Research Article

Experimental Study on Seepage Characteristics of Coal Containing Gas and Water

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The effect of gas drainage is often affected by water after hydraulic infiltration enhancement measures are adopted for soft and weak permeability coal. In order to understand the permeability characteristics of coal in the state of gas and water, a three-phase pipe domain model is established. Using the improved triaxial seepage test platform, three groups of cyclic seepage tests under different pressure and water injection conditions are carried out on three groups of raw coal samples under the conditions of constant temperature, fixed axial pressure, and confining pressure. The test results show that (1) after the test of three groups of circulating coal samples, the moisture content of each group of coal samples is different. The change trend of permeability of the first cycle natural coal sample and the second cycle pressureless water injection coal sample is similar to that of gas pressure, which decreases slowly with the increase of gas pressure and the permeability of the third cycle pressure water injection coal sample increases with the increase of gas pressure, which is different from the first two cycles. (2) In the ultrasonic wave velocity test of pressure water injection, the change trend of longitudinal wave velocity of coal sample is opposite to that of gas pressure, that is, the longitudinal wave velocity decreases with the increase of gas pressure. When the gas pressure is 0.9 MPa to 1.0 MPa, the reduction of longitudinal wave velocity is more significant. (3) During the test, when the gas pressure of the coal sample is less than 1.11 MPa, the gas sensitivity coefficient of the third cycle pressurized water injection coal sample is lower than that of the first two cycles. When the gas pressure increases to 1.11 MPa, there is an inflection point; that is, the gas sensitivity coefficient of the third cycle pressurized water injection coal sample is higher than that of the first two cycles.

1. Introduction

Gas disasters have always seriously affected the safety production of national mines [1]. High-gas mines or coal and gas outburst mines account for more than 48% of China’s coal mines. With the average increase of mining depth of 15 m/n, the corresponding gas pressure increases by 0.15~0.3 MPa on average. The increase of mining depth, mining intensity, and complex geological structure may lead to more serious gas disasters. Coal seam gas extraction is a traditional and effective conventional means of gas control, but gas permeability is the main influencing factor of gas migration and desorption in coal [2]. The permeability characteristics of gas itself are affected by a variety of conditions and are complex and changeable in coal [3]. Therefore, a large number of experts and scholars have studied the influencing factors of coal permeability characteristics and achieved many academic achievements [4–14].

Water in coal is divided into inherent components. In the process of underground gas extraction, water in coal
has a certain influence. Therefore, it is necessary to consider the influence of water on the occurrence and migration of gas in coal seam when studying the gas permeability of gas-bearing coal [15]. Wang et al. [16] studied the permeability of structural coal from the perspective of water content and showed that porosity of coal with water content was inversely proportional, and porosity decreased when water content increased. Jiang et al. [17] fixed the gas pressure and surrounding rock and carried out the full stress-strain gas seepage test of different coal samples on coal bodies containing gas and water and established that the important index of the risk degree of coal and gas outburst is the original water content. Liu et al. [18] carried out isothermal desorption and radial steady seepage tests of different water-bearing coal samples after gas adsorption and high-pressure water injection coal samples. Liu et al. [19] studied the influence of water on the mechanical properties of coal matrix by using the adsorption deformation characteristics and theory of coal matrix and discussed the controlling factors of coal seam fracture deformation and coalbed methane migration, in which water content plays a certain role.

Comprehensive above research, reflecting the permeability of coal and gas desorption characteristics of coal moisture will be the main effect, but for coal containing gas in the condition of water-bearing gas permeability characteristics of the model study is less, while the poor permeability of coal seam hydraulic increasing permeability measures made in pressure water injection status by wetting effect of coal. The gas desorption and permeability characteristics in the pressure relief range are affected accordingly.

Based on research and development to improve triaxial mechanics seepage test platform, the temperature is constant, the fixed stress environment, under the condition of different water wetting effect and gas pressure, seepage characteristic test was carried out on the raw coal sample, in-depth analysis of three-phase state in coal body, the influence factors of coal seepage characteristics, for the purpose of weak permeability coal hydraulic increasing permeability. It provides theoretical guidance for improving gas extraction efficiency and preventing and controlling gas outburst disaster.

2. Establishment of Three-Phase Coupling Model

In order to facilitate the analysis, the coal in the model is characterized by circular granulation. At the same time, in order to express the coupling relationship between coal, fluid, and gas, the solid particle skeleton and liquid two-phase model in soil mechanics are introduced from the meso point of view. By improving the two-phase body model and combining the pipe area model [20], a three-phase body pipe area model with “solid liquid gas” coupling is established, as shown in Figure 1(a).

In Figure 1(a), the cross section 1-1 is locally enlarged and the total horizontal projection area is A. Assuming that there is a total vertical stress acting on this section \( \sigma \), when the pore water pressure is \( u \) and the gas pressure is \( z \), there will be an intergranular force \( P_{si} \) at the particle contact. The size and direction of \( P_{si} \) are random. Now, it is decomposed into vertical and horizontal components and the vertical component is \( P_{sv} \). When there are enough particle contact points, the sum of horizontal components is 0. There are \( n \) contact points in total. Considering

\[
A_w = A - A_s - A_y. \tag{1}
\]

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the vertical force balance of 1-1 surface, it can be seen that

\[ \sigma A = \sum_{i=1}^{n} P_{svi} + uA_w + zA_w. \]  

(2)

Divided by area \( A \) on both sides, then

\[ \sigma = \frac{\sum_{i=1}^{n} P_{svi}}{A} + \frac{u}{A} + \frac{zA_w}{A}, \]  

(3)

where the first term at the right end \( \sum_{i=1}^{n} P_{svi}/Aa \) represents the average vertical stress of the soil skeleton on the whole area \( A \), using \( \sigma \) express. \( A \) in the second item at the right end \( A_w/A \), according to the relevant research of Professor Li Guangxin and others, the particle contact area as generally does not exceed 0.03A, so \( A_w/A \approx 1 \). Thus, the above formula can be simplified as

\[ \sigma = \sigma' + u + z. \]  

(4)

Due to the existence of bound water on the particle surface, the bound water is divided into strong bound water and weak bound water. The strong bound water firmly adsorbs water molecules under the action of electrostatic gravity. Weak bound water is under the surface gravity and is in the outer layer of strong bound water, but it is still affected by the combined force of van der Waals gravity and electrostatic stress of water molecules in the outermost layer of strong bound water [21]. In the model, the space formed between particles is characterized as “domain,” in which fluid and gas are stored, as shown in Figure 1(b), and the red area is part of the “domain.” If the conditions are met, there is a “pipe” for fluid and gas exchange between the “domains” and the Hagen-Poiseuille equation is followed:

\[ Q = \frac{(P_A - P_B)\pi a^4}{8\mu l}. \]  

(5)

Deduce

\[ k = \frac{(P_A - P_B)a^2}{8\mu l}, \]  

(6)

where \( k \) is the micro permeability coefficient and the coefficient is composed of the pressure difference between two

"domains" \((P_A - P_B)\), the "pipe" opening \( a \), the "pipe" length \( l \), and the viscosity coefficient \( \mu \) joint decision. It can be seen from formula (6) that the opening \( a \) affects the permeability of pipeline fluid and the contact state between particles determines the size of the opening.

3. Test Introduction

3.1. Test Material. Guizhou Gaoshan coal mine is selected as the sample. The no. 9 coal seam of the mine has \( f = 0.33 \), and the coal quality is relatively soft. Make the coal sample into \( h = 100 \text{mm} \Phi = 50 \text{mm} \) cylindrical test piece. Grind the test piece to meet the test requirements [22], as shown in Figure 2.

3.2. Test Instrument. The test equipment is the triaxial mechanical seepage test platform developed, which is composed of triaxial stress control system, computer control system, gas supply module, high-pressure water supply module, data collection module, air pressure and high-pressure water sensors, and flowmeter. During the test, gas and pressure water injection is provided by high-pressure methane cylinder and water pump. The computer and data collection module collects the inlet and outlet pressure, axial pressure, confining pressure, axial deformation, and transverse deformation parameters of gas and pressure water injection. The working principle diagram of triaxial mechanical seepage test platform is shown in Figure 3.

3.3. Test Method. Pure methane gas is used as the filling gas in the test, and the concentration is not lower than 99.99%. The initial axial stress and confining pressure applied to the coal sample in the test platform are 1.0 MPa. Under the condition of constant temperature, three cyclic loading tests were carried out on coal samples, in which the pressure water injection was not carried out in the first cycle and the pressure water injection in the second and third cycles was 0 MPa and 1.0 MPa, respectively. See Table 1 for specific test parameters.

According to Table 1, each cycle of this penetration test is divided into five levels and the parameters of each level are different and increase regularly.

The specific test steps are as follows:

(1) Debug the test platform, check the tightness and safety, and ensure the normal operation of the platform

(2) The platform initially applies 1.0 MPa axial pressure and confining pressure to the test piece and 0.2 MPa methane gas is filled at the same time so that the methane gas is fully adsorbed by the test piece for 24 h

(3) After the completion of gas adsorption, inject water at 1.0 MPa pressure for 24h. The water injection process is divided into two stages. In the first stage, the water injection pressure rises slowly to 1.0 MPa (the value does not reach 1.0 MPa), and in the
second stage, the value reaches 1.0 MPa, during which the ultrasonic wave velocity is monitored.

(4) Fill the test piece with adsorbed methane gas and release it for 4~12 min. At the same time, start measuring the gas flow data until the end of the experiment.

(5) Change the parameter loading according to the test scheme, repeat the above test steps (only the third cycle is divided into two stages: pressure water injection and ultrasonic wave velocity monitoring), and record the data for the next analysis.

4. Analysis of Test Results

4.1. Relationship between Gas Pressure and Permeability of Coal. After the test, the moisture content of three groups of circulating coal samples is tested and the measurement results are as follows:

(1) After the first cycle test, the moisture content of coal sample is 1.62~2.02% and the average moisture content is 1.82%.

(2) After the second cycle test, the moisture content of coal sample is 3.34~3.96% and the average moisture content is 3.65%.

(3) After the third cycle test, the moisture content of coal sample is 5.34~6.44% and the average moisture content is 5.89%.

Under the conditions of constant temperature, fixed axial pressure, and confining pressure, combined with the test data, we can know the relationship between gas pressure and permeability under different cycle test conditions, as shown in Figure 4.

According to the analysis of Figure 4, under the conditions of constant temperature, fixed axial pressure and...
confining pressure, and different cyclic loading, the variation characteristics of gas pressure and permeability of coal samples: for the natural coal samples without pressure water injection in the first cycle, the permeability of coal samples decreases slowly to 1.0 MPa with the increase of gas pressure and there is an inflection point and increases slowly. The second cycle carries out 0 MPa water injection and the relationship curve of coal sample permeability with gas pressure is similar to that of the first cycle, but the overall trend is lower than that of the first cycle. The third cycle carries out 1.0 MPa pressure water injection, and the permeability of the coal sample increases with the increase of gas pressure. This is the result of competitive adsorption of water molecules and gas molecules under certain stress conditions [23]. When the pressure water injection conditions are the same as the fixed axial pressure and confining pressure, there are cracks in the coal body. With the increase of gas pressure, the pressure difference between particle “domains” increases. When it is greater than the surrounding stress environment, the cracks in the coal body increase and the permeability increases.

4.2 Relationship between Coal Moisture and Permeability. According to the test data, under the conditions of constant temperature, fixed axial pressure, and confining pressure of 1.0 MPa, the relationship between water content state, permeability, and time of different coal samples is shown in Figures 5 and 6. It can be seen from Figure 5 that under the condition of certain gas pressure, with the increase of water content of coal sample, the permeability becomes smaller and smaller. This is because the gas pressure remains unchanged, the pressure difference between particle “domains” remains unchanged, the water content between coal particles increases, occupies space pores, and then the gas permeability decreases [23]. For the pressure water injection test of 1.0 MPa, the test results are different from those of other coal samples. The internal cracks of coal samples with pressure water injection or the extension of the original cracks lead to the increase of permeability.

During the test, the gas pressure of 1.0 MPa was selected for analysis. It can be seen from Figure 6 that during the cycle test of three groups of coal samples, the coal permeability was at the minimum value in the first 0~7 min and the value slowly increased to the maximum value with the passage of time, while the coal permeability increased to the maximum value in the 7 min and there was an inflection point, which gradually decreased to a certain value from 7 to 12 min and then slowly increased.

4.3 Evolution Law of Ultrasonic Wave Velocity in Coal. In order to explore the internal structure evolution of coal body under the condition of 1.0 MPa pressure water injection, the change law of ultrasonic wave velocity was monitored.
synchronously during the test. This time, the change of longitudinal wave velocity was mainly observed and analyzed and the results are shown in Figure 7.

The process of pressure water injection is divided into two stages. In the first stage, the water injection pressure increases slowly to 1.0 MPa (the value does not reach 1.0 MPa), and in the second stage, the value reaches 1.0 MPa. Monitoring in the first stage: the S-wave velocity of the coal sample does not fluctuate obviously and the P-wave velocity is opposite to the change of gas pressure. It decreases with the increase of gas pressure. When the gas pressure increases from 0.2 MPa to 0.9 MPa, the water injection coal sample decreases from 2136.9 m/s to 2119.0 m/s, with a decrease of 0.84%. This is because under this path, the effective stress of the coal sample gradually decreases and the water injection pressure increases, resulting in a slight increase in the primary fracture, so the sound wave velocity decreases.

In the second stage, the longitudinal wave velocity still decreases with the increase of gas pressure and the decreasing range increases. As the gas pressure increases from 0.9 MPa to 1.0 MPa, the longitudinal wave velocity of coal sample decreases by 3.48%, and the permeability of coal sample increases. The main reason is that the effective stress between coal samples decreases when the pressure water injection reaches a certain pressure under the conditions of constant temperature, fixed axial pressure, and confining pressure of 1.0 MPa, resulting in the increase of particle “domain” opening. At the same time, the micro cracks themselves are further extended, which eventually leads to the generation of new cracks and the reduction of longitudinal wave velocity of coal samples.

4.4. Influence of Moisture on Gas Pressure Sensitivity. By defining the gas pressure sensitivity coefficient $\alpha$, as the evaluation parameter of the sensitivity coefficient of permeability to gas pressure [24, 25], here, it is expressed as the change relationship between gas pressure and permeability under the conditions of constant temperature, fixed axial pressure, and confining pressure [26]

$$\alpha = -\frac{1}{K_0} \frac{\Delta K}{\Delta P}.$$  \hspace{1cm} (7)

where $\alpha$—gas pressure sensitivity coefficient, MPa$^{-1}$; $K_0$—initial permeability (permeability corresponding to 0.2 MPa gas pressure), $10^{-3}$ μm$^2$; $\Delta K$—permeability variation of coal sample, $10^{-3}$ μm$^2$; and $\Delta P$—gas pressure variation, MPa.

The change relationship between gas pressure and sensitivity coefficient is analyzed through the test results, as shown in Figure 8.

According to the analysis of Figure 8, under the condition of fixed axial pressure and confining pressure, the gas pressure sensitivity coefficient of coal sample decreases gradually with the increase of gas pressure and the gas pressure sensitivity coefficient has the trend of exponential decrease.
4.5. Influence of Moisture on Gas Pressure Sensitivity. The comprehensive analysis of Figure 8 shows that the gas pressure sensitivity coefficient of coal samples changes obviously under different test conditions. The gas pressure sensitivity coefficient of wet coal samples injected with 0 MPa in the second cycle pressure is higher than that of coal samples in the natural state of the first cycle. During the test, it is found that water is the main influencing factor of pressure sensitivity coefficient and the effect is obvious. In this paper, the coal structure is regarded as the three-phase model of solid particle skeleton, liquid, and gas. For the water-bearing coal, due to the competition mechanism between gas molecules and water molecules, when the gas in the coal moves, the water molecules preferentially occupy most of the pore space, resulting in the narrowing of the gas migration channel between the solid particles of the coal and the difficulty of gas molecule migration.

During the test, when the gas pressure of the coal sample is less than 1.11 MPa, the gas sensitivity coefficient of the third cycle pressurized water injection coal sample is lower than that of the first two cycles. With the increase of gas pressure and the inflection point at 1.11 MPa, the gas sensitivity coefficient of the third cycle pressurized water injection coal sample is higher than that of the first two cycles. This difference may be due to the cracks of coal samples under pressure water injection, which is basically similar to that in the second stage of ultrasonic wave velocity evolution test. At the same time, pressure water injection has the effect of increasing permeability and reducing gas adsorption capacity of coal samples [18]. Under the same gas pressure change, the change of gas permeability is in direct proportion to the gas pressure sensitivity [27]. With the increase of gas pressure, the opening of gas seepage pipeline between coal samples increases, resulting in the increase of permeability, the decrease of relative change, and the decrease of gas pressure sensitivity. For the third cycle pressure injection coal sample, there are cracks in the coal sample itself and the cracks extend under the action of pressure water. When the gas in the coal flows, the mechanical effect caused by increasing the gas pressure leads to the expansion of the cracks again and gradually forms larger cracks.

5. Field Measurement

5.1. Site Overview. The 1908 bottom extraction roadway of no. 9 coal seam in Guizhou Gaoshan coal mine is selected for the field test. The coal seam thickness is 0.3–6.9 m, the average coal thickness is 2.53 m, the coal seam dip angle is 12–34°, and the average dip angle is 17°. The original gas content is 12.79 m³/t. The firmness coefficient of coal seam
is \( f = 0.33 \), the average permeability coefficient of coal seam is \( 0.06171 \text{ m}^2/\text{MPa}^2 \), and the average attenuation coefficient of borehole gas flow is \( 0.1786 \text{ d}^{-1} \).

5.2. Layout of Hydraulic Punching and Extraction Drilling. According to the overall scheme design of 1908, the second 50 m area near the left boundary within 200 m of the fracturing test is arranged for 5 m × 5 m and 6 m × 6 m gas predrainage drilling, the control range is 1908, and the upper side of the transportation channel is 20 m outward and the lower side is 30 m outward. Intercepting boreholes were arranged on the boundary of the 200 m area of the fracturing test to intercept gas backflow, and the intercepting boreholes were numbered L-1~L-26, as shown in Figure 9.

The hydraulic punching hole is the blue hole in Figure 9, which adopts the method of interval punching. The punching water injection pressure is 10 MPa, and the coal flushing volume is \( 1.0~2.0 \text{t/m} \).

5.3. Analysis of Coal Seam Antireflection Effect. After punching in the test area, the drilling and pumping shall be carried out under the condition of negative pressure of 18kPa. Figures 10 and 11 are the analysis of the pumping effect after drilling and pumping. This time, the 1#~5# boreholes in Figure 9 are selected and only the pumping effect analysis from day 1 to day 7 is carried out.

According to the analysis of Figures 10 and 11, in 1#~5#, the daily drainage concentration in the first 7 days of the drainage borehole basically has a similar trend. The gas concentration ranges from 0 to 5% from the first day to the third day and reaches the peak from the fourth day to the sixth day, in which the maximum concentration in the 5# borehole is 86% and then decreases and fluctuates after the seventh day. Similarly, in 1#~5#, the daily net volume of extraction in the first 7 days of drilling is basically similar. The net volume effect is not ideal from the first day to the third day, reaches the peak from the fourth day to the sixth day, and then decreases and fluctuates after the seventh day.

According to the field data analysis, the change trend of gas concentration and purity in the first 7 days is basically consistent with the fluctuation of the relationship curve between water content state, permeability, and time of different coal samples before the inflection point under the conditions of constant temperature, fixed axial pressure, and confining pressure of 1.0 MPa.

6. Conclusion

(1) After three groups of circulating coal samples are tested, the moisture content of each group of coal samples is different. The permeability of the first cycle natural coal sample and the second cycle pressureless water injection coal sample is similar to the change trend of gas pressure, which decreases slowly with the increase of gas pressure and the permeability of the third cycle pressure water injection coal sample increases with the increase of gas pressure, which is different from the first two cycles.

(2) In the ultrasonic wave velocity test of pressure water injection, the change trend of longitudinal wave velocity of coal sample is opposite to that of gas pressure; that is, the longitudinal wave velocity decreases with the increase of gas pressure. When the gas pressure is 0.9 MPa to 1.0 MPa, the reduction of longitudinal wave velocity is more significant.

(3) During the test, when the gas pressure of the coal sample is less than 1.11 MPa, the gas sensitivity coefficient of the third cycle injection pressure water coal sample is lower than that of the first two cycles, while the inflection point occurs when the gas pressure increases to 1.11 MPa and the gas sensitivity coefficient of the third cycle injection pressure water coal sample is higher than that of the first two cycles.

(4) Under the conditions of constant temperature, fixed axial pressure, and confining pressure of 1.0 MPa, the fluctuation of the relationship curve between water content, permeability, and time of different coal samples before the inflection point is basically consistent with the change trend of onsite gas concentration and purity in the first 7 days.

Data Availability

The data, figures, and tables used to support the findings of this study are included in the article.

Conflicts of Interest

The authors declare that they have no conflicts of interest.

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