CBM exploration: Permeability of coal owing to cleat and connected fracture

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Abstract
Coalbed methane (CBM) resources cannot be efficiently explored and exploited without a robust understanding of the permeability of fracture-size heterogeneities in coal. In this study, two sister coal samples were imparted with pre-developed cleat and connected fractures, and the permeability of the coal samples was measured under different conditions of controlled confining and gas pressures. Furthermore, the implications of the results for CBM exploration and exploitation were discussed. The permeability of coal with cleat development ranged from 0.001–0.01 mD, indicating ultra-low permeability coal. The gas migration in this coal changed from a linear flow to a non-linear flow, with the increase in gas pressure (>1 MPa). Thus, the permeability of the coal initially increased and then decreased. However, the Klinkenberg effect does not exist in this ultralow-permeability coal. For the coal sample with connected fracture, permeability ranged from 0.1–10 mD, which is larger by hundred orders of magnitude than that of the sample with cleat. For this coal, with a decrease in gas pressure (<1 MPa), the Klinkenberg effect significantly increased the permeability of the coal. With an increase in the applied confining pressure, both the Klinkenberg coefficient and permeability of the coal presented a decreasing trend. It is suggested that field fracture investigation is a prerequisite and indispensable step for successful CBM production. The coal beds that cleat network is well conductive to the connected fracture can be an improved target area for CBM production. During CBM production, a variety of flow regimes are available owing to the decrease in CBM reservoir pressure. In particular, under the low CBM reservoir pressure and low in situ geo-stress conditions, the gas migration in the CBM reservoir with connected fracture development exhibits remarkable free-molecular flow. Thus, the reservoir permeability and predicted CBM production will be enhanced.

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Keywords:
Coal; coalbed methane; permeability; cleat; connected fracture

Introduction
Coalbed methane (CBM) is a rapidly growing source of clean energy worldwide. In addition to the USA, Canada, and Russia, the Asia-Pacific countries are presently the fastest-growing CBM markets, with a compound average growth of 14.9% between 2014 and 2020 (Bandyopadhayay et al., 2020). The efficient exploration and exploitation of this huge resource necessitate accurate reserve estimation and production forecasting. This cannot be achieved without a robust understanding of the permeability of coal (Kumar et al., 2018). This is also a prerequisite for N₂ or CO₂ enhanced CBM recovery (Anggara et al., 2016; Flores et al., 2019; Zhang and Ranjith, 2019).

Currently, significant research has been conducted on the permeability of coal, worldwide (Connell et al., 2016; Gensterblum et al., 2014; Li et al., 2019; Niu et al., 2020; Ramandi et al., 2015; Wang et al., 2017; Wang et al., 2018; Xie and Zhao, 2017). Gensterblum et al. (2014) studied the relationship between coal deformation and permeability under the action of cyclic loading and inferred that the volumetric strain of the coal gradually increases with the increase in temperature under applied loading, with a corresponding decrease in its permeability. Li et al. (2019) revealed that the permeability stress sensitivity of coal in the loading process was significantly higher than that in the unloading process. Ramandi et al. (2015) established that a direct relationship existed between the coal lithotype and permeability, that is, bright coal is more permeable than dull coal. Connell et al. (2016) inferred that with an increase in gas pressure, the permeability of coal decreases significantly owing to the adsorption-induced swelling strain. Wang et al. (2017) discussed the relationship between coal permeability and porosity under high-temperature and high-pressure conditions and concluded that an exponential relationship exists between the permeability and porosity of coal. With the increase in temperature, the porosity of low-rank coal increased. However, the porosity decreased for medium-rank coal. Xie and Zhao (2017) revealed that the change in pore size distribution in coal determines the permeability evolution behavior with temperature. Wang et al. (2018) investigated the relationship between coal permeability and fracture fractal dimension and concluded that the permeability of coal increases exponentially according to the fracture fractal dimension. Niu et al. (2020) discussed the permeability of coal from the perspective of vertical bedding and parallel bedding and found that the permeability of coal is anisotropic, with a higher permeability in the parallel bedding direction. Generally, research on the permeability of coal primarily has focused on the influences of stress, temperature, pore pressure, coal lithotype, bedding, and adsorption effect.

In addition, recent studies have exhibited that the permeability of coal is intimately related to the Klinkenberg effect, which is essential for enhancing the CBM productivity at lower reservoir pressures. Li et al. (2014) found that the Klinkenberg effect positively contributes towards improving the permeability of coal for all ranks, which becomes more influential for low-permeability coal. Gensterblum et al. (2014) indicated that the Klinkenberg effect in coal could, at least partly, offset the permeability decrease resulting from the increased effective stress during the CBM production process. This leads to a significant increase in the CBM productivity during the low reservoir pressure phase. Zhou et al. (2016) demonstrated that the Klinkenberg coefficient increases with increasing pore pressure at constant effective stress. For a given confining stress on the coal, the Klinkenberg coefficient reaches a maximum value for the competition relationship between the sorption-induced strain and the stress-strain of the coal.
However, coal is a fracture-size heterogeneous material (Du et al., 2020; Firouzi et al., 2014; Wang et al., 2018). In particular, for high-rank coal, cleats are massively developed as natural fractures, which are usually present in two sets that are perpendicular to the bedding and also mutually perpendicular. In terms of their size, the cleats are meso-fractures. In several situations, cleats are confined to the coal of particular maceral types, such as vitrain and clarain. In a coal bed, the connectivity of the cleat network is commonly limited owing to its termination at the interfaces of the coal types. However, the connection of the cleat network can be accomplished by the fracture of a larger size than the cleat network. This type of fracture crosses through the interbedded coal types, which are macro-fractures in size and are termed as connected fractures. These multiscale fractures act as channels for gas permeation, migration, and flow during CBM production. It not only determines the permeability of the CBM reservoir but also controls the productivity of the CBM (Connell et al., 2016; Laubach et al., 1998; Tan et al., 2018). Currently, limited fundamental knowledge exists on the permeability of cleats and connected fractures for fracture-size heterogeneities in CBM reservoirs. Therefore, this study aimed to provide the steps required for a better understanding of the phenomena involved in CBM production. It investigates the permeability of CBM reservoirs using two typical sister samples of coal with cleat and connected fracture development, implemented from the Permian coal measures, Southern Qinshui Basin, China, along with discussions regarding its implications for CBM exploration and exploitation.

**Materials and methods**

**Sample collection and preparation**

The Qinshui Basin of China is presently a fast-growing target block for CBM exploration and exploitation of high-rank coal in the world (Du et al., 2019; Ye et al., 2007; Zhou et al., 2016). After experiencing four-stage tectonic movements, the Qinshui Basin deformed into a synclinorium structure (Figure 1). For this coal-bearing basin, in the Permain and Pennsylvania coal-bearing measures, the No. 3 coal in the Shanxi Formation and No. 15 coal in the Taiyuan Formation are the primary minable beds. The coal samples for the experiment were collected from the Shanxi Formation of the Permian strata near the edge of the Qinshui Basin. The sampling method was utilized, as in previous studies (Cai et al., 2014). Coal blocks with a volume of $30 \times 30 \times 30 \text{ cm}^3$ were collected from the mining faces of underground coal mines and were transported to the laboratory for further investigation.

Figure 2 displays an illustration of the coal samples collected. This exhibits that cleats in the coal occur in two sets: face cleats and butt cleats, which are mutually perpendicular and perpendicular to the bedding (Figure 2(a)). For this high-rank coal, cleats are primarily confined to particular coal types, such as vitrain and clarain. An investigation from the field displays that the cleat network among the coal types can be connected by the fracture of a larger size. This type of fracture crosses through the interbedded coal types, and even the coal bed, which is important for enhancing the permeability of the CBM reservoir. To distinguish with the cleat, this type of fracture is termed as a connected fracture herein (Figure 2(b)).

Knowledge regarding the permeability of cleats and connected fractures is essential for permeability estimation of CBM reservoirs and production forecasting of CBM, as they influence the control of gas migration. To prepare these sister samples with cleat and connected fractures, the coals were cored vertical to the bedding from the block samples, following standards of the International Society for Rock Mechanics (ISRM) (Figure 3).
Figure 4 displays the sister coals with cleat and connected fractures, which are numbered C-1 and C-2, respectively. Their dimensions are 10 cm in length and 5 cm in diameter.

Device for experimentation

Permeability measurements were performed using the following device (Figure 5). This device consists of six subsystems, as shown in the illustration. Part 1 provides gases including $\text{N}_2$, $\text{CO}_2$, and $\text{He}$; Part 2 is equipped with a temperature control apparatus to achieve a given temperature,
Part 3 is the holder for placing the coal core, Part 4 is the hydraulic pump to provide confining stress, Part 5 is utilized to measure the gas flow through the core, and Part 6 contributes towards vacuuming the device.

**Method of experimentation**

For the sister coals, the permeability experiment was conducted at a constant temperature (30 °C) with controlled confining pressures and gas pressures. For the permeability measurement experiment, two schemes were performed (Table 1): (a) permeability measurement under low gas pressure (< 1 MPa); (b) permeability measurement under high gas pressure (> 1 MPa). Steady-state flow experiments were conducted during each operation.

Notably, for the C-1 coal, because of its poor permeability, the gas cannot penetrate the coal core as the gas pressure is less than 1 MPa. Therefore, the C-1 sample was used for permeability measurement under high gas pressure (> 1 MPa). For the C-2 coal, owing to its higher permeability, the gas penetrates the coal core effortlessly, and the gas flow exceeds the maximum measurement range of the flowmeter as the gas pressure exceeds 1 MPa. Therefore, the C-2 sample was utilized for permeability measurement under low gas pressure (< 1 MPa).

For the C-1 sample, inert gas (He) was utilized for permeability measurements. For the C-2 sample, in addition to the inert gas (He), the sorbing gases (N2 and CO2) were also utilized for permeability measurements. For each given confining pressure, the gas pressure increased...
step-by-step. As all the gas pressure steps were completed, the confining pressure was increased to the following step. The measured gas permeability of the coal was acquired implementing the modified Darcy’s law as follows:

\[ k = \frac{2p_0 q g \mu L}{A(p_1^2 - p_0^2)} \]  

(1)

**Figure 5.** Illustration of the device for permeability measurement.

Note: 1, manual valve; 2, gas booster pump; 3, gas pressure sensor; 4, pneumatic valve; 5, N₂ reference cylinder; 6, CO₂ reference cylinder; 7, He reference cylinder; 8, electric heater; 9, gas pressure regulator; 10, upstream gas flowmeter; 11, coal core; 12, hydraulic pump; 13, downstream gas flowmeter; 14, gas chromatography; 15, vacuum pump. Among them, the gas pressure regulator is made by TESCOM in the United States, which adopts rubber O-ring sealing with a pressure resistance intensity of up to 50 MPa to ensure the sealing effect and pressure accuracy; the gas pressure sensor is made by Guangzhou Sennas Company of China, which has a measurement range from 0 to 250 MPa, with an accuracy of 0.01 MPa; the reference cylinder provides a maximum gas pressure of 40 MPa; the hydraulic pump applies a maximum confining stress of 25 MPa. The gas flowmeter has a measurement range from 0 to 150 mL/min.

| Coal rank | Coal sample | Tem. (°C) | Confining pressure (MPa) | Gas type | Gas pressure (MPa) |
|-----------|-------------|-----------|--------------------------|----------|-------------------|
| High-rank coal (R₀ = 2.75%) | C-1 | 30 | 6 | He | 1, 1.5, 2, 2.5, 3, 3.5, 4, 4.5 |
| | | 30 | 8 | He | 1, 1.5, 2, 2.5, 3, 3.5, 4, 4.5 |
| | | 30 | 10 | He | 1, 1.5, 2, 2.5, 3, 3.5, 4, 4.5, 5, 5.5, 6 |
| | | 30 | 12 | He | 1, 1.5, 2, 2.5, 3, 3.5, 4, 4.5, 5, 5.5, 6, 6.5, 7, 7.5 |
| | C-2 | 30 | 4→6→8→10→12→14 | He | 0.2, 0.3, 0.4, 0.5, 0.6, 0.7 |
| | | 30 | 4→6→8 | N₂ | 0.1, 0.2, 0.3, 0.4 |
| | | 30 | 4→6→8→10→12→14 | CO₂ | 0.1, 0.2, 0.3, 0.4, 0.5, 0.6, 0.7, 0.8, 0.9 |

Permeability measurement of coal with connected fracture under low gas pressure (<1 MPa) MPa)

Table 1. The experiment scheme for the permeability measurement.
where, $p_0$ is the gas pressure at the downstream of the coal core, i.e., atmospheric pressure 0.1 MPa; $p_1$ is the gas pressure at the upstream of the coal core (MPa); $q_g$ is the gas flow at the downstream of the coal core ($\text{cm}^3\cdot\text{s}^{-1}$); $\mu$ is the dynamic viscosity coefficient of the gas (mPa·s); $A$ is the cross-sectional area of the coal core ($\text{cm}^2$); $L$ is the length of the coal core (cm); $k$ is the measured permeability ($10^{-8} \text{ cm}^2$ or D), where $1 \text{ D} \approx 10^{-8} \text{ cm}^2 = 1 \mu\text{m}^2$.

**Results and analysis**

**Method of analysis**

In previous studies, several methods have been proposed and adopted to evaluate the permeability of coal reservoirs (Cui and Bustin, 2005; Levine, 1996; Seidle and Huitt, 1995; Shi et al., 2014; Wu et al., 2010). Generally, these methods can be divided into two types: (1) porosity-permeability models, and (2) stress-permeability models. Herein, the following simplified stress-permeability model was utilized to analyze the permeability characteristics of the sister coals (Seidle and Huitt, 1995):

$$k = k_0 \exp\{-3C_f[(\sigma - \sigma_0) - (p - p_0)]\} \quad (2)$$

where, $k_0$ is the initial permeability of the coal under the condition of $\sigma = \sigma_0, p = p_0$ (mD), $C_f$ is the fracture compression coefficient of the coal (MPa$^{-1}$); $\sigma$ is the applied confining pressure to the coal (MPa), and $p$ is the gas pressure used in the experiment (MPa).

According to Eq. 2, under the condition of constant gas pressure with variable confining pressure, the relationship between the permeability and confining pressure is as follows:

$$k = k_{0-p} \exp\{-3C_f(\sigma - \sigma_0)\} \quad (3)$$

where $k_{0-p}$ is the initial permeability of the coal for each constant gas pressure (mD), $C_f$ is the fracture compression coefficient to the variable confining pressure, expressed by $C_{fp-\sigma}$; and $3C_f$ represents the sensitivity of permeability to the variable confining pressure, expressed by $C_{fa}$.

Similarly, under the condition of constant confining pressure with variable gas pressure, the relationship between the permeability and gas pressure is as follows:

$$k = k_{0-\sigma} \exp\{-3C_f(p - p_0)\} \quad (4)$$

where, $k_{0-\sigma}$ is the initial permeability for each constant confining pressure, $C_f$ is the fracture compression coefficient to the variable gas pressure, expressed by $C_{f\sigma-p}$; and $3C_f$ represents the sensitivity of permeability to the variable gas pressure, expressed by $C_{fp}$.

**Permeability of coal with cleat**

(1) **The Relationship between the permeability and gas pressure of coal with cleat.** Figure 6 displays the measured permeability results for the C-1 sample. For the high-rank coal, the permeability of the coal with cleat ranges is observed to be in the order of 0.001–0.01 mD, which is an ultra-low permeability but agrees with the field result from the Qinshui Basin (Li et al., 2014). This indicates that, for the CBM reservoir of high-rank coal, if the reservoir consists of coal with only cleat development, the reservoir will be nearly impermeable. With the increase in gas pressure, the permeability of the coal exhibits a trend of initial increase and later decrease, under each of the applied confining pressures (Figure 6(a)). Incorporating the gas pressure corresponding to the peak permeability as the critical pressure, the permeability of the coal exhibits an opposite evolutionary trend.
before and after the gas pressure. Figure 6(b) demonstrates the relationship of the gas flow to the gas pressure for the C-1 sample, where the gas flow is measured by the high-precision gas flowmeter (0.01mL·min$^{-1}$). Similar to the permeability, the gas flow also displayed an opposite evolutionary trend before and after the peak flow at a given gas pressure. Before the peak flowed through the coal core, the gas flow exhibited a nearly linear increase in the gas pressure. The larger the applied confining pressure on the coal, the larger the peak flow and the critical pressure. However, after the peak flow, the gas flow through the coal decayed significantly with an increase in gas pressure.

In Eq. 1, parameters such as the dynamic viscosity coefficient of the gas, coal core cross-sectional area, and length are constant in terms of permeability. Compared to gas flow, permeability is only an indirect indicator that reflects the ability of gas to penetrate through the coal under a certain confining pressure and gas pressure. Previous studies have revealed the relationship between the fluid flow and fluid pressure gradient (Zhou and Wang, 2004):

$$v = AJ^a$$

where, $0.5 \leq a \leq 1$, $A$ is the cross-sectional area of the coal core, $J$ is the gas pressure gradient, $v$ is the gas fluid flow. Thus, as the gas migrates in the coal by a laminar flow, the parameter $a = 1$, that is, the gas migrates in the coal by linear Darcy’s flow. Under these conditions, the viscosity force plays a dominant role in controlling the gas flow. With an increase in gas pressure, the gas flow increases linearly. However, as the gas migrates in the coal, and deviates from the linear flow, the parameter $0.5 \leq a < 1$. For a completely turbulent flow, the parameter $a = 0.5$. In this condition, the gas migration in the coal is a non-linear flow and the inertial force plays a dominant role in controlling the gas flow. Furthermore, with the increase in gas pressure, the gas flow will decrease. Compared to the linear Darcy flow region, the gas flow in the nonlinear flow region will be lower. This further suggests that the gas flow in an ultra-low-permeability coal reservoir is complicated. With the increase in gas pressure, the gas in this coal reservoir will translate from a linear flow to a nonlinear flow. Thus, the permeability of the coal will first increase and then decrease at the initial and later stages, respectively.

(2) The Relationship between the permeability and confining pressure of coal with cleat. Figure 7 exhibits the relationship between the permeability and the confining pressure for the coal with
cleat. Generally, the permeability of coal displays a decreasing trend with an increase in the applied confining pressure. Table 2 displays the fitting relationship between the permeability and confining pressure for the coal with cleat using Eq. 3. In Eq. 3, the parameter $C_{fp-\sigma}$ represents the fracture compression coefficient of the coal to the applied confining pressure. The results exhibit that under the condition of given gas pressure, the fracture compression coefficient of the coal under the applied confining stress is in the range 0.0511–0.2742 MPa$^{-1}$. With the increase in gas pressure, the fracture compression coefficient of the coal exhibits a decreasing trend with the applied confining pressure. This suggests that with the increase in gas pressure, the effective stress acting on the coal decreases, which further causes the stress sensitivity of the coal permeability to drop from 0.82227 MPa$^{-1}$ to 0.1534 MPa$^{-1}$. The larger the gas pressure, the smaller the stress sensitivity of the coal permeability.

Permeability of coal with connected fracture

(1) **Relationship Between permeability and confining pressure of coal with connected fracture.** Figure 8 displays the relationship between the permeability and confining pressure for C-2 coal. It can be observed that, for the high-rank coal, the permeability of the coal with connected fracture is in the order of 0.1–10 mD. Compared to coal with cleats, coal with connected fractures has an ultrahigh permeability. Generally, with an increase in the applied confining pressure on the coal, the permeability of the coal exhibits a downward trend. In particular, compared to the initial confining pressure, the permeability of the coal decreased sharply with an increase in the applied confining pressure.

Interestingly, in terms of sorbing gas $N_2$, as the gas pressure is 0.1, 0.2, and 0.3 MPa, the relationship between the permeability of the coal and the confining pressure presents a convex curve trend (Figure 8(b)). As the gas pressure is 0.1 MPa, the coal exhibits a maximum permeability of 1.95 mD for an applied confining pressure of 6 MPa. This is higher than the neighboring permeability of 0.56 mD for an applied confining pressure of 4 MPa. Subsequently, the permeability of
the coal exhibited a decreasing trend with an increase in the applied confining pressure. This may be due to: (1) the experimental error during the operation; (2) less data (three data points) which do not reflect the true regularity; (3) absorption effect; and (4) the gas molecular slippage effect. In practice, during the process of permeability measurement, regardless of the non-absorbing gas (He) or the sorbing gases (N2 and CO2), all the operations conform to the identical procedure. Thus, the first three reasons were excluded. However, it can be observed that, at a given confining pressure of 6 MPa, with the increase of gas pressure from 0.1 MPa to 0.4 MPa, the permeability of the coal

Table 2. Fitting relationship between the permeability and the confining pressure for the coal with cleat.

| Gas pressure (MPa) | Fitting relationship | $R^2$ | RMSE | $C_{fp-\sigma}$ (MPa$^{-1}$) | $C_{fa}$ (MPa$^{-1}$) | $k_{0-p}$ |
|------------------|---------------------|-------|------|-----------------------------|----------------------|----------|
| 1.5              | $k = 0.6079 \times \exp (-0.8227 \times \sigma)$ | 0.99  | 0.0009 | 0.2742 | 0.8227 | 0.6079 |
| 2.0              | $k = 0.0963 \times \exp (-0.3455 \times \sigma)$ | 0.95  | 0.0466 | 0.1152 | 0.3455 | 0.0963 |
| 2.5              | $k = 0.0568 \times \exp (-0.2324 \times \sigma)$ | 0.99  | 0.0006 | 0.0775 | 0.2324 | 0.0568 |
| 3.0              | $k = 0.0309 \times \exp (-0.1556 \times \sigma)$ | 0.98  | 0.9747 | 0.0519 | 0.1556 | 0.0309 |
| 3.5              | $k = 0.0300 \times \exp (-0.1534 \times \sigma)$ | 0.97  | 0.0104 | 0.0511 | 0.1534 | 0.0300 |

Figure 8. Relationship between permeability and confining pressure for the coal with connected fracture: He(a), N2(b), CO2(c).
decreases. In this situation, although the effective stress acting on the coal decreases, owing to the gas molecular slippage effect the permeability of the coal is higher at lower gas pressures. Besides, with the increase of gas pressure from 0.1 MPa to 0.4 MPa, the permeability convex curve for N$_2$ gradually converts to the concave curve, consistent with that of He and CO$_2$. Therefore, it is concluded that the gas molecular slippage effect results in a complicated permeability relationship for ultra-high permeability coal with connected fractures under low gas pressure. According to Klinkenberg, the gas molecular slippage effect is closely related to the gas molecular mean free path and fracture aperture (Klinkenberg, 1941). For confined coal, the fracture aperture of the coal is closely related to the applied confining pressure. Thus, the gas molecular slippage effect was determined by the gas pressure and confining pressure. At lower pressure conditions, the gas molecular mean free path increases, and the slippage effect and permeability of the coal are enhanced.

For the C-2 coal, the relationship between the permeability and confining pressure under each gas pressure was fitted by Eq. 3 (Table 3). It can be observed that under different gas pressures, the relationship between the permeability of the coal and the applied confining pressure satisfies an exponential law. The measured permeability by the non-absorbing gas (He) is between 1.7 to 10.8 mD, the measured permeability by the sorbing gas (N$_2$) is 5.1 mD, and by the sorbing gas (CO$_2$) is between 2.1 to 48.6 mD. Among these, the CO$_2$ measured permeability was the largest. Several studies have demonstrated that there are obvious absorption-induced swelling effects for CO$_2$ by coal, which will narrow the fracture aperture and decrease the permeability. However, this further implies that, for coal with connected fractures or ultra-high permeability, under low gas pressures

| Gas type | Gas pressure (MPa) | Fitting relationship | $R^2$ | RMSE | $C_{fp-\sigma}$ (MPa$^{-1}$) | $C_{f\sigma}$ (MPa$^{-1}$) | $k_{0-p}$ |
|----------|-------------------|----------------------|------|------|--------------------------|--------------------------|----------|
| He       | 0.2               | $k = 10.1 \times \exp (-0.3799 \times \sigma)$ | 0.96 | 0.1949 | 0.1266 | 0.3799 | 10.1 |
|          | 0.3               | $k = 10.8 \times \exp (-0.4287 \times \sigma)$ | 0.97 | 0.1450 | 0.1429 | 0.4287 | 10.8 |
|          | 0.4               | $k = 8.4 \times \exp (-0.4084 \times \sigma)$ | 0.96 | 0.1479 | 0.1361 | 0.4084 | 8.4 |
|          | 0.5               | $k = 1.8 \times \exp (-0.2072 \times \sigma)$ | 0.98 | 0.0220 | 0.0690 | 0.2072 | 1.8 |
|          | 0.6               | $k = 1.7 \times \exp (-0.2127 \times \sigma)$ | 0.99 | 0.0014 | 0.0709 | 0.2127 | 1.7 |
|          | 0.7               | $k = 1.7 \times \exp (-0.2162 \times \sigma)$ | 0.99 | 0.0128 | 0.0721 | 0.2162 | 1.7 |
| N$_2$    | 0.1               | Under the condition of these three gas pressure, the convex curve does not meet the relationship by Eq.3 | | | | | |
|          | 0.2               | | | | | | |
|          | 0.3               | | | | | | |
| CO$_2$   | 0.4               | $k = 5.1 \times \exp (-0.3380 \times \sigma)$ | 0.98 | 0.0813 | 0.1127 | 0.3380 | 5.1 |
|          | 0.1               | $k = 48.6 \times \exp (-0.6145 \times \sigma)$ | 0.99 | 0.1594 | 0.2048 | 0.6145 | 48.6 |
|          | 0.2               | $k = 22.6 \times \exp (-0.5303 \times \sigma)$ | 0.99 | 0.0899 | 0.1768 | 0.5303 | 22.6 |
|          | 0.3               | $k = 45.1 \times \exp (-0.5115 \times \sigma)$ | 0.99 | 0.0764 | 0.1705 | 0.5115 | 45.1 |
|          | 0.4               | $k = 13.5 \times \exp (-0.4658 \times \sigma)$ | 0.99 | 0.0261 | 0.1533 | 0.4658 | 13.5 |
|          | 0.5               | $k = 5.9 \times \exp (-0.4379 \times \sigma)$ | 0.98 | 0.0437 | 0.1460 | 0.4379 | 5.9 |
|          | 0.6               | $k = 5.0 \times \exp (-0.3377 \times \sigma)$ | 0.99 | 0.0388 | 0.1126 | 0.3377 | 5.0 |
|          | 0.7               | $k = 2.3 \times \exp (-0.2546 \times \sigma)$ | 0.94 | 0.0313 | 0.0849 | 0.2546 | 2.3 |
|          | 0.8               | $k = 4.6 \times \exp (-0.3297 \times \sigma)$ | 0.99 | 0.0110 | 0.1099 | 0.3297 | 4.6 |
|          | 0.9               | $k = 2.1 \times \exp (-0.2521 \times \sigma)$ | 0.93 | 0.0195 | 0.0840 | 0.2521 | 2.1 |

Note: There is no fitting relationship for N$_2$ at gas pressures of 0.1, 0.2, and 0.3 MPa.
(<1 MPa), the negative effect of the absorption-induced swelling on the permeability of the coal is no longer remarkable when compared to the positive effect of the gas molecular slippage on the permeability of the coal. This suggests that injecting CO₂ into the coal bed to displace the CBM may be more effective for coal with connected fractures, especially under low injection pressure conditions.

Figure 9 displays the permeability characteristic parameters of the C-2 coal. With the increase in gas pressure, the fracture compression coefficient of the coal exhibits a decreasing trend. Incorporating instance from the non-adsorbing gas (He), under each gas pressure, the fracture compression coefficient of the coal with connected fracture (0.0690–0.1429 MPa⁻¹) is larger than that of the coal with cleat (0.0511–0.2742 MPa⁻¹). This suggests that compared with the coal with cleat, fracture closure via applied confining pressure is more extensive for coal with connected fractures. For this reason, the permeability stress sensitivity of the coal with cleat is inapparent. Furthermore, with an increase in gas pressure, the permeability stress sensitivity coefficient of the coal decreases. Compared with non-absorbing gas (He) and sorbing gas (N₂), an approximately negative linear relationship exists between the gas pressure and the permeability stress sensitivity coefficient for the sorbing gas (CO₂). The permeability stress sensitivity coefficient of the sorbing gas (CO₂) is larger than that of the sorbing gas (N₂). This can be attributed to the more significant sorption-induced fracture closure effect for the sorbing gas (CO₂).

(2) Relationship Between permeability and gas pressure of coal with connected fracture. Figure 10 displays the relationship between permeability and gas pressure for C-2 coal under each confining pressure. In addition to the condition of applied confining pressure at 4 MPa in Figures 10(a) and 10(b), the measured permeability of the coal by the non-absorbing gas (He) and the sorbing gases (N₂ and CO₂) presents a decreasing trend with increasing gas pressure.

**Figure 9.** The relationship of permeability characteristic parameters to the gas pressure for the C-2 sample under low gas pressures (< 1 MPa).
In fact, with the change in gas pressure and applied confining pressure, the gas flow in the fracture-size heterogeneities material can be variable. Under lower pressure conditions, the gas flow regime for the gas molecules can be characterized by studying the Knudsen number ($K_n$) as (Firouzi et al., 2014):

$$K_n = \frac{\lambda}{d}$$  \hspace{1cm} (6)

where, $\lambda$ is the mean free path of the gas, $d$ is the fracture aperture. The mean free path of the gas is defined as:

$$\lambda = \frac{k_B T}{\pi d^2 p \sqrt{2}}$$  \hspace{1cm} (7)

where, $k_B$ is Boltzmann constant; $T$ is the temperature and $p$ is the pressure. Table 4 shows the Knudsen numbers and the corresponding flow types (Hadjiconstantinou, 2006).

For example, as the mean free path at a given gas pressure is 10 nm and the average fracture aperture is 50 nm, the Knudsen number is 0.2, thereby implying a transition flow regime. Clearly, a variety of flow types can occur in the fracture-size heterogeneities of coal with variable confining pressures and gas pressures. With the decrease in gas pressure, as the mean free path is far more than the fracture aperture, the gas will exhibit a free-molecular flow during the flow regimes. When the gas velocity at

Figure 10. The relationship of the permeability to the gas pressure for the coal with connected fracture: He(a), N$_2$(b), CO$_2$(c).
the walls is non-zero, the gas transport is enhanced as the “gas slippage” reduces the viscous drag and increases the apparent permeability. For this situation, the gas flow exhibits the Klinkenberg effect, and the permeability of the coal can be given by (Klinkenberg, 1941):

\[ k = k'_0 \times 1 + \frac{4c\lambda}{r} = k'_0 \times 1 + \frac{b}{p} \]  

(8)

where, \( k \) is the measured permeability, \( k'_0 \) is the permeability at the gas pressure near the liquid density or the Klinkenberg permeability; \( b \) refers to the gas slippage factor or the Klinkenberg coefficient, which is determined by the gas type, gas pressure, and fracture aperture.

From Table 5, it can be observed that, for the non-absorbing gas (He) or the sorbing gases (N\(_2\) and CO\(_2\)), the relationship of the measured permeability by the gas to the gas pressure conforms to the expression of Eq. 8. Compared to the adsorbing gases (N\(_2\) and CO\(_2\)), the non-adsorbing gas (He) has a larger Klinkenberg coefficient in general (Figure 11). For a given confining pressure, the value of the Klinkenberg coefficient is determined by the combined effect of the stress–strain and

| Knudsen numbers | Flow types |
|-----------------|------------|
| \( K_n < 10^{-3} \) | Continuous flow |
| \( 10^{-3} < K_n < 10^{-1} \) | Slip flow |
| \( 10^{-1} < K_n < 10^{1} \) | Transition flow |
| \( 10^{1} < K_n \) | Free-molecular flow |

**Table 4.** Knudsen numbers and flow types.

| Gas type | Gas molecular diameter | confining pressure (MPa) | Fitting relationship | \( R^2 \) | RMSE | \( b \) (MPa\(^{-1}\)) | \( k'_0 \) (mD) |
|----------|------------------------|--------------------------|---------------------|--------|------|----------------|-------------|
| He 0.26  | 4                      | \( k = 1.0820 \times (1 + 0.2267 / p) \) | 0.98                | 0.052  | 0.227| 1.082         |
|          | 6                      | \( k = 0.3922 \times (1 + 0.1687 / p) \) | 0.95                | 0.047  | 0.169| 0.392         |
|          | 8                      | \( k = 0.2007 \times (1 + 0.4124 / p) \) | 0.84                | 0.114  | 0.412| 0.201         |
|          | 10                     | \( k = 0.0861 \times (1 + 0.6549 / p) \) | 0.98                | 0.975  | 0.655| 0.086         |
|          | 12                     | \( k = 0.0876 \times (1 + 0.2143 / p) \) | 0.97                | 0.010  | 0.214| 0.088         |
|          | 14                     | \( k = 0.0536 \times (1 + 0.4979 / p) \) | 0.97                | 0.008  | 0.498| 0.054         |
| N\(_2\) 0.36 | 4                      | \( k = 1.0040 \times (1 + 0.0918 / p) \) | 0.99                | 0.056  | 0.0918| 1.004 |
|          | (under 4 MPa confining pressure, the permeability data point under 0.1 MPa is removed for fitting) |  |  |  |  |  |
|          | 6                      | \( k = 0.2845 \times (1 + 0.5986 / p) \) | 0.99                | 0.056  | 0.5986| 0.285 |
|          | 8                      | \( k = 0.1889 \times (1 + 0.1871 / p) \) | 0.96                | 0.019  | 0.1871| 0.189 |
| CO\(_2\) 0.33 | 4                      | \( k = 1.0940 \times (1 + 0.2857 / p) \) | 0.99                | 0.094  | 0.2857| 1.094 |
|          | 6                      | \( k = 0.6463 \times (1 + 0.0731 / p) \) | 0.94                | 0.043  | 0.0731| 0.646 |
|          | 8                      | \( k = 0.2588 \times (1 + 0.0921 / p) \) | 0.98                | 0.011  | 0.0921| 0.259 |
|          | 10                     | \( k = 0.1256 \times (1 + 0.0859 / p) \) | 0.93                | 0.012  | 0.0859| 0.126 |
|          | 12                     | \( k = 0.0652 \times (1 + 0.1613 / p) \) | 0.95                | 0.010  | 0.1613| 0.065 |
|          | 14                     | \( k = 0.0612 \times (1 + 0.1601 / p) \) | 0.97                | 0.004  | 0.1601| 0.061 |

**Table 5.** The fitting relationship of the permeability and the gas pressure for the coal with connected fracture by Eq. 8.
sorption-induced strain (Zhang et al., 2018). This indicates that the gas slippage phenomenon for the non-absorbing gas is more prominent than that for the adsorbing gas. In addition, for all the gases, with an increase in the applied confining pressure, the Klinkenberg coefficient of the coal exhibits a decreasing trend. The increased confining pressure not only weakened the Klinkenberg effect but also decreased the Klinkenberg permeability of the coal.

For the C-2 coal, the fitting relationship of the fracture compression coefficient to the gas pressure ($C_f\sigma-p$) is listed in Table 6. The negative values of $C_f\sigma-p$ indicates that the fracture aperture of the coal displays an open trend under the action of variable gas pressure, in contrast to the applied confining pressure. The influence mechanisms of gas pressure and confining pressure on the permeability of coal are opposite. Usually, the confining pressure has a negative effect on the permeability, but the gas pressure has a positive effect on the permeability. With an increase in the applied confining pressure, the permeability parameter ($k_{0-\sigma}$) decreased for He, N2, and CO2. However, the absolute value of $C_f\sigma-p$ for the non-absorbing gas (He) is larger than that of the sorbing gases (N2 and CO2). This means that the open effect of the fracture aperture by the gas pressure is obvious for the non-absorbing gas. A possible reason is that under the action of N2 and CO2, the sorption-induced swelling strain causes the closure behavior of the fracture aperture, which, to some extent, offsets the open effect by the increased gas pressure.

**Implication for CBM exploration and exploitation**

Coal is a fracture-size heterogeneous material, which includes macro-, meso-, and micro-fractures. Cleats act as meso-fractures, usually referred to as natural fractures, which are formed and

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**Figure 11.** Permeability characteristic parameter for the coal with connected fracture under the variable confining pressure.
Table 6. The fitting relationship of permeability and the gas pressure for the coal with connected fracture.

| Gas type | Confining pressure (MPa) | Fitting relationship | $R^2$ | RMSE | $C_{fr-p}$ (MPa$^{-1}$) | $C_{fp}$ (MPa$^{-1}$) | $k_{o-\sigma}$ |
|----------|--------------------------|----------------------|-------|------|------------------------|------------------------|-------------|
| He       | 4                        | $k = 3.219*(1.682*p)$ | 0.993 | 0.0282 | -0.561                 | -1.682                 | 3.219       |
|          | 6                        | $k = 1.081*(1.354*p)$ | 0.932 | 0.0558 | -0.451                 | -1.354                 | 1.081       |
|          | 8                        | $k = 1.031*(1.849*p)$ | 0.881 | 0.0789 | -0.616                 | -1.849                 | 1.031       |
|          | 10                       | $k = 0.658*(1.997*p)$ | 0.752 | 0.0827 | -0.666                 | -1.997                 | 0.658       |
|          | 12                       | $k = 0.251*(0.887*p)$ | 0.827 | 0.0265 | -0.296                 | -0.887                 | 0.251       |
|          | 14                       | $k = 0.194*(0.849*p)$ | 0.875 | 0.0157 | -0.283                 | -0.8493                | 0.194       |
| N$_2$    | 4                        | $k = 1.715*(0.820*p)$ | 0.831 | 0.0664 | -0.273                 | -0.820                 | 1.715       |
|          | (under 4 MPa confining pressure, the permeability data point under 0.1 MPa is removed for fitting) | | | | | | |
|          | 6                        | $k = 2.376*(2.799*p)$ | 0.935 | 0.1455 | -0.936                 | -2.799                 | 2.376       |
|          | 8                        | $k = 0.470*(0.948*p)$ | 0.765 | 0.0467 | -0.316                 | -0.948                 | 0.470       |
| CO$_2$   | 4                        | $k = 6.013*(3.702*p)$ | 0.987 | 0.1764 | -1.234                 | -3.702                 | 6.013       |
|          | 6                        | $k = 1.138*(0.906*p)$ | 0.832 | 0.0700 | -0.302                 | -0.906                 | 1.138       |
|          | 8                        | $k = 0.482*(0.859*p)$ | 0.708 | 0.0432 | -0.286                 | -0.859                 | 0.482       |
|          | 10                       | $k = 0.304*(0.637*p)$ | 0.917 | 0.0075 | -0.212                 | -0.637                 | 0.304       |
|          | 12                       | $k = 0.174*(1.175*p)$ | 0.772 | 0.0219 | -0.392                 | -1.175                 | 0.174       |
|          | 14                       | $k = 0.128*(0.687*p)$ | 0.890 | 0.0080 | -0.229                 | -0.687                 | 0.128       |

developed by the coupling mechanism of in-situ geo-stress, coal lithotype, and coal bed thickness during the process of coalification, and are closely related to the coal rank. However, the connected fracture can be of different sizes, including meso- and macro-fractures. This type of fracture usually forms and develops owing to geologic movements, especially in the coal basin suffering from the uplift movement or in the tectonic regions due to the brittle geologic deformation action.

As mentioned previously, in high-rank coal, the cleat (0.001–0.01 mD) is far less permeable than connected fracture (0.1–10 mD). In addition, field investigations exhibit that cleats are usually confined to particular lithotypes of coal, such as vitrain or clarian, whose connectivity is limited by its termination at the interfaces of coal types. Thus, to determine the target blocks for CBM exploration and exploitation, the locations where the cleat network of the coal bed is well connected to the connected fracture may be the best target. Thus, field fracture investigation is a prerequisite and indispensable step for successful CBM production.

In addition, during the process of CBM production, with the downdraw of reservoir pressure, owing to the gas pressure change in the CBM reservoir, a variety of flow regimes are present. In particular, under the conditions of lower reservoir pressure and lower in situ geo-stress, the gas migration in the CBM reservoir exhibits remarkable free-molecular flow. The reservoir permeability and predicted CBM production were enhanced.

**Conclusions**

The permeability of high-rank coal with only cleat development is 0.001–0.01 mD, which represents ultra-low permeability coal. No Klinkenberg effect was observed in this coal. With an increase in the gas pressure (> 1 MPa), the gas migration in the coal changes from linear flow to nonlinear flow. This caused the permeability of the coal to initially increase and then decrease with the increase in gas pressure.
For high-rank coal with connected fracture development, its permeability is in 0.1 of 10 mD, which is much larger than that of the coal with only cleat development. Under low gas pressure conditions (<1 MPa), with the decrease in gas pressure, the Klinkenberg effect significantly increased the permeability of the coal. The Klinkenberg effect for the non-absorbing gas was more prominent than the adsorbing gas. In addition, with an increase in the applied confining pressure, the Klinkenberg coefficient and permeability of the coal presented a decreasing trend.

The stress sensitivity of permeability for coal with cleats was weaker than that of coal with connected fractures. However, because of the sorption-induced fracture closure effect, the permeability stress sensitivity for the sorbing gas (CO₂) was larger than that of non-adsorbing (He) and sorbing gas (N₂). With the increase in gas pressure, the stress sensitivity of the permeability for both coal dropped significantly.

Field fracture investigation is a prerequisite for successful CBM production. It may be the best block for CBM production where the cleat network is well conductive to the connected fracture. During the CBM production process, with the downdraw of reservoir pressure, a variety of flow regimes are present. In particular, under the lower reservoir pressure and lower in situ geo-stress conditions, the gas migration in the CBM reservoir exhibits remarkable free-molecular flow, and the reservoir permeability and predicted CBM production were enhanced.

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**Author contributions**

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