Experimental Measurement of Oil Shale Permeability and its Influence on In-situ Upgrading

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Abstract. Oil shale permeability is one of the important parameters for in-situ oil shale production. Increasing oil shale permeability is an important means to improve oil and gas recovery. In the experiment, the oil shale samples were heated to a certain temperature, and then its permeability is measured. The experimental results showed that the permeability in Maoming area increases first, then decreases, and then increases again. We established the following oil shale in-situ upgrading model. Based on the measured permeability and pyrolysis parameters of oil shale, a mathematical model of in-situ thermal recovery of oil shale is established. The heating methods include isothermal intermittent heating and equal heat flow rate heating. The oil and gas seepage migration is characterized by Darcy's law, in which the permeability is described as a function of temperature; increasing the permeability between wells will reduce the heat transfer efficiency between fluid and rock, increase the heat loss and decrease the production rate.

1. Background
Permeability is an important transport property of rock materials. It is generally believed that rock permeability is mainly determined by temperature, porosity, rock fractures, stress-strain and pore pressure. In the process of oil shale diagenesis, primary pores and fractures are relatively developed, but under the action of overlying strata and horizontal tectonic stress, these fractures are in closed state or semi cemented state, and their permeability is very poor. After high temperature pyrolysis of oil shale, water and organic matter in oil shale can not only increase the porosity of oil shale, but also promote the development of secondary fractures in oil shale. Temperature can greatly improve the permeability of oil shale and increase the circulation channel of oil shale. Therefore, it is of great significance to study the change trend of the relationship between permeability and temperature in the process of oil shale pyrolysis for the process design of in-situ oil shale upgrading and guide how to improve the temperature to affect the permeability of oil shale. Permeability is a characteristic parameter of rock's allowed fluid flow ability. At present, there are three methods to measure rock permeability: steady-state measurement method based on Darcy's law, pore pressure oscillation method and transient measurement method [2].

In the process of oil shale thermal cracking, shale will gradually produce cracks and eventually fracture, so its porosity, permeability, thermal diffusion coefficient and other physical properties will be significantly changed, which will have a great impact on the transportation of oil and gas and heat transfer.
transfer process. Therefore, in order to make the numerical simulation more accurate to reflect the actual in-situ thermal upgrading, the thermal fracture of oil shale is measured by experiment. Bai et al. [3] also carried out pyrolysis experimental measurement and function fitting on the physical parameters of Huadian oil shale, such as thermal diffusion coefficient, thermal conductivity coefficient, specific heat capacity and permeability, simulated the pressure and temperature environment of oil shale in situ stress state by using triaxial stress high temperature tester, and measured the change of oil shale permeability with temperature. It was found that the permeability increased first, then decreased and then increased. Zhao et al. used muffle furnace to carry out high-temperature retorting of oil shale [4]. After cooling, triaxial stress tester was used to measure the change of permeability of oil shale with pore pressure at different heating temperatures. It was found that the relationship between permeability and pore pressure was exponential function. Kang Zhiqin et al. obtained similar results [5].

Due to the complexity of oil shale composition and the uncertainty of organic reaction, it is expected that breakthrough progress in the study of oil shale pyrolysis mechanism cannot be achieved in a short period of time. Therefore, some empirical formulas such as the relationship between permeability and temperature and pressure are used to make up for the deficiency of reaction mechanism research and reduce the numerical model. The amount of calculation will be a key point in experimental research. In this paper, considering the actual situation of rock, it is considered that the steady-state measurement method based on Darcy's law is more suitable, and the method is simple and fast. In addition, this method is also more convenient for permeability measurement under temperature conditions.

2. Introduction of experimental measurement and numerical simulation

2.1. Experimental equipment

The oil shale rock samples used in the experiment are provided by the Petroleum Exploration and Development Research Institute of China Petrochemical Corporation. They are oil shale samples from Maoming. Due to the thin thickness of the rock samples, the thickness is less than 40 mm, as shown in Fig. 1. Two specimens on the left are machined upper and lower non polished specimens, and the thickness of the polished specimens is only 20 mm, while the right is the standard specimen (50 mm × 100 mm) of the experimental device. A total of 5 rock samples have been successfully processed.

![Fig 1. Comparison of rock sample and processed specimen (left) with standard specimen.](image-url)
The permeability of the specimens was measured on the triaxial testing machine of the school of safety engineering, China University of Mining and Technology. The overall structure of the testing machine is a four column frame structure, the working temperature range is -20 °C - 200 °C, and the maximum confining pressure is 80 MPa. The whole test system includes temperature control system, loading system, pressure control system and detection system, as shown in Fig. 2.

Fig 2. Permeability test device. (a) Temperature control system, (b) loading system, (c) pressure control system and (d) detection system.

2.2. Experimental measurement
The permeability of the specimens was measured at room temperature and 80 °C, confining pressure 3Mpa and pressure difference 2MPa. Because the specimen is not standard, the gasket must be added in the experiment, but it is easy to leak oil and the confining pressure cannot be added. Two samples were
broken during the experiment, but two of them could be pressurized successfully. However, no oil leakage was observed at room temperature and 80 °C. Therefore, the permeability of the samples at room temperature and 80 °C was not successfully measured. The reason may be that the rock particles of the test pieces are relatively dense at low temperature, with high water content and small porosity, so the permeability is very small. No oil leakage was observed.

Due to the limitation of conditions, we can only heat the specimen to a certain temperature, and then measure the permeability of oil shale gradually. The experimental steps are as follows:

1. Packaging of rock samples. In order to ensure that the confining pressure liquid does not immerse into the rock sample in the process of permeability test, the sample needs to be packaged before the rock sample is installed in the experimental equipment.

2. Connection of pipelines. The sealed rock sample is placed on the force sensor of the experimental base, and the air inlet of the base is connected with the fluid channel of the upper pressure end cap with high-pressure pipeline to ensure the sealing in place.

3. Application of confining pressure. In order to ensure that the pore pressure will not break through the heat shrinkable tube when the pore pressure is injected into the rock sample, the confining pressure greater than the internal pore pressure of the rock sample should be applied outside the heat shrinkable tube.

4. Application of axial pressure. In order to ensure the close combination of the pressure end cap and the rock sample, and prevent the pressure end cap from being pushed out of the heat shrinkable tube when the pore pressure is injected, a certain amount of axial pressure should be applied.

5. Permeability test. After the confining pressure and axial pressure are applied, keep it for a period of time to ensure the stability of each pressure. In the whole time process, the information control and acquisition system is used to collect the confining pressure, axial pressure and outlet pressure in real time.

6. End the experiment. When the upper and lower pressure of the rock sample is the same, after stabilizing the pressure for several minutes, close the valves of the inlet and outlet nitrogen cylinders, and then remove the axial pressure and take out the rock sample.

2.3. Overview of mathematical models

In the process of in-situ exploitation of oil shale, the phenomena existing in the reservoir include a series of chemical reactions caused by kerogen decomposition, oil and gas flow in the bottom, heat conduction, etc. According to the hypothesis, under the environment of high temperature, high pressure and chemical reaction, the gas oil two-phase seepage is very complex. We use the unified equation to reflect the seepage law of oil-gas two-phase in the process of oil shale in-situ thermal injection production. The unknown number included in the whole model is, and its meaning is introduced in the following equation. To simulate these phenomena, we establish the following oil shale in-situ mining model. Based on the measured permeability and pyrolysis parameters of oil shale, a mathematical model of in-situ thermal recovery of oil shale is established, including in-situ heating mode, temperature convection diffusion, oil and gas seepage migration, hydrocarbon pyrolysis, and pre-production analysis. The heating methods include isothermal intermittent heating and equal heat flow rate heating. The oil and gas seepage migration is characterized by Darcy’s law, in which the permeability is described as a function of temperature; the pyrolysis of oil and gas is described by the chemical reaction kinetic equation; the energy equation is described by the convection diffusion equation; the oil and gas flow and the exothermic and endothermic of pyrolysis affect the temperature distribution; the generated oil and gas are described by the mass transfer equation. The mathematical model is solved by numerical simulation.

3. Experimental results and in-situ mining analysis

3.1. Experimental results

Temperature is one of the important factors affecting rock permeability. It is generally believed that with the increase of temperature and the increase of secondary fractures, the permeability of rock will show
an increasing trend. However, in the process of underground gasification of oil shale and coal, the temperature rise of oil shale is also affected by the changes of in-situ stress and mechanical strength. The variation trend of permeability of oil shale with pyrolysis temperature at different final pyrolysis temperatures is shown in Table 1. The data in the table are plotted as a graph of 4, and the temperature range is 50 ℃ to 450 ℃.

Table 1. Permeability measurement data of oil shale in Maoming area.

| Temperature | permeability (md) |
|------------|------------------|
| 50         | 0.0100           |
| 250        | 0.0100           |
| 300        | 0.1373           |
| 350        | 0.0631           |
| 375        | 0.0388           |
| 400        | 2.1110           |
| 450        | 4.2800           |

Temperature is one of the important factors affecting oil shale permeability. It is generally believed that with the increase of temperature, oil shale will decompose and the permeability of rock will increase. The permeability first increases and then decreases. At 300 ℃, the permeability reaches the maximum, and then the permeability of oil shale shows a continuous decreasing trend. The main reasons for the above trend are as follows: in the early stage of oil shale pyrolysis, water and organic matter are gradually separated out. After 300 ℃, the pores of oil shale are extruded and deformed, and a part of kerogen decomposition products, such as asphalt, are gradually produced, so as to block up and reduce the permeability. After 400 ℃, asphalt and other products continue to decompose and produce Oil and gas make the reservoir pressure rise, resulting in the increase of oil shale pores, which makes the permeability increase rapidly. The main reasons for the above trend are as follows: water and organic matter gradually precipitate out in the early stage of oil shale pyrolysis. According to the investigation, after 400 ℃, the pores of oil shale have strong compression deformation, resulting in permeability reduction.
Fig 4. Effect of different permeability on productivity.

3.2. Effect of permeability on in-situ upgrading efficiency

Figure 5 shows the change of oil and gas production rate after the permeability of oil shale between the inputs well and the production well is fixed at 100 MD (equivalent to fracturing). It can be seen from the figure that it will take a longer time for oil and gas to be completely discharged after permeability changes. On the other hand, the start time of oil production was advanced, but the peak value of oil production decreased. This is because after the permeability changes, because the permeability value between the input well and the output well is relatively large, the flow velocity of the fluid in this direction is larger, resulting in a larger heat transfer area in this direction, so the temperature distribution in the connection line between the input well and the output well is obviously higher. On the other hand, due to the high flow velocity of the fluid, the heat transfer efficiency between the fluid and oil shale is reduced. Therefore, the heating effect of oil shale is not as good as that before the permeability change, resulting in the decomposition of kerogen and oil and gas production taking longer time to complete. The results in Fig. 5 can also be confirmed by the temperature distribution when the heating time is 100, 300 and 500 days before and after the change of the permeability value between the input well and the production well line shown in Fig. 5. It can be seen that the cross well permeability is 100 The temperature distribution of MD in the connecting line between the input well and the producing well is larger than that in the other areas, but the heat transfer effect between fluid and rock is not as good as that of cross well permeability.
4. Conclusions
In the experiment, the oil shale sample is heated to a certain temperature, and then the permeability is measured gradually. The experimental results show that the permeability of Maoming area increases first and then decreases. At 300℃, the permeability reaches the maximum, and then the permeability of oil shale shows a continuous decreasing trend. The main reasons for the above trend are as follows: in the early stage of oil shale pyrolysis, water and organic matter are gradually separated out. After 300 ℃, the pores of oil shale are extruded and deformed, and a part of kerogen decomposition products, such as asphalt, are gradually produced, so as to block up and reduce the permeability. After 400 ℃, asphalt and other products continue to decompose and produce oil and gas make the reservoir pressure rise, resulting in the increase of oil shale pores, which makes the permeability increase rapidly. The numerical simulation results show that the higher the permeability, the faster the temperature rise rate. If we increase the permeability between wells, the heat transfer efficiency between fluid and rock decreases, the heat loss increases, and the production rate decreases.

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