Quantitative Description for the Heterogeneity of Pore Structure by Using Mercury Capillary Pressure Curves

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ABSTRACT

Pore structure of reservoir rock is one of the most important factors to affect microscopic oil and water flowing in porous media and the development efficiency of an oil field developed by water injection. There are now many methods for describing pore structure. However, much attention is being paid to develop better and more efficient methods. Fractal dimension has been used to quantitatively describe the heterogeneity of pore structure in this paper. It has been showed that the larger the fractal dimension of pore structure, the more heterogeneous the pore structure for sandstones, sandstones with gravel and pinhole dolomite rocks. The fractal dimension of pore structure is calculated from the mercury-injection capillary pressure curve of the rock.

The typical two-section fractal behaviour of sandstone pore structure in Lamadian Oilfield, Daqing has been studied in this paper. It has been found that there is a good correlation between the fractal dimension of large pores with fractal behaviour and the oil recovery at water breakthrough while there is also a good relationship between the fractal dimension of the small pores with fractal behaviour and irreducible water saturation. This shows that the large fractal pores affect the amount of oil recovery at water breakthrough and the small fractal pores affect the amount of irreducible water saturation for this type of sandstones from Lamadian Oilfield. It has also been found that there is no relationship between the fractal dimension of pore structure and the oil recovery at water breakthrough if the pore structure of sandstone from Lamadian Oilfield was treated as one-section fractal structure.

INTRODUCTION

There are now two basic methods to study pore structure. One of them is to use mercury-injection capillary pressure curve (mercury-injection method)\(^1\). Another is image analysis method\(^3\). Relatively, mercury-injection method is used more frequently. Some characteristic and statistical factors of a capillary pressure curve such as pore geometry factor \(G\), threshold pressure \(P_a\) proposed by Thomeer\(^4\), puzzler coefficient proposed by Dullien\(^5\) and microscopic homogeneous coefficient \(\alpha\) proposed by Shen Pingping et al\(^6\) are usually used to describe pore structure when mercury-injection method is applied.

In recent years, it was found that pore structures of sandstones or other porous media are fractals. Hence, it is possible to use fractal dimension for describing...
the characteristics of pore structure\cite{8,9,10,11,12}. Different methods (for example, small angle X-ray scattering method\cite{7}, SEM method\cite{8} and image analysis method\cite{12} and so on) for calculating fractal dimension were used by different researchers.

The authors of this paper developed a method to calculate the fractal dimension of pore structure by using mercury-injection capillary pressure curve\cite{11}. This method might be the simplest one among methods for calculating fractal dimension of pore structure. Moreover, this method is of better universality. It is proved in this paper that not only pore structures of sandstones but also those of the sandstones with gravel and pinhole dolomite are fractal structures.

There are many factors to affect oil recovery by water flooding among which the major factors are wettability, oil/water viscosity ratio, flooding velocity and the characteristics of pore structure. Oil recovery by water flooding should be correlated with the characteristics of pore structure in some extent when the wettability, flooding velocity and oil/water viscosity ratio are made constant. It is obvious that the heterogeneity of pore structure would affect the oil recovery by water flooding. The more heterogeneous the pore structure, the smaller the oil recovery at water breakthrough. Dullien\cite{5} showed that there was a good relationship between the puzzler coefficient and the oil recovery. Wardlaw\cite{14} studied the effects of 27 petrophysical factors on the oil recovery and the results showed that the relationships between porosity, pore/throat ratio and oil recovery were the best. Neashaw\cite{15} studied the relationship between pore geometry factor $G$ and oil recovery. Shen Pingping et al\cite{6} studied the relationship between the microscopic homogeneous coefficient $\alpha$ and oil recovery. Li Kevin\cite{12}, Jia Fenshu et al\cite{13} studied the effects of pore structure on the water-flooding characteristics by the combination of image analysis and fractal techniques. The relationships between oil recovery at water breakthrough, irreducible water saturation and fractal dimensions calculated from mercury-injection capillary pressure curves of pore structures are investigated in this paper.

The forming mechanism of 2-section fractal behaviour of Lamadian Oilfield sandstone is also studied in this paper.

**FRACTAL DESCRIPTION OF PORE STRUCTURE**

Fig.1 showed three mercury-injection capillary pressure curves of three samples of sandstone with gravel from an oilfield in Xinjiang. The permeabilities of three core samples are almost the same. It can be seen from the shapes of three capillary pressure curves in Fig.1 that the heterogeneity sequence of the three core samples is A1$<$A2$<$A3. However, this type of description for pore structure is just qualitative. The fractal dimensions of three core samples are calculated from the capillary pressure curves shown in Fig.1 with the method proposed by the authors\cite{11} as follows:

\[
D(A1)=2.85 \\
D(A2)=2.92 \\
D(A3)=3.05
\]

It is clear that:

\[
D(A1)<D(A2)<D(A3), \quad (1)
\]

The larger the fractal dimension of a fractal structure, the more complicated the fractal structure from the basic theory of fractal geometry. It can be summarized from the fractal theory above and the characteristics of capillary pressure curves shown in Fig.1 that the larger the fractal dimension, the stronger the heterogeneity of the pore structure of sandstone with gravel. The fractal behaviours of the three core samples are much different although their permeabilities are the same.

The same rule as described above exists for pinhole dolomite samples. That is, the larger the fractal dimension of the pore structure of pinhole dolomite, the stronger the heterogeneity of its pore structure. An example is given as follows. Fig.2 shows three typical mercury-injection capillary pressure curves of three pinhole dolomite samples from an oilfield. It can be seen from the shapes of three capillary pressure...
cum es m Fw.2 that the heterogeneity sequence of the three core samples is B1<B2<B3. The fractal dimensions of the three pinhole dolomite core samples are calculated as follows:

\[
\begin{align*}
D(B1) &= 2.63 \\
D(B2) &= 2.80 \\
D(B3) &= 3.00
\end{align*}
\]

It is clear that:

\[
D(B1)<D(B2)<D(B3), \tag{2}
\]

It can be summarized from equation (2) and Fig.2 that the larger the fractal dimension of the pore structure of the pinhole dolomite, the stronger the heterogeneity of its pore structure. Analysis results\textsuperscript{111} of sandstone samples also showed that the same rule as described above exists in the pore structure of sandstone.

Pore geometry factor G can also be used to describe the heterogeneity of pore structure. It is assumed that capillary pressure curves would be hyperbolic curves when the value of G is calculated. On the other hand, capillary pressure curves may not be exactly hyperbolic curves for any core samples. The value of G may be negative for some core sample. So there is much limitation to the application of G factor for describing the heterogeneity of pore structure quantitatively.

It may be concluded from the analysis above that the use of fractal dimension to describe the heterogeneity of pore structure is characteristic of more exact theoretic basis and wider universality.

TWO-SECTION FRACTAL BEHAVIOUR AND ITS INTERPRETATION

From the literatures published now, only linear or one-section fractal distribution as shown in Fig.3 is included when fractal technique is used to describe the characteristics of pore structure. The fractal curve shown in Fig.3 is transferred from the mercury-injection capillary pressure curve shown in Fig.4 with the method proposed by the authors\textsuperscript{111}. It is seen in Fig.3 that the fractal curve may be divided into two parts. That is, the linear part with the pore-throat radius less than \(r_0\) and the non-linear part with pore-throat radius larger than \(r_0\). The pore-throats corresponding to the linear part are characteristic of self-similarity that are known as fractal pore-throats. Pore-throats corresponding to the nonlinear part are characteristic of non self-similarity that are known as non-fractal pore-throats. The behaviour of the fractal curve shown in Fig.3 is similar to the result of Krohn\textsuperscript{9} who found that the pore size distribution in sandstone might be divided into 2 regimes by using SEM technique. One is the regime of short-length pores with fractal behaviour. Another is the regime of long-length pores with no fractal behaviour.

However, pore structure is of diversification because of the complexity of geological property and sedimental environment. It is found that two-section fractal behaviour as shown in Fig.5 exists in the pore structure of sandstone from Lamadian Oilfield. The mercury-injection capillary pressure curve corresponding to the fractal curve in Fig.5 is shown in Fig.6. It can be seen in Fig.5 that the pore structure of sandstone from Lamadian Oilfield may be divided in three regimes. The first one is the regime of pore-throat radius larger than \(r_0\) with no fractal behaviour. The second one is the regime of pore-throat radius less than \(r_0\) but larger than \(r_0\) with fractal behaviour and this regime is known as a regime with large fractal pores. The third one is the regime of pore-throat radius less than \(r_0\) with fractal behaviour and this regime is known as a regime with small fractal pores. The two regimes with pore-throat radius less than \(r_0\) are all fractals but the fractal dimensions of the two regimes are much different. Difference between fractal dimensions of two regimes indicates that the properties of pore-throat size distribution in different regimes are different. Existence of the 2-section fractal behaviour in the sandstone pore structure from Lamadian Oilfield is determined by the reservoir geological property.

The major rock in Lamadian Oilfield is mesograin-fine sandstone. The cement material is shale. Its shale content ranges from 3% to 10% and its average value is about 7.85%. The major mineral of shale is kaolinite.
As shown in Fig. 7, the photographs of SEM indicate that the pore space in sandstone from Lamadian Oilfield is dominated by intergranular pores which provide the major flowing paths of fluids through sandstone. It can also be seen in Fig. 7 that the particle surface is clear. Even if there is some kaolinite, the kaolinite particles are filled as a bridge in the granular pore space. The dead pores are very little.

Compared with the fractal curve in Fig. 5, the intergranular pores shown in Fig. 7 with radius larger than \( r_o \) have no fractal behaviour. The intergranular pores with radius less than \( r_o \) but larger than \( r_d \) have fractal behaviour. The analysis to the SEM photographs showed that the shale content in the regime with radius larger than \( r_o \) is less than that in the regime with radius less than \( r_o \) but larger than \( r_d \).

Although the major pores of sandstone from Lamadian Oilfield are intergranular pores, there are some small pores between clay particles which can be observed in Fig. 8. These pores are occupied by irreducible water. There is no contribution of these small pores to the flowing of fluids through rocks. These small pores are corresponding to the regime with radius less than \( r_d \) which also have fractal behaviour. However, the fractal dimension of this regime is higher than that of the regime with radius less than \( r_o \) but larger than \( r_d \).

As said above, the major mineral of shale in Lamadian Oilfield is kaolinite. The occurrence of kaolinite is vermiciform or sheet-like as shown in Fig. 8. The distribution behaviour of the small pores between clay particles is much different from that of intergranular pores. This property is represented by the fractal curve of 2-section with different fractal dimensions as shown in Fig. 5.

Because the small pores between clay particles are occupied by irreducible water, the pore structure property of intergranular pores would affect the oil and water flow. That is, the fractal dimension of the regime with radius less than \( r_o \) but larger than \( r_d \) shown in Fig. 5 should be correlated with the oil recovery by water flooding in laboratory assuming the oil/water viscosity, wettability and flooding velocity constant. The experimental results showed that there is a good relationship between the fractal dimension of the regime with radius less than \( r_o \) but larger than \( r_d \) and the oil recovery while there is no relationship between the fractal dimension of the regime with radius less than \( r_d \) which is occupied by irreducible water and the oil recovery by water flooding. This will be discussed in detail at the next section.

**APPLICATIONS**

To study the effects of the fractal dimension of pore structure on the oil recovery by water flooding and irreducible water saturation, 22 natural core samples are selected from Lamadian Oilfield. Two plug samples are drilled from each large core sample. The porosities and permeabilities of the two plug core samples are almost the same. One plug core sample is used to do mercury-injection test so that its capillary pressure curve is obtained. Another plug core sample is used to do flooding test. At first, this plug core sample is cleaning and drying. Then it is saturated by the formation water after the measurements of porosity and permeability are done. The irreducible water saturation is set up by crude oil flooding. The plug core samples are aged at reservoir temperature and pressure for about one month to restore rock wettability before water flooding. Oil recovery is measured. The experimental procedures in detail and the instrument used are the same as those described in literature [16].

Fig. 9 shows the relationship between oil recovery of 22 natural core samples at water breakthrough and the fractal dimension \( D_{fr} \) of the regime with radius less than \( r_o \) but larger than \( r_d \). It can be seen in Fig. 9 that the larger the fractal dimension \( D_{fr} \), the smaller the oil recovery at water breakthrough. The reason is that the larger fractal dimension \( D_{fr} \) implies the stronger heterogeneity of the pore structure related to the flowing of oil and water. It is obvious that the stronger the heterogeneity of pore structure, the more irregular the propagation of the water flooding front and the smaller the oil recovery at water breakthrough.
breakthrough.

The relationship between oil recovery at water breakthrough and fractal dimension \( D_{n} \) is represented as:

\[ \eta_{wtr} = -17.15D_{n} + 45.40, \]  

(3)

The correlation coefficient is 0.76. The required correlation coefficient for the linear relationship represented by equation (3) is 0.515 at the confidence level of 0.01. So, the oil recovery at water breakthrough and the fractal dimension \( D_{n} \) is correlated obviously.

If the pore structure of sandstone from Lamadian Oilfield is not considered as a 2-section fractal curve shown in Fig.5 but a 1-section line, the data points of oil recovery at water breakthrough and fractal dimensions are plotted in Fig.10. It can be seen clearly in Fig.10 that there is no relationship between the two parameters.

Fig.11 shows the relationship between irreducible water saturation set up by oil flooding and the fractal dimension \( D_{B} \) of regime with radius less than \( r_{B} \). It is shown in Fig.11 that the larger the fractal dimension \( D_{B} \) of regime with radius less than \( r_{B} \), the higher the irreducible water saturation. Its relationship can be represented as:

\[ S_{wtr} = 24.93D_{B} - 46.42, \]  

(4)

The linear correlation coefficient is 0.54. The required linear correlation coefficient for 22 samples is 0.515 at the confidence level of 0.01. So, the irreducible water saturation is obviously correlated with the fractal dimension \( D_{B} \).

The experiment results above showed that the effects of pore structure property of sandstone from Lamadian Oilfield on the oil recovery at water breakthrough are significant. It is found that the pore structure fractal behaviour of regime with radius less than \( r_{d} \) does not affect the amount of oil recovery at water breakthrough.

From what described above, use of fractal technique to describe pore structure quantitatively is a better way to investigate the effects of pore structure on the oil recovery at water breakthrough and the irreducible water saturation of reservoir rock.

**DISCUSSION**

Pore space in reservoir rock may be divided in two parts or pores and throats. Capillary pressure curves of both pores and throats can be measured by using constant-rate mercury-injection method\(^{[17]}\). Fractal dimensions of both pores and throats can be calculated from the capillary pressure curves of both pores and throats respectively. Therefore, the effects of both pores and throats on water flooding characteristics can be investigated in more detail and there is much more understanding to the microscopic flowing of oil and water through porous media.

**CONCLUSIONS**

1. The fractal dimensions calculated from mercury-injection capillary pressure curves can be used to describe the heterogeneities of sandstone, sandstone with gravel and pinhole dolomite rock quantitatively. The larger the fractal dimension, the stronger the heterogeneity of pore structure.

2. The pore space in sandstone from Lamadian Oilfield may be divided into three parts. The first part is the regime with radius larger than \( r_{o} \) and the pore space in this part has no fractal behaviour. The second part is the regime with radius less than \( r_{o} \) but larger than \( r_{d} \) and the pore space in this part has fractal behaviour. The third part is the regime with radius less than \( r_{d} \) and the pore space in this part also has fractal behaviour.

3. There is a good relationship between oil recovery at water breakthrough for sandstone samples from Lamadian Oilfield and the fractal dimension \( D_{B} \) of regime with radius less than \( r_{o} \) but larger than \( r_{d} \). The larger the fractal dimension \( D_{B} \), the lower the oil recovery at water breakthrough.
The larger the fractal dimension of regime with radius less than \( r_d \), the higher the irreducible water saturation in sandstone from Lamadian Oilfield.

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**NOMENCLATURE**

\[ \eta_{sw} = \text{Oil recovery at water breakthrough.} \]
\[ S_w^* = \text{Irreducible water saturation.} \]
\[ D_P = \text{Fractal dimension of regime with radius less than } r_d \text{ but larger than } r_0. \]
\[ D_G = \text{Fractal dimension of regime with radius less than } r_d. \]
\[ \alpha = \text{Microscopic homogeneous coefficient} \]
\[ G = \text{Pore geometry factor.} \]

**REFERENCES**

Fig. 1: Three typical Mercury-Injection Capillary Pressure Curves of Sandstone with Gravel Samples.

Fig. 2: Three typical Mercury-Injection Capillary Pressure Curves of Pinnacle Dolomite Samples.

Fig. 3: Typical Fractal Curve of Sandstone.

Fig. 4: Mercury-Injection Capillary Pressure Curve of GL93 Sandstone Sample.
Fig. 5: Typical 2-Section Fractal Curve of Sandstone Pore Structure in Laminian Oilfield

Fig. 6: Mercury-Injection Capillary Pressure Curve of Sandstone Sample D22 from Laminian Oilfield

Fig. 7: SEM Photograph of Sandstone from Laminian Oilfield
Fig. 8 Clay in Sandstone from Lamadian Oilfield

Fig. 9 Relationship Between Fractal Dimension D2 and Oil Recovery at Water Breakthrough
Fig. 10 Relationship Between Fractal Dimension \( D_f \) and Oil Recovery at Water Breakthrough

Fig. 11 Effect of Fractal Dimension \( D_f \) on Induced Water Saturation