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Seepage law and permeability calculation of coal gas based on Klinkenberg effect

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Abstract: Focused on the Klinkenberg effect on gas seepage, the independently developed triaxial experimental system of gas seepage was applied to conduct research on the seepage characteristics of coal seam gas. By means of experimental data analysis and theoretical derivation, a calculation method of coal seam gas permeability was proposed, which synthesized the respective influences of gas dynamic viscosity, compressibility factor and Klinkenberg effect. The study results show that the Klinkenberg effect has a significant influence on the coal seam gas seepage, the permeability estimated with the method considering the Klinkenberg effect is correct, and this permeability can fully reflect the true seepage state of the gas. For the gas around the standard conditions, the influences of dynamic viscosity and compressibility factor on the permeability may be ignored. For the gas deviating far away from the standard conditions, the influences of dynamic viscosity and compressibility factor on the permeability must be considered. The research results have certain guiding significance in forming a correct understanding of the Klinkenberg effect and selecting a more accurate calculation method for the permeability of coal containing gas.

Key words: coalbed gas; seepage law; Klinkenberg effect; gas adsorption−desorption; permeability

1 Introduction

The permeability of coal is one of the significant parameters affecting the occurrence, migration and extraction of coal seam gas, and the prevention of coal and gas outburst. Therefore, it is of practical significance to study the permeability characteristics of coal containing gas in the efficient extraction of coal seam gas and disaster prevention and control in coal mines. In 1941, KLINKENBERG [1] discovered that if the mean free path of gas molecules matched with the pore size of the porous medium, then slip flow would occur. This later became widely known as the Klinkenberg effect.

In recent years, many studies regarding the Klinkenberg effect of coal seam gas seepage have been performed. LIN and ZHOU [2−3] studied the relationship between the pore pressure and coal permeability in vertical bedding and parallel bedding directions using lump coal samples. The experimental samples presented a clear Klinkenberg phenomenon. The research results of the studies regarding raw and briquette coal samples performed by CAO et al [4] and WANG et al [5−6] showed that, with the increase of gas pressure, the outburst coal permeability presented a clear Klinkenberg effect. YIN et al [7] and HUANG [8] applied independently developed triaxial seepage experimental units of coal containing gas and systematically studied the influences of ground stress field, gas pressure and interior structure on the coal seam gas permeability. FU et al [9] and PENG et al [10] studied the Klinkenberg effect of gas seepage in terms of coal matrix shrink. Their study results showed that the Klinkenberg effect of helium was larger than that of methane, and that the matrix shrink effect was closely related to the mechanical properties of coal. CHEN et al [11] and HU et al [12] studied the Klinkenberg effect of gas seepage, respectively taking rock salt and coal as samples, and proposed a calculation method for permeability considering the Klinkenberg effect. WANG

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et al [13] and YUAN et al [14] studied the influence of gas pressure on the permeability characteristics of coal containing gas; their study results showed that the permeability of coal containing gas decreased with the increase of gas pressure, and was related to the adsorption constant. WU et al [15] studied the Klinkenberg seepage effect of gas in porous media and proposed a calculation method for permeability which was suitable for the steady-state and transient seepage of gas in porous media. TANIKAWA and SHIMAMOTO [16] comparatively studied the seepage characteristics of gas and liquid water in sedimentary rocks, and their study results showed that the Klinkenberg effect was more apparent under low pore pressure and with low permeability materials.

Based on the above studies, it is believed that the permeability of coal containing gas presents a pattern of first decreasing then increasing with the gas pressure; on the other hand, it is believed that the permeability of coal containing gas decreases constantly with the increase of gas pressure. Therefore, it can be seen that researchers have not come to an agreement regarding the Klinkenberg effect of coal containing gas. In this work, an independently developed triaxial experimental system of gas seepage is applied to conduct an in-depth analysis of the Klinkenberg effect in the gas seepage process. By using theoretical derivation and contrastive analysis, a calculation method of coal seam gas permeability with the Klinkenberg effect considered is studied, and the influences of gas dynamic viscosity and compressibility factor on the calculation of permeability are discussed in detail.

2 Experimental equipment and procedure

2.1 Experimental equipment

The equipment used in the test was independently developed for a triaxial experimental system of gas seepage (Fig. 1). The experimental system is composed of a gas container, sample holder, thermostat, manual high-pressure pump, precise pressure gauge and digital flow meter.

The main performance parameters of the experimental system include 1) confining pressure of 0−30 MPa with an accuracy of ±0.1 MPa, 2) gas pressure of 0−10 MPa with an accuracy of ±0.1 MPa, 3) axial pressure of 0−70 MPa with an accuracy of ±0.1 MPa, 4) gas mass flow meter of 0−500 mL/min with an accuracy of ±2.0 mL/min (in standard circumstances), and 5) temperature of 20−100 °C, with an accuracy within 0.1 °C.

2.2 Production of raw coal samples

The coal samples originated from the Zhaogu-II Mine in Jiaozuo City, Henan Province, China. The production method of raw coal is as follows. Extract a rock core longer than 100 mm by drilling with a *d*50 mm core barrel from a fresh lump coal; polish the rock core into a standard coal sample for the test with a *d*50 mm×100 mm double-end grinding machine; dry off the raw coal samples with a drying oven. Figure 2 shows the part of the prepared raw coal samples.

2.3 Experimental procedure

In the experimental process, methane with 99.99% concentration is applied for the seepage medium. A thermostat is used to control the temperature of the experiment to within the range of (30±0.1) °C, so as to avoid the results from being affected by temperature. Under the conditions of constant temperature and constant confining pressure, the permeability characteristics of coal containing gas are studied with the experimental system at different levels of gas pressure.

The detailed experimental procedures are as

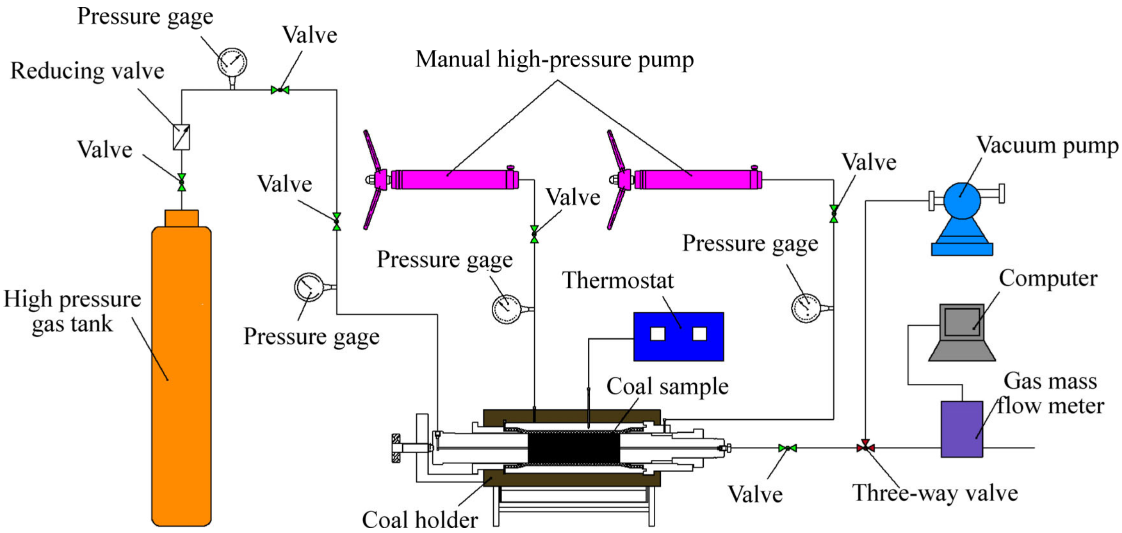

Fig. 1 Schematic diagram of experimental system

Fig. 2 Raw coal samples for testing

follows:

1) Take a well-prepared raw coal sample and place it in the triaxial loading device; after checking the gas tightness of the experimental system, vacuumize the coal sample with a vacuum pump for 12 h.

2) Use the manual high-pressure pump to exert the predetermined confining pressure and axial pressure on the coal sample; keep the confining pressure and axial pressure constant.

3) Open the gas inlet valve and fill gas into the coal sample until it reaches a certain pressure; using the thermostat, the temperature of the experiment is kept constant to be (30±0.1) °C. Ensure that the coal sample fully adsorbs the gas.

4) After the coal sample adsorbs gas and reaches a balance, open the outlet valve; operate the gas flow monitoring software and monitor the gas flow change. After the gas flow has become steady, record the flow data of the coal sample.

5) By changing the gas pressure, carry out the next seepage experiment. Repeat steps 3) and 4) as described above and complete the seepage experiments under these conditions.

6) After changing the coal samples, repeat the above steps 1)−5) until all the seepage experiments have been completed.

The following are required during the experimental process: the confining pressure exerted must be larger than the gas pressure to avoid gas leakage; the data must be recorded when the gas flow of the coal sample is steady after changing the confining pressure to avoid experimental error; at each time, when the experimental condition is changed, the coal sample must reach adsorption equilibrium before the seepage experiment is performed.

3 Calculation method for permeability of coal containing gas

Due to the fact that traditional calculation methods of permeability cannot truly reflect the Klinkenberg effect [2−4] of gas seepage, new calculation methods taking the Klinkenberg effect into consideration have been proposed [11−12, 15]. However, these methods ignore the influences of temperature and pressure changes on the dynamic viscosity and compressibility factor. In this work, a method which synthesizes the influences of gas dynamic viscosity and compressibility factor and more precisely considers the Klinkenberg effect is proposed. The detailed derivation process is described below.

The general form of the partial differential equation of gas seepage is as follows [17]:

$$\nabla \cdot \left(\delta \frac{K_{\mathrm{g}}}{\mu} \frac{p}{Z} \nabla p \right) = \frac{\partial}{\partial t} \left(\varphi \frac{p}{Z} \right) \tag{1}$$

where K_{g} is the gas permeability; u is the gas dynamic viscosity; p is the gas pressure; Z is the gas compressibility factor; φ is the porosity of porous medium; t is the time. Assuming that the gas seepage conforms to the Darcy law, then δ=1.

The calculation formula of gas permeability is as follows [1]:

$$K_{\mathrm{g}} = K \left(1 + \frac{b}{p} \right) \approx K \left(1 + \frac{2b}{p_{\mathrm{i}} + p_{\mathrm{e}}} \right) \tag{2}$$

where K is the absolute permeability (namely, the permeability when the gas is in the high-pressure state and the Klinkenberg effect can be ignored); b is the Klinkenberg coefficient; p_{i} is the inlet gas pressure; p_{e} is the outlet gas pressure.

According to Eq. (2), let p_{k}=p+b; then, Eq. (1) can be rewritten as follows:

$$\nabla \cdot \left(\nabla p_{\mathrm{k}}^2 \right) = \left(\frac{\mu \varphi Z}{\delta K p_{\mathrm{k}}} \right) \frac{\partial p_{\mathrm{k}}^2}{\partial t} \tag{3}$$

Equation (3) is the gas seepage equation which considers the Klinkenberg effect. For the parallel steady-state gas seepage on the plane, let x=0 at the gas inlet end and x=L at the outlet end. Then, the boundary conditions of gas seepage equation are clear:

$$\begin{cases} \dfrac{\mathrm{d}^2 p_{\mathrm{k}}^2}{\mathrm{d}x^2} = 0 \\ p_{\mathrm{k}}^2 \Big|_{x=0} = \left(p_{\mathrm{i}} + b \right)^2 \\ p_{\mathrm{k}}^2 \Big|_{x=L} = \left(p_{\mathrm{e}} + b \right)^2 \end{cases} \tag{4}$$

After solving Eq. (4), then the gas pressure distribution condition in the porous medium may be achieved:

$$p_{\mathrm{k}}^2 = (p_{\mathrm{i}} + b)^2 - \left[(p_{\mathrm{i}} + b)^2 - (p_{\mathrm{e}} + b)^2 \right] \frac{x}{L} \tag{5}$$

Let the gas seepage conform to Darcy's law. The gas flow velocity is not large and the following formula can be used for the calculation of gas mass flow rate:

$$Q_{\mathrm{m}} = A\rho V = -\frac{AMp}{RTZ}\frac{K_{\mathrm{g}}}{\mu}\frac{\mathrm{d}p}{\mathrm{d}x} \tag{6}$$

where ρ is the gas density; V is the gas flow rate; M is the gas molecular mass; R is the gas constant.

After substituting Eq. (2) into Eq. (6), the flow rate Q_{m} can be expressed using the following equation:

$$Q_{\mathrm{m}} = A\rho V = -\frac{AMp_{\mathrm{k}}}{RTZ}\frac{K}{\mu}\frac{\mathrm{d}p_{\mathrm{k}}}{\mathrm{d}x} \tag{7}$$

The parameters μ and Z take their average values, and after carrying out the integral, Eq. (7) may be transformed into

$$\frac{1}{2}\left[(p_{\mathrm{i}}+b)^2-(p_{\mathrm{e}}+b)^2\right]\frac{AMK}{TR\bar{\mu}\bar{Z}} = Q_{\mathrm{m}}L \tag{8}$$

With the gas mass flow rate Q_{m}, the gas volume flow rate Q_0 under standard conditions can be calculated as

$$Q_0 = \frac{Q_{\mathrm{m}}}{\rho_0} = \frac{1}{2}\left[(p_{\mathrm{i}}+b)^2-(p_{\mathrm{e}}+b)^2\right]\frac{AK}{\bar{\mu}\bar{Z}Lp_0}\frac{T_0}{T} \tag{9}$$

where ρ_0 is the gas density under standard condition.

Equation (9) can be simplified as

$$\frac{2Q_0p_0\bar{\mu}\bar{Z}L}{A}\frac{T}{T_0} = K\left[\left(p_{\mathrm{i}}^2-p_{\mathrm{e}}^2\right)+2b(p_{\mathrm{i}}-p_{\mathrm{e}})\right] \tag{10}$$

In Eq. (10), $\bar{\mu}$ and $\bar{Z}$ are the functions of temperature and pressure, namely, $\bar{\mu}(T,p)$ and $\bar{Z}(T,p)$. Since the influence of pressure on the dynamic viscosity is slight [15], then $\bar{\mu}(T,p)\approx\bar{\mu}(T)$. Moreover, $\bar{\mu}(T)$ can be calculated using the Sutherland formula [18−19]:

$$\frac{\bar{\mu}}{\mu_0} \approx \left(\frac{T}{T_0}\right)^{1.5}\frac{T_0+T_{\mathrm{su}}}{T+T_{\mathrm{su}}} \tag{11}$$

where μ_0 is the gas dynamic viscosity under standard condition; T_0=273.15 K; T_{su} is the Sutherland constant.

For $\bar{Z}(T,p)$, when the pressure is low, the gas compressibility is small. For example, when the pressure is 2 MPa (25 °C in the circumstances of the study), the gas compressibility factor is 0.9644 [20] and the error is small. Therefore, under low-pressure conditions, the accuracy is not strictly required and the influence of the compressibility factor can be ignored when calculating the permeability of coal containing gas. Under high-pressure conditions, the gas compressibility is large. For example, when the pressure is 10 MPa (25 °C in this work), the gas compressibility factor is 0.8219 [19]. An error of approximately 18% will occur if the influence of the compressibility factor is ignored. Therefore, the influence of the compressibility factor cannot be ignored under high-pressure conditions. In this case, the equation of the fluid state can be used to calculate the value [21].

Therefore, to obtain the permeability of the gas seepage, the following steps must be followed:

1) Calculate the average dynamic viscosity $\bar{\mu}$ of gas based on Eq. (11), under the condition of the experimental temperature.

2) Calculate the average compressibility factor $\bar{Z}$ of the gas with the equation of the gas state.

3) According to the actually measured gas flow data in the experiment, Eq. (10) is used for the fitting to determine K and b.

4) Use Eq. (2) to calculate the value of the gas permeability K_{g} in the experiment.

Since the Klinkenberg effect is present in the gas seepage process in the porous medium, then the gas permeability must be calculated considering the Klinkenberg effect.

4 Experimental results and analysis

Seepage experiments are carried out using raw coal samples under the conditions of different confining pressures, namely 4, 5, 6, 7 and 8 MPa. According to the experimental data, the relationships between the gas flow and pressure square errors at the inlet and outlet ends are acquired, as shown in Fig. 3.

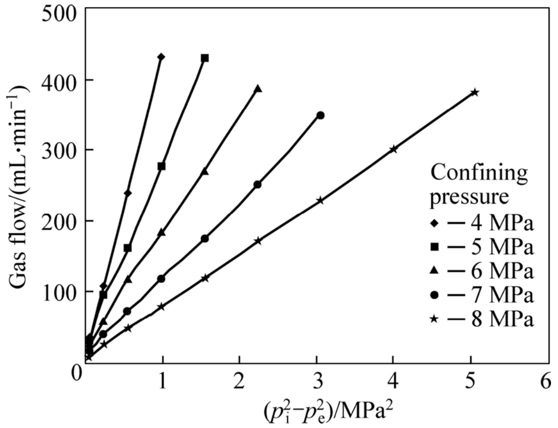

Fig. 3 Relationship between gas flow and inlet and outlet gas pressure square difference

From Fig. 3, it can easily be seen that in the low-pressure stage, the seepage curve of the gas is no longer straight, and it presents non-Darcy seepage characteristics. Therefore, the coal sample shows the Klinkenberg effect in the low-pressure stage.

Table 1 presents the permeability of coal samples obtained by the method considering the Klinkenberg effect proposed in this work.

According to the calculation results in Table 1, the absolute permeability K of the coal samples and the Klinkenberg coefficient b can be obtained through fitting. Table 2 lists the detailed fitting results. The fitting curve

Table 1 Calculated permeability of coal samples

Sample No.	Average gas pressure, $\bar{p}$ /MPa	Permeability/ mD
1	0.18	1.09
	0.30	1.02
	0.43	0.99
	0.55	0.98
2	0.18	0.96
	0.30	0.77
	0.43	0.69
	0.55	0.64
	0.68	0.61
3	0.18	0.71
	0.30	0.54
	0.43	0.47
	0.55	0.43
	0.68	0.40
	0.80	0.39
4	0.18	0.37
	0.30	0.31
	0.43	0.29
	0.55	0.27
	0.68	0.26
	0.80	0.26
	0.93	0.25
5	0.18	0.23
	0.30	0.12
	0.43	0.19
	0.55	0.18
	0.68	0.18
	0.80	0.17
	0.93	0.17
	1.05	0.17
	1.18	0.17

Table 2 Fitting results of K and b

Sample No.	K/mD	b/MPa	R^2
1	0.922	0.031	0.999
2	0.491	0.168	0.997
3	0.295	0.245	0.998
4	0.224	0.117	0.997
5	0.158	0.087	0.999

using the method considering the Klinkenberg effect is shown in Fig. 4.

From Fig. 4 and Table 2, it can be seen that the method considering the Klinkenberg effect has a high accuracy.

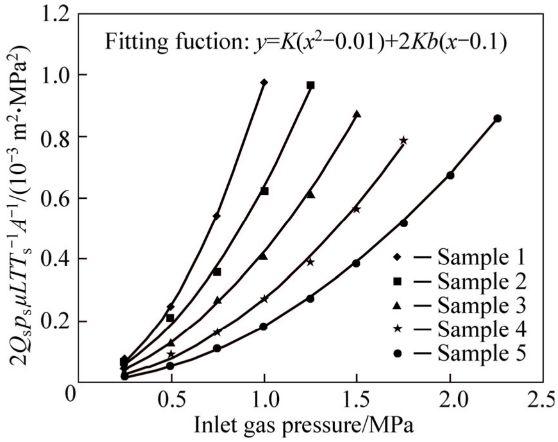

Fig. 4 Fitting results of method considering Klinkenberg effect

5 Influence of dynamic viscosity and compressibility factor on permeability of coal

When estimating the permeability of coal seam gas, the influences of dynamic viscosity and compressibility factor are generally ignored [2−4, 11−16]. If the experimental gas state is around the standard state, then the influences of the dynamic viscosity and compressibility factor are small and can be ignored. Taking gas as an example, the calculation error of permeability is analyzed when the experimental gas state deviates from the standard condition. Table 3 lists the experimental gas state (including temperature and pressure) and detailed calculation errors.

From Table 3, it can be seen that when the temperature is 20−100 °C and the average pressure is

Table 3 Calculation errors of methane permeability caused by deviation from standard condition

Temperature/ °C	Average gas pressure/ MPa	Error caused by $\bar{u}$ /%	Error caused by $\bar{Z}$ /%	Error caused by $\bar{\mu}\cdot\bar{Z}$ /%
20	2	6.0	3.6	5.8
	4		7.0	5.5
	6		10.1	5.4
	8		12.7	5.2
	10		14.8	5.1
40	2	11.3	3.0	11.0
	4		5.8	10.7
	6		8.3	10.4
	8		10.4	10.2
	10		12.1	9.9
60	2	19.0	2.5	18.6
	4		4.8	18.1
	6		6.9	17.7
	8		8.6	17.4
	10		10.0	17.1
80	2	24.5	2.1	24.0
	4		4.1	23.5
	6		5.8	23.1
	8		7.2	22.8
	10		8.4	22.5
100	2	30.5	1.8	29.9
	4		3.4	29.5
	6		4.8	29.0
	8		6.0	28.7
	10		7.0	28.4

2−10 MPa, the smallest calculation error caused by the dynamic viscosity is 5.96%, and the largest is 30.49%. In addition, the smallest calculation error caused by compressibility factor is 1.80%, and the largest is 14.80%. The smallest integrated calculation error caused by dynamic viscosity and compressibility factor is 5.08%, and the largest is 29.94%. At present, the largest gas pressure of a coal mine in China has reached 10 MPa [22]. With the establishment of deep mining, the gas pressure will continue to increase, and the temperature of the coal seam will also increase. Under this condition, the gas state deviates far away from the standard state. Therefore, in the estimation of permeability of coal seam gas, the influences of dynamic viscosity and compressibility factor must be taken into consideration. Otherwise, the calculation error will be too large and distorted.

In conclusion, when estimating the permeability of coal containing gas using the method considering the Klinkenberg effect, if the gas state of the experiment is around the standard state, then the influences of dynamic viscosity and compressibility factor can be ignored; while if the deviation from the standard state is significant, then it cannot be ignored, otherwise, there will be a high calculation error.

6 Conclusions

1) The permeability of coal seam gas decreases with the increase of gas pressure, and presents a clear Klinkenberg effect. Meanwhile, with the gradual increase of gas pressure, the Klinkenberg effect gradually becomes less significant.

2) The method proposed considering the Klinkenberg effect can effectively describe the Klinkenberg effect in the seepage process of coal seam gas. It is reasonable to estimate the permeability of coal seam gas using the proposed method.

3) When the gas state is around or does not deviate far away from the standard condition, then the influences of dynamic viscosity and compressibility factor are slight and can be ignored. If the gas state deviates greatly from the standard state, especially under the condition of high temperature, then the influences of dynamic viscosity and compressibility factor on the calculation of permeability must be considered, otherwise, the calculation error will be too large and distorted.

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