *F* using Archie Tixier and Humble formulas are lower than calculated *F* using proposed and measured values. Applying the determined values seems to reasonably minimize the error in calculating F and therefore Sw%.

Keywords

Formation factor;
clastic horizons;
Water saturation;
core analyze;
Zagros basin.

1. Introduction

For determination of Archie's parameters, the basic method is first to measure the formation factors (*F*) and the corresponding porosity of a sample to measure the resistivity index at different water saturations in laboratory. Then Archie's parameters are determined by graphic or least squares methods [1].

The conventional determination of *a* and *m* is based on modified Archie equation (F =a/ϕm) and is rewritten as [2]:

$$\log F = \log a - m \log \phi \qquad (1)$$

Logarithmic plot *F* vs. ϕ is used to determine *a* and *m* for the core samples.

The classical process to determine saturation

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exponent, n, is based on Archie's water saturation equation ($Sw^n=aR_w/\phi_m Rt=1/Ir$). This equation is rewritten as:

$$\log Ir = -n \log Sw \qquad (2)$$

Logarithmic plot of Ir - Sw gives a straight line with negative slope of *n*.

For Archie conditions, Ir must be independent from formation water salinity and Rw. The first and second Archie equations are governed by the porosity exponent of m and the saturation exponent of n, respectively. These parameters determine from standard resistivity measurements on core samples. Core Archie-Parameters Estimation (CAPE) determines *m* and *n* and optionally a by minimizing the error between computed water and measured water saturations [3].

The saturation exponent n is usually very close to 2 [4] but the values for *m* vary from 0.6 to 7.3. However, *n* factor for water-wet rocks ranges from 1.7 to 2.5, but for oil-wet rocks ranges from 2.5 to 20 [5]. The water saturation Sw as derived from conventional resistivity logs [6] is incorrect (too high). This can be attributed to: 1) the Resistivity Logging Tool related effects, 2) the resistivity of the formation water Rw is incorrect or unknown, due to variable salinity and/or variable ion composition, and 3) the saturation equation and parameters are incorrect due to non-Archie or complex relationships between Sw and resistivity.

Generally, in literature there are three techniques which are applied to determine Archie's parameters: (1) Three dimensional regression (3-D) technique which is based on the analytical expression of three dimension plot of Rt/Rw versus Sw, (2) Core Archie,s parameters estimate (CAPE) and (3) Conventional technique [7].

In the present work, determination of the formation resistivity factor (FRF) and effective factors in the clastic reservoir rock is discussed as an important parameter in formation evaluation. Common formulas for calculating formation resistivity factor (FRF) in clastic reservoirs were given in Table 1. FRF was defined by Archie, 1942 as the ratio of the resistivity of rock when completely saturated with a conducting fluid (R_o) to the resistivity of the saturating fluid (R_w) [8].

$$FRF = R_O/R_W \qquad (3)$$

On plotting *FRF* versus ϕ, Archie found an inverse relationship:

$$FRF = \phi^{-m} \qquad (4)$$

The porosity exponent (cementation factor) *m* was estimated to have a value of 2.0 in clean (clay free) formations [9]. Subsequently, Winsauer et al, 1952 modified the above equation to the following general form [10]:

$$FRF = a\phi^{-m} \qquad (5)$$

Where *a* is referred to the "tortuosity factor" of the pore system. The intercept on the *FRF* axis of a log - log plot of FRF versus ϕ for a group of samples determines the *a* value. It was defined the "tortuosity" τ in a brine-saturated rock as the ratio of the tortuous length of the pore channels traversed by an electric current, flowing between two parallel planes to the direct distance between the planes. FRF can also be related to tortuosity τ [10]:

$$FRF = \tau^2/\phi \qquad (6)$$

The purpose of this study is to determine the *m* and *a* values in clastic sediments.

F= 0.81/ Ø2 (Tixier)

F= 0.62/ Ø2.15 (Humble)

F= 1.45/ Ø1.54 (Philip for sand and sandstones)

F= 1.65/ Ø1.33 (proposed for shaly sandstone)

F= 1.45/ Ø1.7 (proposed for calcareous sandstones)

Table 1. Common formulas for calculating formation resistivity factor (FRF) in clastic reservoirs.

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2. Geology of the study area

Asmari Formation (Oligocene-Lower Miocene) consists predominantly of carbonates with interbedded sandstones, referred to Ahvaz Sandstone Member in Khuzestan Province, SW Iran. Ahvaz Sandstone Member has no exposure/ outcrop in surface in Khuzestan/SW Iran but its present in AbTeymour, Mansour, and Ahvaz oilfields. It was deposited in a passive continental margin setting [11-18]. With an average thickness of about 400 m (1312ft), this rock unit forms one of the principal reservoirs in the Zagros Basin. Carbonate deposition was initiated in a shallow-marine environment [12] and continued through shallowing upward conditions led to a more restricted lagoonal environment. The micro-facies have been interpreted as indicative of the inner and middle ramp. This formation is well studied [13-15]. However, only a few studies were carried out on Ahvaz Sandstone Member [e.g.16-18]. According to petrography and geochemistry [18] concluded that the sandstone member of Asmari Formation deposited under a semiarid climate and low-relief highlands.

The geological interpretation and spatial distribution of the sandstone layers indicate that they may be of deltaic origin and provenanced from the west and southwest [18-19].

The limestone facies range from wackestone to bioclastic, pelletoidal, in-part oolithic packstone-grainstone which were more or less dolomitized. Porosity types are inter-particle, inter-crystalline, moldic and vuggy. The permeability is moderate and enhances through fractures.

Depending on the paleo-environmental setting, the distribution of sandstone layers varied from one field to another, in terms of thickness and position in the stratigraphic column.

Figure 1 shows the subsurface stratigraphic column of Asmari Formation in the borehole study in SW Iran. It presents that sandstone and shale thicknesses increase toward the base of formation while dolomite/dolomitic limestone decreased. This variation can be related to depositional condition.

3. Methodology

3.1. Electrical measurement procedure

In preparation for resistivity measurements, cylindrical plugs (1.5˝ diameter) were cut from each preselected consolidated core samples. These plugs were cleaned by toluene in centrifugal extractor or in Dean Stark apparatus and then dried at low temperature for several days in an oven. The clean plugs were evacuated for six hours and then saturated for sixteen hours under 2000 psi pressure with a brine solution having a sodium chloride content of 172000 ppm, equivalent to the salinity of formation water. Upon removal of the plugs from the saturator, they were allowed to remain in the brines for several days to achieve ionic equilibrium. Electrical resistance of the samples was measured in confining pressure of 5000 psi, equivalent to the net reservoir pressure (overburden pressure minus pore pressure). Then resistivity was computed from the measured resistance, cross – sectional area and the length of the plug. FRF was obtained as the ratio of plug resistivity to brine resistivity.

3.2. Data base

Most commonly, petro-physics is concerned with the technical evaluation of laboratory data and borehole measurements for reservoir properties such as shale-volume fraction *Vsh*, porosity φ, permeability k, net/gross reservoir, water saturation *Sw*, and net/gross pay [20]. Shales affect strongly on the petro-physical characteristics and hydrocarbon prospective of sandstone that causes a major reduction in the porosity [21-22-23].

Petroleum literature contains many reports of the results determining Archie's parameters and related water saturation [24]. In quantitative log interpretation, accurate water saturation calculation requires good values of Archie's parameters [8, 25-27].

The exactness of water saturation value for given reservoir conditions depends on the accuracy of Archie parameters *a*, *m* and *n*. The terms of Archie relationship have been subjected to many laboratory investigations and even more speculation. There are many factors affect porosity exponent, m, saturation exponent, n and tortuosity factor, a. Therefore, it is very difficult to fix Archie param-

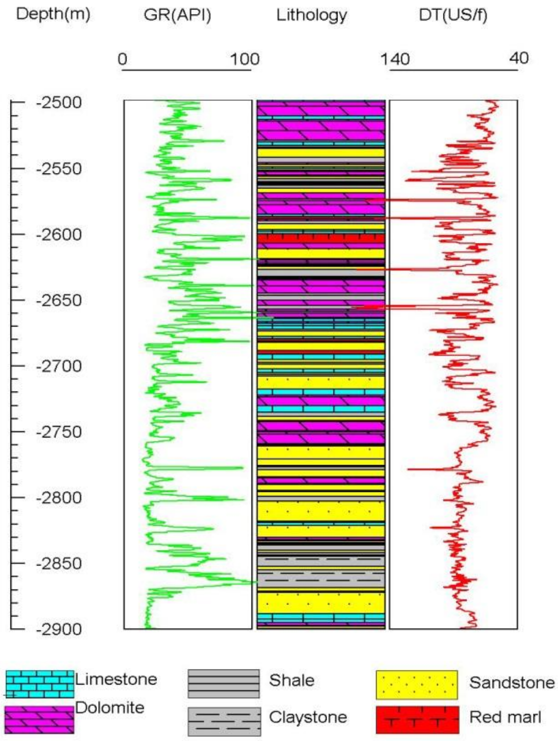

Figure 1. The subsurface stratigraphic column of Asmari Formation in one of oil wells, SW Iran.

eters regardless of reservoir characteristics; rock wettability, formation water salinity, permeability, porosity and fluids distribution [2].

In the present study, a total number of 117 sandstone core samples having resistivity measurements belong to one of the southern Iranian oil reservoirs were analyzed. The main constitute is sub rounded to rounded quartz grains with different size and sorting. In some cases rare carbonate lithic is present. The most common cement is limestone.

The studied samples can be classified as the quartz arenite, sublitharenite and quartz- wacke. In many cases quartz arenites are the products of extended periods of sediment reworking, so that all grains other than quartz have been broken down by mechanical abrasion [28].

The most common porosity is inter-granular, however, vuggy porosity is present in the case of dissolution of carbonate lithoclast and intercrystalline in the presence of coarse crystalline dolomitic cement. The porosity percentage ranged from 8 to 34 with the mean value of 24. The frequency distribution of the porosity of studied samples was presented by the histogram (Fig. 2).

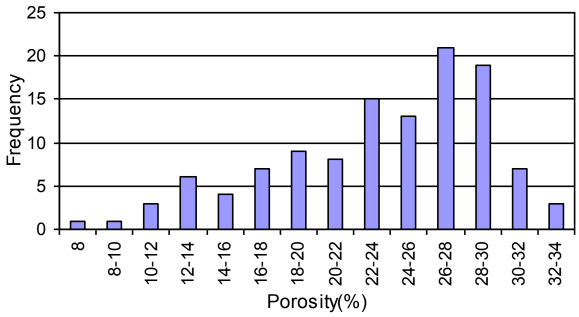

Figure 2. The Frequency distribution of porosity of the studied samples.

As it is shown, the porosity indicates the highest frequency in the range of 22.24-28.3% and after that it is decreased.

3.3. Calculations of m and a parameters

To obtain *m* and *a* parameters, the values of *F* and the porosity were plotted on the logarithmic scale. The intercept is *a* and the gradient is *m* (Fig. 3). Scattering of the data points on this plot imply that the *F* not only is controlled by porosity percentage but also the porosity type is important. *F* values vary from 10-100 while the porosity (fraction) plotted in the range of 0.1-1. In the other words the pore geometry controls the flowing of the electrical current. For instance in a sample with a 0.28 porosity, the *F* can be varied from 9.34 to 42.2 (Fig. 4). The figure indicates that each classes has individual trend that gradually decreased in view of porosity (fraction).

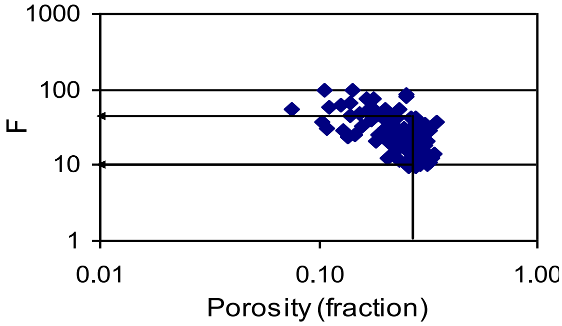

Figure 3. Cross plot of porosity versus *F* (formation factor).

Therefore the effect of porosity is more than *F* in EFU classes. In order to obtain reliable values for m and a, the samples were classified based on current zone indicator (CZI) introduced by Ransom, 1984 into 6 classes of electrical flow unit (EFU) which are separated by different values [26]: Class 1 (CZI<0.2), Class2 (0.2<CZI<0.25), Class 3 (0.25<CZI<0.3), class 4 (0.3<CZI<0.35), class 5 (0.35<CZI<0.4), class 6 (CZI>0.4). The CZI values were calculated using the following equation:

$$CZI = \frac{\sqrt{\frac{\phi}{F}}}{\phi z} \tag{7}$$

where ϕz is the pore volume to matrix ratio which can be calculated through $\phi = \frac{\phi}{1-\phi}$ equation. The obtained values of CZI, *a* and *m* for each classes are listed in Table 2. Then the values of *F* calculated with applying the obtained values of *m* and *a*. Comparison of the calculated *F* and the measured *F* are showing a broad similarity (Fig. 5). It means that these parameters (calculated and measured *F*) are correlated well with a high correlation coefficient value (R^2=0.97).

4. Discussion and results

The overall pore geometry in studied sandstones is homogenous, therefore the *m* variation is little but a significant change suggests the variation of electrical path way and the pore throat size variation [29-30]. This variation is possibly due to

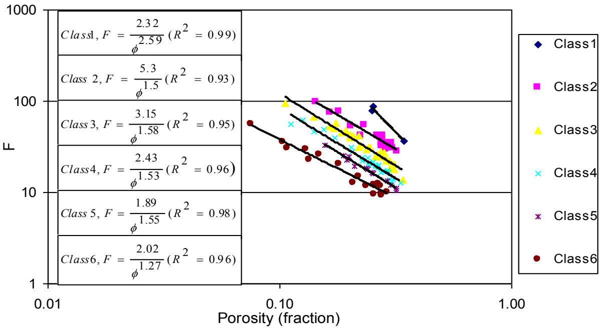

Figure 4. Cross plot of porosity versus *F*, for 6 classes of EFU.

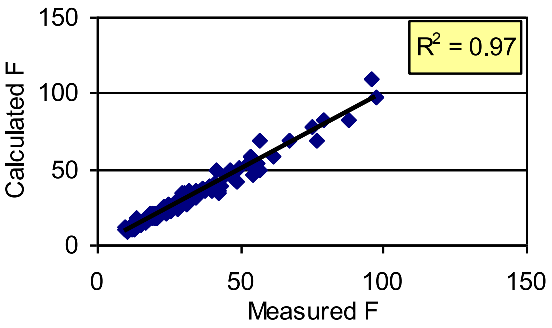

Figure 5. Cross plot of Measure *F* versus Calculated one using obtained values of *m* and *a* in each class.

variation in sorting and grain size and content of occasional carbonate matrix [31]. The *m* values range from 1.27 in class 6 to 1.58 in class 3. The *a* parameter varies from 1.89 in class 5 to 5.3 in class 2. It is presented that although the *m* and *a* values mathematically related via Log *F*=Log *a*-*m*Log ϕ, they have different nature, which could not be compared [32]. The *a* parameter refers to tortuosity of pore throats whereas *m* defines as degree of pores connectivity. The result of this study shows that, there is no clear relationship between these two parameters (Fig. 6). Considering the number of samples in class 1, the *m* and *a* values obtained in this class can be an outlier in the plot (Fig. 6). On the plot of *m* versus *a* (Fig. 6A), the *a* values vary significantly without considerable changes in *m*. Also CZI inversely related to τ with a correlation coefficient of 0.9. With increasing of τ which can be translated to complexity of current pathway, the CZI decreases (Fig. 6B). Therefore the CZI is a function of tortuosity, so the CZI classification can be considered as a tortuosity classification.

In addition, with increasing a value CZI, m decreases, but there is no distinct relationship between CZI and *m*. This suggests that the flowing of the electrical current in porosity network depends on the pore throat size rather than pore size (Figs. 6C, 6D). Considering the number of samples in each class, the mean values of m and a calculated (except *m* and *a* values in class 1). Figure 7 compares the values of measured and calculated *F* using proposed values (this study), Archie, Tixier and Humble. The calculated *F* using Tixier and Humble lie closely and are slightly lower than calculated *F* using Archie equation. However, the computed *F* based on Tixier, Humble and Archie are lower than measured *F* and calculated *F* using proposed values.

In addition, computed *F* using proposed values (a=1.5, m=3.02) have broad similarity to measured *F* (Fig. 8). The correlation coefficient (R^2) is 0.93. Also, the relationship between τ and *a* determined using cross plot of τ versus a:

$$\tau = 1.31a^{0.52} \qquad (8)$$

This equation can be rewritten as the following:

$$\tau = 1.31\sqrt{a} \qquad (9)$$

Therefore, having resistivity measurement, *m* and *a* can be computed for each sample.

Table 2. Values of CZI, a, m and correlation coefficient (R^2) of the 6 classes of EFU.

EFU	CZI class	Average CZI	Number of samples	a	m	R^2
1*	CZI<0.2	0.17	3	2.32	2.59	0.99
2	0.2<CZI<0.25	0.23	20	5.3	1.5	0.93
3	0.25<CZI<0.3	0.28	34	3.15	1.58	0.95
4	0.3<CZI<0.35	0.33	29	2.43	1.53	0.96
5	0.35<CZI<0.4	0.37	13	1.89	1.55	0.98
6	CZI>0.4	0.45	18	2.02	1.27	0.96
Total			117	Mean=3.02	Mean=1.5	

*The values of class 1 are not considered in mean value calculation

5. Conclusion

This study which was carried out based on 117 consolidated sandstone core samples belong to Asmari Formation (Ahvaz sandstone member) was led to the following results:

1. The CZI parameter relates inversely to τ with a strong correlation coefficient of 0.9, hence, the CZI classification is a kind of tortuosity classification.

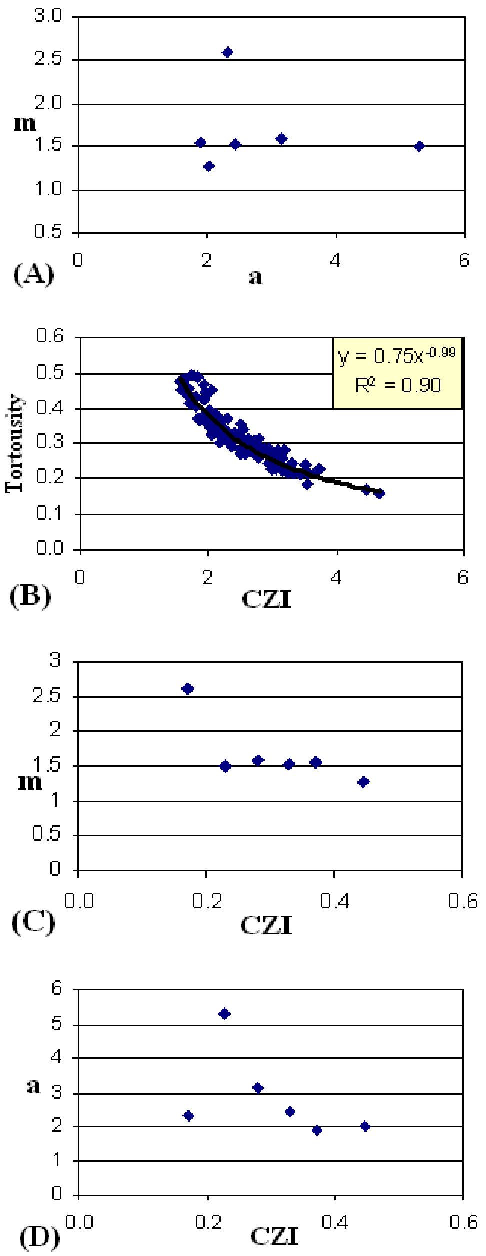

Figure 6. Cross plot of (A) *a* vs *m*, (B) CZI vs tortuosity, (C) CZI vs m, (D) CZI vs *a*.

2. The τ and a are related through equation 9. This equation enables us to calculate a values for each single sample having resistivity measurements, without the necessity to past averaging techniques.

3. We recommend the equation $F=\frac{3.02}{\phi^{1.5}}$ for calculating Sw using Archie's equation in any clastic formation similar cases to Ahvaz sandstone.

4. Considering, the proposed values (a=3.02, m=1.5) obtained with good correlation coefficient, applying these values seems to reasonably minimize the error in Sw calculation.

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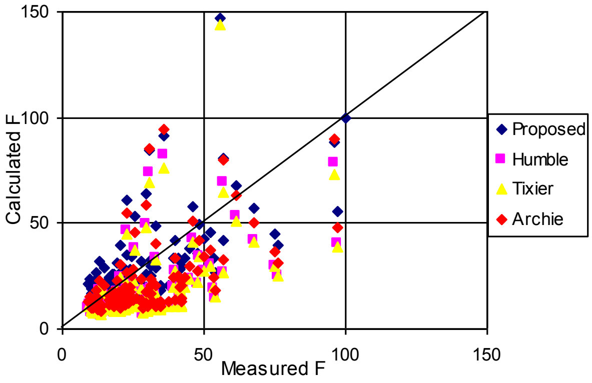

Figure 7. Cross plot of measured F versus calculated F using Archie, Tixier, Humble and proposed values (a=3.02, m=1.5).

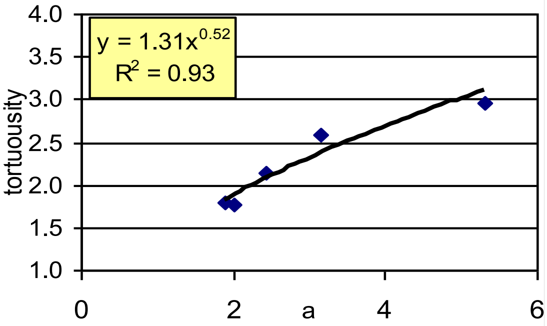

Figure 8. Parameter *a* versus tortuosity cross plot (except class 1).

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