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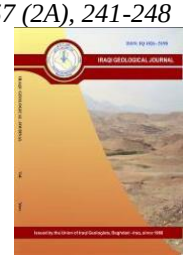

Correlating Capillary Pressure and Resistivity Index for Carbonate Reservoir

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Abstract

Capillary pressure is a significant parameter in characterizing and modeling petroleum reservoirs. However, costly laboratory measurements may not be sufficiently available in some cases. The problem amplifies for carbonate reservoirs because relatively enormous capillary pressure curves are required for reservoir study due to heterogeneity. In this work, the laboratory measurements of capillary pressure and formation resistivity index were correlated as both parameters are functions of saturation. Forty-one core samples from an Iraqi carbonate reservoir were used to develop the correlation according to the hydraulic flow units concept. Flow zone indicator (FZI) and Pore Geometry and Structure (PGS) approaches were used to identify the reservoir hydraulic flow units. The experimentally derived correlations can be used to predict capillary pressure from resistivity, which is widely available from well-logs. FZI and PGS rock typing methods were applied to characterize the reservoir rock types. For both methods, the log-log plot of Leverett J-function and capillary pressure versus resistivity index for each rock type represent a power-law model relationship between these parameters. Despite the good permeability-porosity prediction results, the FZI approach did not yield a good correlation between J and I. PGS resulted in a better performance in terms of both permeability-porosity prediction and Pc with I correlation because PGS honors the pore geometry and structure relationship with the mean hydraulic radius more than FZI. This work introduces a new correlating approach that aims to assist in reservoir characterization and simulation.

Keywords: Capillary pressure; Resistivity index; Hydraulic flow unit; Flow zone Indicator; Pore geometry.

1. Introduction

Capillary pressure is the critical parameter in reservoir simulation that describes fluid distribution in porous media. It is a complex function of fluids and rocks interaction. However, representative measurement of this parameter is only achieved through extensive lab work, which is expensive, time-consuming, and may not be of great benefit in highly heterogeneous reservoirs that require many core samples. On the other hand, resistivity measurement through the well-logging process is much easier and is possible even in real time. Both parameters are functions of fluid saturation and are affected by pore geometry and heterogeneity (Li and Horne, 2010; Li et al., 2019).

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Based on laboratory experiments, Szabo (1974) suggested a correlation between capillary pressure and resistivity index by assuming that the exponent of the relationship between capillary pressure and water saturation is equal to that of resistivity with water saturation. His model assumed the linear relationship;

$$I = \frac{R_t}{R_o} = a + b \times P_c \quad (1)$$

Where I is the resistivity index, Rt is the resistivity of rock at a specific water saturation, Ro is the resistivity of rock at a water saturation of 100%, Pc is the capillary pressure, and a and b are two constants.

Szabo (1974) showed from experimental results that this linear model is applicable only for specific capillary pressure ranges, and each core sample should have its equation. However, it has been found that this model may not be correct in many cases (Li and Williams, 2006).

Liu and Williams (2006) used a powerful mathematical tool that considers irregular geometrical structures, named the fractal model, to theoretically derive a correlation for predicting capillary pressure from resistivity. This model indicated a power relationship between capillary pressure and resistivity index, which showed a good fit for the experimental results on fourteen core samples from two formations in an oil reservoir.

$$P_{CD} = I^{\beta} \quad (2)$$

P_{cD} is the dimensionless capillary pressure (Pc/Pe), Pe is the entry capillary pressure, and β is the exponent of the relation between disjoining pressures and film thickness.

Li and Williams (2006) concluded that their model performs better in the range of low water saturations. Li and Horne (2010) pointed out that the power-law model showed greater goodness of fit to the experimental data in low permeability rocks, and this relationship between capillary pressure and resistivity index does not exist at high wetting face saturations. Hou et al. (2016) applied Li and Williams (2006) power-law model to their experimental data set of sixteen core samples from two wells. The results showed the validity of the model for this case. They were able to correlate the exponent with permeability quantitatively.

Liu et al. (2016) proved mathematically that capillary pressure is a function of resistivity index and residual water saturation (S_{wi}) without any intermediate coefficients, which is a more general relationship that predicts a linear behavior between capillary pressure and the term $\frac{\sqrt{I \times S_w}}{S_w^*}$ as detailed in the equations below:

$$P_{CD} = \frac{\sqrt{I * S_w}}{S_w^*} \quad (3)$$

and

$$S_w^* = \frac{S_w - S_{wi}}{1 - S_{wi}} \quad (4)$$

Mahmoud and Abdelgawad (2013) used a polynomial relationship to correlate capillary pressure with formation resistivity (R_t). The correlation of the carbonate and sandstone formations indicated that a single equation could be derived for sections with the same permeability. A third-degree polynomial was used to predict capillary pressure for sections with low permeability (7md). Increasing the degree of the polynomial to the fourth when predicting capillary pressure in higher permeability regions (130 md) may be risky regarding overfitting the data. This model better predicted capillary pressure in higher permeability regions for carbonate rocks, while sandstone rocks did not have a specified range of

permeability for better performance. Mahmoud and Abdelgawad (2013) also suggested careful examination of a permeability log and lithology to develop a capillary pressure/resistivity relationship.

Al-Ameri et al. (2020) represented the heterogeneity of carbonate reservoir mean hydraulic radius-permeability relations. They denoted that this grouping method gave a better description of the reservoir zones than other grouping methods for the studied tight reservoir.

Awadh et al., (2019) constructed 2D and 3D flow Models of carbonate resirvoirs based on hydraulic head, hydrodynamic pressure and potentiometric surface levels of southern Iraqi fields.

Xie et al. (2024) obtained a distinct relation between a fractal dimension of the capillary pressure curve and the resistivity index. The fractal parameters strongly depend on pore structure properties and have a good relationship with $(K/\phi)^{0.5}$.

This work emphasized characterizing rocks into clusters of hydraulic flow units to enhance capillary pressure prediction from resistivity, considering the effect of pore geometry and structure. The hydraulic flow units of the carbonate reservoir were identified using FZI and PGS methods. Several correlations were developed to predict capillary pressure for each flow unit. PGS method showed priority over FZI in characterizing rock type.

2. Materials and Methods

Capillary pressure and resistivity index measurements were correlated for 41 samples obtained from an Iraqi carbonate reservoir. The permeability of the core samples ranged from 1.9 to 1019 md, and porosities were 0.121 to 0.25. A fairly good correlation can be obtained when the power relationship is used to correlate Pc and I for individual samples, as shown in Fig.1.

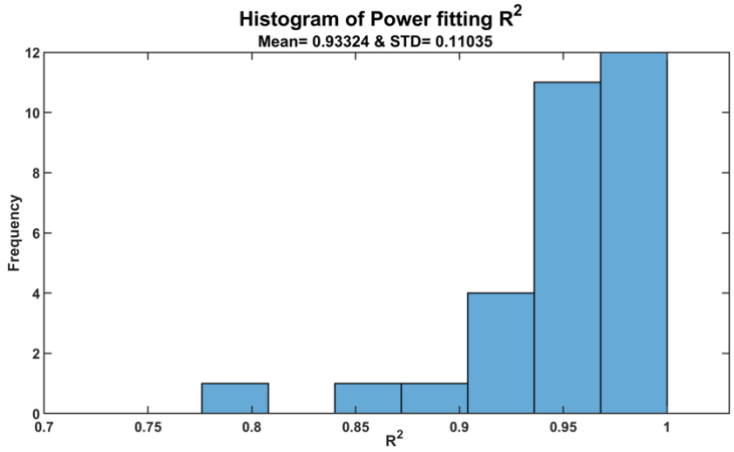

Fig.1. Power fitting R2 when plotting Capillary pressure versus resistivity index for each core sample alone

A global correlation for estimating capillary pressure aims to be developed in the present work using the available measurements of Pc and I. The power model is used first to correlate the Leverett J-function and resistivity index. Fig.2 depicts a single relationship for all core samples. This technique produced a plot with a distinguishable trend and moderate fitting results, highlighting the possibility of improving the relationship by introducing other influential parameters, such as pore geometry.

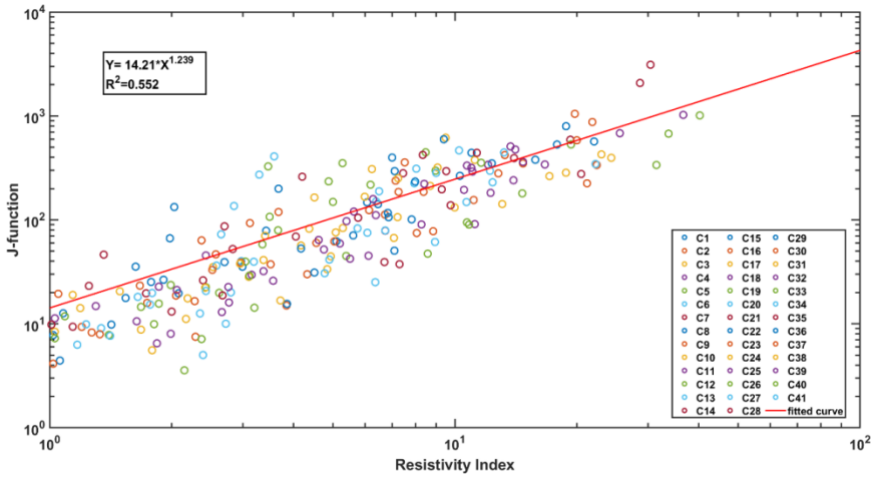

Fig.2. J- function versus J for all core samples

2.1. Flow Zone Indicator (FZI)

The flow zone indicator (FZI) and rock quality index (RQI) concept identify each hydraulic flow unit. This method is widely used for the zonation of carbonate reservoirs (Abdul Hmeed and Hamd-Allah, 2023). Amaefule et al. (1993) introduced the concepts of FZI and RQI to characterize and quantify hydraulic flow units in a reservoir by considering the pore throat and grain distribution along with other microscopic parameters as defined in equations 5, 6, and 7.

$$RQI = 0.0314\sqrt{\frac{k}{\phi}} \tag{5}$$

$$FZI = \frac{RQI}{\phi_z} \tag{6}$$

Where ϕ_z is the ratio of pore volume to grain volume:

$$\phi_z = \frac{\phi}{1-\phi} \tag{7}$$

In the above equations, RQI is the reservoir quality index, kis permeability, and ϕ is porosity. Samples with different FZI values will lie on parallel lines. These samples have similar pore throat characteristics and constitute a flow unit.

2.2. Pore Geometry and Structure (PGS)

Permadi and Susilo (2009) introduced the PGS approach of rock classification. Based on the capillary model derived from the Kozeny–Carman equation, they introduced an approach that utilizes pore geometry and structure relationship with hydraulic rock characteristics of samples to predict permeability and identify similar facies.

$$\left(\frac{k}{\phi}\right)^{0.5} = a\left(\frac{k}{\phi^3}\right)^{b} \tag{8}$$

This $\left(\frac{k}{\phi}\right)^{0.5}$ is called the hydraulic radius, a feature of pore geometry and $\frac{k}{\phi^3}$ the pore structure that manifests the internal structure of pore spaces. A plot $\frac{k}{\phi^3}$ vs $\left(\frac{k}{\phi}\right)^{0.5}$ on a log-log paper would yield a straight-line relationship with a=1 and b= 0.5 for a perfectly rounded, poor shape and smooth capillary tube. However, this is not the case for actual reservoir rocks, where b value must be less than 0.5. This

relationship implies that samples of a similar rock type may lie on the same straight line and identify hydraulic flow units.

3. Results

3.1. Results of FZI Method

Fig.3 is a permeability-porosity log-log plot that shows five hydraulic flow units characterized with the aid of FZI. Permeability is well correlated with porosity for each flow unit, as introduced by the high coefficient of determination (R^2), which denotes the success of the FZI method in specifying reservoir zonation.

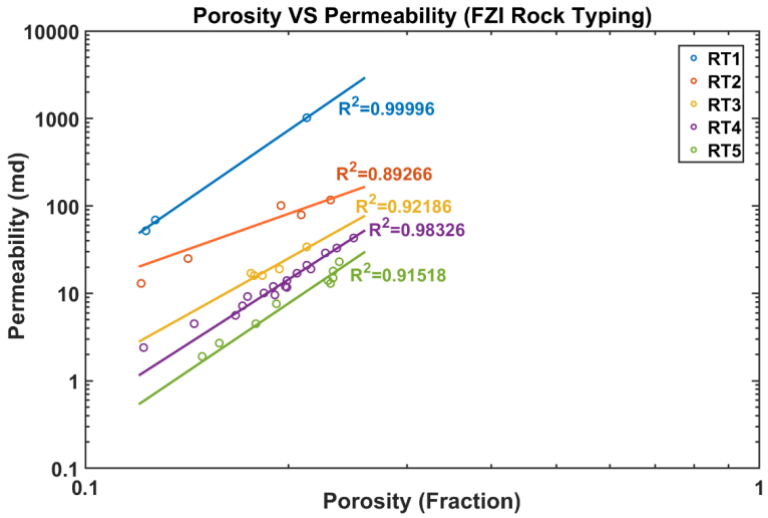

Fig.3. Porosity versus permeability after clustering by FZI approach

The permeability, porosity, and capillary pressure are used to calculate the J-function for each flow unit. Figure 4 depicts the relation of the J-function with the resistivity index for the five rock types identified by the FZI method. These relations are weak, as explained by the high scattering of the points. In addition, no unique trend is seen for the J-function- resistivity index relation. The FZI method failed to develop reasonable J-I relations, and investigating another method for this issue is now crucial.

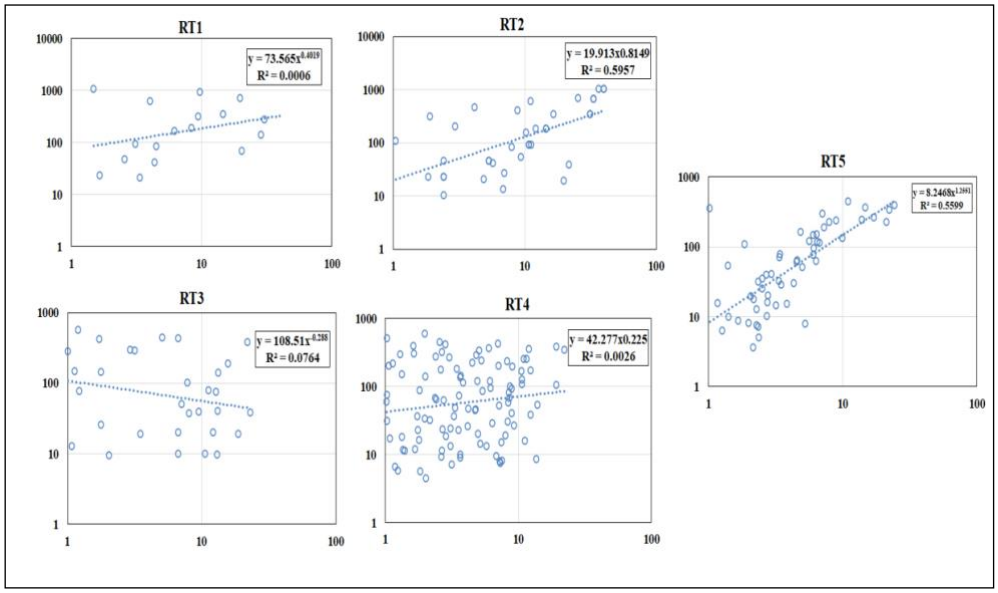

Fig.4. Log-log plot for J-function versus resistivity index for flow units identified by FZI.

3.2. Results of PGS method

Fig.5 presents the four rock types identified by PGS, which are shown to be less than those identified by the FZI approach, which was the five-rock type. However, better predictive results were obtained when correlating J-function and I than from FZI classification, as shown in Fig.6 and Table 1. According to the PGS method, the studied reservoir can be classified into four distinct zones, each with the same pore structure and geometry. These zones are sorted based on their permeabilities.The capillary pressure was calculated from the J-function for each rock type recognized by the PGS method. Fig.7 and Table 2 show the excellent correlation coefficients for rock types 1, 2, and 4 and the good correlation coefficient for rock type 3. These results confirm the superiority of PGS in determining the reservoir zonation.

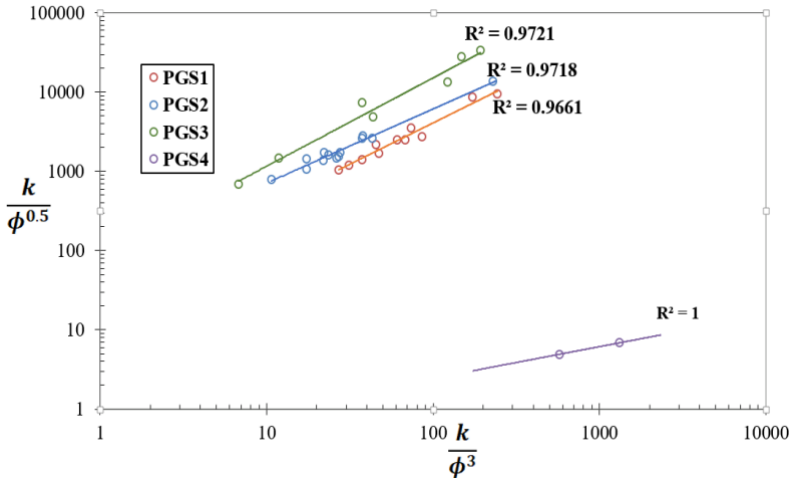

Fig.5. Rock clusters by PGS

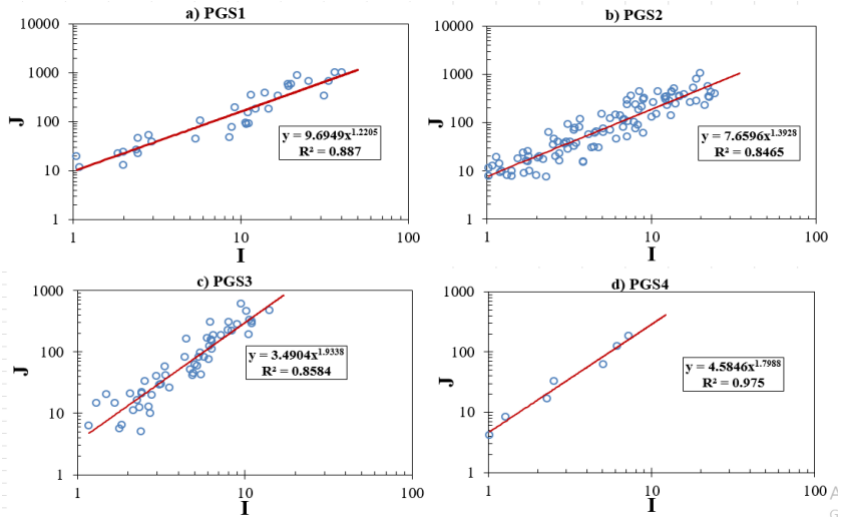

Fig.6. Log-log plot for J-function- resistivity index for each rock type identified by PGS

Table 1. Correlation of J-function - resistivity index for each rock type identified by PGS

Rock-type	Correlation	Correlation coefficient	Range of permeability (md)
PGS1	$J = 9.6949I^{1.2205}$	0.8870	33 – 1019
PGS2	$J= 7.6596I^{1.3928}$	0.8465	9 – 69
PGS3	$J= 3.4904I^{1.9338}$	0.8584	4.5- 52
PGS4	$J= 4.5846I^{1.7988}$	0.9750	1.9- 2.7

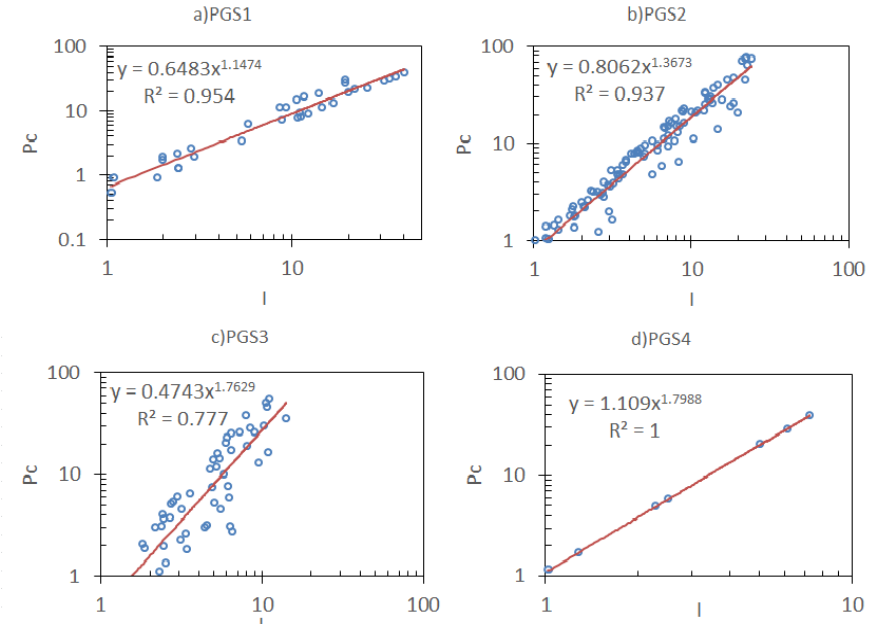

Fig.7. Log-log plot of the capillary pressure-resistivity index for each PGS-identified rock type

Table 2. Correlation of capillary pressure-resistivity index for each rock type identified by PGS

Rock-type	Correlation	Correlation coefficient	Range of permeability (md)
PGS1	$Pc = 0.6483I^{1.1474}$	0.954	33 – 1019
PGS2	$Pc = 0.8062I^{1.3673}$	0.937	9 – 69
PGS3	$Pc = 0.4743I^{1.7629}$	0.777	4.5- 52
PGS4	$Pc = 1.109I^{1.7988}$	1.0	1.9- 2.7

4. Conclusions

This work introduced the idea of correlating capillary pressure with resistivity index in different manners, and more than one sample was used to correlate these parameters in a single cross-plot. The following conclusions may be drawn:

1. The correlation was improved when plotting the Leverett J-function against the resistivity index which pointed out the possibility of improving the correlation when the pore geometry and structure effect are introduced to the relationship.
2. The FZI rock typing method introduced a good porosity-permeability relationship, but this relationship was not reflected in the J versus I plot.
3. PGS rock typing was better for correlating J and I since it focused on pore geometry and structure relationship with mean hydraulic radius.
4. The exponent of Pc-I relationships decreases with an increase in permeability.

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