Three Forms of Minimum Flow Pore Throat Radius of Reservoir and Its Determination Method

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Abstract. The minimum flow pore throat radius of the reservoir is an important indicator to characterize the seepage capacity of the reservoir pore throat. At present, the type of minimum flow pore radius is single, and there are few quantitative methods to determine it. To this end, through the analysis of the seepage capacity at different scale pores and the experimental method of mercury intrusion, the minimum flow pore throat radius and the determination method of the reservoir under the three seepage states of theoretical seepage, production seepage and filling seepage were studied and an example is applied. The analysis shows that the theoretical minimum flow pore throat radius corresponds to the lower limit of the capillary pore radius, and its size is related to the reservoir pore structure, which can be directly determined according to the mercury intrusion curve. The production minimum flow pore throat radius is the lower limit of the flowing pore radius of the reservoir. Its size is related to the reservoir pore structure and the production pressure difference. It can be determined by combining the mercury intrusion curve and the production pressure difference. The filling minimum flow pore throat radius is the lower limit of the filling pore radius. Its size is related to both the pore structure and the filling dynamics. It can be determined by combining the mercury intrusion curve and the original oil saturation. The above method was used to determine the minimum flow pore throat radius of Chang 61 reservoir in X Oilfield, Ordos Basin: the theoretical minimum flow pore throat radius is 0.015 μm, the production minimum flow pore throat radius is 0.017 μm, and the filling minimum flow pore throat radius is 0.085 μm. This study deepened the understanding of the minimum flow pore throat radius of the reservoir, and clarified the determination method of the minimum flow pore throat radius under different seepage states, which has reference significance for the calibration of the lower limit of the reservoir physical properties and the study of the reservoir utilization status.

Keywords: Determination method; Three forms; The minimum flow pore throat radius; Reservoir.

1. Introduction

The minimum flow pore throat radius of the reservoir refers to the minimum throat radius of the reservoir fluid that can seep under a certain displacement pressure. The displacement pressure is different, and the minimum flow pore throat radius is also different. The minimum flow pore throat radius of the reservoir is an important indicator to measure the seepage capacity of the reservoir pore throat under a certain displacement pressure [1]. At present, the type of minimum flow pore radius is single, and there are few quantitative determination methods. In the study of the lower limit of reservoir physical properties [2-9], people usually take 0.1μm as the minimum flow pore throat radius.
It is considered that 0.1 μm is equivalent to the thickness of the water film attached to the surface of the water-wet clastic rock. Oil and gas in pore throats with pore throat radius smaller than this value are not flowing. Since the reservoir seepage state and displacement pressure are not considered, this value is not reliable.

Therefore, through the analysis of the seepage capacity of the reservoir pores at different scales and the study of mercury-intrusion curves, the author proposes a method to quantitatively determine the minimum flow pore throat radius of the reservoir using mercury-intrusion curves combined with production pressure difference and oil saturation and executes application examples.

2. Analysis of Seepage Capacity of Different Scale Pores

Reservoirs are rock formations capable of storing and infiltrating fluids. The storage space of the reservoir is composed of pore-throat networks with different pore-throat sizes and geometric shapes. The complexity of the reservoir pore-throat network, especially the order of pore-throat distribution, will inevitably have a direct and significant effect on the seepage of the reservoir fluid. To this end, the predecessors divided the connected pores of the reservoir into three categories: super-capillary pores, capillary pores and micro-capillary pores according to the pore size [10-12]. Among them, the super-capillary pore refers to the millimeter-level pore with a pore diameter > 0.5mm, in which the liquid can flow freely under the action of gravity. Capillary pores are micron-sized pores with a pore size between 0.5mm and 0.2 μm, in which liquid particles cannot flow freely due to capillary forces and molecular forces at the surrounding solid interface, and can only flow under the action of displacement power. Micro-capillary pores refer to nanometer-sized pores with a pore size of less than 0.2 μm. In this type of pores, the intermolecular attraction is very large, and the liquid cannot flow but is in an adsorbed state. Obviously, oil-water seepage mainly occurs in the super-capillary and capillary pores, while the liquid in the micro-capillary pores does not have the theoretical fluidity. Therefore, some people define super-capillary and capillary pores as effective pores for theoretical seepage, and micro-capillary pores as invalid pores [13]. However, under oilfield production conditions, the liquid in the effective pores cannot fully flow. The flow depends mainly on the relationship between displacement pressure and seepage resistance. When the displacement pressure > seepage resistance, the liquid can flow, this part of the effective pore is the flowable pore. When the displacement power < seepage resistance, the liquid cannot flow, and this part of the effective pore is non-flowable pore. In addition, in the process of oil and gas accumulation, the effective pore space is not completely filled with oil and gas, and the degree of filling depends mainly on the relationship between filling pressure and seepage resistance. When the filling pressure > seepage resistance, the effective pores filled with oil and gas are the filling pores (equivalent to the pores occupied by oil and gas). When the filling pressure is less than the seepage resistance, the effective pores that cannot be filled with oil and gas are unfillable pores.

In summary, under certain displacement pressures, the seepage capacity of pores at different scales in reservoirs is different. However, on the whole, there are regular correspondences and unique seepage characteristics between pores of different scales. This relationship is summarized in Table 1. It can be seen from Table 1: 1) Total pores of the reservoir > connected pores > effective pores ≥ flowing pore. 2) Total pores in the reservoir > connected pores > effective pores ≥ filling pores. 3) The relative size of the flowing pores and filling pores mainly depends on the displacement pressure and the filling pressure. If displacement pressure > filling pressure, flowing pores > filling pores. If displacement pressure < filling pressure, flowing pores < filling pores. 4) Among them, effective pores have theoretical fluidity, flowing pores have production fluidity, and filling pores have filling fluidity.
Table 1. Seepage characteristics and corresponding relationship of reservoir pores.

| Classification basis | Connectivity | Aperture scale         | Theoretical liquidity | Production fluidity | Filling fluidity |
|----------------------|--------------|------------------------|-----------------------|---------------------|-----------------|
| Total pore           | Connected    | Super-capillary pore   | Flowing pore          | Non-flowable pore   | Filling pore    |
|                      |              | Capillary pore         | Effective             | Non-fillable pore   | Non-fillable    |
|                      | Disconnected | Micro-capillary pore   | Ineffective           | Ineffective pore    | Ineffective     |
| (dead pore)          |              |                        |                       |                     |                 |

3. Three Forms of Minimum Flow Pore Throat Radius of Reservoir

The analysis of the seepage capacity of the reservoir pores at different scales (Table 1) shows that the reservoir has three seepage states: theoretical seepage, production seepage and filling seepage: 1) Theoretical seepage state refers to an ideal seepage (or limit seepage) state in which the super-capillary and capillary pores in the reservoir all participate in the seepage. 2) Production seepage state refers to the state in which the super-capillary and capillary pores in the reservoir participate in seepage under production conditions, and the degree of participation depends on the production conditions or production pressure difference. 3) The filling seepage state refers to the state in which the super-capillary and capillary pores in the reservoir are participating in the seepage, and the degree of participation depends on the conditions of reservoir forming or the filling pressure.

Different seepage states and different reservoir displacement dynamics mean that the minimum flow pore throat radius is also different. Corresponding to three kinds of seepage states, the minimum flow pore throat radius of the reservoir can be classified into three forms, namely, the theoretical minimum flow pore throat radius, the filling minimum flow pore throat radius, and the production minimum flow pore throat radius. Among them, the theoretical minimum flow pore throat radius corresponds to the lower limit of the capillary pore radius, and the fluid in the reservoir pore-throat network above the lower limit has the theoretical fluidity. The production minimum flow pore throat radius is the lower limit of the reservoir flow pore radius, and the fluid in the reservoir pore-throat network above the lower limit has production fluidity. The filling minimum flow pore throat radius is the lower limit of the reservoir filling pore radius, and the fluid in the reservoir pore-throat network above the lower limit has filling fluidity.

In summary, the theoretical minimum flow pore throat radius is the smallest among the three minimum flow pore throat radius, while the production minimum flow pore throat radius and the filling minimum flow pore throat radius are relatively large. The theoretical minimum flow pore throat radius is related to the pore structure of the reservoir. The production minimum flow pore throat radius is not only related to the pore structure of the reservoir, but also to the production pressure difference. The filling minimum flow pore throat radius is related to both the pore structure and the filling dynamics.

4. Method for Determining Minimum Flow Pore Throat Radius of Reservoir

It can be seen from Table 1 that the determination of the theoretical minimum flow pore throat radius needs to find the boundary point between the capillary pore and the micro-capillary pore. The determination of the production minimum flow pore throat radius requires finding the boundary between the flowing pore and the non-flowable pore. The determination of the filling minimum flow pore throat radius needs to find the boundary between the filling pore and the non-fillable pore. Therefore, the premise of determining the minimum flow pore throat radius is to first clarify the reservoir pore structure and the corresponding relationship between the pore-throat radius and the displacement pressure under the three seepage states (theoretical seepage, production seepage and filling seepage). At present, there are many methods to study the pore structure of the reservoir, but the method that can directly and quantitatively characterize the pore structure of the reservoir and the correspondence between the pore-throat radius and the displacement pressure is the mercury-intrusion method.
Due to the high pressure of the constant pressure mercury method, it can reach more than 100Mpa (corresponding to the minimum pore radius of 7.35nm). The working pressure of the imported mercury-intrusion instrument can reach up to 400 MPa, and the minimum pore radius of 1.8nm can be measured [14], which is enough to cover the effective pore range. Therefore, the mercury-intrusion method can be combined with production pressure difference and oil saturation data to determine the minimum flow pore throat radius of the reservoir. The main ideas are as follows:

1) The theoretical minimum flow pore throat radius (point A in Figure 1): Because the theoretical minimum flow pore throat radius is the smallest, and it is an ideal limit flow state. It corresponds to the pore-throat radius at the maximum mercury-intrusion saturation on the mercury-intrusion curve. In the process of mercury-intrusion experiment of constant pressure, when the maximum mercury-intrusion saturation is reached, even if the pressure continues to increase, the mercury-intrusion saturation remains unchanged. The initial point at which the maximum mercury-intrusion saturation remains unchanged can be regarded as the boundary point between the capillary pore and the micro-capillary pore, and that is the minimum flow pore throat radius (point A) of the theoretical seepage.

2) The production minimum flow pore throat radius (point B in Figure 1): Since the production minimum flow pore throat radius varies with the production pressure difference, its determination requires not only mercury-intrusion data but also the production pressure difference of the oil field. There are two cases: If the minimum flow pore throat radius corresponding to the production pressure difference < the theoretical minimum flow pore throat radius, the value of the pore-throat radius corresponding to the production pressure difference is the production minimum flow pore throat radius (point B). If the minimum flow pore throat radius corresponding to the production pressure difference > the theoretical minimum flow pore throat radius, the production minimum flow pore throat radius is equal to the theoretical minimum flow pore throat radius.

3) The filling minimum flow pore throat radius (point C in Figure 1): Since the filling minimum flow pore throat radius varies with the reservoir-forming power, its determination requires not only mercury-intrusion data but also the reservoir-forming power. Considering that the reservoir-forming power has a corresponding relationship with the original oil saturation of the reservoir, the lower limit (point C) of the filling seepage pore diameter can be comprehensively determined based on mercury-intrusion data and the original oil saturation.

Taking the X oilfield in the Ordos Basin as an example, the minimum flow pore throat radius of the reservoir is determined using the above method.

5. Calculation Example

5.1. Geological Overview
The structure of the X oil field belongs to the southwest of the Yishan slope in the Ordos Basin. It is located in Huachi and Qingyang in Gansu Province, with an area of 2600km². More than 300
exploration and evaluation wells have been drilled. The main production layer of the oil field is the Chang 6 oil group of the Upper Triassic Yanchang Formation in the Triassic system, which belongs to the gravity flow sedimentation of deep lake-semi-deep lake facies, with an average thickness of 47m and a sand-to-land ratio of 0.52. Analysis of core physical property data shows that the porosity of Chang 6 reservoir in X oilfield is distributed between 4% and 15%, with an average porosity of 9.1%. The permeability distribution is between 0.01 and $0.8 \times 10^{-3} \mu m^2$, and the average permeability is $0.152 \times 10^{-3} \mu m^2$.

5.2. Characteristics of Mercury-intrusion Curve

Based on core observation and sample collection, five rock samples were selected for mercury-intrusion experiment. The characteristics of the rock samples are shown in Table 2. It can be seen that the porosity of the rock samples is distributed between 6.86 and 13.51%, with an average of 9.97%; the permeability is distributed between 0.035 and $0.203 \times 10^{-3} \mu m^2$, with an average of $0.137 \times 10^{-3} \mu m^2$; It can reflect the physical properties of Chang 6 low porosity and low permeability reservoir.

Table 2. Characteristics of rock samples.

| Well no. | Well depth (m) | horizon | Core number | Length (cm) | Diameter (cm) | Porosity (%) | Permeability ($\times 10^{-3} \mu m^2$) |
|----------|----------------|---------|-------------|-------------|--------------|--------------|---------------------------------------|
| Shan 127 | 1951.25        | Chang 6 | 1 #         | 6.45        | 2.53         | 12.06        | 0.203                                 |
| Bai 221  | 2064.1         | Chang 6 | 2 #         | 6.46        | 2.53         | 13.51        | 0.186                                 |
| Bai 269  | 1936.27        | Chang 6 | 3 #         | 6.1         | 2.53         | 9.21         | 0.123                                 |
| Shan 156 | 2060.1         | Chang 6 | 4 #         | 6.41        | 2.53         | 8.23         | 0.137                                 |
| Wu 85    | 1991.79        | Chang 6 | 5 #         | 6.67        | 2.53         | 6.86         | 0.035                                 |
| Average  |                |         |             | 6.42        | 2.53         | 9.97         | 0.137                                 |

According to the experimental data of mercury intrusion, a mercury-intrusion curve (Figure 2) was drawn and the characteristics of mercury-intrusion parameters of rock samples were calculated (Table 3).

It can be seen that the displacement pressure of the five rock samples is distributed between 0.78 and 2.85MPa, with an average of 1.82MPa. The median pressure is distributed between 2.61 and 14.31MPa, with an average of 8.51MPa. The maximum pore-throat radius is distributed between 0.258 and 0.943μm, with an average of 0.524μm. The median throat radius is between 0.051 and 0.282μm, with an average of 0.135μm. The maximum mercury saturation is between 83.94 and 92.13%, with an average of 87.58%. The mercury removal efficiency is distributed between 26.83 and 32.6%, with an average of 30.36%. Overall, the displacement pressure and median pressure of the Chang 6 reservoir are higher, the median throat radius is lower (average 0.135μm), the reservoir throat is small, the maximum mercury saturation is high (average 87.58%), and the mercury removal efficiency is low (average 30.36%).
Figure 2. Mercury-intrusion curve of chang 63 reservoir.

Table 3. Characteristics of mercury-intrusion parameters of rock samples.

| Well no. | Core number | Displacement pressure (MPa) | Median pressure (MPa) | Maximum pore-throat radius (μm) | Median radius of pore throat (μm) | Maximum mercury saturation (%) | Mercury removal efficiency (%) | Original oil saturation (%) |
|----------|-------------|-----------------------------|----------------------|---------------------------------|---------------------------------|-------------------------------|-----------------------------|-----------------------------|
| Shan 127 | 1 #         | 0.98                        | 2.61                 | 0.750                           | 0.282                           | 86.67                         | 32.60                        | 74.4                        |
| Bai 221  | 2 #         | 0.78                        | 3.60                 | 0.943                           | 0.204                           | 87.47                         | 31.50                        | 66.1                        |
| Bai 269  | 3 #         | 2.85                        | 12.63                | 0.258                           | 0.058                           | 87.67                         | 32.19                        | 44.3                        |
| Shan 156 | 4 #         | 2.55                        | 9.38                 | 0.288                           | 0.078                           | 92.13                         | 26.83                        | 49.4                        |
| Wu 85    | 5 #         | 1.93                        | 14.31                | 0.381                           | 0.051                           | 83.94                         | 28.66                        | 46.2                        |
| Average  |             | 1.82                        | 8.51                 | 0.524                           | 0.135                           | 87.58                         | 30.36                        | 56.1                        |

5.3. Determination of the Minimum Flow Pore Throat Radius

In order to determine the minimum flow pore throat radius of Chang 63 reservoir in X Oilfield, the average mercury-intrusion curve of the reservoir was obtained based on 5 mercury-intrusion samples (Figure 3). It can be seen from Figure 3 that when the mercury-intrusion pressure reaches 49.5 MPa, the maximum mercury-intrusion saturation is 88.3%, and thereafter the mercury-intrusion saturation remains constant as the pressure increases. Therefore, point A is the lower limit of theoretical seepage, and the calculation shows that the theoretical minimum flow pore throat radius is 0.015μm. The fluid in the pore-throat network with a radius of throat greater than 15nm in the reservoir is theoretically permeable.

Statistics of production data show that the average production pressure difference of the production wells in X Oilfield is 3MPa. The oil-water interfacial tension under formation conditions is 25mN/m, the wetting angle is 0°, the mercury surface tension under laboratory conditions is 480mN/m, and the mercury wetting angle is 140°[15]. The production pressure difference is converted to the mercury-intrusion pressure under laboratory conditions. The production pressure difference of 3MPa is roughly equivalent to the experimental test pressure of 44.1MPa. Therefore, point B in Figure 3 is the lower limit of production seepage, and the production minimum flow pore throat radius is 0.017μm. This means that the fluid in the capillary pores with throat radius between 15 nm and 17 nm does not participate in seepage during production.

According to the logging interpretation results, the original oil saturation of 5 mercury-intrusion samples was counted. It can be seen from Table 3 that the oil saturation of the five rock samples is distributed between 44.3 and 74.4%, with an average of 56.1%. Therefore, point C in Figure 3 is the
lower limit of the filling seepage, and the minimum flow pore throat radius of the corresponding reservoir is 0.085 μm.

![Average mercury-intrusion curve and pore-throat distribution](image.png)

**Figure 3.** The average mercury-intrusion curve of constant pressure and pore-throat distribution of the X oilfield in the Ordos Basin.

### 6. Conclusion and Understanding

The minimum flow pore throat radius of the reservoir is not a certain value, but changes with the change of the seepage state. Reservoir seepage states are different, minimum flow pore throat radius is also different. There are three kinds of seepage states: theoretical seepage, production seepage and filling seepage. The corresponding minimum flow pore throat radius can be summarized as the theoretical minimum flow pore throat radius, the production minimum flow pore throat radius, and the filling minimum flow pore throat radius.

The calculation of the minimum flow pore throat radius of Chang 6 reservoir in X Oilfield, Ordos Basin shows that the theoretical minimum flow pore throat radius is 0.015 μm, the production minimum flow pore throat radius is 0.017 μm, and the filling minimum flow pore throat radius is 0.085 μm. The determination result of the minimum flow pore throat radius provides a basis for the calibration of the lower limit of petrophysical properties and has certain reference significance for the study of the lower limit of petrophysical properties and the microscopic utilization of reservoir fluid.

### Acknowledgments

This work was financially supported by the National Science and Technology Major Project "Effective Development Technology for Extra Low Permeability Reservoirs" of China (Grants No. 2011ZX05013-006).
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