An experimental study of seepage properties of gas-saturated coal under different loading conditions

Dengke Wang¹,²,³ | Ruihuan Lv¹,³ | Jianping Wei¹,³ | Qichao Fu¹,³ | Yitong Wang⁴ | Ping Zhang¹,³ | Chong Yu¹,³ | Banghua Yao¹,³

¹State Key Laboratory Cultivation Base for Gas Geology and Gas Control, Henan Polytechnic University, JiaoZuo, China
²State Key Laboratory for GeoMechanics and Deep Underground Engineering, China University of Mining & Technology, Jiangsu, China
³The Collaborative Innovation Center of coal safety production of Henan, Jiaozuo, China
⁴Henan Coal Chemical Industry Group Co. Ltd, Zhengzhou, China

Correspondence
Dengke Wang, State Key Laboratory Cultivation Base for Gas Geology and Gas Control, Henan Polytechnic University, JiaoZuo, China.
Email: wdk@hpu.edu.cn

Funding information
the Key scientific research projects of Henan Provincial Education Department, Grant/Award Number: 18A620001; the open fund of State Key Laboratory for GeoMechanics and Deep Underground Engineering, China University of Mining & Technology, Grant/Award Number: SKLGDUEK1814; the Science Research Funds of Henan Polytechnic University, Grant/Award Number: J2018-1; the Chinese Ministry of Education Innovation Team Development Plan, Grant/Award Number: IRT-16R22; National Natural Science Foundation of China, Grant/Award Number: 51774118

Abstract
In order to supply benefits for safe production of coal underground and efficient exploitation of coalbed methane, a self-developed gas seepage experimental device considering gas adsorption and desorption was proposed to study the seepage properties of gas-saturated coal in this paper. A series of gas seepage experiments under different loading conditions were carried out to investigate the change rules of permeability of gas-saturated coal. The experimental results covered the significant effects of confining pressure, gas pressure, temperature change, creep stress, and complete stress-strain process on the seepage laws of gas-saturated coal. The experimental results showed that the permeability of gas-saturated coal is strongly sensitive to the effective stress and decreases with the increase of the effective stress. Under the fixed confining pressure, the permeability of gas-saturated coal showed an obvious Klinkenberg effect, but the Klinkenberg effect would no longer be evident once the gas pressure was larger than 1.0 MPa. And the change law of permeability of gas-saturated coal with temperature was mainly reflected in the comprehensive effect of thermal stress and effective stress on the control of pore deformation. Under the complete stress-strain loading conditions, the change rules of permeability were mainly dependent on the failure mode of gas-saturated coal. And the change rules of permeability, for the condition of triaxial creep stress, were relied on the stage of creep deformation. The deformation at decay creep stage was responsible for a steady permeability after the failure of gas-saturated coal, while the deformation at non-decay creep stage was responsible for a rapid increase of permeability after the failure of gas-saturated coal. The results in this work can offer some helpful suggestions for efficiently exploring coalbed methane in the future.

KEYWORDS
gas-saturated coal, safe exploitation of coalbed methane, safe production of coal, seepage experimental device, seepage property
1 | INTRODUCTION

In recent years, with the increase of mining depth, coal geology and occurrence conditions become more and more complex, gas disaster is still a major problem for safe exploitation of coal. Controlling gas accidents is the key factor to ensure coal mine safety production. At present, the relevant technical standards, engineering design specifications, and theoretical basis of mine gas prevention and control are not perfect. It relies on the experience of relevant technicians of the coal enterprises and sci-tech service organizations for a long time to carry out the work of mine gas prevention and control. The human subjectivity is obvious. Gas drainage in coal is related to the safety of coal mining and the comprehensive utilization of gas, so it is of great practical significance to study the rheological characteristics, load failure characteristics, and adsorption-desorption-seepage law for gas-saturated coal.

In the process of coal seam mining, mining disturbances destroy the original stress distribution balance inside the coal body and resulting in the existence of stress concentration or stress anomaly zones inside the coal body. Since the permeability of the coal seam is controlled to a large extent by the load size, the stress redistribution inside the coal body caused by the mining disturbance also represents the redistribution of the coal seam permeability. In order to study the law of gas seepage and the characteristics of adsorption/desorption of coal, many scholars have developed relevant experimental equipment and carried out a series of studies and obtained a lot of achievements. As early as 1941, Klinkenberg developed both low- and high-pressure gas seepage equipment and proposed the Klinkenberg effect.1 Somerton et al,2 Lin and Zhou,3 Hu et al,4 Tan et al,5 Jasinge et al,6 and others developed a coal rock permeability testing machine and triaxial stress seepage system, which could achieve experimental functions such as triaxial compression, gas seepage, creep seepage, sound wave measurement, and porosity measurement. Peng,7 Liu and Liu,8 Tang et al,9 Long et al,10 Xu et al,11 Wang et al,12-16 Shen et al,17 and others collectively developed coal and rock gas permeameters, which may consider the impacts of gas pressure, confining pressure, temperature, gas adsorption, and desorption on the permeability of coal samples. Danesh et al18 and Guo et al19 investigated the significant impact of creep on coal permeability and gas drainage and found that the effect of creep deformation on coal permeability can reach 20% or more. Zang and Wang20 erected a kinetics-improved permeability model in which the effect of swelling kinetics was considered, and the research shown that the swelling kinetics can mitigate the gas sorption-induced permeability. By carrying out gas seepage experiments, Zou et al,21 An et al,22 and Niu et al23 studied the influence of gas slippage on coal permeability and summarized the action rules of gas slippage according to the experimental data. Zou et al24 and Lin et al25 developed a fluid-solid coupling experimental system of gas-bearing coal subjected to hydraulic slitting and systematically studied the fluid-solid coupling seepage property of gas-bearing coal subjected to hydraulic slitting. Wei et al26 established the relation between coal permeability and the expansion of the gas-invaded area and found that the swelling and shrinkage of coal matrix had a significant effect on permeability change of coal.

The development of devices and related experimental research have actively promoted the study of gas migration in the coal seam. However, there are still some shortcomings in the existing experimental devices. The shortcomings are that the experimental data are recorded manually, and the testing error rate is relatively large; a constant temperature environment cannot be maintained for the adsorption-desorption-seepage experiment; the impacts of adsorption and desorption are not considered in the process of the seepage experiments. In view of the above-mentioned shortcomings, an adsorption-desorption-seepage experimental device was designed and developed for gas-saturated coal. The experimental device has powerful function and can consider the influence of temperature field, seepage field, and stress field on gas flow in coal at the same time.

In this paper, the components and functions of self-developed gas seepage experimental device considering gas adsorption are introduced. And the gas seepage experiments were carried out for the gas-saturated coal under different loading conditions by using the experimental device. The reasons behind the fluences of gas pressure, confining pressure, temperature, complete stress-strain process, and creep load on coal permeability were deeply analyzed and discussed. Especially, the competitive relationship between effective stress and thermal stress which act on the coal permeability was innovatively analyzed. And a certain relation between the failure mode and permeability of coal was creatively proposed to describe the variation property of coal permeability during the process of complete stress-strain loading. This work may provide a more accurate and reliable theoretical basis and technical reference for the safe and efficient exploitation of coalbed methane.

2 | EXPERIMENTAL DEVICE

The adsorption-desorption-seepage experimental system of gas-saturated coal (Figure 1) is mainly composed of six parts, namely the loading system, triaxial pressure vessel, pore pressure control system, temperature control system, data acquisition monitoring system, and an auxiliary system. The schematic diagram of the experimental system is shown in Figure 2.

The experimental device has strong functions. It can implement different loading modes and all kinds of experiments including triaxial seepage experiment, adsorption-desorption experiment, temperature-creep-seepage coupling experiment, and triaxial creep experiment.

The main technical parameters of the adsorption-desorption-seepage experimental device of gas-saturated coal
are as follows: the loading ranges of the axial pressure, confining pressure, and gas pressure are 0-150 MPa with a precision of ±0.1 MPa, 0-40 MPa with a precision of ±0.1 MPa, and 0-12 MPa with a precision of ±0.05 MPa, respectively. The stabilization loads time is 0-2 month, and the loading speed is 0-2 mm/min. The monitoring ranges of the axial displacement, gas flow, and temperature are 0-20 mm with a precision of ±0.001 mm, 0-100 mL/min with a precision of ±0.2 mL/min and 0-100°C with a precision of ±0.01°C, respectively.

3 | EXPERIMENTAL METHOD

3.1 | Preparation of coal samples

The experimental sampling location is in Zhaogu No. 2 Coal Mine, which is located in the eastern area of Jiaozuo Coalfield of Henan Province, China. The collected coal belongs to typical anthracite. The coal samples with a diameter of 50 mm were obtained by using the core tube to drill on the large lump coal. Then, the cutting and grinding machines were used to cut and polish the coal cores into the experimental coal samples of Ф50 × 100 mm. And next, to eliminate the effect of moisture, the coal samples which had been cut and polished were placed in the drying oven to dry for 12 hours. In this work, all the coal samples for permeability testing were cylindric coal samples (Figure 3).

3.2 | Experimental steps

The detailed steps of the gas seepage for the gas-saturated coal are as follows:

1. Two groups of strain gauges were pasted symmetrically on the surface of an experimental coal sample. And the layer of silicon rubber with a thickness of 1-2 mm was wiped on the cylindrical side surface of the coal sample. After the silicon rubber had been completely...
solidified, the upper base of the triaxial pressure vessel was taken off by using the elevator. The lower porous plate, coal sample, upper porous plate, and upper loading head were successively installed above the lower loading head from bottom to top, and their external contours were mutually overlap (Figure 2).

2. The cylindrical side surface of the coal sample was covered by a heat-shrinkable tube whose length was slightly longer than that of the coal sample. Then, the heat-shrinkable tube was evenly heated by a hot blow dryer to make it wrap tightly around the cylindrical side surface of the coal sample. The upper and lower ends of the heat-shrinkable tube were respectively fixed on the upper loading head and the lower loading head by using two metal hoops. Then, the gaps between the heat-shrinkable tube and the upper and lower loading heads were sealed by some silicone rubber. After the silicon rubber was dry and solidified completely, the upper base of the triaxial pressure vessel was installed above the lower base of the triaxial pressure vessel by using the elevator. Finally, the fixing bolts of the experimental system were tightened by a wrench.

3. After the displacement and stress sensors were installed and the metal counterforce frame was assembled, the triaxial pressure vessel was placed on the bearing frame in the constant temperature water bath tank by using the elevator. Then, the paths of all gas and oil were connected and all switch valves were ensured to be close. The temperature of the constant temperature water bath was adjusted to the preset experimental value in order to supply a constant environment for experiments. Eventually, the axial and confining pressures were loaded on to the sample by using the hydraulic oil pump.

4. After ensuring that the system was correctly connected, the airtightness was strong and the temperature of the experiment temperature had been equal to the preset temperature, vacuuming was carried out by using two vacuum pumps for the entire experimental system from the air inlet and air outlet (as shown in Figure 4). Opened valves #1, #3, #4, and #6, closed valves #2 and #5, then turned on the two vacuum pumps to exhaust air from the experimental system. When the system inside reached the required negative pressure (less than 50 Pa), closed valves #1 and #6 which were connected to the vacuum pumps, then turned off the vacuum pumps. If the vacuum degrees of the experimental system were stable within two hours after the vacuum pumps closed, the vacuuming process was finally completed.

5. Gas adsorption. A high-pressure methane tank was connected to valve #1 when the valves #1, #2, and #4 were closed. Then, the gas buffer tank was filled with methane gas through opening the valves #1 and #2 and adjusting the pressure reducing valve. The coal sample was allowed to fully absorb methane gas for more than 24 hours after the valves #4 and #5 were opened. Thus, it indicates that
the adsorption of methane was balanced when the readings of the two pressure gauges were equal and stable.

6. Gas desorption. A stopwatch and a desorber were used to carry out the gas-desorption tests after values of the gas temperature and atmospheric pressure were measured and recorded. When the reading of downstream pressure gauge was equal to the atmospheric pressure, the gas desorption was beginning. The height of the liquid level in desorber was recorded manually every minute to calculate the volume of gas desorption from the coal sample.

7. Gas seepage. After the tests of gas desorption was finished, the following step was gas seepage. The upstream gas pressure was adjusted to the predetermined pressure value and was kept constant throughout the experiment. And the outlet of methane gas was connected to the atmosphere by a gas mass flowmeter which was used to record and save the gas flow data in real time during the gas seepage experiments.

3.3 | Experimental contents

In this paper, gas seepage experiments under different experimental conditions were systematically carried out, and the influence of different factors on gas seepage properties was deeply studied. Firstly, an experiment on the permeability of gas-saturated coal with fixed gas pressures was conducted to investigate the effect of confining pressure on gas seepage, when confining pressures were set to be 2, 3, 4, and 5 MPa. Secondly, an experiment on the permeability of gas-saturated coal with fixed confining pressures was conducted to investigate the effect of gas pressure on gas seepage, when gas pressures were set to be 0.2, 0.4, 0.8, and 1.2 MPa. Thirdly, an experiment on the permeability of gas-saturated coal with fixed effective stresses was conducted to investigate the effect of temperature on gas seepage, when temperatures were set to be 20, 30, and 40°C. Fourthly, a series of complete stress-strain process experiments when confining pressures were set to be 2.0 and 4.0 MPa and gas pressures were set to be 0.2 and 0.4 MPa. And finally, a series of creep-seepage experiments were conducted to investigate the relationship between the creep load and the coal permeability when creep loads were set to be 10, 20, and 28 MPa, and the confining pressure was 2 MPa.

4 | EXPERIMENTAL RESULTS AND ANALYSES

4.1 | The impact of confining pressure on permeability

Under the condition of constant gas pressure, the changing trend of the permeability with confining pressure for the gas-saturated coal is shown in Figure 5.

From Figure 5, it can be determined that the permeability of the coal sample decreases with the increase of confining pressure under the condition of constant gas pressure. According to the principle of effective stress, \( \sigma' = \sigma - p \) (1) where \( \sigma' \) is the effective stress, MPa; \( \sigma \) is the total stress, MPa; and \( p \) is the pore pressure, MPa.

The primary and secondary pores in the coal were connected by the pore throats which had a large extent effect on the size of the permeability of the gas-saturated coal. From Formula 1, the increase of the confining pressure means the increase of the effective stress in the radial direction, thus the volume of the coal sample decreases and the pores volume of the coal becomes accordingly small. The original pores and microcracks shrink, deform and tend to be closed under compaction, and as a result, the permeability of the coal sample reduces. This research result is consistent with the previous research conclusions, and it is also the same as the change rule of the permeability in mining engineering. In mining engineering, the influence of mine pressure on the permeability of coal seam is that the permeability increases in the stress relief area and decreases in the stress concentration area. Therefore, the relationship between in situ stress and permeability of coal seam should be taken into account for gas drainage in coal and relevant measures are taken to prevent from coal and gas outburst for achieving better benefits.

4.2 | The impact of gas pressure on permeability

Under the condition of constant confining pressure, the changing trend of the permeability with gas pressure for gas-saturated coal is shown in Figure 6.
From Figure 6, it can be observed that the permeability of the gas-saturated coal decreases with the increase of gas pressure under the condition of constant confining pressure. In addition, the higher the confining pressure is, the smaller the impact of the gas pressure on permeability will be. Because of the existence of Klinkenberg effect, the permeability of coal sample decreases with the increase of gas pressure. Many researchers proved the existence of the Klinkenberg effect through the experiments. According to the experimental results (Figure 6), it can be determined that, when the gas pressure \( p > 1 \) MPa, the Klinkenberg effect becomes no longer evident, and the impact of the Klinkenberg effect on the permeability becomes smaller and smaller with the increase of the confining pressure.

### 4.3 The impact of temperature pressure on permeability

According to the experimental results, the changing trend of the permeability with the effective stress under the isothermal condition for the gas-saturated coal is shown in Figure 7.

From Figure 7, when the effective stress is between 1.0 and 1.5 MPa, there is an intersection among the change curves. There are two reasons for this phenomenon. Firstly, the coal body under high temperature has a large pore compression amount. For low effective stress, the pore opening degree of the coal body under high temperature is large relatively. When the same external stress is applied, the high temperature can produce a larger compression amount of coal sample than that produced by the low temperature. Secondly, the increase of temperature can reduce coal strength and increase coal plastic deformation to some extent, thus the coal matrix is also easier to compress and deform due to the enhancement of the plastic deformation. If the temperature increases, the pores are easily compressed, and in addition, the increase of the coal matrix deformation degree will also further occupy the pore space, then the porosity of coal under high temperature will decrease further. The interaction of the above two reasons causes the permeability reduction under high temperature to be greater than that under low temperature, directly leading to the existence of the crossing point on the trend curves of coal permeability under different temperatures.

The changing trend of coal permeability with different temperature is mainly reflected the thermal expansion and pore compression of coal. In Figure 7, under the condition of the same effective stress, when \( \sigma_{ef} < 1.4 \) MPa, the permeability of the coal sample at the temperature of 40°C is greater than that at the temperature of 20°C, while the permeability of the coal sample at the temperature of 30°C is between the permeability of 20°C and the permeability of 40°C. It may be seen that, when effective stress is low relatively, the permeability increases with the increase of temperature. When \( \sigma_{ef} < 1.4 \) MPa, the thermal stress produced by heating the coal sample is greater than the effective stress, then the coal sample expands and deforms outward, the pores in the coal sample open outward, and therefore the permeability increases with the increase of temperature. When \( \sigma_{ef} > 1.4 \) MPa, the thermal stress produced by heating the coal sample is less than the effective stress, then the coal sample compresses and deforms inward, the pores in the coal sample shrink inward because of being compressed. And the effective seepage passages in the coal sample become smaller. Thus, the permeability decreases with the increase of temperature.

### 4.4 The impact of complete stress-strain process on permeability

The displacement control loading method was applied for the complete stress-strain experiments of the gas-saturated coal, and the loading velocity was set to 0.1 mm/min during the experimental process. The changing trend of the permeability of the gas-saturated coal under complete stress-strain conditions is shown in Figures 8 and 9. No matter what the seepage medium is, the permeability is closely related to the damage evolution of materials during the deformation process. According to the experimental

**Figure 6** Permeability change law of gas-saturated coal with gas pressure

**Figure 7** Permeability change law of gas-saturated coal with effective stress under isothermal conditions
stress-strain curves, the permeability change trend of the gas-saturated coal could be divided into four characteristic stages.

The first stage was the compaction stage. At this stage, the pores and microcracks in the coal sample closed gradually under the action of the external stress. As a result, the coal sample was compacted, the effective porosity decreased, the seepage space decreased, and the permeability of the coal sample decreased to a certain extent.

The second stage was the elastic deformation stage. At this stage, elastic deformation occurred in the coal sample. The total volume of the coal sample decreased constantly and resulted in the closing of the pores and microcracks in the coal sample. As a result, the permeability of the coal sample decreased constantly until reaching the point of minimum value.

The third stage was the yield deformation to peak strength stage. At this stage, the permeability of the coal sample increased gradually instead of the previous decrease. The deformation of the coal sample transformed from elastic deformation to plastic deformation, and the pores and microcracks in the coal samples began to form and connect continuously, and thus an irreversible plastic deformation was produced. With the approach of the peak strength, macroscopic cut or shear fractures were finally formed in the coal sample, leading to the eventual failure of the coal sample (Figure 10).

When the external stress reached the peak strength of coal, the failure mode of the coal sample could be either shear failure or shear slipping failure. If shear failure was formed in the coal sample (Figure 10A), and then shear fractures were formed from the yielding part of the coal sample. The opening degree and connectivity of the fractures increased rapidly with the expansion of the deformation. Accordingly, much seepage space was provided for gas in a short time, and the permeability of the coal sample increased rapidly at the moment of failure (Figure 8). If the failure surface formed in the coal sample belonged to shear slipping and there was no opening degree at the failure surfaces (Figure 10B), and therefore the permeability of the coal sample after the failure was less than the initial permeability (Figure 9).

The final stage was the strain softening stage. At this stage, the stress began to drop down and the strength of the coal sample decreased slowly. If it was a shear failure mode, the permeability of the coal sample turned to be stable compared with that in the rapid increase stage. However, since macroscopic fractures in the coal sample had already formed, the permeability of the coal samples was still very large. If it was shear slipping failure mode, the constant development of the fractures in the coal sample would lead to the gradual

FIGURE 8 Experimental results with a confining pressure of 2 MPa and gas pressure of 0.2 MPa

FIGURE 9 Experimental results with a confining pressure of 4 MPa and gas pressure of 0.4 MPa

FIGURE 10 Failure mode of coal sample. (A) Shear failure, (B) Shear slipping failure
increase of the permeability of the coal sample at the strain softening stage, and thus the permeability ultimately tended to be stable.

4.5 The impact of creep on permeability

In this study, the creep experiment was conducted under confining pressure of 2 MPa and gas pressure of 0.4 MPa. And the long-term strength of gas-saturated coal was about 27.6 MPa in laboratory. According to the experimental results, the dynamic curves of permeability and creep deformation of the gas-saturated coal with time under three creep stress conditions are shown in Figure 11.

From Figure 11, it can be seen that the permeability change of gas-saturated coal obeys some rules. Firstly, the gas-saturated coal showed the typical characteristics of decay creep when the creep stress was less than the long-term strength because the creep stresses of 10 and 20 MPa were less than 27.6 MPa. At the stage of decay creep, the permeability of the gas-saturated coal decreased gradually until it was stable, which was due to the continuous being compression of the pores and microcracks in the coal sample during creep deformation.

Secondly, the gas-saturated coal also exhibited the characteristics of nondecay creep in which there were three deformation substages including deceleration creep, steady-state creep, and accelerated creep. When the creep stress reached or exceeded the long-term strength of gas-saturated coal because the creep stress of 28 MPa was larger than 27.6 MPa. In the deformation process of nondecay creep, the permeability of the gas-saturated coal gradually decreased at the deceleration creep substage, steadily increased at the steady-state creep sub-stage and rapidly increased with the formation and connection of macro-cracks in coal samples at the accelerated creep substage.

Finally, there is good consistency between the creep load and the permeability of gas-saturated coal based on the curves of creep seepage in Figure 11. The permeability of the gas-saturated coal decreased with the increase of creep load before the creep load reached the long-term strength. Once the creep load reached or exceeded the long-term strength, the permeability of the gas-saturated coal decreased at first, then increased steadily, and finally increased rapidly. The change rule of the permeability of the gas-saturated coal also reflected the change rule of the pore volume.\textsuperscript{15}

5 CONCLUSIONS

In this work, the seepage properties of gas-saturated coal under different conditions were studied using the self-developed gas seepage experimental device considering gas adsorption and desorption. The main conclusions reached in this work are as follows.

1. The permeability of the gas-saturated coal decreases with the increase of confining pressure under the condition of constant gas pressure. The permeability of gas-saturated coal shows an evident Klinkenberg effect under the condition of constant confining pressure; however, the Klinkenberg effect will no longer be evident once the gas pressure \( p > 1.0 \) MPa.

2. Under the effect of the thermal stress caused by the increase of temperature, if the effective stress is relatively small, the deformation of the gas-saturated coal shows an outward expansion, the pores and fractures tend to be also open outward, and the permeability increases with the increase of temperature. While if the effective stress is relatively large, the deformation of the gas-saturated coal shows an inward expansion, the pores and fractures tend to be compacted inward, and the permeability decreases with the increase of temperature.

3. For complete stress-strain conditions, the seepage law of gas is related to the failure mode of the coal sample. Both shear failure mode and shear slipping failure mode can be produced in the coal under the condition of triaxial stress. The shear failure mode corresponds to the rapid increase of the permeability of the gas-saturated coal at the moment of failure, and the permeability after the peak strength is smaller than the initial permeability. While the change law of the permeability caused by the shear slipping failure is different from that of the shear failure, and the permeability after the peak strength is smaller than the initial permeability.

4. If the gas-saturated coal is subjected to triaxial creep stresses, at the stage of decay creep, the permeability of the gas-saturated coal decreases gradually until it is stable. At the stage of nondecay creep, the change trend of permeability can be divided into three substages. The permeability of the gas-saturated coal gradually decreases at the deceleration creep substage, steadily increases at
the steady-state creep stage, and rapidly increases with the formation and connection of macro-cracks in coal samples at the accelerated creep stage.

The above research conclusions in this work can provide a certain theoretical reference for the prevention and control of coal and gas outburst and are beneficial for the safe and efficient exploitation of coalbed methane underground.

ACKNOWLEDGMENTS

The authors would like to thank the grants Supported by the open fund of State Key Laboratory for GeoMechanics and Deep Underground Engineering, China University of Mining & Technology (SKLGDUEK1814), National Natural Science Foundation of China (51774118), the Chinese Ministry of Education Innovation Team Development Plan (IRT-16R22), the Key scientific research projects of Henan Provincial Education Department (18A620001), and the Science Research Funds of Henan Polytechnic University (J2018-1).

CONFLICT OF INTEREST

The authors declare no conflict of interest.

REFERENCES

1. Klinkenberg LJ. The permeability of porous media to liquids and gases. API Drill Prod Pract. 1941;2:200-213.
2. Somerton WH, Siyelmezoglu IM, Dudley RC. Effect of stress on permeability of coal. Int J Rock Mech Min Sci Genomach Abstr. 1975;12:129-145.
3. Lin BQ, Zhou SN. Experimental investigation on the permeability of the coal samples containing methane. J China Univ Min Technol. 1987;1:21-28.
4. Hu YQ, Zhao YS, Wei JP, Ren ZQ. Experimental study of permeating law of coal mass gas under action of 3-dimension stress. J Xian Min Inst. 1996;16:308-311.
5. Tan XS, Xian XX, Zhang GY, Du YG, Xu J. Research on the permeability of coal. J Xian Min Inst. 1994;1:22-25.
6. Jasinge D, Ranjith PG, Choi SK. Effects of effective stress changes on permeability of Latrobe valley brown coal. Fuel. 2011;90:1292-1300.
7. Peng DR. Preparation and application of coal and rock permeability tester. Coal Mine Machinery. 1995;5:29-31.
8. Liu JJ, Liu XG. The effect of effective pressure on porosity and permeability of low permeability porous media. J Geomach. 2001;7:41-44.
9. Tang JP, Pan YS, Li CQ, Shi Q, Dong ZX. Experimental study on effect of effective stress on desorption and seepage of coalbed methane. Chin J Rock Mech Eng. 2006;25:1563-1568.
10. Long QM, Zhao XS, Sun DL, Zou YH. Experimental study on coal permeability by adsorption. J China Coal Soc. 2008;33:1030-1034.
11. Xu J, Peng SJ, Yin GZ. Development and application of triaxial servo-controlled seepage equipment for thermo-fluid-solid coupling of coal containing methane. Chin J Rock Mech Eng. 2010;29:907-914.
12. Wang DK, Wei JP, Wen ZH. Permeability characteristics of gas-bearing coal under different stress paths. Disaster Adv. 2013;6:289-294.
13. Wang DK, Wei JP, Fu QC, Liu Y, Xia YL. Seepage law and permeability calculation of coal gas based on Klinkenberg effect. J Cent S Univ. 2015;22:1973-1978.
14. Wang DK, Lv RH, Wei JP, Zhang P, Yu C, Yao BH. An experimental study of the anisotropic permeability rule of coal containing gas. J Nat Gas Sci Eng. 2015;53:67-73.
15. Wang DK, Peng M, Wei JP, Fu QC, Xia YL. Development and application of tri-axial creep-seepage-adsorption and seepage experimental device for coal. J China Coal Soc. 2016;41:644-652.
16. Wang DK, Liu SM, Wei JP, Wang HL, Yao BH. A research study of the intra-nanopore methane flow law. Int J Hydrogen Energy. 2017;42:18607-18613.
17. Shen J, Qin Y, Wang G, Fu X, Wei C, Lei B. Relative permeabilities of gas and water for different rank coals. Int J Coal Geol. 2011;86:266-275.
18. Danesh NN, Chen ZW, Aminossadatti SM, Kizil MS, Pan ZI. Impact of creep on the evolution of coal permeability and gas drainage performance. J Nat Gas Sci Eng. 2016;33:469-482.
19. Guo ZH, Yu PH, Hussain F. A laboratory study of the effect of creep and fines migration on coal permeability during single-phase flow. Int J Coal Geol. 2018;200:61-76.
20. Zang J, Wang K. Gas sorption-induced coal swelling kinetics and its effects on coal permeability evolution: model development and analysis. Fuel. 2017;189:164-177.
21. Zou JP, Chen WZ, Yang DS, Yu HD, Yuan JQ. The impact of effective stress and gas slippage on coal permeability under cyclic loading. J Nat Gas Sci Eng. 2016;31:236-248.
22. An WQ, Yue XA, Feng XG, et al. Pressure for tight core floods using a novel high pressure gas permeability measurement system. J Petrol Sci Eng. 2017;156:62-66.
23. Niu YF, Mostaghimi P, Shikhov I, Chen ZX, Armstrong RT. Coal permeability: gas slippage linked to permeability rebound. Fuel. 2018;215:844-852.
24. Zou QL, Lin BQ. Fluid-solid coupling characteristics of gas-bearing coal subject to hydraulic slotting: an experimental investigation. Energy Fuels. 2018;32:1047-1060.
25. Lin BQ, Zou QL, Liang YP, Xie J, Yang HM. Response characteristics of coal subjected to coupling static and waterjet impact loads. Int J Rock Mech Min Sci. 2018;103:155-167.
26. Wei MY, Liu JS, Dereck E, Li XJ, Zhou FB. Influence of gas adsorption induced non-uniform deformation on the evolution of coal permeability. Int J Rock Mech Min Sci. 2019;114:71-78.
27. Terzaghi K. Theoretical soil Mechanics. New York, NY: Wiley Press; 1943.
28. Gangi AF. Variation of whole and fractured porous rock permeability with confining pressure. Int J Rock Mech Min Sci Genomach Abstr. 1978;15:249-257.
29. Liu W, Li Y, Wang B. Gas permeability of fractured sandstone/coal samples under variable confining pressure. Transp Porous Media. 2010;83:333-347.
30. Wang DK, Wei JP, Yin GZ. Investigation on change rule of permeability of coal containing gas under complex stress paths. Chin J Rock Mech Eng. 2012;31:303-309.
31. Wu YS, Pruess K, Persoff P. Gas flow in porous media with Klinkenberg effects. *Transp Porous Media*. 1988;32:117-137.

32. Tanikawa W, Shimamoto T. Comparison of Klinkenberg-corrected gas permeability and water permeability in sedimentary rocks. *Int J Rock Mech Min Sci*. 2009;46:229-238.

33. Yu LY, Pan YS, Xiao XC, Lu XF. Experiment on methane Klinkenberg effects in low coal reserve. *J Water Resour Water Eng*. 2011;22:15-19.

34. Perera MSA, Ranjith PG, Choi SK, Airey D. Investigation of temperature effect on permeability of naturally fractured black coal for carbon dioxide movement: an experimental and numerical study. *Fuel*. 2012;94:596-605.

35. Li ZQ, Xian XX, Long QM. Experiment study of coal permeability under different temperature and stress. *J China Univ Min Technol*. 2009;38:523-527.

36. Cao SG, Li Y, Guo P, Bai YJ, Liu YB. Comparative research on permeability characteristics in complete stress-strain process of briquettes and coal samples. *Chin J Rock Mechan Eng*. 2010;29:899-906.

37. Yang YJ, Song Y, Chen SJ. Test study on permeability properties of coal specimen in complete stress-strain process. *Rock Soil Mech*. 2007;28:381-385.

38. Jobmann M, Wilsnack T, Voigt HD. Investigation of damage-induced permeability of Opalinus clay. *Int J Rock Mech Min Sci*. 2010;47:279-285.

39. Jiang T, Shao JF, Xu WY, Zhou CB. Experimental investigation and micromechanical analysis of damage and permeability variation in brittle rocks. *Int J Rock Mech Min Sci*. 2010;47:703-713.

40. Zhou SN, He XQ. Rheological hypothesis of coal and methane outburst mechanism. *J China Univ Min Technol*. 1990;19:1-8.

41. Wei JP, Wang DK, Wei L. Comparison of permeability between two kinds of loaded coal containing gas sample. *J China Coal Soc*. 2013;38:93-99.

**How to cite this article:** Wang D, Lv R, Wei J, et al. An experimental study of seepage properties of gas-saturated coal under different loading conditions. *Energy Sci Eng*. 2019;7:799–808. https://doi.org/10.1002/ese3.309