Experiment investigation on gas flow characteristics of coal considering the integrity of coal samples

Junjun Lius, Jing Xiea, Fei Wanga, Bengao Yanga, Yiting Liu, Chenghang Fua, Ruifeng Tanga, Siqi Yea and Mingzhong Gaoa,b

aCollege of Water Resource & Hydropower, Sichuan University, Chengdu, China; bGuangdong Provincial Key Laboratory of Deep Earth Sciences and Geothermal Energy Exploitation and Utilization, Institute of Deep Earth Sciences and Green Energy, College of Civil and Transportation Engineering, Shenzhen University, Shenzhen, Guangdong, China

ABSTRACT

Gas has been one of the main causes of coal mine safety accidents. At present, the most commonly used treatment method is still gas drainage in advance. The permeability of coal seams is the most important factor affecting gas drainage. According to the coal density, P-wave velocity and fracture distribution, the coal samples are grouped to eliminate the influence of the differences of the coal samples on the experimental results. The results show that due to the decrease of samples integrity and the increase of gas osmotic pressure, the peak strength of the sample will reduce, and eventually the stable permeability will increase. Besides, the starting point of permeability will also appear earlier (relative to the peak intensity point of the samples). It is worth noting that the starting point of the sample permeability is highly consistent with the expansion point of sample volume. As the loading and unloading rate increases, the peak strength of the samples will first decrease and then increase. Similarly, the final stable permeability of the samples also shows a trend of first decreasing and then increasing.

1. Introduction

Until 2050, coal will still be a major part of China’s energy mix. With the depletion of shallow coal resources, China’s coal mining activities gradually extend to the deep (Gao et al. 2018; Jin et al. 2018; Liang 2018). The complex geological structure, high geo-stress, high gas pressure and low permeability of deep coal seam further increase the risk of gas disaster in coal mine (Xie et al. 2012; Kong et al. 2014; Gao et al. 2019). At present, gas drainage is still the main method to reduce gas content and eliminate gas disasters (Xu et al. 2006; Zhang et al. 2018; Lu et al. 2019; Yuan et al. 2019).
2020), and the permeability of coal seam is the most important factor affecting gas drainage (Wang and Yang 2002; Gao et al. 2020; Xie, Gao, Zhang, Liu, et al. 2020).

Because the complexity of fissure structure determines the porosity, connectivity and permeability of coal, it is very important to quantitatively characterize the complexity of coal fissure structure and analyze its influence on gas migration characteristics (Xie, Gao, Zhang, Peng, et al. 2020). Guo et al. (2018) analyzed the influence of fissure structure on oil displacement efficiency, sandstone oil cluster shape, permeability and fractal dimension. Rahner et al. (2018) studied the fractal dimension of shale and tight sandstone pores by box number method based on microcomputer tomography, and analyzed the relationship between fractal dimension and permeability. Shi et al. (2018) analyzed the influence of coal rank on micro fracture structure, and used fractal dimension to identify the relationship between porosity and permeability.

At present, scholars mainly study the influence of coal structure on coal permeability from the distribution characteristics of coal cracks (Ma et al. 2020; Yuan et al. 2020). Fu et al. (2009) used geophysical well testing to study the relationship between coal permeability and coal fracture characteristics. Mitra et al. (2012) considered the stress state of coal seam, studied the variation law of permeability with pore pressure and confining pressure under uniaxial strain condition, and optimized the commonly used permeability model according to the experimental results. Liu et al. (2019) used fractal dimension to characterize coal microstructure and established fractal permeability model. Zou et al. (2016) studied the effect of cyclic loading on the permeability of coal. When the direction of effective stress is different from that of coal seam, the effect of effective stress on coal seam permeability is different. That is to say, when the effective stress is perpendicular to the coal seam direction, its influence is more significant than when it is parallel to the coal seam direction. Liu et al. (2020) and Wang et al. (2018) studied the changes of permeability under different effective stress levels and found that the permeability of coal is more sensitive to the changes of confining pressure than pore pressure.

It can be seen from the above discussion that the permeability of coal is closely related to the structure of coal, such as fractures and coal matrix (Gamson et al. 1993; Liu et al. 2015; Connell et al. 2016; Xie, Gao, Liu, et al. 2020; Gao et al. 2021). According to the coal density, P-wave velocity and fracture distribution, the coal samples are grouped to eliminate the influence of the coal sample's own differences on the experimental results. The main purpose of this paper is to study the mechanical characteristics of coal and gas seepage characteristics under different integrity, different gas osmotic pressure and different loading and unloading rate.

2. Experimental methods

2.1. Specimen

The samples used in this experiment were taken from the Ji group in the Pingmei coal-mining area, with a buried depth of 1050 m. According to the recommendations of ISRM (International Society for Rock Mechanics and Rock Engineering)
(Hatheway 2009), the coal samples were processed into standard cylindrical samples (Ø50 mm × H100 mm). The processed samples are shown in Figure 1.

2.2. Integrity classification of coal samples

The height, diameter and longitudinal wave velocity of all samples were measured, and Figure 2 was drawn based on the measured data.

Figure 2 shows the relationship between P-wave velocity and density, and the box plot of density and P-wave velocity. It can be seen from Figure 2(a) that the density of coal samples is concentrated in the range of 1.327 ~ 1.387 g/cm³, and the P-wave velocity is concentrated in the range of 1.26 ~ 1.732 km/s. Figure 2(b) indicates that there is an obvious positive correlation between the density and P-wave velocity on the whole, that is, as the density of coal samples increases, the P-wave velocity also shows an increasing trend, but there is still a large dispersion between various data.

The physical properties of coal itself have a decisive influence on the mechanics and permeability behaviour of coal. As an external manifestation of the internal characteristics of coal, the density of coal can reflect the difference of coal composition and internal fractures to a certain extent. When the material composition of coal is similar (all samples are taken at the same place), the smaller the coal density, the more developed its cracks and the greater its porosity. As we all know, the propagation speed of P-wave in solids is much greater than that in the air. When the P-wave passes through the fracture surface, its velocity will decrease. Therefore, the propagation velocity of the P-wave is different when passing through different samples, that is, the P-wave velocity can reflect the development of internal cracks and joints of coal to a certain extent. When the joints and cracks of the samples are developed to a high degree, the P-wave velocity of the samples is also lower (Oda et al. 1986; Wang et al. 2019). In this section, the coal samples will be classified according to their density and P-wave velocity, so as to eliminate the influence of coal sample differences on the experimental results as much as possible.
In order to effectively classify the samples and minimize the differences among each group of samples, the average value, range, standard deviation and coefficient of variation of sample density and P-wave velocity were quantitatively calculated by using statistical principles (see Table 1).

From the statistical results of discrete parameters of coal samples, the range, standard deviation and coefficient of variation of coal sample density are generally small, which indicates that density difference among individuals is small. However, it can be seen from the range, average, standard deviation and coefficient of variation of the P-wave velocity that the P-wave velocity shows great difference, that is, the P-wave velocity has greater dispersion than density. Therefore, both coal density and P-wave velocity should be fully considered when grouping.

The sample integrity index (Its symbol is W) is defined as value obtained by adding the density (g/cm$^3$) and P-wave velocity (km/s) (after dimensionless treatment) according to the weight of 0.5 respectively. After sorting in ascending order, Table 2 is obtained.

According to the W-W/Wavg diagram (see Figure 3), the samples can be divided into three groups: [W: 1.000 ~ 1.340], [W: 1.340 ~ 1.500] and [W: 1.550 ~ 2.000]. The standard deviation of integrity index of each group was 0.082, 0.042 and 0.149 respectively, and the coefficient of variation was 0.066, 0.030 and 0.091 respectively. This grouping method takes full account of the material composition and crack distribution, and reduces the dispersion of each group of samples, which lays the foundation for the subsequent seepage experiments.

2.3. Experiment equipment

This experiment was carried out in the multi-field coupled porous media fracturing-seepage experiment system of Chongqing University. The system can realize the study of porous media mechanics and permeability characteristics under the coupling action of temperature, seepage, stress and other fields. The main components of the system...
include loading system, heating system, gas supply system, control and monitoring system, etc. The experimental equipment is shown in Figure 4.

### 2.4. Experimental scheme

There are two experimental schemes in this article, the experimental scheme I corresponds to the experiments in section 3.1 and 3.2, and the experimental scheme II corresponds to the experiments in section 3.3. It is worth noting that the confining
pressure of Experiment 1 is relatively small, only 3.5MPa. The purpose of this is to prevent gas from penetrating the heat shrinkable film.

1) Experiment I can be divided into three stages:

i. The first loading stage: as shown in Section OA in Figure 5(a), the confining pressure is applied at a loading rate of 3 MPa/min until $\sigma_1 = \sigma_2 = \sigma_3 = 3.5$ MPa. The main purpose of this stage is to prevent the thermoplastic film from being broken down by high osmotic pressure gas;

ii. Gas adsorption stage: as shown in point A in Figure 5(a), the sample absorbs gas in the pressurized chamber for 60 minutes, so that the gaps in the sample are filled with gas as much as possible;

iii. The second loading stage: as shown in section AB in Figure 5(a), axial pressure is applied until the sample is broken, and maintain a constant CH$_4$ gas osmotic pressure while loading. First, the axial load control is adopted, and the loading rate is 60 kN/min (about 0.5 MPa/s). When approaching the peak strength of the sample, it is switched to axial displacement control, and the displacement rate is 0.1 mm/min. There are three working conditions of osmotic pressure: 1, 2, and 2.5 MPa.
2) Experiment II can be divided into three stages:

i. The first loading stage: as shown in Section OA in Figure 5(b), the confining pressure is applied to 25 MPa at the speed of 3 MPa/min (Simulate the in-situ stress at 1000 meters underground).

ii. Gas adsorption stage: as shown in point A in Figure 5(b), the sample absorbs gas in the pressurized chamber, so that the gaps in the sample are filled with gas as much as possible;

Figure 6. Stress-strain curves and permeability curves of samples with different integrity.
iii. The second loading and unloading stage: as shown in Section AB in Figure 5(b), the loading rates of the axial stress \( \sigma_1 \) are 0.025, 0.05 and 0.1 MPa/s, and the unloading rates of the circumferential stress \( \sigma_3 \) are 0.02, 0.04 and 0.08 MPa/s, respectively. When the specimens enter the stress yield stage, the axial loading mode is switched to displacement control, and the displacement rate is 0.1 mm/min. Besides, the unloading rate of confining pressure remains unchanged until the specimen is broken.

3. Results and discussion

3.1. Gas seepage characteristics of coal with different initial integrity

It can be seen from the previous discussion that the integrity of coal has a significant impact on the seepage characteristics. The control variable method was used in all experiments. This section is to explore the influence of coal sample integrity on gas seepage characteristics.

In this section, gas seepage experiments with different initial integrity are carried out. The instantaneous gas flow is recorded by the flowmeter in real time. According to the recorded instantaneous gas flow and the set constant osmotic pressure difference, the real-time permeability of coal can be calculated. The calculation formula is as follows:

\[
K = \frac{2Q_0P_0\mu L}{(P_1^2 - P_2^2)A}
\]

where: \( K \) is permeability, md; \( P_0 \) is atmospheric pressure, MPa; \( Q_0 \) is instantaneous seepage flow, cm\(^3\)/s; \( \mu \) is gas viscosity coefficient, Pa·s; \( L \) is sample length, cm; \( P_1 \) is inlet gas pressure, MPa; \( P_2 \) is outlet gas pressure, where is atmospheric pressure, MPa; \( A \) is sample cross-sectional area, cm\(^2\). The specific parameters are as follows:

\( \mu = 0.0158 \text{ Pa·s} \); \( L = 100 \text{ cm} \); \( A = 19.63 \text{ cm}^2 \); \( P_0 = P_2 = 0.1 \text{ MPa} \).

When there is a stress drop, stop the axial load, keep the confining pressure unchanged, and continue to pass gas. Stop the experiment when the monitored gas permeability gradually stabilizes. The gas permeability monitored at this time is the final stable gas permeability. The final stable permeability can characterize the gas permeability after the sample basically loses its bearing capacity.

Figure 6 shows the stress-strain curve and permeability curve of samples with different integrity. It can be seen from Figure 6 that the stress-strain curve still goes through five stages: fracture compaction stage, elastic deformation stage, stress yield stage, stress drop stage and residual strength stage. It is worth noting that neither the high integrity sample nor the medium integrity sample showed effective seepage in the initial stage of the experiment. However, the samples with low integrity showed obvious seepage phenomenon in the initial stage of the experiment. High integrity samples and medium integrity samples do not form effective seepage until they are loaded near the peak intensity. This is because when the integrity of the sample is high, the internal cracks are not fully developed and there is no obvious penetration cracks, so that the samples do not form effective seepage at the beginning of the
experiment. When the integrity of the sample is low, the sample itself has penetration cracks in the sample itself which provide a smooth migration channel for gas. As the loading progresses, the volume of the coal samples is compressed, and the original smooth seepage channel begins to narrow or even close under the action of the force, resulting in a decrease in the permeability of the samples. In the stress yield stage, the cracks inside the samples expanded sharply, and the cracks gradually penetrated, providing a smooth channel for the gas. It is not difficult to see from Figure 6 that as the integrity of the sample becomes smaller, the starting point of permeability will appear earlier (relative to the peak intensity point). This is because the lower the integrity of the sample, the earlier the crack penetration time.

Figure 7 shows the relationship between volumetric strain and permeability. It can be seen from Figure 7 that the starting point of permeability is highly coincident with the inflection point of the volumetric strain curve. The beginning of the expansion of the sample volume means that a large number of cracks in the sample have penetrated and more seepage channels have been formed. In the elastic deformation stage, the sample volume decreases continuously, which means that the gas migration channel is gradually being squeezed. This is a good explanation of why the permeability of samples with low integrity has been decreasing during the elastic deformation stage.
Figure 8 shows the average peak intensity and average final permeability of samples with different integrity. It can be seen from Figure 8 that as the integrity of the samples increases, the average peak strength of the sample continues to increase, and the final permeability of the sample continues to decrease. This verifies the feasibility and rationality of sample grouping to a certain extent.

3.2. Gas seepage characteristics of coal under different osmotic pressures

It is obvious that different gas osmotic pressure has a great impact on the permeability of the samples. This section is to explore the influence of different osmotic pressures on gas seepage characteristics. Taking the samples with medium integrity and low integrity as examples, the influence of different osmotic pressure on the gas seepage characteristics of coal is analyzed.

Figure 9 shows the permeability curve and stress-strain curve of the sample under different osmotic pressures. According to the change law of permeability curve of low integrity sample (the medium integrity sample did not show obvious seepage phenomenon in the initial stage of the experiment), it can be divided into three stages. 1) Initial decline stage: in this stage, the permeability gradually decreases with the compression deformation of the samples, and the decline rate of permeability gradually decreases with the transition of the sample from the elastic deformation stage to the stress yield stage. The permeability drops to the lowest near the peak point of the samples; 2) Permeability enhancement stage: after the samples reach near the peak intensity, the secondary failure structure is formed due to the failure of the bearing structure of the samples, so that new gas seepage channels are connected and the permeability increases sharply; 3) Post-peak stable stage: in the residual stress stage, new seepage channels dominated by secondary failure structural are formed and remain stable, and the permeability tends to be stable. Because coal belongs to typical multiple fracture structure, the secondary failure structure is dominated by primary structural plane to a great extent, and the new seepage channel may be formed by the combination of primary and secondary structures.
Because there are no obvious Penetration cracks in the medium integrity specimens, the medium integrity specimens do not show effective seepage phenomenon at the beginning of the experiment. It is not until the sample is loaded close to the peak strength that the internal cracks of the samples gradually expand and penetrate, and the phenomenon of permeability enhancement appears in stress yield stage. In residual strength stage, as the internal structure of the samples gradually stabilizes, that is, the seepage channel gradually stabilizes, the permeability rate gradually slows.

Figure 9. Stress-strain curves and permeability curves of samples under different osmotic pressure.

Because there are no obvious Penetration cracks in the medium integrity specimens, the medium integrity specimens do not show effective seepage phenomenon at the beginning of the experiment. It is not until the sample is loaded close to the peak strength that the internal cracks of the samples gradually expand and penetrate, and the phenomenon of permeability enhancement appears in stress yield stage. In residual strength stage, as the internal structure of the samples gradually stabilizes, that is, the seepage channel gradually stabilizes, the permeability rate gradually slows.
down and tends to zero. It is worth noting that when the gas osmotic pressure is 2.5 MPa, compared with the other two working conditions, it can be found that the starting point of permeability appears earlier (relative to the peak intensity point).

As can be seen from Figure 10, when the osmotic pressure is 1, 2 and 2.5 MPa, the final stable permeability (average value) of the samples is 0.07, 0.087 and 0.092 md respectively. That is to say, the higher the gas osmotic pressure, the greater the final permeability of the samples, but the difference is not obvious. Similarly, as the gas osmotic pressure increases, the peak strength of the sample gradually decreases. This is caused by the following two aspects. Firstly, the gas osmotic pressure reduces the effective circumferential stress of the samples, so that the circumferential deformation of the specimens cannot be well restrained. Secondly, the flow of gas causes the stress concentration at the tip of the cracks inside the specimens, which promotes the development and penetration of the cracks.

3.3. Gas seepage characteristics of coal under different loading and unloading rates

The experimental scheme in this section is shown in the experimental scheme II. The experiment has three different loading and unloading rates: 1) \( \sigma_1: +0.025 \text{ MPa/s, } \sigma_3: -0.02 \text{ MPa/s} \); 2) \( \sigma_1: +0.5 \text{ MPa/s, } \sigma_3: -0.04 \text{ MPa/s} \); 3) \( \sigma_1: +0.1 \text{ MPa/s, } \sigma_3: -0.08 \text{ MPa/s} \). Among them, ‘+’ stands for axial loading, and ‘-’ stands for circumferential unloading. These three different loading and unloading rates represent three different mining intensities to study the mechanics and permeability of coal under different mining intensities.

Figure 11 shows the stress-strain curves and permeability curves of the samples under different loading and unloading rates. In order to compare the peak strength and permeability of the sample under different loading and unloading rates more intuitively, Figure 12 is specially drawn.
As shown in Figure 12, with the increase of loading and unloading rate, the final stable permeability decreases at first and then increases. The mechanism may be as follows: under the condition of low loading and unloading rates, the action time of the force is long, and the cracks have enough time to develop and expand under the action of the force. As the loading and unloading rates increase, the degree of stress concentration intensifies and the number of microcracks increases due to the uneven distribution of mineral particles and primary fractures in the specimen.

Figure 11. Stress-strain curves and permeability curves of samples under different loading and unloading rates.

As shown in Figure 12, with the increase of loading and unloading rate, the final stable permeability decreases at first and then increases. The mechanism may be as follows: under the condition of low loading and unloading rates, the action time of the force is long, and the cracks have enough time to develop and expand under the action of the force. As the loading and unloading rates increase, the degree of stress concentration intensifies and the number of microcracks increases due to the uneven distribution of mineral particles and primary fractures in the specimen.
However, because of the short duration of the force, the cracks are not fully opened, and the gas permeation channels are blocked by the broken coal dust, which makes the gas flow unsmooth. When the loading and unloading rate increases to a certain extent, the stress concentration further increases, leading to a sharp increase in the number of microcracks. And the microcracks continue to develop under the action of force, providing more seepage channels for gas flow. That is to say, in the game between the action time of force and the number of microcracks expansion caused by strong disturbance, although the action time of force is short, the number of microcracks expansion is dominant due to the aggravation of disturbance, and the permeability is enhanced on the whole. In summary, as the loading and unloading rate increases, the permeability rate first decreases and then increases.

It can also be seen from Figure 12 that as the loading and unloading rate increases, the peak strength of the sample also shows a trend of first decreasing and then increasing. On the one hand, due to the continuous increase of the unloading rate of the confining pressure, the specimen lacks the restraint of the circumferential stress, and the specimen is easier to expand laterally. The internal structure of the sample has not yet undergone sufficient adaptive adjustment, which makes the solid medium around the sample bears too much load, so it is more prone to instability and damage, resulting in a decrease in the strength of the sample. On the other hand, when the axial loading rate is high, the microcracks inside the specimen cannot fully develop and expand, which makes the internal structure of the specimen more complete, thus showing that the compressive strength increases with the increase of the loading rate. When the loading and unloading rate is low, the confining pressure unloading is dominant; as the loading and unloading rate increases, the axial loading takes the dominant position. Under the combined action of the axial pressure loading and the confining pressure unloading, the overall strength of the sample decreases first and then increases with the increase of the loading and unloading rate.

Figure 12. Average peak strength and average final permeability of samples under different loading and unloading rates.
4. Conclusions

Three sets of experiments were carried out to study the effects of coal sample integrity, gas osmotic pressure and loading and unloading rate on coal gas seepage characteristics. Through the analysis of the experimental results, the following conclusions are obtained:

1. The decrease of sample integrity and the increase of gas osmotic pressure will reduce the peak strength of the sample, and finally the stable permeability will increase.
2. The decrease in the integrity of the sample and the increase in gas osmotic pressure will cause the starting point of permeability to appear earlier (relative to the peak strength point of the sample).
3. The starting point of sample permeability is highly consistent with the expansion point of sample volume.
4. As the loading and unloading rate increases, the peak strength of the sample will first decrease and then increase. Similarly, the final stable permeability of the sample also shows a trend of first decreasing and then increasing.

Funding

This work was financially supported by National Natural Science Foundation of China (52004167; U2013603), the Applied Basic Research Programs of Sichuan Province (No. 2021YJ0411), the Program for Guangdong Introducing Innovative and Entrepreneurial Teams (No. 2019ZT08G315), and the Shenzhen Fundamental Research Project (JCYJ20190808153416970).

Disclosure statement

The authors declare that they have no competing interests.

Data availability

The data used and generated in this study is available from the corresponding author upon reasonable request.

References

Connell LD, Mazumder S, Sander R, Camilleri M, Pan Z, Heryanto D. 2016. Laboratory characterisation of coal matrix shrinkage, cleat compressibility and the geomechanical properties determining reservoir permeability. Fuel. 165:499–512.
Fu X, Qin Y, Wang GG, Rudolph V. 2009. Evaluation of coal structure and permeability with the aid of geophysical logging technology. Fuel. 88(11):2278–2285.
Gamson PD, Beamish BB, Johnson DP. 1993. Coal microstructure and microporosity and their effects on natural gas recovery. Fuel. 72(1):87–99.
Gao M, Liu J, Lin W, Deng G, Peng G, Li C, He Z. 2020. Study on in-situ stress evolution law of ultra thick coal seam in advance mining. Coal Sci Technol. 048:28–35.
Gao M, Xie J, Gao Y, Wang W, Li C, Yang B, Liu J, Xie H. 2021. Mechanical behavior of coal under different mining rates: A case study from laboratory experiments to field testing. Int J Min Sci Technol. doi: 10.1016/j.ijmst.2021.06.007

Gao M, Zhang S, Li J, Wang H. 2019. The dynamic failure mechanism of coal and gas outbursts and response mechanism of support structure. Therm Sci. 23(Suppl. 3):867–875.

Gao M, Zhang R, Xie J, Peng G, Yu B, Ranjith P. 2018. Field experiments on fracture evolution and correlations between connectivity and abutment pressure under top coal caving conditions. Int J Rock Mech & Min Sci. 111:84–93.

Guo C, Wang X, Wang H, He S, Liu H, Zhu P. 2018. Effect of pore structure on displacement efficiency and oil-cluster morphology by using micro computed tomography (µCT) technique. Fuel. 230:430–439.

Hatheway AW. 2009. The complete ISRM suggested methods for rock characterization, testing and monitoring: 1974–2006. Environ Eng Geosci. 15(1):47–48.

Jin K, Cheng Y, Ren T, Zhao W, Tu Q, Dong J, Wang Z, Hu B. 2018. Experimental investigation on the formation and transport mechanism of outburst coal-gas flow: Implications for the role of gas desorption in the development stage of outburst. Int Journal Coal Geol. 194: 45–58.

Kong S, Cheng Y, Ren T, Liu H. 2014. A sequential approach to control gas for the extraction of multi-gassy coal seams from traditional gas well drainage to mining-induced stress relief. Appl Energy. 131:67–78.

Liang Y. 2018. Strategies of high efficiency recovery and energy saving for coal resources in China. J China Univ Min Technol. 1:3–20.

Liu Q, Cheng Y, Haifeng W, Hongxiong Z, Liang W, Wei L, Hongyong L. 2015. Numerical assessment of the effect of equilibration time on coal permeability evolution characteristics. Fuel. 140:81–89.

Lu S, Zhang Y, Sa Z, Si S, Shu L, Wang L. 2019. Damage-induced permeability model of coal and its application to gas predrainage in combination of soft coal and hard coal. Energy Sci Eng. 7(4):1352–1367.

Ma K, Wang L, Peng Y, Long L, Wang S, Chen T. 2020. Permeability characteristics of fractured rock mass: a case study of the Dongjiahe coal mine. Geomat Nat Haz Risk. 11(1): 1724–1742.

Mitra A, Harpalani S, Liu S. 2012. Laboratory measurement and modeling of coal permeability with continued methane production: Part 1–Laboratory results. Fuel. 94:110–116.

Oda M, Yamabe T, Kamemura K. 1986. A crack tensor and its relation to wave velocity anisotropy in jointed rock masses. Int J Rock Mech Min Sci. 23(6):387–397.

Rahner MS, Halisch M, Fernandes CP, Weller A, dos Santos VSS. 2018. Fractal dimensions of pore spaces in unconventional reservoir rocks using X-ray nano-and micro-computed tomography. J Nat Gas Sci Eng. 55:298–311.

Shi X, Pan J, Hou Q, Jin Y, Wang Z, Niu Q, Li M. 2018. Micrometer-scale fractures in coal related to coal rank based on micro-CT scanning and fractal theory. Fuel. 212:162–172.

Wang Z, Pan J, Hou Q, Niu Q, Tian J, Wang H, Fu X. 2018. Changes in the anisotropic permeability of low-rank coal under varying effective stress in Fukang mining area, China. Fuel. 234:1481–1497.

Wang J, Ren Z, Song Z, Huo R, Yang T. 2019. Study of the effect of micro-pore characteristics and saturation degree on the longitudinal wave velocity of sandstone. Arab J Geosci. 12(13): 1–11.

Wang R, Yang P. 2002. Gas prevention and control during construction of diversion tunnel in Zipingpu Project. Water Resour Hydropower Eng. 11:45–47.
Xie J, Gao M, Liu J, Li C, Peng G. 2020. Permeability-enhanced rate model for coal permeability evolution and its application under various triaxial stress conditions. Arab J Geosci. 13(17):1–12.

Xie J, Gao M, Zhang R, Liu J, Lu T, Wang M. 2020. Gas flow characteristics of coal samples with different levels of fracture network complexity under triaxial loading and unloading conditions. J Petrol Sci Eng. 195:107606.

Xie J, Gao M, Zhang R, Peng G, Lu T, Wang F. 2020. Experimental investigation on the anisotropic fractal characteristics of the rock fracture surface and its application on the fluid flow description. J Petrol Sci Eng. 191:107190.

Xie H, Zhou H, Xue D, Wang H, Zhang R, Gao F. 2012. Research and consideration on deep coal mining and critical mining depth. J China Coal Soc. 37:535–542.

Xu T, Tang C, Yang T, Zhu W, Liu J. 2006. Numerical investigation of coal and gas outbursts in underground collieries. Int J Rock Mech Min Sci. 43(6):905–919.

Yuan A, Wang P, Li Y. 2020. Movement laws of overlying strata and prevention measures of dynamic disasters under deep adjacent coal seam group with high gas. Geomat Nat Haz Risk. 11(1):2340–2360.

Zhang R, Cheng Y, Zhou H, Yuan L, Li W, Liu Q, Jin K, Tu Q. 2018. New insights into the permeability-increasing area of overlying coal seams disturbed by the mining of coal. J Nat Gas Sci Eng. 49:352–364.

Zou J, Chen W, Yang D, Yu H, Yuan J. 2016. The impact of effective stress and gas slippage on coal permeability under cyclic loading. J Nat Gas Sci Eng. 31:236–248.