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Bo Zhao
University of Wollongong

Jie Cao


Haitao Sun

Guangcai Wen

Linchao Dai

See next page for additional authors

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Authors

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RESEARCH ARTICLE

Experimental investigations of stress-gas pressure evolution rules of coal and gas outburst: A case study in Dingji coal mine, China

Bo Zhao^{1,2,3,4}  | Jie Cao^{1,2,4} | Haitao Sun^{1,2} | Guangcai Wen^{1,2,4} | Linchao Dai^{1,2} | Bo Wang^{1,2}

¹China Coal Technology and Engineering Group Chongqing Research Institute, Chongqing, China

²State Key Laboratory of The Gas Disaster Detecting, Preventing and Emergency Controlling, Chongqing, China

³School of Civil, Mining & Environmental Engineering, University of Wollongong, NSW, Australia

⁴State Key Laboratory of Coal Mine Disaster Dynamics and Control, Chongqing University, Chongqing, China

Correspondence

Bo Zhao, China Coal Technology and Engineering Group Chongqing Research Institute, Chongqing 400037, China.
Email: zhaobo91@cqu.edu.cn

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Abstract

Coal and gas outburst is a potentially fatal risk during the mining of gassy coal seams, which seriously threatens the safe mining of collieries. To understand the outburst mechanism and evolution rules, a new apparatus (LSTT) was developed to conduct simulated experiment. In the context of an outburst accident in Dingji coal mine, the authors launched an authentic outburst experiment to replay the outburst accident. Experimental apparatus, similar criterion, coal-like materials and gas sources, and experimental design were discussed systematically in this paper. Experimentally, the study analyzed the geo-stress has significant influence on the outburst evolution. At the driving face, the stress concentration possibly caused gas outburst, under the influence of mining-induced stress. After the outburst occurred, the stress balance of the coal changed, resulting in the instability of the coal. Furthermore, the elastic energy, gas enthalpy, and gravitational potential energy were released rapidly. The experimental result stated that outburst coal has the sorting characteristics, in line with the field outburst law. The intensity prediction model has been built based on the energy model. Moreover, the factors that impact outburst intensity were analyzed. In the process of coal and gas outburst, the gas enthalpy of gas and the elastic potential of coal are the main energy sources. This study provides guidance for the development of the outburst mechanism and outburst mine management.

KEYWORDS

gas pressure, geo-stress, intensity prediction model, mass distribution characteristics, outburst experiment, outburst mechanism

1 | INTRODUCTION

Outburst (hereinafter referred to as “outburst”) is regarded as a potential hazard to be managed in gassy coal seams around the world.¹⁻⁷ Since the first-recorded outburst happened in Isaac Coal Mine in Lule coalfield in 1843, more

than 40 thousand outbursts have occurred around the world.⁸ Recently, China averagely increases 37 pairs of coal mine and more than 280 times outburst accident every year.⁹⁻¹³ Outbursts also occur in other countries, like Russia, Poland, and Australia.¹⁴⁻¹⁶ However, methane hazard mechanism has not yet been fully understood. This is partly due to the

increasing depths of modern mines and also to other mining-related circumstances, like geological structure and geo-stress.¹⁷⁻²⁸ Meanwhile, thermo-hydro-mechanical-chemical couplings in the gas outburst process are concerned by the researchers. Numerous experimental measurements and numerical simulations were conducted to investigate permeability and damage evolution process in coal seam.²⁹⁻³¹

Lots of efforts have been made to analyze the cause of outburst. Researchers proposed many theories/hypotheses to explain outburst mechanism. Nekrasovski and Skochinski, for the first time, stated outburst is due to geo-stress, gas, and physical-mechanical properties of coal in 1951 and 1954, respectively.³² Soon afterward, Lama and Saghafi pointed geologic structure, gas pressure, and physical-mechanical properties synthetically impact outburst.³³ Wold et al presented the CSIRO, which states gas, geo-stress, coal structure, strength, geologic structure all will provoke outburst collectively (Figure 1).³⁴ The spherical shell destabilization theory was proposed by Jiang, which indicated the geo-stress causing shell spall.^{35,36} In summary, it includes the gas leading role hypothesis, the geo-stress leading role hypothesis, the chemical effect hypothesis, and combination hypothesis.^{37,38} And the last one has been widely recognized to explain the intact outburst process. It stressed that geo-stress, gas, physical properties, and occurrence state of coal comprehensively impact outbursts (Figure 2).³⁹⁻⁴¹ Four major stages in the outburst process are proposed, including accumulation stage (stress concentration); motivation stage (rapid damage of ejection); development stage (ejection and pause); and over stage (stabilization). Generally, the combination hypothesis has been accepted, and almost all effective factors have been summarized. So far, the main research methods include theoretical research, numerical simulation, and experimental research, among which, experimental research is an important means to explore outburst mechanism.⁴²⁻⁴⁵ In addition,

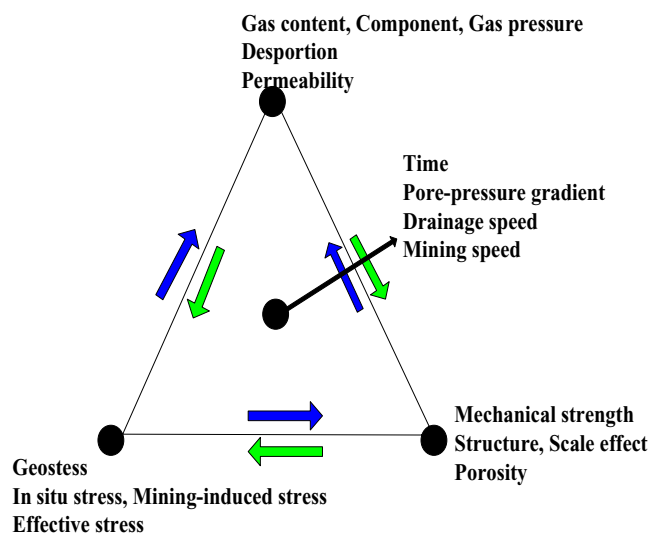


FIGURE 1 The influence of factors in CSIRO outburst model

coal and gas outburst is much complex, and there are so many influencing factors. Coal and gas outburst has different patterns in the condition of different areas, different coal seams, different structures, and different mining disturbances. Due to incredible outburst damage, field outburst test is almost impossible to conduct. Therefore, it can be concluded that it may be the best way to further explore the outburst mechanism with the experimental conditions under control.⁴⁶

With experimental technology improving, the outburst mechanism was further studied. Tu et al⁴⁷ stated that outbursts always occur in tectonic areas, like faults. An et al found that low permeability tends to abnormal methane distribution.⁴⁸ Xue et al⁴⁹ discussed many factors, especially structure, impact outburst, by the mathematical model and using COMET3 and Flac3D programming. The influence of parameters such as buried depth and coal thickness on the outburst of coal and gas is discussed by Fisne et al and Nie et al^{50,51} Peng et al⁵² considered that gas seepage impacts the strength of coal containing gas and accelerates its failure process, by the heat-flow-solid coupling device and the outburst device. Wang et al discussed the relationship between adsorption constant and outburst risk.^{24,25} Wang stated that resistance of coal does not distribute homogeneously in the coal seam, which is always induced by methane, stress, structure, and water via direct current (DC) prospecting instrument.⁵³

Geo-stress, gas pressure, gas adsorption and seepage, and properties of coal were regarded to result in outburst, collectively (Figure 3). Despite a large number of experiments have been conducted to explain specific questions, most researchers adopted to reduce geo-stress or mechanical property of coal in previous experiments, which would decrease similarity, owing to the limit of experiment condition. Therefore, the true outburst experiment in the actual geological environment (eg, the same geo-stress and gas pressure) is still lacking in previously published data and models. In this paper, a new apparatus, large-scale true triaxial apparatus (LSTT), which can simulate the true geological environment, was used to give comprehensive investigations on the outburst mechanism, especially, the stress-gas pressure evolution rules in the outburst process. Furthermore, the evolution rules of outburst will be discussed to provide some implications for the prevention of outburst disasters.

2 | EXPERIMENTAL

2.1 | Experimental background

The experiment was based on the outburst accident in Dingji coal mine, Huainan, China. The outburst occurred in 1331 driving working face, East 2 mining area, in April 2009 (Figure 4). First, 35t coal was thrown out, and 235.4m gas was gushed out in this outburst accident. Three persons died in the accident. Second, the coal seam thickness of

FIGURE 2 Stage classification for the dynamic process of outburst

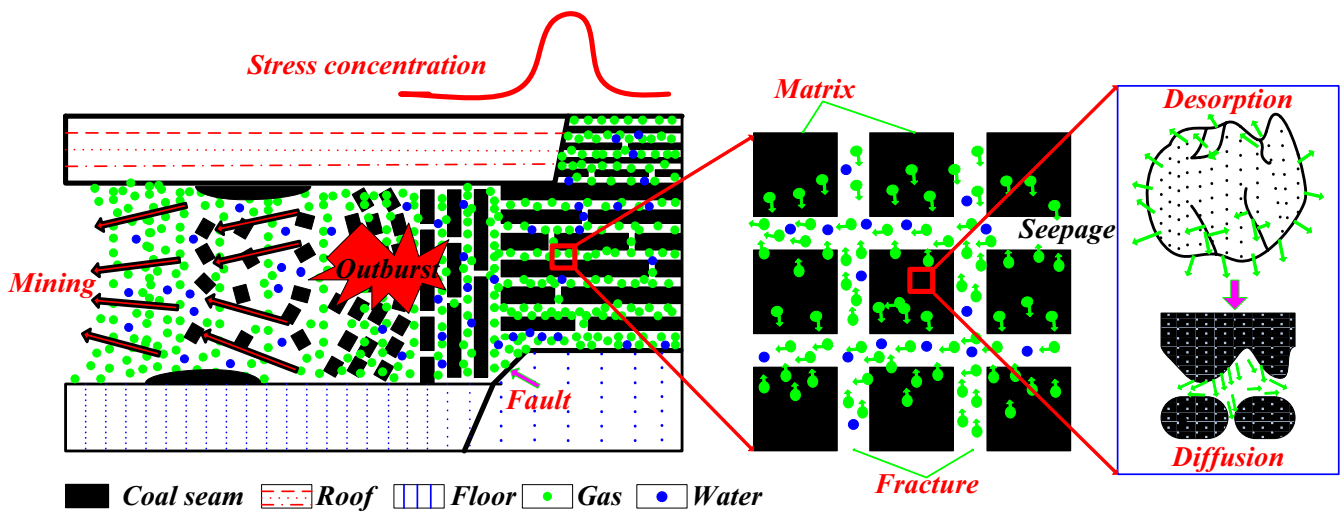
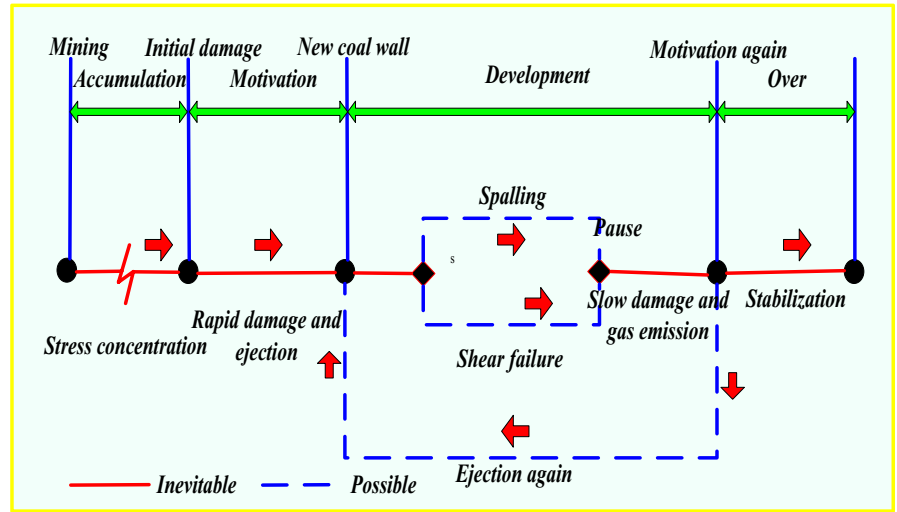


FIGURE 3 The diagram of the entire process of outburst

East 2 mining area is about 0.9 m, and dip angle of coal seam is 2°. Third, the buried depth of coal seam is about 570 m, and the calculated geo-stress is close to 16 MPa. In the last, the coal seam is soft (Firmness coefficient is about 0.18), which does not have the ability in resisting damage. When the outburst accident happened, the gas pressure of East 2 mining area was about 0.5 MPa. After the accident investigation, the typical accident was directly caused by the geo-stress unloading in the stress concentration area caused by the mining activities.

2.2 | Similar criterion

Similar criterion is significant when researchers conduct coal and gas outburst tests. The problems of coal and gas outburst are solved usually by classic elastic-plastic mechanics. It can be considered that coal and gas outburst consists of three continuous or alternate processes: the static deformation and failure of coal in the preparation process, the crushing

of gas-containing coal in the development process, and the movement of crushed coal and gas flow in the excavation space.³⁷ For outburst dynamic phenomena, stress, gas pressure, and physical-mechanical properties of coal and rock are the main parameters that determine their occurrence and development. The experiment similar design was based on the reference.⁵⁴

Dimensionless similarity constant:

$$C_\epsilon = C_\mu = C_\phi = 1 \tag{1}$$

Mechanical similarity constant:

$$\frac{C_\rho C_l}{C_\sigma} = 1, \quad C_p = C_\sigma, \quad C_E = C_\sigma \tag{2}$$

Seepage similarity constant:

$$C_K = \sqrt{C_l} / c_\gamma \tag{3}$$

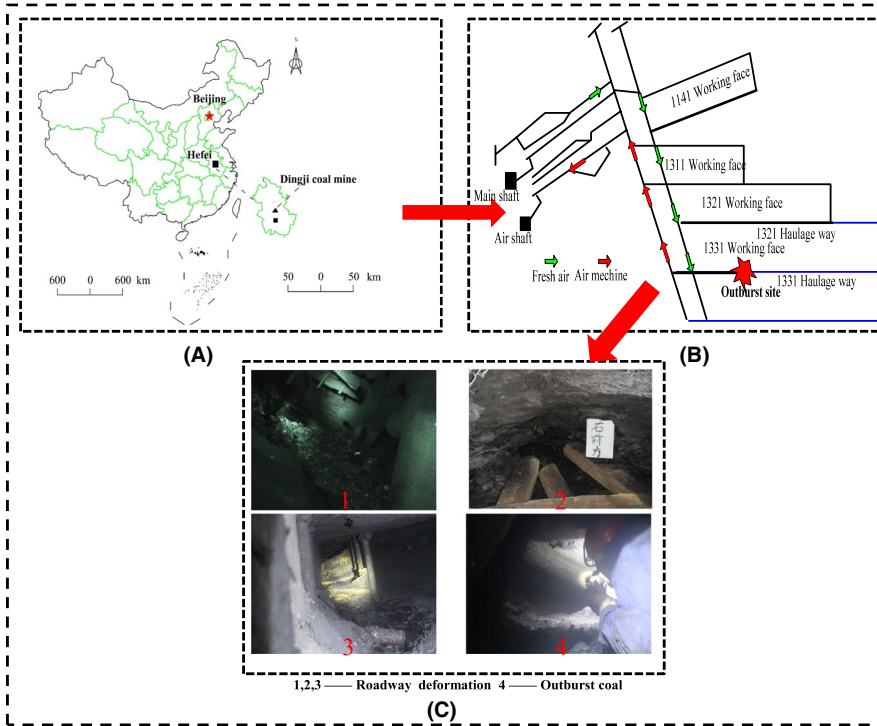


FIGURE 4 The outburst accident site

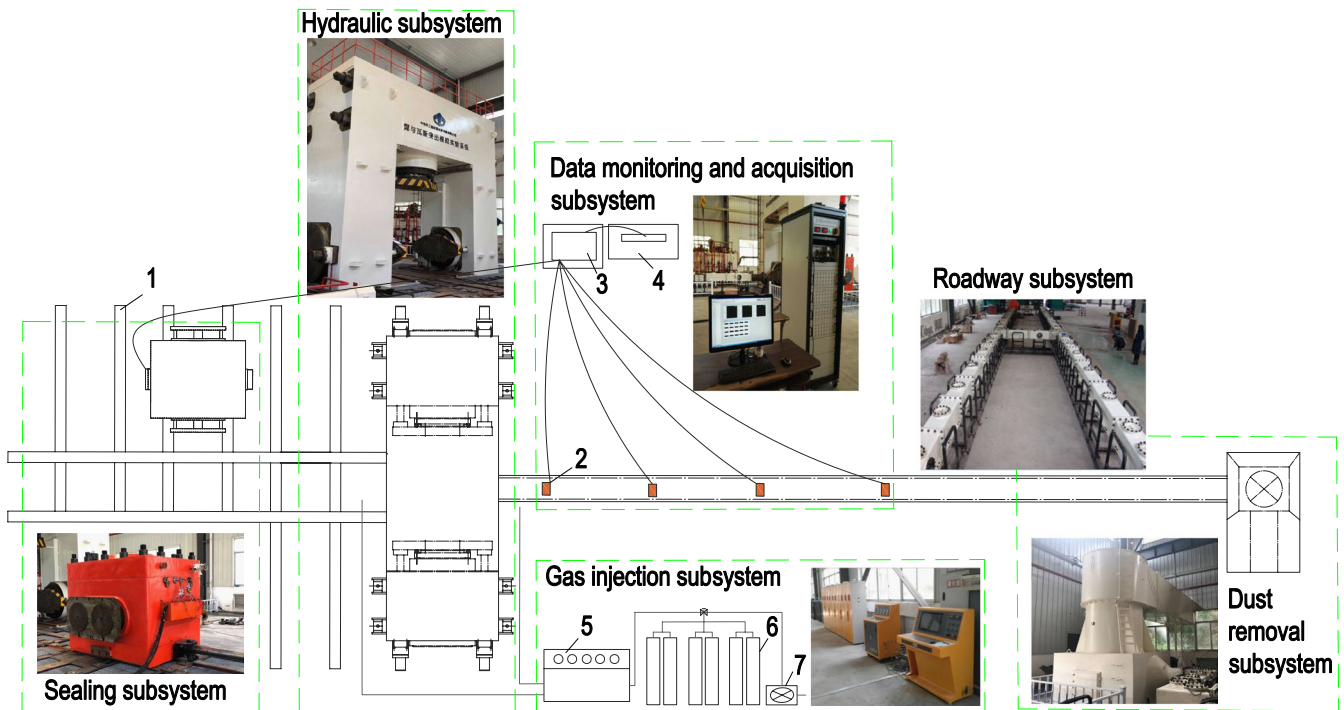


FIGURE 5 Schematic diagram of outburst simulating device (LSTT)

Time similarity constant:

$$C_t = \sqrt{C_l} \quad (4)$$

Adsorption and desorption similarity constant:

$$C_a = 1, \quad C_b C_p = 1 \quad (5)$$

where C_e represents strain similar ratio, C_μ represents Poisson's ratio similar ratio, C_ϕ represents frictional angle similar ratio, C_ρ represents density similar ratio, C_l represents size similar ratio, C_σ represents stress similar ratio. C_E represents elasticity modulus similar ratio, C_p represents gas pressure similar ratio, C_K represents permeability similar ratio, C_γ represents

TABLE 1 Raw materials of coal-like materials for outburst experiment⁶⁰

Category	Material	Size fraction	Remarks
Skeletal	Crushed coal (CC)	80-40 mesh/40-20 mesh	Outburst coal seam
Grouting agent	Cement (C)	425# ordinary Portland cement	–
Auxiliary	Sand (S)	40-20 mesh	River sand
	Activated carbon (AC)	$\phi 5.6 \times 5.3 \text{ mm}^2$	Granule
	Water (W)	–	Ordinary tap water

unit weight similar ratio, C_t represents time similar ratio, C_α represents limited absorbed capacity similar ratio, and C_b , C_b represents adsorption constant similar ratio.

2.3 | Experimental apparatus

With the mining deepen, outburst area is characterized by high stress and gas pressure. To simulate authentic stress, this LSTT (large-scale true triaxial apparatus) was designed by selecting the “stress-solid-time similar” as the dominant guideline. According to this guideline, the LSTT system consists of pathway subsystem, hydraulic subsystem gas, injection subsystem, roadway subsystem, data monitoring, and acquisition subsystem and dust removal subsystem, as shown in Figure 5. The anisotropic hydraulic machine with the maximum axial applied force of 30 000 kN was utilized as the pressurization system in this experiment. And the horizontal loading can reach 20 000 kN. The effective size of the container is 1500 mm * 800 mm * 800 mm. The sealing container has the feature that the maximum working pressure is 6.0 MPa, which can not only simulate the seam and the outburst hole, but also launch the outburst. A various network roadway simulation of fluid routing can be completed, using straight pipe (1.0 m, 1.5 m), tee pipe, rectangular pipe, and inclined pipe (10°, 20°). The total length of the roadway is 50 m.⁵⁵

2.4 | Coal-like materials and gas sources

To replay veritably outburst in the laboratory, coal-like material research is the necessary link in the outburst experiment. To meet the needs of the large size of outburst simulation models, this experimental study on the coal-like material chooses crushed coal, cement, sand, activated carbon, and

water as raw materials (Table 1). The crushed coal was collected closed to the “outburst zone” in Dingji coal mine. 425# ordinary Portland cement was selected as grouting agent, which would play an important role in molding and increasing the mechanical properties of similar materials. Sand and activated carbon would control the porosity and adsorption constant, respectively. The coal-like material ratios in this experiment are based on the research of Zhang and Wang.⁵⁶ The coal-like materials were made by cold pressing. Meanwhile, the forming pressure was 25MPa. And the pressure holding time was 30 minutes. The basic parameters of the similar materials are listed in Table 2 after 30 days.

Due to a large number of methane, which has the flammable and explosive properties, being needed for the experiment within a finite space, high-concentration CO₂ was selected to guarantee laboratory safety. The previous research showed that the adsorption capacity of coal-like materials can be compensated by using CO₂ with stronger adsorption capacity as experimental gas.⁵⁴

2.5 | Experimental design

The critical procedure of experiment can be concluded as Figure 6. Outburst experiment procedures mainly include basic parameters collection, load similar materials, airtightness test, link the chamber with the roadway and start experiment, etc. We used helium gas to test the air-tight condition of the chamber. In our experiment, the CO₂ was selected to be the adsorption gas. The adsorption time is about 3 days. When the gas sensors in the chamber all showed 0.5 MPa, we considered the similar materials to reach the adsorption equilibrium.

TABLE 2 Coal-like material ratios and physical-mechanical parameters

Coal-like material ratios,%					Uniaxial compressive strength(MPa)	Firmness coefficient	Elasticity modulus(MPa)	Density (g/cm ³)	Porosity (%)	Adsorption constant	
C	S	W	AC	CC						a	b
7	5.5	8.5	0.84	78.16	1.1 ~ 1.5	0.188	62.1 ~ 113	1.39 ~ 1.40	5.36	33.97	1.62
Raw coal					1.5	0.18 ~ 0.25	1230	1.4	5.48	32.5	1.56

Note: Where “a” represents limited absorbed capacity, cm³/g•r, and “b” represents adsorption constant, MPa⁻¹.

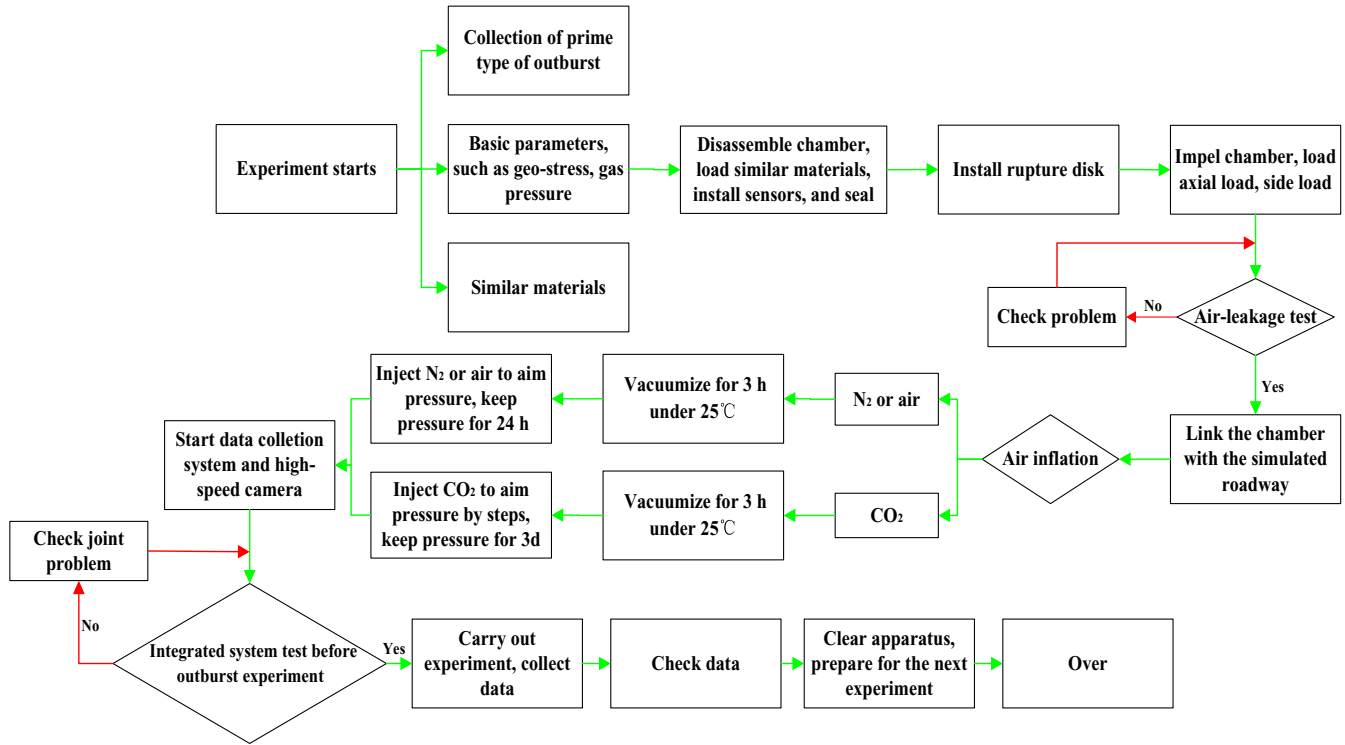


FIGURE 6 Flowchart of the outburst experiment

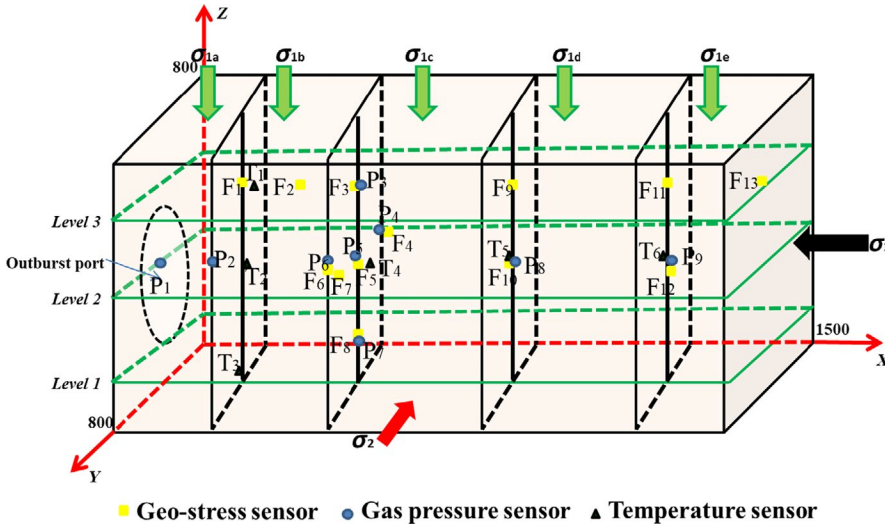


FIGURE 7 Sensor layout in container

The sensors consist of gas sensors, geo-stress sensors, and temperature sensors. To facilitate the quantitative analysis of test results, a space rectangular coordinate system was established. The space coordinate system was established with the lower left corner of the box body as the origin in Figure 7. And the coordinate of center outburst port is 0, 400, and 350 mm. In order to stimulate the mining-induced stress distribution in the driving working face, the chamber was divided into 5 areas in vertical direction. The different stress sensors, 2.5 MPa (σ_{1a}), 10 MPa (σ_{1b}), 16MPa (σ_{1c}), and 10MPa (σ_{1d} , σ_{1e}), were applied to simulate the mining-induced stress in the driving face. Meanwhile, the sensors in the chamber were arranged in

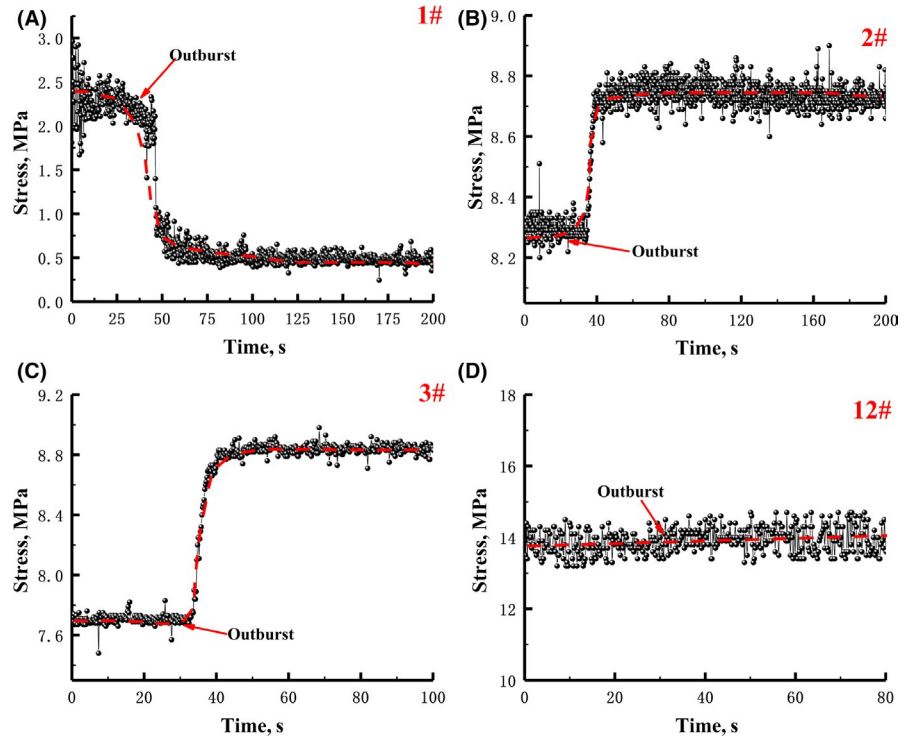
three levels, level 1, level 2, and level 3. Nine gas sensors, 13 geo-stress sensors, and 6 temperature sensors were put in the chamber to monitor the changes in the rules. The coordinate of sensors in chamber is listed in Appendix S1.

3 | RESULTS AND DISCUSSION

3.1 | Stress evolution rules in the outburst process

The vertical stress of unloaded area σ_{1a} as shown in Figure 8A decreased rapidly. In Figure 8A, the outburst occurred at

FIGURE 8 Stress evolution rules in the outburst process



30.4 seconds and undergone stress decrease rapidly to rebalance at 50 seconds. However, the vertical stress of area σ_{1b} and σ_{1c} increased, which indicated the geo-stress transfer after the outburst, as shown in Figure 8B,C. In Figure 8B,C, the vertical stress of 2# and 3# changed at 33 and 34.4 seconds, respectively, after the outburst. Figure 8D states that the in situ stress area σ_{1d} and σ_{1e} stayed the same. We can conclude that the geo-stress has influence on the outburst evolution. During the driving face, the stress concentration often happens under the influence of mining-induced stress, which always tends to outburst. The initial support pressure mainly occurs at the exposed surface of the coal wall, and then, due to the elastic recovery of the coal wall at the exposed surface, the horizontal stress is released. Coal stress changes from three-stress state to uniaxial compression state. Under the supporting pressure, compression failure occurs at the exposed surface of coal wall, and its ability to bear overburden load is further reduced. When the outburst happened, the overburden load continued to transfer to the depth of the coal wall in this process.

3.2 | Gas pressure evolution rules in the outburst process

In the experiment, the inflation pressure was about 0.50 MPa. The coal achieved adsorption equilibrium at 25°C in 10 days. When the gas and coal was ejected, the gas pressure decreased promptly. The law of pressure evolution with time at different measuring points in the outburst process is shown in Figure 9. Figure 9A-D represents 1 #, 2 #, 7 #, and 8 # gas pressure evolution rule, respectively. It can be found that

gas pressure decreases sharply in the initial time (30.4 seconds) and then levels off in the area σ_{1a} . It showed that the gas pressure of the outburst port approached to 0MPa in 1s as shown in Figure 9A,B. After outburst occurs, the stress balance of the coal changed, resulting in the instability of the coal. Furthermore, the internal elastic potential energy, gas enthalpy, and gravitational potential energy were released rapidly. Under the combination of ground stress and gas pressure, the coal in the vicinity of the outburst hole wall was damaged and thrown out, and the air pressure dropped and formed a new outburst hole. In Figure 9C, it can be concluded that gas pressure decreased from 0.54 to 0.4 MPa after 70 seconds. The reason for decrease in gas pressure is that the coal and gas is gradually ejected. In Figure 9D, we can find that the gas pressure drop off slightly from 0.41 to 0.405, later gas pressure increase to 0.42 in 170 seconds. With the accumulation of coal outburst, the gas-coal circulation channel was blocked. However, the gas in the coal desorb continuously, resulting in a rise in gas pressure as Figure 9D. As the coal-contained gas is suddenly unloaded, a gas pressure gradient appears near the exposed surface and has a tensile effect on the coal. With the gas emissions and the energy releasing, the gas pressure gradient and the outburst energy decrease continuously during the unstable failure of coal.⁴⁷

3.3 | The mass distribution of the outburst coal during an outburst

When the kinetic energy of outburst coal was exhausted, the ejected coals in the simulated roadway presents

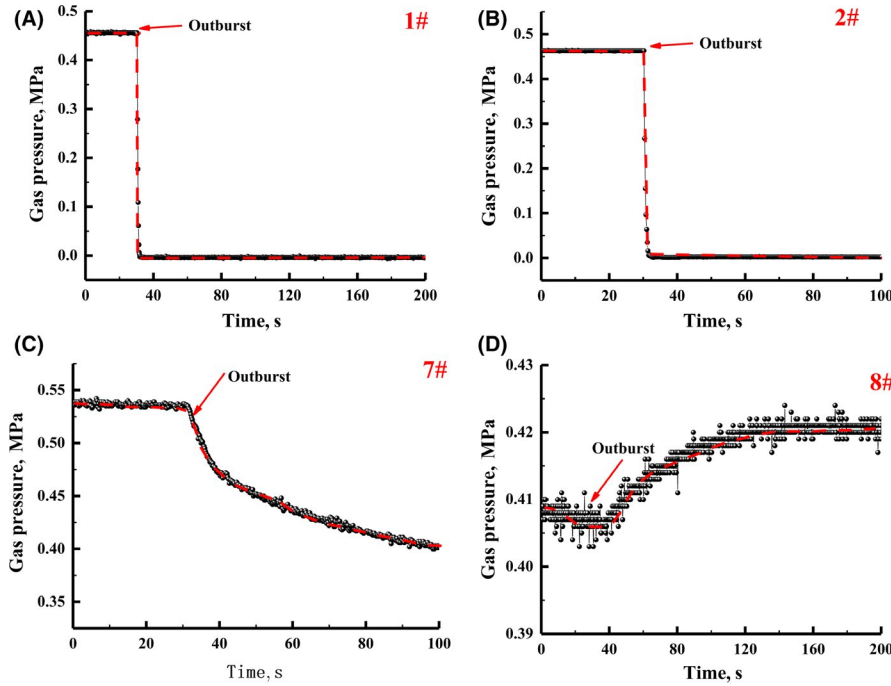


FIGURE 9 Gas pressure evolution rules in the outburst process

different distribution characteristics.^{57,58} After the experiment, the ejected coal in the roadway would be carefully taken out and weighed, and the mass distribution characteristics of the deposited coal are shown in Figure 10. The results showed that outburst pulverized coal was mainly distributed in the main roadway. It was concluded that the farthest thrown distance was 4.7 m. Therefore, the roadways were divided into 7 statistical zones (Figure 10), and the outburst pulverized coal mass and size distribution were separately counted. According to the experiment result, we can see that large amounts of coal are piled up at outburst port. 7.2 kilograms of coal was deposited within 0.2 m of the outburst port. As the distance increased, the amount of coal piled up decreased gradually in the roadway. In order to obtain the size distribution law of outburst pulverized coal, 100-mm, 50-mm, 30-mm, 9-mm, 3-mm, 1-mm, 0.25-mm, and 0.2-mm screens were used to pulverize each statistical region. Figure 11 demonstrates that the coal (>10 cm) was only distributed in 1 # area. As the distance increased, the particle size of coal reduced gradually in the roadway. The experimental result stated that outburst coal has the sorting characteristics, in line with the field outburst law.

3.4 | Outburst intensity prediction based on energy model

The elastic deformation of coal and rock mass under the action of dead weight stress, tectonic stress, and mining stress makes the coal and rock mass have high elastic potential. Meanwhile, due to the large amount of adsorbed

gas and free gas in the pore fissures of coal and rock, these gases have high gas enthalpy. If the elastic potential and gas enthalpy reach a certain degree, coal and gas outburst may occur, which is called as outburst risk. Therefore, the calculation of coal and rock mass energy is helpful to predict coal and gas outburst.

$$W_1 + W_2 = A_1 + A_2 + A_3 \quad (6)$$

where W_1 represents elastic energy of outburst coal, J, W_2 represents gas enthalpy of outburst coal, J, A_1 ejection work, J; A_2 represents crush work, J, and A_3 represents residual gas kinetic energy, J.

$$W_1 = \frac{3(1-2\mu)}{2E} \sigma_0^2 V_0 = \frac{3(1-2\mu)}{2E\rho} \sigma_0^2 B \quad (7)$$

where E represents elasticity modulus, ρ represents density, σ_0 represents geo-stress, μ represents Poisson's ratio, and B represents outburst intensity.

1. Gas enthalpy of outburst coal

Gas enthalpy of outburst coal consists of adsorbed gas energy W_2^a and free gas energy W_2^f .

$$W_2 = \frac{p_0}{n-1} (V_a + V_f) \left[\left(\frac{p_1}{p_0} \right)^{\frac{n-1}{n}} - 1 \right] = W_2^a + W_2^f \quad (8)$$

where p_1 and p_0 represent gas pressure before and after outburst, respectively, MPa, V_a , and V_f represent adsorbed gas

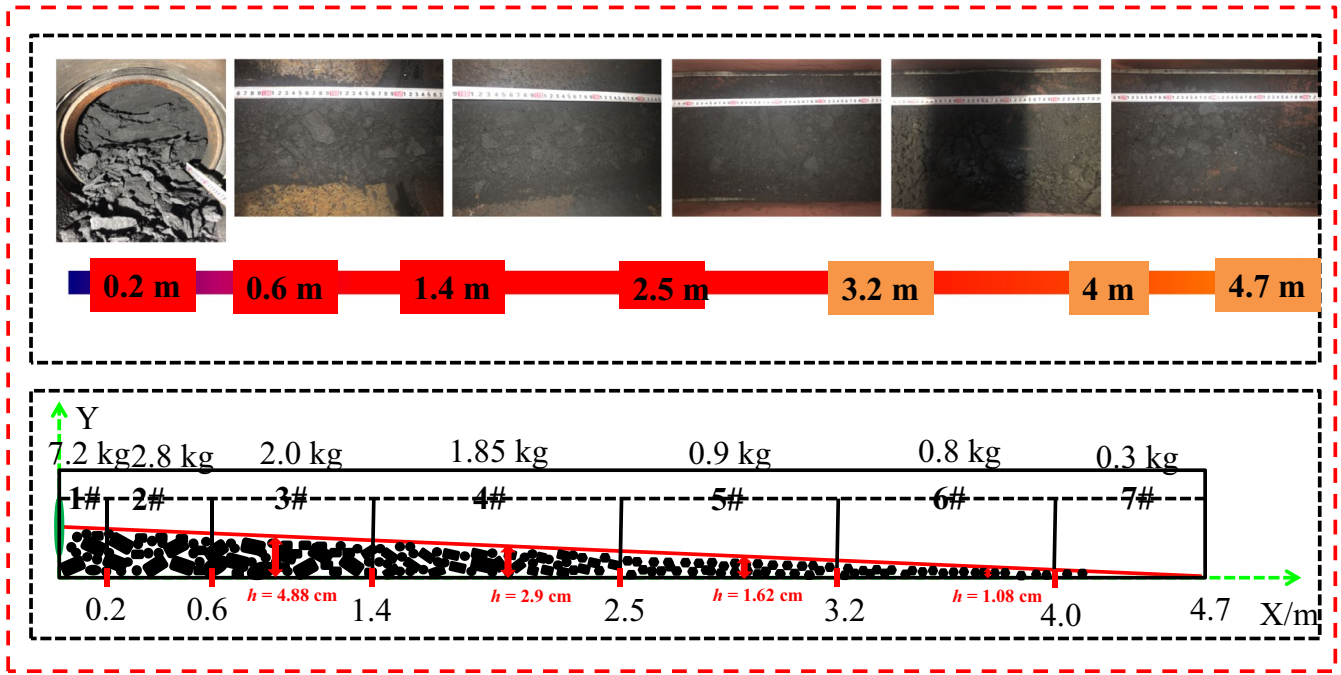
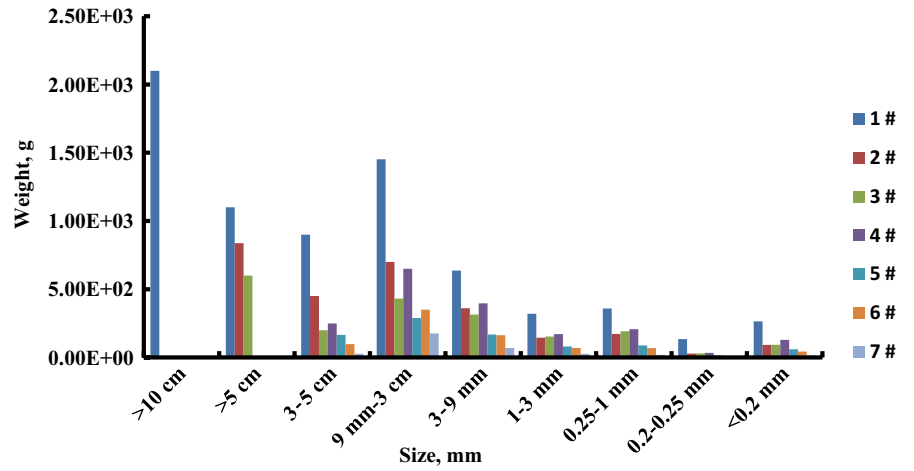


FIGURE 10 Characteristics of areas of ejected coal masses

FIGURE 11 Size distribution in different regions



volume and free gas volume, respectively, m^3 , and n represents adiabatic coefficient.

(2) Ejection work

When the condition of coal seam is near horizontal, the ejection work of outburst coal can be calculated by plane throwing formula:

$$A_1 = \frac{M_t g L_p^2}{2h} \tag{9}$$

where M_t represents ejected coal mass, g represents gravity coefficient, N/Kg , h represents inner diameter of roadway;

L_p represents effective distance of crushed coal, m . L_p can be calculated by the equation:

$$L_p = \frac{1}{M_t} \int x dM \tag{10}$$

where dM represents ejected coal mass, kg , and x represents the distance to outburst port, m .

(3) Crush work

The relationship between coal crushing work and particle size after crushing conforms to the new surface theory,⁵⁹ which means that the work consumed by coal and rock crushing is

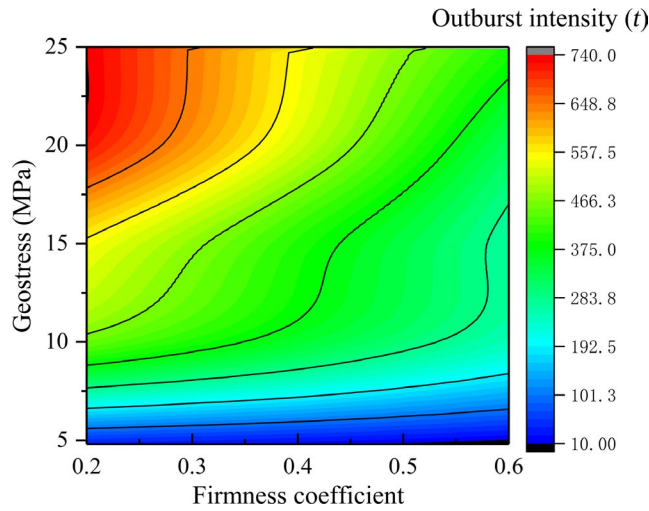


FIGURE 12 The relationship between outburst intensity and stress, firmness coefficient

positively proportional to the additional surface area after crushing. It can be shown as equation:

$$A_2 = 91.8fS = 91.8f \frac{6}{\rho} \left(\frac{1}{d} - \frac{1}{D} \right) \quad (11)$$

where f represents firmness coefficient, S represents additional surface area of coal after crushing, m^2/kg , ρ represents apparent density of crushed coal, kg/m^3 , D , d represents average diameter of crushed coal before and after outburst, m .

(4) Residual gas kinetic energy

$$A_3 = \frac{1}{2}mv_r^2 = \frac{1}{2}m \left(\frac{G}{A\rho_b} \right)^2 \quad (12)$$

Based on the Equation (6), the equation Equation (7) + Equation (8) = Equation (9) + Equation (11) + Equation (12) can be calculated.

$$\begin{aligned} & \frac{3(1-2\mu)}{2E\rho} \sigma_0^2 B + \frac{p_0}{n-1} (V_a + V_f) \left[\left(\frac{p_1}{p_0} \right)^{\frac{n-1}{n}} - 1 \right] \\ & = \frac{M_t g L_p^2}{2h} + 91.8f \frac{6}{\rho} \left(\frac{1}{d} - \frac{1}{D} \right) + \frac{1}{2}m \left(\frac{G}{A\rho_b} \right)^2 \end{aligned} \quad (13)$$

The outburst intensity equation is as follows:

$$B = \frac{2E\rho \left[\frac{M_t g L_p^2}{2h} + 91.8f \frac{6}{\rho} \left(\frac{1}{d} - \frac{1}{D} \right) + \frac{1}{2}m \left(\frac{G}{A\rho_b} \right)^2 - \frac{p_0}{n-1} (V_a + V_f) \left[\left(\frac{p_1}{p_0} \right)^{\frac{n-1}{n}} - 1 \right] \right]}{3(1-2\mu)\sigma_0^2} \quad (14)$$

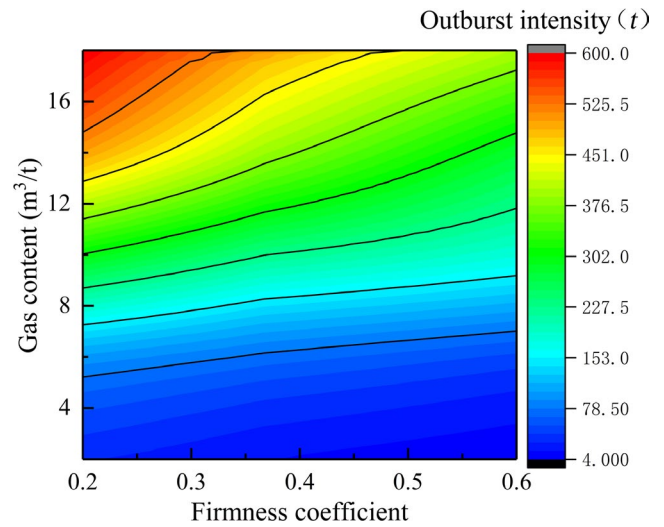


FIGURE 13 The relationship between outburst intensity and gas content, firmness coefficient

3.5 | The factors that impact outburst intensity

In the process of coal and gas outburst, the gas enthalpy and the elastic potential in the coal are the main energy sources. Moreover, gas content is the most direct reflection of internal gas energy, which is an important index to reflect outburst risk, and the firmness coefficient of coal reflects directly its physical and mechanical properties.⁵⁶ Based on the energy model of Section 3.4, a coal and gas outburst case in Dingji coal mine was selected to analyze the factors affecting different outburst intensity, such as geo-stress, gas content, coal firmness coefficient, and mining length.

Figures 12 and 13 show the effects of geo-stress, gas content, and firmness coefficient on outburst intensity. In the figures, we can find that the firmness coefficient is 0.2, 0.3, 0.4, 0.5, and 0.6, respectively, mining rate is 2 m/d, atmospheric pressure is 0.1 MPa, ejected rate is 42.3 m/s, and gas pressure is 1 MPa. The effects of geo-stress on outburst intensity are shown in Figure 12. Figure 13 demonstrates the effects of gas content on outburst intensity, when geo-stress is 10 MPa. The greater the geo-stress and gas content, the smaller the firmness coefficient, and the greater the outburst intensity will be. With the increase of geo-stress and gas content, the effect of firmness coefficient on outburst intensity increases, gradually. The smaller firmness coefficient, the greater the influence of geo-stress and gas content on outburst intensity, which show that the contribution of geo-stress and gas content in outburst is more, when the firmness coefficient of coal is not high.

Figures 14 and 15 show the effects of geo-stress, gas content, and mining rate on outburst intensity. In the figures, mining rate is 0.5, 0.75, 1.0, 1.25, and 1.5 m/d, respectively, the firmness coefficient is 0.4, atmospheric pressure is

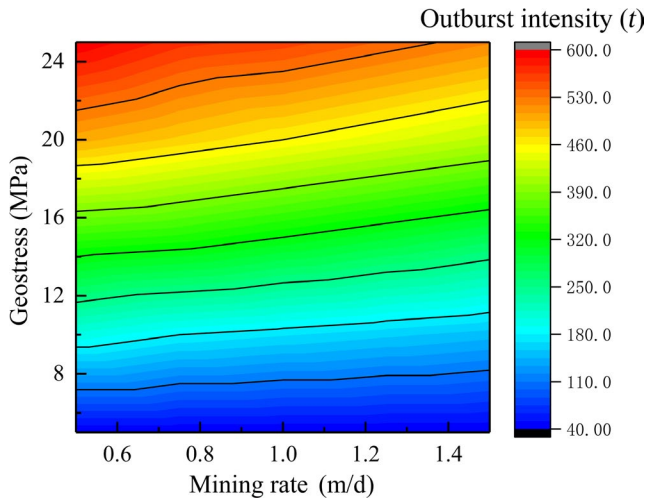


FIGURE 14 The relationship between outburst intensity and stress, mining rate

0.1 MPa, ejected rate is 42.3 m/s, and gas pressure is 2 MPa. The effects of gas content on outburst intensity are shown in Figure 15, when geo-stress is 10 MPa. Figures 14 and 15 suggest that the greater the geo-stress, gas content, and mining rate, the greater the outburst intensity will be. With the increase of geo-stress and gas content, the mining rate has little effect on outburst intensity, which suggests that the mining rate is not the key factor to the outburst intensity. Under a certain mining rate, the outburst intensity is approximately linear with the geo-stress, while the outburst intensity is approximately exponential with the gas content, which further indicates that the sensitivity of the outburst intensity to changes in the gas content is higher than that to changes in the geo-stress.

4 | CONCLUSION

The study carried out the outburst simulation experiment by using a self-developed outburst simulation device. In the context of an outburst accident in Dingji coal mine, the authors launched an authentic outburst experiment. Experimental apparatus, similar criterion, coal-like materials and gas sources, and experimental design were discussed systematically in this paper. Experimentally, the study analyzed the geo-stress and gas pressure evolution rules in the outburst process. Meanwhile, the authors also analyzed the mass distribution characteristics of the deposited coal during an outburst. Eventually, the outburst energy model has been built, and based on the model, the factors that impact outburst intensity were analyzed. The conclusions are as follows:

1. It was concluded that the farthest thrown distance was 4.7m. Large amounts of coal are piled up at outburst

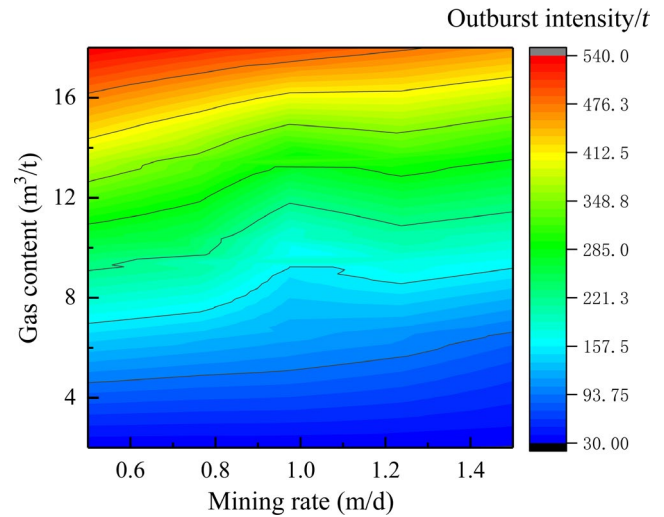


FIGURE 15 The relationship between outburst intensity and gas content, mining rate

port. There is 7.2 kilograms of coal deposited within 0.2 m of the outburst pork. As the distance increased, the particle size of coal reduced gradually in the roadway. The experimental result stated that outburst coal has the sorting characteristics, in line with the field outburst law.

2. After outburst occurred, the stress balance of the coal changed, resulting in the instability of the coal. Furthermore, the internal elastic potential energy, gas enthalpy, and gravitational potential energy were released rapidly.
3. The greater the geo-stress, gas content, and mining rate, the greater the outburst intensity will be.

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CONFLICT OF INTEREST

None declared.

ORCID

Bo Zhao  <https://orcid.org/0000-0001-6632-6175>

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SUPPORTING INFORMATION

Additional supporting information may be found online in the Supporting Information section.

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