Determination of the sensitivity index and its critical value for outburst risk prediction: A case study in Fuxiang mine, China

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Abstract
Gas occurrence in coal seams shows zonation, and the outburst risk prediction index is significantly affected by coal seam gas. For different coal mine, the sensitivity of prediction index of outburst risk is inconsistent, and the different area of the same coal mine can present different sensitivities to the same index. In this study, we measured the industrial analysis of coals and determined the degree of outburst risk of each coal seam using coal samples with the particle size of 1 ~ 3 mm. The relationships between the equilibrium gas pressure and gas desorption index of drill cuttings, between the desorption index of drill cuttings and the adsorption pressure, and between the critical values of the indexes of drill cuttings were also analyzed using the fuzzy clustering method. Based on the analysis of the particle size distribution of coal samples, the influence of grain size on the critical value of the drill cuttings desorption index was studied. The results showed that the critical values of the desorption index of drill cuttings were different under different adsorption equilibrium gas pressures, and those critical values increased with increasing adsorption equilibrium gas pressure. The desorption index of drill cuttings and adsorption equilibrium gas pressure had a linear relationship, and the higher the degree of outburst risk
was, the greater the slope of the fitting function and the smaller the intercept; under the same gas pressure of adsorption equilibrium, there was a linear relationship between $\Delta h_2$ and $K_1$, and the higher the outburst risk of coal seam was, the smaller the slope of the fitting function and the greater the intercept. The drill cuttings desorption index $\Delta h_2$ was more sensitive than the index $K_1$. Under the same test pressure, the smaller the particle size of the coal samples was, the greater the value of desorption index of drill cuttings and the higher the outburst risk of coal seam. The research results have significant theoretical importance and practical value for the prediction and prevention of coal and gas outbursts in coal mines with similar occurrence conditions of coal seams.

**Keywords**  
Coal and gas outburst, sensitivity index, desorption index of drill cuttings, fuzzy clustering method

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**Introduction**

Coal is the main nonrenewable energy resource consumed in China. Due to the advancement of coal mining in recent years, mining depths have reached 1,300 m and are estimated to reach 1,500 m within the next 20 years (Fan et al., 2019a; Hasiah et al., 2013; Levine, 1986). As mining depth increases, the in situ stress as well as the pressure and content of gas in coal seams will increase, causing a corresponding increase in the outburst risk of coal seams (Li et al., 2017; Zou and Lin, 2018; Li et al., 2018). Coal and gas outbursts are the worst disasters in the mining industry. With increasing exploitation depth, outbursts when uncovering coal in cross-cut are becoming more riskous (Fan et al., 2019b; Liu et al., 2020). Coal and gas outburst accidents occur frequently during the process of uncovering coal in deep mines (Fan et al., 2019c; Feng et al., 2020; Tian et al., 2016; Wang et al., 2018). For example, on January 5, 2006, a coal and gas outburst accident occurred in the Wangfenggang coal mine of the Anhui Huainan Mining Industry Group. The accident occurred at a point 956 m down the main shaft, where an operation to uncover coal was located. It could be regarded as a typical outburst accident while uncovering cross-cut coal in a deep mine. This is because inaccurate validation of the outburst prevention effect leads to outburst accidents. In fact, the validation of the outburst prevention effect is the last outburst forecast before uncovering the coal seam, and the validation of the outburst prevention effect is the main factor in determining whether the coal seam can be uncovered directly (Guo and Saghafi, 2014; Kong et al., 2019, 2020; Yu et al., 2020). Hence, the accurate validation of the outburst prevention effect is a necessary method to ensure the safety of deep coal mine operations.

A number of scholars have developed sensitivity indexes to predict outburst-prone coal seams through research on the desorption properties of coal. For instance, the variation $K_v$ of gas emission was adopted to predict outburst proneness in Russia (Cheng et al., 2017; Li et al., 2019a, 2019b). The gas emission $V$-index is a measure of the volume of gas desorption in the interval between 35 and 70 s under atmospheric pressure (De Vegeron and Belin, 1966; Somnier, 1960; Zhang et al., 2020). The gas adsorption-desorption index ($K_1$ and $\Delta h_2$) of
drill cuttings has been conducted frequently in China. $K_1$ represents the volume of gas desorption in 1 min, and $\Delta h_2$ is the amount of gas desorption in the interval between 3 and 5 min under atmospheric pressure (State Administration of Work Safety of China and State Administration of Coal Mine Safety of China, 2009). Moreover, the initial rate of the gas emission index ($\Delta P$) has been widely adopted worldwide. The higher the initial emission rates of coals, the more outburst prone it will be. Therefore, an indicator reflecting the gas desorption characteristics (Table 1) is proposed to predict coal and gas outbursts. These indexes correspond to the volume of gas desorbed at different intervals after the coal is exposed to the atmosphere (Frid, 1997; Hu et al., 2018).

These sensitivity indexes play a very important role in outburst risk prevention. In China, after years of application and verification, it is found that the outburst risk prediction index and its critical value are inconsistent with the actual outburst risk of the mine, which is the phenomenon of ‘outburst occurrence with low index value’ (Liu et al., 2018; Nandi and Walker, 1975; Yang et al., 2018). Cheng et al. (2016) established the relationship between the gas desorption index drill cuttings $\Delta h_2$ and gas pressure in coal seams; Sun and Sun (2000) conducted a similar simulation study on the $K_1$ index in the laboratory and analyzed the results using a multiple regression method. They highlight the relationship between the index $K_1$ value and gas pressure and other related parameters and initially discuss the variation law of the critical value of the $K_1$ index; Tian et al. (2016) studied the influence the measurement error of the gas desorption index of the drill cuttings $K_1$. The common factors were analyzed and researched, and some measures and precautions to reduce errors in the measurement were proposed.

The above studies are outburst risk predictions with single-index. Due to the uncertainty of individual indexes, it is difficult to obtain accurate outburst risk judgments. To avoid the occurrence of ‘outburst occurrence with low index value’, multi-index prediction should be adopted as much as possible (Wang et al., 2018). Practice shows that different geology predictions may be different for different geological conditions. Even for the same working face under different conditions of mining technology, there may be different prediction sensitivity indexes; conversely, different prediction indexes result from different geological and mining process conditions. The working face has different sensitivities whether the predictors used are sensitive to determining the accuracy of the forecasting risk. Therefore, research on the sensitivity of outburst risk prediction indexes has become a very important technical problem in the process of outburst prediction.

In this paper, the sensitivities and critical values of $K_1$ and $\Delta h_2$ are investigated using self-developed laboratory equipment to simulate the temperature conditions of the original coal seam, and numerous experiments under different gas pressures were carried out. Identifying the sensitivity of predictive indicators and determining their critical values are very significant tasks, which can be used to avoid the occurrence of ‘outburst occurrence with low index value’ and protect mine safety.

Table 1. Gas desorption indexes.

| Index                  | $K_1$   | $\Delta h_2$ | $\Delta P$ | $K_v$  | $\Delta P_{\text{express}}$ | $V_1$ |
|------------------------|---------|--------------|------------|--------|-----------------------------|-------|
| Exposure time of coal  | 0–60 s  | 3–5 min      | 0–60 s     | 0–60 s | 0–60 s                      | 35–70 s |
| Region                 | China   | China        | World      | Russia | Turkey                       | France|
Experimental research

Experimental principle

Generally, the outburst risk prediction for a mining face is performed before mining, so the regional outburst risk prediction method (including gas pressure $P$ and gas content $W$) can be adopted. However, the determination of gas content and gas pressure in coal seams is complicated due to being time-consuming as well as being economically and technically unfavorable. Therefore, the index of outburst risk prediction often adopts the desorption values of $K_1$ and $\Delta h_2$. The theoretical basis of the two types of indexes involves the “comprehensive action mechanism of coal and gas outburst”.

The determining principle of the outburst risk prediction index of the working face is as follows: Coal-containing gas was instantly exposed to the atmosphere or instrument similar to atmospheric environmental conditions, according to the volume or variable volume pressure desorption principle determined at different times of gas desorption quantity or different times of gas desorption rate. According to the relationship between the measured data and the exposure time of the coal samples, the corresponding mathematical treatment was carried out to obtain the gas desorption index of drill cuttings.

When using the constant volume gas desorption instrument or the variable volume gas desorption instrument, indications on the instrument are the pressure values, which need to be converted into the desorption amount according to the coefficient provided by the instrument. The conversion formula (The Chinese Academy of Sciences Institute of Mathematical Statistics, 2008) is:

$$Q_i = \frac{a \times P_i + b}{G} \quad i = 1, 2, 3, \ldots, 10$$

(1)

where $Q_i$ is the coal gas desorption amount, ml/g; $a$, $b$ are instrument conversion factors, dimensionless; $P_i$ is pressure, Pa; and $G$ is the mass of the coal sample, g. The coal sample exposure time $t_i$ is:

$$t_i = t_0 + 0.5 \times i$$

(2)

where $t_i$ is the exposure time of the coal sample from the beginning of self-deflation until the data measurement, min, and $t_0$ is the exposure time of the coal sample from the beginning of self-deflation until the initiation of the gas desorption instrument, min.

The gas desorption law of the coal sample obeys the following formula:

$$Q = K_1 \sqrt{t}$$

(3)

where $Q$ is the coal gas unit mass from the exposure time to time “$t$” of desorption, ml/g, and $t$ is the coal sample exposure time, min.

Because $Q_i$ is the amount of gas desorption accumulated from time $t_0$ when the coal sample is exposed, and the amount of gas that has been desorbed before the $t_0$ moment is $W$, the following formula is obtained:

$$Q_i = K_1 \sqrt{t_i} - W$$

(4)
where \( W \) is the gas desorption loss of the unit mass of coal sample before time \( t_0 \), ml/g.

When using a variable volume and variable pressure gas desorption instrument for measurement, the gas desorption values at the times \( t_0 = 3 \) min and \( t_1 = 5 \) min correspond to the desorption amount of the gas in the cuttings \( \Delta h_2 \), and the unit of measurement is Pa.

**Experimental equipment**

The definition of a gas desorption instrument is as follows: an electronic or physical measuring instrument that is based on an equal volume and variable capacity pressure desorption principle.

In this paper, according to the Chinese standard “determination method of gas desorption index of drill cuttings” (AQ/T 1065–2008) (The Chinese Academy of Sciences Institute of Mathematical Statistics, 2008), a device for measuring the gas desorption index of drill cuttings was designed.

A schematic diagram of the test device is shown in Figure 1, which mainly includes a charging system, a high-pressure vessel, a vacuum system, and a desorption system. The high-pressure vessel was connected to the desorption system through check valves. The compression release valve was installed on the charging system to achieve the specified gas pressure.

The application of both an equal volume and variable volume gas desorption data acquisition system is the most significant feature of the experimental equipment. To obtain enough pressure data during adsorption/desorption, the time interval of desorption pressure recording was reduced to approximately 10 seconds. In general, the number of data measurements was unrestricted, and the final gas pressure was almost reduced to the level of atmospheric pressure. To ensure the accuracy of the experimental data, the high-pressure

![Figure 1](image_url)

**Figure 1.** Schematic diagram of the test system for determining the gas desorption index of drill cuttings.
vessel was placed in the constant temperature water bath, and the temperature setting was the same as the temperature of the coal seam.

Test instrument requirements:

a. Constant volumetric gas desorption instrument (for determination of “\(K_1\)”) with pressure ranges of 0 kPa–10 kPa, error ±2%.
b. Variable capacitance type gas desorption instrument (for determination of \(\Delta h_2\)) with pressure ranges of 0 kPa–3 kPa, error ±2%.
c. Vacuum pump with a flow rate of 1000 ml/s, and the vacuum limit was not greater than 0.1 Pa.
d. Coal sample tank with a volume of 300 ml, coal sample cup with a volume of 8.6 ml (wall thickness should be no more than 2 mm), connection pipe space volume of 30 ml, and the volumetric error should not exceed 5%.
e. When the coal sample tank should bear a gas pressure of 6 MPa or 4 Pa, the pressure drop in 30 h should be less than 1% under the condition that the coal sample tank did not hold the test sample.
f. The pressure gauge range was 6 MPa, and the accuracy was 0.4.
g. The tested gas methane concentration should not be less than 99.9%.
h. The electronic balance sensibility was 0.1 g.

According to the basic requirements of the above design, the experimental system for \(K_1\) and \(\Delta h_2\) determination of the drill cuttings gas desorption index was designed, and the experimental system is shown in Figure 1.

**Coal sample preparation**

The coal samples were obtained from the Fuxiang mine (FX) of Shandong Energy Guizhou Co., Ltd., which is located in Bijie City, Guizhou Province. The geographical location of the FX is shown in Figure 2. The to-be-mined coal seams in this coal mine are abundant, and the geological occurrence is common. The possibilities of outburst occurrence are different; thus, the possibility of outburst proneness in this coal mine cannot be accurately predicted by a single method. Therefore, a combination of laboratory measurements and field tests were used in this study. As shown in Figure 3, the coal samples were collected from coal seams #6, #8 and #13 and marked as N-6, N-8 and N-13, respectively. Each coal sample was taken from the same site, and the temperatures of the above three coal seams were also measured.

Sampling and sample preparation methods (flow chart shown in Figure 4) were as follows:

a. Sampling method-relevant regulations were carried out from “coal and rock physical and mechanical properties determination method first parts: sampling General Provisions” (GB/T 23561.1-2009) (The People’s Republic of China Ministry of Machine Building, 2009a); on-site sampling of #6, #8, and #13 coal seams produced samples of more than 1 kg.
b. According to the relevant provisions of the “preparation method of coal sample” (GB/T 474-2001) (The People’s Republic of China Ministry of Machine Building, 2008), the sample preparation method first broke the coal sample, and then the broken coal samples
were screened between 1 mm and 3 mm; the mass of the test coal sample was not less than 20 g, and the particle size was 1 mm-3 mm.
c. To analyze the relationship between the size of the coal sample and the critical value of the desorption index of drill cuttings, the particle size distribution of the 1-3 mm coal sample was analyzed using a particle size analyzer.

Experimental methods

According to the experimental objective, the experiment could be divided into three groups: basic coal property characterization (group I), explosive index determination (group II) and coal adsorption performance characterization (group III).

Group I: True density and proximate analysis of coal mines were included. According to the “proximate analysis of coal (GB/T 212-2008)” (The People’s Republic of China Ministry of Machine Building, 2008), the analysis of coal was carried out. The main process was as follows: the specified amount of coal was placed in a drying chamber at 105-110°C and dried to a constant mass in a dry nitrogen air stream. Therefore, the air-drying-based coal could be calculated according to the mass loss of the coal sample. At a certain heating rate of 815 ± 10°C, a specific amount of coal sample was placed in a muffle furnace for combustion and burned to a constant mass. The true density of the coal sample was measured using an MDMDY-300 automatic densimeter. The true and apparent densities of each group are taken as the average of three different measurements.

Group II: The initial gas diffusion velocity measurement, coal strength coefficient measurement and gas pressure measurement were included in this group. The initial gas diffusion velocity of coal was determined according to the “Determination method of gas initial
diffusion velocity index ($\Delta P$) of coal (~2009) (The People’s Republic of China Ministry of Machine Building, 2009b). According to the 12th part of the “Determination method of physical and mechanical properties of coal rock”, the methods of determining the coefficient of coal resistance were determined. According to the “Direct measurement method of gas pressure in coal mine”, the gas pressure in the coal seam was determined (Nos. 6, 8, and 13).
The experimental procedures for critical value determination of drill cuttings indexes under different pressures could be summarized as follows: First, a coal sample with a certain particle size and a certain moisture content was put into a coal sample tank. Then, a vacuum pump was used to vacuum the coal sample tank below 133 Pa, and then the tank was degassed for 6 hours. The purpose was to remove the gas, such as air and other gases adsorbed by coal samples; then, the desorption index of drill cuttings was tested under the equilibrium pressure of adsorption at 0.5 MPa, 0.6 MPa, 0.74 MPa, 0.9 MPa, 1.2 MPa, 1.4 MPa and 1.5 MPa. The constant temperature was the measured temperature of each coal seam. This study only considered the influence of adsorption gas pressure on the adsorption constants. Factors such as temperature, moisture content, ash content, volatile matter and particle size were set as constant values. Atmospheric environmental pressure ($P_0$) and temperature ($T$) were recorded in laboratory desorption tests.

### Experimental results

#### Proximate analysis

The results of the proximate analysis are shown in Table 2. Table 2 shows that all the coal samples had the same coal rank, and the true and apparent relative densities presented minor differences. Moreover, $C_{daf}$ was fixed carbon content on a dry-ash-free basis. where $M_{ad}$ is the moisture content on an air-dry (ad) basis, %; $A_{ad}$ is the ash content on an air-dry (ad) basis, %; $V_{daf}$ is the volatile matter content on a dry-ash-free (daf) basis, %; $C_{daf}$ is the fixed carbon content on a dry-ash-free (daf) basis, %; $TRD$ is the true relative density, g/cm$^3$; and $ARD$ is the apparent relative density, g/cm$^3$.

### Outburst risk degree classification of coal seams

The results of gas pressure determination, coal strength coefficient measurement and initial gas diffusion velocity measurement are displayed in Table 3.
Table 3 shows that different coal seams (N-6, N-8 and N-13) had various outburst risk degrees, namely, having different values of gas pressure, coal strength coefficient and initial gas diffusion velocity of coal. In addition, the values of gas pressure could be ranked as N-6 > N-8 > N-13, the values of the coal strength coefficient could be ranked as N-13 > N-8 > N-6, and the values of the initial gas diffusion velocity of coal could be ranked as N-6 > N-8 > N-13. Generally, the gas pressure represented the amount of gas stored in the coal seam, the coal strength coefficient represented the strength of the coal, and the initial gas diffusion velocity of coal represented the gas diffusion capacity of coal during the initial desorption period. Therefore, the coal seam N-6 had the largest amount of stored gas, lowest coal strength and strongest gas diffusion capacity at the initial desorption period. Coal seam N-13 had the lowest amount of stored gas, largest coal strength and weakest gas diffusion capacity at the initial desorption period of.

To classify the outburst risk degree of the coal seams according to the “Provision of prevention and control of coal and gas outburst” issued by China, the outburst risk degree classification criteria are summarized and listed in Table 4. In accordance with the above-mentioned classification criteria, the outburst risk degrees of N-6, N-8 and N-13 were obtained and are displayed in Table 3. Table 3 shows that the outburst degree of the three coal seams could be ranked as N-6 > N-8 > N-13. In addition, the selection of the target coal mine was reasonable because the coal samples from the same coal mine had three different outburst risk degrees.

The threshold value of drill cuttings desorption

Judging from the outburst risk division of a coal seam, the greater the gas pressure was, the greater the outburst risk degree of a coal seam; the gas pressure of a coal seam with 0.74 MPa represented the critical pressure for the coal seam with outburst risk, while the drill cuttings desorption index could reflect the residual gas pressure in the coal seam. When the adsorption equilibrium gas pressure was 0.74 MPa, the desorption index of drill cuttings was the critical value for the evaluation of the mining face.

The critical values of the desorption index of laboratory cuttings in three locations (N-6, N-8 and N-13) in FX were determined, and the results were obtained from the average values of those tests. Table 5 is the critical value of the desorption index of drill cuttings under different adsorption equilibrium gas pressures.

Table 5 shows that the measured values of N-6 were different under different adsorption equilibrium gas pressures, and the values increased with increasing adsorption equilibrium gas pressure. The larger that the gas pressure of adsorption equilibrium was, the larger the value would be and vice versa. Under different adsorption equilibrium gas pressures, the \( \Delta h_2 \) value was different, and the \( \Delta h_2 \) value increased with increasing adsorption equilibrium gas pressure. The larger the adsorption equilibrium gas pressure was, the greater the value of \( \Delta h_2 \) and vice versa. N-8 and N-13 follow the same rule as N-6, which means that, through
the test data, the critical values of desorption indexes $K_1$ and $\Delta h_2$ of drill cuttings increased with increasing adsorption equilibrium gas pressure (Cao and Wang, 2011).

Meanwhile, by comparing the test data of the desorption index of drill cuttings in different coal seams, it was found that the critical values were different under the same adsorption gas pressure; the desorption indexes of drill cuttings $K_1$ and $\Delta h_2$ had the same law. If the gas pressure of a coal seam increased, the two indexes increased and vice versa. The mining depths of N-6, N-8 and N-13 increased successively. The occurrence depth of the coal seam reflected the magnitude of in situ stress, and the greater the mining depth was, the greater the stress. The critical value of the desorption index of drill cuttings in each coal seam did not increase with increasing mining depth. Under the same adsorption equilibrium gas pressure, the critical value of the desorption index of drill cuttings in N-13 was the largest; in addition, the desorption index of N-8 drill cuttings was obviously smaller than those of N-6 and N-13.

Table 5. Under different gas pressure values, the critical values of $K_1$ and $\Delta h_2$ index.

| Coal seam | Sequence | $P$/MPa | $K_1$/ml/(g·min$^{0.5}$) | $\Delta h_2$/Pa |
|-----------|----------|---------|----------------|---------------|
| N-6       | 1        | 0.452   | 0.29            | 144           |
|           | 2        | 0.602   | 0.37            | 163           |
|           | 3        | 0.741   | 0.47            | 182           |
|           | 4        | 0.899   | 0.58            | 205           |
|           | 5        | 1.125   | 0.65            | 238           |
|           | 6        | 1.347   | 0.76            | 257           |
|           | 7        | 1.489   | 0.87            | 275           |
| N-8       | 1        | 0.463   | 0.33            | 140           |
|           | 2        | 0.601   | 0.40            | 167           |
|           | 3        | 0.741   | 0.46            | 181           |
|           | 4        | 0.886   | 0.52            | 198           |
|           | 5        | 1.139   | 0.63            | 230           |
|           | 6        | 1.305   | 0.70            | 257           |
|           | 7        | 1.498   | 0.78            | 271           |
| N-13      | 1        | 0.447   | 0.35            | 146           |
|           | 2        | 0.599   | 0.41            | 172           |
|           | 3        | 0.741   | 0.48            | 188           |
|           | 4        | 0.888   | 0.52            | 206           |
|           | 5        | 1.059   | 0.62            | 236           |
|           | 6        | 1.324   | 0.67            | 250           |
|           | 7        | 1.471   | 0.74            | 270           |

Table 6. Thresholds of four indicators for the identification of outburst-prone coal seams.

| Risk degree | $D$ | $\Delta P$/mmHg | $f$ | $P$/MPa |
|-------------|-----|-----------------|-----|---------|
| Outburst risk | III, IV, V | $\geq 10$ | $\leq 0.5$ | $\geq 0.74$ |
| No outburst  | Others                      |
Discussion

Relationship between critical value and gas pressure

From the comprehensive mechanism of coal and gas outbursts, it is known that the power of coal and gas outbursts mainly be produced by gas pressure. For the conditions of in situ stress and coal strength, the greater the gas pressure is, the greater the outburst risk of coal seam. According to the China safety production standard “coal and gas outburst mine identification standard” (-2006) (The People’s Republic of China Ministry of Machine Building, 2006), determining the outburst risk of coal seam must meet the critical conditions of a single index, as shown in Table 6. The coal seam with a dynamic phenomenon can be considered an outburst-prone coal seam only if all the indexes reach or exceed the critical value in Table 6.

The critical value of a single index for assessing the outburst risk of coal seams is given in Table 6, in which the failure type of coals was an objective evaluation index. The initial velocity of gas emission and the coefficient of coal strength were determined by experiment; accordingly, the accuracy was high. The gas pressure in coal seams needed to be measured in the field, but there are many related problems, such as the duration of the process, the facilities affected by the quality of the borehole sealing and data inaccuracy. In contrast, the desorption index of drill cuttings had the characteristics of short measuring time and accurate results, and it was the key parameter for predicting coal and gas outburst risk in the mining face. This could reflect the gas pressure of the mining face to a certain extent. Therefore, the residual gas pressure in the working face could be deduced accurately by finding the relationship between the critical value of the desorption index of drill cuttings and the gas pressure. At the same time, the risk degree of the mining face could be accurately determined.

In addition, the “coal and gas outburst prevention regulations” (2009) (State Administration of Work Safety of China and State Administration of Coal Mine Safety of China, 2009) give the critical value of drill cuttings desorption index prediction, as shown in Table 7.

The critical reference values of the outburst risk prediction index given in Table 7 showed that when the coal seam gas pressure was 0.74 MPa, the desorption index of drill cuttings in the corresponding mining face was 200 Pa and 0.5 mL/(g·min^{0.5}). In view of the complexity of coal seam gas occurrence conditions, the metamorphic degree and adsorption/desorption performance of coal were quite different. “Prevention and control regulations on coal and gas outburst” (2009) (State Administration of Work Safety of China and State Administration of Coal Mine Safety of China, 2009) stipulates that the critical risk value of each index should be determined according to the measured data from each mine. Therefore, the critical value of the coal seam gas pressure outburst index and the critical value of the gas desorption index of drill cuttings outburst prediction might not have a one-to-one correspondence. When the gas pressure of the coal seam was 0.74 MPa, the measured

| $P$/MPa | $W$/m$^3$/t | $\Delta h_2$/Pa | $K_1$/mL/(g·min$^{0.5}$) | Risk degree |
|---------|-------------|----------------|--------------------------|-------------|
| $\geq 0.74$ | $\geq 8$ | $\geq 200$ | $\geq 0.5$ | Outburst |
| $< 0.74$ | $< 8$ | $< 200$ | $< 0.5$ | No outburst |
values of desorption indexes $\Delta h_2$ and $K_1$ were not equal to the reference critical values in Table 7; thus, it was necessary to determine the sensitivity and critical values of the desorption index of drill cuttings. The critical values of the desorption index of drill cuttings measured under different adsorption pressure conditions in N-6, N-8, and N-13 were plotted and analyzed, as shown in Figure 5.

Figure 5 shows the measured points $K_1$ and $\Delta h_2$ of the drill cuttings desorption index and trend line of N-6, N-8 and N-13 under different adsorption equilibrium pressures.

From Figure 5, it can be seen that the critical values of $K_1$ and $\Delta h_2$ for each coal seam increase linearly with increasing pressure of adsorbed gas. The slope of the trend line of $\Delta h_2$ was greater than the slope of the trend line of $K_1$, indicating that the critical value of $\Delta h_2$ increased more than the critical value of $K_1$ when the same gas pressure was increased. That is, $\Delta h_2$ was more sensitive than $K_1$. The $K_1$ and $\Delta h_2$ trend lines for each coal seam did not intersect at the critical gas pressure of 0.74 MPa, indicating that the degree of outburst risk for each coal seam was different and that the sensitivities of desorption indexes $K_1$ and $\Delta h_2$ were also different. This verified that the coal seams in the same mine had different sensitivities to the same drill bit desorption index (Truni, 1986).

According to the Langmuir monolayer adsorption theory, the greater the gas pressure was, the greater the amount of gas adsorbed by coal; similarly, the amount of gas will be larger during desorption. The gas desorption index of drill cuttings characterizes the gas desorption and release ability of coal in unit time. Therefore, the greater the adsorption equilibrium gas pressure was, the greater the desorption index of drill cuttings.

The trend values of $K_1$ and $\Delta h_2$ of the desorption index of drill cuttings measured under different adsorption pressures for N-6, N-8 and N-13 are shown in Table 8.

From Table 8, it can be seen that the gas desorption index of drill cuttings was a linear function with the gas pressure of adsorption equilibrium, and the slopes of the fitted curves

![Figure 5. The critical values of indexes $K_1$ and $\Delta h_2$ under different pressures, where a is N-6, b is N-8, and c is N-13.](image-url)
were all different. Concerning the slopes of \( K_1 \), we found that N-6 > N-8 > N-13, and for the intercept, N-8 < N-13; the slope of \( \Delta h_2 \) is the same as that of N-6 > N-8 > N-13, and for the intercept, we found that N-8 < N-6 < N-13. The correlation coefficients of each fitting function were all greater than 0.98, and the fitting curves were in good agreement with the measured data.

First, this showed that there was a linear function between the gas desorption index and the equilibrium gas pressure in the coal seams, which was inconsistent with the power function relationship between \( K_1 \) and \( \Delta h_2 \) and adsorption equilibrium pressure (Fisne and Esen, 2014; Jiang et al., 2015). Second, the gas desorption index of coal seam cuttings reflected the sensitivity of the actual gas pressure in coal seams. This verified that the gas occurrence in coal seams presents a zonation, and different types of outbursts might have different prediction sensitivity indexes and critical values. Third, using the curve fitting formula of the desorption index, we could predict the residual pressure of the coal seam at a certain temperature and desorption index of drill cuttings, which provided a reference for assessing the outburst risk of coal seams.

According to the theory of gas adsorption and desorption, the gas in coal exists in the adsorbed state and free state. The amount of adsorbed gas is affected by pore characteristics and pore pressure, and the amount of free gas is affected by the pore volume of the coal body, the coal seam temperature and the pore pressure (Xue et al., 2020). Adsorbed gas is deposited on the micropore surface and particle structure, and most of the gas will be adsorbed in the coal body. The process of coal adsorption/desorption is also a percolation diffusion process (Black, 2011). The measurement process of the gas desorption index of drill cuttings is similar to the adsorption equilibrium gas desorption diffusion process, which includes not only the seepage of pore free gas but also the desorption and diffusion of adsorbed gas. The slope of the fitting curve of the desorption index of drill cuttings reflects the desorption rate of coal, which is the direct embodiment of gas occurrence characteristics of coal; the intercept reflects the pore feature of coal seams and the pore volume of coal bodies and is an inherent attribute of coal seams. Compared with nonoutburst coal, the characteristic of outburst coal in gas desorption is that the gas desorption velocity is high at the beginning and decreases rapidly with time. Therefore, the critical value of the desorption index of N-6 drill cuttings is lower than that of nonoutburst N-13; that is, the greater the slope of the trend fitting function is, the higher the risk of coal seam outburst. This is consistent with the assessment results of outburst risk of N-6, N-8 and N-13.

The analysis of the critical values of \( K_1 \) and \( \Delta h_2 \) of the drill cuttings of N-6, N-8 and N-13 are shown in Figure 6.

### Table 8. Regression analysis of the gas desorption index of drill cuttings under different adsorption equilibrium pressures.

| Coal seam | Best suitable model | Fitting Formula | Adj. R-Squared |
|-----------|---------------------|-----------------|----------------|
| N-6       | Linear function     | \( K_1 = 0.0593 + 0.5373 P \) | 0.9874         |
|           | Linear function     | \( \Delta h_2 = 88.15 + 127.39 P \) | 0.9942         |
| N-8       | Linear function     | \( K_1 = 0.1373 + 0.4310 P \) | 0.9994         |
|           | Linear function     | \( \Delta h_2 = 86.62 + 126.31 P \) | 0.9913         |
| N-13      | Linear function     | \( K_1 = 0.1919 + 0.3748 P \) | 0.9842         |
|           | Linear function     | \( \Delta h_2 = 100.02 + 117.62 P \) | 0.9777         |
Figure 6. Relationship between the critical values of indexes $K_1$ and $\Delta h_2$ of N-6 (a), N-8 (b) and N-13 (c).
According to Figure 6(a) to (c), the critical values of the \(D_h^2\) index of each seam increased linearly with increasing critical value of the \(K_1\) index, but the degree of increase was different, which indicates that the sensitivity of each seam to the two indexes was different.

The trends of the \(K_1\) and \(D_h^2\) critical value data for the desorption indexes of coal seam cuttings are shown in Table 9.

As shown in Table 9, \(K_1\) of each coal seam and the trend of \(D_h^2\) showed a linear function. The slope of the fitted curve was greater than 1, and the slope of the fitted curve was as follows: N-6 < N-8 < N-13; the intercept values were as follows: N-6 > N-8 > N-13. The correlation coefficients of each fitting function were all greater than 0.98, and the trends of the fitting curves were in good agreement with the measured data. First, the critical value of \(D_h^2\) increased more with increasing rate of gas pressure than the critical value of \(K_1\) did. Second, \(D_h^2\), which was the predominant risk index of the coal face, was more sensitive than the value of \(K_1\). That is, the index \(D_h^2\) reflected the actual coal gas pressure more accurately. Third, the slope of the fitting curve was large, indicating that the change in the critical value of \(D_h^2\) was larger than that of \(K_1\) under the same gas pressure variation condition. That is, the critical value of \(D_h^2\) was more sensitive, and the larger the slope was, the more sensitive the index.

Judging from the outstanding risk assessment results of N-6, N-8 and N-13, it could be concluded that the higher the risk of coal seam outburst was, the smaller the slope of the fitting trend of the desorption index of drill cuttings, and therefore, the greater the slope of the fitting curve of the desorption index of coal seam cuttings was, the lower the risk of coal seam outburst. The higher the risk of coal seam outburst was, the greater the intercept value of the fitting trend line of the desorption index of drill cuttings. Therefore, the smaller the intercept curve of the desorption index of coal seam drill cuttings was, the lower the risk of coal seam outburst. Thus, coal seam cuttings desorption index values could be fitted with trend line slopes and intercepts to determine the degree of risk of coal outbursts. The specific coal seam could be determined according to the measured value, which provided a new technical means for the risk assessment of coal seam outbursts.

**Index sensitivity and critical value**

Based on the measured data, the sensitivities and critical values of the desorption index of drill cuttings of coal seams N-6, N-8 and N-13 were further determined by the fuzzy clustering method.

The fuzzy clustering method is a method based on the measured data, through the establishment of a mathematical model of predictive sensitive indicators, to determine the abstract sensitivity index with specific numerical values (Beamish and Crosdale, 1998; Ruppel et al., 1972). Its steps are as follows:

1. All measured data are nondimensional

\[
X'_i = \frac{X_i - \bar{X}}{C} \tag{5}
\]
where \( X_i \) is the initial data; \( \bar{X} \) is the average value of the initial data; and \( C \) is the standard deviation of the initial data.

(2) All data are standardized

\[
X'_i = \frac{X_i - X_{\min}}{X_{\max} - X_{\min}}
\]  

(6)

(3) Sensitivity function of the prediction index for coal and gas outburst

Taking \( K_1 \) as an example, other indicators follow the same rule. Set \( E(K_1) \) as the mathematical expectation corresponding to the discrete variable of the index. According to formula (5) and formula (6), the dimensionless treatment of \( K_1 \) is obtained by:

\[
E(K_1) = \frac{K_{1i} - K_{1 \text{min}}}{K_{1 \text{max}} - K_{1 \text{min}}}
\]  

(7)

Establish the sensitivity function of the forecast index. Differences in forecasting index analysis are different from those in mathematical statistics. The deviation in mathematical statistics reflects the degree of deviation between each discrete index and its mathematical expectation. In the forecasting index analysis, the discrepancy was reflected between each pair of forecasting indexes and the critical index. Because the deviation has positive and negative points, the average of the sum of squares of each index deviation can reflect the discrete degree of the index as a whole. If the descriptive index is defined as \( D(X) \), then we have:

\[
D(X) = \frac{\sum^n_{i=1} \left[ X'_i - E(X) \right]^2}{n} \quad (i = 1, 2, 3 \ldots n)
\]  

(8)

The sensitivity function of the index is defined as follows:

\[
M(X) = \sqrt{D(X)}
\]  

(9)

The sensitivity functions \( M(K_1) \) and \( M(\Delta h_2) \) of the prediction indexes \( K_1 \) and \( \Delta h_2 \) can be obtained by formulas (5)–(9). The larger the value is, the more sensitive the corresponding index; otherwise, it is not sensitive.

The sensitivity of the gas desorption index of drill cuttings in each coal seam in Table 4 is calculated using (5)–(9). The results are shown in Table 10.

From Table 10, the sensitivity calculation results of the gas desorption index of drill cuttings showed that the calculation results for the coal seams indicate \( M(\Delta h_2) > M(K_1) \).
The outburst prediction index $\Delta h_2$ was more sensitive than $K_1$, which was consistent with the test data and analysis results of the critical value of the gas desorption index of drill cuttings. These results showed that $\Delta h_2$ was more accurate than $K_1$ in reflecting the gas pressure at the working face.

The sensitivity histogram of the critical values of the desorption index of drill cuttings in coal seams N-6, N-8 and N-13 are shown in Figure 7.

It can be seen from Figure 7 that $M(\Delta h_2)$ of each coal seam was greater than $M(K_1)$, indicating that $\Delta h_2$ of drill cuttings of coal seams was more sensitive than $K_1$ and that sensitivity increases as coal seam number increases, while $K_1$ in N-8 had the lowest sensitivity. Therefore, the sensitivity index of the outburst risk prediction of every coal seam mining face was $\Delta h_2$, and the auxiliary prediction index was $K_1$. A fuzzy clustering method was used to determine the sensitivity of the outburst prediction index of each coal seam mining face. It was also necessary to determine the critical value of the desorption index of drill cuttings to guide the field application. According to Table 6, the critical gas pressure value of the regional coal seam was 0.74 MPa. This value was taken as the desorption index of drill cuttings for the desorption gas balance of each seam, and the measured result was the critical value of the desorption index of drill cuttings. In the following section, the critical value of the desorption index of drill cuttings in each seam was determined according to the test data in Table 5.

When the N-6 adsorption equilibrium gas pressures were 0.741 MPa, 0.742 MPa and 0.739 MPa, the values of $\Delta h_2$ were less than the reference critical value of 200 Pa given in Table 4; they were 180 Pa, 187 Pa and 179 Pa, respectively. Similarly, the values of $K_1$ were less than the reference critical value of 0.5 ml/(g·min$^{0.5}$) given in Table 4; they were 0.48 ml/(g·min$^{0.5}$), 0.47 ml/(g·min$^{0.5}$), and 0.46 ml/(g·min$^{0.5}$), respectively. The mathematical expectation of the three measurement values was the critical value of the desorption index of drill cuttings, and the critical value of $\Delta h_2$ of N-6 was 182 Pa; similarly, the critical value of $K_1$ was 0.47 ml/(g·min$^{0.5}$).

If N-6 used the critical value of the desorption index given in Table 6 as the prediction index of the outburst risk of the mining face, the true coal seam gas pressure range would be 0.79 MPa-0.81 MPa > critical gas pressure 0.74 MPa. That is, when the measured cuttings

![Figure 7. Sensitivity histogram of the desorption index of drill cuttings in each coal seam.](image)
desorption index was $188 \text{ Pa} < \Delta h_2$ reference critical value $200 \text{ Pa}$, $0.47 \text{ ml/(g·min}^{0.5}) < K_1 < \text{ reference critical value } 0.5 \text{ ml/(g·min}^{0.5})$, the coal seam would have prominent risk and the value of the desorption index of drill cuttings < reference critical value; at the same time, the outburst of low index might occur, which was lower than that of the outburst prediction critical value. That is, the reference critical value cannot accurately predict the actual degree of outburst risk of coal seams. Similarly, the critical values of N-8 were $181 \text{ Pa}$ and $0.46 \text{ ml/(g·min}^{0.5})$; for N-13, the critical value of $\Delta h_2$ was $188 \text{ Pa}$, and the critical value of $K_1$ was $0.48 \text{ ml/(g·min}^{0.5})$. The reference critical values of the desorption indexes of N-8 and N-13 could not accurately predict the risk of coal seam outburst.

As shown in Figure 8, the critical values of $\Delta h_2$ and $K_1$ for the desorption index of N-8 were lower than those of N-6 and N-13. The desorption index of drill cuttings was the index of the adsorption and desorption properties of coal and the inherent attributes of coal seams, such as pore characteristics and pore volume of coal. The differences between the coal components and industrial analysis indexes were due to the geological conditions and the degree of metamorphism of coal seams. Therefore, under the condition of a critical gas pressure of $0.74 \text{ MPa}$, the measured values of the gas absorption index of cuttings in different coal seams were different, which were different from the recommended reference values.

In summary, the maximum critical value of $\Delta h_2$ in N-6, N-8 and N-13 was $188 \text{ Pa}$, and the maximum critical value of $K_1$ was $0.48 \text{ ml/(g·min}^{0.5})$, which was less than the recommended critical value in Table 5. Among those, the critical value of the desorption index of N-13 drill cuttings was close to the recommended critical value in Table 6, whereas the critical value of desorption quality of N-8 drill cuttings diverged from the recommended critical value. When the measured critical value < coal seam value of the desorption index of drill cuttings < reference critical value, if the critical value of the cuttings desorption index recommended by Table 6 was taken as the prediction index of outburst risk in the mining
face, the low index outburst phenomenon might occur in the mining face, which would seriously threaten the production safety of the coal mine. Therefore, it is of great importance to determine the outburst risk sensitivity index and its critical value for the mining face to improve the safety status of the mine, improve the efficiency of outburst prevention projects, and reduce the occurrence of outburst accidents.

**Particle size distribution of sensitivity indicators**

The desorption index of coal samples reflects the law of releasing gas after the exposure of underground coal (Zhou et al., 2020). The gas desorption index of drill cuttings reflects the gas pressure of coal seams, while different indexes show different sensitivities and critical values due to the zonation characteristics of gas occurrence in coal seams. The desorption index of drill cuttings value of $K_1$ reflects the 1st min of coal gas desorption (Liu et al., 2019); $\Delta h_2$ is the difference corresponding to the amount of desorption from the coal sample at 3 min and 5 min (Fan et al., 2019d; Toda and Toyoda, 1972), the degree of metamorphism and the type of failure of the coal. The desorption rate of gas may cause the differences between $K_1$ and $\Delta h_2$ and the recommended critical value. Coal particle size is the embodiment of physical and mechanical properties of coal, reflecting the stress and strength of the coal body. To analyze the influence of the particle size distribution of coal samples on the determination of sensitivity indexes, the particle size distribution of 1 mm-3 mm coal samples was analyzed, and the results are shown in Figure 9.

As shown in Figure 9(a), it can be seen that for N-6, particle sizes of 2092 μm–2637 μm accounted for 79.9% of the total, while minerals with particle sizes of 2334 μm–2637 μm accounted for 46.49% of the total. From Figure 9(b), it can be seen for N-8 that particle sizes of 1934 μm–2635 μm accounted for 71.54% of the total, while minerals with a grain size of 2170 μm–2635 μm accounted for 53.86% of the total. From Figure 9(c), it can be seen for N-13 that particle sizes of 2034 μm–2834 μm accounted for 78.25% of the total, while

![Figure 9. Analysis of the particle size distribution of coal particles with 1–3 mm diameter, where (a) is N-6, (b) is N-8, and (c) is N-13.](image-url)
minerals with particle sizes of 2297 µm–2834 µm accounted for 58.47% of the total. From the overall trend, the mineral particle distributions of N-6 and N-13 are relatively similar. The mineral particles of N-8 with dimensions less than 2000 µm are slightly larger than those of N-6 and N-13. Under the same sieving condition, more coal particles would be easier to crush, or in other words, the coefficient of solidity of the coal would be smaller. According to the single index of outburst risk evaluation, the smaller the coefficient of solidity of coal was, the higher the risk of coal seam outburst.

The results show that under the same pressure conditions, the smaller the particle size of coal samples were, the greater the desorption index value of drill cuttings (Beamish and Crosdale, 1998; Zhou et al., 2020). According to the Langmuir monolayer adsorption model, the greater the specific surface area of coal was, the larger the amount of gas adsorbed under the same temperature and pressure conditions (Liu et al., 2019; Toda and Toyoda, 1972; Fan et al., 2019d) and the smaller the amount of desorption gas. Under the same adsorption equilibrium gas pressure condition, the critical values of $K_1$ and $\Delta h_2$ of the desorption index of N-8 were less than the critical values of N-6 and N-13, and the differences of outburst prediction index critical values were verified from the standpoint of particle size distribution. In addition, due to the degree of metamorphism, industrial analysis index, geological conditions and other reasons, the measured values of the desorption index of drill cuttings were different for different coal seams. The differences between the values of

![Figure 10. Determined drilling arrangement diagram.](image)
the gas desorption indexes of drill cuttings were more obvious between the soft and hard coal of the same coal seam.

Field verification results of the desorption index of drill cuttings

When using the desorption index of drill cuttings to investigate the effect of the regional measurements on the 12619 (N-6 coal seam) mining face of FX, 3 holes with a diameter of 42 mm and a hole depth of 8–10 m were drilled into the front of the working face. First, the borehole should be drilled in the soft coal seam as much as possible. Second, at least one of the boreholes should be located in the middle of the cross-section of the excavation alley, and it also should be parallel to the direction of the heading face. Third, the final position of other boreholes should be outside the contour line on both sides of the alley section at 2–4 m. Moreover, the indexes $K_1$ and $\Delta h_2$ should be measured at least once every 2 meters. The determined drilling arrangement diagram is shown in Figure 10.

The gas desorption index $\Delta h_2$ of N-6 was $\Delta h_2 = 88.15 + 127.39 P$ with the change of gas pressure, and the critical pressure value of 0.74 MPa was substituted into the formula to obtain $\Delta h_2 = 182$ Pa. The actual desorption index of drill cuttings $\Delta h_2$ in the coal seam N-6 mining face of FX is shown in Figure 11.

As shown in Figure 11, a total of 70 $\Delta h_2$ values were determined during the preparation of the mining face, and the range of the $\Delta h_2$ values of the measured gas desorption index of drill cuttings was 152–221 Pa. In the actual determination of $\Delta h_2$, there were 8 data values greater than 182 Pa, and the rest were less than 182 Pa. According to the relevant data of N-6, there were 7 gas dynamic phenomena occurring in the 8 boreholes of the actual $\Delta h_2$

![Image](image.png)

Figure 11. Desorption index of actual drill cuttings.
greater than 182 Pa. The reliability of $Dh_2$ was high, and it was reasonable to predict the gas outburst risk of each coal seam with the desorption index $Dh_2$ of drill cuttings. From the determined requirements and the process of finding the gas desorption index $Dh_2$ of drill cuttings, the result was influenced by the exposure time of the coal sample, the type of coal destruction, the size of the coal sample and the sealing property of the instrument. In terms of the exposure time of coal samples, the gas desorption indexes of drill cuttings were usually measured using the orifice sampling method in the field. Therefore, it cannot be guaranteed that all the drill cuttings are taken from a predetermined depth, causing different gas desorption times for the coal samples and leading to errors when measuring the gas desorption index of drill cuttings. In addition, the operational skills of coal mine technicians also affect the exposure time.

**Conclusions**

In this paper, through on-site sampling, a laboratory-designed experimental device using the isobaric pressure desorption principle is used to measure the gas desorption index of coal samples in different time periods, and the test results have been theoretically analyzed and discussed. Finally, the following conclusions have been drawn:

1. Under the conditions of different adsorption equilibrium gas pressures, the critical values of the desorption index of drill cuttings were different, and the critical value increased with increasing adsorption equilibrium gas pressure. The trend slope of $Dh_2$ was greater than the trend slope of $K_1$, indicating that $Dh_2$ was more sensitive than $K_1$. Data trend fitting showed that the gas desorption index of drill cuttings has a linear relationship with the adsorption equilibrium gas pressure, and the critical value increases with increasing adsorption equilibrium gas pressure. The desorption index of drill cuttings and adsorption equilibrium pressure are linear functions. The higher the risk of coal seam outburst is, the greater the slope of the fitting function and the smaller the intercept. Under the same adsorption equilibrium pressure, $Dh_2$ and $K_1$ showed a linear relationship, and the higher the risk of coal seam outburst is, the smaller the slope of the fitting function; likewise, the greater the intercept will be.

2. The fuzzy clustering method was used to analyze the measured data. From the numerical calculation, it was concluded that $Dh_2$ was more sensitive than $K_1$ in the coal seams of FX; therefore, the sensitivity index of coal and gas outburst risk was $Dh_2$, whereas $K_1$ was used as the auxiliary prediction index.

3. Through repeated tests, the mathematical expectation was used to determine the critical value of the desorption index of drill cuttings of N-6, N-8 and N-13. The sensitivity indexes $Dh_2$ were 182 Pa, 181 Pa, and 188 Pa, and the auxiliary predictive indexes $K_1$ were 0.47 ml/(g·min$^{0.5}$), 0.46 ml/(g·min$^{0.5}$), and 0.48 ml/(g·min$^{0.5}$), respectively.

4. Coal seams with different outburst risk levels had different sensitivities to the desorption index of drill cuttings; the sensitivity of different coal seams to the desorption indexes of the same drill cuttings was different for the same mine; the sensitivity and critical value of the desorption index of drill cuttings in different coal seams were also different.

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References

Beamish BB and Crosdale P J (1998) Instantaneous outbursts in underground coal mines: An overview and association with coal type. International Journal of Coal Geology 35(1-4): 27–55.

Black DJ (2011) Factors affecting the drainage of gas from coal, and methods to improve drainage effectiveness. Sports Biomechanics 13(2): 123–134.

Cao YL and Wang M (2011) Sensitivity and its critical value of gas desorption index $\Delta h_2$ in coal drilling cutting at Panyi coal mine. Journal of Liaoning Technical University (Natural Science Edition) 30(5): 685–688.

Cheng LB, Wang L, Cheng YP, et al. (2016) Gas desorption index of drill cuttings affected by mafic sills for predicting outbursts in coal seams. Arabian Journal of Geosciences 9(1): 61.

Cheng WM, Hu XM, Xie J, et al. (2017) An intelligent gel designed to control the spontaneous combustion of coal: Fire prevention and extinguishing properties. Fuel 210: 826–835.

De Vegeron M and Belin J (1966) Étude des Degagements Instantanés de Méthane. Paris: Ann. Mines Carb, pp.1–16. (in French).

Fan CJ, Elsworth D, Li S, et al. (2019d) Modelling and optimization of enhanced coalbed methane recovery using CO$_2$/N$_2$ mixtures. Fuel 253: 1114–1129.

Fan CJ, Elsworth D, Li S, et al. (2019c) Thermo-hydro-mechanical-chemical couplings controlling CH$_4$ production and CO$_2$ sequestration in enhanced coalbed methane recovery. Energy 173: 1054–1077.

Fan JY, Chen J, Jiang DY, et al. (2019b) A stress model reflecting the effect of the friction angle on rockbursts in coal mines. Geomechanics and Engineering 18(1): 21–27.

Fan JY, Jiang DY, Liu W, et al. (2019a) Discontinuous fatigue of salt rock with low-stress intervals. International Journal of Rock Mechanics and Mining Sciences 115(3): 77–86.

Feng JJ, Wang EY, HuangQS, et al. (2020) Study on coal fractography under dynamic impact loading based on multifractal method. Fractals 28(01): 2050006.

Fisne A and Esen O (2014) Coal and gas outburst hazard in Zonguldak coal basin of Turkey, and association with geological parameters. Natural Hazards 74(3): 1363–1390.

Frid V (1997) Electromagnetic radiation method for rock and gas outburst forecast. Journal of Applied Geophysics 38(2): 97–104.

Guo Q and Saghafi A (2014) Comparing potentials for gas outburst in a Chinese anthracite and an Australian bituminous coal mine. International Journal of Mining Science and Technology 24(3): 391–396.
Hasiah A W, Chai P L, Gou P, et al. (2013) Coal-bearing strata of Labuan: Mode of occurrences, organic petrographic characteristics and stratigraphic associations. Journal of Asian Earth Sciences 76(20): 334–345.
Hu ZX, Hu XM, Cheng WM, et al. (2018) Performance optimization of one-component polyurethane healing agent for self-healing concrete. Construction and Building Materials 179: 151–159.
Jiang C, Xu L, Li X, et al. (2015) Identification model and indicator of outburst-prone coal seams. Rock Mechanics and Rock Engineering 48(1): 409–415.
Kong B, Wang EY, Lu W, et al. (2019) Application of electromagnetic radiation detection in high-temperature anomalous areas experiencing coalfield fires. Energy 189(12): 116144.
Kong XG, Wang EY, Li SG, et al. (2020) Dynamic mechanical characteristics and fracture mechanism of gas-bearing coal based on SHPB experiments. Theoretical and Applied Fracture Mechanics 105: 102395.
Levine JR (1986) Deep burial of coal-bearing strata, anthracite region, Pennsylvania: Sedimentation or tectonics. Geology 14(7): 577.
Li H, Zheng C, Lu J, et al. (2019a) Drying kinetics of coal under microwave irradiation based on a coupled electromagnetic, heat transfer and multiphase porous media model. Fuel 256: 115966.
Li X, Jiang C, Tang J, et al. (2017) A fisher’s criterion-based linear discriminant analysis for predicting the critical values of coal and gas outbursts using the initial gas flow in a borehole. Mathematical Problems in Engineering 2017(16): 1–11.
Li XL, Li ZH, Wang EY, et al. (2018) Pattern recognition of mine microseismic (MS) and blasting events based on wave fractal features. Fractals 26(03): 1850029.
Li ZH, Niu Y, Wang EY, et al. (2019b) Experimental study on electric potential response characteristics of gas-bearing coal during deformation and fracturing process. Processes 7(2): 72.
Liu SM, Li XL, Wang DK, et al. (2020) Mechanical and acoustic emission characteristics of coal at temperature impact. Natural Resources Research 29(3): 1755–1772.
Liu XF, Song DZ, He XQ, et al. (2019) Nanopore structure of deep-burial coals explored by AFM. Fuel 246: 9–17.
Liu YH, Nie W, Jin H, et al. (2018) Solidifying dust suppressant based on modified chitosan and experimental study on its dust suppression performance. Adsorption Science & Technology 36(1–2): 640–654.
Nandi SP and Walker PL Jr (1975) Activated diffusion of methane from coals at elevated pressures. Fuel 54(2): 81–86.
Ruppel TC, Grein CT and Bienstock D (1972) Adsorption of methane/ethane mixtures on dry coal at elevated pressure. Fuel 51(4): 297–303.
Somnier J (1960) La desorption naturelle des charbons son application à la prevention des dégagements instantanés et a l’explication de leur mecanisme. Revue Industrielle Miner 9: 776–784. (in French).
State Administration of Work Safety of China and State Administration of Coal Mine Safety of China (2009) Prevention and Control Regulations on Coal and Gas Outburst. Beijing, China: China Coal Industry Press.
Sun X and Sun D (2000) Trial study of determining critical values of outburst prediction indicators value $K_1$ and $f$. Mining Safety & Environmental Protection 27(4): 23–26.
The Chinese Academy of Sciences Institute of Mathematical Statistics (2008) Determination Method of Gas Desorption Index by Drill Cuttings (T1065), AQ/2008. China: Author.
The People’s Republic of China Ministry of Machine Building (2006) Specification for Identification of Coal and Gas Outburst Mine (AQ 1024-2006). China: Author.
The People’s Republic of China Ministry of Machine Building (2008) Method for Preparation of Coal Sample, GB/T474-2008. China: Author.
The People’s Republic of China Ministry of Machine Building (2008) Proximate Analysis of Coal, GB/T 212-2007. China: Author.
The People’s Republic of China Ministry of Machine Building (2009a) Determination Method for Index (ΔP) of Initial Velocity of Diffusion of Coal Gas (AQ 1080-2009). China: Author.
The People’s Republic of China Ministry of Machine Building (2009b) Methods for Determining the Physical and Mechanical Properties of Coal and Rock – Part 1: General Requirements for Sampling, GB/T 23561.1-2009. China: Author.
Tian S, Jiang C, Xu L, et al. (2016) A study of the principles and methods of quick validation of the outburst-prevention effect in the process of coal uncovering. Journal of Natural Gas Science and Engineering 30: 276–283.
Truni AT (1986) Prediction and Prevention of Gas Dynamic Phenomena in Coal Mines. Beijing: China Coal Industry Press, pp.25–30.
Toda Y and Toyoda S (1972) Application of mercury porosimetry to coal. Fuel 51(3): 199–201.
Wang C, Yang S, Li J, et al. (2018) Influence of coal moisture on initial gas desorption and gas-release energy characteristics. Fuel 232: 351–361.
Xue YC, Sun WB and Wu QS (2020) The influence of magmatic rock thickness on fracture and instability law of mining surrounding rock. Geomechanics and Engineering 20(6): 546–557.
Yang D, Chen Y, Tang J, et al. (2018) Experimental research into the relationship between initial gas release and coal-gas outbursts. Journal of Natural Gas Science and Engineering 50: 157–165. 2
Yu SJ, Zhang XY, Zhang B, et al. (2020) Research on inversion and application of failure depth of coal seam roof and floor based on triangular network acoustic CT tomography. Environmental Earth Sciences 79(13): 1–14.
Zhang R, Liu J, Sa ZY, et al. (2020) Fractal characteristics of acoustic emission of gas-bearing coal subjected to true triaxial loading. Measurement 169: 108349.
Zhou F, Sun WB, Shao JL, et al. (2020) Experimental study on nano silica modified cement base grouting reinforcement materials. Geomechanics and Engineering 20(1): 67–73.
Zou Q and Lin B (2018) Fluid-solid coupling characteristics of gas-bearing coal subject to hydraulic slotting: An experimental investigation. Energy & Fuels 32(2): 1047–1060.