Research Article

Prediction of Intraformational Remaining Oil Distribution Based on Reservoir Heterogeneity: Application to the J-Field

Jie Zhang,1 Feifei Fang,2 Jie Wang,2 Yajie Tian,3 Fei Mo,2 Qi Li,1 Sainan Li,2 Xiaoliang Huang,2 and Yi Yang1

1Institute of Porous Flow and Fluid Mechanics, University of Chinese Academy of Sciences, Langfang 065007, China
2School of Petroleum Engineering, Chongqing University of Science & Technology, Chongqing 401331, China
3Oil Field Development Research Institute, Research Institute of Petroleum Exploration and Development, PetroChina, Beijing 100089, China

Correspondence should be addressed to Feifei Fang; fangfeifei@cqust.edu.cn

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At high water cut stage, the study of remaining oil distribution in water-flooding reservoir is the basis of implementing potential-tapping measures and enhancing oil recovery. At present, most of the oilfields in China have entered the stage of ultrahigh water cut. The reserves of the oilfields are highly developed, the situation of water flooding is extremely complex, and it is difficult to predict the distribution of the remaining oil, which seriously restricts the adjustment of the production measures, tapping the potential and improving the ultimate recovery rate. In view of aforementioned difficulties, this study puts forward a research approach to predict remaining oil distribution based on reservoir heterogeneity, which can quantitatively characterize reservoir heterogeneity. In order to avoid the drawback that a single parameter cannot fully describe the characteristics of pore structure, the composite index of pore structure (SQRT(K/Φ)) is introduced to study the pore microstructure. The composite index of pore structure is used to predict the distribution of remaining oil in the formation, and the results are basically consistent with those calculated by numerical simulation. It is concluded that the larger the fractal dimension of the composite index of pore structure is, the stronger the heterogeneity of reservoir is; the smaller the composite index of pore structure is, the smaller the recovery degree is. The composite index of pore structure is used to analyze and predict the distribution of remaining oil in the layer, which provides a new direction for the prediction method of remaining oil.

1. Introduction

At present, the development of the main oilfields in China mostly enters the stage of high water cut stage, the distribution of underground fluid is becoming more and more complex, and the exploitation is becoming increasingly challenging. Therefore, it is of great significance to know exactly the remaining oil reserves and their distribution for the adjustment of the production measures, potential tapping, and ultimate recovery enhancement of the oilfield, and it is also an important means to realize the development strategy of “water control and oil stabilization” [1].

In recent years, although the method of remaining oil description has developed rapidly, most of them are qualitative description except numerical simulation method, and the further development of this technology is hindered by the degree of popularization, the depth of research, and the high cost of testing [2]. Present research on remaining oil mainly focuses on the following three aspects: (1) remaining oil distribution and characteristic study [3], (2) measuring and monitoring study on remaining oil saturation (ROS) [4], and (3) potential-tapping technology study [5].

Because of the complexity of oil-water relationship of the reservoir in the high water cut stage, it is more difficult to study the distribution of remaining oil. It is inevitable to have great limitations to predict the distribution of remaining oil based on a single subject. Therefore, only the application of multidisciplinary theory, method, and
technology can accurately predict the distribution of remaining oil.

The manifested evidences suggest that interlayer heterogeneity, interior-layer heterogeneity, and plane heterogeneity have an effect on the remaining oil distribution [6]. Because of the difference of heterogeneity in the reservoir layer, the water drive effect of different microfacies in the vertical direction is different, and the distribution of remaining oil is uneven and concentrated in the strongly heterogeneous region. Influenced by the heterogeneity of reservoir layers, the remaining oil is usually concentrated in the single layer with large permeability range and poor physical properties. In the plane, restricted by the distribution, scale, connectivity, and spatial combination of sand bodies, the microfacies with relatively poor physical properties and large permeability range in the reservoir are also the main enrichment areas and potential exploration targets of remaining oil.

Webber puts forward the classification system of quantitative recognition of heterogeneity in the stage of oilfield evaluation and development [7]. Considering heterogeneity and its influence on fluid flow, reservoir heterogeneity is divided into seven types: closed or semiclosed or unclosed fault, unit boundary, permeable unit in unit, interlayer in unit, lamination or cross bedding, micro-heterogeneity, and closed or open fracture. Daws and Prosser proposed to divide reservoir heterogeneity into five grades from large to small: sedimentary strata, sedimentary facies, boundary/beding, lamination, and diagenesis [8]. According to the characteristics of continental reservoirs and production practice, Qiu et al. put forward a classification scheme to study reservoir heterogeneity from interlayers and interior layers, plane, and microlevel [9]. In addition, there are some effective methods for studying reservoir heterogeneity that uses dynamic-based indicators such as tracers and local grid refinement and downscaling [10–13].

The heterogeneity of oil and gas reservoir is not only the main factor to control oil and gas accumulation but also the basis of remaining oil distribution research [14, 15]. With the increasingly severe exploitation situation of major oil fields and the deepening understanding of the importance of remaining oil exploration, the research on reservoir heterogeneity has been deepened and developed, and the research contents and methods have been improved and enriched.

According to the present situation of oil and gas field development in China, the relationship between reservoir heterogeneity and remaining oil distribution is discussed by studying reservoir heterogeneity. We introduce the parameter of the composite index of pore structure and apply it to the study of the heterogeneity in the macroscopic layer. The composite index of pore structure can accurately represent not only the characteristics of micropore structure but also the degree of heterogeneity in the reservoir, which is a kind of parameter connecting the micro- and macro-description. Based on this, the composite index of the pore structure combined with the numerical simulation method is proposed to analyze and predict the distribution of remaining oil.

2. Quantitative Characterization of Reservoir Heterogeneity

According to the reservoir classification scheme put forward by Qiu and Chen [9], reservoir heterogeneity is classified into interlayer heterogeneity, plane heterogeneity, interior-layer heterogeneity, and pore heterogeneity. Interlayer heterogeneity includes the rhythmicity of rock granularity, the sequence of bedding structure, the permeability difference and the location of high permeability section, the distribution frequency and size of discontinuous thin shale in the layer, the distribution of other impermeable interlayer, and the ratio of vertical permeability. Pore heterogeneity mainly refers to the heterogeneity of micropore structure, including sand body pore, throat size and its uniformity, configuration, and connectivity of pore throat. In this paper, the quantitative characterization of heterogeneity of the study area is described from a macro-perspective.

2.1. Geological Characteristics. The study area is about 25 km east of “K” City, which is located in a reverse fault zone in the northwest margin of “J” basin. The north, southeast, and west are, respectively, bounded by faults. The faults in the north act as the function of blocking the reservoir. The study area is a structural- lithological reservoir blocked by faults (Figure 1).

In general, the study area is a NW-SE structural reservoir blocked by faults, with a dip angle of 2–30, and the depth of the middle part of the reservoir is 1340 m. The block is formed by three faults.

Sedimentary microfacies can be divided into three subfacies: fan root, fan subfacies, and fan margin. Among them, fan root subfacies mainly develop braided channel microfacies, fan subfacies mainly develop braided channel and slow flow sand microfacies, and fan margin mainly develops overland mud microfacies.

The “K” formation in the study area is unconformity deposited on the carboniferous reservoir, and the upper layer is successively deposited by the Baijiantan formation (T1b), Badaowan Formation in Jurassic System (J1b), Sanronghe Formation (J1s), Xishanyao Formation (J1x), Toutunhe Formation (J1t), Qigu formation (J1q), and Tugulu group (K1t) of Cretaceous System. The study area is K7 sand formation, and K7 sand consists of four layers K7−1, K7−2, K7−3, and K7−4 and is subdivided into nine layers K7−1, K7−2, K7−3, K7−4, K7−5, K7−6, K7−3−2, K7−3−3, K7−4−1, and K7−4−2. The main oil layers are K7−1, K7−2, and K7−3.

2.2. Study on the Heterogeneity of Permeability in Layers.

The heterogeneity in a single sand layer refers to the change of its internal vertical reservoir properties, including the change of permeability in the vertical layer. The variation range of porosity of K7−1 sand group in the study area is mainly from 12%–16%, and the variation range of permeability is 8 × 10−3 μm²–17 × 10−3 μm². According to the results of stratigraphic division, K7 sand consists of four layers K7−1, K7−2, K7−3, and K7−4 and is subdivided into nine layers K7−1, K7−2−1, K7−2−2, K7−2−3, K7−3−1, K7−3−2, K7−3−3, K7−4−1, and K7−4−2.
The permeability heterogeneity parameters of each sublayer are shown in Table 1.

The analysis of permeability heterogeneity shows that porosity and permeability have little change, and the heterogeneity in the layer is weak. In general, the average permeability difference of each small layer in K7 sand formation is small, and the heterogeneity is not strong [2].

Generally speaking, the larger the \( V_k \), \( T_k \), and \( J_k \), the stronger the reservoir heterogeneity, otherwise weaker. The classification standard of the heterogeneity of clastic rock reservoir in China mainly adopts the standard issued by China National Petroleum Corporation (CNPC), as shown in Table 2.

According to Table 2, we judged that the heterogeneity type in K7 sand group is a relatively homogeneous type. Permeability contour map of K7 sand formation is shown in Figure 2. It can be seen that the plane permeability is also relatively uniform, mainly concentrated in 10–18 mD.

2.3. Study on Heterogeneity in Layers with Pore Structure Index. The size and distribution of pore radius can be roughly reflected by the pressure and saturation of mercury withdrawal [16, 17]. It is not only a function of pore throat radius distribution and pore volume but also a function of porosity, permeability, and saturation. The quantitative characteristic parameters of capillary pressure curve, which can characterize the pore structure of reservoir, mainly include displacement pressure, saturation median pressure and median radius, maximum mercury saturation, and efficiency of mercury withdrawal, which are the important basis to reflect the microheterogeneity of the reservoir. Mercury injection data of K7\(^1\), K7\(^2\), K7\(^3\), and K7\(^4\) are collected, as shown in Figure 3.

According to the mercury injection data of each layer, the curves of the K7\(^3\) layer are similar, which proves that the pore structure of the rock samples taken from the K7\(^4\) layer is similar. After analysis and comparison, we conclude that the heterogeneity of four small layers is gradually weakened.

The composite index of the pore structure in four layers of K7 sand group is used to study the reservoir heterogeneity, which can truly reflect the pore structure characteristics of samples. Using geological model data to calculate the frequency distribution of composite index of pore structure of each layer, it can be seen from Figure 4 that the heterogeneity in layer K7\(^3\) is strong, and the index is widely changed between 0.5–2.5 as can be seen from Figure 4(a). The heterogeneity in layer K7\(^4\) is relatively weak, and the index is mainly changed between 0.5–1.5 as can be seen from Figure 4(d).

It is generally believed that the fractal dimension of \( \text{SQRT}(K/\Phi) \) in three-dimensional Euclidean space is mostly in the range of 2–3 [18, 19]. The closer the fractal dimension is to 2, the weaker the heterogeneity is and the better the reservoir capability is. The closer the fractal dimension is to 3, the rougher the pore throat surface is, the worse the reservoir capability is, and the stronger the heterogeneity of the reservoir is [20]. We used the core data to analyze the fractal dimension of the composite index of pore structure \( \text{SQRT}(K/\Phi) \) in the layer, as shown in Figure 5. The fractal dimension of the K7\(^3\) layer is 2.88, that of the K7\(^2\) layer is 2.74, that of the K7\(^3\) layer is 2.73, and that of the K7\(^4\) layer is 2.38. The fractal dimension of the K7\(^3\) layer is the largest, so the heterogeneity in the layer is relatively the strongest. At the same time, the fractal dimension of the K7\(^4\) layer is the smallest, and the heterogeneity in the layer is also the smallest. We conclude that, from the K7\(^3\) layer to K7\(^4\) layer, the heterogeneity in the reservoir is gradually weakened.
The intraformational heterogeneity obtained by using the frequency distribution of the composite index of the pore structure calculated by the geological model data is consistent with the intraformational heterogeneity obtained by using the core data to analyze the interlayer’s composite index of pore structure. The larger the fractal dimension of...
SQRT (K/Φ) is, the stronger the heterogeneity is. The composite index of the pore structure can well reflect the heterogeneity in the layer.

3. Study on the Distribution Law of Remaining Oil in the Layer Based on Heterogeneity

The macroheterogeneity of the reservoir is mainly reflected in the geometry of sand body, reservoir lithology, physical property, permeability heterogeneity, and interlayer distribution, which have different controls over the distribution of remaining oil. The main factors controlling the distribution of remaining oil in this study area are as follows.

The heterogeneity is the key factor that affects the sweep volume of vertical injection water and the distribution of remaining oil. In the positive rhythm sand body, the remaining oil is mainly distributed in the upper-middle section with low permeability and weak washing degree. In the reverse rhythm sand body, the swept volume of injected water is large, the displacement of injected water is uniform, and the upper and lower parts are all the potential areas of remaining oil. It is generally believed that water is always injected along the relatively high permeability section, resulting in high water drive degree and low remaining oil saturation.

The intraformational heterogeneity obtained by using the frequency distribution of the composite index of the pore structure calculated by the geological model data is consistent with the intraformational heterogeneity obtained by using the core data to analyze the interlayer’s composite index of the pore structure. From the K71 layer to K74 layer, the heterogeneity in the reservoir is gradually weakened. From the oil saturation of the K72 and K73 layer (Figure 6), the displacement effect of the K74 layer is better than that of the K72 layer.

It can be seen from Table 3 that the recovery degree of the K74 layer is 19.18% and that of the K72 layer is 27.20%.
Figure 4: Frequency distribution of composite index of pore structure. (a) $K_1$. (b) $K_2$. (c) $K_3$. (d) $K_4$.

\[ y = -2.8898x + 3.8297 \] \[ R^2 = 0.9523 \]

Figure 5: Continued.

\[ y = -2.7465x + 3.7197 \] \[ R^2 = 0.9436 \]
Fractal dimension of composite index of the pore structure. (a) $K_7^1$. (b) $K_7^2$. (c) $K_7^3$. (d) $K_7^4$.

Figure 6: Continued.
Figure 6: Oil saturation of (a) K₇² and (b) K₇⁴ (at present).

Table 3: Statistics of crude oil recovery (at present).

| Layer | Geological reserves (10⁴ t) | Cumulative oil production (10⁴ t) | Recovery degree (%) | Remaining oil volume (10⁴ t) |
|-------|-----------------------------|----------------------------------|---------------------|-----------------------------|
| K₇¹   | 25.7                        | 3.2434                           | 12.62               | 22.46                       |
| K₇²   | 22.1                        | 6.0123                           | 27.20               | 16.09                       |
| K₇³   | 39.6                        | 11.9182                          | 30.10               | 27.68                       |
| K₇⁴   | 28.3                        | 5.4282                           | 19.18               | 22.87                       |

Figure 7: Frequency distribution of the composite index of the pore structure. (a) K₇². (b) K₇⁴.
4. Conclusions

In this study, the composite index of the pore structure (SQRT(K/Φ)) is introduced to study the pore microstructure of the reservoir, which can be used to quantitatively characterize the heterogeneity of the reservoir, and this parameter (SQRT(K/Φ)) can comprehensively describe the characteristics of the micropore structure well. The interlayer distribution of remaining oil can be predicted by using the composite index of the pore structure (SQRT(K/Φ)), and the result is basically consistent with that calculated by the numerical simulation method. It is found that the larger the fractal dimension of the composite index of the pore structure is, the stronger the heterogeneity of reservoir is; the smaller the fractal dimension of the composite index of the pore structure is, the weaker the intraformational heterogeneity of the reservoir is.

(1) The intraformational heterogeneity is related to the composite index of the pore structure. The larger the fractal dimension of the composite index of the pore structure is, the stronger the intraformational heterogeneity of the reservoir is; the smaller the fractal dimension of the composite index of the pore structure is, the weaker the intraformational heterogeneity of the reservoir is.

(2) The interlayer distribution of remaining oil can be predicted by using the composite index of pore structure (SQRT(K/Φ)), and the result is basically consistent with that calculated by the numerical simulation method. The smaller the index is, the lower the recovery degree is, and the remaining oil is also relatively richer. This also explains the abnormal phenomenon that the displacement effect of the K7 layer is better, but the recovery degree is smaller.

Data Availability

The data used to support the findings of this study are available from the corresponding author upon request.

Conflicts of Interest

All authors declare that there are no conflicts of interest regarding the publication of this article.

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