Derivation of Regression Models for Flow Zone Indicator (FZI) which using in Permeability Prediction

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Abstract

Knowledge of permeability values and its variations within a pay zone is an important and significant criterion in developing an effective reservoir description and evaluation. The determination of permeability in heterogeneous and anisotropic reservoirs is a complex problem, because core samples and well test data are usually only available for limited number of wells. This paper will focus on the evaluation of formation permeability for a Carbonate reservoir in one Iraqi field from well log data using the concept of Flow Units (FU). A statistical model was developed by the regression method using correlations between the Flow Zone Indicator (FZI) from core data and well logs data for each reservoir unit in this Formation in this study. The validity of the proposed model was tested for each reservoir unit, and it was used together with the (FZI) values to estimate the permeability in the un-cored sections of the wells.

Keywords: Carbonate reservoir, Flow Zone Indicator (FZI), Hydraulic Flow Unit (HFU), Permeability

Introduction

Permeability is the measurement of a rock’s ability to transmit fluids which may be subdivided into absolute and effective (Kumar N. and Frailey, 2003) [1].

Permeability is a function of effective porosity and irreducible water saturation. Thus, in many cases, estimates of permeability are obtained from porosity values. The most reliable local permeability values may be obtained from core analysis. However, core samples are usually not available for all the layers either because of borehole conditions or due to the high cost of coring (thus, it is usually carried out in limited cases of drilling operations), (Lacentre E. and Carrica M., 2008) [2].

Statistical models, which are based on multiple regression approach, were used to develop a relationship for permeability predictions in cored and un-cored intervals of the wells. The multiple regression technique was applied to develop a relationship between log responses with Flow Zone Indicator (FZI) to predict the permeability of the reservoir units for all the wells under this study.

Theoretical Background of Flow Unit Concept

Amaefule et al. (1993) [3,4,5] considered the role of the mean hydraulic radius in defining hydraulic flow units and correlating permeability from core data. Their approach was essentially based on a modified Kozeny-Carmen equation (Wyllie, 1958) [6].
\[ k = \left\{ \frac{1}{2 \tau \phi_e} \right\} \left( \frac{\phi_e^3}{(1-\phi_e)} \right) \]  \hspace{1cm} (1) \]

\( S_{gv} \): may also be define as the surface area of grains exposed to fluid per unit volume of solid material.

The Amaefule et al. (1993) approach was essentially based on a modified Kozeny-Carmen equation (Wyllie, 1958) coupled with the concept of mean hydraulic radius:

\[ r_{mh} = \frac{\text{Cross Section Area}}{\text{Wetted surface area}} = \frac{r}{2} \]  \hspace{1cm} (2) \]

The concept of sub-grouping reservoir volume into flow units, suggests that the term \( 2\tau^2 \) in Eq. (1), which is classically referred to as Kozeny constant, is actually “variable constant”. This means that Kozeny constant may vary for different hydraulic units, but is constant for a specific unit. Based on that, Taib (2004) \([7]\) introduced the “variable constant” \( k_\tau \) referred to as the effective zoning factor:

\[ k_\tau = \left\{ \frac{1}{k_S S_{gv}^2} \right\} \left( \frac{\phi_e^3}{(1-\phi_e)} \right) \]  \hspace{1cm} (3) \]

\( k_\tau \): it is a function of pore-pore throat size and geometries, tortuosity and cementation.

Taib (2004) proposed to estimate the effective zoning factor:

\[ k_\tau = F_s \tau^2 \]  \hspace{1cm} (4) \]

\( F_s \) is the effective pore throat shape factor.

Kozeny and Carmen simulated a porous medium as a bundle of capillary tubes. They combined Darcy’s law for flow in a porous medium and Poiseuille’s law for flow in tubes. A tortuosity factor was also included, because for a realistic model of porous media the connected pore structure is not straight capillary tubes. The following relationship between porosity and permeability was suggested:

\[ k = \frac{r^2 \phi_e^2}{8 \tau^2} = \frac{\phi_e}{2 \tau^2} \left( \frac{r}{2} \right)^2 = \frac{r_{mh}^2 \phi_e}{2 \tau^2} \]  \hspace{1cm} (5) \]

The mean hydraulic radius can be related to the specific surface area per unit grain volume, \( S_{gv} \), and the effective porosity, \( \phi_e \), by the following equation:

\[ S_{gv} = \frac{1}{r_{mh}} \left( \frac{\phi_e^2}{1-\phi_e} \right) \]  \hspace{1cm} (6) \]

Combining Eqs. (5) and (6), gives the generalized Kozeny –Carmen equation:

\[ k = \left\{ \frac{\phi_e^3}{(1-\phi_e)} \right\} \frac{1}{F_s \tau^2 S_{gv}^2} \]  \hspace{1cm} (7) \]

The term \( F_s \tau^2 \) is known as the Kozeny constant, which is usually between 5 and 100 in most reservoir rocks. The term \( F_s \tau^2 S_{gv}^2 \) is a function of geological characteristics of porous media and varies with changes in pore geometry. The determination of the \( F_s \tau^2 S_{gv}^2 \) group is the focal point of the Hydraulic Flow Unit (HFU) classification technique.

Amaefule et al. (1993) addressed the variability of Kozeny’s constant by dividing Eq. (7) by the effective porosity, \( \phi_e \) and taking the logarithm:

\[ 0.0314 \sqrt{\frac{k}{\phi_e}} = \left[ \frac{\phi_e}{(1-\phi_e)} \right] \frac{1}{\sqrt{F_s \tau^2 S_{gv}}} \]  \hspace{1cm} (8) \]

Where, the constant 0.0314 is the permeability conversion factor from \( \mu \text{m}^2 \) to md.

Defining the flow zone indicator FZI (\( \mu \text{m} \)) as:

\[ FZI = \frac{1}{S_{gv} \tau F_s} \]  \hspace{1cm} (9) \]

Reservoir quality index RQI (\( \mu \text{m} \)) as:
RQI=0.0314 \sqrt[n]{\frac{1}{\varphi_e}} \tag{10}

and normalized porosity \( \varphi_z \) (fraction) as:
\[
\varphi_z = \varphi_e \left( \frac{1 - \varphi_e}{1 - \varphi_z} \right) \tag{11}
\]

Eq. (8) becomes:
\[
RQI = FZI \times \varphi_z \tag{12}
\]

Taking the logarithm of both sides of Eq. (12) yields:
\[
\log RQI = \log FZI + \log \varphi_z \tag{13}
\]

RESULTS AND DISCUSSIONS

A-Identifying Flow Zone Indicator

Ideally, in a Log-Log plot of RQI versus \( \varphi_z \), all the samples with similar FZI values lie on a straight line with a slope of one (that is, having similar flow characteristics) and data samples with the same FZI values, but significantly different from the preceding one, will lie on another, parallel, unit-slope lines; and so on. Samples that lie on the same straight line have similar pore throat attributes, and thereby constitute a unique hydraulic flow unit. Each line represents a Hydraulic Flow Unit (HFU) and the intercept of this line with \( \varphi_z = 1 \) is the mean FZI value for that Hydraulic Flow Unit (HFU) each flow unit is characterized by a Flow Zone Indicator (FZI).

Figs. (1-a, 1-band 1-c) show a cross plot of the logarithm of the reservoir quality index (RQI) versus the logarithm of the normalized porosity (\( \varphi_z \)) for various values of the Flow Zone Indicator (FZI). All the data points that fall on the same (FZI) straight line can be considered to have similar pore throat attributes (i.e., they represent the same hydraulic unit). Fig. (1-b) shows the existences of five distinct hydraulic subunits within the cored interval of xx-2 unit in the study field. Figs. (1-a and 1-c) show the existences of three distinct hydraulic subunits within the cored interval for each of the xx-land xxx units in the study field.

B-Flow Zone Indicator (FZI) Correlation with Well Logs

The Flow Zone Indicator (FZI) is then correlated to certain combinations of logging tool responses to develop regression models for permeability predictions in cored and un-cored intervals of the wells. The use of several types of well logs will improve the overall behavior of a correlation and establish a more consistent statistical model. Such well log types may comprise:

- The gamma ray log response, which provides evidence of shale content, has an impact on permeability and Flow Zone Indicator (FZI); it also provides information about the lithology of the formation.
- The bulk density, sonic, and neutron logs which are functions of porosity, and help to differentiate between hydrocarbons.
- The resistivity log response provides information about the presence of hydrocarbons and the relative mobility of the fluid in the formation.

The depth correlation between logs and core data are performed by comparing log-derived porosity (effective porosity) with core porosity data after the reported core data depth has been adjusted to match the well log depth.

C-Data Correlation

A multiple regression technique was applied to develop a model for the parametric correlation of Flow Zone Indicator (FZI) with well log responses, for each reservoir unit in all the wells in this study. The statistical program “Statistica Software” was used for this purpose. The model was applied to each reservoir unit (about 70% of the core samples data was used for model development and 30% for model validation) within well formations of the study field. Several trial were attempted, in each of which the anomalous log or FZI data were omitted in order to get a better average absolute error (AAE) and improve the correlation coefficient \( R^2 \). The trials were terminated when it has been found that any further omission of anomalous values would not improve the (AAE) and \( R^2 \) values.

It was found that omission of 9 to 13 values out of values, which were used to formulate the model from each unit that was sufficient to get the final parametric correlation model whose coefficients are given in Table 1.

\[ \text{Table 1} \]
The parametric correlation equation for determining the Flow Zone Indicator (FZI) for each unit is given by:

\[ \text{FZI} = e^{(C_0 + C_1 + C_2 + C_3 + C_4 + C_5 + C_6 + C_7)} \]  \hspace{1cm} (14)

Where,

\[ C_0 = B_0, \]

\[ C_1 = B_1 \times \ln(\text{GRC}), \]

\[ C_2 = B_2 \times \ln(\text{GRC}) \times \ln(\phi_e), \]

\[ C_3 = B_3 \times \ln(\text{GRC}) \times \ln(\phi_e) \times \ln\left(\frac{R_t}{R_{xo}}\right), \]

\[ C_4 = B_4 \times \ln(\phi_e), \]

\[ C_5 = B_5 \times \ln(\phi_e) \times \ln\left(\frac{R_t}{R_{xo}}\right), \]

\[ C_6 = B_6 \times \ln\left(\frac{R_t}{R_{xo}}\right), \]

\[ C_7 = B_7 \times \ln(\text{GRC}) \times \ln\left(\frac{R_t}{R_{xo}}\right). \]

D-Validation

The validity of the proposed Eq. (14) was tested for each reservoir unit in all the wells in this study. It is to be noted that, the data that were used for model verification are those representing the unused 30%, which was kept for this purpose. The verification is a necessary step prior to development of a general model for each reservoir unit of all the wells. Acceptable agreement, between the predicted and observed Flow Zone Indicator (FZI) values, may be noticed from Figs. (2-a, 2-b, and 2-c) for most intervals.

The permeability can be computed for those points on the same straight line (with same FZI) using the equation (Amaefule et al. (1993)[3,4,5]):

\[ k = 1014FZI^2 \frac{\phi_e^2}{(1-\phi_e)^2} \]  \hspace{1cm} (15)

Thus, Eq. (15) was used for permeability prediction using the average values of Flow Zone Indicator (FZI) which were computed by the parametric correlation equation Eq. (14). This process was carried out for each reservoir unit in the study field. Figs. (3-a,3-b and 3-c) show the profile of measured permeability vs. predicted permeability by multiple regression. A good agreement between the k-predicted and k-core values along most depth intervals of the three units may be noticed from the figures.

CONCLUSION

- Reservoir porosity permeability relationship is best achieved if rocks with similar fluid-flow conductivity are identified and grouped together. Each group is referred to as a flow unit.
- The analyses that were based on the Flow zone indicator (FZI) showed the existence of five distinct hydraulic subunits within the cored interval of the lithological unit xx-1. It also showed that, only three hydraulic subunits were indicated in the cored interval of each of the two lithological units xx-2 and xxx.
- Permeability estimation using the FZI method was extended to uncored wells by statistical regression model and may be noticed a good agreement between the k-predicted and k-core values along most depth intervals of the three units in this study.

NOMENCLATURE

- \( \tau \): is the tortuosity
- \( \phi_e \):is the effective porosity
- \( F_{st}\tau = \) Kozeny constant
- \( S_{sp} \): is specific surface area per unit grain volume
- \( k \): is the permeability
- \( r \): is the pore throat radius
- \( r_{mah} \): is the mean hydraulic radius
- \( R_{t} \): is the Deep Resistivity
- \( R_{xo} \): is the Shallow Resistivity
- \( \text{FZI} \): is the flow zone indicator
- \( \text{GRC} \): is the Corrected gamma ray
- \( \text{HFU} \): is the Hydraulic Flow Unit
- \( \text{RQI} \): is the Reservoir quality index
Table 1: The coefficients of the parametric correlation of FZI model

<table>
<thead>
<tr>
<th>Unit Name</th>
<th>B0</th>
<th>B1</th>
<th>B2</th>
<th>B3</th>
<th>B4</th>
<th>B5</th>
<th>B6</th>
<th>B7</th>
<th>N</th>
<th>R²</th>
<th>AAE</th>
</tr>
</thead>
<tbody>
<tr>
<td>XXX</td>
<td>-2.6</td>
<td>-1.3</td>
<td>-0.5</td>
<td>1.3</td>
<td>-0.3</td>
<td>-0.3</td>
<td>-0.5</td>
<td>1.6</td>
<td>167</td>
<td>0.68</td>
<td>0.23</td>
</tr>
<tr>
<td>xx-1</td>
<td>-2.8</td>
<td>-1.2</td>
<td>-0.3</td>
<td>1.8</td>
<td>-0.2</td>
<td>-0.5</td>
<td>-0.4</td>
<td>2.3</td>
<td>382</td>
<td>0.54</td>
<td>0.28</td>
</tr>
<tr>
<td>xx-2</td>
<td>-1.8</td>
<td>-1.2</td>
<td>-0.6</td>
<td>1.3</td>
<td>-0.8</td>
<td>-0.9</td>
<td>-0.6</td>
<td>2.1</td>
<td>117</td>
<td>0.69</td>
<td>0.21</td>
</tr>
</tbody>
</table>

Fig. (1- a): xxx unit

Fig. (1- b): xx-1 unit
Fig. (1- c): xx-2 unit

Fig. 1: Cross plot of logarithm RQI versus logarithm φZ with Flow Zone Indicator (FZI) for (a) xxx unit, (b) xx-1 unit and (c) xx-2 unit

Fig. (2-a): xxx unit

Fig. (2- b): xx-1 unit
Fig. 2: Cross plot of measured vs. predicted Flow Zone Indicator (FZI) for (a) xxx unit, (b) xx-1 unit and (c) xx-2 unit.
Fig. (3- a): xxx unit
Fig. 3: Cross plot of core permeability vs. predicted permeability values by multiple regressions for (a) xxx unit, (b) xx-1 unit and (c) xx-2.

REFERENCES


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