INTRODUCTION

Coal and gas outburst is a dynamic phenomenon with violent eruptions of coal and gas from the coal seam, resulting in economic loss and casualties. It is becoming increasingly serious as the mining depth extends. Based on field observations and laboratory simulations, many hypotheses regarding the mechanism of coal and gas outburst have been proposed by researchers to provide theoretical foundation for prevention and control of the outburst disaster. Most of them hold that gas plays a vital role in the development of coal and gas outburst. One of the characteristics of coal and gas outburst is of short duration but accompanied by the desorption of a large amount of adsorbed gas. Furthermore, it has been proved that the high pressure gradient produced by a large volume of gas desorbed within a short period is an essential condition to push the crushed coal into the mining space.

According to the theory of the comprehensive effect of coal, gas, and crustal stress, the gas pressure is the power source of coal and gas outburst, and the adsorption and desorption characteristics of coal partly determine the gas occurrence and gas pressure, which affect the probability and
level of the coal and gas outburst accidents. Numerous achievements regarding the adsorption property of coal have been obtained. Brenner et al. found that the adsorption of coal was the result of the solid-gas coupling under certain temperature and pressure conditions. Hol et al. studied the thermodynamic effects of CO₂ and CH₄ competitive adsorption on the surface of coal and pointed out that the adsorption capacity of CO₂ was about 2–10 times to that of CH₄. Lafortune et al. tested the volumetric deformation of coal after the adsorption of CO₂, CH₄, and H₂S and found that the relationship between the volumetric strain and pressure could be expressed by a similar Langmuir equation. Besides, the volumetric strain was approximately linear with the amount of adsorbed gas. Nie et al. held that the process of gas adsorption on the surface of coal was physical adsorption. He et al. found that the adsorption characteristics of the same adsorption system were unique, which was independent of the adsorption temperature. Jiang et al. found that the adsorption capacity of coal under the action of acoustic wave was weak, and the amount of adsorbed gas decreases with the increase in sound intensity. Liu et al. performed CH₄ adsorption experiments under the conditions of high temperature and pressure and equilibrium water, and found that the Langmuir volume of lignite decreases with the increase in the temperature, and the Langmuir volume of coking coal presents an opposite variation tendency. Besides, the Langmuir volume of gas coal and anthracite increases and then decreases with the increase in the temperature. Liang et al. divided the coal deformation under the same gas pressure into three stages and found that the expansion deformation amount of coal subjected to one-time pressurization is smaller than the cumulative expansion deformation amount of coal subjected to the pressurization with the same gradient. According to the giant regular ensemble theory, Liu et al. derived the approximation formula of the Langmuir monolayer adsorption heat model.

A large number of experiments conducted in China and abroad showed that the adsorption isotherms of coal are consistent with the Langmuir equation. The adsorption constant \( a \) is the ultimate adsorption capacity of coal. The experiment shows that with the increase in temperature, the saturated adsorption capacity of coal decreases but eventually tends to reach a stable value. The adsorption constant \( b \) is the slope of the starting point of the isothermal adsorption curve. The larger the value of \( b \) is, the faster the curve increases. The constant \( b \) is an indicator of coal adsorption gas velocity, which belongs to the inherent properties of coal. Li et al. found that the gas adsorption capacity of coal decreased with the increase in water content, and the adsorption constant \( a \) and the initial velocity \( \Delta P \) reach the maximum when the quality of the soft coal and the upper hard coal is approximately equal. At the same time, the adsorption constant \( b \) reaches the minimum value. Xu et al. got the results that the higher the gas pressure is, the more the amount of gas adsorption increases with the size of the particle size. Lin et al. come to the conclusion that there was a linear relationship between the moisture and the adsorption constant \( a \), the reciprocal of the correlation coefficient, and the initial velocity of the gas dispersion. Zhang et al. studied the relationship between the adsorption energy, adsorption, specific surface area, and adsorption capacity of coal.

The research results of Zhong et al. show that: Under the isobaric conditions, as the temperature increases, the amount of methane adsorbed by the coal is approximately linearly reduced. Under the same temperature change conditions and different pressure, the reduction degree of adsorption capacity in different coal samples is not the same. Lian et al. studied and analyzed the values of \( a \) and \( b \) in Langmuir equation by changing the adsorption conditions of coal gas under the temperature field. It pointed out that when the temperature rises, the value of \( a \) decreases gradually, and the value of “\( b \)” is not changed obviously. Xu et al. believed that the change of the internal structure of coal is due to the increase in temperature, and then, the effect of coal and gas adsorption also plays a certain role, therefore increasing the content of free gas in the pores of coal.

Gas adsorption characteristics play an important role and significance in the prevention and control of gas accident disasters. Previous studies focused on the relationship between gas adsorption capacity and equilibrium pressure under isothermal conditions, and the effect of the physical and chemical properties of coal on the adsorption performance of gas. The influence of coal seam on the adsorption performance of different coal and gas outbursts under the same geological conditions is not considered; however, the coexistence of coal seam in the same mine area is more common. In addition, with the increase in mine depth and the enhancement of mine ventilation capacity, the temperature gradient between coal wall and roadway and the application of phase change cracking technology such as liquid nitrogen increase the variation range of coal seam temperature. So, under the same geological conditions, the study on the adsorption performance of coal with different coal and gas outburst risk is of great practical significance to the outburst prevention work in mine.

In this paper, based on the specific coal mine samples, the test of high-pressure capacity method is used to investigate the adsorption constants \( a \) and \( b \) of coal under different set of temperature conditions as well as the variation rule of their values with the temperature. Therefore, the relationship between the adsorption constants \( a \) and \( b \) and the temperature of coal is established, and the relationship between the adsorption constants \( a \) and \( b \) of coal and the dangerous degree of outburst in coal seam is determined. Moreover, the distribution characteristics of the pore structure of coal seam with different outstanding risk degrees were obtained by using the scanning electron microscopy (SEM) and low-temperature nitrogen adsorption test. The research results provide certain theoretical basis and technical support for optimizing gas control technology and realizing coal and gas safety mining.
2 | EXPERIMENTAL

2.1 Determination method of adsorption constants $a$ and $b$

Microporous surface of coal has surface energy. When the gas comes into contact with the inner surface, the force of the molecules causes the methane gas molecules to accumulate on the surface, which is known as adsorption. The number of adsorbed gas molecules gradually increases for the adsorption process. The gas molecules return to the free state of the gas phase, and the number of gas molecules on the surface decreases gradually, which is called as desorption. On the surface, the gas molecules maintain a certain amount, and the adsorption rate and desorption rate are equal, which is called as the adsorption equilibrium.

When the adsorbent and adsorbate are specific, the amount of adsorption is a function of pressure and temperature, namely

$$ X = f(T, P). $$

(1)

When the temperature is constant, the below equation is obtained

$$ X = f(P). $$

(2)

Equation (2) is called as adsorption isotherm.

During the test, the adsorption capacity of different equilibrium pressure points was calculated by the Equation (3) in accordance with the equilibrium pressure and temperature of the reference cylinder and sample cylinder.

$$ PV = nZRT, $$

(3)

where $P$ is gas pressure, MPa. $V$ is gas volume, cm$^3$. $N$ is the number of moles of gas, mol. $Z$ is gas compression factor. $R$ is molar gas constant, J/(mol.K). $T$ is thermodynamics temperature, K.

The number of moles ($n_1$) of the gas in the sample before the equilibrium of the pressure point and the number of moles ($n_2$) of the gas in the sample after the equilibrium were calculated, and the number of moles ($n_i$) of the adsorbed gas of the coal sample was as follows:

$$ n_i = n_1 - n_2. $$

(4)

Adsorbed gas volume at each pressure point ($V_i$) is

$$ V_i = n_i \times 22.4 \times 1000. $$

(5)

The adsorption capacity of each pressure point ($X_i$) is

$$ X_i = V_i / m, $$

(6)

where $X_i$ is adsorption capacity, cm$^3$/g. $V_i$ is the total volume of adsorbed gas, cm$^3$. $m$ is coal sample weight, g.

The adsorption isotherm can be obtained through plotting the relationship between the measured adsorption capacity and the corresponding gas pressure, which can be fitted using the Langmuir equation (Equation 7),

$$ X = \frac{abP}{1 + bP}, $$

(7)

where $X$ is the amount of gas adsorbed by the unit mass at a certain temperature, when the equilibrium gas pressure is $P$, m$^3$/t. $a$ is the adsorption constant, which represents the maximum amount of adsorbed gas when the gas pressure approaches infinity at a certain temperature, and m$^3$/t. $b$ is adsorption constant, MPa$^{-1}$, which is the reciprocal of Langmuir pressure.

2.2 Preparation of coal samples

The coal samples were obtained from the Lvtang Coal Mine of Shandong Energy Guizhou Co., Ltd., which is located in Bijie City, Guizhou Province. The coal mine contains several minable coal seams, whose geological conditions are simple, and outburst degrees are different. In this paper, a combination of laboratory measurement and field test was used to investigate the relationship between the outburst degree and coal adsorption capacity. As shown in Figure 1, the coal samples were collected from coal seams #6, #7, and #8, and marked as N-6, N-7, and N-8, respectively. Each group of coal samples was taken from the same site and prepared according to “Method of Preparation of Coal Sample (GB/T474-2001).” Besides, as shown in Figure 2, the gas pressures of the above three coal seams were also measured.

2.3 Experimental methods

According to experimental objectives, the experiments can be divided into three groups, namely coal fundamental property characterization (group I), outburst indicators determination (group II), and coal adsorption property characterization (group III).

Group I: The true and apparent relative density and proximate analysis of coal were included in this group. In accordance with “Proximate analysis of coal (GB/T 212-2008),” the proximate analysis of coal was conducted. Its main procedures are as follows: A specified amount of coal sample was placed in a drying chamber under 105-110°C and dried in a dry nitrogen stream to a constant mass. Thus, coal on the air-dry basis can be calculated according to the mass loss of the coal sample. Under a certain heating speed to 815 ± 10°C, a specified amount of coal sample was put into the muffle furnace to be incinerated and burnt to a constant mass. The air-drying of coal ash is the ratio of the quality of the residue to the quality of the coal sample. At a temperature of 900 ± 10°C, a certain amount of coal was heated in a porcelain crucible with a cover
for 7 minutes, which was insulated from the air. The volatility of the coal sample is calculated as follows:

\[ V_{daf} = \left( \frac{m_1}{m} \right) \times 100 - M_{ad} - \left( \frac{M_{ad} - A_{ad}}{100} \right) \times 100, \]  

where \( m_1 \) is decreased quality of the coal sample; \( m \) is the specified amount of coal sample; \( M_{ad} \) is air-dry basis of coal sample; \( A_{ad} \) is air-drying of coal sample ash; \( V_{daf} \) is volatile matter of coal without ash-based.

The true relative density and apparent relative density of coal samples were measured by MDMDY-300 automatic density instrument (helium). The true relative density and apparent relative density of each group were the average value of three different measurements.

**Group II:** The initial gas diffusion velocity measurement, coal hardiness coefficient measurement, and gas pressure determination were included in this group. According to the “determination method for index (\( \Delta P \)) of gas initial diffusion velocity of coal,” the determination of gas initial diffusion velocity of coal was conducted. According to the “Methods for determining the physical and mechanical properties of coal and rock-Part 12: Methods for determining coal hardiness coefficient,” the determination of coal hardiness coefficient was conducted. According to “the direct measuring method of gas pressure in coal mine,” the gas pressure of coal seams (N-6, N-7, and N-8) was determined, respectively.

**Group III:** The experimental procedures of coal adsorption constants determination under different temperatures can be summarized as follows: First of all, one of the coal samples with a certain granularity and certain equilibrium water content is placed in the sample container (as shown in figure 3). Then, the sample cylinder was vacuumed to below 133 Pa using the vacuum pump, and then, the degassing was carried out for 6 hours. The purpose was to remove gas such as the adsorbed air of the coal sample, and then, the methane isothermal adsorption test was carried out at a constant temperature of 20, 30, 40, 50, 60, and 70°C, respectively. Then, according to Equation (7), the adsorption constants \( a \) and \( b \) were obtained by fitting. This paper only considers the effect of temperature on the adsorption constants. Factors such as water content, ash content, volatiles, and particle size were set as fixed value.

### RESULTS

#### 3.1 Proximate analysis

The result of proximate analysis is shown in Table 1. It can be seen from Table 1 that all the coal samples have the same coal rank, whose true relative density (TRD) and apparent relative density (ARD) present a little difference.

#### 3.2 Outburst degree classification of coal seams

The results of gas pressure determination, coal hardiness coefficient measurement, and initial gas diffusion velocity measurement are displayed in Table 2. It can be seen from Table 2 that different coal seams have various outburst degrees, namely have different values of gas pressure, coal hardiness coefficient, and initial gas diffusion velocity of coal. Besides,
The values of gas pressure can be ranked as: N-6 > N-7 > N-8, the values of coal hardiness coefficient can be ranked as: N-8 > N-7 > N-6, and the values of initial gas diffusion velocity of coal can be ranked as: N-6 > N-7 > N-8. Generally, the gas pressure represents the amount of gas stored in the coal seam, coal hardiness coefficient represents the strength of the coal, and initial gas diffusion velocity of coal represents the gas diffusion capacity of coal at the initial period of outburst. Therefore, the coal seam N-6 has the largest amount of stored gas, lowest coal strength, and strongest gas diffusion capacity at the initial period of outburst. Coal seam N-8 has the lowest amount of stored gas, largest coal strength, and weakest gas diffusion capacity at the initial period of outburst.

In order to classify the outburst degree of the coal seams, according to the “Provision of prevention and control of coal and gas outburst” issued by China, the outburst degree classification criteria were summarized and are listed in Table 3. In accordance with the above-mentioned classification criteria, the outburst degrees of coal seams N-6, N-7, and N-8 were obtained and are displayed in Table 2. It can be seen from Table 2 that the outburst degree of the three coal seams can be ranked as: N-6 > N-7 > N-8. Besides, it also can be found that the selection of the target coal mine is reasonable since the coal samples from the same coal mine have obviously three different outburst degrees.

3.3 | Gas isotherm of coal seams under different temperatures

The results of the isothermal adsorption curves of each coal sample under different temperatures are shown in Figure 4. It can be seen from Figure 4 that different coal seams have different isothermal adsorption curves. Besides, the adsorption curve of different coal seams at the same temperature can be ranked as: N-6 > N-7 > N-8. It can be seen from the adsorption curves of the same coal seam at different temperatures that when the temperature increases, the amount of adsorbed gas decreases, and the adsorption curves present a similar variation tendency with the increase in adsorption pressure, namely rapid rise firstly and then gradually stabilize.

The results of adsorption constants of each coal sample at different temperatures are shown in Figure 5. It can be seen from Figure 5 that different coal seams have different adsorption constants. Besides, the adsorption constants of different coal seams at the same temperature present the similar variation tendency: When the temperature increases, the adsorption constants decreases. Generally, the adsorption constant $a$ represents the maximum amount of adsorbed gas. Therefore, the coal seam N-6 has the largest amount of adsorbed gas. Coal seam N-8 has the lowest amount of adsorbed gas.

4 | DISCUSSION

4.1 | Effect of temperature on adsorption constants

From the experimental data, it can be seen that the increase in the limit adsorption coefficient $a$ of methane to coal decreases...
with the increase in temperature, and there is a certain correlation between the value of \(a\) and the temperature \(T\). In order to establish the regression equation between \(a\) and \(T\), the experimental data are analyzed by three analytical models:

\[ Y = A \cdot B^X \]

\[ Y = A \cdot X^B \]

\[ Y = A + B \cdot T + C \cdot T^2 \]

Let \(a\) be the dependent variable and \(T\) be the independent variable. On the basis of the measured data, the equations including the adsorption constant \(a\) and temperature \(T\) are shown in Table 4.

**TABLE 2** Results of gas pressure determination, coal hardness coefficient measurement, and initial gas diffusion velocity measurement

| No. | Gas pressure (MPa) | Coal hardness coefficient | Initial gas diffusion velocity of coal (mmHg) | Outburst degree |
|-----|-------------------|---------------------------|-----------------------------------------------|----------------|
| N-6 | 1.32              | 0.22                      | 25                                            | Outburst       |
| N-7 | 0.98              | 0.45                      | 22                                            | Weak outburst  |
| N-8 | 0.64              | 0.52                      | 18                                            | Non-outburst   |

**TABLE 3** Outburst degree classification criteria of coal seams

| Outburst degree | Gas pressure (MPa) | Coal hardness coefficient | Initial gas diffusion velocity of coal (mmHg) |
|-----------------|--------------------|---------------------------|-----------------------------------------------|
| Outburst        | >1.1               | <0.3                      | ≥10                                           |
| Weak outburst   | 0.74-1.1           | 0.3-0.5                   | ≥10                                           |
| Non-outburst    | <0.74              | >0.5                      | <10                                           |

**FIGURE 3** Schematic of the experimental setup of adsorption constants determination. 1—reference cylinder; 2—sample cylinder; 3—constant temperature system; 4—constant temperature control; 5—vacuum gauge; 6—vacuum system; 7—inflatable gas source; 8—pressure reducing valve; 9—gas flow monitoring; 10—pressure monitoring; 11—data processing system.

**FIGURE 4** Isothermal adsorption curves of the coal samples.
It can be seen from Table 4 that the quadratic polynomial model coefficient $R^2$ of the three groups of coal samples is close to one, indicating that the model is highly fitted and the trend curve is highly reliable. In comparison, the correlation coefficients of the model $Y = A \cdot B^X$ and $Y = A \cdot X^B$ are close to $-1$ for the three groups of samples which shows that the relative fitting degree is good, and when the temperature is lower, the methane adsorption constant $a$ of coal is smaller and it maintains at a stable value. But if temperature increases, it drastically decreases. The measured data curve and the quadratic polynomial fitting trend line are shown in Figure 6.

Based on the measured curve and the fitting trend curve, we can see that the relationship between adsorption constants $b$ and the temperature $T$ of the N-6, N-7, and N-8 coal and three groups of coal samples can be described by quadratic polynomial functions. The measured curve (red solid line in

### Table 4: Analysis equation of adsorption constant $a$ and temperature $T$

| No. of models       | N-6                                  | N-7                                  | N-8                                  |
|---------------------|--------------------------------------|--------------------------------------|--------------------------------------|
|                     | $Y = A \cdot B^X$ model              | $Y = A \cdot B^X$ model              | $Y = A \cdot B^X$ model              |
|                     | $a = 33.966 \times 0.9964 T$         | $a = 32.3713 \times 0.9913 T (r = -0.9871)$ | $a = 26.687 \times 0.9895 T (r = -0.9872)$ |
|                     | $(r = -0.9894)$                      | $(r = -0.9760)$                      | $(r = -0.9999)$                      |
|                     | $Y = A \cdot X^B$ model              | $Y = A \cdot X^B$ model              | $Y = A \cdot X^B$ model              |
|                     | $a = 47.0482 \times T^{-0.1300}$     | $a = 73.4693 \times T^{-0.3233} (r = -0.9999)$ | $a = 71.745 \times T^{-0.3901} (r = -0.9999)$ |
|                     | $(r = -0.9760)$                      | $(r = -0.9998)$                      |                                      |
| Quadratic polynomial| $a = 0.0007 T^2 - 0.1578 T + 34.555$ | $a = 0.003 T^2 - 0.4503 T + 35.518$ | $a = 0.0029 T^2 - 0.4264 T + 29.489$ |
|                     | $(r = 0.9851)$                       | $(r = 0.9980)$                       | $(r = 0.9973)$                       |
the temperature rises, the ratio of decrease of adsorption constant \( b \) decreases with increasing temperature, which is different from the adsorption constant \( a \): the relative stable stage, the slow decreasing stage, and the accelerated decreasing stage. From the measured curve and the fitting curve shown in Figure 6, it is noted that the adsorption constant \( b \) of N-6 coal maintains at a relative steady value of about 0.77 MPa\(^{-1}\) when the temperature varies between 20 and 30°C. Above 40°C, as the temperature rises, the ratio of decrease of adsorption constant \( b \) with temperature increases.

From the measured curve and the fitting curve as shown in Figure 6, we see that adsorption constant \( b \) of N-7 coal decreases slowly in the range of experimental setting temperature. The experimental fitting curve did not show a stable phase and a sharp decreasing stage. From the measured curve and the fitting curve shown in Figure 6, we know that the adsorption constant \( b \) of N-8 coal decreases slowly when the temperature varies between 30 and 40°C. Above 40°C, as the temperature rises, the ratio of decrease of adsorption constant \( b \) with temperature increases. There is no stable phase in the test fitting curve. The measured data curve and the fitting curve show that the adsorption constants \( b \) of the outburst, weak, and non-outburst coal have a good correlation with the temperature \( T \) and the lower the temperature, the greater the value of the coal adsorption constant \( b \). The value of \( b \) is stable at low temperature, and the value decreases slowly. It decreases with the increase in temperature and has a quadratic function relationship with temperature.

According to the Langmuir theory, the adsorption constant \( b \) can be expressed by:

\[
b = \frac{b_c}{\sqrt{T}} \exp \left( \frac{\Delta H}{RT} \right),
\]

where \( T \) is adsorption system temperature, K; \( T = t + 273, t \) is the set test temperature, °C. \( \Delta H \) is adsorption heat, J/mol. \( R \) is gas constant, 8.314 J/(K·mol). \( b_c \) is adsorption constant values affected by constants such as the diffusion pressure.

From the Langmuir theoretical formula, we can see that the adsorption constant \( b \) has a quadratic function with temperature, which is consistent with the measured data curve and fitting curve.

### 4.2 Relationship between the adsorption constants and the degree of the outburst risk under various temperatures

It has been proved that the N-6 coal is the seam with coal and gas outburst, the N-7 coal is the weak coal and gas outburst seam, and the N-8 coal is the coal seam without coal and gas outburst. From Figure 5, the adsorption constant \( a \) curves of each coal seam show that in the same coalfield, the adsorption constant \( a \) of different coal samples follows a certain trend in accordance with the degree of outburst risk. Therefore, the adsorption constant \( a \) of the outburst coal seam longer than the adsorption constant \( a \) of the weak outburst coal seam longer than the adsorption constant \( a \) of the non-outburst coal seam. In the test temperature range of 20-70°C, with the increase in temperature, N-6 outburst coal seam adsorption constant \( a \) value decreased slightly by 14.73%; the decrease in adsorption constant \( a \) of N-7 weak outburst coal seam is larger, with a value of 32.76%. The adsorption constant \( a \) of the N-8 coal non-outburst coal seam had the maximum decrease amount of 38.22%. That means, the value of adsorption constant of outburst coal seam \( a \) decreases with the increase in temperature, and the adsorption constant \( a \) of the weak outburst coal seam and non-outburst coal seam decreases by a relatively large margin.

From Figure 6, the coal seam adsorption constant \( b \) curve shows that in the same coalfield, the adsorption constant \( b \) of different coal samples follows a similar trend in accordance with the degree of outburst risk. And then, the adsorption constant \( b \) of the outburst coal seam longer than the adsorption constant \( b \) of the weak outburst coal seam longer than the adsorption constant \( b \) of the non-outburst coal seam. In the test temperature range of 20-70°C, with the increase in temperature, the value of adsorption constant \( b \) of outburst coal seam (N-6 coal) has the largest decrease amount with a value of 60.57%. The decrease in the adsorption constant \( b \) of the weak outburst coal seam (N-7 coal) was the smallest with a value of 30.02%. The value of adsorption constant \( b \) of non-outburst coal seam (N-8 coal) had a relatively large decrease of 37.16%. Therefore, the adsorption constant \( b \) of the outburst coal seam decreases with the increase in temperature, and the adsorption constant \( b \) of the weak outburst seam and the non-outburst seam relatively decreases small.

It can be seen from Figures 7 and 8 that the trend curve of N-6 coal \( a \times b \) and temperature shows three stages, which are a relatively stable stage, a slow decreasing stage, and accelerated decreasing stage. Moreover, N-6 coal \( a \times b \) and adsorption constant \( b \) present a linear relationship with the temperature. Besides, it can be seen from Figures 7 and 8 that the N-7 coal \( a \times b \) and temperature curve show a linear trend, and when the temperature is low, N-7 coal \( a \times b \) data are close to N-6 coal; at higher temperatures, N-7 coals \( a \times b \) data are close to N-8 coal. The adsorption constants \( a \) and \( b \) and temperature show a quadratic function relationship; the curves of N-7 coal \( a \times b \) and adsorption constant \( a \) are similar.

Figures 7 and 8 show that the variation trend of N-8 coal \( a \times b \) and adsorption constant \( a \) is similar, which can be divided into three stages: the accelerated decreasing stage, decelerated decreasing stage, and the stable stage. The adsorption constants \( a, b \), and \( a \times b \) have a quadratic function relationship with the temperature. As shown in Figure 7, the weak outburst N-7 coal \( a \times b \) is linear with
the temperature, with a correlation coefficient of 0.9796. The measured data curve and the fitting curve correlation ratio is high, and it can be concluded that the weak outburst coal $a \times b$ is linear with the temperature, and the relationship between the outburst coal, the non-outburst coal, and the temperature is divided into two kinds of trends. Moreover, in the same coalfield, the value of $a \times b$ of different coal seams shows a certain relationship with the degree of outburst, which means, the value of $a \times b$ of weak outburst seam is smaller than that of non-outburst seam and is larger than that of outburst seam.

### 4.3 Meso-mechanism of the relationship between the adsorption constants and the degree of the outburst risk

Coal, a porous medium, consists of coal matrix and crack network. The matrix is characterized as solid grains, micropores (<10 nm), and transition pores (10-100 nm). Changes in adsorption and desorption properties of coalbed methane are due to volumetric changes in the coal matrix skeleton and pores.\(^{42,43}\) The fractal theory proposed by Mandelbrot (1982) has been widely applied to the study of coal pore structure.\(^{44,45}\) Based on the FHH model,\(^{46-48}\) Pfeifer et al\(^{49}\) derived an expression for the surface fractal dimension ($D_s$) from an analysis of multilayer adsorption and the equation is as follows:

\[
\ln \left( \frac{V}{V_0} \right) = \text{constant} + A \ln \left( \ln \left( \frac{P_0}{P} \right) \right),
\]  

where $V$ is the volume of gas adsorbate at equilibrium pressure, $V_0$ is the volume of gas in a monolayer, $P$ is the adsorption equilibrium pressure of a gas, $P_0$ is the saturation pressure of the gas at the given temperature, $A$ is a power law exponent dependent on $D_s$.

As shown in Figure 9, the SEM has been conducted to observe the coal samples with different outburst degrees. It is found that coal sample with outburst has micropores and cracks. However, the surface of weak outburst coal sample and non-outburst coal sample was smooth, with a common and similar level of pore development.

It can be found from the low-temperature nitrogen adsorption test (Table 5) that the specific surface area, pore volume, and average pore size of coal samples with different outburst danger levels were different, which is consistent with the SEM observation. According to the Langmuir monolayer adsorption model, the larger the specific surface area of coal, the more the amount of gas adsorbed at the same temperature and pressure, and the larger the adsorption constant $a$, which is consistent with the experimental results. With the increase in temperature, the adsorption constants $a$ and $b$ decrease. The possible reason is that the increase in temperature will change the internal structure of coal, resulting in a decrease in the specific surface area of coal. The results of low-temperature nitrogen adsorption test of three groups of coal samples show that the specific surface area of coal samples with outburst risk is the biggest. The specific surface area of coal sample is the smallest in non-outburst coal seam, and the specific surface area of coal samples in weak outburst and non-outburst seams is close. This test results verified the relationship between the adsorption constants and the degree of the outburst risk.

## 5 CONCLUSIONS

1. The measured data curve and the fitting curve show that the adsorption constants decrease gradually with the increase in temperature, and there is a quadratic function polynomial relationship between the adsorption constants $a$ and $b$ and the temperature $T$. The adsorption constant $a$ decreases with the increase in temperature, and this
phenomenon contains three stages, which are the accelerated decreasing stage, the decelerated decreasing stage, and the stable stage. The adsorption constant $b$ decreases with the increase in temperature, and this also contains three stages, which are the relatively stable stage, the slowly decreasing stage, and the accelerated decreasing stage.

2. The adsorption constant $a$ of weak outburst coal seam is smaller than that of outburst coal seam and is greater than that of non-outburst coal seam. With the rise in temperature, the adsorption constant $a$ of N-6 outburst coal seam decreases slightly to 14.73%. The decrease value of the adsorption constant $a$ of weak outburst coal seam is larger, and it decreases to 32.76%. The value of the adsorption constant $a$ of N-7 non-outburst coal seam has the maximum decrease to 38.22%.

3. The adsorption constant $b$ of weak outburst coal seam is larger than that of outburst coal seam and is smaller than that of non-outburst coal seam. The adsorption constant $b$ of the outburst coal seam has the maximum decrease to 60.57% with the rise in temperature. The decrease value of the adsorption constant $b$ of the weak outburst coal seam is the smallest, and it decreases to 30.02%. The decrease value of the adsorption constant $b$ of the non-outburst coal seam is relatively large and it decreases to 37.16%.

4. The value of $a \times b$ of the coal sample from different coal seams in the same coalfield shows a certain correlation with the outburst dangerous degree, that is, the value of $a \times b$ of weak outburst seam is smaller than that of outburst seam and is larger than that of burst seam.

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REFERENCES

1. Zhang Y, Zou Q. A prediction model for the slot depth of high pressure water jet. *Results Phys*. 2018;11:1105-1109.

2. Zou Q, Lin B. Fluid–solid coupling characteristics of gas-bearing coal subjected to hydraulic slotting: an experimental investigation. *Energy Fuels*. 2018;32:1047-1060.

3. Guan P, Wang H, Zhang Y. Mechanism of instantaneous coal outbursts. *Geology*. 2009;37:91-95.

4. Chen KP. A new mechanistic model for prediction of instantaneous coal outbursts dedicated to the memory of Prof. Daniel D. Joseph. *Int J Coal Geol*. 2011;87:72-79.

5. An F, Cheng Y, Wang L, Li W. A numerical model for outburst including the effect of adsorbed gas on coal deformation and mechanical properties. *Comput Geotech*. 2013;54:22-31.

6. Zhao W, Cheng Y, Jiang H, Jin K, Wang H, Wang L. Role of the rapid gas desorption of coal powders in the development stage of outbursts. *J Nat Gas Sci Eng*. 2016;28:491-501.

7. Chang WB, Zhang L, Sun XJ, Zhang ZR. Research on the relationship between gas emission capacity and adsorption constant of coal particle. *Coal Sci Technol*. 2013;8(41):229-231.

8. Zou Q, Lin B, Liu T, Hu X, Zheng C. Variations in coalbed gas content, initial gas desorption property and coal strength after drilling-slotting integration technique and gas drainage: insight into pore characteristics. *Int J Oil Gas Coal Technol*. 2017;15:235-266.

9. Zhang X, Lin B, Li Y, Zhu C, Kong J, Li Y. Enhancement effect of NaCl solution on pore structure of coal with high voltage electrical pulse treatment. *Fuel*. 2019;235:744-752.

10. Zhang Q, Yang XL. Isothermal adsorption of coals on methane under equilibrium moisture. *J Coal Soc*. 1999;24(6):566-570.

11. Shang XG. Experimental study on influencing factors of methane dispersion. *J Henan Polytechnic Univ*. 2010.

12. Research Institute of Methane Geology of Jiaozuo Mining Institute. *Introduction to Methane Geology*. Beijing: Coal Industry Press; 1999:7-31, 116-137.

13. Burgert BH, Raymond CE, Hein WJPN, John RB, van Daniel N, Ben PA. Modeling the nonisothermal devolatilization kinetics of typical South African coals. *Energy Fuels*. 2014;28(2):920-933.

14. Hol S, Gensterblum Y, Massarotto P. Sorption and changes in bulk modulus of coal- experimental evidence and governing mechanisms for CBM and ECBM applications. *Int J Coal Geol*. 2014;128-129(3):119-133.

15. Mitra A, Harpalani S, Liu S. Laboratory measurement and modeling of coal permeability with continued methane production: part1-Laboratory results. *Fuel*. 2012;94(1):110-116.

16. Liu S, Harpalani S. Permeability prediction of coalbed methane reservoirs during primary depletion. *Int J Coal Geol*. 2013;113(3):1-10.

17. Silva PNKD, Ranjith PG. Understanding and application of CO₂ adsorption capacity estimation models for coal types. *Fuel*. 2014;121(2):250-259.

18. Lafontune S, Adelise F, Bentivegna G, et al. An experimental approach to adsorption of CO₂+CH₄ gas mixtures onto coal (European RFCS CARBOLAB research project). *Energy Proc*. 2014;63:5870-5878.

19. Pan ZJ, Luke DC. A theoretical model for gas adsorption-induced coal swelling. *Int J Coal Geol*. 2007;69(4):243-252.

20. Nie BS, Duan SM. The adsorption essence of gas on coal surface. *J Taiyuan Univ Technol*. 1998;29(4):417-420.

21. He MC, Wang CG, Feng JL, Li DJ, Zhang GY. Experimental investigations on gas desorption and transport in stressed coal under isothermal conditions. *Int J Coal Geol*. 2010;83(4):377-386.

22. Jiang YD, Song X, Liu H, et al. Adsorption model and law of methane under the effect of high-power acoustic wave. *J Coal Soc*. 2014;39(1):152-157.

23. Liu GF, Zhang ZX, Song ZM, Lang PP. Adsorption experiments on CH₄ under the conditions of high temperature and pressure and equilibrium water. *J Coal Soc*. 2012;37(5):794-797.

24. Liang B, Yu HW, Sun WJ, Shi YS. An experimental on deformation of coal adsorption of low pressure gas. *J Coal Soc*. 2013;38(3):373-377.

25. Liu ZX, Feng ZC. Theoretical study on adsorption heat of methane in coal. *J Coal Soc*. 2012;37(4):647-654.

26. Gregg SJ, Sing KSW. *Adsorption Surface Area and Porosity*, 2nd edn. London: Academic Press; 1982.

27. Do DD. *Adsorption Analysis: Equilibria and Kinetics*. London: Imperial College Press; 1998.

28. Yu QX. *Mine Methane Control*. Xuzhou: China University of Mining and Technology Press; 1992:1-19.

29. Lamond TG, Price CR. Size of carbon black micropores deduced from nitrogen and dye adsorption. *J Colloid Interface Sci*. 1969;31(1):104-110.

30. Li SG, Zhao PX, Lin HF, Pan HY, Cheng LQ. Effect of mass ratio change of hard and soft coal on adsorption of methane gas. *J Min Saf Eng*. 2013;30(1):118-122.

31. Zhou F, Liu S, Pang Y, Li JL, Xin HH. Effects of coal functional groups on adsorption microheat of coal bed methane. *Energy Fuels*. 2015;29(3):1550-1557.

32. Xu MG, Ma ZH, Chen J, Xu SQ. Experimental study on influencing factors of adsorption proper ties of methane on coal. *Mineral Eng Res*. 2009;24(2):51-54.

33. Lin HF, Zhao PX, Cheng LH, Li ZL, Suo L. Experimental study of influence of water content on gas adsorption constant and initial velocity of gas diffusion. *Min Saf Environ Protect*. 2014;41(2):16-19.

34. Zhang TJ, Xu HJ, Li SG, Lin TJ. The effect of particle size on adsorption of methane on coal. *J Hunan Univ Sci Technol*. 2009;24(1):9-12.

35. Zhong LW, Zheng YZ, Yuan ZR, Lei CL, Zhang H. The adsorption capability of coal under integrated influence of temperature and pressure and predicted of content quantity of coal bed gas. *J Coal Soc*. 2002;27(6):581-585.

36. Liang B. Research gas on temperature effects on the absorption performance. *J Heilongjiang Min Inst*. 2000;1:20-22.

37. Xu J, Zhang DD, Peng SJ, Liu D, Wang L. Experimental research on influence of temperature on mechanical properties of coal containing methane. *Chin J Rock Mechan Eng*. 2011;S1:2730-2735.

38. Liao ZH. Coal and gas outburst law analysis of a coal mine in Guizhou. *J Guizhou Univ Technol*. 2008;3:31-35.

39. Nie BS, He XQ, Wang EY, Liu ZT, Sa ZY. Present situation and progress trend of prediction technology of coal and gas outburst. *J Coal Sci Technol*. 2003;6:41-45.

40. Tang JP, Pan YS, Li CQ, Dong ZX. Experimental study on adsorption and desorption characteristics of coalbed methane under three-dimensional stress. *Nat Gas Ind*. 2007;7:35-39.

41. Yao Y, Liu D, Tang D, et al. Fractal characterization of seepage- pores of coals from China: an investigation on permeability of coals. *Comput Geosci*. 2009;35(6):1159-1166.
42. Li Y, Lu GQ, Rudolph V. Compressibility and fractal dimension of fine coal particles in relation to pore structure characterisation using mercury porosimetry. Part Part Syst Charact. 1999;16(1):25-31.

43. Shao P, Wang X, Song Y, Li Y. Study on the characteristics of matrix compressibility and its influence factors for different rank coals. J Nat Gas Sci Eng. 2018;56:93-106.

44. Mahamud M, López Ó, Pis JJ, Pajares JA. Textural characterization of coals using fractal analysis. Fuel Process Technol. 2003;86(2):135-149.

45. Zhou S, Liu D, Cai Y, Yao Y, Che Y, Liu Z. Multi-scale fractal characterizations of lignite, subbituminous and high-volatile bituminous coals pores by mercury intrusion porosimetry. J Nat Gas Sci Eng. 2017;44:338-350.

46. Frenkel J. Kinetic Theory of Liquids. Oxford: Clarendon Press; 1946.

47. Halsey G. Physical adsorption on non-uniform surfaces. J Chem Phys. 1948;16(10):931-937.

48. Hill TL. Theory of physical adsorption. Adv Catal. 1952;4(6):211-258.

49. Pfeifer P, Wu YJ, Cole MW, Krim J. Multilayer adsorption on a fractally rough surface. Phys Rev Lett. 1989;62(17):1997-2000.

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