# Experimental study on the effect of moisture on low-rank coal adsorption characteristics

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## ARTICLE INFO

## ABSTRACT

To study the effect of moisture on the adsorption characteristics of low-rank coals, samples from the Shenbei and Tiefa coalfields in China were examined. Here, a new water injection and gas adsorption device was developed to prepare the coal samples with a variety of moisture contents, and the isothermal adsorption characteristics of the coal samples for methane were tested. The results indicate that the methane adsorption isotherms of low-rank coals are consistent with the Langmuir adsorption law. Moisture clearly inhibits the adsorption ability of low-rank coals for gas and the degree of inhibition increases with increasing moisture content. However, the growing amplitude of the inhibitory effect decreases gradually as the moisture content increases. The exponential formula can properly fit the data of the gas adsorption capacity of low-rank coals with changing moisture content, and the fitting parameters $y_0$, $A$ and $c$ show the change in the gas adsorption law at the different gas pressures. Meanwhile, these fitting parameters have an exponential relationship with gas pressure. Furthermore, the Langmuir pressure of the experimental coal samples decreases with increasing moisture content. On this basis, the influence of moisture on low-rank coal bed methane (CBM) development is discussed in this paper.

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## 1. Introduction

In China, low-rank coals (with a vitrinite reflectance $R_0 < 0.65\%$) are widely distributed, and CBM resources in the low-rank coals account for approximately 43% of the proven total CBM resources (Ye et al., 2009). In past decades, the United States has achieved remarkable success in CBM development of the Powder River Basin (mainly related to lignite), in which the gas content is only 0.028–2.1 m³/t (Bustin and Clarkson, 1999; Fu et al., 2005; Pratt et al., 1999). The achievement demonstrates the significant scientific research and commercial value of low-rank coals; therefore, it is of vital realistic significance to study the coals' adsorption characteristics. Now, the CBM recovery projects are currently being developed commercially in many countries, such as Australia, China and the United States, and exploration is ongoing in many additional regions, such as Europe (Busch and Gensterblum, 2011).

For a long time, most research (e.g., Li et al., 2014; Wang et al., 2013; Yu et al., 2014) was concentrated on the medium-rank and high-rank coals, and, by comparison, scholars have paid less attention to low-rank coals, especially lignite. The porosity of low-rank coal is high, its specific surface area is large and it has many polar functional groups, such as the hydroxy and carboxyl groups, therefore, therefore, it can absorb more water than coals of the other ranks (Crosdale et al., 1998; Ettinger et al., 1966; Fu et al., 2005, 2012; Wang et al., 2011). The statistical data shows that, in China, the moisture content of long flame coal is mostly in the range of 3%–12% and the moisture content of lignite is typically 10%–28% (Qiao, 2009; Yin, 2004). In particular, the moisture content of the Neogene lignite can be as high as 40–50%. Moisture in the coal matrix has significant impact on gas adsorption capacity and also plays a key role in desorption and migration of gas (Pan et al., 2010). Therefore, the influence of moisture must be considered when adsorption characteristics of low-rank coals are studied. In the past, scholars (Crosdale et al., 2008; Joubert et al., 1974; Krooss et al., 2002; Moore and Crosdale, 2006; Xie and Chen, 2007; Zhang et al., 2009) have studied the methane adsorption regularity of the same coal with different moisture contents. However, due to limited experimental conditions, it was difficult to

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uniformly humidify the experimental coal sample and ensure accurate moisture content when coal samples with different moisture contents were prepared via artificial addition of the humidity.

Aiming at improving upon the shortcomings of previous experiments, a water injection and adsorption device that can uniformly humidify experimental coal samples was developed to prepare coal samples with different moisture contents. Then, the adsorption characteristics of the coal samples with different moisture contents were tested to study the adsorbability of low-rank coals along with the change of moisture content. Based on the results, the effect of moisture on low-rank CBM development is discussed.

## 2. Experimental analyses

### 2.1. Coal samples

The samples used in the experiment are lignite from the Shenbei coalfield and long-flame coal from the Tiefa coalfield in China. Following the ISO 17246:2010 (Coal – Proximate analysis) and ISO 7404-5:2009 (Methods for the petrographic analysis of coals – Part 5: Method of determining microscopically the reflectance of vitrinite), proximate analysis was conducted with a 5E-MAG6600 proximate analyzer, and petrographic analysis was performed with a German Zeiss microscope photometer to investigate the detailed components of the experimental samples. The results are shown in Table 1.

The coal samples were crushed in a pulverizer and screened to obtain the desired sample size of 0.2–0.25 mm. Then, the specimen were placed in a vacuum drying oven at 105 °C to completely dry for 12 h to remove the moisture in the coal.

### 2.2. Experimental instrument

The goal of this study is to evaluate the effect of moisture on the gas adsorption properties of low-rank coals, but coal samples must be vacuum degassed to exclude the influence of any impurity gas when the isothermal adsorption experiment is performed. In the process of vacuum degassing, most of the water in the coal samples will be lost, thus rendering them unable to meet the requirement of the moisture experiment. Therefore, advanced methods are required to add water to the coal samples after vacuum degassing so that the moisture content of the coal samples can achieve the desired value. To ensure that the experiment has good repeatability and accurately examines the general effect of moisture on gas adsorption characteristics of low-rank coals, we needed to ensure the uniformity of water injection as much as possible. Therefore, we researched and developed a water injection and adsorption device that can inject water into the coal sample after vacuum degassing and then stir the experimental coal sample to humidify it uniformly. The schematic diagram of the experimental device is shown in Fig. 1.

The experimental device consists of seven systems. (1) A vacuum degassing system, which includes a vacuum pump, a compound vacuum gauge and some hoses. This system is able to remove the gas existing in the pipeline network, the coal sample tank and the coal pore. The limiting vacuum of the vacuum pump is $6.7 \times 10^{-2}$ Pa, and the measuring range of the compound vacuum gauge is $1.0 \times 10^{-8} - 1.0 \times 10^5$ Pa. (2) A thermostatic system, which includes a thermostatic oil bath, an electric heater and a temperature sensor. This system is primarily used to ensure a constant temperature in the coal sample tank during the experiment being conducted, and the temperature is adjustable in the range from the room temperature to 300 °C. (3) An inflation system, which includes a high pressure $CH_4$ cylinder, a pressure reducing valve, a reference tank, four precise pressure gauges and some copper tubes. High-pressure methane gas can fill the coal sample tank quantitatively through this system. (4) An adsorption equilibrium system, which includes a coal sample tank and a pressure gauge. The volumes of the sample tanks were measured using the method of vacuum degassing, which is in accordance with the coal industry standard of the People's Republic of China (MT/T 752-1997), with a measurement is $130 \pm 0.1$ mL. This system can ensure that the coal sample in the coal sample tank filled with high-pressure $CH_4$ achieves equilibrium. (5) A water injection system, which includes a constant-flux pump and some copper tubes. The water injection pressure and flow in this system is adjustable. (6) A stirring system, which includes a blender motor, a stirring apparatus and some agitating vanes. The coal sample in the coal sample tank can be stirred through the system, and the stirring rate is adjustable. More importantly, the coal sample tank has no gas leakage during stirring. (7) A measurement system of the gas adsorption capacity, which includes several graduated cylinders, a gas sample bag and some leveling bottles, etc. The measuring equipment is produced and calibrated by China Coal Technology Engineering Group Chongqing Research Institute. The role of the system is to quantitatively measure the $CH_4$ adsorption capacity of the coal sample in the coal sample tank, which is in accordance with the coal industry standard of the People's Republic of China (MT/T 752-1997).

### 2.3. Methodology

To obtain coal samples with different moisture contents, 60 g of dried coal samples were placed into the coal sample tank in the thermostatic oil bath at a temperature of $60 \pm 0.2$ °C. The valve of the coal sample tank was opened, and the vacuum pump was used to degas the coal sample. When the vacuum level in the coal sample tank dropped below 4 Pa, the valve of the coal sample tank and the vacuum pump were turned off. After degassing, the temperature of the thermostatic oil bath was adjusted to $30 \pm 0.2$ °C. The stirring apparatus and the constant-flux pump were used to inject distilled water into the coal sample tank. The injected water volume was determined by the amount of water calculated in advance, according to the requirement for the experiment. The constant-flux pump and the corresponding valve in the coal sample tank were closed after the water injection was completed. To uniformly humidify the experimental coal sample, the stirring apparatus required continuous stirring for 45 min before being closed. After closing the stirring apparatus, the coal sample in the sample cell was equilibrated for 48 h to allow the injected water to fully humidify the experimental coal sample.

Before the isothermal adsorption experiment of the coal sample in the coal sample tank, methane, with >99.99% purity, was prepared. Generally, 6 equilibrium pressure points were required during the experiment, and every two adjacent points were at intervals approximately one-sixth of the maximum equilibrium pressure. In addition, the adsorption equilibrium of each pressure point was determined to be reached after 6 h of unchanged pressure.

**Table 1**
Proximate and petrographic analysis of the coal samples from the Shenbei and Tiefa coalfield.

| Sampling area | $M_{ad}$ (%) | $A_d$ (%) | $V_{daf}$ (%) | $V_C$ (%) | $I_C$ (%) | $L_C$ (%) | $M_C$ (%) | $R_0$ (%) |
|---|---|---|---|---|---|---|---|---|
| Shenbei coalfield | 19.56 | 8.49 | 48.83 | 96.71 | 0.35 | 0 | 2.94 | 0.41 |
| Tiefa coalfield | 4.89 | 10.86 | 44.43 | 93.22 | 1.97 | 0.88 | 3.93 | 0.61 |

$M_{ad}$ – moisture content; $A_d$ – ash content; $V_{daf}$ – volatile content; $V_C$ – vitrinite content; $I_C$ – inertinite content; $L_C$ – liptinite content; $M_C$ – mineral content; $Ro$ – vitrinite reflectance.
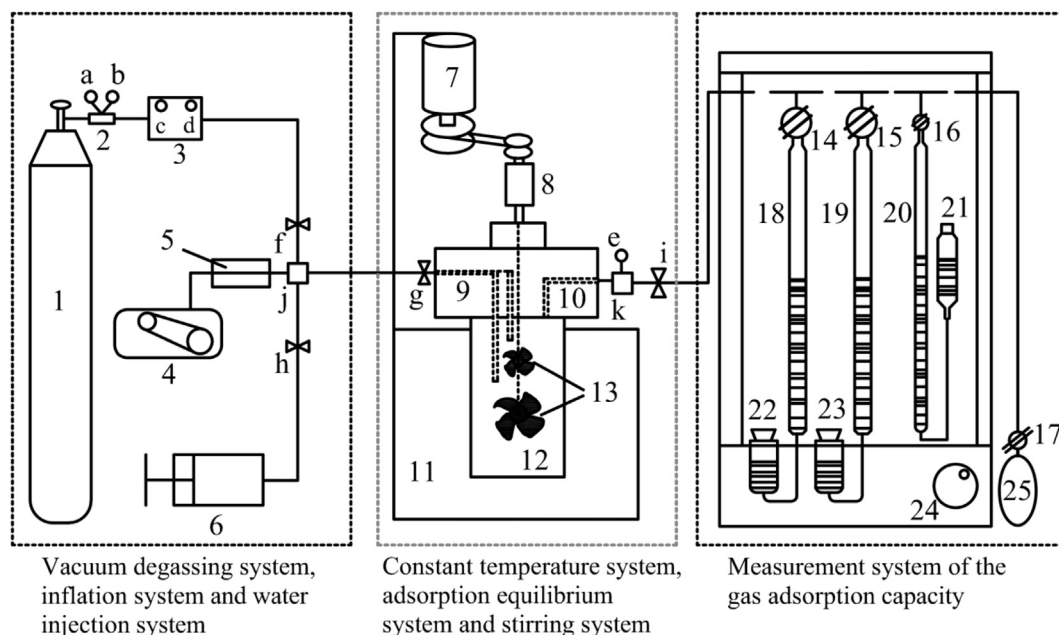
**Fig. 1.** A schematic diagram of the water injection and adsorption device. 1- High pressure $CH_4$ cylinder; 2- Pressure reducing valve; 3- Reference tank; 4- Vacuum pump; 5- Compound vacuum gauge; 6- Constant-flux pump; 7- Blender motor; 8- Stirring apparatus; 9- Water inlet and gas intake; 10- Gas outlet; 11- Thermostatic oil bath; 12- Coal sample tank; 13- Agitating vane; 14–17- Glass valve; 18–20- Graduated cylinder; 21–23- Leveling bottle; 24- Lifter knob; 25- Gas sample bag; a–e- Pressure gauge; f–i- Valve; j- Four-way joint; k- Three-way joint.

When the adsorption experiment ended, the coal sample tank was quickly opened and six coal samples from the upper, middle and lower portions of the coal sample tank were collected, respectively. Then, proximate analysis of the six coal samples was immediately performed. The results indicated that the moisture contents of the six collected coal samples were basically identical and consistent with that calculated in advance. Thus, the average moisture content was considered to be the moisture content of the coal sample in the coal sample tank. Furthermore, the void volumes were calculated according to the true density, apparent density and mass of the coal samples during the experiment. The true density and apparent density of the coal samples were measured using the Ultrapyc 1200e – Automatic Gas Pycnometer for Density from Quantachrome, with resolution and accuracy of which are 0.0001 g/mL and 0.02%, respectively.

## 3. Results and discussion

### 3.1. Pore size distribution

#### 3.1.1. Mercury intrusion porosimetry

The mercury intrusion porosimetry was conducted in the analysis and test center of the China University of Mining Technology. The instrument used was an Auto Pore IV 9500 mercury porosimeter, which could measure pore diameters of 0.003–360 μm over a pressure range of 0.1–228 MPa.

The results of the mercury intrusion porosimetry of the lignite sample are shown in Fig. 2. Following the IUPAC classification method (Kondo et al., 2006), we can obtain the pore volume and area distribution. The porosity of the lignite sample is 18.3%, and the total pore volume (total intrusion volume) is 0.1872 mL/g. In terms of pore volume, macropores with diameters of greater than 50 nm account for 29.9%, and pores with diameters ranging from 3 nm to 50 nm (mesopores) account for 70.1%. The total pore area is 94.65 $m^2$/g. Macropores account for only approximately 0.4% of the total area, and mesopores account for the remaining 99.6%.

Fig. 2 shows that the mercury intrusion curve of the coal sample

rises rapidly when the pressure is 50 MPa, and the hysteresis loop is broad, which indicates that open pores constitute a large ratio of the total and that the pores are well connected. The mercury ejection curve is slightly concave, and the mercury saturation remains at 67.4% when the pressure is down to 0.1 MPa. Additionally, the efficiency of mercury withdrawal is relatively low, which indicates that a certain amount of semi-closed pores exists (Cai et al., 2013; Chen et al., 2012). This pore structure is favorable for reservoir, diffusion and migration of CBM (Cai et al., 2013; Clarkson and Bustin, 1999; Zhao et al., 2012).

#### 3.1.2. $N_2$ adsorption/desorption test

Considering the limitation in measuring micropores and the compression effect on the coal matrix at high pressure of the mercury intrusion porosimetry, we measured the micropores of lignite using the $N_2$ adsorption/desorption test, the result of which is shown in Fig. 3.

Fig. 3 indicates that the range of the $N_2$ adsorption/desorption test is mainly 2–10 nm (mesopores), and is very similar to the data obtained from the mercury intrusion porosimetry.

### 3.2. Characteristics of the adsorption isotherm

Fig. 4 shows the adsorption isotherm of lignite based on the isothermal adsorption experiment of lignite samples with different moisture contents. Fig. 4 reveals that moisture restrains the adsorbability of lignite for the methane. When the moisture content of the coal sample rises from 0 to 4.93%, the methane adsorption capacity per unit mass of the coal sample falls to approximately 1/3 at the same pressure. Gensterblum et al. (Gensterblum et al., 2014a, 2013) has shown that the oxygen-containing functional groups are the primary sorption sides where the competition between pre-adsorbed water and $CH_4$ occurs. Many polar functional groups, such as carboxylic groups (–COOH) and hydrophilic groups (–OH), are present in the low-rank coal and these oxygen-containing functional groups are preferentially occupied by water in moist coal due to its polarity
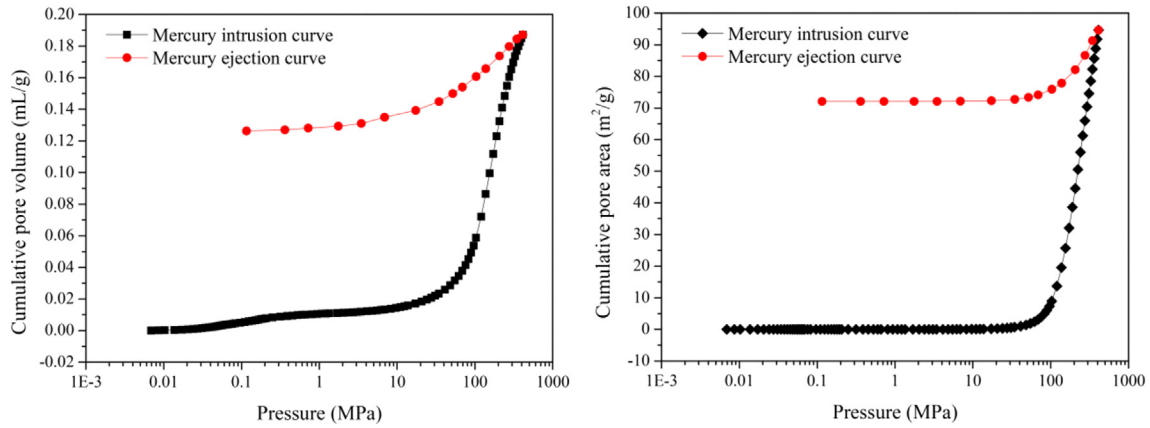
**Fig. 2.** Changes of mercury intrusion/ejection volumes and cumulative pore areas of lignite with pressure.
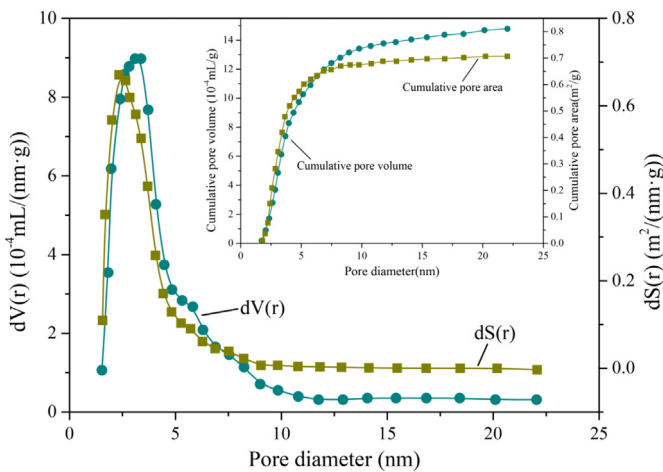


**Fig. 3.** Pore size distribution of lignite from the N$_2$ adsorption/desorption test.

(Busch and Gensterblum, 2011; Day et al., 2008; Gensterblum et al., 2014a, 2013; Moore and Crosdale, 2006). As a result, the methane adsorption capacity of the coal sample decreases.

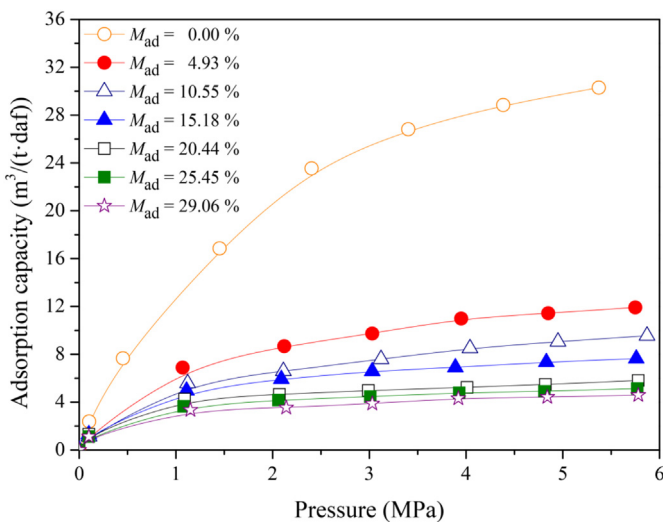Fig. 4 also shows that the growing amplitude of the inhibitory



**Fig. 4.** Methane adsorption isotherms of lignite at a constant temperature of 30 °C with different moisture contents.

effect of water on the gas adsorption of the lignite decreases with increasing moisture content and that when the moisture content is higher than 20%, a further increase in the moisture content has a negligible effect on the gas adsorption capacity of the coal. This phenomenon also exists in coals of other ranks. Joubert et al. (Joubert et al., 1974) studied the effect of water on the gas adsorption characteristics from low-volatile coal to high-volatile coal in America and found that the moisture content that affects the gas adsorption has a critical value. Day et al. (Day et al., 2008) investigated the effect of moisture on the CO$_2$ and CH$_4$ sorption capacity of three bituminous coals from Australia and China at 55 °C and at pressures up to 20 MPa and found that all coals exhibited a certain moisture content, beyond which further moisture did not affect the sorption capacity. The methane adsorption capacity per unit mass of the coal samples decreases with increasing moisture content at the same pressure when the water content does not reach the critical value, but the gas adsorption capacity of the coal will be affected insignificantly by moisture when the moisture content exceeds the critical value. This result shows that the gas adsorption properties of low-rank coals are similar to coals of other ranks. When the moisture content of the coal reaches a certain value, the effect is not a simple negative correlation between the gas adsorption capacity and the moisture content, and water is no longer the primary factor affecting the gas adsorbability.

The adsorption isotherms of the coal samples are monotonically increasing curves that all show the same trend of change. This study shows that adsorption isotherms of the coal samples follow type one of the six types of adsorption isotherm curves proposed by IUPAC in 1985 (Kondo et al., 2006; Li et al., 2010) and are very similar to the Langmuir isothermal adsorption curve. Here, we use the Langmuir equation to fit the isothermal adsorption data of the coal samples and judge their consistency with the Langmuir isothermal adsorption law through the correlation coefficient $R^2$. The Langmuir equation is as follows (Langmuir, 1918):

$$V = \frac{V_L p}{p_L + p} \tag{1}$$

where $V$ is the adsorption capacity of the unit mass of coal at pressure $p$, m$^3$/t; $V_L$ is the Langmuir volume, m$^3$/t; and $P_L$ is the Langmuir pressure, MPa.

Table 2 shows the results of using the Langmuir equation to fit the isothermal adsorption data of lignite with different moisture contents. Table 2 reveals that the correlation coefficients $R^2$

between the Langmuir equation and the experimental data of the coal sample with different moisture contents are above 0.99; therefore, the adsorption isotherm of the low-rank coal is consistent with the Langmuir equation.

### 3.3. Variation of the adsorption capacity

#### 3.3.1. Relationship between gas content and moisture content

When studying the relationship between the adsorption capacity of the coal sample and the moisture content, many scholars typically use the empirical formula proposed by a scholar from the former Soviet Union (Cheng et al., 2010; Zhang, 2004). The general formula is as follows:

$$V_m/V_d = 1/(1 + AM_{ad}) \tag{2}$$

where $V_m$ and $V_d$ are the gas adsorption capacity of the moist and dry coal, respectively, m³/t; $M_{ad}$ is the moisture content, %; and $A$ is a coefficient.

Fig. 5 shows the variation of the adsorption capacity of lignite, which is calculated according to the Langmuir volume and the Langmuir pressure as shown in Table 2, with the moisture content at the different pressures.

The isothermal adsorption data from Fig. 5 was fitted using formula (2), the result of which is shown in Table 3. Table 3 indicates that the correlation coefficient $R^2$ is low, especially in a low-pressure region. Therefore, formula (2) is not suitable for the quantitative description of the change in the gas adsorption capacity law of the low-rank coal with the moisture content.

Thus, a new method has to be developed to quantitatively analyze the relationship between the gas adsorption capacity of the low-rank coal and the moisture content. Through further research and validation, it is shown that the relationship over this range of moisture content is well described by formula (3), as shown as follows:

$$V = y_0 + Ae^{-M_{ad}/c} \tag{3}$$

where $V$ is the gas adsorption capacity of the coal, m³/t; $M_{ad}$ is the moisture content, %; and $y_0$, $A$ and $c$ are coefficients.

Table 4 shows that the influence of the gas pressure on the change of the relation between the gas adsorption capacity of lignite and the moisture content is reflected in the difference of the coefficients $y_0$, $A$ and $c$ in formula (3). The coefficients $y_0$ and $A$ increase with increasing gas pressure, and the coefficient $c$ decreases with increasing gas pressure. According to the least squares method, we find that the coefficients $y_0$, $A$ and $c$ have an exponential relationship with the gas pressure, which is shown in Table 5.

#### 3.3.2. Experimental verification

From the above analysis, we can derive the formula that quantitatively describes the relationship between the gas adsorption

**Table 2**
The result of using the Langmuir equation to fit the isothermal adsorption data of lignite.

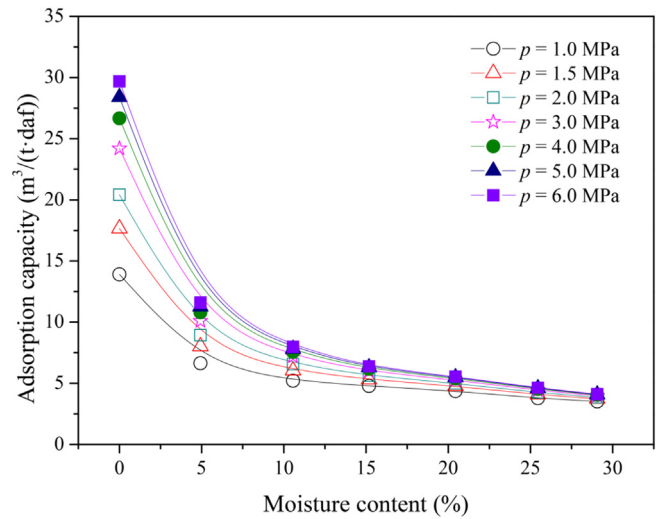| $M_{ad}$ (%) | $V_L$ (m³/(t·daf)) | $P_L$ (MPa) | $R^2$ |
|---|---|---|---|
| 0.00 | 38.39 | 1.76 | 0.9988 |
| 4.93 | 13.63 | 1.05 | 0.9901 |
| 10.56 | 8.92 | 0.71 | 0.9931 |
| 15.18 | 6.85 | 0.43 | 0.9903 |
| 20.44 | 5.86 | 0.34 | 0.9991 |
| 25.45 | 4.85 | 0.28 | 0.9972 |
| 29.06 | 4.26 | 0.21 | 0.9914 |



**Fig. 5.** Variation of the adsorption capacity of lignite with the moisture content at different pressures.

**Table 3**
The result of using formula (2) to fit the experimental data of lignite with different moisture contents.

| $p$ (MPa) | 1.00 | 1.50 | 2.00 | 3.00 | 4.00 | 5.00 | 6.00 |
|---|---|---|---|---|---|---|---|
| $A$ | 0.110 | 0.136 | 0.155 | 0.181 | 0.198 | 0.210 | 0.219 |
| $R^2$ | 0.8843 | 0.9328 | 0.9519 | 0.9676 | 0.9743 | 0.9778 | 0.9798 |

**Table 4**
The result of using formula (3) to fit the experimental data of lignite with different moisture contents.

| $p$ (MPa) | $y_0$ | $A$ | $c$ | $R^2$ |
|---|---|---|---|---|
| 1.0 | 4.066 | 9.783 | 4.389 | 0.9906 |
| 1.5 | 4.399 | 13.179 | 4.321 | 0.9919 |
| 2.0 | 4.597 | 15.727 | 4.230 | 0.9927 |
| 3.0 | 4.817 | 19.265 | 4.184 | 0.9936 |
| 4.0 | 4.943 | 21.596 | 4.133 | 0.9940 |
| 5.0 | 5.025 | 23.246 | 4.093 | 0.9943 |
| 6.0 | 5.083 | 24.475 | 4.061 | 0.9945 |

**Table 5**
Variation of the coefficients $y_0$, $A$ and $c$ with the gas pressure.

| Coefficient | Fitted formulas | $R^2$ |
|---|---|---|
| $y_0$ | $y_0 = -1.93e^{-0.61p} + 5.14$ | 0.9939 |
| $A$ | $A = -25.82e^{-0.24p} + 31.07$ | 0.9901 |
| $c$ | $c = 0.56e^{-0.34P} + 3.98$ | 0.9951 |

capacity and the moisture content of the lignite. To test whether the formula is suitable for other low-rank coals, long-flame coal from the Dalong coal mine in the Tiefa coalfield in China, with its proximate and petrographic analysis results shown in Table 1, was analyzed for methane adsorption with a variety of moisture contents (Table 6).

Based on the experimental data in Table 6, the isothermal adsorption curves of long-flame coal with a variety of moisture contents were constructed, and the experimental results were compared with the calculated data obtained according to formula (3) and Table 5 and are shown in Fig. 6. Fig. 6 shows that the measured values are consistent with the calculated values, demonstrating that formula (3) has wide applicability for the

**Table 6**
The result of the adsorption experiment of the long-flame coal with a variety of moisture contents.

| $M_{ad}$ (%) | $V_L$ (m³/(t·daf)) | $P_L$ (MPa) | $R^2$ |
|---|---|---|---|
| 0.00 | 38.97 | 1.78 | 0.9976 |
| 7.89 | 9.83 | 0.81 | 0.9935 |
| 21.21 | 6.01 | 0.59 | 0.9928 |

quantitative analysis of the effect of moisture on the gas adsorption characteristics of low-rank coals.

### 3.4. Variation of the Langmuir pressure

For moisturized coals, several publications (Gensterblum et al., 2014b; Moore and Crosdale, 2006) reported the application of the shape of the adsorption isotherm (mainly related to the Langmuir pressure) for CBM assessment. As is well known, the Langmuir pressure is defined as the pressure that gives a gas content equal to one-half of the maximum capacity of the coal and reflects the degree of difficulty of gas desorption, and thus it is important for studying the CBM drainage (Yu et al., 2008).

The experimental results (Fig. 7) reveal that the Langmuir pressure decreases with increasing moisture content, which is consistent with the conclusions drawn by Gensterblum et al. (Gensterblum et al., 2014b).

Although the adsorption rate decreases as the moisture content increases, the adsorption capacity also decreases rapidly with increasing moisture content. As a result, the adsorption equilibrium is reached at a faster rate when the moisture content is high as compared to low.

According to previous studies (Gensterblum et al., 2014b; Yu et al., 2008) and combining Figs. 5 and 7, it can be concluded that when the moisture content of the coal is low, the Langmuir pressure is large and the degree of curvature of the corresponding isothermal adsorption curve is small. This result indicates that the adsorption capacity is relatively small in a low-pressure region and relatively large in a high-pressure region, and the coal seam gas is desorbed easily when the gas pressure decreases. However, when the moisture content of the coal is high, the Langmuir pressure is small and the degree of curvature of the corresponding isothermal adsorption curve is large. This result indicates that the adsorption
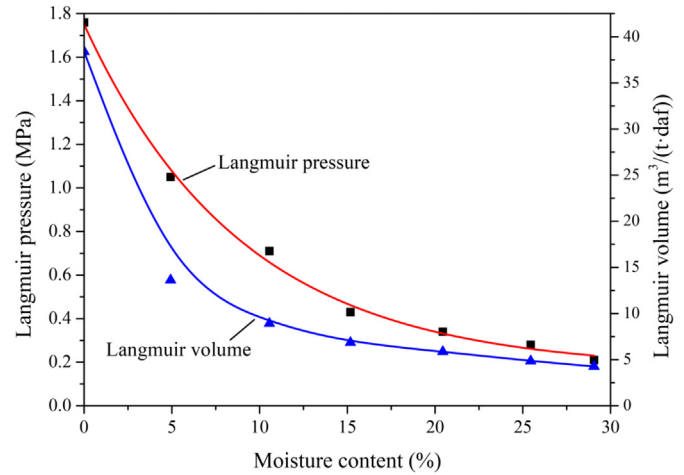


**Fig. 7.** Variation of the Langmuir pressure and Langmuir volume of lignite with the moisture content.

capacity is relatively large in a low-pressure region and relatively small in a high-pressure region, and desorption of the coal seam gas is relatively difficult.

## 4. Influence of moisture on CBM extraction of low-rank coals

CBM drainage is a process of desorption, permeation and diffusion of methane in the pores of coals, and affected primarily by the coal seam permeability. In practice, significant permeability change has been observed during CBM production (Pan and Connell, 2007). Porosity is an important parameter used to determine the free gas content and to evaluate the coal seam permeability. The mercury intrusion porosimetry shows that the porosity of lignite in the Shenbei coalfield in China is up to 18.3%. Consequently, the porosity has a significant effect on the free gas content and the coal seam permeability. Assuming that the original gas pressure of the low-rank coal seam is 2 MPa, then the gas adsorption amount of the coal is 4.71 m³/t according to formula (3) and Table 5, whereas the free gas amount calculated by the ideal gas state equation is 2.71 m³/t and accounts for 37% of the total, which is much higher than medium-and high-rank coal. Thus, the free gas amount is indispensable in CBM development of low-rank coals. However, when the gas pressure of the coal seam is reduced to 0.5 MPa after implementing gas extraction, the free gas amount decreases to 0.67 m³/t, a 75% decrease, whereas the gas adsorption amount of coal is reduced to 3.87 m³/t, decreasing by only 18%, and the gas drainage efficiency is merely 39% under ideal conditions, which does not conform to the results of the pore size distribution. The author believe it is closely related to a large amount of water in the coal. Therefore, it is very important to reduce the water content in coals by taking certain measures in CBM development.

## 5. Conclusions

Based on previous studies, a water injection and adsorption device was developed to prepare coal samples with a variety of moisture contents. Then, the effect of the moisture on the adsorption properties of low-rank coal was tested, and the conclusions are as follows:

(1) The adsorption isotherm of low-rank coal in both a dry state and a moisture state is in accordance with the Langmuir adsorption law. Moisture clearly inhibits the adsorption
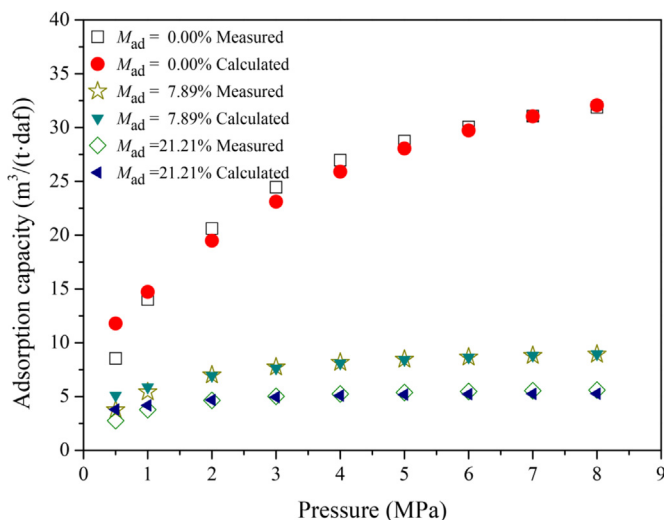


**Fig. 6.** Experimental data for long-flame coal compared with the modeled data with various moisture contents.

ability of low-rank coals for the gas, and the degree of inhibition increases with increasing moisture content. However, the growing amplitude of the inhibitory effect decreases gradually as the moisture content increases. The study shows that it is not a simple negative correlation between the gas adsorption properties of low-rank coals and the moisture content and that the moisture is no longer the primary factor affecting the gas adsorbability when the moisture content of the coal reaches a certain value.

(2) The formula $V = y_0 + Ae^{-M_{ad}/c}$ can quantitatively describe the change in the gas adsorption capacity law of low-rank coal with the moisture content. Further study showed that the change in the relation of the gas adsorption capacity and the moisture content changes with the gas pressure, and the influence of the gas pressure is reflected in the difference of the fitting parameters $y_0$, $A$ and $c$. Using the least squares method, the parameters $y_0$, $A$ and $c$ have an exponential relationship with the gas pressure.

(3) The Langmuir pressure of the coal sample decreases with increasing moisture content, reflecting the degree of difficulty of CBM desorption to a certain extent.

## Conflict of interest

The authors declare no competing financial interest.

## Acknowledgments

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