The lower limit of the flowing pore throat radius in the extra-low permeability reservoir

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Abstract. In this paper, a method for determining the lower limit of flowing pore throat radius of the extra low permeability reservoir in the periphery of Changyuan Oil Fields is given. The capillary pressure curve is divided into linear type and concave type. The nuclear magnetic resonance (NMR) T2 spectrum is divided into 3 types: the left peak is greater than the right peak, the left peak is equal to the right one, and the left peak is smaller than the right one. The method for determining the lower limit of flowing pore throat radius is, first, converting the nuclear magnetic resonance T2 spectrum to the capillary pressure curve calculated, then fitting the capillary pressure curves measured by the constant speed mercury injection experiment and the capillary pressure curve calculated. After finding the relevant parameters, converting the horizontal axis of the NMR T2 spectra from relaxation time to pore throat radius, and the pore throat radius corresponding to the T2 cutoff value is the lower limit of the flowing pore throat radius. The lower limit of the flowing pore throat radius of the extra low permeability Fuyang Oil Reservoir in the periphery of Changyuan Oil Fields is about 0.68μm

1. Preface
The micro structure of pore in a reservoir is the main factor which will make its seepage characteristics. Reservoirs with extra low permeability, like the one in the periphery of Changyuan Oil Fields, are very difficult in operating with low rate of recovery. Recent studies [1-3] suggest that, the lower the permeability of the reservoir, the smaller the pore throat radius, the greater the resistance of fluid flow. The lower limit of flowing pore throat radius is defined as the minimum value of throat radius where the fluid can flow. When the pore throat radius is larger than the value, the crude oil in the corresponding pore throat can flow, and then is produced; on the contrary, when the pore throat radius is less than the value, the fluid cannot flow, and ultimately becomes residual oil. The present researches [4-7] mainly focus on the qualitative description and quantitative analysis of the characteristics of microscopic pore structure, less research on quantitative analysis of the relationship between characteristics of micro pore structure and seepage characteristics has been done. In this paper, the low permeability reservoir in the periphery of Changyuan Oil Fields is chosen as the field work. The characteristics of micro pore structure and movable fluid are analyzed, the method and formula for determining the lower limit of the flowing pore throat radius are given by using capillary pressure curve and nuclear magnetic resonance T2 spectrum. Finally, the lower limit of the flowing pore throat radius is given, which provides the basis for determining the development limits of the extra low permeability reservoir.
2. Characteristic of the capillary pressure curve

10 cores of the extra low permeability Fuyang Oil Reservoir in the periphery of Changyuan Oil Fields are chosen, and their capillary pressure curves are measured by constant speed mercury injection experiment \(^{[8-11]}\). Statistical analysis of the capillary pressure curves of the ten cores shows that, the capillary pressure curve is generally divided into 2 types: the linear type and the concave one. When the permeability is less than \(5 \times 10^{-3}\) μm\(^2\), the capillary pressure curve is a linear type. With the continuous decrease of permeability, the shape of the capillary pressure curve is getting closer and closer to the straight line, which means that the distribution of pore throat becomes more and more uniform, and that the proportion of different sizes of pore throats is more balanced. When the permeability is greater than \(5 \times 10^{-3}\) μm\(^2\), the capillary pressure curve is a concave type. With the increase of the mercury injection saturation, the rising rate of the curve is faster. With the increase of permeability, the upward trend of the curve is more and more obvious. It shows that the heterogeneity of the reservoir becomes stronger, and the proportion of large pore throats is larger and larger, which reduces the difficulty of reservoir development, but meanwhile it might trigger the occurrence of the phenomenon of the finger.

3. Characteristic of the movable fluid

As many as 23 cores of the extra low permeability Fuyang Oil Reservoir in the periphery of Changyuan Oil Fields are taken as the research examples, and used for nuclear magnetic resonance (NMR) experiments. NMR test data of these 23 samples are analyzed. It shows that, the T2 relaxation time spectrum curve is generally divided into 3 types: the left peak is greater than the right one, the left peak is equal to the right peak, and the left peak is smaller than the right one. When the permeability is lower than \(5 \times 10^{-3}\) μm\(^2\), with the decrease of permeability, the left peak becomes obviously higher than the right one, indicating that the movable fluid is less and less, and the development potential is greatly reduced. When the permeability is higher than \(5 \times 10^{-3}\) μm\(^2\), the difference between the two peaks tends to become closer. With the increase of permeability, the right peak is higher than the left one, it tells that the percentage of the movable fluid in the reservoir is relatively high, therefore its development is more efficient.

![Fig 1 The capillary pressure curves](image1)

![Fig. 2 T2 relaxation time](image2)

According to the T2 relaxation time spectrum of these 23 cores, the percentage of the movable fluid of the rock samples can be obtained. The results are shown in table 1.

| Core number | Permeability/10^{-3}\mu m^2 | Porosity/\% | Percentage of movable fluid/\% |
|-------------|-----------------------------|-------------|-------------------------------|
| T 4-7       | 1.04                        | 12.6        | 18.32                         |
| C 4-7       | 1.24                        | 12.16       | 27.80                         |
| T 4-2       | 1.37                        | 16.13       | 22.31                         |
| Y 4-5       | 1.65                        | 12.25       | 30.02                         |
| Y 4-3       | 1.89                        | 15.51       | 25.39                         |
| Y 4-7       | 2.08                        | 16.76       | 26.87                         |
In this experiment, 23 cores for the nuclear magnetic resonance test are completed. The core permeability ranges from $1.04 \sim 13.08 \times 10^{-3} \mu m^2$. The percentage of movable fluid ranges from 18.32% to 57.34%, with an average of 39.08%.

In order to further understanding the relationship between the percentage of the movable fluid and the physical parameters of the cores, the relationship between the percentage of the movable fluid and the permeability, the average throat radius is drawn. The results are shown in Figure 3 and Figure 4.

The relation between the percentage of the movable fluid and the permeability is a semi-logarithmic one. Small throat is a main factor restricting flow of fluid. The smaller the throat radius, the greater the resistance of the fluid going through. Also due to the interaction between solid and liquid, a boundary layer often exists on throat wall and that will further reduce flow area of fluid in the throat, so as to make the flow having bigger resistance. What can be seen from Fig 4, the percentage of the movable fluid is linear with the average throat radius, the greater the average throat radius, the greater the percentage of the movable fluid.

The characteristics of the movable fluid of the extra low permeability of Fuyang Oil Reservoir in the periphery of Changyuan Oil Fields:

1) Curve shape: The T2 relaxation time spectrum curve is generally divided into 3 types: the left peak is greater than the right peak, the left peak is equal to the right one, and the left peak is smaller than the right one. When the permeability is lower than $5 \times 10^{-3} \mu m^2$, the left peak is larger than the right. When the permeability is higher than $5 \times 10^{-3} \mu m^2$, the difference of the two peaks becomes closer, and then gradually, the right peak takes the higher one.
2) Characteristic parameters: When the permeability of the core is less than $5 \times 10^{-3} \mu m^2$, the percentage of the movable fluid is lower, it ranges from 18.32% ~ 41.13%, with an average 29.55%; when the permeability of the core is higher than $5 \times 10^{-3} \mu m^2$, that percentage ranges from 39.28% ~ 57.34%, with an average of 46.42%. The percentage of the movable fluid has a good semi-logarithmic relationship with the permeability, and has a good linear relationship with the average throat radius.

4. Determination of the lower limit of the flowing pore throat radius

The shape of the capillary curve is impacted by the rock pore and the throats. The mechanism of the nuclear magnetic resonance [12-15] tells that the relaxation time of the hydrogen nucleus is positively correlated with the size of the rock pores, that is, the larger the pore, the longer the transverse relaxation time of the hydrogen nucleus. If the core is fully saturated with a single fluid (usually water), the distribution of the T2 spectrum can reflect the size and distribution of the pore throats. Obviously, there is close relationship between the capillary pressure curve and the T2 relaxation time spectrum. The derivation process of the formula for determining the lower limit of the flowing pore throat radius is following.

The relationship between the capillary pressure and the capillary radius is:

$$P_c = \frac{2\sigma \cos \theta}{r_c} \quad (1)$$

In the formula, $P_c$ represents the capillary pressure, unit for MPa; $\sigma$ represents the interface tension between the fluid and the capillary; $\theta$ represents the wetting contact angle.

For mercury, $\sigma = 49.44 N/cm^2$, $\theta = 140^\circ$, put them into formula (1), and omit a minus sign, then

$$P_c = \frac{0.735}{r_c} \quad (2)$$

By the principle of nuclear magnetic resonance, the transverse relaxation time T2 measured in a homogeneous magnetic field is:

$$\frac{1}{T_2} = \rho_2 \left(\frac{S}{V}\right) \quad (3)$$

As can be seen from formula (3), the T2 relaxation time is related to the specific surface area of pores, and that area is related to the size and shape of the pore space. In general, it is simplified into spherical and cylindrical pore structures. The specific surface area has a linear relationship with the pore radius. However, the pore structure of the actual extra low permeability reservoir is very complex. It is difficult to characterize the linear relationship between the specific surface area and the pore size, so it can be described by the nonlinear relation:

$$\frac{1}{T_2} = \frac{\rho_2}{f(r_c)} \quad (4)$$

Through the analysis of a large number of experimental results, it is found that the T2 spectral distribution is not linear relationship with the pore size, but the power function relationship, so it can be written:

$$T_2 = \frac{(r_c)^n}{\rho_2 F_s} \quad (5)$$

Make $C = \frac{1}{\rho_2 F_s}$, then the formula above can be expressed as:

$$T_2 = C(r_c)^n \quad (6)$$

In the formula: $r_c$ is pore radius, unit for $\mu m$; $F_s$ is the pore shape factor, dimensionless. It can be obtained by formula (2) and (6):
\[ P_c = 0.735 \times \left( \frac{C}{T_2} \right)^n \] (7)

Therefore, after obtaining the value of C and n, putting the NMR T2 spectra transformed to the capillary pressure curve, and the distribution of the pore throat radius can be obtained.

The specific approach is: according to formula (7), converting the nuclear magnetic resonance T2 spectrum to the capillary pressure curve, and then fitting the capillary pressure curves measured by the constant speed mercury injection experiment and the capillary pressure curve obtained by nuclear magnetic resonance test, and then calculating the parameters C and n. The fitting results are shown in Fig 5 (a). Then using formula (6), converting the nuclear magnetic resonance T2 spectrum to distribution curve of the pore throat radius. Those corresponding to the T2 cutoff value \(^{[16]}\) are the lower limit of the flowing pore throat radius of the reservoir, as shown in Fig 5(b).

![Fig. 5 Lower limit of flowing pore throat radius of 1.4×10⁻³μm² core](image)

In this experiment, 5 cores are calculated, and the permeability of the 5 cores are 1.4、3.2、5.4、6.9, and 8.0×10⁻³μm². The conversion table between the nuclear magnetic resonance T2 spectrum and the capillary pressure curve is shown in Table 2. From the fitting results, the fitting degree between the capillary pressure curve obtained by the nuclear magnetic resonance and the capillary pressure curve measured by constant speed mercury injection test, is high, and the difference is mainly manifested in the stage of the lower intake of mercury. The average value of conversion coefficient C is 11, the average value of conversion coefficient n is 1.11. Thus, the lower limit of the flowing pore throat radius of the extra-low permeability reservoir in the periphery of Changyuan Oil Fields is approximately 0.68μm.

| Permeability (10⁻³μm²) | Conversion actor C | Conversion factor n | the lower limit of flowing pore throat radius (μm) |
|------------------------|--------------------|---------------------|-----------------------------------|
| 1.4                    | 10                 | 1.14                | 0.63                              |
| 3.2                    | 14                 | 1.28                | 0.65                              |
| 5.4                    | 13                 | 1.18                | 0.68                              |
| 6.9                    | 11                 | 1.01                | 0.70                              |
| 8.0                    | 9                  | 0.93                | 0.72                              |

5. Conclusion

1) The capillary pressure curve is generally divided into 2 types: linear type and concave one. When the permeability is less than 5×10⁻³μm², the capillary pressure curve is a linear type. When the permeability is greater than 5×10⁻³μm², the capillary pressure curve is a concave one.
2) The nuclear magnetic resonance T2 spectrum is divided into three types: the left peak is greater than the right peak, the left peak is equal to the right one and the left peak is smaller than the right one. The percentage of the movable fluid ranges from 18.32% to 57.34%, with an average of 39.08%.

3) The lower limit of the flowing pore throat radius of the extra low permeability Fuyang Oil Reservoir in the periphery of Changyuan Oil Fields is about 0.68μm.

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