Characteristics of Oil-Water Relative Permeability and Influence Mechanism in Fractured-Vuggy Medium

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Abstract

The fracture system of fractured-vuggy reservoir is dominated by orthogonal fracture, and the vug system develops along the fracture. In view of this characteristic, two different kinds of models were made in this paper: the fracture medium model and the fractured-vuggy medium model. A series of two-phase fluid flow experiments were conducted to obtain the relative permeability curves. The results show that the oil and water relative permeability curves have a regular alternative relation of growing and declining, while the percolation resistance changes little, which indicates that there is no Jamin action that caused by the complexity of pore structure. Fracture aperture, fracture network structure, vug density and vug porosity have different influence on the relative permeability characteristic of fractured-vuggy medium, and the influence shows a obvious regularity.

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1. Introduction

The storage and seepage space of fractured-vuggy carbonate reservoir is significantly different from sandstone reservoir, therefore fractured-vuggy reservoir is difficult to exploit. In the late 20th century, the large-scale fractured-vuggy carbonate reservoirs were discovered from Ordovician system in Tarim basin of China. After that researchers began to take up some research work on fractured-vuggy reservoir[1-8]. Most studies focused mainly on reservoir geology characteristic and little research has been done on flow mechanism of fractured-vuggy medium. Tahe oilfield as one of fractured-vuggy reservoir has been

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developed by waterflooding and initial success has been achieved. However, the variation of dynamic index in fractured-vuggy reservoir is more complicated, and it is difficult to forecast and adjust. Therefore, there is an urgent need to research the oil-water flowing law and influence mechanism of fractured-vuggy medium so as to provide the basis for accurately prediction of reservoir performance and scientific policy-making of oilfield development.

The flowing law of oil-water two phases is based on the relative permeability curves. In order to investigate the characteristic and influence mechanism of relative permeability curve in fractured-vuggy medium, a series of fluid flow experiments were conducted on fracture network models firstly, and then added vugs with different position and various density into fracture network model. Field outcrop and core observation show that the fracture system of carbonate reservoir is dominated by orthogonal fracture and the cave system develops along the fracture because of the influence of palaeocurrent direction. According to this rule, the experimental models are designed by similarity criterion. Experimental data are gathered by computer automatically to ensure the accuracy of the data.

2. Relative permeability characteristic and influence mechanism of fracture medium

2.1. Influence of fracture aperture

Three physical models with different fracture aperture were made to study the influence of fracture aperture on relative permeability characteristic, as shown in Figure 1. In the same model, all the fractures are parallel and the fracture aperture is equal. The fracture aperture varies in the range of 100 μm, 150 μm and 200 μm in different model.

Figure 1. Fracture medium model with different fracture aperture: 100 μm, 150 μm and 200 μm

Figure 2 shows the relative permeability values versus water saturation with different fracture aperture. The sum of oil relative permeability and water relative permeability is less than 1 in the oil-water two phase region. This shows that there is an additional flow resistance between oil phase and water phase when the fluid is flowing. The relative permeability has a regular alternative relation of growing and declining between oil relative permeability and water relative permeability. The shape of the oil relative permeability curves indicate that the relative permeability to oil is sharply decreasing when there is a small increase in water saturation. However, the decline rate of oil relative permeability reduces when the water saturation is more than 50%, while the water relative permeability curves show the opposite tendency. The main difference between fracture medium and porous medium is that the sum of oil and water relative permeability changes little in the oil-water two phase region. This means that the
percolation resistance has little change in the flowing process and there is no Jamin action that caused by the complexity of pore structure.

![Figure 2](image1.png)

Figure 2. Relative permeability curves with different fracture aperture

Figure 2 also shows that fracture aperture has little effect on the oil relative permeability whereas the value of water relative permeability changes obviously when fracture aperture varies from 100μm to 200μm. With the increment of fracture aperture, irreducible water saturation declines. The water relative permeability increases more slowly with water saturation increasing and water injection capacity becomes worse, meanwhile, the value of water relative permeability at residual oil saturation is smaller. This means that the oil phase becomes more discontinuous with water saturation increasing when fracture aperture is small, thus hinders the flowing of water phase.

2.2. Influence of fracture density

In order to research the influence of fracture density, three physical models were made and the fracture aperture is equal to 100μm in all models, but the fracture density varies in the range of 45, 75 and 90 fractures per meter in different model.

![Figure 3](image2.png)

Figure 3. Relative permeability curves with different fracture density
Figure 3 shows the relative permeability values versus water saturation with different fracture density. The curves characteristic in figure 3 is similar to figure 2. With the increment of fracture density, residual oil saturation declines and the changing trend of relative permeability curves become slow gradually, while the regular alternative relation of growing and declining between oil and water relative permeability is more obvious. This means that the ascending rate of water phase curves and the declining rate of oil phase curves in Figure 3 are smaller than that in Figure 2.

2.3. Influence of fracture network structure

In order to research the influence of fracture network structure, water flooding experiment was conducted on three different fracture network models, as shown in Figure 1, Figure 4 and Figure 5. The fracture aperture is also equal to 100μm in the three models, but the fracture connectivity is 1, 100 and 207 respectively. The fracture connectivity is defined as follows:

\[ C = \text{Branch number} - \text{Node number} + 1 \]

Figure 4. Fracture network model with \( C = 100 \), vertical fractures along the flow direction

Figure 5. Fracture network model with \( C = 207 \), two kinds of vertical fractures: along and perpendicular to the flow direction

The fracture system of the first model is composed of horizontal fractures only with \( C = 1 \). The second model is composed of horizontal fractures and vertical fractures along the flow direction with \( C = 100 \). It is
more complex in the third model with $C=207$ that there are not only those two kinds of fracture, but also vertical fractures that perpendicular to the flow direction.

Figure 6 shows the relative permeability values versus water saturation with different fracture network structure. The curves characteristic is the same as mentioned in Figure 2: The sum of oil relative permeability and water relative permeability is less than 1 in the oil-water two phase region; the curves show a regular alternative relation of growing and declining between oil relative permeability and water relative permeability; the shape of the oil phase curves show decreasing trend and the water phase curves present a gradually increasing trend while the declining rate and ascending rate are both decreased. The formation mechanism of this characteristic is somewhat the same as Figure 2.

The trend of relative permeability curve with fracture network is that irreducible water saturation increases with the increment of fracture connectivity. The existence of vertical fractures that perpendicular to the flow direction makes residual oil saturation increasing and the oil-water two phase region reducing, also the isotonic saturation point reducing. On the contrary, residual oil saturation reduces, the oil-water two phase region and isotonic saturation point increases when vertical fractures that along the flow direction are present. The residual oil saturation at $C=1$ is larger than that at $C=100$, this indicates that displacement efficiency is low when there are no vertical fractures to conjugate the horizontal fractures. There also is a larger residual oil saturation at $C=207$ because part of oil in the vertical fractures can not be displaced by water, and it is not conducive to the development of oilfield.

3. Relative permeability characteristic and influence mechanism of fractured-vuggy medium

3.1. Influence of vug spatial configuration

According to the different spatial configuration between fracture and vug, three fractured-vuggy models were made: vugs are symmetrical with fracture, vugs lie on top of fracture and vugs underlie fracture. Figure 7 shows the relative permeability values versus water saturation with different vug spatial location. Compared the experiment results carried on fracture-vug medium with that on fracture medium, the relative permeability curves of fractured-vuggy medium are similar to fracture medium. The sum of oil relative permeability and water relative permeability is also less than 1 in the oil-water two phase region. This indicates that there is an additional flow resistance between oil phase and water phase. The
relative permeability has a regular alternative relation of growing and declining between oil relative permeability and water relative permeability. The main difference between fracture medium and porous medium is that the sum of oil and water relative permeability changes little in the oil-water two phase region. This means that the percolation resistance has little change in the flowing process and there is no Jamin action that caused by the complexity of pore structure. However, residual oil saturation and irreducible water saturation are somewhat increased and the isotonic saturation point are also increased, while the oil-water two phase region is reduced. The residual oil saturation increases most when vug is above the fracture and the extent of increasing irreducible water saturation is the largest when vug is under the fracture. The main factor is gravity that influences oil-water distribution inside the vug. In another word it is the density difference between oil and water that causes the redistribution of oil and water.

Figure 7. Relative permeability curves with different vug location

3.2. Influence of vug density

The displacement experiment is also conducted on single-fracture model with different vug density, and the vug density varies in the range of 10 to 50 vugs per square meter. Figure 8 shows the relative permeability values versus water saturation with different vug density. Residual oil saturation and irreducible water saturation are also somewhat increased with the number of vugs increasing and the oil-water two phase region is reduced, while the isotonic saturation point changes little.

Figure 8. Relative permeability curves with different vug density
3.3. Influence of vug porosity

In order to study the influence of vug porosity on water flooding, the displacement experiment was conducted on multi-fracture model with different vug porosity. The fracture aperture is 100μm, the vug is 1m in diameter and 2m in depth, the ratio of vug porosity to total porosity( $\phi_v/\phi$ ) is 0–67.7%.

![Relative permeability curves with different vug porosity](image)

Figure 9. Relative permeability curves with different vug porosity

The oil and water relative permeability curves have an obvious drop and ascend trend individually, as shown in Figure 9. The relation of ebb and flow between oil relative permeability and water relative permeability is more obvious. Each pair of curves are symmetrical with the isotonic saturation point, which is the significant characteristic of those curves. This indicates that the sum of oil relative permeability and water relative permeability is constant and there is no Jamin action that existed in the porous medium. Residual oil saturation and irreducible water saturation are also increased with vug porosity increasing and the oil-water two phase region is reduced, while the isotonic saturation point changes little.

3.4. Influence of fractured-vuggy network structure

The influence of fractured-vuggy network structure on relative permeability is also studied, two physical models were made and the fracture aperture, fracture density, vug porosity and vug density are all the same except fracture connectivity. The fracture connectivity of the two models is 119 and 207 respectively.

Figure 10 shows the relative permeability values versus water saturation with different fractured-vuggy network structure. The shape of relative permeability curves shows obvious characteristic of fractured-vuggy medium. There is a relation of ebb and flow between oil relative permeability and water relative permeability and each pair of curves are also symmetrical with the isotonic saturation point. The relative permeability curves tend to straight line as the fracture connectivity increased. This indicates that the fluid of fracture system and vug system tend to flow simultaneously as the connectivity increases, and the isotonic saturation point shifts to the right.
4. Conclusions

- There is a relation of ebb and flow between oil relative permeability and water relative permeability in fractured-vuggy medium. The shape of the oil phase curves show decreasing trend and the water phase curves present a gradually increasing trend while the declining rate and ascending rate are both decreased.
- The sum of oil and water relative permeability changes little in the oil-water two phase region and the percolation resistance has little change in the flowing process because there is no Jamin action that caused by the complexity of pore structure.
- When fracture aperture is small, the oil phase becomes discontinuous with water saturation increased and that hinders the flowing of water. Therefore, the relation of ebb and flow between oil and water relative permeability is more obvious.
- The existence of vertical fractures that perpendicular to the flow direction makes residual oil saturation increasing and the oil-water two phase region reducing, also the isotonic saturation point reducing. When vertical fractures along the flow direction are present, the variation is opposite respectively.
- Because of the existence of vugs, residual oil saturation and irreducible water saturation are somewhat increased. The main factor is gravity that influences oil-water distribution inside the vug.
- The fluid of fracture system and vug system tend to flow simultaneously as the connectivity increases, therefore, the relative permeability curves tend to straight line.

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References

[1] Jianhua Guo. Burial hill palaeokarst and its controlled reservoir heterogeneity in Ordovician, Lunnan region of Tarim basin. *Acta Sedimentologica Sinica*, 1993, 11(1): 56-63

[2] Chip Story, et al. An integrated geoscience and reservoir simulation study of Liuhua 11-1 field: south China sea, *SPE11958*, 2000
[3] Huashan Jiang, Desheng Ye. The Ordovician reservoir characteristics of Tahe oilfield. In: Bingnan JIANG, editors. Proceedings of oil and gas exploration and development in the north of Tarim basin, Beijing: Geological Publishing House; 2000, p. 56-68.

[4] Ximing Zhang. The characteristics of Lower Ordovician fissure-vug carbonate oil and gas pools in Tahe oilfield, Xinjiang. Petroleum exploration and development, 2001, 28(5): 17-22.

[5] Zhongmin Lin, Zhengfen Li, Chuanrong Luo. The development of Karst and its Control Factors in Ordovician of Tahe oilfield. In: Bingnan JIANG, editors. Proceedings of oil and gas exploration and development in the north of Tarim basin, Beijing: Geological Publishing House; 2000, p. 24-35.

[6] Chengjun Tan, Jingying Lu, Guorong Li. Correlativity between productivity features and reservoir type in carbonate oil reservoirs of Tahe oilfield. Petroleum Geology and Recovery Efficiency, 2001, 8(3):43-45.

[7] Chengjin Tan, Yingjie Zhou, Yushan Du, et al. Reservoir heterogeneity of Ordovician in district No.4 of Tahe oilfield. Xinjiang Petroleum Geology, 2001, 22(6):509-510.

[8] Xingxi Zhou. A primary discussion on the network-like oil and gas pools in carbonate rocks-Taking the Lunnan Ordovician buried-hill pool in Tarim basin as an example. Petroleum exploration and development, 2000, 27(3): 5-8.