Threshold pressure experiment of liquid flows through nanochannels and tight cores

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Abstract. Compared with low-permeability oil reservoirs, tight oil reservoirs have more nanopores, complex pore structure, and more obvious nonlinear seepage characteristics. Under the macro-scale channel flow, the influence of micro-forces is often ignored, but micro-forces of the micro-nano-scale have become the main factors affecting the flow. The micro-nano-scale flow is different from the macro-scale flow, and the flow requires the force between the fluid and the micro-nano tubes. The article conducts the threshold pressure experiment of nanochannels and cores, and results show that exists a pressure threshold under liquid flows through nanochannels and cores. The influence of the threshold pressure gradient in the micro-nanochannels is analyzed, and it is found that the nature of the fluid and the diameter of the pores affect the threshold pressure of micro the tube; core experiments prove the threshold pressure gradient exists in the core. The main factors affecting the threshold pressure gradient of the core are the permeability of the core and the nature of the experimental fluid.

1. Introduction

The rock formations of tight oil reservoirs have a large number of nanopores, and the pore structure is complex. Compared with low-permeability reservoirs, the non-linear flow characteristics of tight oil reservoirs are more obvious. Tight oil reservoirs mean the lower 0.1mD of permeability. Some scholars have found the complex flow characteristics under the nanometer scale. Driving fluids in nanochannels is difficult. Only when the driving pressure reaches a certain range, can the fluid will flow through the channel, which is called the threshold pressure [1]. In some cases, the concept of threshold pressure under the nanoscale is not recognized by some scholars [2-4]. There are also some scholars don’t believe the existence of threshold pressure gradient, but a different concept " Pseudo-threshold pressure gradient " [5].

The seepage flow in the low-permeability cores deviates from the traditional Darcy's law of seepage flow, which presents a concave nonlinear seepage characteristic, and includes a threshold pressure gradient, as shown in Figure 1 style④: There are also non-linear characteristics do not have a threshold pressure gradient, as shown in Figure 1 style②, and a linear characteristic with threshold pressure gradient, as shown in Figure 1 style③. In fact, under the condition of non-Newtonian Bainham fluid seepage, due to the special nature of the fluid, the threshold pressure gradient exists, and the classical relationship of laminar flow is [7]:

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where: \( v \) is velocity, \( K_e \) is permeability, \( \mu \) is viscosity, \( dp/dL \) is pressure gradient, \( \lambda_0 \) is threshold pressure gradient.

\[
v \approx \left( \frac{K_e}{\mu_e} \frac{dP}{dL} \right) \left[ 1 - \frac{4\lambda_0}{3} \frac{dP}{dL} \right]^{-1}
\]  

(1)

The early research methods of flow under nanometer scale are not yet mature, and people's research and understanding of the flow is not perfect and insufficient. The fluid flow characteristics under the nanometer scale are significantly different from those under the macroscale or even the micrometer scale. When the fluid flows at the micro-nano scale, there are many micro-scale effects, such as molecular force effects, low Reynolds number effects and surface tension effects and so on. Compared with the macro-scale, the study of fluid flow laws under micro-scale conditions is limited by experimental conditions and measurement accuracy, molecular dynamics simulation becomes the main research method for micro-nano scale flow. The molecular dynamics model based on the interaction between atoms does not introduce conventional assumptions and can describe the flow characteristics of fluids near adjacent walls with atomic-level accuracy. It is currently the main numerical simulation method for studying micro-scale flow problems. The flow characteristics of nano-scale fluid are difficult to observe using current experimental methods [8]. Some foreign scholars thought experiments prove permeability has effects on injection of CO₂ [9], and find the phenomenon of boundary constraints and viscosity account for the higher pressure [10].

The current methods for testing the minimum threshold pressure gradient mainly include measuring the instantaneous pressure [11-13] of the fluid and the liquid level difference before and after the core is stabilized [14-16]. A combination of unstable equilibrium method is used to carry out the threshold pressure experimental measurement. Through the micro-nano-scale threshold pressure experiment and the tight-core threshold pressure experiments, the characteristics of the threshold pressure under the micro-nano scale and the analysis of influencing factors are carried out.

2. Experimental method

The experiment is designed in two parts, namely, the threshold pressure experiment of the anode alumina membranes containing nanochannels and the threshold pressure experiment of the tight core.

2.1 Experimental method of nanochannels

Anode alumina membranes are used as the experimental material, and composed of lots of nanochannels with relatively regular arrangement. The experimental fluid is water of a minerality of 1g/L and silicone oil of 30mpa·s viscosity. The process of the experimental is shown in the figure 2:
Figure 2. Threshold pressure experiment process of anode alumina membranes

The experimental fluid is stored in a liquid storage tank, and the outlet pressure of the high-pressure nitrogen cylinder is adjusted by a regulating valve as the driving force for the displacement of the fluid. Before placing the alumina film, the air tightness check and rinse of the experimental equipment should be carried out. After the start-up pressure experiment is performed, the pressure is controlled to adjust the flow rate of the end outlet. After the end flow is stable for a period of time, the valve on the upper end of the alumina film should be closed immediately. And record the pressure, time, the displacement distance of the final liquid column, etc., until the inlet pressure at the upper end of the membrane is stable.

2.2 Experimental method of cores
The core materials are from Shengli Oilfield. Before the threshold experiments, the physical properties, such as permeability, porosity, scale and weight of the cores are measured on the experimental cores.

Figure 3. Threshold pressure experiment process of cores

The core experiment has the same principle with the experiment of the anode alumina membranes, and threshold pressure gradients are measured through experiments of the flow through cores. Threshold pressure experiments of cores measured the physical parameters of the experimental core and the saturated core before the experiment (because the membrane is much smaller than the core, the membrane is not saturated). The confining pressure of the core is greater than 2~5MPa of the gas pressure, the experiment fluid is driven by the constant flow of the injection pump, and the computer records the data every 1 minute. When the pressure at the upper end of the core is stable, close the upper inlet of the core and keep the computer continuing to record the data until the inlet pressure is stable.
3. Results and discussions

In the experiment, threshold pressures of nanochannels and the cores are measured, and influencing factors of the threshold pressures are analyzed of nanochannels from the nanochannel experiments, and further analyze influencing factors of the threshold pressure of tight cores.

3.1 Threshold pressure of liquid flow through nanochannels

For the nanochannels experiments, three anode alumina membranes with different pore diameters are selected, respectively, 30nm, 50nm and 100nm. The experimental fluid selected formation water and silicone oil of 30.0mPa·s viscosity, and finally measured the threshold pressure under different pore diameters and different viscosities.

The result of experiment under the anode alumina membrane is shown in following table:

| Aperture | Threshold pressure of formation water /kPa | Threshold pressure of silicone oil /kPa |
|----------|------------------------------------------|--------------------------------------|
| 30nm     | 2.2                                      | 1.7                                  |
| 50nm     | 1.5                                      | 1.6                                  |
| 100nm    | 1.5                                      | 1.4                                  |

The process of threshold pressure of formation water and silicone oil in the micro-nano channel is measured by threshold pressure experiments, as shown in the following figures:

![Figure 4. Pressure change of formation water](image)

![Figure 5. Pressure change of silicone oil](image)

The threshold pressure experiment of the anode alumina membranes of the formation water is carried out in multiple groups of experiments. As shown in figure 4, it can be seen from the experimental results of the formation water that there is threshold pressure when the formation water flow in the anode alumina membrane. As shown in Table 1, the threshold pressure in the 30nm aperture channel is the maximum threshold pressure of 2.2kPa in the three diameter experiments, and threshold pressures under 50nm and 100nm are the same 1.5kPa.

In the nanochannel experiments, silicone oil also obtained multiple groups of experimental data to obtain the average threshold pressure. As shown in figure 5 and table 2, three tube diameters can be seen in the silicone oil experiments. In the 30nm size experiment, the maximum threshold pressure of the anode alumina membrane is 1.7kPa, and the smallest is the 100nm pore size of 1.4kPa. Comparing the experiment results of the three sizes, with the increase of the size, the threshold pressure decreases.

Comparing the formation water and silicone oil experiments, it can be found that the threshold pressure of the formation water is higher than in the silicone oil experiment of the three size experiments. The threshold pressures of the three sizes can be seen from the average threshold pressures of formation
water and silicone oil. Among the three sizes, the 30nm has a maximum threshold pressure of 1.95kPa, and the 100nm pore size alumina membrane has a minimum threshold pressure of 1.45kPa.

3.2 Threshold pressure of liquid flow through cores
In the core experiments, three cores are selected for the core experiment, and the formation water of 1.0mPa·s and the low-viscosity silicone oil of 30mPa·s are selected to measure the threshold pressure with the two fluids in the cores. The physical property of the three cores used for the threshold pressure experiment is shown in the following table.

| Core number | Length /cm | Diameter /cm | Weight /g | Porosity/% |
|-------------|------------|--------------|-----------|------------|
| 1           | 9.90       | 2.534        | 114.295   | 9.47       |
| 2           | 9.76       | 2.53         | 113.054   | 13.04      |
| 3           | 9.97       | 2.53         | 115.496   | 8.82       |
| Average     | 9.88       | 2.53         | 114.28    | 10.44      |

The three cores based on the same block, and the porosity and permeability of these cores are similar. The results of the threshold pressure gradient between the water phase and the oil phase are measured under the experiment are shown in the following table:

| Core number | Permeability /mDc | Threshold pressure gradient of water phase MPa/m | Threshold pressure gradient of oil phase MPa/m |
|-------------|--------------------|-----------------------------------------------|---------------------------------------------|
| 1           | 1.674              | 0.61                                          | 1.26                                        |
| 2           | 2.311              | 0.51                                          | 0.89                                        |
| 3           | 1.563              | 0.60                                          | 0.81                                        |
| Average     | 1.850              | 0.57                                          | 0.99                                        |

Experiments of nanochannels shown the size of nanochannels and the viscosity of the fluid affect the threshold pressure gradient of nanochannels. The core experiment is the same as the actual principle of microtubes. Pressure changes of formation water flow in cores are shown in the figure 6 and figure 7:

![Figure 6. Pressure changes of formation water flow in cores](image-url)
Results of the core experiments are similar to nanochannel experiments. After closing the upper air inlet, the pressure decreases with time, and finally the pressures at both ends of cores is stable and no longer changes. Compared with the microtubule experiment, the steady state required for the balance of the cores experiment takes longer. As shown in figure 6 and table 2, under the formation water experiments, the maximum threshold pressure of core. 1 core is 0.61 MPa/m, and the minimum threshold pressure is 0.51 MPa/m of core. 2 core. As shown in figure 7 and table 3, under the silicone oil experiment, the core with the maximum and minimum threshold pressures is the same as the water phase, and the maximum threshold pressure gradient and the minimum threshold pressure gradient are 1.26 MPa and 0.81 MPa, respectively.

In both the nanochannel experiment and the core experiment, it is found that there is a threshold pressure under the nanopore size and the core. The nanochannel experiment found the threshold pressure is related to the size of the nanopore size and the nature of the fluid. The core experiment is not only related to the nature of the fluid, the permeability of the core will also affect the threshold pressure of the core.

4. Conclusions
It is found that the fluid flow exhibited this obvious difference from the conventional pore size in nanochannel experiments. There is a flow threshold for the fluid in the channel, which called the threshold pressure. The flow experiments of liquid show that the threshold pressure through the nanochannels is affected by the nature of the fluid and the size of the nanopore size.

The threshold gradient of the cores is related to the permeability of the core and fluid properties, and the threshold pressure of silicon oil is greater than one of formation water.

There is threshold pressure of liquid flow through tight cores and nanochannels, and the threshold pressure increases with the pore size decreasing. The flow mechanism of the threshold pressure of the fluid in the nanochannels is still unclear, and it is difficult to determine the influence mechanism of the properties of the fluid on the threshold pressure.

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