Permeability variation of sandstone under different water pressures after unidirectional heating

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Abstract. In the process of Underground Coal Gasification (UCG), the permeability of rock around coal seam will change after high temperature. In order to investigate the influence of UCG and groundwater level change on groundwater seepage, an experimental study on permeability change of sandstone under unidirectional heating under different water pressures was carried out. Taking unidirectional heating sandstone as the research object, confining pressure, axial pressure and different water pressure are set to simulate different water pressure environment, and permeability changes are obtained through experiments. The results show that: water pressure has an effect on the permeability of S01, but the permeability does not increase with the increase of water pressure. Under certain stress conditions, there is such a region in S01. When the water pressure is in the region, it has little or even negative effect on the improvement of rock permeability. When the water pressure is not in the region, it has significant effect on the improvement of rock permeability. Through the fitting of permeability and water pressure, it is concluded that the permeability of S07 increases linearly with water pressure, and the permeability of S05 increases nonlinearly with water pressure.

1. INTRODUCTION
Underground Coal Gasification (UCG) is a technology that uses controlled combustion and gasification of unmined coal underground to produce combustible gas, and it has the advantages of low gas production cost, high safety and good environmental benefits, and has been valued worldwide[1]. During and after UCG, high temperature occurs in the rock around the coal seam, and the permeability changes, which has an impact on groundwater seepage[2]. At the same time, solid residues (ash and semi-coke) will remain in place, when groundwater infiltrates through the pores of the surrounding rock, the toxic heavy metals and organic matter in the solid residue will pollute the groundwater[3]. Therefore, it is of great significance to study the change of rock permeability under unidirectional heating under different water pressures.

Scholars all over the world have conducted a lot of research on the seepage law of rocks. W. H. Somerton et al.[4] found that the sandstone permeability increased by 50% after high temperature treatment. Lu et al.[5] studied the permeability of coal-rock composite materials under true triaxial stress conditions. Guo et al.[6] studied the influence of temperature on the sensitivity of rock permeability. Yang et al.[7] studied the permeability law of loose sandstone under high hydrostatic pressure compaction. The above research provides a reference for the research of this paper. In this paper, the influence of
different water pressures on the permeability of unidirectionally heated sandstone samples is studied through the seepage test of unidirectionally heated sandstone samples.

2. Materials and Methods

2.1. Materials

| Table 1. Basic physical properties of sandstone |
| Sample | Height/mm | Diameter/mm | Mass/g | Density/g/cm³ | Saturated water content /% |
|--------|-----------|-------------|--------|---------------|----------------------------|
| S01    | 98.8      | 49.65       | 420    | 2.20          | 5.16                       |
| S05    | 100.3     | 49.62       | 417    | 2.15          | 7.16                       |
| S07    | 96.9      | 49.63       | 413    | 2.20          | 6.02                       |

Sandstone samples from a mine are selected as rock samples. Sandstone samples were selected for unidirectional heating experiment. In the experiment, a temperature controller was used to heat the heating plate quickly to 600 °C. The heating time is constant. S01, S05 and S07 specimens are selected for seepage test. The temperature measured at 8 cm away from the heating end is 433 °C, 461 °C, 435 °C, and the temperature measured at 95 cm away from the heating end is 44 °C, 47 °C, 25 °C. The basic physical properties of sandstone after heat treatment are shown in Table 1.

2.2. Methods

The experimental instrument adopts the multi-field coupling coal and rock enhanced water injection seepage experiment processing system independently developed by Shandong University of Science and Technology, see Figure 1.

Figure 1. Multi-field coupling coal and rock enhanced water injection seepage experimental treatment system.

The seepage test steps are as follows: (1) Put the heated sandstone sample in water to saturate and immerse it. The physical parameters are shown in Table 1. (2) Put the processed rock sample inside the pressure chamber and install the pipeline, see Figure 2. (3) Close the pressure chamber and set the axial pressure and confining pressure to 12 MPa. (4) Inject water to the bottom of the rock sample, the hydrostatic pressure system is pressurized to 2 MPa. (5) After a period of time, increase the water pressure to 4 MPa, 6 Mpa, 8 Mpa and 10 MPa in turn.
The principle of permeability measurement is Darcy's law, and the calculation formula is:

\[ K = \frac{Q \mu L}{\Delta P} \]

In the formula: 
- \( K \) — the permeability of the sample, \( \mu \text{m}^2 \), square micrometer is the SI unit system of permeability, millidarcy is the unit of permeability, the conversion relationship between the two is: 1 md = 0.0009869 \( \mu \text{m}^2 \); 
- \( Q \) — the fluid passes per unit time flow rate of rock, \( \text{m}^3/\text{s} \); 
- \( \mu \) — dynamic viscosity coefficient of liquid, \( 1.3077 \times 10^{-3} \text{Pa} \cdot \text{s} \); 
- \( L \) — length of rock, \( \text{m} \); 
- \( \Delta P \) — pressure difference before and after the liquid passes through the rock, \( \text{MPa} \); 
- \( A \) — cross sectional area of the liquid through the rock, \( \text{m}^2 \).

3. Results and Discussions

The permeability of the sandstone layer under the action of groundwater will not only affect the quality and effect of gas production in the UCG process, but also affect the seepage of groundwater after UCG, which may cause pollution. Therefore, it is very important to fully understand the evolution law of permeability characteristics of sandstone in the process of infiltration under water pressure. In this paper, sandstone samples are taken from the site, fixed axial pressure (12 MPa) and confining pressure (12 MPa), and different hydrostatic pressures (2 MPa, 4 MPa, 6 MPa, 8 MPa, 10 MPa) are used for infiltration to test the evolution law of sandstone permeability.

See Figure 3 for the images of the seepage flow of rock sample S01 and the remaining water volume of injection pump changing with time and water pressure.

![Figure 3](image)

Figure 3. The image of the flow of rock sample S01 changing with time and pressure.

It can be seen from the figure that when the water pressure of S01 reaches 2 MPa, the flow rate rises vertically to 0.415 ml/s, then decreases in a wavy shape, and finally tends to be stable. The flow rate is about 0.097 ml/s and the permeability are maintained at 0.062 MD. When the water pressure is increased to 4 MPa, the flow rate rises to 0.210 ml/s, and reaches a stable level after a small fluctuation. The flow rate is about 0.190 ml/s and the permeability is about 0.137 MD. After 3 min, the flow rate fluctuated up and down, the highest was 0.244 ml/s, and the lowest was 0.134 ml/s. When the water pressure was increased to 6 MPa, the flow increased to 0.328 ml/s, then decreased to 0.246 ml/s, then increased to...
0.304 ml/s, and then decreased to 0.248 ml/s, and then gradually decreased in a wave like manner. The flow in this section generally showed a downward trend, and the final flow was about 0.158 ml/s, and the permeability was about 0.119 MD. When the water pressure was increased to 8 MPa, the flow rate increased to 0.928 ml/s, and then decreased to 0.254 ml/s. After the wave change, it gradually stabilized. At this time, the flow rate is 0.127 ml/s and the permeability is 0.092 MD. When the water pressure was increased to 10 MPa, the flow rate increased to 0.196 ml/s, and then decreased to 0.188 ml/s. After the wave type change, it tended to be stable. After stabilization, the flow rate is 0.153 ml/s and the permeability is 0.112 MD.

In the seepage test of S01, when the water pressure is between 2 MPa and 4 MPa, the relationship between the permeability and the water pressure is clear. The permeability increases linearly with the increase of water pressure. When the water pressure is doubled, the permeability also doubles. When the water pressure is between 4 MPa and 10 MPa, the permeability under 6, 8 and 10 MPa is lower than that under 4 MPa. Water pressure affects the permeability of rock, but the permeability does not increase with the increase of water pressure. Under certain stress conditions, there is such a region in S01. When the water pressure is in the region, it has little or even negative effect on the improvement of rock permeability. When the water pressure is not in the region, it has significant effect on the improvement of rock permeability. When the water pressure rises, the flow rate fluctuates greatly, and the water quantity in the injection pump decreases rapidly, especially when the water pressure reaches 8 MPa. This shows that when the water pressure increases, a certain space between the heat shrinkable pipe and the rock sample is propped up by the water pressure, and part of the water enters into it. When the heat shrinkable tube is tightly bound, the space will be smaller, the water entering will be less, and the fluctuation will be smaller.

According to the permeability test results of S01 rock sample, the relationship between water pressure (4 MPa ~ 10 MPa) and permeability is fitted. The relationship between permeability (k) and water pressure (p) under the condition of fitting test stress is shown in Figure 4. The fitting equation is as follows:

\[
k = 0.137 - 0.045\exp\left(-0.5\left((p - 8)/1.645\right)^2\right)
\]

Figure 4. Fitting curve of permeability - water pressure relationship of rock sample S01.

See Figure 5 for the images of the seepage flow of rock sample S05 and the remaining water volume of injection pump changing with time and water pressure. When water pressure is applied to 2 MPa, 4 MPa, 6 MPa, 8 MPa and 10 MPa, the flow of rock sample S05 is 0.220 ml/s, 0.337 ml/s, 0.396 ml/s, 0.451 ml/s and 0.557 ml/s respectively, and the permeability is 0.155 MD, 0.255 MD, 0.270 MD, 0.311 MD and 0.338 MD respectively. In the S05 seepage test of rock sample, the permeability of rock sample increases by 0.0998 MD from 2 MPa to 4 MPa, and only increases by 0.0829 MD from 4 MPa to 10 MPa. This shows that when the water pressure is greater than 4 MPa, the influence of water pressure on the permeability of S05 sample is greatly reduced.
Figure 5. The image of the flow of rock sample S05 changing with time and pressure.

By fitting the data, we can get the relationship between permeability and water pressure of rock sample S05 under a certain pressure, as shown in Figure 6. The fitting equation is as follows:

$$k = 0.0792 + 0.04681p - 0.00214p^2$$

Figure 6. Fitting curve of permeability - water pressure relationship of rock sample S05.

It can be seen from Figure 6 that under certain pressure conditions, the permeability of rock sample S05 increases nonlinearly with water pressure.

See Figure 7 for the images of the seepage flow of rock sample S07 and the remaining water volume of injection pump changing with time and water pressure. When water pressure is applied to 2 MPa, 4 MPa, 6 MPa, 8 MPa and 10 MPa, the flow of rock sample S07 is 0.394 ml/s, 0.424 ml/s, 0.569 ml/s, 0.664 ml/s and 0.779 ml/s respectively, and the permeability is 0.280 MD, 0.305 MD, 0.407 MD, 0.477 MD and 0.552 MD respectively.

In the rock sample S07 test, when the water pressure increases from 2 to 4 MPa, 4 MPa to 6 MPa, 6 MPa to 8 MPa, 8 MPa to 10 MPa, the permeability increases by 0.025 MD, 0.102 MD, 0.070 MD and 0.075 MD respectively. When the water pressure exceeds 4 MPa, the improvement effect of water pressure on the permeability of rock sample S07 is increased. When the water pressure exceeds 8 MPa and 10 MPa, the improvement of S07 permeability is slightly lower than before.

By fitting the data, the relationship between permeability and water pressure of rock sample S07 under certain pressure can be obtained, as shown in Figure 8. The fitting equation is as follows:
Figure 7. The image of the flow of rock sample S07 changing with time and pressure.

It can be seen from Figure 8 that under a certain pressure, the permeability of rock sample S07 increases linearly with the water pressure.

Figure 8. Fitting curve of permeability - water pressure relationship of rock sample S07.

Figure 9. The rock sample image after seepage test.

The rock sample image after seepage test is shown in Figure 9.

4. Conclusions
The seepage of unidirectionally heated rock during UCG was studied. The results are as follows:

(1) Water pressure has an effect on the permeability of S01, but the permeability does not increase with the increase of water pressure. Under certain stress conditions, there is such a region in S01. When the water pressure is in this area, the improvement of rock permeability is very small or even negative. When the water pressure is not in this area, it has a significant effect on improving rock permeability.

(2) The permeability of S05 and S07 increases with the increase of water pressure. By fitting the permeability and water pressure, we can get that the permeability of S07 increases linearly with water pressure.
pressure, which conforms to Darcy's law of seepage. And the permeability of S05 increases nonlinearly with water pressure. The permeability - pressure curve of S05 is convex, the higher the water pressure is, the slower the permeability increases.

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