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Research Article

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Experimental Study of Coal Seepage and Deformation under the Influence of Hot Nitrogen Gas

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Abstract The aim of this study is to investigate the permeability characteristics and strain variation law of nitrogen gas in φ50×100mm columnar raw coal under different temperature and injection pressure conditions through experimental methods, in order to investigate the influence of coal rock permeability on the effect of gas injection heat mining. The experimental results show that under different injection pressure conditions, the nitrogen permeability shows a complex trend of "W" and "U" shape with increasing temperature. At the same time, as the gas injection pressure increases, the coal rock volume shows a change in the trend of outward expansion and overall compression at different temperature conditions, with the most significant overall compression occurring at 150°C. These experimental results provide theoretical support for the feasibility of thermal injection mining of gas from coal reservoirs, and provide some theoretical basis for the optimisation of thermal gas injection incentive gas mining technology.

Keywords Hot Nitrogen, Penetration rate, Temperature, Coal

1. Introduction

Global greenhouse gas emissions are increasing, leading to a serious deterioration of environmental problems. In this context, coal seam methane is of great interest as a clean, efficient and environmentally friendly energy source, yet its extraction can also reduce coal mine methane disasters, making its extraction of coal seam methane of great value and significance. The extraction of coal seam gas not only helps to mitigate environmental degradation, but also provides a powerful alternative energy source for the energy revolution and reduces the incidence of mine gas disaster accidents, thereby ensuring miner safety. The extraction of coal seam gas is therefore of great strategic value and practical importance for the sustainable development of the energy sector, environmental protection and the development of human society.

Thermal gas extraction as a new CBM mining technology [1-4] can promote the desorption of gas from coal matrix by injecting high temperature gases (e.g. nitrogen, water, CO_2, etc.) to improve the recovery of coal seam gas. At present, many scholars have conducted in-depth studies on the effects of heat-injected gases on coal rocks, and have achieved a wealth of research results. Among them, Zhao Yang sheng [5-7] and other scholars found that high-temperature gas injection would lead to changes in the overall structure of the coal rock, with changes in porosity and permeability, and that irreversible thermal damage to the coal rock would occur when the temperature reached a certain value. Shengcheng Wang [8,9] and other scholars established a numerical model for thermal nitrogen injection, suggesting that after coal rock is injected with high-temperature nitrogen, the coal matrix will undergo adsorption expansion and thermal expansion causing changes in the overall strain of the coal rock, thus increasing the coal rock permeability and stimulating the gas yield in the coal matrix. Alireza Salmachi [10] and others have argued that hot water injection can effectively increase the temperature of coal reservoirs and increase gas recovery. Teng [11,12] and others argue that heat injection improves gas recovery by stimulating gas desorption in the coal matrix, and that although the temperature increases, the efficiency of heat gain does not necessarily increase. In addition, some scholars have improved the coal-bed gas recovery rate by injecting hot CO_2 that can effectively repel gas outputs such as CH_4 [13-15]. These research results have important theoretical and practical significance for the in-depth understanding of the mechanism of thermal gas extraction, the optimization of coal-bed gas mining technology and the promotion of the sustainable development of the coal-bed gas industry.

In this paper, the nitrogen gas permeability and deformation patterns of coal rocks under different temperature conditions are investigated using a high temperature thermal gas extraction system. The reasons for the variation in permeability are explained through a comprehensive analysis of the relationship between strain and permeability.

2. High temperature nitrogen gas percolation test

2.1 Experimental setup and coal sample preparation

In order to determine the nitrogen gas permeability of coal rocks under different injection temperature conditions, this study conducted nitrogen percolation and transport experiments on coal samples using a high temperature thermal gas extraction system. The experimental setup mainly consisted of a nitrogen gas heating system, a shaft envelope pressure system and a gas measurement unit, as shown in Figure 1.

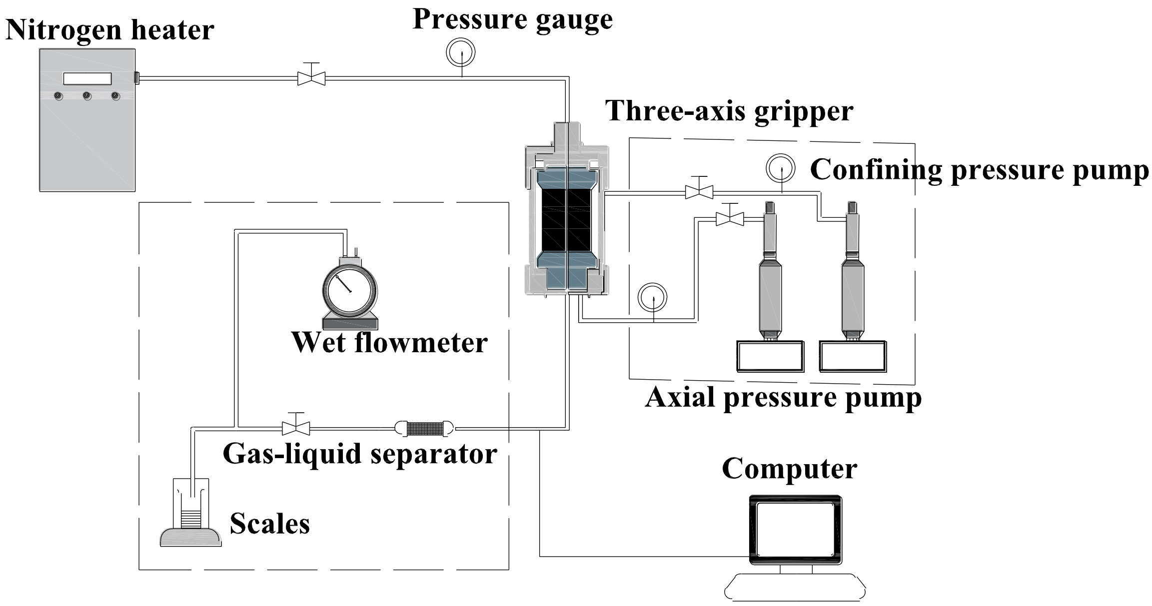


Figure 1: Diagram of the high temperature nitrogen gas percolation experimental setup

In order to reduce the influence of moisture on the gas permeability of the coal samples, the raw coal was processed into columnar coal samples of φ50mm×100mm and then dried in a constant temperature apparatus for more than 24 hours and stored in a cling film.

Table 1: Basic parameters of columnar coal samples

Basic parameters	Mad/%	Aad/%	Vad/%	ρ/(g.cm^{-3})
Coal	0.0108	0.1017	0.089	1.59

2.2 Experimental protocol and procedures

(1) First place the coal sample on the dummy core, wrap the two heat shrink sleeves around the exterior of the columnar coal, heat blowers are evenly heated to make a complete fit, wait for cooling then install the axial and

radial strain gauges, put them into the triaxial gripper cavity positioning slot, silicone oil is added to the scale line, the gripper cover body is fixed with hexagonal screws and the device is checked for air tightness.
(2)Turn on the shaft pressure, perimeter pressure pump and valve, and gradually load the shaft pressure to 6MPa and perimeter pressure to 5MPa simultaneously, so that the shaft pressure and perimeter pressure are stabilized at a certain value, and always ensure that the perimeter pressure is less than the shaft pressure during the pressurization process
(3) Start the nitrogen heater and valve, set the target pressure (0.5MPa, 1MPa, 2MPa, 3MPa) and temperature (30 ℃, 60 ℃, 90 ℃, 120 ℃, 150 ℃, 180 ℃), and connect the gripper when there is high temperature nitrogen output at the outlet.
(4) The computer is switched on to monitor the experimental process data for 30 minutes and the amount of hot nitrogen seepage is monitored by a wet flow meter with a balance.
(5) When changing the experimental conditions, repeat the above experimental steps by changing the set values.

2.3 Data processing

The results of the experiments were obtained by testing the permeability by the steady-state method, which was calculated mainly by the following equation:

$$K = \frac{2QP_a\mu L}{S(p_1^2 - p_2^2)} \tag{1}$$

Where: K is the gas permeability, mD; Q is the gas flow rate, cm^3/s; Pa is the standard atmospheric pressure, 0.1MPa; is the gas viscosity, $\times 103Pa/s^{-1}$; S is the permeable area of the coal sample, cm^2; p1 is the pressure at the inlet end, MPa; p2 is the pressure at the outlet end, MPa.

3. Experimental results and analysis

Under constant pseudo-triaxial pressure conditions, this study determined the patterns of deformation and permeability of bituminous coal from Shaanxi, China, under the conditions of injection of hot nitrogen gas at different temperatures. The experimental results show that as the temperature increases, the permeability of the bituminous coal shows a "U" and "W" shaped pattern. In the low temperature (30-180 °C) interval, as the temperature increases, the coal rock porosity increases and the coal rock volume changes, resulting in the permeability first increasing and then becoming saturated. As the temperature continues to increase, biochemical and thermochemical reactions occur within the coal rock, the structure of the coal rock matrix is irreversibly altered, the porosity decreases and the permeability decreases accordingly. As the temperature continues to rise, the microscopic pores in the coal matrix are dilated, again increasing the permeability and creating a "W" shaped pattern.

3.1 Variation of nitrogen permeability of coal rocks under different temperature conditions

In this study, the variation pattern of nitrogen permeability of coal rocks with time under different gas injection pressure conditions was investigated under constant triaxial pressure conditions. The results of the experimental data show that the nitrogen permeability of the coal rock shows a complex non-linear trend with time, and its variation pattern is influenced by various factors such as gas injection pressure and temperature.

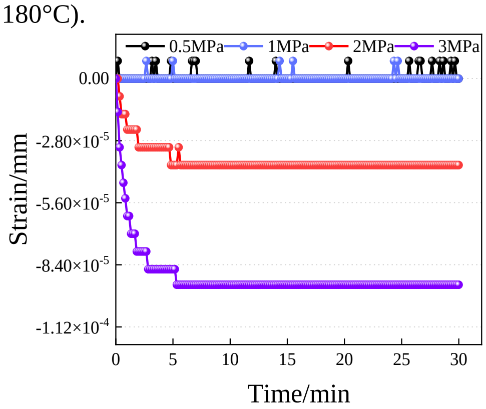
(1) The experimental results show that the permeability of the specimens is shown in Figures 2a, 2b, 2c and 2d when the gas injection pressure is 0.5 MPa, 1 MPa, 2 MPa and 3 MPa respectively. where the permeability of the specimens varied from 0.0085 to 0.0091 mD for an injection pressure of 0.5 MPa; The permeability of the specimens ranged from 0.0026 to 0.0032 mD when the gas injection pressure was 1 MPa; The range of permeability variation of the specimen at an injection pressure of 2 MPa was 0.0065 to 0.0085 mD; And when the gas injection pressure was 3 MPa, the permeability of the specimens varied from 0.0029 to 0.0042 mD.
(2) According to the experimental results in Figure 3 (d~l), it can be seen that at a temperature of 60°C, the gas injection pressure also has different effects on the axial, radial and volumetric expansion changes of the coal

rock. At 0.5 MPa and 1 MPa injection pressure, the axial strain in the coal rock varies less, while the radial strain in the coal rock gradually increases. Under 1 MPa to 3 MPa injection pressure conditions, the volume of the coal rock expands uniformly outwards. This suggests that an increase in gas injection pressure can promote changes in the microscopic pore structure of the coal rock, resulting in an overall expansion of the coal rock volume. At the same time, the change in the microscopic pore structure of the coal rock is more pronounced at a temperature of 60°C, which may be due to the increased temperature further promoting the deformation and expansion of the microscopic pores of the coal rock.

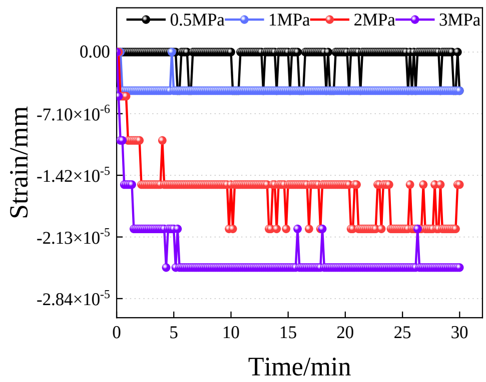
(3) According to the experimental results in Figure 3 (g~i), the pattern of change in the volume of coal rock at temperatures of 90°C and 120°C is slightly different from that at low temperatures. This indicates important changes in the microscopic pore structure and physical properties of the coal rock under high temperature conditions. As the temperature rises, the microscopic pore structure within the coal rock may expand or contract, and when a certain amount of gas is injected, the coal rock volume expands rapidly outwards. This phenomenon suggests that coal rocks under high temperature conditions are more sensitive and more susceptible to gas injection pressure and gas volume than coal rocks under low temperature conditions.

(4) According to the experimental results in Figure 3 (m~o), the gas injection pressure has a complex effect on the volume change of the coal rock at a temperature of 150°C. At low pressures (0.5 MPa), the coal rock compresses inwards as a whole, reducing in volume. As the pressure increased, the volume of the coal rock increased, but the overall contraction remained inward. It is noteworthy that at 2 MPa injection pressure, although the overall volume of the coal rock shrinks, the radial strain increases. When the gas injection pressure reaches 3 MPa, the volume of the coal rock expands rapidly. This suggests that the microscopic pore structure and physical properties of the coal rock undergo important changes under high temperature conditions, resulting in a more complex response to the gas injection pressure. Overall, the response characteristics of the coal rock at a temperature of 150°C are significantly different from the previous low temperature conditions, reflecting significant changes in the physical properties of the coal rock and the challenges faced in recovering CBM in a high temperature environment.

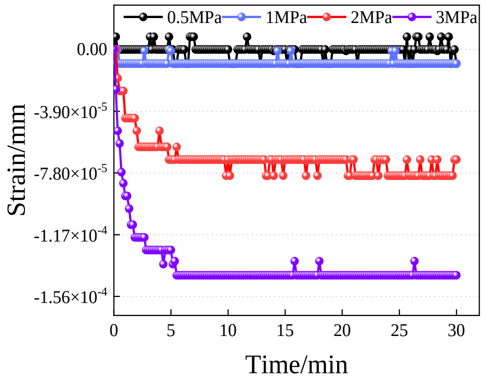
(5) According to the experimental results in Figure 3, the effect of gas injection pressure on the volume change of the coal rock decreases gradually at a temperature of 180°C. At low pressures (0.5 MPa and 1 MPa), the volume change in the coal rock is essentially the same, indicating that the effect of gas injection pressure on the volume change in the coal rock has stabilised. The volume changes in the coal rock are essentially the same at 2 MPa and 3 MPa injection pressures, suggesting that the increase in injection pressure no longer contributes further to the microscopic pore structure changes and volume changes in the coal rock under high temperature conditions. This experimental result also indicates that the physical properties and microscopic pore structure of the coal have been importantly altered and stabilised at high temperatures (e.g. 180°C).



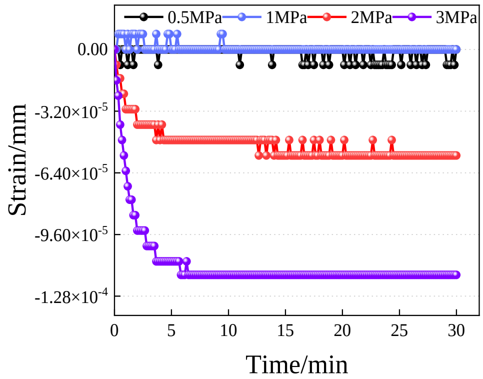
(a) Axial strain diagram at 30° C



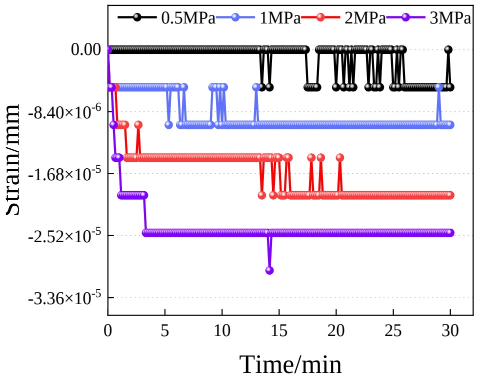
(b) Radial strain diagram at 30°C



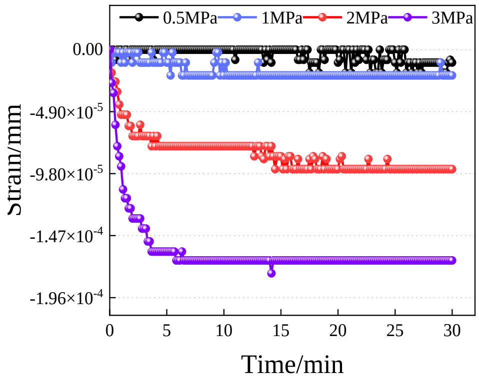
(c) Volume strain diagram at 30° C



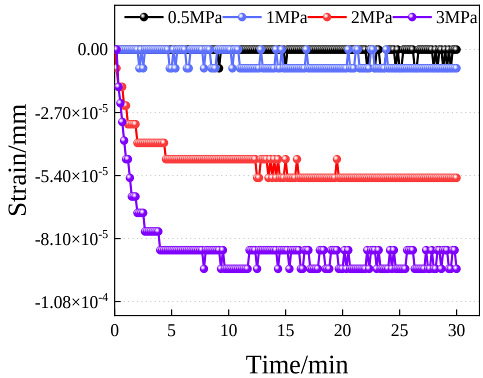
(d) Axial strain diagram at 60° C



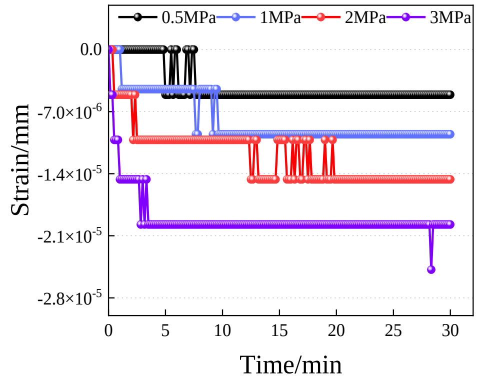
(e) Radial strain diagram at 60° C



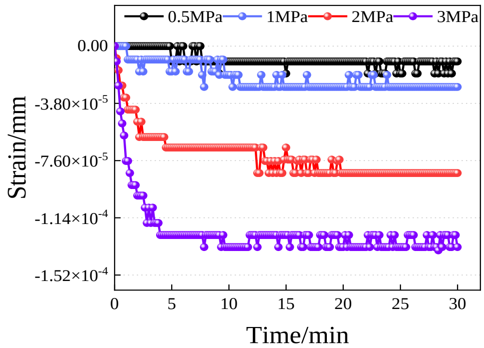
(f)Volume strain diagram at 60° C



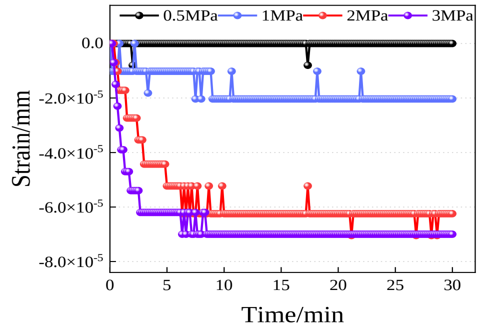
(g) Axial strain diagram at 90° C



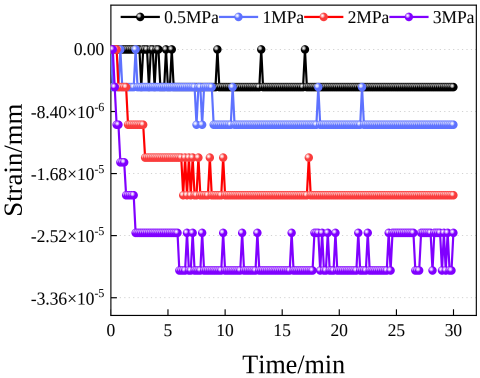
(h) Radial strain diagram at 90° C



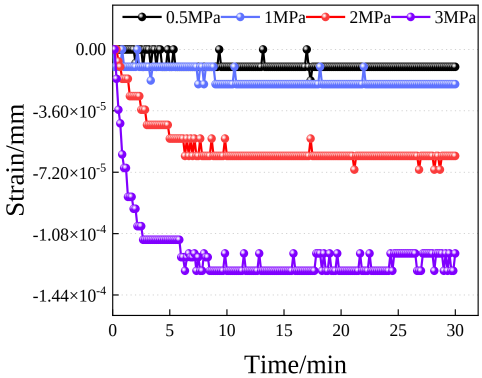
(i) Volume strain diagram at 90° C



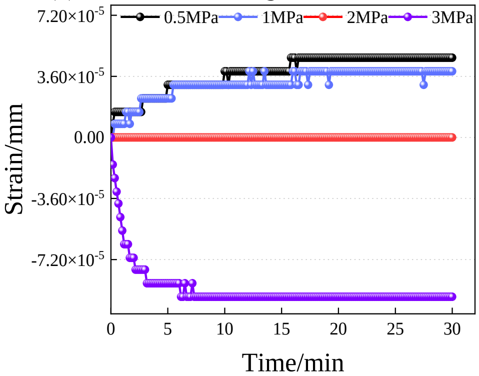
(j) Axial strain diagram at 120° C



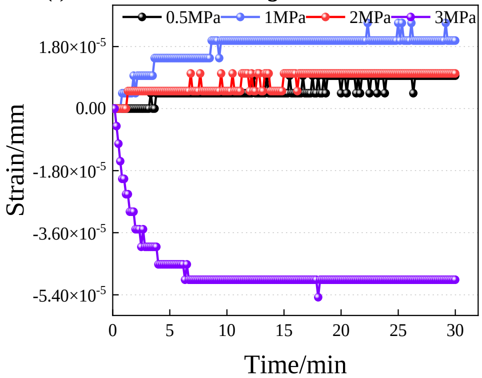
(k) Radial strain diagram at 120° C



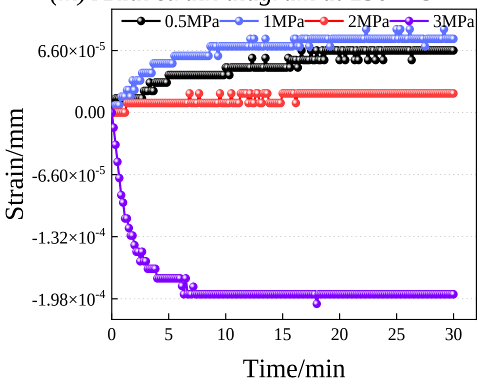
(l) Volume strain diagram at 120° C



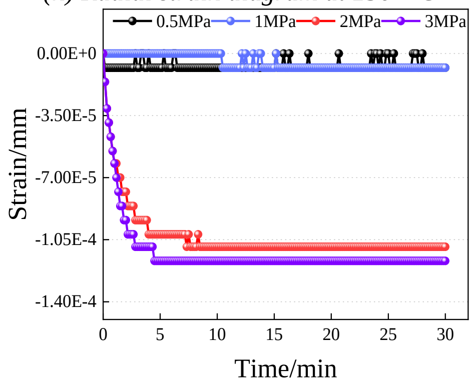
(m) Axial strain diagram at 150° C



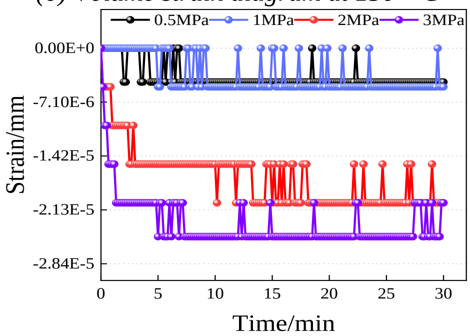
(n) Radial strain diagram at 150° C



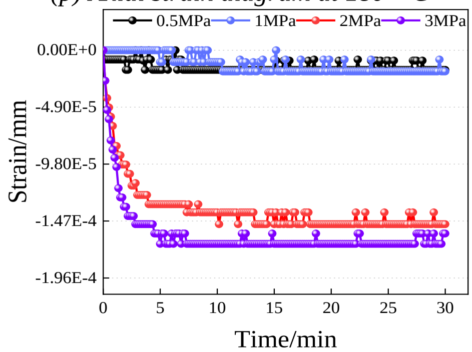
(o) Volume strain diagram at 150° C



(p) Axial strain diagram at 180° C



(q) Radial strain diagram at 180° C



(r) Volume strain diagram at 180° C

Figure 3: Variation of strain at different pressures at different temperatures

In summary, a trend of outward expansion of the coal rock volume change under the influence of temperature and gas injection pressure was observed in the experiments. As the gas injection pressure increases, the coal rock volume gradually expands outwards. It should be noted, however, that this trend may be related to a number of factors such as temperature and gas injection pressure, so further in-depth studies are needed to better understand the mechanism of coal rock volume change and its impact on CBM recovery. In addition, in-depth research and exploration is needed in the context of actual engineering and recovery process specifics to improve recovery efficiency and production effectiveness.

4. Conclusion

According to the experimental results of this paper, the nitrogen permeation of coal rocks shows a complex "W" and "U" shaped trend under the influence of temperature and gas injection pressure. This indicates that temperature and injection pressure have an important influence on the change of microscopic pore structure and physical properties of coal rocks. In addition, the experimental results show that the volume of the coal rock tends to expand outwards at 30, 60, 90, 120 and 180°C, while the overall volume of the coal rock compresses at 150°C. These results have some guiding significance for the practical engineering and technology of CBM recovery and need to be fully considered in the actual recovery process.

Overall, the experimental studies in this paper are scientifically significant for an in-depth understanding of the gas permeation behaviour of coal rocks, and also provide important theoretical support for related industries and fields (e.g. coal bed methane development, coal mining, etc.). Due to the complexity of the physical properties and microstructure of coal rocks, the study of gas permeation in coal rocks still faces a variety of challenges and difficulties that require continuous and enhanced exploration and innovation.

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