

## Research Article

# A New Method for the Measurement of Gas Pressure in Water-Bearing Coal Seams and Its Application

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Coal seam gas pressure is one of the fundamental parameters used to assess coal seam gas occurrence and is an important index in assessing the risk of gas disaster. However, the geological characteristics of coal seams become increasingly complex with increasing mining degree, thus decreasing the accuracy and success rate of direct methods for measuring gas pressure. To address such issues, we have developed a new method for direct measurement of gas pressure in water-bearing coal seams. In particular, we developed a pressure measurement device based on theoretical analysis and quantified the basic parameters of the device based on well testing. Then, we verified the applicability of our method based on comparative analysis of the results of field experiments and indirect measurements. Our results demonstrate that this new method can resolve the effects of water pressure, coal slime, and other factors on the estimation of gas pressure. The performance of this new method is considerably better than that of traditional methods. In particular, field test results demonstrate that our method can accurately and efficiently measure gas pressure in water-bearing coal seams. These results will be of great significance in the prevention and control of coal seam gas disaster.

## 1. Introduction

Coal is the most important primary energy source and an important raw material in China [1, 2]. Nevertheless, coal output in China has decreased in recent years and more coal mines have progressed to deep mining [3, 4]. With increasing mining depth, both geological characteristics and mining conditions become increasingly complex, increasing the risk of gas disaster [5, 6].

Coal seam gas pressure is a fundamental parameter in the study of coal seam gas occurrence [7, 8]. This gas pressure is an important index describing the risk of gas outburst from coal seams; accordingly, accurate determination and control of coal seam gas pressure is critical for coal mine safety [9–11].

Previously, gas pressure has been determined based primarily on predictive models and field tests [12]. In particular, many studies have considered the relationship

between gas pressure and surface depth, typically adopting one-dimensional linear or polynomial regression methods. Such studies have derived empirical relationships based on measured gas pressure data and the specific geological characteristics of mining areas [13]. However, there are shortcomings associated with regression methods, because many factors cause estimated gas pressure to deviate considerably from measured values; accordingly, regression methods are often inaccurate and can introduce additional risk [14–17]. Furthermore, geological conditions, the construction environment, and space restrictions can make it difficult to validate these methods on site. Thus, the distribution of coal seam gas pressure has yet to be constrained accurately.

To date, measurement of coal seam gas pressure has relied heavily on certain geological criteria being met. Geological characteristics become increasingly complex with increasing mining depth and concomitant increases in gas pressure and temperature; heat damage and the risk of water

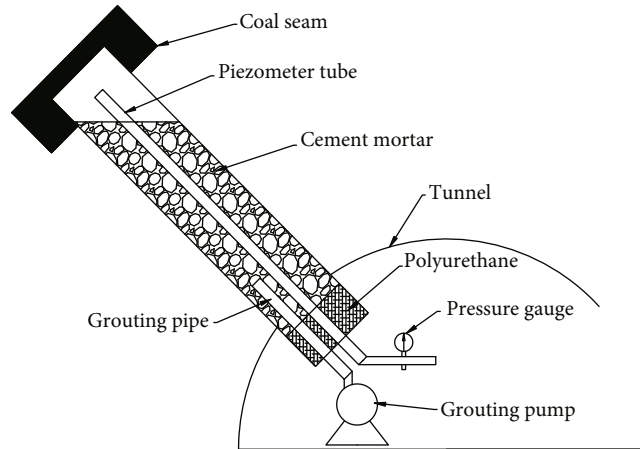


FIGURE 1: Schematic diagram illustrating direct determination of gas pressure.

inrush also increase with mining depth [18, 19]. Therefore, the measurement of gas pressure in water-bearing coal seams becomes increasingly difficult with depth [20]. In particular, achieving accuracy in the measurement of gas parameters in coal seams is extremely difficult under the coupled gas-liquid flow field, thus restricting the accuracy of prediction and on-site measurement of gas risk. Such inaccuracy has serious implications for the safety of coal mine production. Traditional methods for measuring gas pressure in water-bearing coal seams have a number of disadvantages. For example, water and coal cinder can flood into the pressure measuring borehole; this can block the borehole or produce a potential energy gradient (due to water pressure) that can affect the accuracy of the measured pressure. Devices developed in recent years are more suited to measuring pressure in water-bearing coal seams. These more recent devices typically measure pressure using a double pipe in the upper hole: a high-level pipe is used to tighten the connection between the pressure measuring gas chamber and the pressure gauge, whereas a low-level pipe is used to connect the external water discharging device to the pressure release. Although this type of device is of some practical use, it remains difficult to prevent water and coal cinder from entering the upper hole; this makes it impossible to monitor changes in water flow in real time and can result in gas leakage in the borehole. Development of an accurate means of measuring the gas pressure of water-bearing coal seams will help constrain the laws governing gas occurrence in deep coal seams. This constitutes important theoretical research that will have considerable practical significance.

The present study discusses the limitations of existing methods for the direct determination of gas pressure in water-bearing coal seams and proposes a new method for the determination of gas pressure in such coal seams. Here, the accuracy of this new method is demonstrated based on an indirect measurement method and field comparison tests. The results show that this method is sufficiently robust for application in real coal mine settings. Moreover, the proposed method provides an important theoretical basis for the determination of coal seam gas parameters and will help inform gas control measures.

## 2. Traditional Methods of Gas Pressure Measurement

**2.1. Direct Measurement Method.** Coal seam gas pressure is pressure generated by gas within coal seams, expressed in MPa. In the absence of any other constraining factors, coal seam gas pressure will reflect absolute pressure. Direct measurements of coal seam gas pressure can be obtained using boreholes and other methods that allow measurement at depth. When gas pressure is measured using a borehole, the borehole is first sealed to allow gas pressure to equilibrate in response to the natural permeability of the coal seam; then, the gas pressure is measured within a measuring chamber [21]. In practice, this is achieved as shown in Figure 1. First, the piezometer tube is installed to a predetermined depth; the length of the pipe is determined by underground roadway and transportation conditions. Then, the pipe is sealed at the orifice with polyurethane and the grouting pipe is installed. The borehole is filled with expandable/nonshrinking material comprising clean water and cement; this cement slurry is injected into the borehole in one continuous process using the cement pump. The grout is left to dry for 24 h before the pressure gauge is installed at the orifice [22, 23].

If gas pressure changes considerably within one week of installation of this apparatus, the observation time interval should be shortened appropriately. Observation results are typically plotted with time (in days) on the abscissa and gas pressure (MPa) on the ordinate. When the pressure measurement process is complete and the pressure gauge is removed (adhering to relevant safety measures), the quantity of water released from the borehole can be measured. If the borehole is connected to an aquifer or karst cave, any water flow measurements obtained from the borehole will be invalid; accordingly, the borehole should be sealed. Otherwise, measurement of water flow from the borehole can proceed. Flow rates can be obtained by measuring the volume of water released from the borehole and various borehole and sealing parameters. When there is no water flow from the borehole, for upward drilling, the results of gas pressure measurement can be expressed as shown in equation (1).

$$P^* = P_1, \quad (1)$$

where  $P_1$  is the measured value, read from the pressure gauge, and  $P^*$  is the gas pressure (both in MPa).

When the borehole contains water, correction should be undertaken as follows. When  $V > V_1$  and  $V - V_1 < V_2$ , the correction described by equation (2) should be applied.

$$P^* = P_1 - 0.01L \sin \theta - 0.01 \frac{4(V - V_1)}{\pi D^2} \sin \theta. \quad (2)$$

Conversely, when  $0 < V \leq V_1$ , correction should be undertaken according to equation (3).

$$P^* = P_1 - 0.01 \frac{4V}{\pi d^2} \sin \theta, \quad (3)$$

where  $V$  is water flow out of the borehole ( $\text{cm}^3$ ),  $V_1$  is the volume of air inside the measuring pressure tube ( $\text{cm}^3$ ),  $V_2$  is the volume of air remaining in the borehole ( $\text{cm}^3$ ),  $L$  is the length of the pressure measuring tube (m),  $D$  is the diameter of the borehole (m), and  $d$  is the diameter of the piezometer tube (m).

When  $V > V_1$  and  $V \geq V_2 + V_1$ , the volume of water flowing out of the borehole exceeds the combined volume of the air remaining in both the pressure measuring tube and the borehole. However, the potential energy of water present in the borehole means that the measured pressure is not an accurate reflection of the actual coal seam gas pressure  $P^*$ . To address this, the present study proposes a new method for measuring coal seam gas pressure that is suitable for seams with high water content.

**2.2. Indirect Measurement Method.** The indirect method described here is based on the coal seam gas adsorption theory. Coal seam gas pressure can be calculated according to equation (4), based on gas content and some basic parameters [24].

$$Q = \frac{abP}{1 + bP} \cdot \frac{1}{1 + 0.31M_t} \cdot \frac{100 - A_d - M_t}{100} + \frac{10\pi P}{\gamma}, \quad (4)$$

where  $Q$  is the adsorption gas content of coal ( $\text{cm}^3/\text{g}$ ),  $P$  is the coal seam gas pressure (MPa),  $a$  is an adsorption constant (when  $P$  tends to infinity, this represents the saturation adsorption capacity) in  $\text{cm}^3/\text{g}$ , and  $b$  is a second adsorption constant ( $\text{MPa}^{-1}$ ). Here,  $A_d$  and  $M_t$  represent the ash and water content (%) of coal, respectively;  $\pi$  is coal porosity ( $\text{cm}^3/\text{cm}^3$ ), and  $\gamma$  is the bulk density of coal ( $\text{g}/\text{cm}^3$ ).

This method of determining coal seam gas content was first investigated based on an exploration drilling desorption method that considers geological characteristics. The determination of gas content is a recognized industrial standard, and a desorption method for coal seam gas content has been established previously [25]. Smith and Williams proposed a method of calculating air leakage during coring [26]; the Smith–Williams desorption method was established based on this method [27]. Subsequently, a direct method of determining gas content based on dynamic equilibrium and gas

desorption characteristics was developed, building upon the geological exploration desorption method. This direct method originated in the United States and has been used widely, including as the Chinese national standard (GBT 23250-2009) [24, 28].

Determination of coal seam gas content can be achieved by considering the volumes of desorption gas ( $X_2$ ), gas lost during sample collection (i.e., lost gas,  $X_1$ ), and gas emitted during degassing before crushing ( $X_3$ ) and after crushing ( $X_4$ ), all measured in  $\text{cm}^3$ . Calculation in this manner is described by equation (5) [29, 30]

$$Q_i = \frac{\sum_{j=1}^3 X_i^j}{m}, \quad (5)$$

where  $Q_i$  is the coal gas content of a sample at each stage ( $i = 1, 2, 3, 4$ ) in  $\text{cm}^3 \cdot \text{g}^{-1}$ ,  $m$  is the coal sample quality (g), and  $X_i^j$  is the volume of gas at each stage ( $i = 1, 2, 3, 4, j = 1, 2, 3$ ) in  $\text{cm}^3$ .

A degassing method can be adopted to determine the adsorption gas content of coal seams, as described by equation (6).

$$Q = Q_1 + Q_2 + Q_3 + Q_4, \quad (6)$$

where  $Q$  is the adsorbed gas content,  $Q_1$  is the lost gas content,  $Q_2$  is the desorption gas content, and  $Q_3$  and  $Q_4$  are the gas contents degassed before and after crushing, all measured in  $\text{cm}^3 \cdot \text{g}^{-1}$ .

### 3. The New Method of Gas Pressure Measurement

Water pressure and water inflow are the primary factors affecting determination of gas pressure in water-bearing coal seams. In particular, water pressure in the seam can make it difficult to obtain a pressure estimate that reflects gas pressure in the coal seam accurately. Similarly, the influx of water and coal slime induces error in the pressure measuring device, further reducing the accuracy of the pressure estimate obtained.

To account for the influence of water on the piezometer, a new method has been developed that can separate water and gas and prevent coal slime obstruction. This device was designed based on the principle of automatic compensation and balancing of the water level (Figure 2) and is ideal for use in water-bearing coal seams. The primary components of the device include a piezometric tube, gas pressure gauge, water level sensor, solenoid valve, drain valve, power supply, and control devices. When the device is connected to a pressure measuring borehole, the gas and water in the coal seam enter the gas inlet and the water inlet device, respectively. Gas also enters the gas pressure gauge via the piezometric tube to allow measurement of the true coal seam gas pressure. Water and coal cinder are collected at the bottom of the device to promote gas-liquid separation, and the liquid level is controlled by the water level sensor to ensure a stable pressure measuring space. Thus, the application of this device can

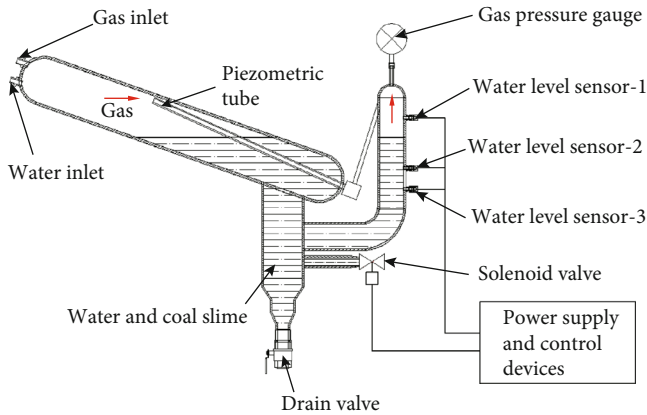


FIGURE 2: Schematic diagram of gas pressure measuring device for water-bearing coal seams.

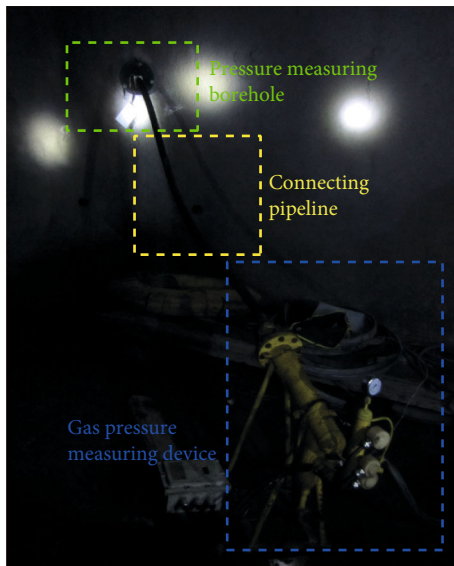


FIGURE 3: Schematic diagram showing underground connection of gas pressure measuring device.

eliminate the influence of water pressure and coal cinder on gas pressure, allowing measurement of the true gas pressure of water-bearing coal seams.

Our method for field testing can be summarized as follows.

- (1) Measurement sites were selected carefully, focusing on those in tunnels, in areas of massive lithology with no faults, cracks, or other geological structures. Drilling was undertaken to a depth of at least 15 m and proceeded through the rock surrounding the roadway until the edge of the coal seam was reached. The drilling diameter and dip angle were 146 mm and  $>0^\circ$ , respectively. Then, the coal dust was cleaned up and the drilling parameters were recorded
- (2) A pressure measuring pipe with a diameter of 108 mm was placed into the borehole, and the grouting pump was used to fill the borehole with expanding/nonshrinking cement slurry in one continuous

process, as shown in Figure 3. Then, water discharge (per minute) from the borehole was recorded

- (3) The pressure measuring borehole was connected to the pressure measuring device through the flange and the high-pressure hose. Then, the drain valve of the pressure measuring device was closed and the power supply was started; the value exhibited by the gas pressure gauge was recorded after it had stabilized
- (4) Figure 3 illustrates the discharge of water by the pressure measuring device during the pressure measuring process. After measuring the pressure, the power was turned off and the drain valve was opened slowly to discharge the pressure. When the pressure gauge reached 0, the flange and high-pressure hose were removed. The steps above were then repeated at the next measurement location. In this manner, it was possible to determine the distribution of gas in the coal seam at different locations

## 4. Results and Discussion

**4.1. Parameter Measurement.** The experimental setup shown in Figure 4 was designed to simulate real conditions in water-bearing coal strata and allow both the determination of pressure parameters and the measurement of error for the gas pressure measuring device.

The following procedure was adopted. First, 20 L of water was measured and injected into the tank; then, the high-pressure gas valve was opened and the pressure reducing valve was adjusted to achieve the desired gas pressure. The gas and water inlet valves were opened simultaneously to observe the action of the solenoid valve, and the inlet and outlet speeds and any changes in the pressure gauge were recorded.

The gas pressure was varied, and the start and end times of water flowing from the solenoid valve were recorded. Simultaneously, a measuring cylinder was used to determine the volume of water flowing out of the electromagnetic valve and thus calculate its water flow. The inlet and outlet flow rate and velocity at various gas pressures are illustrated in Figure 5.

The results demonstrate that water discharge increases linearly with increasing pressure (Figure 5(a)). Broadly, the inlet flow rate remains unchanged with increasing pressure (fitting equation:  $Q_i = 1.87P + 30.25$ ). The average water outlet velocity increases with increasing pressure (Figure 5(b), fitting equation:  $V_o = 1.973P + 2.443$ ), whereas the inlet velocity remains relatively unchanged with increasing pressure (fitting equation:  $V_i = 0.04P + 0.6$ ). In this experimental setup, the inlet of the pressure measuring device is connected to the tank of the device simulating coal seam conditions. According to the Bernoulli equation, the inlet flow rate and velocity are affected only by the weight of the water under gravity and so remain constant.

Our field experiments have shown that, when the gas pressure has a stable output, the pressure measured by the pressure gauge changes with the gas pressure (Figure 6). In particular, when the air source pressure is less than 1 MPa,  $P = P^*$  and pressure has little effect on drainage. Thus, under

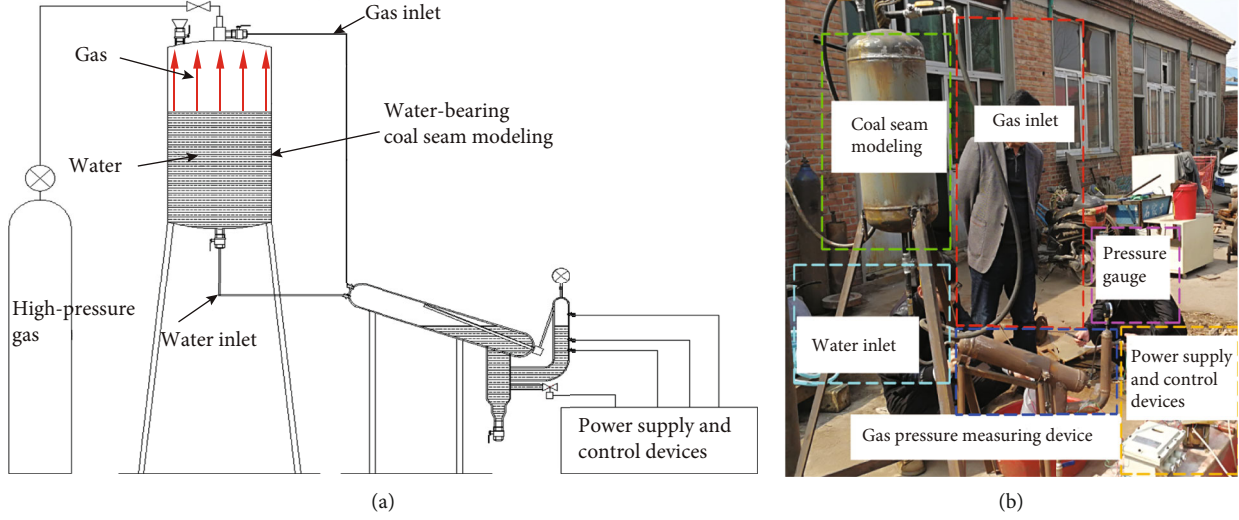


FIGURE 4: Gas pressure simulation testing in water-bearing coal seams: (a) experimental schematic diagram and (b) field test.

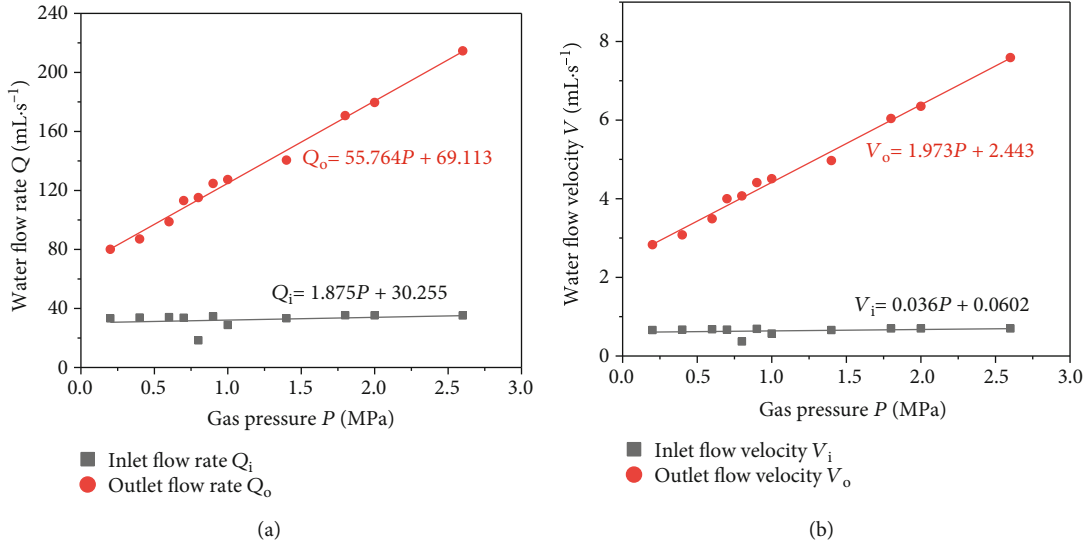


FIGURE 5: Inlet and outlet (a) flow rate and (b) flow velocity for the pressure measuring device at different gas pressures.

such conditions, drainage can be considered to be effectively zero and the pressure measured by the gauge is equal to the gas pressure. When the air source pressure exceeds 1 MPa, the pressure measured by the gauge is affected by the high gas pressure and the release of pressure during drainage; this relationship can be described by the equation  $P^* = 0.977 P^{0.937}$ . Conversely, when the solenoid valve remains closed for a certain time,  $P = P^*$  and the pressure measured by the gauge equilibrates to the air source pressure. Under these conditions, the measured pressure reflects the real gas pressure in the water-bearing coal seam accurately.

#### 4.2. Indirect Method of Measuring Gas Pressure

**4.2.1. Coal Samples.** Coal samples from three coal seams in the Kailuan mining area, China, were analyzed in the present study. Proximate analysis of these coal samples was undertaken, and the density of each sample was measured

(Table 1). All samples were ground before analysis, and the following fractions were selected to meet testing requirements: <0.05 mm, 0.20–0.25 mm, and >5 mm.

**4.2.2. Determination of Methane Adsorption Parameters.** Gas in coal typically exists in two states: free gas and adsorbed gas. Free gas content can be calculated based on the porosity and gas pressure of coal, whereas adsorbed gas content can be calculated based on the adsorption constants  $a$  and  $b$ . In the present study, we derived gas adsorption curves for the obtained coal samples using the HAC-1 high-pressure capacity method (Figure 7). The Langmuir function was used to fit the methane adsorption curve in the range 0–5 MPa. We determined adsorption constants based on equation (7).

$$Q_c = \frac{abP}{(1 + bP)}, \quad (7)$$

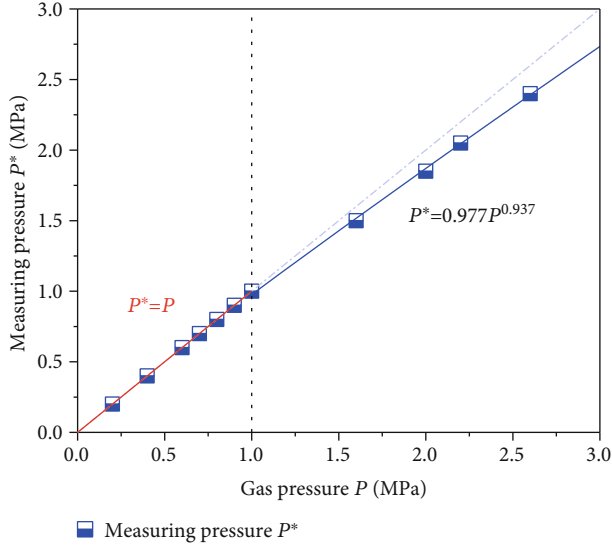


FIGURE 6: Relationship between simulated gas pressure  $P$  and measured gas pressure  $P^*$ .

TABLE 1: Density and proximate analysis results for coal samples.

Parameters	1 <sup>#</sup> coal	2 <sup>#</sup> coal	3 <sup>#</sup> coal
Proximate analysis			
Total moisture ( $M_t$ , %)	0.9	2.7	2.7
External moisture ( $M_f$ , %)	0.3	0.9	0.8
Inherent moisture ( $M_{inh}$ , %)	0.6	1.8	1.9
Ash content ( $A_d$ , %)	27.73	11.80	6.80
Volatile ( $V_d$ , %)	18.41	34.54	36.86
Total sulfur ( $S_{t,d}$ , %)	0.51	0.48	0.90
Density			
True relative density ( $\text{g}/\text{cm}^3$ )	1.62	1.42	1.37
Apparent relative density ( $\text{g}/\text{cm}^3$ )	1.58	1.39	1.32

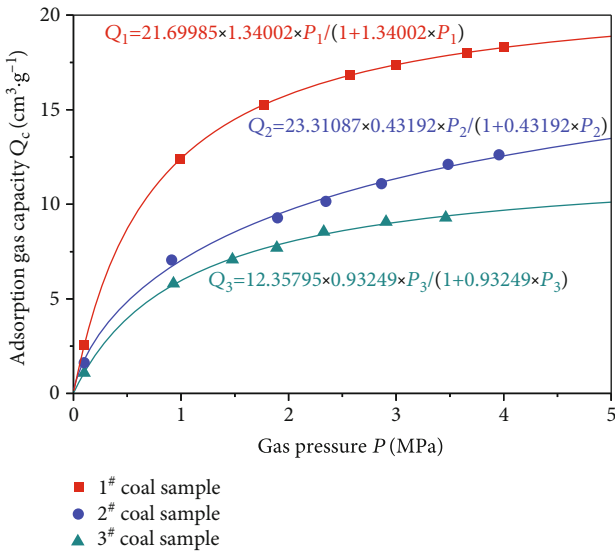


FIGURE 7: Gas adsorption curves for three coal samples under various pressures.

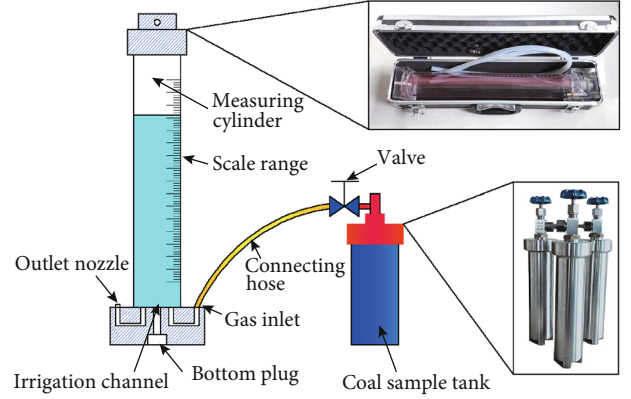


FIGURE 8: Schematic illustrating connection of DGC device.

where  $Q_c$  is gas adsorption capacity ( $\text{cm}^3 \cdot \text{g}^{-1}$ ) and  $P$  is gas pressure (MPa). We obtained the following values for the adsorption constants (in  $\text{MPa}^{-1}$ ):  $a = 21.70, 23.31,$  and  $12.36$  and  $b = 1.34, 0.43,$  and  $0.93$  for samples 1<sup>#</sup>, 2<sup>#</sup>, and 3<sup>#</sup>, respectively.

#### 4.2.3. Indirect Method of Gas Pressure Measurement

(1) *Lost Gas,  $X_1$ , and Desorption Gas,  $X_2$ .* The DGC device (Figure 8) is used widely to measure gas desorption. Here, we used this device for both downhole sampling and the measurement of gas desorption velocity.

After drilling to the required depth, we used a core tube to obtain fresh coal samples from the bottom of the hole and transferred the samples quickly to a sealed tank. To determine gas desorption  $X_2$ , we measured the calibrated liquid level every 1 min for 30 min and recorded the total exposure time ( $t_1$ ) during the sampling period, ambient temperature, and atmospheric pressure. Then, we calculated the volume of lost gas  $X_1$  based on the curve shown in Figure 9, which illustrates both gas desorption and gas lost.

(2) *Gas Released during Degassing before Crushing,  $X_3$ .* The coal sample tank was connected to the degasser using a puncture needle and vacuum hose. Each coal sample was degassed at room temperature until gas leakage was less than  $10 \text{ cm}^3$  over a period of 30 min. Then, each sample was heated to  $95^\circ\text{C}$  at a constant rate. This degassing process was repeated until degassing was deemed to be complete; the total gas released during this stage was recorded as  $X_3$ .

(3) *Gas Released during Degassing after Crushing,  $X_4$ .* The coal sample tank was removed. Then, the coal samples were removed rapidly and placed into a kibble; the tank was sealed by tightening its cover. The coal samples were crushed in the tank, and pulverized samples with particle size  $< 0.25 \text{ mm}$  (typically  $> 80\%$  of each sample) were retained.

Degassing after crushing was measured in the same way as that before crushing, and  $X_4$  was recorded after the measuring device had stabilized. After obtaining the

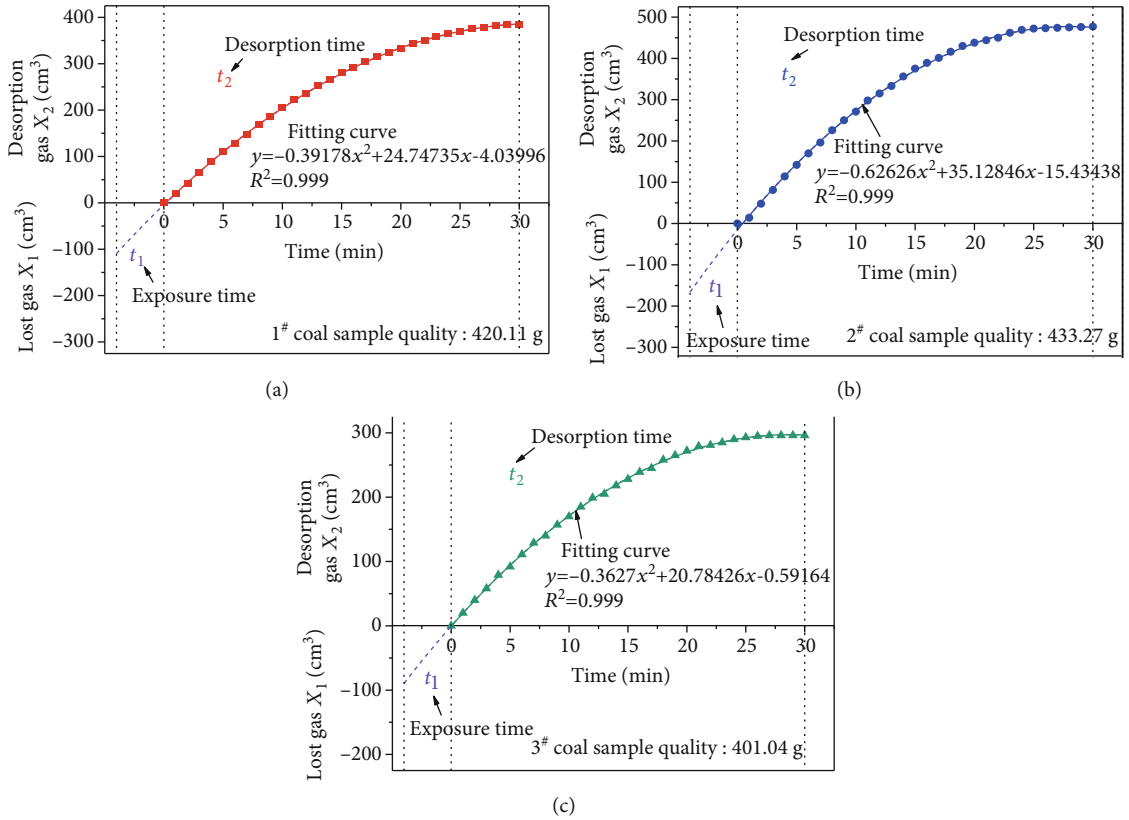


FIGURE 9: Fitting curve for lost gas  $X_1$  and desorption gas  $X_2$ .

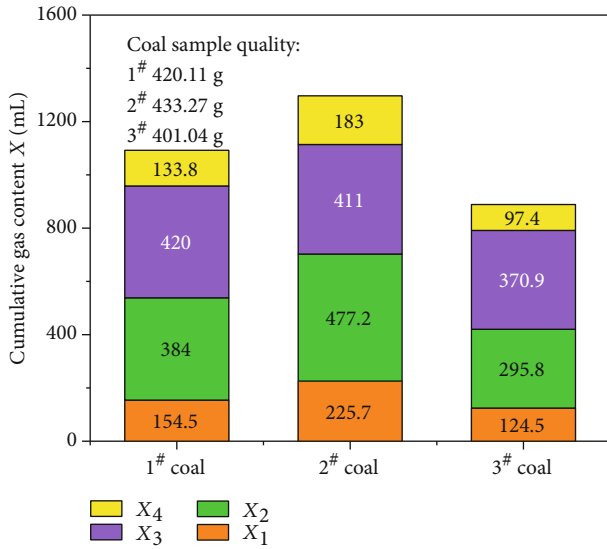


FIGURE 10: Gas content and coal quality for three coal samples.

measurements, the ball grinding tank was removed and the tank was cooled to ambient temperature before the coal sample was removed from the tank and weighed.

Gas volume and coal quality for each stage are shown in Figure 10 for the coal samples considered. Based on equation (6), the gas contents  $Q$  of the 1<sup>#</sup>, 2<sup>#</sup>, and 3<sup>#</sup> coal seams were calculated to be 2.60, 2.89, and 2.22 cm<sup>3</sup> · g<sup>-1</sup>, respectively. The gas pressure for each coal seam was calculated based

on several parameters (i.e., gas content, adsorption constant, density, and proximate analysis parameters) according to equation (4) (Table 2).

### 4.3. Application and Validation of the New Method

**4.3.1. Gas Pressure Measurement in the Field.** Field experiments were conducted on three working faces in different coal mines to determine coal seam gas pressure empirically. During testing, we drilled pressure measuring holes directly into water-bearing coal seams and grouted the holes to seal them. Then, we used both a traditional method and our new method to measure coal seam gas pressure. To allow comparison between the two methods, three pressure measuring holes were arranged at the same level for each working face, maintaining a spacing of 2 m between holes, and the pressure was measured over a period of 15 days. The drilling parameters for each working face are summarized in Table 3. Theoretically, gas is discharged slowly while the hole is being sealed; accordingly, pressure loss during sealing can be ignored. Measurements were obtained using the traditional method first, to avoid any influence of the changing of equipment on the test results.

The new method was validated by drilling three boreholes into each of the working surfaces considered. The results are presented in Figure 11. Using this novel method, maximum gas pressures of 0.25, 0.26, and 0.22 MPa were recorded for three of the boreholes considered; these values can be considered to exhibit low variability. In contrast,

TABLE 2: Gas pressure in three coal seams.

No.	Gas content ( $\text{cm}^3 \cdot \text{g}^{-1}$ )	Moisture (%)	Ash content (%)	Adsorption constant		Porosity ( $\text{cm}^3/\text{cm}^3$ )	Apparent relative density ( $\text{g} \cdot \text{cm}^{-3}$ )	Gas pressure (MPa)
				$a$ ( $\text{cm}^3 \cdot \text{g}^{-1}$ )	$b$ ( $\text{MPa}^{-1}$ )			
1 <sup>#</sup>	2.60	0.9	27.73	21.70	1.34	0.0253	1.58	0.2
2 <sup>#</sup>	2.89	2.7	11.80	23.31	0.43	0.0216	1.39	0.79
3 <sup>#</sup>	2.22	2.7	6.80	12.36	0.93	0.0388	1.32	0.54

TABLE 3: Drilling parameters for pressure boreholes in coal seams.

Borehole parameters	1 <sup>#</sup> coal seam			2 <sup>#</sup> coal seam			3 <sup>#</sup> coal seam		
	$B_1$	$B_2$	$B_3$	$B_4$	$B_5$	$B_6$	$B_7$	$B_8$	$B_9$
Drilling depth (m)	24	25	28	32	31	34	28	29	31
Hole sealing length (m)	8	8	8	10	10	10	8	8	8
Drilling diameter (mm)	$\Phi 146/108$								
Seam inclination ( $^\circ$ )	20	20	20	12	12	12	30	30	30
Water flow rate ( $\text{mL} \cdot \text{s}^{-1}$ )	5	30	22	44	62	58	55	51	90

Note: drilling diameter  $\Phi 146/108$  (coal seam drilling diameter was 146 mm and diameter of pressure measuring hole after sealing was 108 mm).

results of 0.06, 0, and 0.2 MPa were obtained for different boreholes using the traditional method. When the testing equipment was disassembled after completing the pressure measurement process, large amounts of water and coal were found to have accumulated in the  $B_1$  and  $B_2$  boreholes for the traditional method. Accordingly, it can be inferred that the results for the  $B_1$  and  $B_2$  boreholes may have been affected by water pressure and/or by coal slime blocking the pressure measurement boreholes. In contrast, only small quantities of water were found in the  $B_3$  borehole, which yielded pressure measurements similar to those obtained for the new method described in the present study (Figure 11(b)). Gas pressure measurements of 0.8 and 0.84 MPa were obtained for the  $B_4$  and  $B_5$  holes, respectively, using the new method; however, the result obtained for the  $B_6$  hole using this method is considered to be invalid. The detection of higher gas pressures for the  $B_4$  and  $B_5$  holes using the traditional method (relative to the novel method) can be explained with reference to the Bernoulli equation (8).

$$P^* + \rho gh = P_1, \quad (8)$$

where  $P^*$  is gas pressure (MPa),  $\rho$  is the density of the coal slime water (which exceeds  $1000 \text{ kg} \cdot \text{cm}^{-3}$ ),  $g$  is the acceleration due to gravity ( $\text{m} \cdot \text{s}^{-2}$ ),  $h$  is the vertical height of the hole (m), and  $P_1$  is the measured pressure (MPa). This explains why the measured pressure exceeds the real gas pressure. The result obtained for the  $B_6$  hole using the traditional method is also considered to be invalid, although this method yielded gas pressures of 1.1 and 1.0 MPa for the  $B_4$  and  $B_5$  holes, respectively. Based on these results, it can be concluded that the  $B_4$  and  $B_5$  holes were both well sealed. The higher pressures obtained using the traditional method can be attributed to the joint action of water pressure and gas pressure. Additionally, the failure of the  $B_6$  hole can be attributed

to poor sealing of the hole due to the appearance of numerous primary cracks around the hole entrance.

For the three boreholes in the 3<sup>#</sup> coal seam (Figure 11(c)), gas pressure was found to be 0.55, 0.54, and 0.58 MPa according to our new method and 0, 0.1, and 0.14 MPa according to the traditional method; as for the  $B_7$  and  $B_8$  boreholes, this discrepancy can be attributed to differences in water and gas pressure. Based on this analysis, it can be concluded that the novel method is more accurate and reliable than the traditional method and offers a higher success rate. In particular, it can effectively resolve the effects of water, slime, and other factors relevant to water-bearing coal seams on the obtained gas pressure values.

**4.3.2. Comparison of New Method with Indirect Method.** To verify the accuracy of the novel method, gas pressures obtained using this method were compared with those obtained using the indirect method (Figure 12). The results were broadly consistent between methods, thus demonstrating the accuracy and feasibility of the new method. However, the gas pressures obtained using the new method are higher than those obtained using the indirect method; this is likely because the new method is not subject to the errors in gas desorption testing and gas content calculation that typically affect the indirect method. Moreover, the novel method reduces both the number of experimental steps and the engineering input required. In summary, the present study demonstrates that the novel method is both feasible and reliable for the determination of gas pressure in water-bearing coal seams. Therefore, the results presented here will have practical significance in addressing common engineering problems in settings involving water-bearing coal seams and will help ensure coal mine production safety.

## 5. Conclusions

We have established a new method for measuring gas pressure in water-bearing coal seams to address the shortcomings of existing methods. Our main conclusions are as follows.

- (1) We have developed a new method to determine gas pressure in water-bearing coal seams based on the principle of automatic water level compensation and balance. Our novel device can effectively resolve the effects of water pressure, slime water, and other factors on measurement results and can determine gas pressure in water-bearing coal seams accurately. In particular, our device includes a solenoid valve controlled by a water level sensor that can eliminate



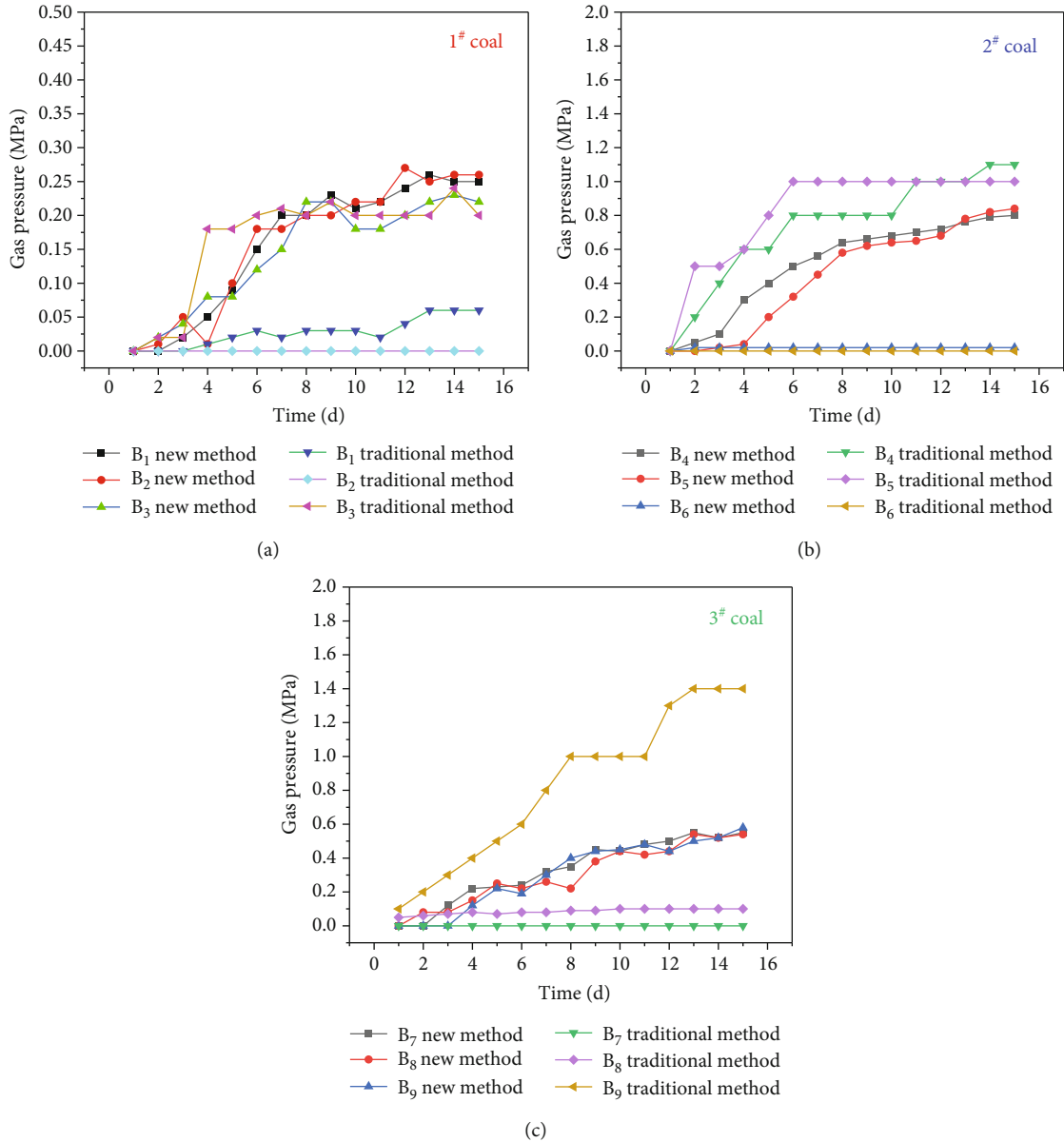


FIGURE 11: Gas pressure measurements obtained using new method and traditional method.

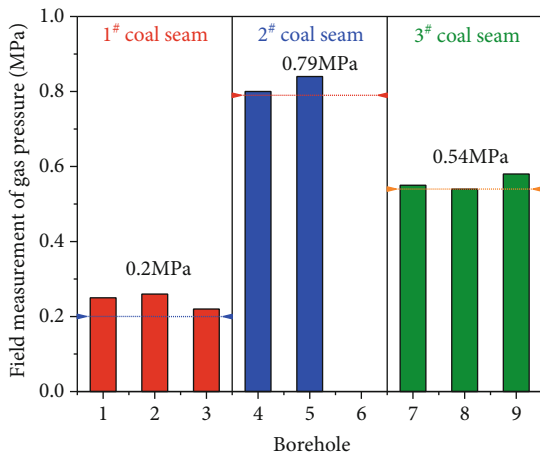


FIGURE 12: Comparison between new method and indirect method.

the effects of water over time and a drain valve that excludes the influence of coal slime

- Based on experiments considering well parameters, both water inflow and rate increase with increasing coal seam gas pressure; similarly, drainage rate increases with increasing pressure. Gas pressure has a minor effect on drainage when gas pressure < 1 MPa. Broadly, the measured gas pressure is consistent with gas pressure in the coal seam under such conditions, such that  $P^* = P$ . In contrast, when the gas pressure is > 1 MPa, the pressure relationship can be separated into drainage and nondrainage stages. The measured pressure decreases with increasing gas pressure, and the drainage flow rate and velocity are both rapid. This relationship can be described by the following composite fitting curve:

$P^* = 0.977P^{0.937}$ . When drainage has occurred continuously for a specific time period, the pressure indicated by the gauge is the same as the air source pressure value. Thus, when the gas pressure exceeds 1 MPa, the pressure measured when the solenoid valve is closed can be considered an accurate reflection of the true coal seam gas pressure

- (3) Based on field tests measuring gas pressure in water-bearing coal seams, the new method exhibits both a higher success rate and lower error than the traditional method. Moreover, there is only a small difference between the gas pressure calculated using the indirect method and that measured in the field tests of the present study, further demonstrating the accuracy of the new method. These results demonstrate that this novel method is both feasible and reliable for the determination of gas pressure in water-bearing coal seams

### 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 there is no conflict of interest regarding the publication of this paper.

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