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The influence mechanism of effective stress, adsorption effect and Klinkenberg effect on coal seam permeability

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Permeability is an important parameter in the process of coalbed methane exploitation. To improve the production efficiency of coalbed methane and explore the control mechanism of the gas flow law in coal, the permeability of helium and nitrogen in the same coal sample was tested under different effective stress (the difference between external stress and pore pressure of coal mass) and pressure by using the seepage device. Based on the gas flow theory, the interaction mechanism of effective stress, adsorption effect and Klinkenberg effect in controlling the permeability has been analyzed. Increasing the gas pressure will enhance the adsorption and deformation ability of coal, causing the reduction of pore size, while it will also cause the reduction of effective stress and stress deformation. There is a certain competition between them under the same external stress condition, which will lead to the change of pore and then affect the permeability of coal seam. The Klinkenberg effect will lead to more complex change factors of permeability, especially in laboratory experiments. Both adsorption deformation and stress deformation will affect the pore structure of coal body, which will also lead to changes in the influence degree of Klinkenberg effect on apparent permeability. Under the influence of adsorption effect, the Klinkenberg effect may be a variable. The experimental results in this work elaborate the microscopic control mechanism of gas permeability change in coal. It can not only provide important guidance for gas injection technology, but also enrich the theory of coal seam gas flow.

KEYWORDS

coal reservoir, gas adsorption, permeability, Klinkenberg effect, coalbed methane exploitation

Introduction

In the process of coal mining, a lot of methane is discharged into the atmosphere casually, however, the greenhouse effect caused by methane is 20 times stronger than carbon dioxide, and long-term random discharge of methane causes serious greenhouse effect (Hou et al., 2022; Li et al., 2022; Xue et al., 2022). On the other hand, methane is a kind of clean energy. As a result, it is particularly important to improve the exploitation of coalbed methane (CBM), which not only mitigates greenhouse effect but also improves energy efficiency (Ji et al., 2020; Liu et al., 2020; Si et al., 2021; Zhou et al., 2019). Coal permeability is an important index for CBM extraction (Pan and Connell 2012; Wei et al., 2021; Xiao et al., 2021; Zhou et al., 2021). It is therefore of great significance to explore the seepage characteristics of gas in coal.

Coal is a special reservoir with dual pore structure (Wang et al., 2021; Wang et al., 2022). Gas flow in coal is closely related to pore structure. Meanwhile, changes in stress and gas pressure will significantly affect permeability of coal (White et al., 2005; Si et al., 2018). The change of gas pressure not only leads to the change of adsorbed gas quantity of coal body, but also causes the change of coal matrix body, which then effects the width of cracks in coal and causes the change of permeability of coal body. On the other hand, under the influence of effective stress, the change of stress will also lead to the change of elastic strain variable of coal, which will also affect the width of coal crack and permeability (Singh and Javadpour 2016). Because of such complicated deformation characteristics of coal, the permeability value is an important variate during the process of coalbed methane exploitation. As a result, it is particularly important to explore the variation law of coal permeability for the prediction of coalbed methane production (Levine and J. 1996; Towler et al., 2016; Rathnayake et al., 2022).

In order to further deeply analyze the flow characteristics of gas in coal, it is critical to clarify the influence of coal stress deformation, adsorption deformation and Klinkenberg effect on permeability. In the aspect of the influence of coal stress deformation, Somerton et al. (1975) analyzed the relationship between average stress and coal permeability through experiments and obtained an empirical fitting equation. Gray (1997) reconstructed the permeability equation of coal based on the horizontal effective stress, considering the matrix expansion factor. Seidle and Huitt (1995) assumed that the coal was a matchstick model, constructed the coal permeability model and considered that the coal permeability decreased with the increase of effective stress Somerton et al. (1975). Selected three bituminous uranium and analyzed the flow characteristics of gas in coal under axial and radial stress conditions, determining the functional relationship between the permeability of coal fissure and applied stress Zhang et al. (2008). Analyzed coal stress deformation and adsorption deformation by theoretical modeling, established FE model of permeability, verified the experimental data, and discussed the control law of coal deformation on permeability in detail. Mitra et al. (2012) have discussed the changes of coal permeability under uniaxial strain field in the laboratory, and proposed that the increase of coal permeability under low pressure is due to matrix Shrinkage effect.

Coal is a kind of rock mass, which conforms to certain elastic mechanical properties. The stress change will lead to deformation of coal structure. The change of pore size of gas flow will lead to the variation of permeability. During deep coal seam mining, the stress will be redistributed under the influence of mining, which will also lead to the change of coal permeability. In early studies, stress variation was also considered as the main factor affecting permeability, and relevant theoretical equations were established. However, with the deepening of experimental research, researchers gradually realized that stress deformation alone could not explain the permeability changes of some high pressure or different gases. With the improvement of testing technology, it is observed that coal is prone to deformation in the process of gas adsorption, especially under high pressure. This phenomenon cannot be ignored and will also have a significant impact on permeability.

In terms of the influence of adsorption deformation, Mitra et al. (2012) researched the sorption-induced volumetric strain caused by coal adsorbing gas with experimental methods, and verified and improved the permeability model on this basis. Perera et al. (2013) developed a state-of-the-art core flooding apparatus to verify the influence of expansion factors caused by the adsorption of carbon dioxide on coal permeability. Based on matrix-fractures, Jianhua et al. (2021) improved the adsorption deformation equation, established a permeability model of coal, and discussed the influence of adsorption-induced deformation on coal permeability. Lin and Kovscek (2014) used experimental methods to analyze the flow characteristics of gas in coal, tested the permeability of nitrogen, carbon dioxide and mixed gas, and analyzed the influence characteristics of adsorption deformation on permeability of coal in detail.

Adsorption deformation is the special property of coal body, because of the adsorbability of coal, especially for methane and carbon dioxide gas has extremely significant adsorption effect. After adsorbing gas, the expansion of coal matrix leads to the reduction of coal pore size, which is easy to cause the decrease of gas permeability, which is very obvious in carbon dioxide injection into coal seam. On this basis, researchers have a more and more clear understanding of gas flow in coal seam, and a relevant theoretical model was established to explain the experimental results. The flow phenomenon of gas in tiny pores is significantly different from that of liquid. The Klinkenberg effect is a special phenomenon of gas flow, especially in the state of low pressure, and this effect will be very significant. The coal seam is a low permeability reservoir, and the methane gas pressure in the coal seam is generally low, so the Klinkenberg effect cannot be ignored in the theoretical study of coal seam gas flow. Therefore, researchers take the Klinkenberg effect into account and further modify the current permeability model in order to have a clearer understanding of the gas flow law in coal seam.

Under the condition of low gas pressure, the Klinkenberg effect of gas flow in coal cannot be ignored. According to the deformation characteristics of coal matrix, Wang et al. (2014) established the Klinkenberg effect model towards the change of crack width, and proposed that the Klinkenberg coefficient of gas flow in coal is a variation. Through theoretical analysis, Moghadam and Chalaturnyk (2014) also proposed that the Klinkenberg coefficient of gas flow changes with gas pressure, and established a new model, which enabled be used to verify the field permeability data. In the aspect of the influence of Klinkenberg effect, Zhu et al. (2007) verified the gas permeability equation with Klinkenberg effect using finite element method, and considered that Klinkenberg effect has an important contribution to gas flow in coal. El Amin Mohamed and El Beltagy Mohamed (2021) established a random Klinkenberg slip coefficient model with theoretical method, and analyzed the role of this model in apparent permeability, indicating that this model was suitable for low permeability reservoirs. The factors affecting the gas flow in coal are complex, and it is difficult to explain the change mechanism of coal permeability by a single theoretical method (Zhen et al., 2021). The variation of coal permeability is affected by pore deformation, which is also the key factor to establish permeability model. Therefore, scholars have established classical SD model and PM model based on effective stress deformation and adsorption deformation. These theoretical models have a strong guiding role in laboratory and industrial experiment data (Shi and Durucan 2004). Zhou et al. (2020) constructed a theoretical model of coal permeability based on the changes of coal matrix body, obtaining the variation characteristics of Klinkenberg effect and Knudsen number during the process of gas flow in coal, which accurately predicted coal permeability. These results laid a theoretical foundation for coalbed methane exploitation. Zhou et al. (2016) established a theoretical permeability model coupled with effective stress, adsorption deformation and Klinkenberg effect, which has a higher fitting degree than the conventional model.

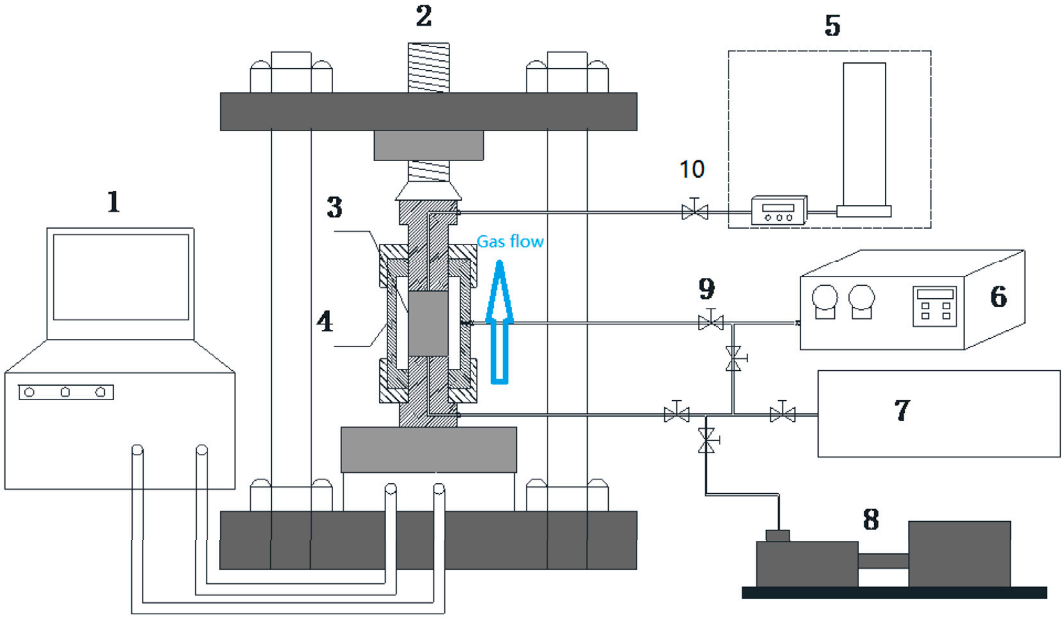
There are many complex factors affecting gas flow in coal, and it is impossible to take all of them into account in a single study. Therefore, studies are conducted with one or both factors as the object. A large number of articles taken pore deformation as the research object, discussed the change of gas flow by considering the pore size variation caused by stress and adsorption, and predicted and verified the relationship between mathematical model and actual gas permeability through experiments, numerical simulation and theoretical calculation. These conclusions are of great significance to understand the law of gas flow in coal and help engineers to understand the influence mechanism of stress and other factors on coal permeability. Coal is a low-permeability reservoir, the Klinkenberg effect is an important part of gas flow in coal, which has a significant impact on the prediction of coalbed methane production. With the increasing popularity of CBM exploitation, a large number of researchers gradually focus on the influence of Klinkenberg effect on gas permeability, especially in China. The Klinkenberg effect is a special property in gas flow and is affected by many factors. Although a large number of experiments have been conducted on this effect, there are not enough experiments to quantify its effect on permeability. The adsorption capacity of different gases on coal is clearly different, and different gas pressure will also lead to the variation of effective stress. Stress and gas adsorption will not only affect the permeability of coal, but also lead to the change of Klinkenberg effect. The permeability change law of different gases under different effective stresses is studied by experimental method, and then the contribution of Klinkenberg effect, stress and gas adsorption to permeability is analyzed in detail, which is helpful to understand the change mechanism of gas flow process in coal.

The permeability of gas in coal is mainly controlled by stress, gas adsorption and content (Banerjee et al., 2021), Klinkenberg effect, the fracture and cleats (Banerjee et al., 2022). Although a large number of experimental studies have been done on permeability of coal, the quantitative experiments are lacking to reveal the relationship between adsorption effect and Klinkenberg effect in permeability measurement. Herein, the permeability of helium gas and nitrogen gas in the same coal sample under different effective stress and gas pressure has been tested by seepage device, and the influence of effective stress and gas pressure on permeability change was expounded. Meanwhile, based on the theoretical model of Klinkenberg effect, the effect of effective stress on Klinkenberg coefficient was compared. Moreover, apparent permeability was decomposed, and the contribution degree and control law of adsorption effect and Klinkenberg effect on apparent permeability were quantified. Based on the experiment, this paper could intuitively show the influence of various factors on permeability, which was also suitable for the actual situation of coalbed methane mining. This work will provide theoretical guidance for coalbed methane exploitation.

Experimental methods and theoretical analysis

Samples and experimental devices

To compare the difference of various gas permeability, the permeability of nitrogen and helium was tested with single coal sample under the same conditions. The coal samples were taken from Qincheng Coal Mine in Shanxi Province, and the standard samples of 50*100 mm were drilled after large raw coal were taken out from underground. The coal samples in this area are



1.Computer; 2. Servo press; 3. Coal sample; 4. Steel cell; 5. Measurement system; 6. Constant flux pump; 7. Gas supply; 8. Vacuum pump; 9-10. Valve

FIGURE 1
Schematic of coal permeability experimental apparatus. 1.Computer; 2. Servo press; 3. Coal sample; 4. Steel cell; 5. Measurement system; 6. Constant flux pump; 7. Gas supply; 8. Vacuum pump; 9-10. Valve.

anthracite. Qincheng is rich in CBM reserves and is the most favorable area for CBM resource development in China. The triaxial seepage device is adopted in the seepage experiment (Figure 1), which enables to accuratly control the confining and axial pressures and meet the seepage experiment requirements for various gases.

Experimental methods

For gas seepage experiment, the axial pressure and confining pressure of coal sample gripper are controlled by the device, and the effective stress of coal body is kept fixed in combination with gas pressure. The seepage law of gas in coal under constant effective stress is investigated, and the gas permeability is calculated by steady-state method. The coal sample was vacuum dried for 48 h, and then put into the percolation instrument for degassing. Helium gas was firstly used as the experimental gas to test the permeability of the coal sample under the gas pressure of 0–6 MPa. After the helium experiment, the permeability of nitrogen in the same coal sample was carried out to test the change of permeability of nitrogen under the same pressure range. In addition, the permeabilities of helium and nitrogen were measured under the effective stress of 2 MPa, 3 MPa and 4 MPa.

Theoretical methods

Coal is a kind of special porous medium, which has good adsorption capacity for gases (Abouloifa et al., 2021; Chen et al., 2022). At the same time, the gas adsorption changes the internal pore structure, which has a non-negligible influence on the gas flow. The flow law of gas and liquid in porous media is obviously different. At low pressure condition, the moving velocity of gas molecules near the channel wall is not zero, and the apparent permeability measured is higher in low pressure stage, which is also called Klinkenberg effect (Ertekin et al., 1986; Li et al., 2014; Xian et al., 2022). A theoretical model between apparent permeability and Klinkenberg effect have been established (Wang et al., 2014):

$$k_a = k_0\left(1 + \frac{b}{P}\right) \tag{1}$$

Where k_a is apparent permeability, mD. There is a Klinkenberg effect in the flow of gas in coal, which will change the permeability obtained from the experimental test, and this experimental value is also called the apparent permeability. k_0 is the absolute permeability of coal. The permeability of porous media is related to the channel and flow medium. The absolute permeability of rock mass is an inherent value that there is no physical and chemical reaction between flow medium and rock mass and is independent of fluid properties. Md. b is the Klinkenberg coefficient, MPa; P is the gas pressure, MPa. The coefficient b reflects the strength of the Klinkenberg effect of gas in porous media, which is controlled by the width of gas channel and the nature of gas. The theoretical model of b have also been summarized (Harpalani and Schraufnagel 1991):

$$b = \frac{16c\mu}{w}\sqrt{\frac{2RT}{\pi M}} \tag{2}$$

Where c is a constant, which is 0.9; μ is the dynamic viscosity of the gas; M is the molecular mass of the gas; R, T are universal gas constant and absolute temperature, respectively; w is the average width of the gas flow channel. The flow process of gas in coal is complicated, and b value of non-adsorptive gas is mainly controlled by gas properties. For adsorptive gas, the channel width w of coal body changes under the influence of adsorption deformation, so the factors which affect b value are more complicated. In the initial state of the experiment (the air pressure is zero), the flow channel width of the two gases is the same during the experiment. Therefore, the b value of nitrogen is calculated based on helium gas, and the following results can be obtained:

$$b_{N_2} = \frac{\mu_{N_2}}{\mu_{He}}\sqrt{\frac{M_{He}}{M_{N_2}}} \times b_{He} \tag{3}$$

Absolute permeability k_0 of coal sample is a fixed parameter related to pore structure, and the value increases with the width of the passage. The change of pore structure will lead to the change of permeability. Therefore, the apparent permeability of adsorbent gas in coal can be divided into three parts: k_0, Δk_e, and Δk_K, which jointly control the apparent permeability of gas:

$$\begin{aligned} k_a &= k_0 + \Delta k_e + \Delta k_K \\ &= k_0 + \Delta k_e + \frac{k_0 \times b_{N_2}}{P} \end{aligned} \tag{4}$$

Here, Δk_e is the adsorption effect in apparent permeability; Δk_K is for Klinkenberg effect. If the influence of gas adsorption on Klinkenberg effect is not considered, the following formula can be derived to measure the contribution of adsorption effect to apparent permeability change in the nitrogen experiment:

$$\Delta k_e = k_a - k_0 - \Delta k_K \tag{5}$$

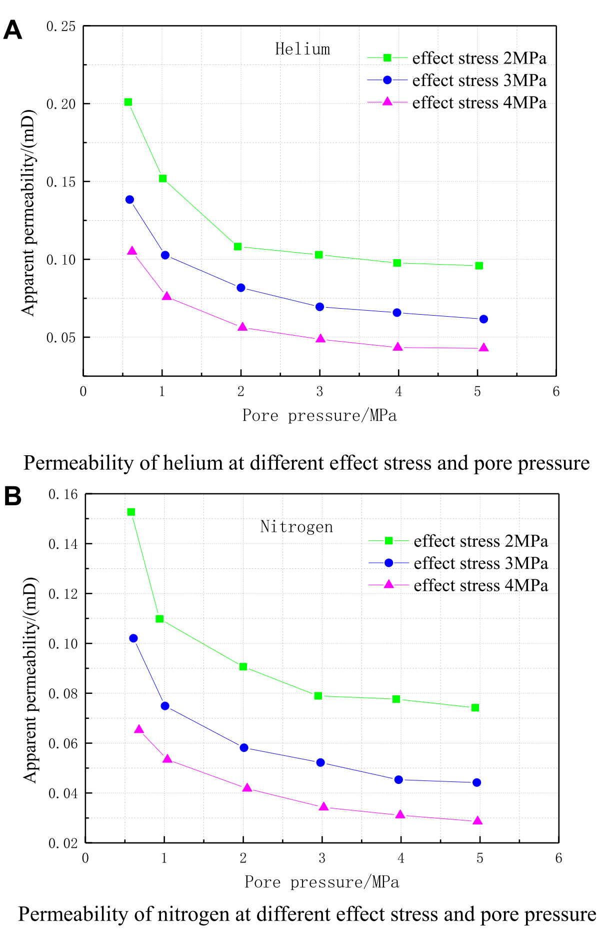


FIGURE 2
The permeability of helium and nitrogen varies with the different effective stress and pressure. **(A)** Permeability of helium at different effect stress and pore pressure. **(B)** Permeability of nitrogen at different effect stress and pore pressure.

Analysis of experimental results

Effect of effective stress on gas permeability

Helium and nitrogen were used as experimental gases, owing to that helium do not be adsorbed in coal, which would not lead to adsorption deformation, while nitrogen, as an adsorbent gas, could lead to adsorption deformation of coal. Therefore, the control law of adsorption effect and effective stress on gas flow characteristics in coal can be reflected by comparing the permeability results of the two gases. Figure 2 show the relationship between gas permeability and gas pressure under different effective stresses.

As can be found in Figure 3 and Table 1, along with the increase of effective stress, the apparent permeability decreases gradually under the same gas pressure. Moreover, the apparent

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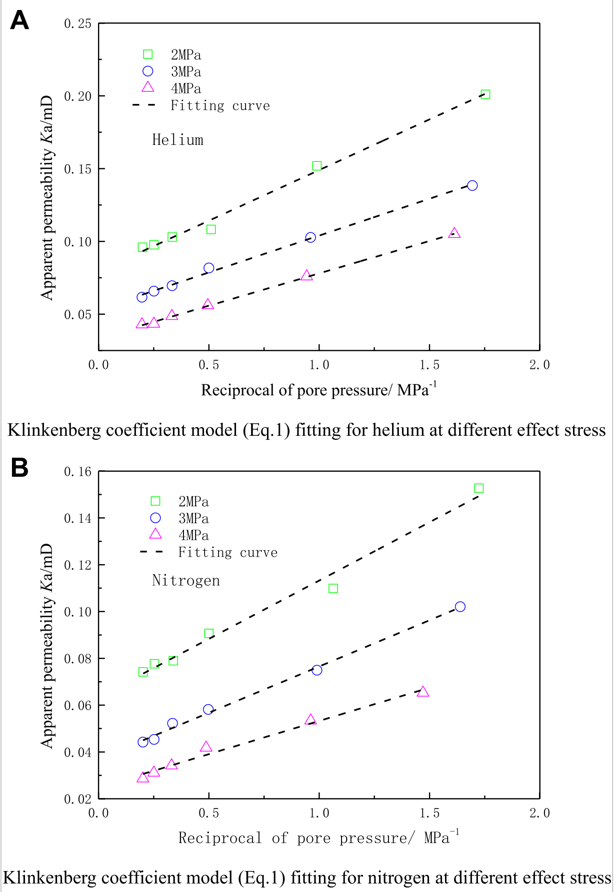

FIGURE 3
Klinkenberg coefficient model fitting results of experimental data. **(A)** Klinkenberg coefficient model (Eq. 1) fitting for helium at different effect stress **(B)** Klinkenberg coefficient model (Eq. 1) fitting for nitrogen at different effect stress.

permeability decreases significantly in the initial stage, and the downward trend gradually changes in the later stage. In particular, owing to the influence of gas adsorption, the permeability for nitrogen is obviously lower than that for helium in the same coal sample under the same effective stress and gas pressure.

There is an obvious Klinkenberg effect for the gas flow in porous media. Gas molecules have greater mobility at low pressure, leading to the more significant Klinkenberg effect. Thus, the permeability measured at low pressure usually is higher than that measured at high pressure. Due to the influence of Klinkenberg effect, the measured apparent permeability of helium gas is higher than the absolute permeability under the same effective stress. Moreover, along with the increase of gas pressure, the effect decreases, leading to the smaller difference between apparent permeability. Coal is an organic rock mass. Stress change and gas adsorption could lead to the deformation of the pore structure of coal, while the increase

TABLE 1 Absolute permeability and Klinkenberg coefficient of the two gases under different effective stresses.

Gas	Effective stress/MPa	k_0/mD	b	R^2
Helium	2	0.0794	0.8766	0.9906
	3	0.0534	0.9476	0.9959
	4	0.0336	1.3214	0.9988
Nitrogen	2	0.0634	0.7855	0.9821
	3	0.0370	1.0676	0.9945
	4	0.0249	1.1406	0.9788

of effective stress and gas adsorption could result in the pore contraction of coal and in turn the decrease of permeability. In helium experiment, the increase of effective stress leads to the decrease of permeability, mainly owing to the stress deformation of coal. In nitrogen experiment, the decrease of permeability is controlled by both effective stress and adsorption effect.

Variation analysis of Klinkenberg effect on gas flow

Klinkenberg effect is a phenomenon that cannot be ignored for gas flow. In order to deeply analyze the effect of effective stress and gas adsorption on Klinkenberg effect, a fitting analysis of the experimental results was carried out by Eq. 3 with the results shown in Figure 3.

As shown, the experimental data of the two groups of gases fits well with the Eq. 1. Along with the increase of effective stress, the coal sample is compressed and the width of the fracture decreases, resulting in the decrease of the absolute permeability of the coal sample and the increase of the Klinkenberg coefficient. k_0 is positively correlated with channel width, while b is negatively correlated with channel width. The Klinkenberg effect is controlled by gas properties and channel width. Nitrogen can lead to adsorption expansion and channel contraction of coal samples. Under the same effective stress, both the absolute permeability and Klinkenberg coefficient measured by nitrogen are smaller than those by helium. The fitting rates for the two groups of gases show that the average fitting rate for helium is above 0.99, while the average fitting rate for nitrogen is 0.98. This is because that there are more influencing factors for Klinkenberg coefficient in nitrogen experiment due to gas adsorption.

Analysis of the effect of adsorption on apparent permeability

For two groups of gases in the same coal sample, the coal body is only affected by stress deformation under the same effective stress, and the absolute permeability of the coal

TABLE 2 Calculation results of Nitrogen Klinkenberg coefficient under different effective stresses.

Effective stress/MPa	b
2	0.3121
3	0.3373
4	0.4704

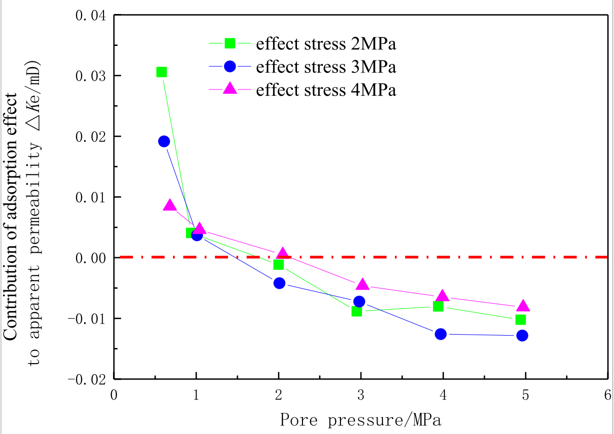

FIGURE 4
Contribution of adsorption effect to apparent permeability in nitrogen experiment.

sample remains unchanged. The test results of helium are adopted for K_0 under different effective stresses in calculation. The Klinkenberg coefficient of nitrogen under different effective stresses is calculated by Eq. 3 with the results shown in Table 2.

In nitrogen seepage experiment, coal is affected by both stress and gas adsorption. Along with the increase of gas pressure, coal expands and deforms, leading to the gas flow channel shrinks. These make that the measured apparent permeability changes under the influence of gas adsorption effect and Klinkenberg effect. According to Eq. 5, K_0 is calculated using the helium test result with the result shown in Figure 4.

As displayed in Figure 4, Δk_e value is positive under low pressure, but becomes negative along with the increase of pressure. The contribution of Klinkenberg effect to apparent permeability, Δk_K, is related to gas pressure and absolute permeability. The increase of gas pressure or decrease of absolute permeability leads to the decrease of Δk_K. However, this effect results in that the apparent permeability is greater than the absolute permeability in the experiment of non-adsorbent gas. At low pressure stage, the expansion variable of coal body is small, and Δk_e for nitrogen is positive, owing to that Klinkenberg effect is stronger than the reduction degree of absolute permeability. With the further increase of gas pressure, the amount of expansion deformation increases. Meanwhile, gas adsorption effect is dominant with a negative Δk_e, and the decrease degree of absolute permeability of coal sample is stronger than Klinkenberg effect.

Gas flow in coal is a very complicated process, which is not only affected by stress, but also closely related to gas properties (Wang et al., 2021). With the increase of coalbed methane mining intensity, the injection of inert gas (nitrogen and carbon dioxide) has been widely used in the field, and the implementation process is accompanied by the change of effective stress and gas pressure of coal seam. The increasing pressure of adsorbent gas will reduce the Klinkenberg effect of adsorbent gas, while the adsorption effect will narrow the fracture channel and reduce the absolute permeability and apparent permeability. In the process of coalbed methane exploitation, permeability is an important parameter to predict the gas production rate, so it is particularly important to explore the gas flow law under the complex factors in the process of coalbed methane exploitation.

When the pore pressure is the same, the increase of the external stress of coal can lead to the increase of the effective stress, causing the enhancement of the pore size contraction effect. Therefore, the greater the effective stress is, under the same pore pressure, the weaker the contribution of the gas adsorption effect to the apparent permeability is, and the value of Δk_e gradually decreases. When the pore pressure is about 1.5 MPa, the contribution of gas adsorption effect to the apparent permeability changes from positive promotion to negative weakening. According to the coal deformation theory and seepage theory, under the same effective stress, the adsorption gas of coal leads to pore size contraction and permeability reduction. That is, the contribution of adsorption effect to apparent permeability is negative and weakened, the obtained Δk_e also should be negative. However, the experimental results in this paper got positive values in the low pressure stage. This phenomenon is based on the assumptions of Eqs 4, 5. According to Eq. 1, the apparent permeability is only composed of Klinkenberg effect and initial permeability. Through experiments, it was found that the *b* value of Klinkenberg effect under different conditions of gas in coal was also affected by pressure and stress. The Klinkenberg effect is also a variable, which was assumed to be a fixed value in Eq. 4. Therefore, the value obtained in Eq. 5 showed that the theoretical Eq. 1 ignored the change of b value in the Klinkenberg effect. In the later research, the variation law of Klinkenberg effect *b* of gas in coal under different conditions can be analyzed, and the variation law of *b* value can be revealed through theoretical modeling, so as to modify the permeability model of gas in coal.

Discussion

Coalbed methane is an important clean energy. Promoting the exploitation of coalbed methane can not only improve the utilization of energy, but also ensure the exploitation of underground coal resources. In China, most coal seams are low permeability rock, greatly limiting the extraction of methane in coal. To improve the production of methane, many scientific and technological workers began to study the technology of injecting inert gas into coal seam to promote methane extraction. This technique is to inject nitrogen or carbon dioxide gas into the coal seam, high pressure gas flow in the coal seam, under the pressure difference and displacement adsorption, promoting methane flow to the extraction borehole.

Coal is a complex porous medium, the process of gas flow is restricted by many factors, and permeability is an important evaluation index in coalbed methane mining. The injection of nitrogen or carbon dioxide into coal seam may cause the increase of gas pressure in coal and the change of effective stress, especially the high strength adsorption gas can produce the ignored pore deformation of coal. These will have a serious impact on the production rate of coalbed methane. Therefore, it is necessary to study the changes of different gas permeability in coal, which has important theoretical guidance for inert gas injection technology and coalbed methane mining.

In this article, through the experimental device, the influence of adsorption expansion caused by adsorbed gas on coal permeability was analyzed in depth, and the decrease degree of coal permeability caused by adsorption expansion was quantified. At the same time, the influence of different effective stress on gas Klinkenberg coefficient was also analyzed. These experimental results play an important role in understanding the microscopic changes of coal permeability. However, in the actual situation of coal seam *in situ*, there are more influencing factors on gas flow, such as temperature, uneven fracture and so on. These factors cannot be fully reflected in the experiment. In particular, small-scale coal permeability is a conventional method to study coal permeability. While small-scale coal samples cannot represent large-scale coal seams. The application of experimental results in practice still needs further verification and improvement. Although the theoretical and experimental research conditions are significantly different from the actual situation of coalbed methane mining, the research results can also provide suggestions for the improvement of actual coalbed methane mining technology. According to the actual situation, the experimental conditions are constantly improved to promote the continuous optimization and improvement of coalbed methane mining technology.

Permeability is a important index in coalbed methane development, and it has a clear impact on predicting coalbed methane production. Due to the special property of coal seam itself, the pore structure of coal body will change when the stress and gas pressure change, which will affect the permeability of gas in coal. Experimental results showed that with the CBM extraction, gas pressure drop would cause the decrease of the effective stress of coal and the increase of gas permeability, which played an active role in CBM extraction. Meanwhile, low pressure also would cause the more significant phenomenon of the Klinkenberg effect. The permeability value of gas flow in coal can be changed in real time by theoretical calculation. In the process of coalbed methane extraction, the coalbed methane production should be predicted according to the variable permeability. The increase of permeability may lead to the increase of the extraction amount.

Conclusion

(1) With the increase of effective stress, the coal is compressed with the decreased permeabilities of both gases. Under the same effective stress, the apparent permeability gradually decreases along with the increase of gas pressure. Under the same conditions, the permeability of nitrogen is lower than that of helium due to the influence of gas adsorption.
(2) The Klinkenberg effect leads to that the apparent permeability of coal is higher than the absolute permeability, while the gas adsorption effect weakens the fitting degree of the theoretical model. The increase of effective stress can enhance the Klinkenberg coefficient but reduce the absolute permeability at the same time.
(3) At low pressure stage, the decrease of absolute permeability caused by adsorption effect is weaker compared to Klinkenberg effect, giving a positive Δk_e. In contrast, at high pressure stage, The decrease of absolute permeability caused by adsorption effect is stronger compared to Klinkenberg effect, leading to a negative Δk_e. El Amin Mohamed and El Beltagy Mohamed, 2021, Liu et al., 2021, Perera et al., 2013, Mitra et al., 2012

Data availability statement

The original contributions presented in the study are included in the article/Supplementary Material; further inquiries can be directed to the corresponding author.

Author contributions

MW: Formal analysis, Investigation, Writing YY: Conceptualization, Resources, Methodology YZ:

Conceptualization, Methodology, Writing HS: Formal analysis, Investigation JH: Formal analysis, Investigation.

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Conflict of interest

The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

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