Quantitative analysis of the influence of pore structure parameters on remaining oil after polymer flooding based on digital network model

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Abstract. There is still a large amount of remaining oil in formation after polymer flooding. Therefore, it is of great significance to clarify the factors affecting the distribution of remaining oil to further improve the oil recovery. By constructing a digital pore network model, this paper considers pore structure factors and simulates oil displacement efficiency after water flooding and polymer flooding. It simultaneously analyzes their influence of pore structure parameters on remaining oil and quantitatively characterizes the coordination number, shape factor, pore-throat ratio affected on pore-throat oil content ratio and oil saturation ratio. Evaluate the influence of the above factors on the remaining oil distribution after polymer flooding. The research results show that: the more coordination number, the larger the shape factor. However, other structural parameters, such as pore-throat ratio, the number of pore-throat oil content, the pore-throat oil saturation ratio and the probability of forming remaining oil, is smaller at the same time.

1. Introduction
In recent years, Li Zhenquan et al. have used pore network models to construct digital cores, study the theory of water flooding microscopic seepage, and analyze the influence of the model’s wettability on remaining oil distribution on the basis of CT scanning technology [1]. Xia Huifen [2, 3] did similar research about network model. Based on the water flooding, the effects of pore structure parameters and polymer injection parameters on the polymer flooding consequence were studied. Sun Yanyu [4] used a digital network model to study the relative permeability curves of polymer flooding and summarized some rules which the value of polymer concentration and the molecular weight was large, the relaxation time was long to cause higher the oil phase relative permeability curve. Xingjun et al. [5, 6] analyzed the parallel comparison between digital and real core experiments and the theory of seepage simulation. But they failed to analyze the influence of remaining oil distribution after polymer flooding by the number of oil content and oil saturation ratio of pore-throat. The author built a digital pore model through the pore network model to realize the characterization of the microscopic parameters of the reservoir in the model, and further studied the influence factors of the pore-throat oil ratio and oil saturation ratio after polymer flooding with a micro perspective on the remaining oil distribution after polymer flooding.
2. The construction of digital network model

In order to truly describe the pore structure of the underground rocks, the porous medium is used as the research object, and the corrugated tubular structure [4] is used to describe the complex pore throat channel of the reservoir. The pore radius is expressed by the following formula:

\[ r_p = \frac{\sum_{i=1}^{n} r_i}{n \times \alpha} \]  (1)

Where \( r_p \) is pore radius, \( r_i \) is throat radius, \( \alpha \) is average pore-throat ratio.

The mercury penetration experiment is used to determine the distribution frequency of pore-throat and the coordination number determined by CT scanning. The shape factor \( G \) studied by Mason et al. [7] is used to define the shape of the pore-throat section. \( G \) is:

\[ G = \frac{A}{P^2} = \frac{1}{4} \tan \alpha_1 \tan \alpha_2 \cot(\alpha_1 + \alpha_2) \]  (2)

Where \( G \) is shape factor, \( A \) is sectional area, \( P \) is section perimeter.

Using the principle of adaptive porosity, according to the porosity of the real reservoir core as the standard, the distance and offset between nodes are automatically adjusted to make the porosity of the constructed model reach the reference value of the real reservoir core, and the adjacent nodes are determined. The length of the throat can be calculated by formula (3).

\[ \phi = \frac{\sum_{i=1}^{n} V_{pi}}{\sum_{i=1}^{n} V_{tj}} + \frac{\sum_{i=1}^{n} V_{pi}}{D_x D_y D_z} \]  (3)

Where \( V_{pi} \) is some pore volume of porosity; \( i \) is the number of porosity in the model; \( V_{tj} \) is oil some volume of throat; \( J \) is the number of pore throat in the model;

\( D_x, D_y, D_z \) are the distances of the model in the X, Y and Z directions.

In this paper, the pore structure parameters of five natural cores are selected for calculation, and the calculation results of the digital pore model are compared with the actual results. The error is small, so as to verify the accuracy of the model.

| Table 1. Comparison of measured porosity and calculated porosity of rock. |
|------------------------|-------|-------|-------|-------|-------|
| Item                  | 1     | 2     | 3     | 4     | 5     |
| Measured porosity (%) | 25.4  | 24.5  | 24.2  | 25.0  | 27.7  |
| Calculated porosity (%)| 25.2  | 24.9  | 25.3  | 25.4  | 28.6  |

| Table 2. Basic parameters of pore structure model. |
|-----------------------------------------------|--------|--------|--------|--------|--------|
| Model parameter                            | Core 1 | Core 2 | Core 3 | Core 4 | Core 5 |
| Porosity (%)                               | 25.2   | 24.5   | 24.2   | 25.0   | 27.7   |
| Measured permeability \((10^{-13}\text{m}^2)\) | 598    | 39     | 185    | 370    | 623    |
| Throat length \((\mu m)\)                  | 15~167 | 3~65   | 8~155  | 21~187 | 16~168 |
| Throat radius \((\mu m)\)                  | 1~20   | 1~12   | 1~18   | 1~22   | 2~25   |
| Average coordination number                | 5.3    | 4.1    | 4.2    | 4.6    | 4.1    |
| Average pore throat ratio                  | 4.6    | 5.1    | 4.7    | 5.4    | 4.2    |
| Proportion of sectional circle             | 0.3    | 0.3    | 0.3    | 0.3    | 0.3    |
| Calculated permeability \((10^{-13}\text{m}^2)\) | 604    | 40     | 169    | 404    | 598    |

The digital pore network model constructed in this paper can reflect the geometric characteristics and topology of real reservoir rocks, and represent them to some extent. The established pore network model has \(8 \times 8 \times 8\) nodes. As shown in Fig.1, the sphere is the pore and the tube is the throat, which contains 512 pores and 993 throats. The simulation parameters of the pore model are shown in Table 1.
3. Results and Discussion

According to the basic parameters of the core, the digital network model is used to simulate and verify the polymer flooding process, which is compared with the results of the core flooding experiment.

### Table 4. Core polymer flooding experiment.

| Item | Porosity (%) | Permeability to water ($10^{-13}$ m$^2$) | Polymer molecular weight (10$^4$) | recovery |
|------|--------------|----------------------------------------|-----------------------------------|----------|
| 1    | 25.4         | 598                                    | 1600                              | 54%      |

### Table 5. Basic parameters of network model.

| parameter                        | value       | parameter                        | value   |
|----------------------------------|-------------|----------------------------------|---------|
| Throat radius ($\mu$m)           | 1~20        | Average pore throat ratio        | 4.6     |
| Throat length ($\mu$m)           | 15~167      | Aqueous density (g/cm$^3$)       | 1       |
| Average shape factor             | 0.062       | Oil phase density (g/cm$^3$)     | 0.88    |
| Porosity (%)                     | 25.2        | Aqueous viscosity (mPa·s)        | 0.6     |
| Average coordination number      | 5.3         | Oil phase viscosity (mPa·s)      | 10      |
| Polymer concentration (mg/L)     | 1000        | Polymer molecular weight (104)   | 1600    |

According to the settings of the basic parameters of the network model, the polymer flooding process is simulated. As shown in Figure 2, the correctness of the polymer flooding process simulation results has been verified, and the calculated values are in good agreement with the experimental values.

### Figure 2. Variation curve of the recovery degree of polymer flooding with PV number.
3.1. The effect of coordination number on remaining oil

After performing water flooding and polymer flooding in the digital pore model, the number of throats, pores, pore-throat oil content, and the percentage of oil contented in pore-throat, respectively in Table 6. It can be seen that as the coordination number increases, the channels connecting the pores to each other increase accordingly. So the number of oil in the throat and pores gradually decreases, and the probability of forming remaining oil reduces. It concludes that as the coordination number increases, the proportion of oil in the throats and pores is reduced.

| Coordination number | 4.3 | 5.4 | 6.1 |
|---------------------|-----|-----|-----|
| Total number of pore throat | 1234 | 1528 | 1632 |
| After water flooding | Total number of oil-bearing in pore throat | 751 | 830 | 864 |
| Oil content ratio of throat | 0.56 | 0.54 | 0.53 |
| After polymer flooding | Total number of oil-bearing in pore throat | 698 | 776 | 791 |
| Oil content ratio of throat | 0.52 | 0.5 | 0.48 |

From Table 1, it follows that the data are the oil saturation ratios of the pores and throats corresponding to the coordination number. With the increase in the coordination number, the oil saturation ratio of water flooding and polymer flooding decreases in the interval of 0.8-1, indicating that the effect of polymer in oil displacement is improved. Polymer flooding reduces the proportion of excess water flooding. The proportion of oil saturation increases when the oil saturation is in the range of 0.6~0.8, 0.4~0.6, 0~0.4 and 0 intervals, showing that the oil content of the pore throat decreases as the coordination number increases. The probability of remaining oil in the throat becomes smaller.

![Figure 3: Ratio of number of oil-bearing throat in different So](image1)

(a) Ratio of number of oil-bearing throat in different So

(b) Ratio of oil-bearing pore number in different So

3.2. Influence of shape factor on remaining oil

The number of oil-bearing pores is counted after water and polymer flooding, and the oil-bearing number and oil saturation ratio of throats, pores, and pores are listed respectively in Table 2. It shows that the round throats which proportion of the channel is 0.2, 0.5, 0.7 in the three models, the shape factor increases in turn, the oil-bearing probability in the corner becomes smaller. The number of oil-bearing pores and throats after polymer flooding under the same shape factor is much smaller than that of water flooding. The oil content of the throat is 0.59, 0.48, 0.44, respectively. It draws a conclusion that the larger the shape factor, the smaller the oil content of the pores and throats. The remaining oil content of the pore throat is reduced.
Table 7. Proportion of oil in pore after water drive and polymer flooding.

| Shape factor | round:square:triangle | round:square:triangle | round:square:triangle |
|--------------|------------------------|------------------------|------------------------|
|              | 0.2: 0.3: 0.5          | 0.5: 0.3: 0.2          | 0.7: 0.3: 0.0          |
| After water flooding | Total number of oil-bearing in porous channel | Total number of oil-bearing in porous channel | Total number of oil-bearing in porous channel |
|                | 1513                   | 1513                   | 1513                   |
|                | Total number of oil-bearing in porous channel | Total number of oil-bearing in porous channel | Total number of oil-bearing in porous channel |
|                | 935                    | 900                    | 819                    |
|                | Oil content ratio of porous channel | Oil content ratio of porous channel | Oil content ratio of porous channel |
|                | 0.62                   | 0.59                   | 0.54                   |
| After polymer flooding | Total number of oil-bearing in porous channel | Total number of oil-bearing in porous channel | Total number of oil-bearing in porous channel |
|                | 888                    | 733                    | 665                    |
|                | Oil content ratio of porous channel | Oil content ratio of porous channel | Oil content ratio of porous channel |
|                | 0.59                   | 0.48                   | 0.44                   |

The data in Table 7 are the oil content and oil saturation ratio of the pores and throats corresponding to the coordination number. With the increase of the shape factor, the oil saturation ratio of water and polymer flooding in the intervals of 1 to 0.8 and 0.6 to 0.8 decreases significantly. When the oil saturation is on the range of 0.4 to 0.6, 0 to 0.4, and 0, the proportion of oil saturation in these intervals has increased, indicating that with the increase of the shape factor, the proportion of throats and pores with high oil content will decrease, and those with low oil saturation will gradually increase. At the same time, the proportion of the throat increases until the oil saturation is 0. The probability of remaining oil in the pore-throat becomes smaller.

![Figure 4](image-url) (a) Proportion of different oil saturation in throat (b) Proportion of different oil saturation in pore

3.3. The influence of pore-throat ratio on remaining oil

The number of oil-bearing channels after water and polymer flooding and the oil contented ratio after polymer flooding are counted, respectively. The following table 2-3 analyzes the parameter conditions which pore-throat ratios of 3, 4.5, and 6.4. As the pore-throat ratio increases, when the pore radius is constant, the throat radius decreases resulting in an increase in the resistance coefficient. The number of oil in the throat and pores gradually increases, and the probability of forming remaining oil increase. On the condition of the polymer flooding, the larger the pore-throat ratio, and the increase in the number of throat and pore oil content, the pore-channel oil content ratio is 0.49, 0.51, and 0.56, respectively. With the increase of pore-throat ratio, the oil content and remaining oil of pores and throats increases.
Table 8. Proportion of oil in pore after water drive and polymer flooding.

| Pore throat ratio | 3   | 4.5 | 6.4 |
|-------------------|-----|-----|-----|
| Total number of pore throat | 1513 | 1513 | 1513 |
| Total number of oil-bearing in porous channel | 820  | 845  | 915  |
| Oil content ratio of porous channel | 0.54 | 0.56 | 0.60 |
| Total number of oil-bearing in non-porous channel | 735  | 778  | 842  |
| Oil content ratio of non-porous channel | 0.49 | 0.51 | 0.56 |

From the data in Table 3 are the oil content and oil saturation ratio of the pores and throats corresponding to the coordination number. As the pore-throat ratio increases, the oil saturation ratios of water flooding and polymer flooding in the intervals of 1 to 0.8, 0.6 to 0.8 and 0.4 to 0.6 increase significantly, and the oil saturation in the intervals of 0 to 0.4 and 0 The oil saturation ratio of the interval has decreased. This rules indicates that as the pore-to-throat ratio increases, the ratio of throats and pores with high oil content will increase, and the ratio of throats with low oil saturation will gradually decrease. The probability of remaining oil in the pore and throat increases.

Figure 5. Oil saturation ratio

4. Conclusion

(1) As the coordination number increases, the number of oil in the pores and throats decreases, the proportion of oil saturation and forming remaining oil decreases.

(2) The larger the shape factor, the smaller the number of oil in pore-throat, the lower the proportion of oil saturation, and the proportion of remaining oil reduced.

(3) Under the condition of keeping the pore radius constant, with the increase in pore-throat ratio, the number of pore-throat oils gradually increases resulting in the enlargement oil saturation ratio and the ratio of remaining oil.

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