

## Research Article

# Effect of Gas Adsorption on the Application of the Pulse-Decay Technique

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The permeability of coal is an indispensable parameter for predicting the coalbed methane (CBM) and enhanced CBM (ECBM) production. Considering the low permeability characteristics of coal, the permeability is usually measured by the transient technique in the laboratory. Normally, it is assumed that the calculated permeability will not greatly vary if the pulse pressure applied in the experiment is small (less than 10% of pore pressure) and previous studies have not focused on the effect of the pulse pressure on the measurement permeability. However, for sorptive rock, such as coals and shales, the sorption effect may cause different measurement results under different pulse pressures. In this study, both nonadsorbing gas (helium) and adsorbing gas (carbon dioxide) were used to investigate the adsorption effect on the gas permeability of coal measurement with the pulse-decay technique. A series of experiments under different pore pressures and pulse pressures was performed, and the carbon dioxide permeability was calculated by both Cui et al.'s and Jones' methods. The results show that the carbon dioxide permeability calculated by Jones' method was underestimated because the adsorption effect was not considered. In addition, by comparing the helium and carbon dioxide permeabilities under different pulse pressures, we found that the carbon dioxide permeability of coal was more sensitive to the pulse pressure due to the adsorption effect. Thus, to obtain the accurate permeability of coal, the effect of adsorption should be considered when measuring the permeability of adsorptive media with adsorbing gas by the transient technique, and more effort is required to eliminate the effect of the pulse pressure on the measured permeability.

## 1. Introduction

To alleviate the problems of energy shortage and global warming, researchers pay more attention to the technologies of CBM, ECBM, and carbon dioxide storage in coal seams. The permeability of coal is one of the most important parameters for those projects. To predict the methane production of a coal seam and evaluate its storage potentiality, it is essential to accurately and quickly measure the coal permeability. At present, the steady flow method (SFM) and pulse-decay method (PDM) are the main methods to measure the permeability. However, for tight reservoir rocks, such as coal and shale, it is time-consuming to attain equilibrium in SFM and difficult to accurately measure the flow rate. Thus, com-

pared with SFM, PDM becomes popular due to its shorter experimental time and higher resolution [1, 2].

The PDM was used by Brace et al. [3] to measure the permeability of a granite sample, and the permeability was calculated by the decay curve of the differential pressure between upstream and downstream. However, this approximation method to assess the permeability did not consider the effect of compressive storage [4]. Hsieh et al. [5] presented a general analytical solution in the transient test considering the compressive storage of the sample. However, this solution was difficult to evaluate [6]. To more easily obtain the sample permeability, Dicker and Smits [6] constrained the volume of the storage reservoir and quickly obtained the single-exponential decay of the pressure decline curve. Jones [7]

improved the work of Dicker and Smits. In Jones' method, the permeability is calculated from "late-time" measurements which yield the overall effective permeability of a core plug in the same manner as steady-state measurements [7]. All of these methods assume that there is no interaction between the sample and the gas. However, for absorbing gases (such as methane and carbon dioxide), gas molecules will interact with the adsorbing media (such as coal and shale) [8–11], which make the matrix swell or shrink. Thus, it is necessary to discuss the effect of gas adsorption on the permeability measurement when using the pulse-decay method. Based on the previous work, Cui et al. [2] revised the pulse-decay technique to correct the impact of adsorption on the effective permeability measurement. In Cui et al.'s work, Langmuir isotherm was used to describe the gas adsorption in coal seams. However, Mahmoud et al. [12] noted that the heterogeneity of the rock surface was the main factor that affects the adsorption strength. The single-layer Langmuir isotherm adsorption model cannot accurately describe the adsorption of gas molecules on the rock surface, so the formula is revised based on the Freundlich isotherm adsorption model.

All studies assume that the fluid viscosity, fluid compressibility, porosity, and permeability are constant during the experiment if the initial differential pressure is small (within 10% of pore pressure). Thus, the gas permeability measured under different pulse pressures is relatively stable. Intuitively, it is feasible to measure the helium permeability of coal because the change in small initial differential pressure may have little effects on the differential pressure decay during the experiment. However, for adsorbing gases and media, such as carbon dioxide and coal, the changes in pore pressure may break the original ad-/desorption balance between gas and matrix and induce the difference in measured differential pressure decay curves under different pulse pressures during the experiment. The purpose of this article is to investigate the effect of the initial pulse pressure on the measurement results of the gas permeability of coal when the transient technique is used in the laboratory, especially for carbon dioxide.

## 2. Experimental Work

The PDM was used to measure the permeability of Sihe coal. Brace et al. [3] mentioned that the pulse pressure should be less than 10% of the upstream pressure because both viscosity and compressibility of fluids varied with pressure. Thus, the minimum upstream pressure is 1 MPa, and the maximum pulse pressure is 100 kPa during the experiment.

**2.1. Sample Preparation.** The sample in this study is from Sihe coal mine in Qinshui Basin. A cylindrical coal sample was prepared before the experiment. As shown in Figure 1, the length of the coal sample is 50.53 mm and its diameter is 24.99 mm. The sample surfaces were polished to enable the smooth contact between the coal and the shrinkable tube, which can prevent the shrinkable tube from rupturing and causing the confining fluid to flow into the sample. To remove residual moisture and adsorbed gases from the coal sample, the core was placed in a 60° vacuum environment



FIGURE 1: Photograph of the cylindrical core sample.

and dried for 48 hours before the experiment. The initial weight of the coal is 40.96 g, and the weight becomes 40.90 g after drying.

**2.2. Experimental Setup and Procedures.** The schematic diagram of the transient pulse-decay testing apparatus in our study is shown in Figure 2 [3, 13]. A core holder which is made of stainless steel was used to measure the gas permeability of coal under hydrostatic pressure conditions, and it can maintain a maximum confining pressure of 20 MPa. A confining pump was used to apply the confining pressure during the experiment. A thin lead foil was used to wrap the cylindrical core sample to prevent gas diffusion from the core to the confining fluid at high pressures [14], and a heat-shrinkable tube was employed to isolate the core from the confining fluid. An ISCO pump, which is with the full scale of 68.95 MPa and the accuracy of  $\pm 0.5\%$  FS at constant temperature, was applied to supply the initial pore pressure to the sample. A differential pressure transducer with the accuracy of  $\pm 0.25\%$  FS (FS = 220 kPa) was used to accurately record the pressure difference between upstream and downstream every second. The volumes of the upstream and downstream are 6.115 ml and 4.505 ml, respectively. During the experiment, the temperature was maintained at  $26 \pm 1^\circ\text{C}$ , and the net confining pressure is 3 MPa. The experimental conditions are shown in Table 1.

The test procedure is as follows: (1) Test the leakage rate of the measurement system. (2) Install the dried and wrapped coal sample into the core holder and apply a confining pressure according to the experimental condition. (3) Close valve 1, open other valves, and connect the coal sample with a vacuum pump to eliminate residual gases in the pipeline and coal sample for 1 hour. After vacuuming, close valve 4. (4) Open valve 1 and apply the initial pore pressure in the system through the ISCO pump at the constant-pressure mode. When the residual gas volume in the ISCO pump remains unchanged, close valves 2 and 3 and impose a pressure difference in the upstream through the ISCO pump. When the pressure difference between the upstream and downstream is equal to the designed value, close valve 1. (5) When the upstream pressure stabilizes, open valve 2 and collect the data of the differential pressure transducer. (6) According to the

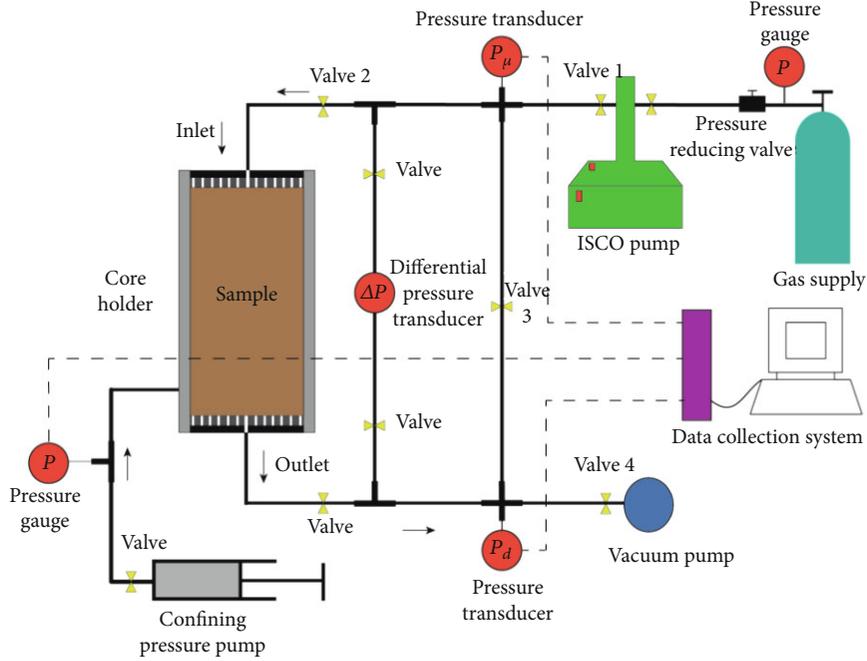


FIGURE 2: Sketch of the experimental setup for the permeability measurement.

TABLE 1: Experimental scheme for the permeability test.

Gas type	Confining pressure (MPa)	Pore pressure (MPa)	Pulse pressure (kPa)
	4	1	
Carbon dioxide,	5	2	40, 60, 80, 100
helium	6	3	
	7	4	

change in differential pressure with time, calculate the permeability using the solution. (7) Change the injected pore pressure and applied pulse pressure and measure the permeability under different conditions. When the test fluid is carbon dioxide, inject the gas into the sample for a week to achieve the balance between adsorption and desorption. When the pore pressure changes, the permeability was measured after 24 hours until equilibrium was achieved. The applied pressure difference is slightly larger than the designed pulse pressure due to the effect of the dead volume ( $V_{\text{dead}}$ ) which is the volume between valve 2 and the top face of the coal sample.

### 3. Calculation of Permeability

A tremendous amount of work has been performed to study the permeability calculation when using the PDM. Because the coal permeability is a gas type-dependent property, both carbon dioxide (adsorbing gas) and helium (non-adsorbing gas) are used in our experiment. To compare the difference in carbon dioxide permeability of coal obtained by different solutions (whether we consider the adsorption effect), both Jones' method and Cui et al.'s method were applied in this study.

3.1. *Jones' Method (1997)*. The pressure decay curve is described by the differential equation of the gas through the sample. With the given boundary conditions and initial conditions, Dicker and Smits [6] provided the relationship between dimensionless pressure difference  $\Delta P_D$  and dimensionless time  $t_D$  as follows:

$$\Delta P_D(a, b, t_D) = 2 \sum_{m=1}^{\infty} \exp(-t_D \theta_m^2) \cdot \frac{a(b^2 + \theta_m^2) - (-1)^m b \sqrt{(a^2 + \theta_m^2)(b^2 + \theta_m^2)}}{\theta_m^4 + \theta_m^2(a + a^2 + b + b^2) + ab(a + b + ab)}, \quad (1)$$

$$\tan \theta = \frac{(a + b)\theta}{\theta^2 - ab}, \quad (2)$$

where  $a$  and  $b$  are the ratios of the compressive storage of the sample's pore volume to that of the upstream and downstream reservoirs, respectively;  $\theta_m$  are the roots of Equation (2);  $t_D$  is the dimensionless time;  $t_D = kt/(c\mu\phi L^2)$ , where  $k$  is the permeability,  $t$  is the real time,  $c$  is the fluid compressibility,  $\mu$  is the fluid viscosity,  $\phi$  is the porosity, and  $L$  is the sample length.

Because Equation (1) is a form of infinite series, and Equation (2) is difficult to solve, Jones [7] defined  $f_1$  as follows:

$$f_1 \equiv \frac{\theta_1^2}{a + b}, \quad (3)$$

where  $\theta_1$  is the first root of Equation (2).

For rigid gas reservoirs, the compressibility of the reservoir is negligible compared to that of gas. If  $a$  and  $b$  are equal and  $t_D$  is sufficiently large, only the first term in Equation (1) is significant, all even terms are zero, and the sum of the remaining odd terms has little effect on the results. Thus, the dimensionless differential gas pressure is as follows:

$$\Delta P_D = \frac{2 \left[ a(b^2 + \theta_1^2) + b\sqrt{(a^2 + \theta_1^2)(b^2 + \theta_1^2)} \right]}{\theta_1^4 + \theta_1^2(a + a^2 + b + b^2) + ab(a + b + ab)} \cdot e^{\alpha t}, \quad (4)$$

$$\alpha = \left( \frac{f_1 A k_g}{\mu_g L c_g} \right) \left( \frac{1}{V_u} + \frac{1}{V_d} \right), \quad (5)$$

where  $A$  is the cross-sectional area of the cylindrical core plug;  $k_g$  is the effective permeability to gas;  $c_g$  is the gas compressibility and given by  $c_g \equiv f_z/p$  ( $f_z$  is the gas compressibility correction factor, and  $p$  is the pore pressure);  $\mu_g$  is the viscosity of gas;  $V_u$  and  $V_d$  are the volumes of the upstream and downstream, respectively.

With the linear regression of Equation (4), slope  $\alpha$  of the late-time experimental data can be obtained. Thus, the gas effective permeability can be calculated by

$$k_g = - \frac{\alpha \mu_g L f_z}{f_1 A p_m ((1/V_u) + (1/V_d))}, \quad (6)$$

where  $p_m$  is the mean absolute pore pressure (the gas compressibility is evaluated at  $p_m$ ).

**3.2. Cui et al.'s Method (2009).** Considering the effect of adsorption on the permeability measurement, Cui et al. [2] combined the Langmuir isotherm adsorption model with Jones' simplified algorithm, and the adsorption term was introduced into the seepage equation to modify the traditional algorithm. The modified values of  $a$  and  $b$  are as follows:

$$a = \frac{V_p(1 + (\varnothing_a/\varnothing))}{V_u}, \quad (7)$$

$$b = \frac{V_p(1 + (\varnothing_a/\varnothing))}{V_d},$$

where  $V_p$  is the pore volume of the sample, and  $\varnothing_a$  is the effective porosity.

The effective porosity due to gas adsorption is as follows:

$$\varnothing_a = \frac{\rho_s}{V_{\text{std}}} \frac{(1-\varnothing)}{c_g \rho} \frac{q_L p_L}{(p_L + p)^2}, \quad (8)$$

where  $\rho_s$  is the skeleton density of the porous samples;  $\rho$  is the density of gas;  $q_L$  and  $p_L$  are the Langmuir volume and pressure, respectively;  $p$  is the gas pressure;  $c_g$  is the gas compressibility;  $V_{\text{std}}$  is the molar volume of gas at the standard pressure and temperature (i.e., 273.1 K and 101325 Pa).

Substituting  $a$  and  $b$  into Equation (2) and Equation (3), we obtain  $f_1$ . The permeability can be calculated by Equation (6). Both porosity and adsorption characteristic parameters are required in the permeability calculation when we use Cui et al.'s method. The sample in this experiment was collected in coal seam # 3 in Sihe coal mine, which is similar to the sample in Han et al.'s [15] and Sun's [16] studies. Based on their experimental results, it is reasonable to assume that the porosity is approximately 5%, the Langmuir volume is approximately  $40 \text{ cm}^3 \text{ g}^{-1}$ , and the Langmuir pressure is  $2 \times 10^6 \text{ Pa}$ .

## 4. Results and Discussion

**4.1. Measurement Results.** Thirty-two permeability measurements were conducted with helium and carbon dioxide under different pore pressures and pulse pressures using the transient technique. Figure 3 shows the typical curves (recorded in the experiment with the helium pressure of 1 MPa and the pulse pressure of 100 kPa) of the pressure difference between upstream and downstream  $\Delta P(t)$  with time and  $\ln(\Delta P(t)/\Delta P(0))$  with time. Although the designed initial pulse pressure is 100 kPa, the applied pressure difference ( $\Delta P'(0)$ ) between upstream and downstream is up to 216 kPa due to the effect of  $V_{\text{dead}}$ . The volume of the pipeline in the blue-shaded part (from the valve to the top face of the sample) in Figure 3 is  $V_{\text{dead}}$ , which causes the steep drop of  $\Delta P(t)$  (dotted line). The initial pulse pressure ( $\Delta P(0)$ ) is the actual pressure difference between the upper and lower surfaces of the coal sample without the effect of  $V_{\text{dead}}$ . All other fitted slopes of  $\ln(\Delta P(t)/\Delta P(0)) - t$  and corresponding calculated permeability are listed in Table 2.

**4.2. Comparison of the Carbon Dioxide Permeability of Coal Calculated by Jones' and Cui et al.'s Methods.** Both Jones' and Cui et al.'s methods were used to calculate the carbon dioxide permeability of coal in this study to investigate their differences. The main difference between these two methods is whether the density of adsorbed gas changes with time. In Jones' method, the control equation only contains the term of free gas. If we use Jones' method to calculate the carbon dioxide permeability of coal, the density of adsorbed gas remains constant during the experiment. In Cui et al.'s method, both free gas and adsorbed gas are considered. The results calculated by these two methods are shown in Figure 4. The relative error is defined as the ratio of the absolute values of the difference to the value calculated by Cui et al.'s method. The carbon dioxide permeability calculated by Cui et al.'s method is larger than that by Jones' method. In addition, when the pore pressure increases from 1 MPa to 4 MPa, the relative error decreases from 57% to 27%. Thus, the carbon dioxide permeability calculated by Jones' method is severely underestimated, and the underestimation declines with the increase in pore pressure. This phenomenon may be attributed to the sorption behavior between carbon dioxide and coal matrix. As shown in Figure 5, on the one hand, according to Feng et al. [4] and Wang et al. [17], it is reasonable to speculate that the pulse pressure may break the ad-/desorption balance between gas and matrix, which makes the free

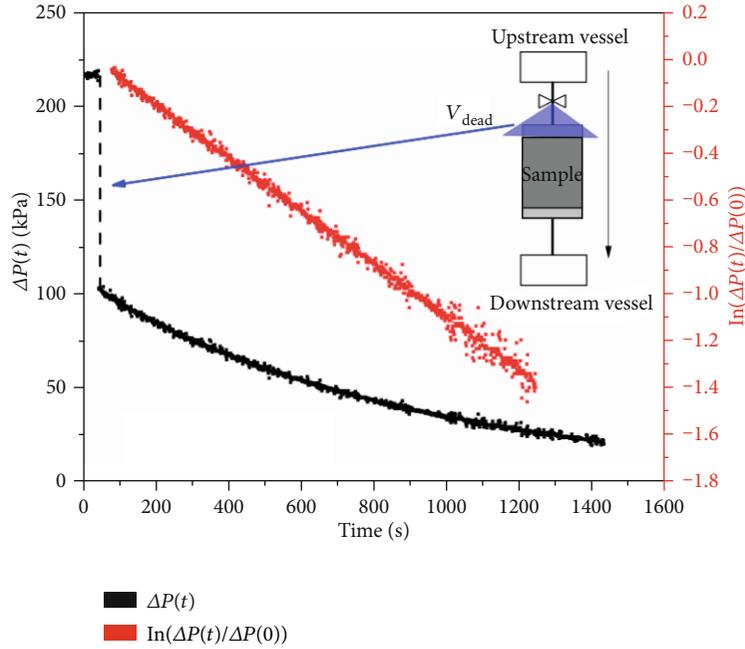


FIGURE 3: Typical curves of  $\Delta P(t) - t$  and  $\ln(\Delta P_t/\Delta P_0) - t$  measured in the experiment.

TABLE 2: Permeability measurement results under different conditions in the experiment.

Pore pressure (MPa)	Pulse pressure (kPa)	Slope	Helium		Slope	$R^2$	Carbon dioxide	
			$R^2$	$K$ ( $\mu\text{D}$ ) (Jones, 1997)			$K$ ( $\mu\text{D}$ ) (Jones, 1997)	$K$ ( $\mu\text{D}$ ) (Cui et al., 2009)
1	40	-0.0011	0.9843	5.86	-0.0441	0.9843	185.5	432.1
	60	-0.0011	0.9923	5.81	-0.0395	0.9936	163.52	379.13
	80	-0.0011	0.9951	5.77	-0.0375	0.9953	154.02	356.85
	100	-0.0011	0.9973	5.72	-0.0349	0.9974	141.13	323.91
2	40	-0.0017	0.9738	4.65	-0.0461	0.9519	97.4	164.71
	60	-0.0018	0.9885	4.88	-0.0407	0.9913	85.66	144.02
	80	-0.0018	0.99253	4.86	-0.038	0.9976	79.66	133.34
3	100	-0.0018	0.99503	4.84	-0.0354	0.9946	73.93	123.02
	40	-0.002	0.9819	3.68	-0.0307	0.9829	44.46	62.49
	60	-0.002	0.9907	3.67	-0.0289	0.9958	41.74	58.4
4	80	-0.002	0.9935	3.66	-0.0264	0.9957	37.85	53.34
	100	-0.002	0.9969	3.64	-0.0244	0.9979	34.98	49.01
	40	-0.0025	0.9777	3.47	-0.0199	0.9896	20.39	27.84
4	60	-0.0026	0.9904	3.6	-0.0175	0.9886	17.9	24.25
	80	-0.0026	0.9945	3.6	-0.0162	0.9973	16.51	22.37
	100	-0.0026	0.9967	3.58	-0.015	0.9964	15.29	20.85

gas change into adsorbed gas, and the real equilibrium pressure is less than the pseudoequilibrium pressure. On the other hand, the hysteresis of the downstream pressure caused by the adsorption of upstream gas may also change the differential pressure. For nonadsorbing gas, the decrease in upstream pressure will quickly trigger a response in the downstream and induce the increase in downstream pressure. For adsorbing gas, after the pulse pressure is applied, the upstream gas is adsorbed, and the response of the increase in downstream pressure becomes relatively slow.

Therefore, the differential pressure decay in the permeability measurement process is slower than that of nonadsorbing gas. If the adsorption effect is not considered in the calculation, the permeability will be underestimated. In addition, according to Langmuir isotherm, the carbon dioxide adsorption capacity, which is defined as the slope of the amount of gas adsorbed to the gas pressure, weakens with the increase in pore pressure. The hysteresis and deviation between real equilibrium pressure and pseudoequilibrium pressure are not apparent at high pressure. Thus, with the increase in pore

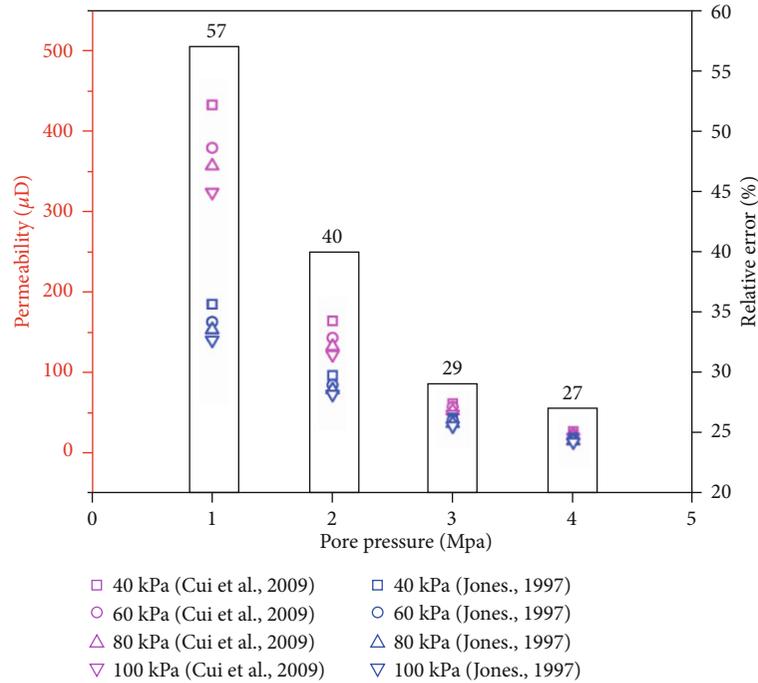


FIGURE 4: Comparison of the carbon dioxide permeability of coal calculated by Jones' and Cui et al.'s method.

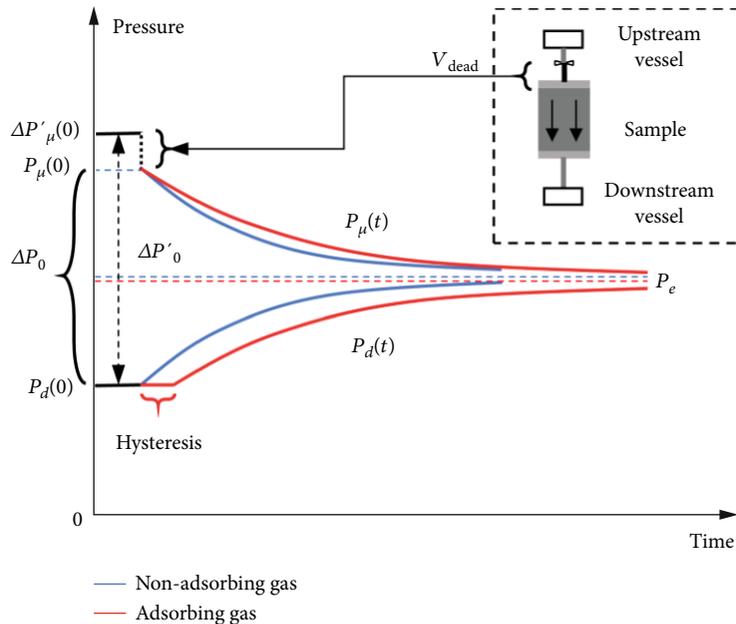


FIGURE 5: Change in pressure for adsorbing and nonadsorbing gases in the transient pulse-decay technique ( $P_u(t)$  and  $P_d(t)$  are the upstream pressure and downstream pressure, respectively;  $P'_u(0)$  and  $P_u(0)$  are the pseudo and actual upstream pressures, respectively (the difference between them is caused by  $V_{dead}$ );  $P_d(0)$  is the initial downstream pressure;  $P_e$  is the final equilibrium pressure; hysteresis is caused by the sorption of gas in the upstream).

pressure, the relative error between these two solutions decreases. Thus, when we test the adsorbing gas permeability of coal using the pulse-decay technique, the adsorption effect must be considered to accurately determine the measurement result. In this paper, the carbon dioxide permeability of coal is calculated by Cui et al.'s method, which better reflects the actual permeability of coal.

4.3. *Gas Permeability under Different Pore Pressures.* To further test the adsorption effect on the permeability of coal, we performed the gas permeability measurements under different pore pressures with PDM. The result is shown in Figure 6. In Figure 6(a), the permeability of helium decreases with the increase in pore pressure under constant net confining pressure, which was also observed by Chen et al. and Pan

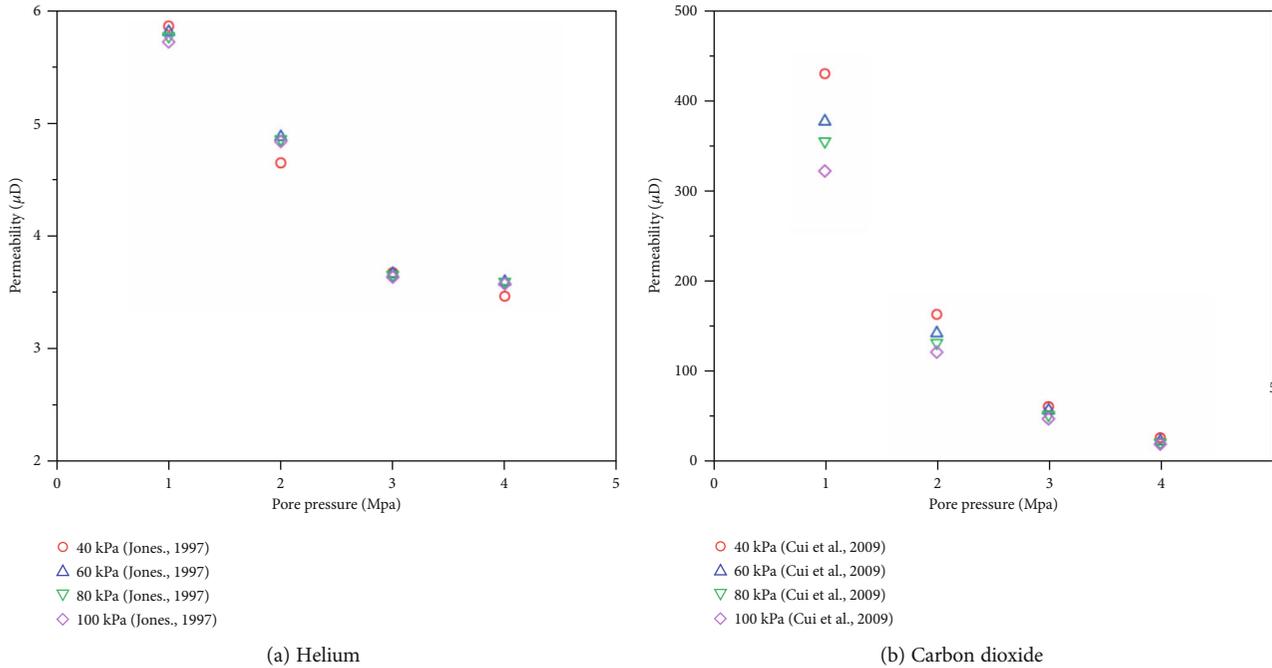


FIGURE 6: Gas permeability under different pore pressures (net confining pressure = 3 MPa).

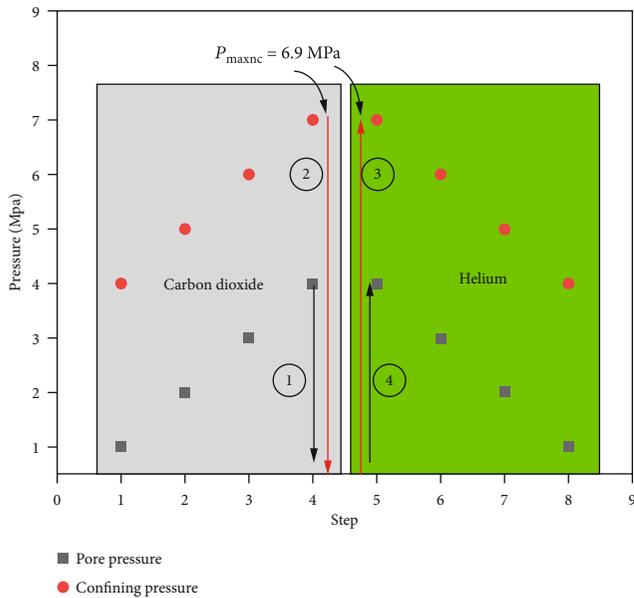


FIGURE 7: Experimental steps during the experiment.

et al. [18, 19]. When the pore pressure is 1 MPa, the measured permeability under different pulse pressures is 5.72-5.86  $\mu\text{D}$  with an average of 5.79  $\mu\text{D}$ . When the pore pressure increases to 2 MPa, the permeability is 4.65-4.88  $\mu\text{D}$  with an average of 4.81  $\mu\text{D}$ . When the pore pressure is 3 MPa, the permeability is 3.64-3.68  $\mu\text{D}$  with an average of 3.66  $\mu\text{D}$ . When the pore pressure continues to increase to 4 MPa, the permeability becomes 3.47-3.60  $\mu\text{D}$  with an average of 3.56  $\mu\text{D}$ . The decrease in permeability may be attributed to the combined impact of Klinkenberg effect [20] and effective stress effect.

On the one hand, Klinkenberg effect may significantly affect the gas flow behavior in low-permeability media [21–23]. In the experiment, when the pore pressure is low, the mean free path of helium molecules approaches the aperture of the coal cleats, and significant molecular collisions occur with the solid walls instead of other gas molecules [24]. Then, the gas permeability can be enhanced by the “slip flow.” Therefore, with the increase in pore pressure, the gas slippage effect diminishes, and the permeability decreases. On the other hand, based on the law of effective stress [25], the effective stress depends on the confining pressure, pore pressure, and effective stress coefficient. Zhao et al. [26] noted that the effective stress coefficient is not a constant for coal and is a bilinear function of volumetric stress and pore pressure. Thus, with the change in pore pressure, the effective stress coefficient may also change, which causes various permeabilities.

Similar to the result obtained in helium, the carbon dioxide permeability of coal decreases with the increase in pore pressure when the net confining pressure remains constant, as shown in Figure 6(b). The result is consistent with Chen et al. [19], Feng et al. [4], and Pan et al. [18]. The carbon dioxide permeability has a deeper decline with the increase in pore pressure than helium permeability. When the pore pressure increases from 1 MPa to 4 MPa, the carbon dioxide permeability decreases from approximately 400  $\mu\text{D}$  to 20  $\mu\text{D}$  (95% reduction), while the helium permeability only decreases from approximately 5.8  $\mu\text{D}$  to 3.5  $\mu\text{D}$  (40% reduction). In addition to Klinkenberg effect and effective stress effect, the adsorption effect may also decrease the permeability. Because carbon dioxide is an adsorbing gas to coal, it is well accepted that the decrease in permeability can be attributed to the swelling of the coal matrix induced by carbon dioxide adsorption [27–30].

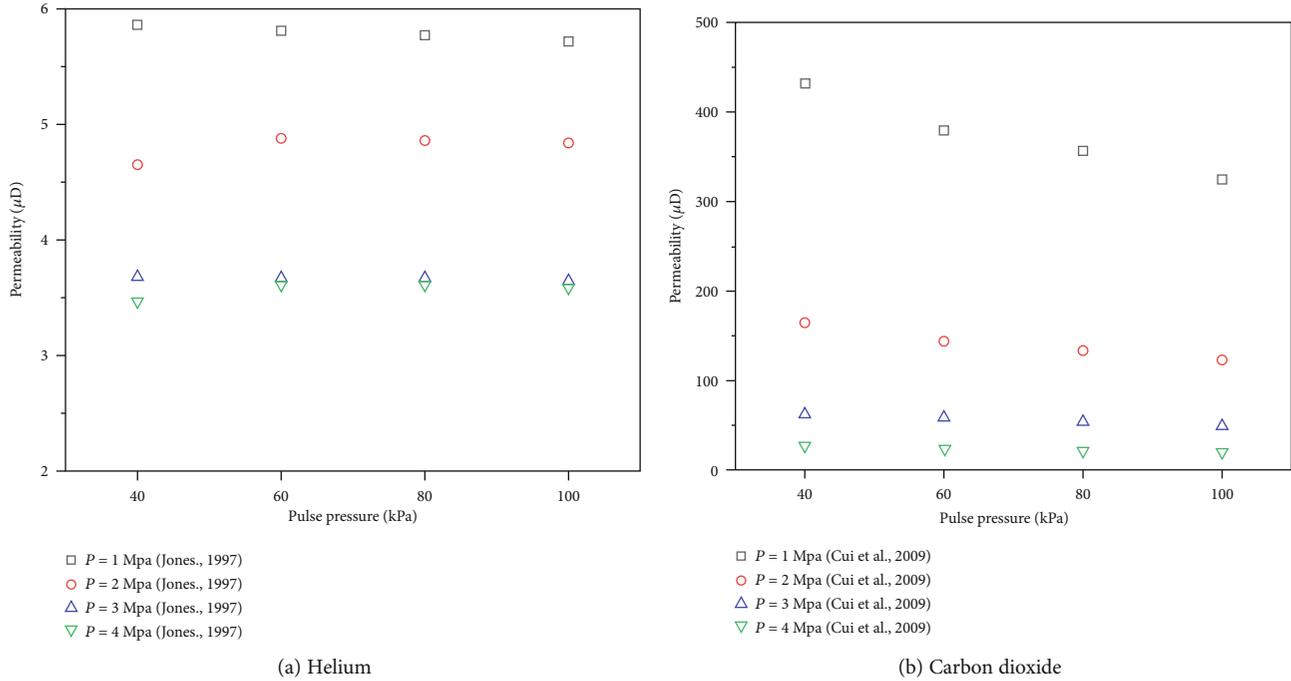


FIGURE 8: Gas permeability under different pulse pressures (net confining pressure = 3 MPa)

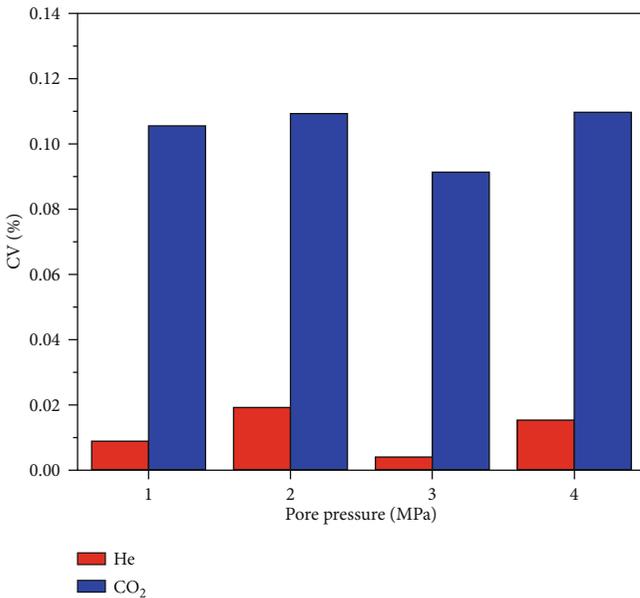


FIGURE 9: CV of the gas permeability measured by different pulse pressures under different pore pressures.

The permeability of coal tested by helium is obviously less than that tested by carbon dioxide, which may be related to the experiment process in our study. As shown in Figure 7, carbon dioxide was first used as the test fluid. It is commonly accepted that the change in pore structure induced by gas adsorption is irreversible [29, 31–33]. Thus, even when the carbon dioxide was released after the test, the pore structure of the coal will not revert to the original state. In addition, the permeability of coal is sensitive to stress [18, 34]. After step 4,

carbon dioxide was firstly exhausted (①); then, the confining pressure decreased (②). In this process, the maximum net confining pressure ( $P_{\max nc}$ ) is 6.9 MPa. Before the helium test (step 5), the confining pressure was first applied (③); then, helium was injected (④), and  $P_{\max nc}$  was also 6.9 MPa. Thus, the maximum net confining pressure of coal in history is 6.9 MPa before the helium test, which may also cause the decrease in coal permeability.

**4.4. Gas Permeability under Different Pulse Pressures.** To investigate the effect of the pulse pressure on the measurement of helium and carbon dioxide permeability of coal using the transient technique, a series of experiments were conducted, and the result is shown in Figure 8. Figure 8(a) visually shows the calculated values of helium permeability measured at each pulse pressure. With the increase in pulse pressure, the changing trend of helium permeability under different pore pressures is inconsistent. When the pore pressure is 1 MPa and 3 MPa, the calculated permeability decreases with the increase in pulse pressure. When the pore pressure is 2 MPa and 4 MPa, the permeability first increases and subsequently decreases. However, by comparing the decay curve of the pulse pressure, we easily find that the slope of  $\ln(\Delta P_t/\Delta P_0) - t$  is almost the same (Table 2) under different pulse pressures at each pore pressure condition. The fluctuation of the calculated permeability is attributed to the change in pore pressure, which changes the gas compressibility and viscosity. Generally, the change in helium permeability with pulse pressure is negligible, especially when the pulse pressure is 60–100 kPa.

The change in carbon dioxide permeability with pulse pressure is shown in Figure 8(b). The carbon dioxide permeability of coal decreases with the increase in pulse pressure, and the degree of permeability decrease is related to the pore

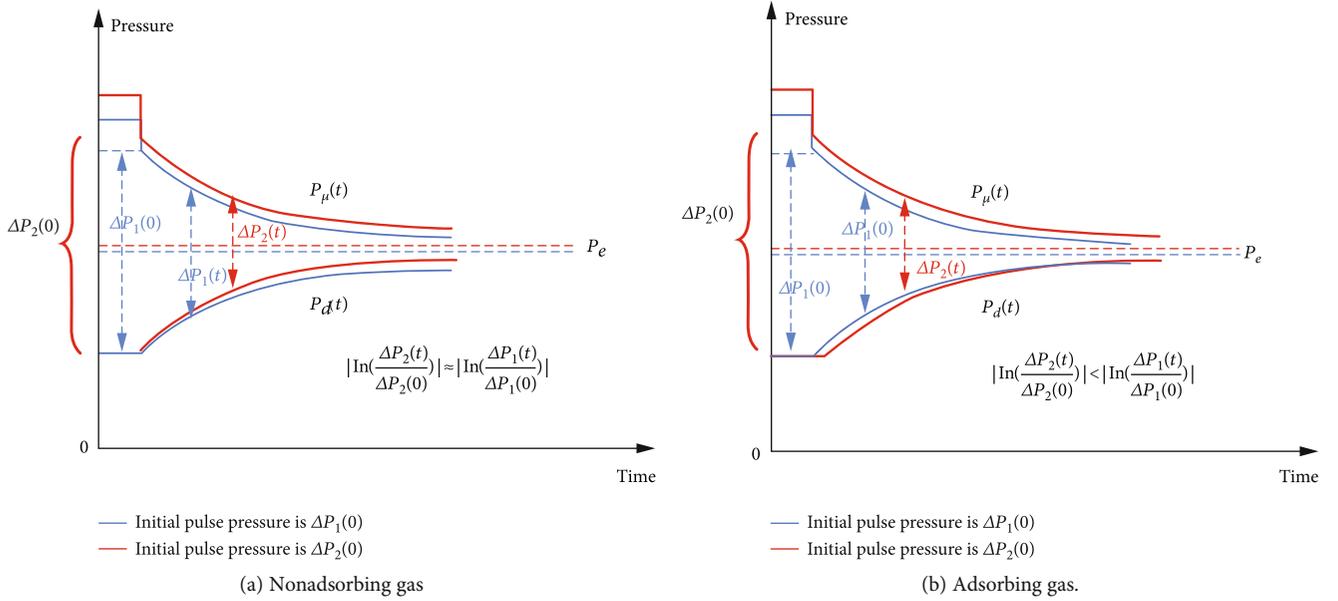


FIGURE 10: Changes of pressure for nonadsorbing and adsorbing gases under different pulse pressures in the transient technique.

pressure. In our experiment, when the pore pressure is 1 MPa, as the pulse pressure increases from 40 kPa to 100 kPa, the measured permeability decreases from 432.1  $\mu\text{D}$  to 323.91  $\mu\text{D}$ . When the pore pressure becomes to 2 MPa, the calculated permeability decreases from 164.71  $\mu\text{D}$  to 123.02  $\mu\text{D}$ . When the pressure further increases to 3 MPa and 4 MPa, the measured permeability only decreases from 62.49  $\mu\text{D}$  to 49.01  $\mu\text{D}$  and from 27.84  $\mu\text{D}$  to 20.85  $\mu\text{D}$ , respectively, i.e., it becomes relatively stable.

To illustrate and compare the degree of dispersion of the data measured by different pulse pressures under different pore pressures, the coefficient of variation (CV) was calculated, and the result is shown in Figure 9. The CV is extremely small for helium (less than 0.02) but greater than 0.1 for carbon dioxide. By comparing the CV of helium and carbon dioxide under each pore pressure, we find that the CV for carbon dioxide is at least five times larger than that for helium, which indicates that the carbon dioxide permeability of coal is more sensitive to the pulse pressure than the helium permeability.

The survey of the fitted slopes of  $\ln(\Delta P_t/\Delta P_0) - t$  for helium and carbon dioxide under different pulse pressures (Table 2) indicates that their difference may be attributed to the hysteresis caused by the adsorption effect. As shown in Figure 10(a), for nonadsorbing gas, with the decrease in pressure in the upstream, the pressure in the downstream can immediately respond. Thus, when the pulse pressure increases, the downstream pressure can correspondingly increase, and the differential pressure under different pulse pressures is almost constant. For adsorbing gas, as shown in Figure 10(b), due to the effect of hysteresis, the attenuation of the pressure difference between upstream and downstream slows down when the pulse pressure increases, which makes the permeability underestimated. Therefore, when the PDM is used to measure the permeability of coal, if the test fluid is carbon dioxide, the pulse pressure applied during the

experiment (within 10% of the pore pressure) will greatly affect the measurement result; if the test fluid is helium, its effect on the measurement result is negligible.

## 5. Conclusion

In this study, the PDM was employed to measure the gas permeability of coal. Both helium and carbon dioxide were used in our study, and the coal permeability was measured under different pore pressures and pulse pressures. According to the completed work, we made the following conclusions:

- (1) The carbon dioxide permeabilities of coal calculated by Jones' and Cui et al.'s methods show a great difference, which decreases with the increase in pore pressure. The difference may be attributed to the combined effect of gas adsorption and hysteresis of the downstream pressure, which decreases the differential pressure decay in the permeability measurement process. Thus, when measuring the permeability of coal with adsorbing gas, it is necessary to consider the adsorption effect.
- (2) For nonadsorbing gas (helium), the calculated permeabilities under different pulse pressures are extremely similar, while for adsorption gas (carbon dioxide), the measured permeability greatly varies. The carbon dioxide permeability of coal is more sensitive to the pulse pressure than the helium permeability due to the adsorption effect.

## Data Availability

The data used to support the findings of this study are available from the corresponding author upon request.

## Conflicts of Interest

The authors declare that they have no conflicts of interest.

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