Classification and application of flow units in carbonate reservoirs

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Abstract. In the carbonate oil field offshore of Sumatra block in Sunda basin, RQI (Rock Quality Index) and FZI (Flow Zone Index) have proved to be effective method of dividing the flow units. The method utilizes the porosity and permeability of the core rock samples to divide the flow units of the K oil field carbonate reservoirs. The field consists of six flow units, and they represent different flow characteristics. The results show that each flow unit has a specific relationship of porosity and permeability and a specific capillary pressure curve (J function); this feature is related to the rock pore structure and pore size. In the application, the flow unit model is built by a stochastic modeling method, and the permeability model and the oil saturation model are built under the control of the flow unit model.

1. Introduction

In 3D geological model, property model has important significance for reservoir evaluation and reserves calculation. In the modeling process, researchers relied on well-interpreted permeability curves and oil saturation curves to build a permeability model and an oil saturation model using stochastic modeling. The study found that most of the established permeability models and oil saturation models differ greatly from the actual conditions of the reservoir, especially in highly heterogeneous carbonate reservoirs. The reason is that the distribution of reservoir permeability and oil saturation is not only affected by the facies, lithology and porosity, but also related to the microstructure of the rock [1]. Taking the K oilfield in Sumatra area of Indonesia as an example, the relationship between core porosity and permeability is very complex. This complex relationship is reflected in the small change in porosity, and the permeability increased by several orders of magnitude, or the same porosity corresponds to a very wide range of permeability. Currently, well logging interpretations of permeability and oil saturation are mostly derived from simplified models. They are quite different from the core experimental data and they do not match the production dynamic data. Therefore, K Oilfield needs to adopt a certain method to establish a permeability model and an oil saturation model that can truly reflect the geological conditions of the oil field and reduce the uncertainty in development.

2. The basic theory of flow units

The concept of flow units was first proposed by Hearn (1984). He defined a reservoir zone with vertical and horizontal continuum with similar permeability, porosity and bedding features as flow units [2]. After the study by different experts and scholars, the flow units have more and deeper understanding. W. J. Banks et al. (1987) consider flow units to be further subdivided according to changes in the physical
and petrophysical properties that affect the fluid flow in the rock [3]. D.C. Barr et al. (1992) consider flow unit as a rock block with similar water features in a given rock [4]. Yinan Qiu et al. (1996) consider that flow unit is a naturally occurring fluid flow channel due to the heterogeneity of the reservoir, the baffle and the by-pass conditions [5]. Longxin Mu et al. (1996) believe that flow unit is a reservoir unit that is consistent with percolation characteristic due to boundary constraints, discontinuous thin barrier layers, various sedimentary micro-interfaces, small faults, and permeability differences within an oil sands body [6]. Gunter, G.W. et al. (1997) believe that flow unit is deposited under similar geological conditions and undergone a similar diagenetic process, and forming a rock with a unique pore structure and wettability [7].

There are many ways to identify flow units [8-9], pore throat structure parameter method, flow zone index method (FZI/DRT), pore throat radius method, comprehensive parameter method, outcrop depositional interface analysis method, production dynamic parameter method and cluster analysis method. At present, the mainstream technologies for quantitatively identifying flow units in carbonate reservoirs are the flow zone index (FZI) method and Winland's R35 method [10-12].

3. FZI method
FZI method includes two petrophysical methods, rock quality index and flow zone analysis. The rock quality index reflects the reservoir's ability to store and seep. Flow units indicators can be inferred by the rock quality index, which reflect the seepage abilities of different rock types under current conditions, regardless of the rock deposition in the formation. Porosity and permeability data from core test were used to calculate the flow units according to the following formula [13],

\[
RQI = \frac{K}{\Phi_e^{\alpha}} \quad (1)
\]

In formula (1), \( K \) is permeability (md), \( \Phi_e \) is effective porosity (fraction), RQI is rock quality index (\( \mu \)m).

\[
\Phi_e = (\frac{\Phi_e}{1+\Phi_e}) \quad (2)
\]

In formula (2), \( \Phi_e \) is a normalized porosity.

\[
FZI = \frac{RQI}{\Phi_e} = 0.0314 \left( \frac{1-\Phi_e}{\Phi_e} \right)^{\frac{K}{\Phi_e}} \quad (3)
\]

In formula (3), FZI is the flow zone index (\( \mu \)m).

FZI is a continuous variable, which is a parameter that determines the pore structure by combining structural and rock mineralogical and pore throat features, and it can accurately describes the heterogeneous characteristics of the reservoir. We can apply statistical rules to convert FZI to discrete variables DRT.

\[
DRT = \text{Round}[2 \ln(FZI) + 10.6] \quad (4)
\]

In formula (4), DRT is rock type. Eq.4 is merely a simple tool to convert a continuous rock type variable (FZI) into a discrete one [14].

161 core samples from 15 wells in K oil field were taken and flow units of the oilfield were calculated according to the FZI method. By calculating the RQI, FZI, and DRT parameters, the FZI value can be divided into 6 flow units from small to large. Different color (Fig. 1) represents different flow unit.

Figure 2 is a typical thin section of six rock types representing six different pore throat structures in the field. DRT8 is interparticle-moldic micropore, DRT9 is interparticle mesopore, DRT10 is interparticle-moldic mesopore, DRT11 is interparticle-moldic macropore, DRT12 is vuggy-moldic macropore, and DRT13 is vuggy-channelling. DRT8 is identified as having the worst pore geometry and pore structure, DRT13 has the best pore geometry and pore structure.

By fitting a simple function to study the relationship between porosity and permeability in each flow unit, it is found that the relationship between core porosity and core permeability becomes regular and no longer chaotic and unsystematic. Table 1 shows the relationship of porosity and permeability for different flow units, with correlations above 0.9.
Table 1. The relationship of porosity and permeability in DRT

| Flow Units | Relationship formula | Correlation coefficient |
|------------|----------------------|------------------------|
| DRT8       | $K = 213.19 \times \phi^{3.3115}$ | 0.97                   |
| DRT9       | $K = 453.56 \times \phi^{3.1505}$ | 0.97                   |
| DRT10      | $K = 1535.9 \times \phi^{3.4334}$ | 0.98                   |
| DRT11      | $K = 4320.3 \times \phi^{3.2931}$ | 0.98                   |
| DRT12      | $K = 12663 \times \phi^{3.3931}$  | 0.98                   |
| DRT13      | $K = 29008 \times \phi^{3.2849}$  | 0.99                   |

In order to verify the relationship between flow units and capillary pressure curve (J function), the initial water saturation and J-function relationships in different flow units were calculated by fluid test.
data from K Oilfield. The J function can be calculated by porosity, permeability, and capillary pressure (equation 5)

\[ J = \frac{P_e}{\sigma \cos \theta} \sqrt{\frac{K}{\Phi}} \]  

(5)

Where \( K \) is permeability (md), \( \Phi \) is porosity (fraction), \( \sigma \) is interfacial tension (dynes/cm), and \( \theta \) is contact angle (degrees).

According to the core mercury regression analysis, the relationship between the J function and the water saturation can be obtained. Figure 3 shows the relationship between the J function and the water saturation of different flow units. It can be seen from the plate that the J function for DRT13 has best reservoir properties, while the J function for DRT8 has poor reservoir properties, and the J functions of DRT12 to DRT9, the curves are arranged in order from good reservoir to bad reservoir.

Through function fitting, we can get the relationship of J function and \( S_w \) in different flow units (equation 6).

\[ S_w = a \cdot J^b \]  

(6)

Where \( a \) and \( b \) are regression constants. In different flow units, the regression constants are different (Table 2):

| Flow units | a    | b    | R2   |
|------------|------|------|------|
| DRT8       | 0.3054 | -3.391 | 0.7527 |
| DRT9       | 0.0505 | -6.218 | 0.8979 |
| DRT10      | 0.0763 | -3.552 | 0.9469 |
| DRT11      | 0.0452 | -4.388 | 0.8803 |
| DRT12      | 0.0623 | -2.705 | 0.9026 |
| DRT13      | 0.184  | -1.446 | 0.9715 |

Through the above method research, the classification method of flow units in K Oilfield can reveal the specific relationship between porosity and permeability and the correlation with J function.

4. Establishment and Application of Flow Units Model

Flow unit classification is based on core data, and its calculation method provides us with a more reliable quantitative template, but the core data is limited after all. How to apply it to a well or even the whole
field? Here we use the multiple linear regression method to establish the relationship between log data and FZI.

Several Well log curves that are sensitive to FZI are selected. In this study, six log curves of caliper (CALI), acoustic (DT), natural gamma ray (GR), resistivity (ILD), neutron (NPHI), and density (RHOB) were selected and normalized by using the following formula:

\[
N_x = \frac{(X-X_{\text{min}})}{X_{\text{max}}-X_{\text{min}}}
\]  

In formula (10), \( N_x \) is the normalized value, \( X \) is the logging curve value, \( X_{\text{min}} \) is the minimum value of the logging curve, and \( X_{\text{max}} \) is the maximum value of the logging curve.

Multivariate linear regression was used to get the relationship between FZI and each curve (equation 11).

\[
FZI = a + b \cdot \text{CALI} + c \cdot \text{DT} + d \cdot \text{GR} + e \cdot \text{ILD} + f \cdot \text{NPHI} + g \cdot \text{RHOB}
\]  

Where \( a=-5.728; b=-2.587; c=7.345; d=0.256; e=0.714; f=1.39; g=9.312 \).

Using the above formula, the FZI curve for all non-coring wells can be calculated.

The FZI curve was scaled up and the FZI model (Fig. 4) was built by sequential gaussian simulation conditioned to the porosity model. The FZI model is an interpolation model with continuous variables. In order to characterize different flow units more clearly, the FZI model was transformed into the DRT model (Fig. 5) using formula (4). The DRT model is a discrete volume. The data type is similar to sedimentary facies or lithofacies. DRT11 is the main rock type distributed throughout the reservoir, especially in the upper part (Fig. 5). At the edge of the oil field, the distribution is poorly physical flow units (DRT8 and DRT9), which are interpreted as being in the transition zone near the slope of the basin phase.
According to the previous study of the flow units, each flow unit has a unique pore-permeability curve and capillary pressure curve (J-function). Therefore, on the basis of the porosity model, according to the formula of table 2, the permeability in each DRT is calculated and the permeability model (Fig. 6) is obtained.

Using the established porosity model, permeability model, and oil column height model, a three-dimensional J-function model was calculated using formula (5). Then we use Formula (6) can be used to calculate the water saturation model (Fig. 7).

The established permeability model and oil saturation model are controlled by flow units and verified by numerical simulation to meet the dynamic needs. This study shows that the permeability model and the oil saturation model of carbonate reservoirs can be established using flow units control. After the established model has been verified by numerical simulation, it can provide the basis for the determination of the next stage oilfield development plan.

5. Conclusions
1) The K oil field carbonate reservoir was studied by the FZI method. According to the core porosity data and core permeability data, the reservoir was divided into 6 flow units using an empirical formula. Each flow unit has only pore-penetration relationship and capillary pressure curve (J function).
2) Since each flow unit has similar pore structure and percolation characteristics, the flow units can be used as a property to establish a 3D geological model, and the flow units constrains the establishment of the permeability model and the oil saturation model.
3) Through numerical simulation, the established permeability model and oil saturation model meet the dynamic needs and they can provide the basis for the determination of the next stage development plan.

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