Study on Pore Structure and Seepage Characteristics in Huhenuoren Oilfield

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Abstract. Pore structure and seepage characteristics have been studied in view of the problem of watercut rose rapidly in Nantun formation of huhenuoren oilfield of Hailar basin. Fan delta deposition with characteristics of close resource, rapidly accumulation results in pore distribution does not uniform, communication are weak. Throat distribution takes on dual peak. Left peak corresponds to smaller throat, which is invalid throat; Right peak corresponds to bigger throat, which is valid throat and seepage channel. There exists big difference in pore structure. Microanisotropy is very strong. Movable oil saturation is relatively low. Water relative permeability takes on convex shape. Strong water sensitivity and big Jamin effect brought about that injection water hard to displace oil below 1 μm throat radius. The oil production above 1 μm throat radius is about 77% of total oil production by NMR test. Throats above 1 μm radius are preferred path of injection water, are the main reason for watercut rising rapidly.

Nantun Formation is the main oil-bearing formation in hulenoren oilfield, Hailar basin. The reservoir of Nantun Formation is fan delta deposit with near provenance, short flow, rapid transportation and rapid accumulation. The rock types are glutenite, fine sandstone, siltstone, argillaceous siltstone and silty mudstone. Because the sediments are mainly of near provenance and rapid accumulation, the maturity of rock composition is very low, the content of unstable minerals is high, and the content of cuttings is as high as 78.8%. The distribution of oil and water is mainly controlled by structure, and the reservoir type is structural reservoir. The average permeability of Nantun Formation reservoir is 44.8 MD, and the heterogeneity between and within layers is strong. In the process of waterflooding development, the oil wells in the low part of the structure have early water breakthrough and rapid water flooding. When the recovery rate is only 8.12%, the water cut has reached 55.2%, and it has entered the middle water cut stage. According to the change trend of the theoretical curve, the water cut will rise faster before the water cut is 70%. In view of the problems existing in the development process of Huhe nuren oilfield, it is urgent to study the pore structure characteristics of the reservoir from the microscopic point of view, and clarify the fundamental reason for the rapid rise of water cut from the seepage mechanism.
1. Pore structure characteristics

1.1. Pore type

The results of SEM and cast thin section show that the main pore type is intergranular residual pore, followed by intergranular solution pore. Due to the lack of adequate screening during the rapid accumulation of Nantun Formation reservoir, the mud and sand are mixed, and the size particles are mixed. The diameter of large gravel can reach 5cm, and the diameter of small gravel is only a few millimeters. The clay content is high, the particles are mostly in point contact, the connectivity is poor, and the pore structure is very complex.

1.2. Characteristics of capillary pressure curve

Capillary pressure curves of 50 rock samples from 5 wells in Huhe nuren oilfield were measured by mercury injection method. Figure 1 shows a representative capillary pressure curve. The higher the permeability is, the lower the displacement pressure is, and the lower the curve is to the left, which is closer to the abscissa axis; the lower the permeability is, the higher the displacement pressure is, and the curve is to the upper right, which is farther away from the abscissa axis.

![Figure 1. Capillary pressure curve with different permeability](image1)

![Figure 2. Distribution frequency of throat in well 36-54 Permeability contribution rate (k = 21.6md)](image2)

1.3. Variation of pore structure parameters

The 50 capillary pressure curves are divided into 4 grades according to permeability: 0.1-1, 1-10, 10-50 and above 50md. It can be seen from table 1 that the average throat radius is 2.32 μ M. with the increase of permeability, the throat radius gradually increases. When the permeability is 0.56md, the throat radius is 0.46 μ m; when the permeability is 188md, the throat radius increases to 5.05 μ M.

The average sorting coefficient is 3.82. With the increase of permeability, the number of large throats increases and the distribution range of throats becomes wider, which leads to the further deterioration of throat sorting, from 2.86 to 4.53. Due to the small throat radius and poor connectivity, when the maximum mercury inlet pressure (41mpa) is reached, the maximum mercury inlet saturation is only 59.1%, and 40.9% of the pore space is controlled by the throat below 0.016 μ M.
Table 1. Calculation results of pore structure parameters

| Permeability Level (mD) | Number of blocks | Average Porosity (%) | Average Permeability (mD) | Laryngeal tract Radius (μm) | Sorting coefficient | Mercury saturation maximum (%) | Mercury saturation remnant (%) | Mercury removal efficiency (%) | Displacement Pressure (MPa) | Mean laryngeal half diametral Jamin effect (MPa) |
|-------------------------|------------------|----------------------|--------------------------|-----------------------------|----------------------|-------------------------------|-------------------------------|-------------------------------|-----------------------------|----------------------------------|
| 0.1<K≤1                | 3                | 18.1                 | 0.56                     | 0.46                        | 2.86                 | 61.8                          | 48.5                          | 21.5                          | 0.34                        | 0.11                             |
| 1<K≤10                 | 19               | 18.7                 | 3.90                     | 0.92                        | 3.37                 | 55.9                          | 45.1                          | 19.3                          | 0.30                        | 0.05                             |
| 10<K≤50                | 13               | 20.7                 | 20.2                     | 1.65                        | 3.87                 | 63.3                          | 53.1                          | 16.1                          | 0.13                        | 0.03                             |
| K>50                   | 15               | 21.7                 | 188                      | 5.05                        | 4.53                 | 59.1                          | 54.0                          | 8.6                           | 0.04                        | 0.01                             |
| Average                |                  | 20.1                 | 63.2                     | 2.32                        | 3.82                 | 59.1                          | 50.0                          | 18.9                          | 0.15                        | 0.02                             |

1.4. Distribution of laryngeal tract

From the distribution of laryngeal tract, the peak value is distributed at both ends, mainly bimodal (Figure 2). The left peak corresponds to a smaller throat radius, and the right peak corresponds to a larger throat radius. For example, for the rock sample with permeability of 21.6md in well 36-54, the left peak value is 8.2%, the corresponding throat radius is 0.025 μm, the right peak value is 10.2%, the corresponding throat radius is 2.5 μm, which is 100 times of the left peak corresponding throat radius. The bimodal morphology shows that the throat distribution is complex and the micro heterogeneity is strong. In terms of permeability contribution, the right peak contributes 38.1% to the permeability, and the corresponding throat is effective; while the left peak contributes 0, and the corresponding throat is invalid.

1.5. Contribution of throat to permeability

Table 2 shows the distribution frequency and permeability contribution of three throat radius intervals (below 0.1 μm, 0.1-1 μm and above 1 μm) under each permeability level. When the permeability is 0.1-1md, the throat distribution frequency below 0.1 μm is 38%, and the permeability contribution is only 0.2%; the throat distribution frequency between 0.1-1μm is 15.3%, and the permeability contribution is 13.1%; although the throat distribution frequency above 1 μm is only 8.5%, it is the main seepage channel, and the permeability contribution is 86.7%. With the increase of permeability, the contribution of throat below 0.1 μ m and between 0.1 μ m and 1 μ m to permeability decreases gradually, which is negligible; while the distribution frequency of throat above 1 μ m increases gradually, from 8.5% to 38.6%, and the contribution to permeability also increases, from 86.7% to 99.9%. From the average value of all rock samples, the throat distribution frequency above 1 μ m is 24.9% on average, and the permeability contribution is 95.6%, which is the main seepage channel in Huhe nuren oilfield.

Table 2. Throat distribution frequency and permeability contribution rate under different permeability levels

| Permeability Level (mD) | Average Porosity (%) | Average Permeability (mD) | r>1μm | 0.1<r≤1μm | r≤0.1μm |
|-------------------------|----------------------|--------------------------|-------|------------|--------|
| 0.1<K≤1                | 18.1                 | 0.56                     | 8.5   | 86.7       | 15.3   |
| 1<K≤10                 | 18.7                 | 3.90                     | 14.2  | 91.5       | 24.4   |
| 10<K≤50                | 20.7                 | 20.2                     | 28.7  | 98.4       | 19.2   |
| K>50                   | 21.7                 | 188                      | 38.6  | 99.9       | 11.8   |
| Average                | 20.1                 | 63.2                     | 24.9  | 95.6       | 18.7   |

| Permeability Level (mD) | Laryngeal tract cloth frequency (%) | Permeability contribution rate (%) | Laryngeal tract cloth frequency (%) | Permeability contribution rate (%) | Laryngeal tract cloth frequency (%) | Permeability contribution rate (%) |
|-------------------------|-----------------------------------|-----------------------------------|-----------------------------------|-----------------------------------|-----------------------------------|-----------------------------------|
| 0.1<K≤1                |                                    | 8.5                               | 15.3                              | 38.0                              | 0.2                               |
| 1<K≤10                 |                                    | 14.2                              | 24.4                              | 8.5                               | 17.3                              | 0                                 |
| 10<K≤50                |                                    | 28.7                              | 19.2                              | 1.6                               | 15.3                              | 0                                 |
| K>50                   |                                    | 38.6                              | 11.8                              | 0.1                               | 8.8                               | 0                                 |
| Average                |                                    | 24.9                              | 18.7                              | 4.4                               | 15.5                              | 0                                 |
2. Characteristics of oil-water two-phase flow

![Figure 3](image)

**Figure 3.** Average oil-water relative permeability curve

The relative permeability curves of 5 samples from 62-60 well in Huhe nuren oilfield are measured. The characteristic values of the relative permeability curves of each rock sample are shown in Table 3. The average relative permeability curves are obtained by using the method in reference [1] (Figure 3).

2.1. Irreducible water saturation and residual oil saturation

The irreducible water saturation is relatively high, ranging from 34.3% to 50.1%, with an average of 42.7%, which corresponds to the fact that 40.9% of the pore volume is not invaded by mercury under the maximum mercury saturation in pore structure analysis. The residual oil saturation ranges from 22.0% to 33.4%, with an average of 28.2%.

2.2. Movable oil saturation

The two-phase span in Table 3 is the movable oil saturation. The higher irreducible water saturation and residual oil saturation lead to the lower movable oil saturation, ranging from 24.0% to 34.8%, with an average of 29.0%. It is close to 24.9% of the distribution frequency of throat above 1 μ m in pore structure analysis, indicating that movable oil is mainly distributed in the pores connected by throat above 1 μ M.

2.3. Oil phase relative permeability and water phase relative permeability

With the increase of water saturation, the relative permeability of oil phase decreases rapidly, while the relative permeability of water phase increases slowly. The final value is low, ranging from 27.0% to 30.0%, with an average of 28.8%. The relative permeability of water phase is convex (Figure 3), which is caused by the following two reasons:
Table 3. Characteristic value of oil-water relative permeability curve in well 62-60

| Rock specimen number | Air Permeability (mD) | Porosity (%) | Bound water Saturation (%) | Residual oil Saturation (%) | Residual oil is water phase relative permeability (%) | Oil displacement Efficiency (%) | Two-phase Span (%) | Point of intersection Saturation (%) |
|----------------------|-----------------------|--------------|-----------------------------|----------------------------|-----------------------------------------------|----------------------------------|------------------|-----------------------------------|
| 166-1                | 119.2                 | 23.2         | 39.2                        | 33.4                       | 29.3                                          | 45.1                            | 27.4             | 59.2                              |
| 166-2                | 114.0                 | 22.9         | 40.2                        | 28.7                       | 30.0                                          | 52.0                            | 31.1             | 53.8                              |
| 118-2                | 186.6                 | 34.3         | 26.1                        | 30.9                       | 28.5                                          | 53.0                            | 34.8             | 50.8                              |
| 118-4                | 8.84                  | 17.0         | 50.1                        | 22.0                       | 29.0                                          | 55.9                            | 27.9             | 58.5                              |
| Average              | 87.8                  | 20.8         | 42.7                        | 28.2                       | 28.8                                          | 50.8                            | 29.0             | 55.9                              |

2.3.1. Clay mineral composition of reservoir. The absolute content of clay minerals is high, 14.3%, and the absolute content of montmorillonite is 2.6%, which leads to the strong water sensitivity of the reservoir, with an average water sensitivity index of 0.81. In the process of relative permeability experiment, although anti swelling agent is added, the problem of clay mineral expansion still exists. With the increase of water saturation, the increase of water phase permeability caused by water sensitivity damage gradually slows down and forms a convex curve.

2.3.2. Pore structure of reservoir. According to the previous analysis, the throat above 1 μ m is the main seepage channel, so the water displacement process mainly occurs in the pores connected by the throat above 1 μ M. When the throat above 1 μ m is occupied by water, with the increase of water saturation, the water phase gradually enters into the small throat below 1 μ M. Because the throat radius is small, it often breaks and produces a large number of dispersed oil droplets, resulting in a strong Jamin effect at the throat entrance [2-4], resulting in limited increase of water phase seepage channel, slow growth of water phase seepage capacity and formation of convex curve.

2.4. Jamin effect

According to the throat radius of each permeability level in Table 1, the seepage resistance of dispersed oil droplets passing through a single throat radius is calculated. The Jamin effect at the throat radius of 5.05 μ m is 0.01Mpa, and the Jamin effect at the throat radius of 0.46 μ m is 0.11mpa. It can be seen that the lower the permeability is, the smaller the throat radius is, the greater the seepage resistance of Jamin effect is.

2.5. NMR and seepage characteristics

In reference [5], nuclear magnetic resonance (NMR) technology was used to study the oil-water two-phase flow characteristics in Huhe nuren oilfield. Under the saturated oil condition of two rock samples, the oil saturation in throat above 1 μ m is 25.5%, accounting for 65.2% of the total saturation. In the process of water flooding, the injected water mainly enters into the throat above 1 μ m for oil displacement, and the oil production in the throat above 1 μ m accounts for 77% of the total oil production. It is the dominant channel of injected water seepage, and the seepage resistance in this channel is far lower than that in the throat below 1 μ m, which makes it difficult to improve the injected water wave and range, and the water cut of oil wells rises rapidly.

3. Concluding remarks

The reservoir of Nantun Formation is fan delta sedimentary glutenite with near provenance and rapid accumulation. The reservoir sorting is poor and the average throat radius is small. The throat distribution is mainly bimodal, the right peak is effective throat, the left peak is invalid throat, and the micro heterogeneity is serious. It is difficult for the injected water to enter into the throat below 1 μ m for oil displacement due to the strong water sensitivity of reservoir and the high seepage resistance of Jamin
effect. The throat above 1 μ m is the dominant channel for injected water seepage, which is the main reason for the rapid rise of water cut in oil wells.

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