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A permeability model for gas flow in coal considering the water content and slippage effect

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Abstract: Coal seams are usually in a state of gas-water coexistence and for coal-bed methane (CBM) reservoirs, coal permeability is essential to the extraction process of CBM. The purpose of this study is to experimentally analyse the coal permeability characteristics under different water content conditions and to propose a permeability model for gas flow in coal seams. Experiment results show that when the pore pressure is fixed, the gas adsorption decreases with the increase of water content. Similar behaviour is also found for the adsorption deformation which can discourage the coal permeability. In the process of increasing pore pressure, under the control of sorption-induced deformation and slippage effect, the permeability of coal shows a trend of decreasing first and then tending to be gentle. In addition, based on gas flow experiments, an improved permeability model considering water content and slippage effect is established based on the classic matchstick model. We also proposed a calculation model of slip factor considering the influence of water content. Wherein, the slippage factor showed an increasing trend under the combined effect of water content and pore pressure.

Keywords: pore pressure; adsorption; water content; slippage effect; permeability.

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1 Introduction

Coal-bed methane (CBM) is one of the main types of unconventional energy that have been widely commercialised (Tan et al., 2018). The extraction of CBM in practice relies largely on permeability enhancement of the reservoir, which gives the study of gas seepage in coal media with high potential profits to the industry (Clarkson, 2013). For coal media, natural cleats or fractures are often observed in coal seams and thus the coal media is often treated as a dual porosity porous media (Wu et al., 2011). In CBM reservoirs, coal seams commonly contain water and water molecules can easily form a thin film in pore and fracture surfaces, which affect the gas flow in coal. Therefore, a more comprehensive understanding on the effect of water content on the gas flow behaviour for coal can provide improved quantification of coal permeability in realistic conditions.

In CBM exploration, the rise and fall of pore pressure can effectively alter the process of gas adsorption/desorption (Zhou et al., 2020). Gas adsorption/desorption during the complex evolution process of coal deformation and permeability has attracted great research interests in this field (Niu et al., 2017; Li and Kang, 2016; Zeng et al., 2017). Numerous scholars have found that under the condition of constant confining pressure, the increase of gas pressure could cause coal swelling and coal permeability drop accordingly (Wang et al., 2011; Mazumder and Wolf, 2008; Robertson and Christiansen, 2005; Cui and Bustin, 2005; Harpalani and Chen, 1997; Weniger et al., 2012). The desorption of methane in coal can cause matrix shrinkage and leads to enhanced pore size and permeability (Weniger et al., 2012). With the increase of adsorption equilibrium pressure, the gas is constantly adsorbed by the coal matrix and the increase of gas adsorption amount induces gradually the swelling strain (Meng et al., 2018a). The relation between the coal deformation and gas adsorption amount is intricacy. When the relationship is linear, the coal is in the elastic phase in which the deformation is reversible. When it becomes nonlinear, the coal is in the elastoplastic stage and the deformation is irreversible. Chareonsuppanimit et al. (2014) improved the coal swelling deformation model by introducing a simplified local density (SLD) adsorption model. Others have constructed new sorption-induced deformation models to simulate the adsorption characteristics of the coal matrix when it shrinks or swells (Liu and Harpalani, 2013; Kumar et al., 2012; Liu et al., 2010). In these studies, mathematical models for coal matrix absorption-induced deformation are established based on the surface energy changes.

Slippage effect occurs commonly at low gas pressure for seepage process in low-permeability porous media (Li et al., 2018; Woignier et al., 2018). For coal media, the slippage phenomenon plays an important role in the CBM production process by changing the permeability characteristic of coal (Li et al., 2014a, 2014b; Zhao et al., 2015). The slippage phenomenon through low-permeability porous media gas has been widely studied. The slippage effect can lead to increased coal permeability from the CBM reservoir (Zou et al., 2016). However, coal matrix properties, e.g., matrix sorption-induced deformation can be changed with various pore pressure, even for fixed effective stress and confining pressure (Meng et al., 2018a). In reality, the coal matrix is under the coupling of ground pressure and gas adsorption/desorption which may not only cause coal swelling/shrinking, but also alter the joint aperture and the slip constant B (Zhou et al., 2016). In addition, coal seams usually contain unequal amounts of water, and water easily occupies or blocks gas seepage channels (Wang et al., 2019; Zhang et al., 2019; Li et al., 2016, 2017). Within a certain range of water content, the coal permeability increases with the increase of water content. When the water content of coal exceeds a critical value, the effect of water content on gas adsorption amount weakens gradually (Day et al., 2008). As the water content increases, coal porosity decreases, which further reduces the coal permeability (Wang et al., 2011). Meanwhile, swelling strain induced by water grows with the increase of moisture content while swelling strain caused by gas adsorption amount decreases with the increase of water content (Chen et al., 2012). However, the overall swelling strain mainly depends on the interaction among gas, water and coal matrix (Teng et al., 2016). When the water is non-existing, clay minerals could encourage methane adsorption (Ji et al., 2012; Jin and Firoozabadi, 2014). Otherwise, the methane adsorbed may mainly occur on the surface of organic material in geological conditions which are more hydrophobic than clay minerals (Chalmers and Bustin, 2007, 2008). Therefore, the evaporation of water film can enhance methane migration and adsorption characteristics by improving coal permeability (Teng et al., 2016). Water content has a non-negligible effect on the adsorption of coal and rock, and the deformation caused by adsorption has a certain hindrance to gas seepage. For permeability, some models have related the permeability with porosity based on cubic law (Palmer, 2009; Wang et al., 2018). Other studies have associated the permeability evolution with effective stress changes through the exponential function (Wei et al., 2015; Pan et al., 2012; Shi and Durucan, 2004). To explore the effect of water content on permeability, Yin et al. (2012) constructed the gas effective permeability equation under the combined effect of water content and effective stress. Their result showed that different water contents have dissimilar effects on permeability of the coal seam in the ground stress field. Miao et al. (2018) verified the effect of relative humidity on the permeability of coal rock through experiments, and constructed a permeability model of coal considering the effect of water content. Thararoop et al. (2015) improved the permeability calculation method of coal rock under the conditions of solid-liquid-gas coexistence according to the mechanism of the influence of moisture on the expansion/contraction process of coal matrix adsorption gas. These studies indicate that water content is a critical factor that influence the process of gas seepage.

This paper aims to experimentally study the evolution mechanism of adsorption-permeability considering the influence of water content. Experiments of adsorption-permeability evolution of coal under the influence of different water content was carried out in previous study (Li et al., 2020a). Based on experimental results, a coal permeability model that incorporates the effects of water content and slippage effects is proposed. It is suggested that the proposed model provide results that are consistent with the test results. Meanwhile, we will further analyse the variation law of the slippage effect of water-bearing coal by constructing a slippage factor calculation model considering the influence of water content.

2 Coal permeability model considering the combined effect of water content and slippage effect

2.1 Sorption-induced deformation under different water-bearing conditions

It is assumed that: each adsorption site in coal can only contain one methane molecule, and its surface is uniform, and there is no interaction force between the molecules. Then, the amount of gas adsorption in coal can be estimated by Langmuir (1918) equation:

$$V = \frac{abp}{1+bp} \tag{1}$$

where V is the adsorption amount, a is Langmuir volume constant, b is the Langmuir pressure constant.

For CBM extraction, water often co-exists with gas in coal seams and when water enters the capillary pores, the seepage channel can be blocked due to the capillary condensation phenomenon (Romanov et al., 2013), resulting in changes in gas adsorption for different water contents. The gas absorption of coal, when considering the water content (Chen et al., 2012), can then be expressed as:

$$V = \frac{abp}{1+bp}\exp(-\lambda m) \tag{2}$$

where λ is the adsorption decay coefficient of the coal to water content (fitting parameter), p is the pore pressure and m is the water content.

In the gas-solid or gas-liquid adsorption interface, the surface free energy is defined as the energy generated by the work of the molecules on the coal surface (Liu and Harpalani, 2013), which can be expressed as:

$$\pi = RT\int_{p_0}^{p} \Gamma d(\ln p) \tag{3}$$

where π is the surface free energy, R is the ideal gas constant, Γ is the surface excess, T is the temperature and p_0 is the initial pressure . The surface excess Γ represents the amount of material adsorbed in the surface layer per surface area, which is given by:

$$\Gamma = \frac{V}{V_0 S} \tag{4}$$

where S is superficial area, V_0 is the gas molar volume.

The linear deformation in gas-solid or gas-liquid adsorption interface could be expressed as:

$$\frac{\Delta l}{l} = \gamma \cdot \pi \tag{5}$$

where $\Delta l/l$ is relative linear deformation and γ is deformation of the constant given by:

$$\gamma = \frac{S\rho_c}{E_A} \tag{6}$$

where ρ_c is the density of coal, E_A is the adsorption of modulus.

The sorption-induced linear deformation under different water content conditions could be expressed based on equations (2)–(6) as:

$$\varepsilon_{ls} = \frac{\Delta l}{l} = \frac{\rho_c RT}{V_0 E_A}\int_{p_0}^{p}\frac{V}{p}dp \tag{7}$$

where $\Delta\varepsilon_s$ is adsorption-induced deformation under water-containing conditions.

Assuming that coal is isotropic, the sorption-induced deformation under different water content conditions could be obtained as:

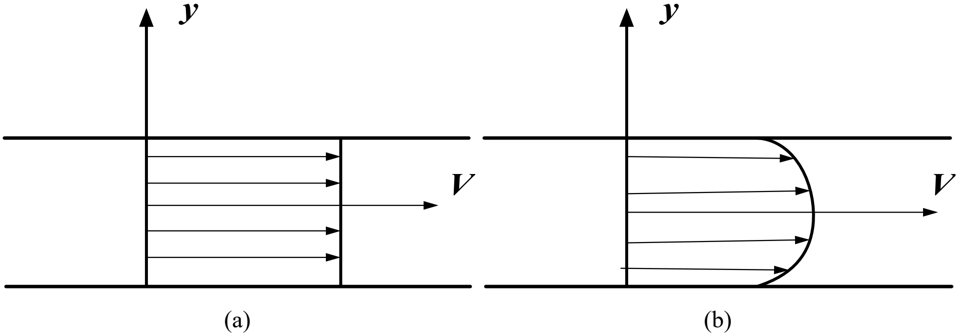
$$\Delta\varepsilon_s = 3\frac{\Delta l}{l} = \frac{3a\rho_c RT}{V_0 E_A}\exp(-\lambda m)\int_{p_0}^{p}\frac{b}{1+bp}dp \tag{8}$$

2.2 The calculated model of slip factor under different water contents

2.2.1 Slippage theory

When the pore pressure is low, the flow velocity between the gas molecules near the pore wall surface and the gas molecules in the centre of the pore fracture are basically the same, this phenomenon called as slippage effect (Zou et al., 2016). Related researches show that the gas slip factor in dense porous media is related to the fracture width (Zhou et al., 2016; Wang et al., 2014). The value of slip factor changes with the change of pore/fracture width. The flow diagram of liquid/gas molecules in the capillary is shown in of Figures 1(a) and 1(b).

Figure 1 Schematic diagram of the flow of liquid/gas in the capillary, (a) gas molecules flow in the capillaries (b) liquid molecules flow in the capillaries



(a) (b)

Source: Wang et al. (2016)

Wherein, the relationship between the linear relationship between apparent permeability and absolute permeability can be expressed as (Klinkenberg, 1941):

$$k = k_a\left(1+\frac{B}{p}\right) \tag{9}$$

where k_a is the absolute permeability, B is the slip factor.

2.2.2 The change in fracture width

The compressibility is one of the inherent properties of coal, which depends on the stress changes experienced by the coal (Meng et al., 2018a). Generally, the compressibility of a fracture is defined as the change in porosity:

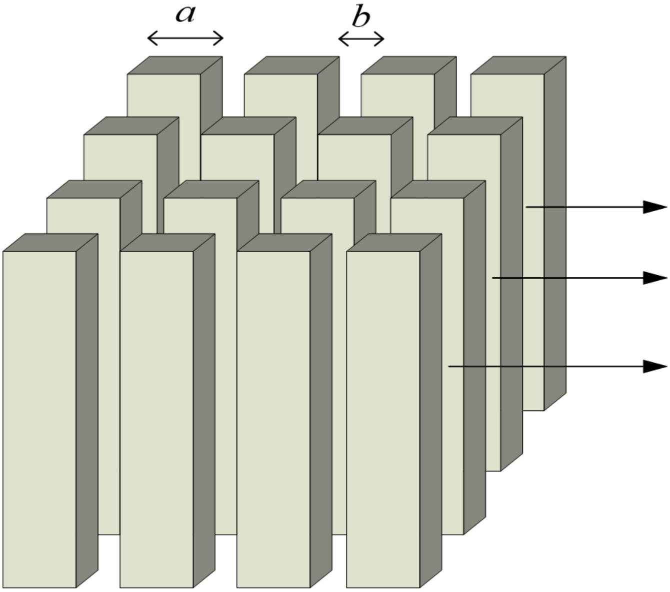
$$C_f = \frac{-\Delta\phi}{\phi_0 \Delta\sigma} \tag{10}$$

where C_f is the cleat compressibility, $\Delta\Phi$ is the change of porosity, Φ_0 is the initial porosity, $\Delta\sigma$ is the change of stress, b_0 is the initial fracture width.

The compressibility of coal will produce varying degrees of change. When external stress was constant, the change of fracture width can be only affected by pore pressure. The change in width due to the compressibility of the fracture is (Robertson and Christiansen, 2008):

$$\Delta b_f = b_0 C_f \left(p - p_0\right) \tag{11}$$

Figure 2 The matchstick model (see online version for colours)



Source: Seidle et al. (1992)

In order to simplify the calculation, the relevant scholars usually treat the coal body as a bundled match stick (i.e., the match stick model, as shown in Figure 2) (Wang et al., 2014). Wherein, the change in pore pressure has a certain effect on the elastic compressibility of the matrix. It is assumed that the change in fracture width caused by the elastic strain of the matrix due to the stress is only related to the change in pore pressure. When the pore pressure changes, the coal matrix will produce elastic deformation, and the volumetric strain generated in this process can be expressed as (Robertson and Christiansen, 2008):

$$-\varepsilon_V = -\frac{V_c}{V_c - V_i} = \frac{p - p_0}{K} \tag{12}$$

where ε_V is the volumetric strain; K is the bulk modulus $\left(K = \frac{E}{3(1-2v)}\right)$; E is the Young's modulus; v Poisson's ratio; V_c is the volume of coal matrix; V_i is the initial volume of coal matrix.

Coal is isotropic which had assumed, then the elastic strain generated by the coal matrix can be expressed as:

$$-\varepsilon_V = \frac{(1-2v)\left(p - p_0\right)}{E} \tag{13}$$

Due to the change in the width of the matrix, it will have a negative effect on the width of coal fractures ($\Delta a = -\Delta b$). At this time, the change of coal fracture width under the influence of elastic deformation (Δb_m) can be expressed as (Robertson and Christiansen, 2008):

$$\Delta b_m = \frac{a_0(1-2v)\left(p - p_0\right)}{E} \tag{14}$$

where a_0 is the initial size of coal matrix.

Similarly, the coal matrix swells due to adsorbed gas Δa_s, which also has a certain effect on the fracture width Δb_s:

$$\Delta b_s = -\Delta a_s = -a_0 \Delta \varepsilon_{ls} \tag{15}$$

Therefore, the change of fracture width of water-bearing coal is mainly controlled by sorption-induced deformation, the cleat compressibility and elastic deformation:

$$\Delta b_t = \Delta b_f + \Delta b_m + \Delta b_s = b_0 C_f \left(p - p_0\right) + \frac{a_0(1-2v)}{E}\left(p - p_0\right) - a_0 \varepsilon_{ls} \tag{16}$$

where Δb_t is the total fracture width.

2.2.3 Calculation of slippage factor

The fracture is the main path of gas seepage, and the width of the fracture is related to the size of the slip factor. Therefore, the slip factor of methane and helium in this paper can be solved by the following equations (Wang et al., 2014):

$$B_{\mathrm{CH4}} = \frac{16c\mu_{\mathrm{CH4}}}{b_{\mathrm{CH4}}}\sqrt{\frac{2RT}{\pi M_{\mathrm{CH4}}}} \tag{17}$$

$$B_{\mathrm{He}} = \frac{16c\mu_{\mathrm{He}}}{b_{\mathrm{He}}}\sqrt{\frac{2RT}{\pi M_{\mathrm{He}}}} \tag{18}$$

where B_{CH4} and B_{He} are the slip factor of the CH_4 and He, respectively, c is a constant, μ_{CH4} and μ_{He} are the kinetic viscosity of the CH_4 and He, respectively, M_{CH4} and M_{He} are the molecular weight of CH_4 and He, respectively, R is the universal gas constant, b_{CH4} and b_{He} are the fracture width of CH_4 and He, respectively.

Based on equations (19)–(20), the slip factor for methane can be further obtained as:

$$B_{\mathrm{CH4}}=\frac{b_{\mathrm{He}}}{b_{\mathrm{CH4}}}\frac{\mu_{\mathrm{CH4}}}{\mu_{\mathrm{He}}}\sqrt{\frac{M_{\mathrm{He}}}{M_{\mathrm{CH4}}}}B_{\mathrm{He}} \tag{19}$$

Wherein, helium is a non-adsorbed gas, so its change of fracture width is not controlled by sorption-induced deformation. At this time, the slip factor of methane can be solved by the following formula:

$$B_{\mathrm{CH4}}=\frac{\overbrace{b_0+b_0C_f\left(p-p_0\right)+\frac{a_0\left(1-2v\right)}{E}\left(p-p_0\right)}^{\text{Cleat wideth for He}}}{\underbrace{b_0+b_0C_f\left(p-p_0\right)+\frac{a_0\left(1-2v\right)}{E}\left(p-p_0\right)-a_0\varepsilon_{ls}}_{\text{Cleat wideth for CH}_4}}\frac{\mu_{\mathrm{CH4}}}{\mu_{\mathrm{He}}}\sqrt{\frac{M_{\mathrm{He}}}{M_{\mathrm{CH4}}}}B_{\mathrm{He}} \tag{20}$$

Based on solid geometry, the initial porosity could be expressed as (Wang et al., 2014):

$$\phi_0=\frac{3b_0}{a_0} \tag{21}$$

Therefore, the calculation equation of methane slip factor can be simplified as:

$$B_{\mathrm{CH4}}=\frac{\overbrace{1+C_f\left(p-p_0\right)+\frac{3(1-2v)}{\phi_0E}\left(p-p_0\right)}^{\text{Cleat wideth for He}}}{\underbrace{1+C_f\left(p-p_0\right)+\frac{3\left(1-2v\right)}{\phi_0E}\left(p-p_0\right)-\frac{3}{\phi_0}\varepsilon_{ls}}_{\text{Cleat wideth for CH}_4}}\frac{\mu_{\mathrm{CH4}}}{\mu_{\mathrm{He}}}\sqrt{\frac{M_{\mathrm{He}}}{M_{\mathrm{CH4}}}}B_{\mathrm{He}} \tag{21}$$

2.2.4 Influence of water content on slippage effect

Related researches show that in dense porous media, there is a linear relationship between the size of slip factor and water saturation (Wu et al., 2014; Gao and Yu, 2018; Li and Horne, 2004). The relationship between water content and slippage factor is:

$$B\infty\alpha_b s_w \tag{22}$$

where s_w is the water saturation, α_b is the related coefficient of slip factor, which can be determined from matching the experimental data.

Wherein, the relationship between water saturation and water content is (Ren et al., 2019):

$$m=\frac{s_w\phi\rho_w}{\rho_bM_w} \tag{23}$$

where ρ_b is the bulk density of rock, kg m^{-3}; Φ the porosity; s_w the water saturation; M_w the molar mass of water, kg mol^{-1}; and ρ_w the water density, kg m^{-3}.

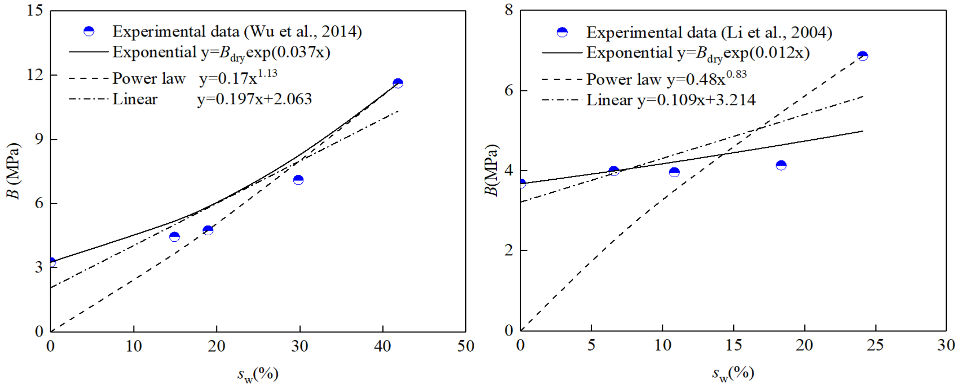
Therefore, in order to explore the effect of water content on slippage effect in coal, we propose an exponential equation to quantify the effect of content:

$$\frac{B_{CH_4}(wet)}{B_{CH_4}(dry)} = \exp(\alpha_b m) \quad (0 \le m \le m_c) \tag{24}$$

where $B_{CH4}(dry)$ and $B_{CH4}(wet)$ are the slip factor of CH_4 in dry/wet conditions, respectively, mc is the equilibrium water content of the coal in weight percentage.

In order to verify the applicability of the model, we used publicly published experimental data (Wu et al., 2014; Li and Horne, 2004) to describe this law of influence, as shown in Figure 3.

Figure 3 Data matching of slip factor considering the effect of water content (including exponential, linear and power-law models) (see online version for colours)



(a) (b)

The results show that the linear model is not suitable for quantifying the effect of water content on the slippage effect, and the power law model is less applicable at low water saturation. The proposed exponential equation can better describe the change rule of the slippage factor in the process of water content change. Therefore, the slippage factor of methane in water-bearing coal can be expressed as:

$$B_{CH4}(wet) = \frac{\overbrace{1+C_f(p-p_0)+\frac{3(1-2v)}{\phi_0 E}(p-p_0)}^{\text{Cleat wideth for He}}}{\underbrace{1+C_f(p-p_0)+\frac{3(1-2v)}{\phi_0 E}(p-p_0)-\frac{3}{\phi_0}\varepsilon_{ls}}_{\text{Cleat wideth for CH4}}}\frac{\mu_{CH4}}{\mu_{He}}\sqrt{\frac{M_{He}}{M_{CH4}}}B_{He}\exp(\alpha_b m) \tag{25}$$

2.3 Permeability model

According to matchstick model, the equation that considers the change in permeability due to pore pressure and other changes could be expressed as (Robertson and Christiansen, 2008):

$$\frac{\Delta k}{\Delta p}=\frac{3b_0{}^2}{12a_0}\frac{1}{\Delta p}\left[b_0C_f\Delta p+\frac{a_0(1-2v)}{E}\Delta p-a_0\varepsilon_{ls}\right] \tag{26}$$

where Δk is the variation of permeability, Δp is the variation of pore pressure.

Equation (26) could be simplified as:

$$\frac{\Delta k}{\Delta p}=\frac{3b^3}{12a}C_f+\frac{3b^2}{12a}\frac{a}{b}\left[\frac{1-2v}{E}-\varepsilon_{ls}\frac{1}{\Delta p}\right] \tag{27}$$

Relation between permeability, fracture width and matrix size of coal could be expressed as (Robertson and Christiansen, 2008):

$$k=\frac{b^3}{12a} \tag{28}$$

Through calculation and simplification, equation (27) can be expressed as:

$$\frac{\Delta k}{\Delta p}=3k\left[C_f+\frac{3}{\varphi_0}\left(\frac{1-2v}{E}-\varepsilon_{ls}\frac{1}{\Delta p}\right)\right] \tag{29}$$

where φ_0 is the initial porosity.

Rearranging equation (29) to fit a form capable of integration:

$$\frac{dk}{3k}=C_fdp+\frac{3}{\phi_0}\frac{1-2v}{E}dp-\frac{3}{\phi_0}\varepsilon_{ls}\frac{dp}{\Delta p} \tag{30}$$

The permeability equation can be integrated and then obtain as:

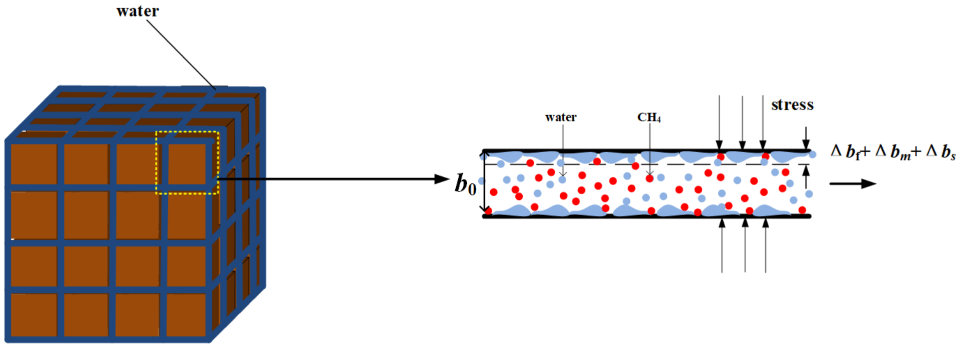
$$\frac{k}{k_0}=\exp 3\left\{C_f\left(p-p_0\right)+\frac{3}{\phi_0}\left[\frac{1-2v}{E}\left(p-p_0\right)-\varepsilon_{ls}\right]\right\} \tag{31}$$

In summary, the permeability of water-bearing coal is affected by the combined effects of stress, water content and slippage effect. Therefore, the permeability equation of water-bearing coal is:

$$k=k_a\exp 3\left\{C_f\left(p-p_0\right)+\frac{3}{\phi_0}\left[\frac{1-2v}{E}\left(p-p_0\right)-\varepsilon_{ls}\right]\right\}\left(1+\frac{B_{CH_4}(wet)}{p}\right) \tag{32}$$

Equation (32) is a coal permeability model under the influence of different water content and considering the slippage effect. The schematic diagram of coal methane seepage under the influence of moisture is shown in Figure 4. According to the experimental conditions, coal was in the elastic deformation phase, its permeability was affected by the water content and pore pressure. Adsorption swelling and water absorption will be jointly led to a change in pore and fracture. Therefore, the effects of water content, pore pressure, and slippage must be examined, when estimating the change of coal fractures.

Figure 4 Schematic diagram of gas seepage of water-bearing coal (see online version for colours)



3 Experiment

3.1 Sample preparation

Due to the extremely soft raw coal in the Songzao mining area, the processing of the test piece is difficult. Due to the soft coal quality of Songzao coal mine, it is relatively difficult to extract. According to previous studies, it can be seen that reshaped coal and the raw coal have a good consistency in the gas permeability change law (Jasinge et al., 2011; Su et al., 2019). Therefore, the reshaped coal was used for test. After the raw coal is collected and then crushed using a pulveriser. After that, 60–80 meshes pulverised coal particles were selected. The crushed coal were then mixed with purified water to be pressed into standard test pieces using the adopt rigidity machine. Among them, the industrial analysis results of coal samples are shown in Table 1 and the sample shown in Figure 5.

Table 1 Coal sample industry analysis results

Sampling location	*Mad/%*	*Aad/%*	*Vad/%*	*Fad/%*
Songzao mining area	1.60	22.82	10.90	64.68

Figure 5 Standard coal sample (see online version for colours)

To obtain coal samples with different water contents, the dried standard test pieces were wrapped with water-permeable cloth and soaked in water in a closed container for 3 h of vacuuming. The water content of the coal samples can be expressed as:

$$m = \frac{w_s - w_0}{w_0} \times 100\% \tag{33}$$

where m is the water content, w_0 is the weight of dried sample and w_s is the weight of the aqueous sample. Four coal samples were prepared with water content of 1.02%, 2.01%, 3.01%, 4.03%.

3.2 Experiment procedures

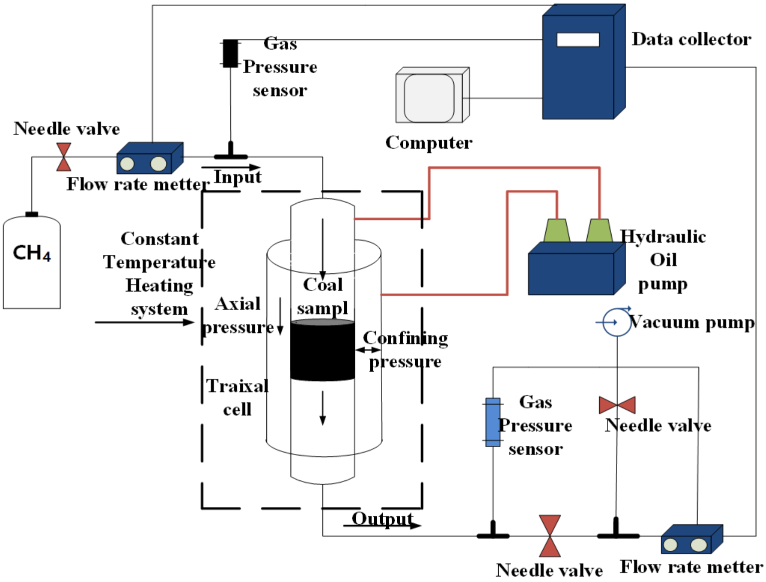
The coal adsorption experiment was carried out by the isothermal adsorption system (Pan and Connell, 2010). The seepage experiment was carried out by the heat-fluid-solid coupling device (Yin et al., 2013), as shown in Figure 6. CH_4 was selected as the for seepage experiments with different water contents. The axial pressure and confining pressure value was set at 6.00 MPa, and a constant temperature of 30°C is prescribed. The pore pressure is sequentially increased from 0.20 MPa to 1.80 MPa to analyse the coal permeability variation for different pore pressure. Multiple gas adsorptions were performed prior to the start of the seepage test. After coal sample reaches the first adsorption equilibrium, gas outlet is opened, the gas in the coal sample is discharged, and the methane volume fraction of the exhaust gas is measured; after the gas discharge is finished, gas outlet valve is closed, and coal sample is filled with methane. After the gas and the coal sample reach the adsorption equilibrium, the gas is discharged again, and the volume fraction of the methane of the exhaust gas is measured; if methane volume fraction of the gas discharged from coal sample reaches 99% or more, it can be considered that the coal sample adsorbs methane. The gas reaches equilibrium. After assigning the gas pressure, the triaxial pressure chamber with coal specimen is placed in a constant temperature water tank with a temperature of 30°C. Gas is continued injected until reaching the adsorption equilibrium. The steady flow rate is recorded and the permeability is calculated by:

$$k = \frac{2Qp_u\mu_g L}{A\left(p_i^2 - p_u^2\right)} \tag{34}$$

where k is the permeability under the corresponding gas pressure, Q is seepage velocity, μ_g is the dynamic viscosity of the gas under temperature and gas pressure, L is the length of coal, A is the cross-sectional area, p_i is the intake pressure, p_u is the outlet pressure.

Meanwhile, in order to explore the effect of slippage effect on coal permeability characteristics, a seepage test was conducted to increase the pore pressure at a constant effective stress of 30°C, and the permeability of helium was measured. The specific test operation can refer to our previous research (Li et al., 2020a).

Figure 6 Illustration of experiment device (see online version for colours)



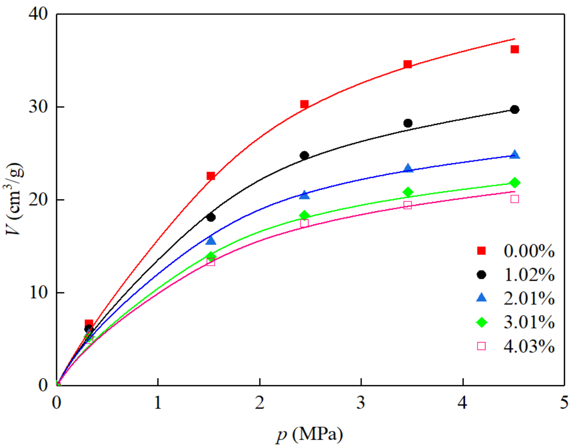
Source: Li et al. (2020b)

4 Results and discussion

4.1 *Adsorption characteristics of coal under different water content conditions*

Figure 7 shows the matching relationship between coal gas adsorption capacity and adsorption model at different water contents. Figure 8 shows the relationship between coal adsorption deformation and pore pressure at different water contents.

Figure 7 Adsorption amount with respect to the pore pressure for different water content



Note: Solid line indicates model results.

Figure 8 The sorption-induced deformation against the pore pressure for different water content (see online version for colours)

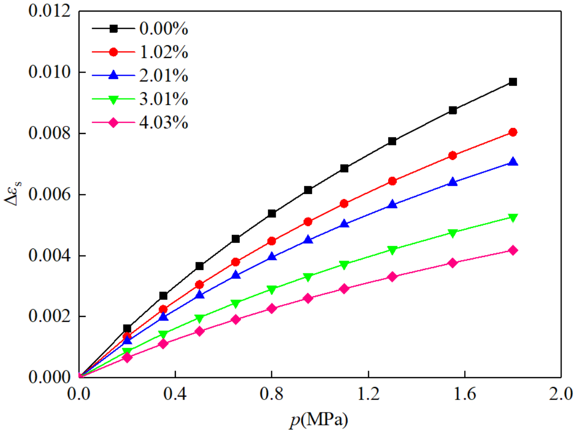


Figure 7 is shown that equation (2) agrees well with the experiment results, indicating a good performance in predicting the adsorption amount under different water content. The equation fitting parameter results are shown in Table 2. Due to the increase of pore pressure, the adsorption process is enhanced gradually towards saturation (Chen et al., 2012). Therefore, as shown in Figure 7, the gas adsorption amount has a relatively sharp rise at first and then increases gradually. As the water content increases, the amount of adsorption gradually decreases. This is mainly due to the hydrophilic nature of the coal matrix, which preferentially adsorbs water (Li et al., 2016). The water in the coal matrix indicates that the adsorption will produce a water film or capillary plug, which directly reduces the adsorption amount (Li et al., 2017). The existences of water film attached to solid surface act as barriers to prevent the process of gas adsorption since water molecules can hardly be replaced by methane molecules in the seepage process (Romanov et al., 2013).

Table 2 Adsorption model matching parameters

Water content (%)	*a* (*cm*^{3}/*g*)	*b* (*MPa*$^{-1}$)	λ
0.00	48.56	0.79	/
1.02	38.27	0.81	0.15
2.01	32.66	0.85	1.83
3.01	29.95	0.76	1.89
4.03	28.73	0.66	0.79

In addition, it can be seen from Figure 8 that the sorption-induced deformation increases with the rise of pore pressure for all the water content tested in this study. This is because when the pore pressure is increased, thicker adsorbed gas layer is formed in the pore, which results in greater adsorption amount and swell strain. As the water content increased gradually, which lead sorption-induced deformation gradually reduced. This is mainly due to the reduction in the amount of adsorption caused by the amount of deformation caused by the adsorption is also reduced.

4.2 *Coal permeability evolution mechanism under the coupling effect of water content and slippage effect*

Based on the experiment data for the adsorption amount and the sorption-induced deformation amount under different water content, the input parameters in Table 3 were substituted into equation (32) to obtain the estimated permeability. Figure 8 shows the comparison on the permeability between the proposed model, i.e., equation (32) and the measured results from experiments.

Table 3 Parameters used for permeability calculation in this study

Parameter	*Value*	*Source*
E (30°C) (MPa)	178.88	Measured
E_A (MPa)	1,900	Liu and Harpalani (2013)
v	0.32	Measured
ρ_c (g/cm^3)	1.6	Measured
R (J/mol^{-1}K)	8.314	Wang et al. (2014)
V_0 (L/mol)	22.4	Wang et al. (2014)
Φ_0	0.042	Measured

Figure 8 results comparison between equation (32) in the present study and results from experiments on permeability for varying pore pressure with different water content (solid line indicates model results).

Figure 8 shows the comparison between the permeability calculated from the proposed model, i.e., equation (32) and the measured results from experiments. In general, it is observed that the permeability calculated from equation (32) is consistent with experiment results. With the increase of pore pressure, the coal permeability shows an initial drop for all the tested water content and then tends to be stabilised. This is because that as the pore pressure increases, the gas adsorption amount increases and leads to coal matrix swelling, hence narrowing the available channels for gas seepage and reducing the coal permeability. During the loading process, gas adsorption dominates the real-time permeability change (Meng et al., 2018b). However, when the pore pressure is low, the coal permeability is determined by the combined effect of adsorption and slippage (Zhou et al., 2016). As the pore pressure increases, the role of the slippage effect gradually weakens and then the gas adsorption amount reaches its peak and the effect of adsorption becomes less. Therefore, in the process of increasing pore pressure, the permeability of coal quickly decreases first, and then the smaller speed gradually tends to be gentle. However, as the water content increases, the permeability of coal decreases linearly, as shown in Figure 9.

It is shown in Figure 9 that, generally, the coal permeability decreases with the increase of water content. As greater water content is assigned to the coal specimen, thicker water film is formed on the pore surface which causes the drop of gas adsorption amount and thus a decrease in the deformation induced by adsorption (Figures 7 and 8). When the water content is increased to 4.03%, the permeability of coal decreases by 0.690×10^{-3} μm^2, 0.555×10^{-3} μm^2, 0.529×10^{-3} μm^2 and 0.521×10^{-3} μm^2 under each pore pressure, respectively. It is revealed in this work that the effect of the water content on the coal permeability is due to the coupling mechanism of adsorption-deformation-seepage. The reason is that: first of all, the coal matrix exhibited strong hydrophilicity and water is preferentially adsorbed by the coal as the water content increases to an extent and a certain thickness of water film is formed on the pore surface (Li et al., 2017). As a result, the adsorption site of methane in coal is decreased and the gas seepage channel of coal is largely occupied (Li et al., 2016). Thus, the gas adsorption amount declines with the increase of the water content. Secondly, the specific surface area of coal decreases with the increase of the water film thickness on the pore surface and the effects on coal of compression deformation may change accordingly. The effect of adsorption plays a dominant role in the whole deformation process of the coal (Meng et al., 2018b). Meanwhile, coal reservoirs are often moist (Li et al., 2016) and the viscous resistance of gas can be changed due to the wettability of water molecules. The greater the water content of coal has, the greater the viscosity is for the gas, thus the seepage process can produce greater viscous resistance. The water film formed on the surface of the pores can cause the gas flow channels to gradually decrease and the coal permeability always decreases as the water film thickness increases. Different water film thickness can be found on pore surfaces due to the different molecular weight of the adsorbed water and the adsorption characteristics of the coal gradually change throughout the process. The adsorption of methane molecules gradually changes from monolayer adsorption to multi-layer adsorption and then becomes capillary condensation in micro-pores (Li et al., 2016). In addition, in the process of water content changes, some mechanical parameters of coal are not the same (Zhao et al., 2018). Wherein, through the calculation of equation (32), the unknown parameters are obtained as shown in Table 4.

Figure 9 Coal permeability for different water content (see online version for colours)

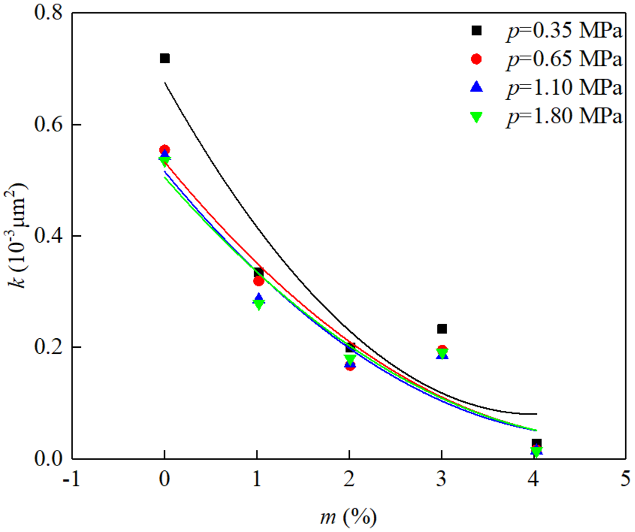


Table 4 Fitting parameters of permeability model

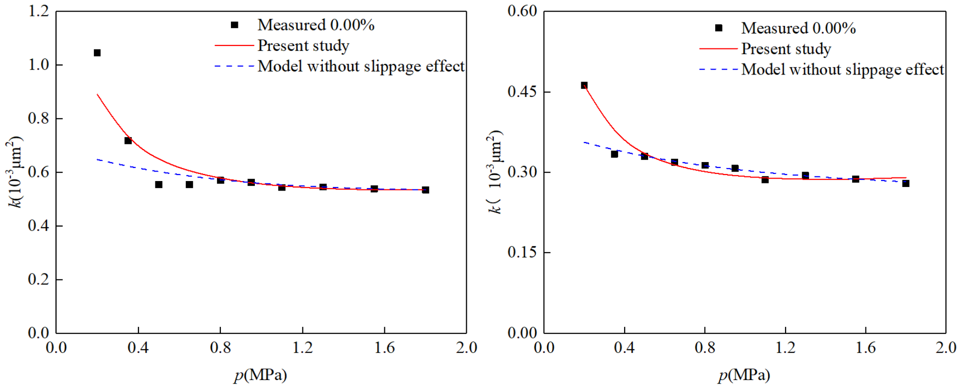
m/%	C_f	α_b	$k_a/10^{-3}\ \mu m^2$
0.00	–0.037	/	0.587
1.02	–0.038	14.99	0.280
2.01	–0.008	14.23	0.146
3.01	–0.027	19.61	0.142
4.03	–0.221	18.00	0.017

Wherein, the negative sign translates to increasing fracture volume with methane depletion, thus resulting in changed permeability which has verified in some studies (Zahner, 1997; Liu and Harpalani, 2014).

4.3 *Influence of slippage effect on the permeability of water-bearing coal*

Figure 10 shows the variation of coal permeability when the water content is 0.00% and 1.02%, considering the slippage effect and neglecting the slippage effect.

Figure 10 The permeability at different pore pressure with and without consideration of slippage, (a) m = 0.00% (b) m = 1.02% (see online version for colours)



(a) (b)

Coal permeability when the slippage effect is considered is obtained according to equation (31) and the coal permeability without slippage effect is calculated from equation (32). As shown in Figure 10, the permeability laws described by the two equations are similar. All change with the increase of pore pressure first and then tend to be gentle. However, it is also demonstrated that the coal permeability is relative higher when the slippage effect is incorporated and closer agreement with the experimental measured value. When the pore pressure is greater than 1.10 MPa, permeability from both equations gradually tends to be superposed, which is consistent with the experimental results. When the pore pressure is low, the gas molecules are sparsely distributed and the mean free path of the gas molecules is close to the width of the pore. In this case, the gas molecules are more likely to collide with the surfaces of pores and the slippage effect becomes significant (Zhou et al., 2016). For low pore pressure, equation (32) shows more accurate estimation of coal permeability because of the consideration of slippage effect. The slippage effect gradually weakens as the pore pressure increases, results from both equations become nearly identical. Therefore, equation (32) is concluded to provide more accurate prediction of coal permeability, especially when the pore pressure is low. That indicates that the slippage effect is very important and should not be ignored in the experiment.

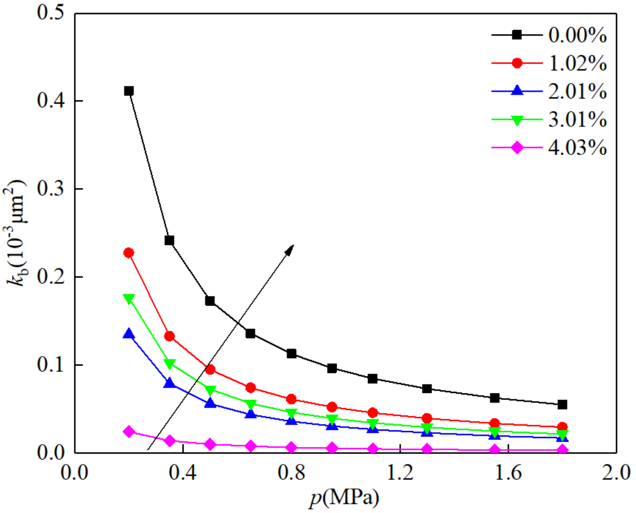
To further quantify the contribution of slippage effect to coal permeability, we used method of Harpalani and Chen (1997) to further analyse the permeability change caused by slippage effect with different water content:

$$k_b = k - k_a = k_a\left(1 + \frac{B_{\mathrm{CH4}}(wet)}{p}\right) - k_a = k_a\frac{B_{\mathrm{CH4}}(wet)}{p} \tag{35}$$

where k_b is the change in permeability due to slippage effect.

Based on the calculation of the above equation, the permeability change law caused by the slippage effect of different water content is obtained, as shown in Figure 11.

Figure 11 Permeability change caused by slippage effect (see online version for colours)

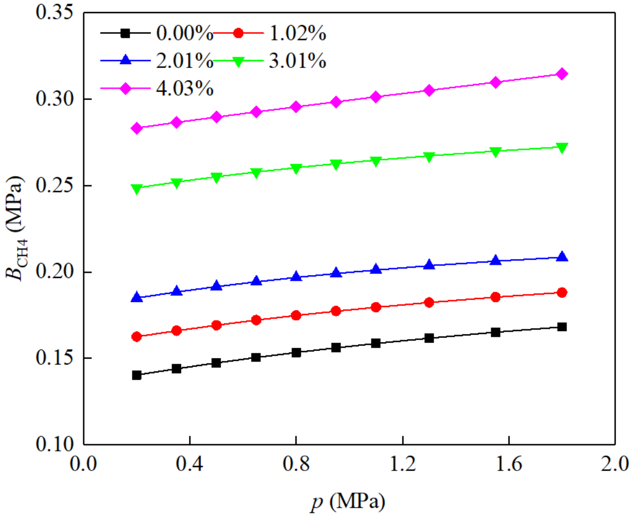


It can be seen from Figure 11 that under different water content conditions, the permeability caused by slippage effect decreases with increasing pore pressure. This can be attributed to the decrease in the average free path of gas molecules due to the increase in pore pressure, and the weakening of the slippage effect caused by the increase in the collision frequency between gas molecules (Zou et al., 2016). In the process of increasing water content, the effect of slippage effect on permeability is increasing. It may be due to the presence of moisture, which leads to a reduction in the width of the fracture and an increase in the slippage effect.

4.4 Variation law of coal slippage effect under different water content

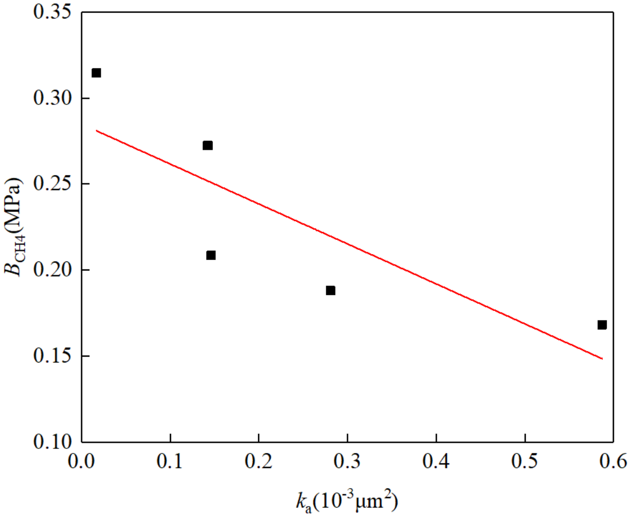
Based on the calculation of equation (25), the relationship between the slip factor of different water content and pore pressure can be obtained, which has shown in Figure 12.

Figure 12 The relationship between the slip factor of different water content and pore pressure (see online version for colours)



It can be seen from Figure 12 that there is a significant positive correlation between the moisture content and the methane slip factor. That is completely consistent with previous research results (Wu et al., 2014; Li et al., 2004). In the process of increasing pore pressure, the methane slip factor is increasing. This is mainly because the width of the methane flow channel is dominated by effective stress and matrix swell (Zhou et al., 2016). In the process of increasing pore pressure, the adsorption of coal is enhanced, and the resulting sorption-induced deformation gradually increases, resulting in a decrease in the width of the fracture. Meanwhile, the effective stress is also increasing, which also leads to a reduction in the fracture width. Therefore, the effect of sorption-induced deformation and effective stress on the fracture width is a 'synergistic negative effect'. Under the combined effect of effective stress and gas adsorption, the methane slip factor in coal is increasing. In the process of increasing the water content, the slippage factor gradually increases, which is basically consistent with the Klinkenberg theory (Klinkenberg, 1941; Wu et al., 2014; Li et al., 2004). This is mainly due to the effect of moisture on the crack width. In addition, the slip factor is related to the absolute permeability and porosity of coal. There is a correlation between porosity, absolute permeability and slippage factor, i.e., $B = \beta\left(\frac{ka}{\phi}\right)^{-1/2}$ (Civan, 2010). We keep the pore pressure constant at 1.80 MPa, and based on the calculation formula of slip factor [equation (25)], we get the relationship between absolute permeability and slippage factor as shown in Figure 13.

Figure 13 Relationship between slippage factor and absolute permeability (see online version for colours)



It can be clearly seen in Figure 13 that there is a significant negative correlation between slippage factor and absolute permeability. The smaller the permeability, the larger the slip factor and the more obvious the slippage effect. That is because under the same conditions of other parameters, the smaller the permeability, the smaller the fracture width and the greater the slippage factor. This change law has also been verified in previous studies (Wang et al., 2016; Tan et al., 2017).

5 Conclusions

The accurate estimation of coal permeability is key to the CBM extraction process. For most CBM reservoirs, the existence of water can affect significantly the coal permeability. This work analyses the effect of water content and slippage effect on coal permeability characteristics. An improved coal permeability model that considers the effect of water content and slippage effect is proposed. We further proposed a slippage effect model considering the influence of water content. Based on above analysis, the following conclusions are drawn:

1 The gas adsorption amount decreases with the increase of water content, and the change trend of coal sorption-induced deformation is the same as its. The adsorption model considering the influence of water content can better reflect the change law of the adsorption of water-bearing coal. After that, the coal permeability and water content are not a simple linear relation. Due to the influence of water content on pores/fractures, coal permeability decreases linearly. In the process of increasing pore pressure, the permeability of coal rock decreases first and then trend to be gentle.

2 Based on the percolation experiment, a permeability model considering the coupling effects of adsorption deformation, water content and slippage effects is established. The model curve is basically consistent with the test data, which can better describe the change law of permeability of water-bearing coal. In addition, we also analysed the matching of permeability models which considering and ignoring slippage effects with experimental data, and analysed the impact of slippage effects on permeability. The contribution of slippage effect to permeability increases with the increase of water content.

3 A slippage effect model considering the effect of water content is established. The changing law of slippage effect were further analysed. Wherein, the effect of pore pressure and moisture on the strength of slippage effect is a 'synergistic positive effect'. Slippage factor increases with pore pressure and water content. In addition, there is a significant negative correlation between absolute permeability and slippage factor.

This research has provided a deep understanding on the coupling mechanism of adsorption-deformation-seepage in wet coal reservoirs, it has also demonstrated some reasonable explanations for the relation between permeability and water content. Theoretical research in the future could be combined with on-site practice to establish a permeability model which considering the coupling of different water content and temperature to further simulate the gas flow mechanism.

Acknowledgements

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