EXPERIMENTAL INVESTIGATIONS OF CO_2 SEEPAGE BEHAVIOR IN NATURALLY FRACTURED COAL UNDER HYDRO-THERMAL-MECHANICAL CONDITIONS

by

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Gas-flow in coal or rock is hypersensitive to the changes of temperature, confining pressure and gas pressure. This paper implemented a series of experiments to observe the seepage behavior, especially the permeability evolution of CO_2 in naturally fractured coal sample under coupled hydro-thermal-mechanical conditions. The experimental results show that coal permeability increases exponentially with the increasing gas pressure, and tends to be linear when the confining pressure is high. Coal permeability decreases exponentially with the increasing confining pressure. Coal permeability decreases with the increasing temperature generally, but it may bounce up when the temperature rises to high. The results provide reference for the projects of coal gas extraction and carbon dioxide geological sequestration.

Key words: *gas seepage behavior, thermo-hydro-mechanical interaction, coal sample, experimental analysis*

Introduction

Gas-flow in coal or rock is hypersensitive to the change of temperature [1, 2]. It is reported that the effects of temperature change on the permeability turn out to decrease or increase the permeability [3-5]. Lyu *et al*. [6] analyzed the permeability evolution of sedimentary rocks at different temperatures based on the Katz-Thompson theory, and found that the permeability increased with the high temperature. Lin *et al*. [7] studied the characteristics of pressure-temperature induced permeability variation of typical carbonate rock to determine its performance as reservoir or cap rock. Liu *et al*. [8] investigated the enhancing coal permeability with high temperature, and computed the change of permeability at different temperatures. Tian *et al*. [9] measured the permeability evolution and crack characteristics in granite under treatment at high temperature, and found that the initial and residual permeability and porosity changed little when $T \leq 300$ °C, but increased rapidly when 300 °C $\leq T \leq$ 600 °C before entering a stable phase when 600 °C $\leq T \leq$ 750 °C. Xia *et al*. [10] used ultra-low ash anthracite with ash content of 1.55% to conduct high temperature heating in the laboratory and found that

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the hydrophobicity of anthracite could be rapidly reduced after high temperature heating. Luo *et al*. [11] found that there was an obvious lag effect in the adsorption and desorption of CO_2 by coal, as the concentration of CO_2 increased, the concentration of CH_4 decreased, and the temperature of coal matrix increased. Meng *et al*. [12] found that the permeability decreased gradually with increasing pore pressure when the pore pressure was less than 2.5 MPa, and the relationship between temperature and permeability was complicated. Liu *et al*. [13] established a real deformation pore structure model to simulate water seepage in coal seam. The pore distribution and stress loading direction have significant influence on the failure mode of coal-based materials. Zhang *et al*. [14] investigated the influence of cyclic hot/cold shock on the change in the permeability of coal sample under different temperature gradients, and found that after two treatments, the maximum increment of the permeability of coal samples reached 1129.79%.

This paper implemented a series of experiments to observe the seepage behavior, especially the permeability evolution of CO_2 in naturally fractured coal sample under coupled hydro-thermal-mechanical conditions. The results provide reference for the projects of coal gas extraction and CO_2 geological sequestration.

Experimental methodology

Selection and validation of coal samples

In this series of experiments, three kinds of raw coal samples from Ping Dingshan Coal Mine, Changzhi Coal Mine, and Jinjia Coal Mine from China were selected. Raw coal blocks from the aforementioned coal mine fields were directly transported to the Mechanics Experimental Center in China University of Mining and Technology, and subsequently processed into cylindrical samples with the height of about 100 mm and the diameter of about 50 mm that are suitable for penetration testing. In order to preserve the basic physical, structural and chemical properties of the raw coal, the sharped coal samples were sealed and stored until the experiments were implemented.

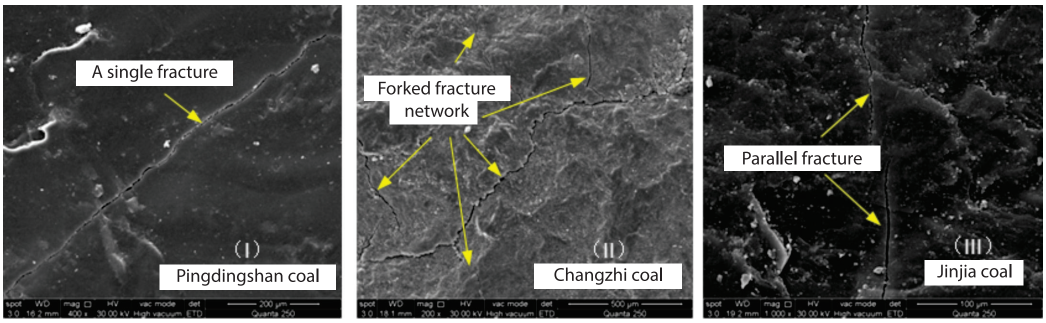

Figure 1. Observed natural fracture on coal surface by SEM experiment

To validate the peculiarities of three kinds of coal samples, the SEM experiments for the natural fracture section on coal surface and mercury intrusion porosimetry (MIP) experiments for the micro-pores in coal cubic were, respectively carried out anteriorly. The SEM results of three kinds of coal samples in fig. 1 show that raw coals have natural fractures or pores. The comparison of SEM results (note the different magnification) indicates that the JJ coal has a maximal aperture of natural fracture in these three kinds of coals, whereas the CZ coal has the minimal aperture, and the aperture of PDS coal is between them. The comparison of MIP results indicate that the porosities of Ping Dingshan coal, Changzhi coal and Jinjia coal are 5.04%, 4.39%, and 12.5%, repectively. Figure 2(a) shows the observed aperture of micro pore in coal cubic by MIP experiment. Although the apparent porosities of Pingdingshan and Changezhi coals equal mostly, the distributions of pore aperture differ a lot. For the PDS coal sample, most pores have aperture of about 0.001~0.1 μm, but about 0.1~1 μm for the CZ coal sample. Figure 2(b) represents the fractural dimension evolution of the micro-pore sizes in three kinds of coal under different temperature treatment. It is obvious that the fractal dimension increases with the increment of temperature. That is because temperature treatment leads to the development of micro-pores, which may affect the seepage behavior.

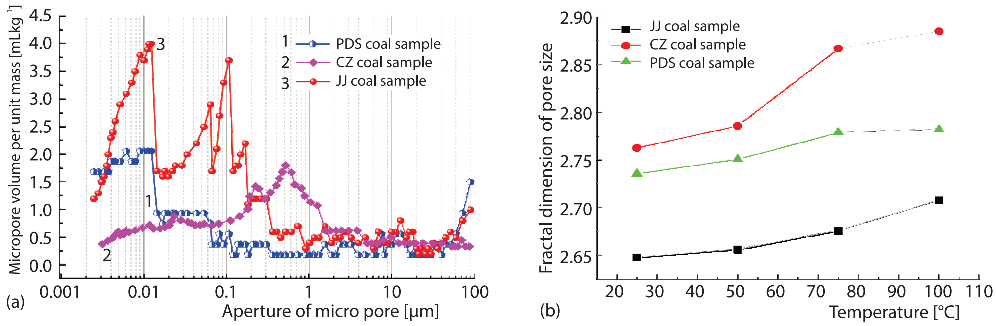

Figure 2. Observed aperture of micro-pore in coal cubic by MIP experiment: (a) initial distribution of pore size and (b) fractal dimension of pore size with different temperature

Experiment apparatus and procedure

The permeability experiments were carried out by using the Coal and Rock Mechanics-Seepage System (TAWD-2000). During the experiment, the conditions of axial pressure, confining pressure and temperature around coal samples are servo controlled through the computer terminal system. This experiment comprehensively explored the effects of temperature, confining pressure and gas pressure on the CO_2 seepage behavior. The controlling targets of confining pressure are 6 MPa, 10 MPa, 15 MPa, and 20 MPa, corresponding to the reservoir depths of 500 m, 100 m, 1500 m, and 2000 m, respectively. The controlling targets of gas pressure are 1-6 MPa, the controlling targets of temperature are 25 °C, 45 °C, 65 °C, and 90 °C. Gas pressure is controlled by the gas seepage module that the CO_2 gas goes through a series of processes of drying, pressure servo control and sensor monitoring, flows into the coal sample from the upstream air inlet (the bottom of coal sample), and then flows out through the downstream air inlet (the top of the sample). In the data processing, this experiment assumes that the flow of gas satisfies the Darcy's law. Flowchart of experiment operation and the equipment are drawn in figs. 3 and 4.

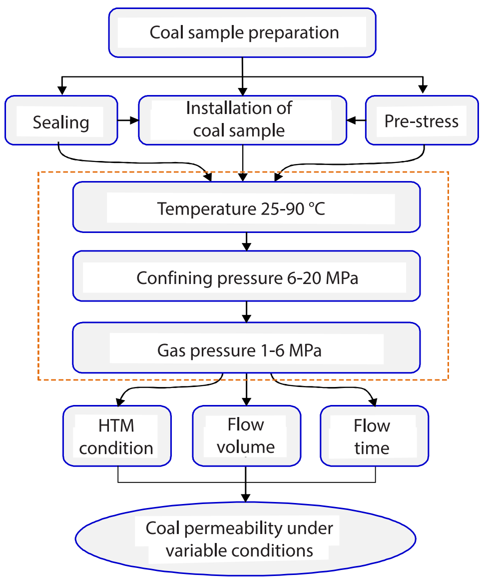

Figure 3. Flowchart for the experiment

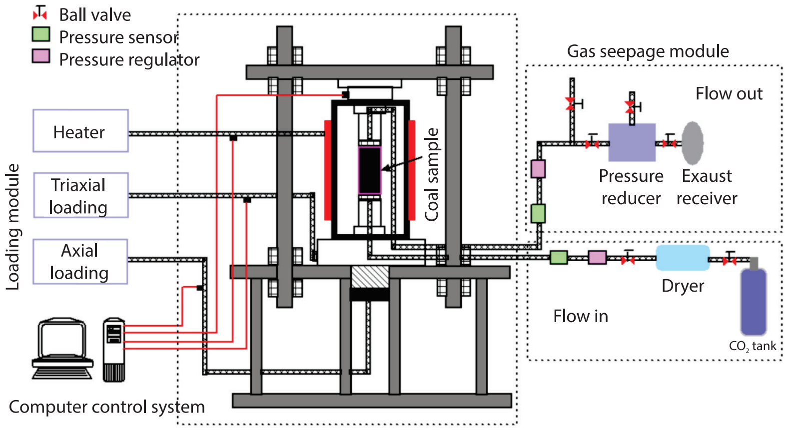

Figure 4. Schematic diagram of the TAWD-2000 system

Experimental results and discussion

Evolution of coal permeability with gas pressure under room temperature

Figure 5 shows the evolution of coal permeability with variable injection gas pressure under the confining pressures of 6 MPa and 10 MPa. The temperature for the used data in fig. 5 is obtained under room temperature. It can be seen that the permeability of raw coal shows an exponential increasing trend with the increasing gas pressure. The permeability increases rapidly when the pressure of injection gas is low, whereas the permeability increases slowly when the gas pressure is high. Considering the effect of confining pressure on the evolution trend of

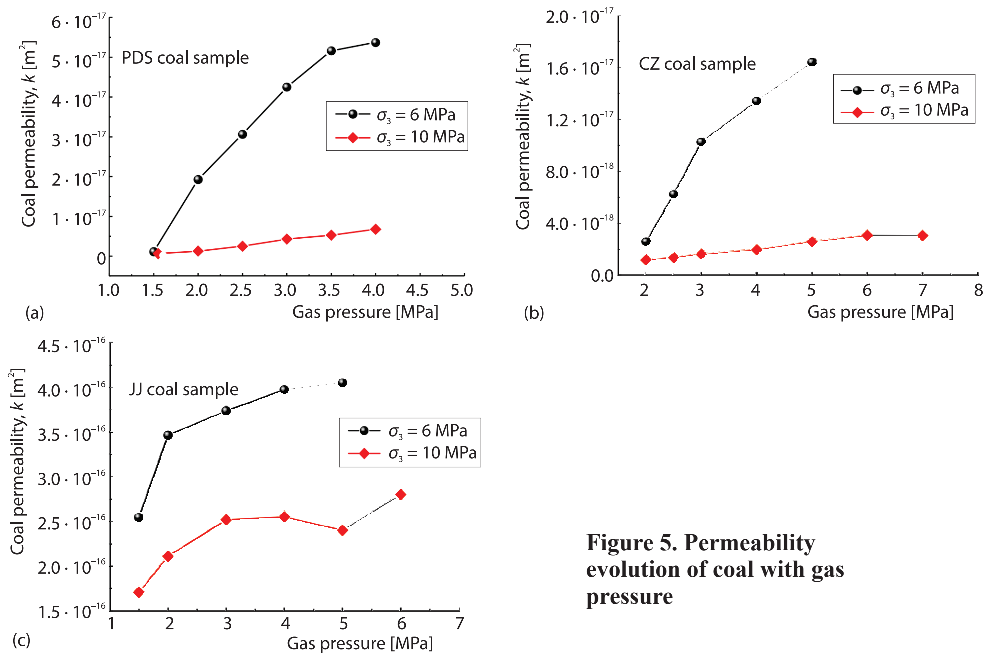

Figure 5. Permeability evolution of coal with gas pressure

coal permeability with gas pressure, one can conclude that the exponential growth pattern of coal permeability is obvious when the confining pressure is low, however, it tends to be a linear relation when the confining pressure is high.

The main reason for the different evolution of coal permeability is the combined effects of gas and confining pressure. When the confining pressure is low, the effect of gas pressure on permeability is obvious. On the one hand, the crack aperture in coal is relatively large, and the gas easily enters into the cracks in coal and changes the effective stress. On the other hand, high gas pressure in the coal crack supports the crack structure to a certain extent and opens the crack channel. While the confining pressure is high, the effect of gas pressure is small. On the one hand, coal sample is compacted and gas is difficult to enter into. On the other hand, the pressure of gas entering into the coal sample is far less than the confining pressure, because of the effective effect of the gas pressure on the coal sample is small, as a result the improvement of gas pressure on the porosity and permeability is small.

Evolution of coal permeability with confining pressure under room temperature

Figure 6 represents the comparative evolutions of coal permeability with confining pressure for three kinds of different coal samples under the room temperature and the gas pressures of about 3 MPa and 5 MPa, respectively. According to the observed experimental results of coal samples, the permeability of raw coal shows an exponential decreasing trend with the increased confining pressure under different gas pressures. When the confining pressure is low, coal permeability is very sensitive to the change of confining pressure that it decreases rapidly with the increasing confining pressure, and then decreases slowly until it tends to be very

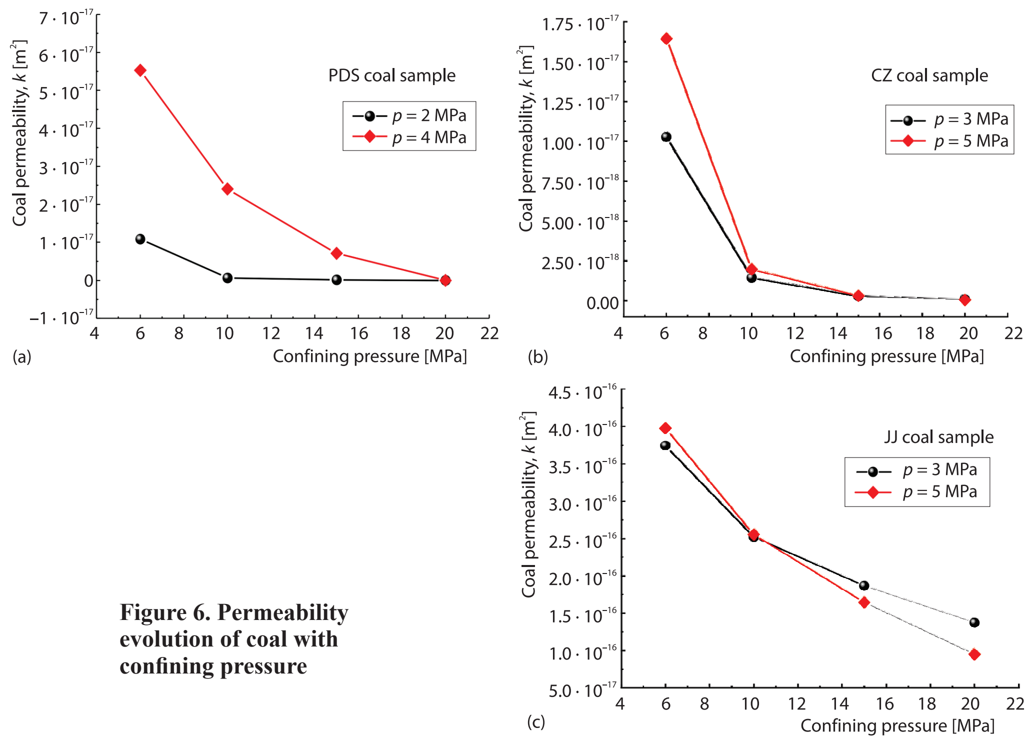

Figure 6. Permeability evolution of coal with confining pressure

steady. Considering the effects of gas pressure on the evolution law of coal permeability, gas pressure cannot change the exponential decreasing trend of coal permeability with confining pressure, but it has a mitigation effect.

Evolution of coal permeability with temperature under variable gas pressure

Figure 7 is the evolution curves of permeability for three kinds of coal samples with temperature under conditions of different gas pressure. It can be seen from the figures that the permeability of three kinds of coal samples generally show a decreasing trend with increasing temperature under different gas pressures, but there are also some cases that the permeability first decreases and then increases with the increasing temperature under specific gas pressure. Take the gas pressure of 5 MPa as an example, when the temperature rises from 25-55 °C and 95 °C, the permeability of PDS coal sample decreases from $5.6 \cdot 10^{-17}$ m^2 to $1.1 \cdot 10^{-17}$ m^2 and $3.2 \cdot 10^{-18}$ m^2 by the drop rates of 78.6 % and 70.9%. When the temperature increases from 25-45 °C, 65 °C and 85 °C, the permeability of CZ coal sample decreases from $1.7 \cdot 10^{-17}$ m^2 to $2.7 \cdot 10^{-18}$ m^2 and $1.6 \cdot 10^{-18}$ m^2 firstly with the drop rates of 84.1% and 90.6%. It then increases to $2.9 \cdot 10^{-18}$ m^2, with the increasing rate of 81.2%. The permeability of JJ coal sample decreases from $4.1 \cdot 10^{-16}$ m^2 to $2.9 \cdot 10^{-16}$ m^2, $2.6 \cdot 10^{-16}$ m^2, and $2.2 \cdot 10^{-16}$ m^2 with the drop rates of 29.2%, 36.6%, and 46.3%.

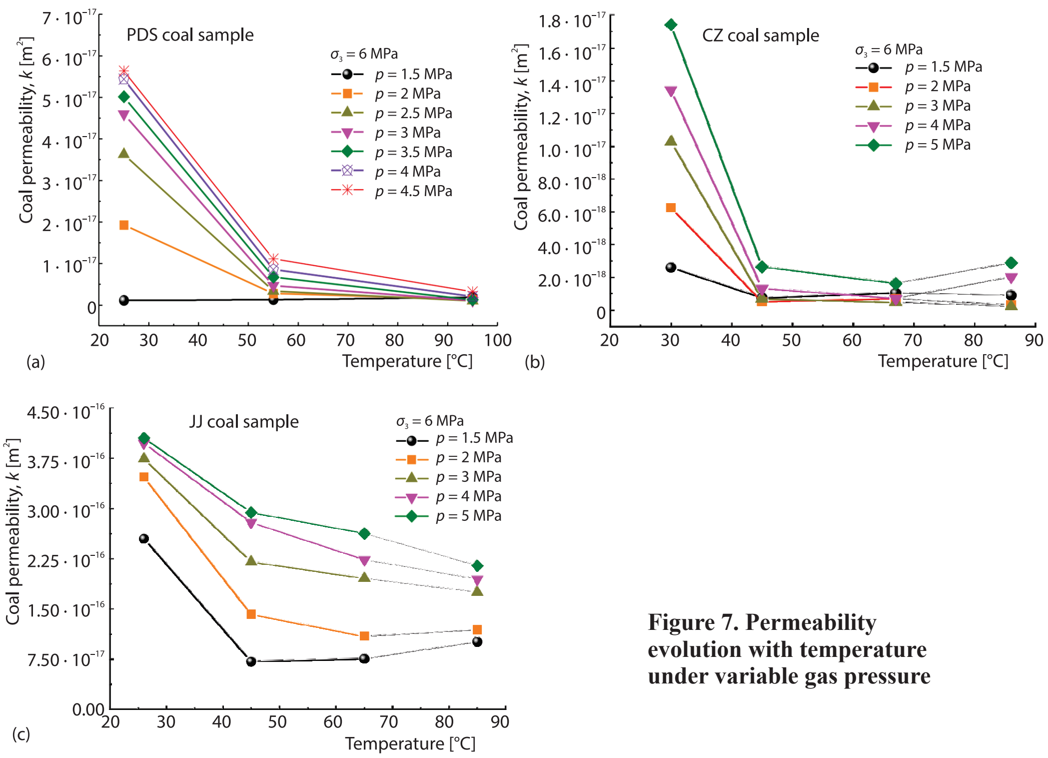

Figure 7. Permeability evolution with temperature under variable gas pressure

Permeability evolution of coal is a comprehensive result due to the changes of properties such as coal adsorption capacity, internal material composition and pore-fracture structure caused by the increasing temperature. Gas pressure has little effect on the evolution of coal permeability with the increasing temperature. However, with the increase of gas pressure, permeability of coal generally increases that leads to the strengthening to the evolution intensity of permeability with increasing temperature, as a result the rate of evolution becomes larger.

Evolution of coal permeability with temperature under variable confining pressure

Figure 8 shows the evolution curves of coal permeability with the variable temperature under conditions of different confining pressure and a certain gas pressure of about 5 MPa. It can be seen from the figures that the permeabilities of three kinds of coal samples under different confining pressure are generally decreasing with the increasing temperature. However, the decreasing evolution pattern of coal permeability for CZ coal sample changes, it decreases first and then increases indicating that the aperture of coal fracture enlarges. On the whole, the permeability of coal is very sensitive to confining pressure. The permeability of coal decreases with the increasing confining pressure greatly, especially under low confining pressure of 6 MPa and 10 MPa. The permeability of raw coal maintains unchanged with the increment of temperature, but the evolution intensity decreases obviously.

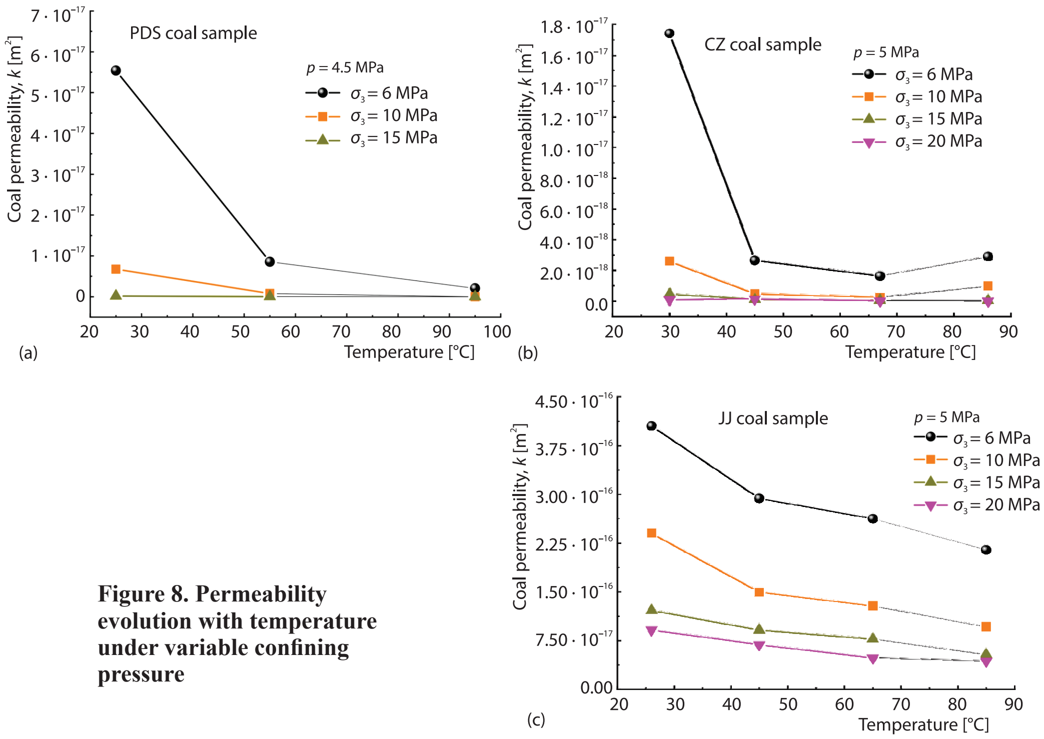

Figure 8. Permeability evolution with temperature under variable confining pressure

Conclusions

This paper implemented a series of experiments under coupled hydro-thermal-mechanical conditions to research the seepage behavior of CO_2 in naturally fractured coals from Ping Dingshan Coal Mine, Changzhi Coal Mine, and Jinjia Coal Mine, China, that have different micro-pore structures. Following experimental results can be drawn:

- Coal permeability increases exponentially with the increasing gas pressure and the exponential trend is obvious when the confining pressure is low whereas it tends to linearity when the confining pressure is high.

- Coal permeability decreases exponentially with the increasing confining pressure.
- Gas pressure cannot change the exponential decreasing trend of permeability with confining pressure, but it has mitigation effect to a certain extent.
- Coal permeability decreases with the increasing temperature generally, but it may bounce up as the temperature rises.

The results provide reference for the projects of coal gas extraction and carbon dioxide geological sequestration.

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