Distribution characteristics of pulverized coal and stress–gas pressure–temperature response laws in coal and gas outburst under deep mining conditions

Bo Zhao¹ ² | Guangcai Wen² | Qianwei Ma³ | Haitao Sun² | Fazhi Yan¹ | Jun Nian¹

¹School of Safety and Emergency Management Engineering, Taiyuan University of Technology, Taiyuan, China
²Gas Research Branch, China Coal Technology and Engineering Group Chongqing Research Institute, Chongqing, China
³Department of Civil, Environmental, and Geodetic Engineering, The Ohio State University, Ohio, USA

Correspondence
Bo Zhao, School of Safety and Emergency Management Engineering, Taiyuan University of Technology, Taiyuan 030024, China.
Email: zhaobo91@cqu.edu.cn

Abstract
Deep mining will increase the likelihood of coal and gas outburst accidents and do harm to the safety of coal mining. In this study, a coal and gas outburst experiment under deep high-stress conditions was carried out and stress–gas pressure–temperature response laws in coal and rock surrounding the burst hole were evaluated. The experimental results showed that the stress response around the burst hole was intense and stress variation decreased as distance from the position to burst port increased. The gas pressure in the coal decreased sharply and oscillated several times during the burst process. The maximum rebound range was 0.05 MPa during this process. The decreasing rate of gas pressure reduced with the increase of the position–burst port distance. The temperature response near the burst port was stronger than peripheral area. The gas internal energy was still the main energy source of coal and gas outbursts, accounting for 75% of the total energy, and played a key role in the burst process. The contribution of elastic potential energy was 22% under deep high-stress conditions in this study. Based on the analysis of burst energy, the gas and stress were key factors of an outburst.

KEYWORDS
coal and gas outburst, deep high-stress conditions, elastic potential energy, gas internal energy, multiphysics field

1 | INTRODUCTION

Coal and gas outbursts which are dynamic phenomena of mine gas are caused by throwing numerous coals and rocks carrying a great deal of air into the mining space suddenly.¹–⁵ In the transportation industry, the ejected coal gas can spread for even thousands of meters against the wind or fill in the entire roadway on other conditions.⁶–¹⁰ A mixture of coal and gas and the fire source in the roadway may cause gas explosions, coal dust explosions, gas and coal dust explosions, and so forth, which seriously harm the safety of mine workers and cause large financial losses.¹¹–¹⁶

A series of hypotheses on the mechanism of coal and gas outbursts have been established in major coal-producing countries, including China, Canada, Australia, and Poland, by means of theoretical analysis, laboratory test, numerical simulation, field test, and so forth,¹⁷–²¹ mainly gas, geostress, synthesis, chemical nature, and synthetic action
The energy hypothesis proposed by the former Soviet Union scholar B. B. Hodote further supports and explains the synthetic action hypothesis. The energy hypothesis states that the outburst energy consists of the elastic potential energy of coal and gas internal energy. When the stress conditions of the coal seam change in a short time, the discharge of elastic potential energy will contribute to the rapid breakage of coal and rock. The research on coal and gas outbursts is based mainly on the synthetic action hypothesis currently. The theory that the in-situ stress and gas pressure provide an energy source for the occurrence and development of coal and gas outbursts is generally believed. The physical and mechanical properties of coal and rock reflect the ability of coal and rock to resist damage.

Experiments are effective means of studying coal and gas outburst mechanisms. Researchers have developed different experimental devices to achieve different experimental objectives. An increase of leap scale can be seen in the test equipment, for example, stress loading was developed from single axial to three-dimensional. Moreover, the airtightness of the test device was further improved. However, no device is the best because of the different research objectives among scholars. For example, most researchers may ignore the influence of external roadways on coal and gas outbursts when analyzing the evolution of stratified cracks in the burst development process. In this case, more coal and gas will be thrown out to a further distance, leading to a larger calculation of coal and gas outburst energy. Besides, to study the gas-pulverized coal migration law in the roadway after burst, the broken coal with a certain particle size distribution is often packed into the sealed tank ignoring the crushing effect of stress on the coal in the burst process.

The comprehensive action of stress, gas pressure, and physical and mechanical parameters of coal and rock will cause coal and gas outbursts. The stress, gas pressure, and temperature evolution rules in the coal and gas outburst process are always in the focus of the outburst mechanism. However, owing to the difficulties in field tests and limited scale of the laboratory test, it is challenging to monitor the stress–gas pressure–temperature (S–GP–T) of coal and rock mass around the outburst hole during the entire burst process. On this condition, we developed a coal and gas outburst experimental system (CGOES) to study the coal and gas outburst mechanism and to provide a theoretical support to understand the prevention of coal and gas outbursts. Based on a physical simulation test of coal and gas outburst under deep high-stress conditions, this study analyzes the spatio-temporal evolution rules of S–GP–T in the burst process.

2 | EXPERIMENTAL METHODS

2.1 | Coal and gas outburst accident prototype in Dingji coal mine

The Dingji coal mine is a super large mine with an annual designed production capacity of 5.0 Mt/a in China. The mine field is located in the central and northern parts of the Huainan syncline in China, which is the western section of the Panji anticline, covering an area of approximately 100.534 km². The overall regional structural complexity was moderate. The accident occurred at the 1331 (1) haulage roadway driving working face of the Dingji coal mine (Figure 1). The 1331 (1) driving working face is located in the East No. 2 mining area of the Dingji coal mine, where the surrounding areas are unmined beds. The strike length of the haulage roadway design is 1740 m, while the average coal seam thickness is 2.2 m. The average burial depth of the coal seam is 1070 m. During the coal and gas outburst accident on April 19, 2006, the total outburst coal amount was 35 t, while the burst gas emission was 235.4 m³. The sizes of the burst hole were approximately...
0.65 m (width) × 3 m (depth). The distance between the thrown coal body and burst port was 4–6 m (Table 1).

2.2 | CGOES

A CGOES was developed, which consisted of six subsystems: high-stiffness mechanical loading, triaxial loading cavity, discharge and charge/degassing, roadway, monitoring, and dust removal subsystems (Figure 2A). The high-stiffness mechanical loading subsystem can support a maximum vertical working pressure of 25 MPa and maximum horizontal symmetric loading pressure of 16.7 MPa (Figure 2B). The maximum geometric dimensions (length × width × height) of the similar material sealing subsystem were 1500 × 800 × 800 mm. The geometric size of the burst port was φ300 mm, while the maximum charging pressure was 6 MPa (Figure 2C). Two blasting discs under positive pressure were used to induce blasting to open burst holes without blocking. The simulated roadway is a square with a section length of 0.3 m, which can resist the impact damage of the roadway is a square with a section length of 0.3 m, which can resist the impact damage of the roadway (Figure 2D). The data monitoring system can monitor outburst parameters such as gas pressure, shock wave pressure, stress, temperature, and vibration (Figure 2E). The dust removal subsystem was designed to avoid environmental pollution during the test (Figure 2F).

2.3 | Experimental design

The dimensions of the experimental model were 1500 × 800 × 800 mm. The burst port center was 350 mm away from the bottom of the box on the left side. The diameter of the burst port was 300 mm. The experimental parameters are listed in Table 2. To facilitate the sensor positioning, a three-dimensional coordinate system is established with the lower-left corner of the burst port direction as the origin of the coordinates. The x-axis is perpendicular to the protrusion, the y-axis is parallel to the protrusion, and the z-axis is vertical, as shown in Figure 3. The coordinates of the vertices of the box are (0, 0, 0), (1500, 0, 0), (0, 800, 0), (0, 0, 800), (1500, 800, 0), (1500, 0, 800), (0, 800, 800), and (1500, 800, 800), respectively. σ1 is the vertical stress, while σ2 is the lateral stress. The face perpendicular to the direction of the X-axis is referred to as section, while the face perpendicular to the direction of the Z-axis is referred to as plane.

### Table 1

| Coal seam thickness | Burial depth | Gas pressure | Firmness coefficient | Adsorption constant | Burst coal mass |
|--------------------|--------------|--------------|---------------------|---------------------|----------------|
| 2.2 m              | 1070 m       | 0.5 MPa      | 0.3                 | 15.12 cm³/g         | 35 t           |

To monitor the data, the model was divided into five levels and six regions (0–150, 150–250, 250–350, 350–450, 450–550, and 550–800) in the horizontal direction and four sections and five regions (0–250, 250–500, 500–750, 750–1250, and 1250–1500) in the vertical direction. The sensors were arranged on the intersection line between the plane and section, on which 36 gas pressure sensors, 36 stress sensors, and 20 temperature sensors were arranged (Figure 3).

3 | DISTRIBUTION CHARACTERISTICS OF BURST COAL

3.1 | Burst pulverized coal in the burst hole and roadway

In the triaxial loading cavity, the burst hole is a wedge-shape semicircular hole with a large mouth and small cavity, approximately 0.3 m wide and 0.4 m deep, which is consistent with the site hole. Multiple layered fracture structures exist in the burst hole. These strata are arranged in sequence. In addition, there are some short cracks in the coal body, which are generally inclined to intersect with the bedding crack structure and cut off the bedding crack into several pieces of coal (Figure 4).

In the simulated roadway, the broken coal thrown out after the outburst occurs is piled up in the roadway, while the broken coal samples are piled up near the outburst in large quantities. The broken coal with a relatively large volume is piled up within 2 m from the outburst hole. With the increase in throwing distance, the thickness of the broken coal samples gradually decreases. The thrown broken coal exhibits a sword-shaped distribution at the farthest end. Most of them are small particles and pulverized coal. The area of pulverized coal in the roadway was divided into six regions as the distance from the burst hole increased, 1# (0–0.4 m), 2# (0.4–1.2 m), 3# (1.2–2.3 m), 4# (2.3–3.05 m), 5# (3.05–3.8 m), and 6# (3.8–4.5 m).

Most of the burst coal is distributed in 1#, 2#, and 3# statistical areas, while a small amount of burst coal is distributed in 4#, 5#, and 6# statistical areas (Table 3). The burst coal is mainly concentrated in the first half of the simulated roadway because the acceleration conditions of large coal particles in the
1. Stress operation table, 2. Hydraulic pump, 3. Box guide rail, 4. Sensor, 5. Multi-function data acquisition system, 6. Data monitoring and operation platform, 7. Inflating device, 8. High pressure cylinder assembly System diagram

**TABLE 2** Experimental parameters

| Parameters                      | Coal seam thickness | Stress  | Gas pressure | Firmness coefficient | Adsorption constant | Initial speed of methane diffusion |
|--------------------------------|---------------------|---------|--------------|----------------------|---------------------|-----------------------------------|
| Experimental parameters        | 800 mm              | 16 MPa  | 0.5 MPa      | 0.2–0.4              | 14.50–16.12 cm³/g   | 6–8                               |
gas flow are harsh. Although the broken coal located in front of the outburst can obtain a larger ejection velocity owing to the higher initial gas pressure, only a small part of the subsequent coal bodies can meet the ejection conditions.

3.2 Burst coal pulverization characteristics

As shown in Figures 5–10, the broken coal (10 cm) is basically deposited at the bottom of the coal accumulation sample, while the pulverized coal (<0.25 mm) mostly floats at the top of the coal accumulation. Most of the burst coal with a relatively large volume (statistical maximum length) is deposited in 1# area. The calculation of the outburst coal masses in different statistical areas showed that the mass and volume of outburst coal gradually decreased with the increase in distance from the outburst port. Generally, a large amount of thrown-out coal and rock is concentrated near the outburst hole. The amount of outburst coal decreases considerably with the increase in distance. On the other hand, the larger burst coal is mostly concentrated near the burst hole. The size of the outburst decreases with the increase in the distance. The burst coal appears as a powder at the largest distance from the outburst hole.

![Figure 3: Coal and gas experimental model](image)

**Figure 3** Coal and gas experimental model

![Figure 4: Burst hole in the experiment](image)

**Figure 4** Burst hole in the experiment

| No. | Location (m) | Length (m) | weight (kg) | Percentage of total weight (%) | Percentage of total outburst coal (%) |
|-----|--------------|------------|-------------|-------------------------------|-------------------------------------|
| 1#  | 0–0.4        | 0.4        | 5.85        | 0.585                         | 32.21                               |
| 2#  | 0.4–1.2      | 0.8        | 5.20        | 0.520                         | 23.3                                |
| 3#  | 1.2–2.3      | 1.1        | 4.85        | 0.485                         | 21.26                               |
| 4#  | 2.3–3.05     | 0.75       | 0.90        | 0.090                         | 10.07                               |
| 5#  | 3.05–3.8     | 0.75       | 0.80        | 0.080                         | 9.28                                |
| 6#  | 3.8–4.5      | 0.7        | 0.34        | 0.034                         | 3.91                                |

**Table 3** Burst coal quality distribution

ZHAO ET AL.
FIGURE 5  Burst coal size distribution in 1# area

FIGURE 6  Burst coal size distribution in region 2# area

FIGURE 7  Burst coal size distribution in region 3# area

FIGURE 8  Burst coal size distribution in region 4# area

FIGURE 9  Burst coal size distribution in region 5# area

FIGURE 10  Burst coal size distribution in region 6# area
The pulverization rate of outburst coal has two characteristics. The pulverization rate of coal near the outburst area is smaller compared with that far from the outburst area. In the area where pulverized coal is relatively concentrated in the simulated roadway, the pulverization rate of the coal mass was higher, which may be related to the high particle collision frequency in the process of pulverized coal-gas flow transport in the region with a higher pulverized coal mass distribution. As shown in Figure 11, a location closer to the outburst hole has a larger proportion of large-grained coal in the roadway.

4 | S–GP–T RESPONSE LAWS IN THE WHOLE BURST PROCESS

4.1 | S response laws in the process of coal and gas outburst

Figure 12 shows the stress variations curves of the different areas in the first section in different times with time. The distance between the first section and outburst was 250 mm. Figure 12A indicates that the overall trends of stress at F₁, F₂, and F₄ in the vertical direction of the first section are consistent. The stress fluctuated, but remained stable at 16 MPa before the outburst occurred in the gestation stage. The stress sensor responds quickly in the vertical direction of the first section after the outburst occurs. For example, the stress of F₁, F₂, and F₄ decreases from 16 to 0.5 MPa. The average response rate was 1.55 MPa/s, while the decrease range was 15.5 MPa. Figure 12B shows that the overall stress trends of F₁, F₃, F₅, F₇, and F₉ in the horizontal direction of the first section are that the stress fluctuates but remains stable at 16 MPa before the burst occurs. The F₁ response is strongest, while the decrease range is 15.5 MPa, after the outburst excitation. F₃ and F₅ were 100 mm away from the central point F₁ on both sides. The stress decreased from 16 to 4 MPa and 5 MPa, respectively. The average response rates were 1.2 and 1.1 MPa/s, respectively. F₇ and F₉ were 200 mm away from the central point F₁ on both sides. However, the stress was relatively stable. The stress decreased from 16 to 8 and 8.5 MPa, respectively. The average response rates were 0.8 and 0.75 MPa/s, respectively. The variation trend of stress in the first section consisted of an initial vibration–sudden plunge–stability.

Figure 13 shows the stress distribution in the first section at different time nodes. With the development of the outburst, the attenuation range of the stress gradually spread out from the center. The stress shows that, in the first section, the coal body near the outburst lost its bearing capacity, the stress transferred to the deep parts and maintained a downward trend. In the horizontal direction, the stress at F₃, F₅, F₇, and F₉ kept decreasing, but the decreasing range was smaller than that in the vertical direction. Figure 14 shows the stress variation curves of different areas in the second section with time. The distance between the second section and outburst

\[
\text{FIGURE 11} \quad \text{Burst coal pulverization characteristics}
\]

\[
\begin{align*}
\text{FIGURE 12} & \quad \text{Stress evolution laws in the first section} \\
\text{(A)} & \quad \text{Stress} \quad \text{MPa} \\
\text{10} & \quad 15 & \quad 20 & \quad 25 & \quad 30 & \quad 35 \\
\text{0.0} & \quad 4.0 & \quad 8.0 & \quad 12.0 & \quad 16.0 \\
\text{Burst gestation stage} & \quad \text{Burst development stage} & \quad \text{Burst termination stage} \\
\text{Starting point} & \quad \text{F₁} & \quad \text{F₂} & \quad \text{F₄} \\
\text{FIGURE 13} & \quad \text{Stress variation curves of different areas in the second section} \\
\text{FIGURE 14} & \quad \text{Stress variation curves of different areas in the second section} \\
\end{align*}
\]
was 500 mm. Figure 14A indicates that the overall trends of stress at F10, F11, and F15 in the vertical direction of the first section are consistent. After the outburst, the stress in the initial stage increased rapidly from 16 to 17.5 MPa, and then decreased to 11.5 MPa with the development of outburst. Figure 14B shows the general trend of stress at F10, F12, F16, and F18 in the horizontal direction of the second section. After the outburst excitation, F10, F12, F16, and F18 increased sharply in a short time, and then rapidly decreased to 11 MPa. However, the stress exhibited multiple vibrations accompanied by multiple increases in the process of decrease.
Figure 15 shows the stress distribution in the second section at different time nodes. The stress in the second section increased rapidly at the beginning of the coal and gas outburst, because the coal near the hole was thrown out and thus the stress shifted rapidly. However, with the development of the outburst, the coal body constantly breaks and plastic failure occurs in the second section. In this case, the mechanical strength of the coal body is insufficient to hinder the occurrence of coal and gas outbursts, further leading to the continuous transfer of stress to the depth. Therefore, the stress exhibited a subsequent rapid decrease. Even in this case, the stress in the second section was still 8.5 MPa in the center. Figure 16 shows the stress variations of different areas in the third section with time. The distance between the second section and outburst port was 750 mm. Figure 16A shows that the overall trends of stress at F19, F20, and F24 in the vertical direction of the first section are consistent. After the outburst, the stress at F19, F20, and F24 increased slowly, from 16 to 18.5 MPa within 16–19 s. Figure 16B shows the stress response laws at F19, F21, F23, F25, and F27 in the horizontal direction of the third section. F19 had the strongest response, followed by those of F21 and F23, which increased from 16 to 17 MPa. Those at F25 and F27 were relatively gentle, increasing from 16 to 16.5 MPa. Figure 17 shows the stress distribution at different time nodes in the third section after the outburst. After the outburst, the stress response of the third section increased slowly during the entire outburst process. Figure 18 shows the stress variation curves of the different areas in the fourth section with time. The distance between the fourth section and outburst port was 1250 mm. It was generally stable and not affected by coal and gas outbursts in the fourth section.

In general, the broken coal and rock mass are thrown out and poured into the roadway. The initial abutment pressure in the hole acts on the fresh coal wall after the outburst. The coal wall in the hole is seen a status change from three-directional equilibrium stress to vertical stress compression and surface of the fresh coal wall exhibits a compression failure owing to the sudden decrease in the horizontal normal stress of the fresh coal wall. The ability of the coal wall to bear a vertical load was degraded, while the stress concentration in the coal body was transferred to the deep parts.
4.2 GP response laws in the process of coal and gas outburst

The internal energy of the gas is the main energy source for coal and gas outbursts. Gas pressure has an important role in the occurrence and development of coal and gas outbursts. The gas pressure in the burst box is stable before the outburst. Therefore, a large amount of elastic potential and gas internal energy is accumulated in the coal. The sudden exposure of the outburst port results in a pressure gradient at the outburst location and inside the coal body. When the coal body is destroyed because
the strength cannot resist the stress, the internal energy and elastic potential of the gas will be released quickly and the outburst will start. Figure 16 shows the evolution law of gas pressure in the first section. As shown in Figure 19, the gas pressure in the pressure-relief zone begins to increase suddenly, a large amount of free gas gushes out, and the gas pressure near the outburst port decreases rapidly. The gas pressure dropped from 0.5 to 0.01 MPa and approached 0 MPa, with a rate of decrease close to 0.05 MPa/s in 10 s. The gas pressure decreased as time goes on. However, the gas pressure increased several times with small amplitudes (at 17.5 and 19.2 s) and then kept decreasing till the end of outburst process. This indicates that the decrease in gas pressure during outburst is the overall trend, accompanied by an increase in gas pressure several times, because of the occurrence of an outburst. A burst hole was formed at the front burst box. Numerous free gas channels were formed inside the coal seam. However, the adsorbed gas began to desorb, resulting in an increase in the gas pressure in the local space.

Figure 20 shows the gas pressure distribution in the first section at different times. The gas pressure at the center of the outburst responds most rapidly, which decreases from 0.5 to 0.01 MPa within 5 s. With the development of the outburst, the decreasing range of gas pressure extends from the center of the hole to the coal wall. The area where the gas pressure is 0.01 MPa at 30 s is larger than the area of the outburst hole, which proves that in addition of the participation of gas in the outburst hole, gas near the outburst hole also desorbs and participates in the process after the outburst. Figure 21 shows the evolution law of the gas pressure in the second section. The gas pressure sensor P10 exhibited the strongest response at the central point. In 10 s, the gas pressure decreased from 5.0 to 0.01 MPa and approached 0 MPa. The rate of decrease was 0.5 MPa/s. P15 and P17 were 100 mm above and below the central point P10, respectively. The gas pressure variation trend was weaker than that of P10; the values were 0.2 and 0.25 MPa at P15 and P17 after the outburst, respectively. However, the gas pressure had several small increases during the outburst process, at 18.5, 22.2, and 24.8 s, respectively. Figure 17B shows the variation trends of the gas pressure at the horizontal positions of P10, P12, P16, and P18 in the second section, which indicates that a closer location to the center of the outburst corresponds to a faster gas pressure drop.

Figure 22 shows the gas pressure distribution in the second section at different times. The gas pressure at the center of the outburst responds most rapidly, which decreases from 0.5 to 0.01 MPa within 5 s. With the development of outburst, the decreasing range of gas pressure expands from the hole center to the coal wall and the area of gas pressure of 0.01 MPa is close to the area of the outburst hole at 30 s. The decreasing range of the gas pressure in the second section is smaller than that in the first section.
Figure 23 shows the evolution law of the gas pressure in the third section. The gas pressure in the third section attenuates after the outburst. The gas pressures at P20, P22, P21, and P23 in the vertical and horizontal directions decreased from 0.5 to 0.25 MPa in the burst process. After the outburst for 27 s, the gas pressure remained a downward trend, which indicates that the gas in the third section outside the outburst hole was involved in the occurrence and development of coal and gas outbursts. After the outburst, an overall trend of decline can be indicated although the response of the gas pressure in the third section lagged behind that of the gas pressure in the first and second sections. However, the decline rate was largely reduced; a relatively slow

![Graph of gas pressure distribution in the first section](image1)

**Figure 20** Gas pressure distribution in the first section. (A) t = 12 s; (B) t = 18 s; (C) t = 24 s; (D) t = 30 s

![Graph of the evolution law of gas pressure in the second section](image2)

**Figure 21** The evolution law of gas pressure in the second section
decline was observed. Simultaneously, a slight increase in the gas pressure appeared during the gas pressure drop, which is similar to the first and second sections.

Figure 24 shows the gas pressure distribution in the third section at different times. In the time range of 16–22 s, the gas pressure at the center point of the third section decreased from 0.5 to 0.46 MPa and the gas pressure change was not considerable. In the time range of 22–30 s, the gas pressure remained at a high decrease speed. This indicates that a large amount of gas in the third section behind the outburst hole was involved in the process of coal and gas outburst. The adsorbed gas in the third section continuously supplied the energy of the coal and gas outburst.

Figures 25 and 26 show the evolution law of the gas pressure in the fourth section. Compared to the first three
sections, the response speed of the gas pressure lagged behind significantly. After the occurrence of gas outbursts in the original rock stress area, the original stress balance status was destroyed owing to the reduction in lateral pressure. Under the action of stress, the cracks in the coal seam began to develop slowly. However, the gas pressure decreased with a continuously slow speed and thus could not provide energy for coal and gas outbursts.

In summary, the coal body near the outburst port was destroyed and thrown out under the action of stress and gas pressure. The gas pressure in the coal body changed significantly and oscillated several times. The gas pressure

---

**FIGURE 24** Gas pressure distribution in the third section. (A) $t = 12$ s; (B) $t = 18$ s; (C) $t = 24$ s; (D) $t = 30$ s

**FIGURE 25** The evolution law of gas pressure in the fourth section
dropped faster in areas closer to the outburst port. With the decrease in gas pressure, the decreases in the effective stress and shear strength in the coal accelerated the tensile shear failure of the coal leading to the crack propagated to the deep parts. The free gas gushes into the outburst hole under a gas pressure difference. The adsorbed gas also provide energy for the outbursts.

4.3 | T response laws in the process of coal and gas outburst

Physical phenomena such as coal body rupture and gas desorption cause temperature changes during the process of coal and gas outbursts. To monitor the temperature of the coal body, some temperature sensors were placed in the coal seam during the formation of similar materials. In the test, 20 temperature sensors were arranged in four sections. However, most temperature sensors were damaged during the loading owing to the overprecision of the sensors. Regarding the response of a part of the temperature sensors during the burst process, as shown in Figure 27, the $T_1$ sensor in the first section had the highest temperature response. The temperature dropped to at most 5.5 K. The average rate of decrease was 0.5 K/s in the time period of 16–27 s. The temperature of the $T_2$ sensor in the second section dropped to at most 2.5 K, while the average rate of decrease was 0.23 K/s. The temperature of the $T_3$ sensor in the third section dropped to at most 1.6 K, while the average rate of decrease was 0.15 K/s. In addition, the temperature of $T_{19}$ in the fourth section remained stable throughout the outburst process. The coal body was gradually damaged from the burst port to the deep parts. The gas adsorbed on the surface of the coal matrix desorbed largely and worked by expansion. The temperature at a position close to the outburst dropped rapidly since the desorption and expansion is an endothermic process.

5 | ENERGY SOURCE OF COAL AND GAS OUTBURST UNDER DEEP HIGH-STRESS CONDITION

Regarding the outburst energy, it consists of the elastic potential of the coal rock and internal energy of the gas, which can be converted into the crushing work of coal,
throwing work of broken coal in the roadway, and frictional heat, vibration, and sound energy generated by the impact of the coal body on the roadway wall and other obstacles in the outburst process. The equation of outburst energy is shown as follows:

\[ W = W_1 + W_2 + W_3 + A_1 + A_2 + A_3, \]  

(1)

where \( W_1 \) is elastic potential energy, \( W_2 \) means gas internal energy, J. \( A_1 \) represents thrown work, J. \( A_2 \) is crushing work, J. \( A_3 \) signifies residual gas kinetic energy, J.

where \( U_0^s \) is the releasable elastic potential of coal and rock mass per unit volume, J. \( v \) is the volume of energy release zone of coal-rock mass when outburst occurs, \( m^3 \).

\[ W_1 = \int U_0^s \, dv, \]  

(2)

\[ W_2 = W_{2P} + W_{2J} = \left[ a_2 p_1 \ln \left( \frac{p_1}{p_0} \right) + m_1 \right] v_0, \]  

(3)

\[ A_2 = \alpha S = \frac{6}{\rho} \left( \frac{1}{d} - \frac{1}{D} \right), \]  

(5)

where \( M_t \) is the burst coal mass, kg. \( g \) represents gravity coefficient, N/kg. \( h \) is inside diameter of simulated roadway, and \( L_p \) is the effective distance of burst coal.

After substituting values into Equations (1)–(5), the elastic potential energy was 20.1 kJ, the gas internal energy was 68.52 kJ, the crushing work was 61.41 kJ, and the throwing work was 23.88 kJ in the coal and gas outburst experiment under deep high-stress conditions. The analysis indicates that the sum of the elastic potential and gas internal energy is larger than the sum of the crushing work and ejection work, mainly owing to the energy loss of frictional heat, vibration, and sound during the process of coal flow containing gas being thrown out. As shown in Figure 28, the internal energy of the gas is larger than the elastic potential of the coal and rock mass. The gas internal energy accounts for 75% of the total energy in the coal and gas outburst process under deep high-stress conditions. The internal energy of the gas is still the largest portion of energy source for coal and gas outbursts, which had a leading role in the outburst process. However, the elastic potential of coal and gas outbursts under deep
high-stress conditions can account for 22%. With the continuous increase in mining depth, the elastic potential energy becomes increasingly important. On the other hand, the breaking work of coal and rock mass in the test is larger than the corresponding throwing work. A large part of the energy is consumed during the breaking of coal mass during an outburst. Therefore, based on the energy analysis, gas and stress were the main factors for the outburst.

6 | CONCLUSIONS

In this study, a coal and gas outburst experiment under deep high-stress conditions was carried out and the distribution characteristics of pulverized coal being thrown out after the outburst and stress–gas pressure response laws during the outburst were obtained. The findings of this study can be summarized as follows.

(1) The characteristics of the outburst hole, burst coal quality distribution, and burst coal pulverization were obtained under deep high-stress conditions. In the outburst hole, there were several layers of shell-like lamellar cracks with a certain thickness distributed in the coal body. Moreover, these lamellar cracks were in sequence. The vast majority of the burst coal was distributed within 2.3 m (1–3# statistical areas) from the outburst, while a small amount of outburst coal was distributed within 2.3–4.5 m (4–6# statistical areas). The coal pulverization rate near the outburst was smaller, while it was higher far from the outburst.

(2) The S–GP–T response laws of coal and rock masses around the outburst hole in the process of coal and gas outbursts were evaluated. The stress variation decreased with the increase in the distance from the outburst port. On the other hand, the gas pressure in the coal body changed sharply and oscillated many times during the process of decrease. The decrease in the gas pressure near the outburst was the fastest. The rate of decrease gradually decreased with the increase in the distance from the outburst port.

(3) The gas internal energy was larger than the elastic potential of coal and rock mass. The internal energy of the gas accounted for 75% of the total energy in the process of coal and gas outbursts under deep high-stress conditions. Therefore, the gas internal energy was still the main energy source for coal and gas outbursts and had a leading role in the process of coal and gas outbursts. However, the elastic potential of coal and gas outbursts under deep high-stress conditions could account for 22%. With the continuous increase in mining depth, the elastic potential energy becomes increasingly important. Therefore, based on the energy analysis, gas and stress were the main factors for the outburst.

ORCID
Bo Zhao http://orcid.org/0000-0001-6632-6175

REFERENCES
1. Cheng Y, Pan Z. Reservoir properties of Chinese tectonic coal: a review. Fuel. 2020;260:116350.
2. Kursunoglu N, Onder M. Application of structural equation modeling to evaluate coal and gas outbursts. Tunn Undergr SP Tech. 2019;88:63-72.
3. Jiang L, Wu Q, Wu Q, et al. Fracture failure analysis of hard and thick key layer and its dynamic response characteristics. Eng Fail Anal. 2019;98:118-130.
4. Lu S, Zhang Y, Sa Z, Si S. Evaluation of the effect of adsorbed gas and free gas on mechanical properties of coal. Environ Earth Sci. 2019;78(6):218.
5. Zhao B, Wen G, Nian J, et al. Numerical simulation study on the multi-physical field response to underground coal and gas outburst under high geo-stress conditions. Minerals. 2022;12:151.
6. Zou Q, Liu H, Zhang Y, Li Q, Fu J, Hu Q. Rationality evaluation of production deployment of outburst-prone coal
7. Wei Z, Cheng Y, Guo P, Jin K, Wang H. An analysis of the gas-solid plug flow formation: new insights into the coal failure process during coal and gas outbursts. *Powder Technol.* 2017;305:39-47.

8. Zhou B, Xu J, Yan F, Peng S, Cheng L. Effects of gas pressure on dynamic response of two-phase flow for coal-gas outburst. *Powder Technol.* 2020;377.

9. Zhao B, Cao J, Sun H, Wen G, Wang B. Experimental investigations of stress-gas pressure evolution rules of coal and gas outburst: a case study in Dingji coal mine, China. *Energy Sci Eng.* 2019;8(3):402-416.

10. Yan F, Xu J, Peng S, et al. Breakdown process and fragmentation characteristics of anthracite subjected to high-voltage electrical pulses treatment. *Fuel.* 2020;275:117926.

11. An F, Yuan Y, Chen X, Li Z, Li L. Expansion energy of coal gas for the initiation of coal and gas outbursts. *Fuel.* 2019;235:551-557.

12. Yang W, Wang H, Lin B, et al. Outburst mechanism of tunnelling through coal seams and the safety strategy by using “strong-weak” coupling circle-layers. *Tunn Undergr SP Tech.* 2018;74:107-118.

13. Shi Q, Qin B, Liang H, Gao Y, Bi Q, Qu B. Effects of igneous intrusions on the structure and spontaneous combustion propensity of coal: a case study of bituminous coal in Daxing Mine, China. *Fuel.* 2018;216:181-189.

14. Zhao T, Guo W, Tan Y, Yin Y, Cai L, Pan J. Case studies of rock bursts under complicated geological conditions during multi-seam mining at a depth of 800 m. *Rock Mech Rock Eng.* 2018;51(5):1539-1564.

15. Fan C, Elsworth D, Li S, Zhou L, Yang Z, Song Y. Thermo-hydro-mechanical-chemical couplings controlling CH4 production and CO2 sequestration in enhanced coalbed methane recovery. *Energy.* 2019;173:1054-1077.

16. Fan C, Li S, Luo M, Du W, Yang Z. Coal and gas outburst dynamic system. *Int J Mining Sci Technol.* 2017;27(1):49-55.

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

18. Skoczylas N, Dutka B, Sobczyk J. Mechanical and gaseous properties of coal briquettes in terms of outburst risk. *Fuel.* 2014;134:45-52.

19. Wang L, Cheng Y, An F, Zhou H, Kong S, Wang W. Characteristics of gas disaster in the Huaibei coalfield and its control and development technologies. *Nat Hazards.* 2014;71(1):85-107.

20. Xue S, Yuan L, Wang Y, Xie J. Numerical analyses of the major parameters affecting the initiation of outbursts of coal and gas. *Rock Mech Rock Eng.* 2014;47(4):1505-1510.

21. Zhang R, Jiang Z, Zhou H, Yang C, Xiao S. Groundwater outbursts from faults above a confined aquifer in the coal mining. *Nat Hazards.* 2014;71(3):1861-1872.

22. Zhou H, Yang Q, Cheng Y, Ge C, Chen J. Methane drainage and utilization in coal mines with strong coal and gas outburst dangers: a case study in Luling mine, China. *J Nat Gas Sci Eng.* 2014;20:357-365.

23. Wang S, Elsworth D, Liu J. Permeability evolution during progressive deformation of intact coal and implications for instability in underground coal seams. *Int J Rock Mech Min.* 2013;58:34-45.

24. 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;54:222-231.

25. Lu Y, Tang J, Ge Z, Xia B, Liu Y. Hard rock drilling technique with abrasive water jet assistance. *Int J Rock Mech Min.* 2013;60:47-56.

26. Aguado MBD, Nicieza CG. Control and prevention of gas outbursts in coal mines, Riosa–Olloniego coalfield, Spain. *Int J Coal Geol.* 2007;69(4):253-266.

27. Wold MB, Connell LD, Choi SK. The role of spatial variability in coal seam parameters on gas outburst behaviour during coal mining. *Int J Coal Geol.* 2008;75(1):1-14.

28. Jiang C, Wang C, Li X, et al. Quick determination of gas pressure before uncovering coal in cross-cuts and shafts. *J China Univ Mining Technol.* 2008;18(4):494-499.

29. Sobczyk J. The influence of sorption processes on gas stresses leading to the coal and gas outburst in the laboratory conditions. *Fuel.* 2011;90(3):1018-1023.

30. Xusheng Z, Qianting H, Xiaoliang N. Research on comprehensive early-warning technology of coal and gas outburst. *Procedia Eng.* 2011;26:2376-2382.

31. Huang B, Liu C, Fu J, Guan H. Hydraulic fracturing after water pressure control blasting for increased fracturing. *Int J Rock Mech Min.* 2011;48(6):976-983.

32. Karacan CÖ, Ruiz FA, Coté M, Pipps S. Coal mine methane: a review of capture and utilization practices with benefits to mining safety and to greenhouse gas reduction. *Int J Coal Geol.* 2011;86(2-3):121-156.

33. Lu T, Zhao Z, Hu H. Improving the gate road development rate and reducing outburst occurrences using the waterjet technique in high gas content outburst-prone soft coal seam. *Int J Rock Mech Min.* 2011;48(8):1271-1282.

34. Hu Q, Zhang S, Wen G, Dai L, Wang B. Coal-like material for coal and gas outburst simulation tests. *Int J Rock Mech Min.* 2015;74:151-156.

35. Jiang C, Xu L, Li X, et al. Identification model and indicator of outburst-prone coal seams. *Rock Mech Rock Eng.* 2015;48(1):409-415.

36. Niu Q, Cao L, Sang S, Zhou X, Wang Z, Wu Z. The adsorption-swellling and permeability characteristics of natural and reconstituted anthracite coals. *Energy.* 2017;141:2206-2217.

37. Qiu L, Song D, Li Z, Liu B, Liu J. Research on AE and EMR response law of the driving face passing through the fault. *Saf Sci.* 2019;117:184-193.

38. Wang Z, Cheng Y, Qi Y, Wang R, Wang L, Jiang J. Experimental study of pore structure and fractal characteristics of pulverized intact coal and tectonic coal by low temperature nitrogen adsorption. *Powder Technol.* 2019;350:1-10.

39. Zhao W, Cheng Y, Pan Z, Wang K, Liu S. Gas diffusion in coal mines: a case study of nantong coal mine in Chongqing, China. *Safety Sci.* 2020;122:104515.
