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The mechanism of rockburst-outburst coupling disaster considering the coal-rock combination: An experiment study

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Abstract. With the ongoing development of deep mining of coal resources, some coal mine dynamic disasters have exhibited characteristics of both coal-gas outbursts and rockbursts. Therefore, research is required on the mechanism of rockburst-outburst coupling disaster. In this study, the failure characteristics of coal-rock combination structures were investigated using lab-scale physical simulation experiments. The energy criterion of the rockburst-outburst coupling disaster was obtained, and the mechanism of the disaster induced by the gas-solid coupling instability of the coal-rock combination structure was determined. The experimental results indicate that the damage of the coal-rock structure is significantly different from that of a coal body. The influence of the coal-rock structure should be considered in the study of rockburst-outburst coupling disaster. The deformation degree of the roof is controlled by the more significant main role of the gas pressure and the difference in the strength between the rock body and the coal body. The outburst holes and spall characteristics of the coal body after the failure of the coal-rock structure are strongly affected by the difference in strength between the roof and the coal body. The research results provide an in-depth understanding of the mechanism of rockburst-outburst coupling disasters in deep mining.

Keywords: coal-rock combination structure; coal-gas outburst; rockburst; coupling dynamic disaster; damage and failure; gas-solid coupling

1. Introduction

Coal resources account for more than 50% of China's primary energy consumption (Dudley 2017, Höök *et al.* 2010). Although China has implemented restrictions on coal consumption to reduce greenhouse gas emissions (NRDC 2016), it is foreseeable that coal will remain the most common energy source in China in the future. In recent years, with the increase in coal mining depth, high gas mines and coal-gas outburst mines have appeared rockburst disasters. Rockburst and coal-gas outburst disasters often interact and induce each other, showing the characteristics of coupling disasters (Du *et al*. 2018, Iannacchione and Zelanko 1995, Lama and Bodziony 1998). In this paper, the simultaneous occurrence of rockburst (Adoko *et al.* 2013, Bräuner 1994, Driad-Lebeau *et al.* 2015, Konicek *et al*. 2013) and coal-gas outburst (Aguado and Nicieza 2007, Kursunoglu and Onder 2019, Wold *et al*. 2008) is referred to as a rockburst-outburst coupling dynamic disaster. Since the rockburst-outburst coupling dynamic disaster is always accompanied by the dynamic failure of the gas-bearing coal-rock combination structure, the study of the damage and failure characteristics of the gas-bearing coal-rock combination structure is of great practical significance for understanding the mechanism of the rockburst-outburst coupling dynamic disaster.

Numerous studies have been conducted on the mechanical failure characteristics of coal-rock bodies. Petukhov and Linkov (1979) firstly analyzed the damage characteristics of coal-rock structure. Landriani and Taliercio (1987) analyzed the mechanical properties of layered composite rocks. Zhao *et al*. (2015) systematically studied the failure characteristics of a coal-rock combination, and obtained the compression-shear failure criterion of a coal-rock three-body system. Chen *et al*. (2019) conducted an experimental and numerical study of coal-rock combinations under uniaxial compression; it was concluded that the mechanics and deformation characteristics of the coal-rock combinations mainly depended on the coal body. Huang and Liu (2013) focused on the effect of the loading rate on the mechanical behavior of a coal-rock body and found that the higher the loading rate, the larger the peak strain was, and the lower the dynamic failure time of the coal-rock body was. As for the mechanical properties of the gas-bearing coal-rock combination bodies, Du *et al*. (2018) conducted the experimental research on the damage characteristics of the gas-bearing coal-rock bodies. However, these studies generally used triaxial or uniaxial small-scale mechanical experiments. There is a lack of physical simulation studies on the failure of gas-bearing coal-rock combinations. It is widely known that physical simulation experiments play an important role in determining the mechanism of coal-gas

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outbursts (Alexeev *et al*. 2004, Atapour and Mortazavi 2019, Sobczyk 2011, 2014, Yin *et al*. 2016). Therefore, it is necessary to conduct an in-depth study on the mechanism of rockburst-outburst coupling dynamic disaster using physical simulation experiments to determine the failure of the gas-bearing coal-rock combination.

In this work, the lab-scale physical simulation experiments of a gas-bearing coal-rock combination system under true triaxial unloading conditions were conducted. The effects of the gas pressure, coal strength and roof strength on the failure characteristics of the coal-rock combination structure were investigated. Moreover, the characteristics of the roof failure, coal body failure hole, and the coal seam fractures were analyzed. Finally, the energy criterion and fluid-solid coupling mechanism of the rockburst-outburst coupling disaster were determined.

2. Physical simulation experiments of the failure of a coal-rock structure

2.1 Sample preparation

Anthracite from the No. 15 coal seam of the Yangquan Sijiazhuang Mine was collected and shipped to the laboratory. The coal sample with a diameter of less than 0.5 mm was sieved using a vibrating screen with a diameter of 0.5 mm, and the coal sample was dried in a drying oven. About 15 kg of the pulverized coal was used in each test, and a 5% aqueous solution containing polyvinyl alcohol was added to the coal. Because the coal body was relatively soft, we added and pressed the coal sample two times using a servo test machine. After the second coal addition, the specified stress (3000 kN or 3500 kN) was used, and the load was applied for 50 min to obtain the 18 cm-thick formed coal seam used in the experiments. The basic parameters of the coal seam are shown in Table 1. For the sake of convenience, the coal body under stress of 3000 kN is called soft coal, and the coal body under stress of 3500 kN is called hard coal. A 7 cm-thick roof was prefabricated and placed into the outburst chamber before the experiments. The roof material consisted of river sand, rosin, gypsum, and water. In this experiment, two different proportions of the roof were used. The first ratio was: sand: gypsum: water: rosin: borax = 80:8:10:1.9:0.1. The roof with this ratio is called the hard roof in this work. The second ratio is: sand: gypsum: water: rosin: borax = 83:5:10:1.9:0. 1. The roof with this ratio is called the soft roof in this work. The formed roof is shown in Fig. 1.

Fig. 1 The picture of the similar formed roof (Its dimensions are 0.25 m × 0.25 m × 0.07 m)

Table 1 The basic parameters of the coal sample

Industrial Analysis			Adsorption constant		Density (t/m^3)
M_{ad} (%)	A_d (%)	V_{daf} (%)	a (m^3/t)	b (MPa^{-1})	
4.61	6.24	7.00	40.717	0.939	1.4

M_{ad}-moisture content on air-dried basis, A_d-dash content on dry basis, V_{daf}-volatile matter content on dry-ash-free basis

2.2 Experimental device and scheme

Because there are few test devices suitable for the physical testing of rockburst-outburst coupling dynamic disasters, we decided to perform the physical simulation tests of the failure of the coal-rock composite structure using a system designed for the simulation of coal-gas outbursts. The system is mainly composed of a triaxial physical simulation chamber, a triaxial stress loading device, a vacuum/injection device, a data acquisition and recording device, a constant temperature control device. The internal dimension of the triaxial chamber is: length × width × height = 25 cm × 25 cm × 31 cm, and its structural diagram is shown in Fig. 2. Technical details of the triaxial testing device can be found in Tu *et al*. (2016).

The steps of the physical simulation test included coal body crushing and screening, roof prefabrication, coal particle proportioning and compaction molding, chamber sealing and aeration, outburst simulation, and data acquisition and analysis. After the coal sample was pressed and the prefabricated roof was placed in the chamber, the airtightness of the device was checked. Next, the air was degassed for 24 h. Then the CO_2 was adsorbed and equilibrated for 60 h, and triaxial stress was applied to the coal sample. Finally, the outburst was triggered, and the fracture characteristics of the hole and the deformation and failure characteristics of the roof (coal-rock combination body) were observed after the termination of the outburst. All tests were conducted at 25°C.

Pilot experiments conducted before this study showed that, for CO_2, there was no outburst in the test at 0.3 MPa and below. Therefore, three gas pressures (0.4 MPa, 0.5 MPa, and 0.6 MPa) were used to ensure the occurrence of the outburst so that we were able to investigate the failure characteristics of the coal-rock structure under different gas pressures. Two kinds of coal and two rock strengths have been evaluated. The details of the test scheme are listed in Table 2. It should be noted that the design of the whole experimental system satisfies the similarity rule, which indicates that the lab-scale experimental results of this work are transferrable to a large scale or in-situ.

Table 2 Physical simulation test scheme

Number	Coal	Roof	Gas pressure (MPa)
a	coal-soft	roof-soft	0.4
b	coal-soft	roof-soft	0.5
c	coal-soft	roof-soft	0.6
d	coal-soft	roof-hard	0.5
e	coal-hard	roof-soft	0.6
f	coal-hard	roof-hard	0.5

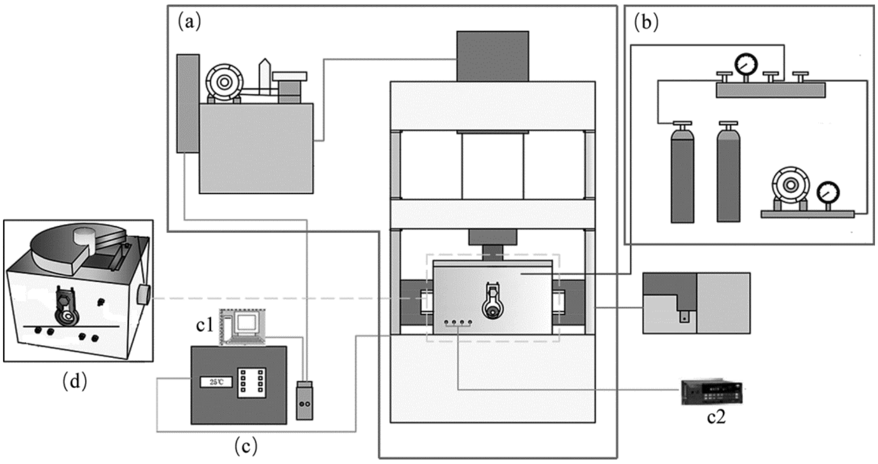

Fig. 2 Structure diagram of the experimental system. (a) Triaxial loading device, (b) Gas injection/evacuation device, (c1) Mechanical data acquisition device, (c2) Gas pressure data acquisition device and (d) Triaxial test chamber

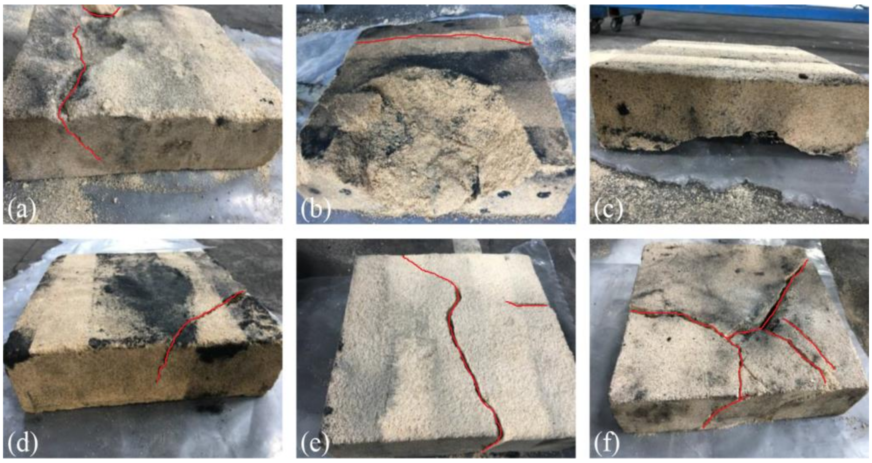

Fig. 3 Photos of the failure of roof rock

2.3 Experimental results and analysis

2.3.1 Failure characteristics of roof rock

After the test, the upper cover plate of the chamber was opened to observe the failure of the roof rock, as shown in Fig. 3. Failure had occurred in the rock portion of the coal-rock structures in all six groups, although there were some differences in the failure degree of the rock between the groups due to different test conditions. The results indicate that a coal-rock coupling dynamic disaster not only damages or destroys the coal part but also the rock part under certain conditions. Therefore, a difference exists between the failure of the coal-rock body and the failure of the coal body. The occurrence of the coupling disaster results in the dynamic instability of the coal-rock system under specific gas pressures and ground stress conditions. Therefore, we conclude that it is not possible to obtain an accurate understanding of the mechanism of the rockburst-outburst coupling disaster if we only focus on the failure characteristics of gas-bearing coal bodies. The coal-rock composite structure should be considered in research on rockburst-outburst coupling dynamic disasters.

The effect of gas pressure changes on the failure of the roof rock was determined by comparing the test results of Groups A-C in Fig. 3 (Group A represents the Number “a” in the test scheme). The deformation and damage of the roof are most significant at 0.5 MPa, indicating that a higher gas pressure does not result in the largest deformation of the roof. The strength difference between the rock mass and coal mass at 0.6 MPa is much larger than that at 0.5 MPa. Although the gas pressure increases, the rock body does not exhibit more damage at 0.6 MPa due to the significant strength difference between the rock part and the coal part. Although the strength difference between the rock mass and coal mass is lower at 0.4 MPa than at 0.5 MPa, the effect of the gas pressure is greater at 0.5 MPa, and there is less damage to the rock part at 0.4 MPa. Similarly, since the roof strength of Group D is greater than that of Group B and the other conditions are the same, the failure strength of the roof in Group D is smaller than that in Group B. The effect of the coal strength on the damage degree of the roof was determined by comparing the test results of Group D and Group F and those of Group C and Group E. The higher the coal strength, the larger the roof damage is. The reason is that under the same conditions, the higher the strength of the coal body, the smaller the strength difference between the rock body and coal body is, and the greater the degree of failure of the rock part is after the final failure of the coal-rock body.

2.3.2 The failure characteristics of the outburst holes

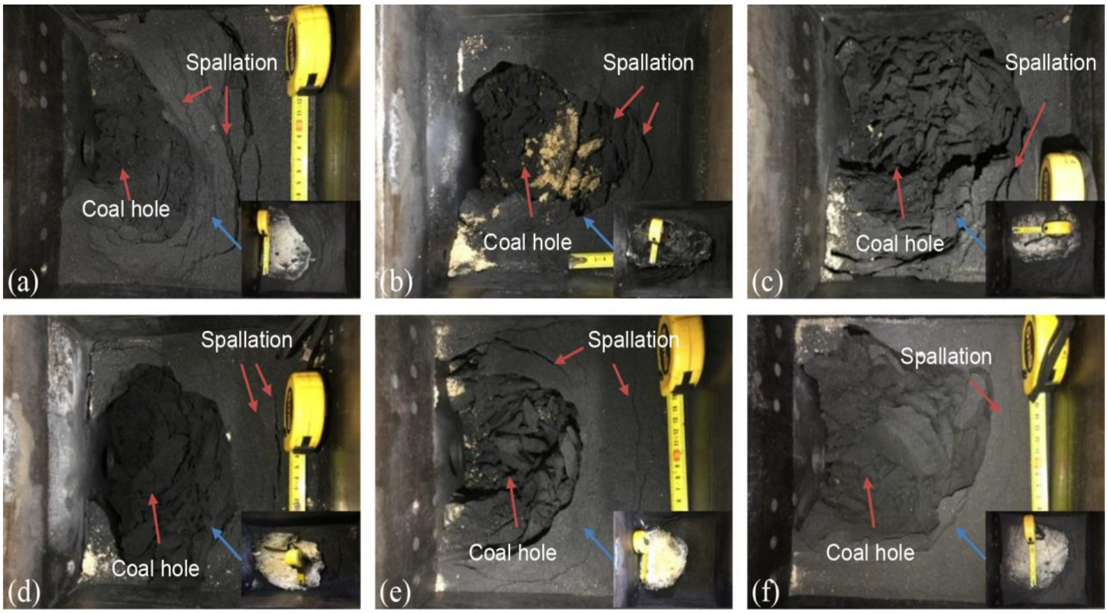

Fig. 4 Photos of the failure characteristics of the outburst coal holes

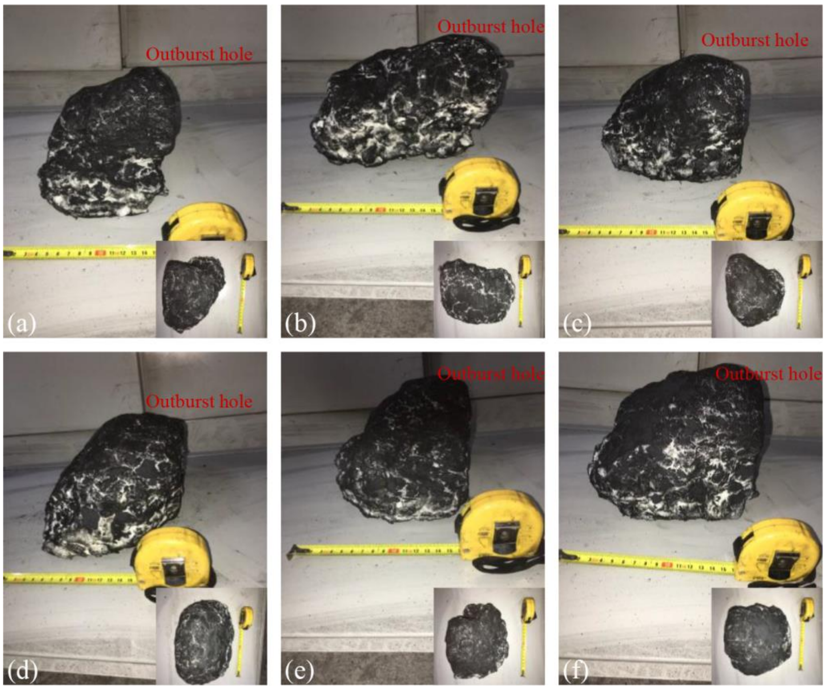

Fig. 5 Side and top views of the hole failure models

After the opening of the upper cover plate of the chamber at the end of the test, the roof rock was removed carefully to observe the failure characteristics of the outburst coal holes, as shown in Fig. 4. Some unspoiled broken coal and some spherical shells that have been stripped but not thrown in the gas outburst hole are observed. The broken coal for each condition in the outburst hole was cleaned, and the hole was filled with polyurethane foam caulk to facilitate the visual observation of the characteristics of the outburst hole. After the hole was stabilized, a photo of the lower right corner was obtained. It is observed that the shapes of the outburst holes are different for the six groups, but the holes are all hemispherical or semi-tapered. The wall surface of the holes is curved. A comparison of the results of Groups A-C in Fig. 4 shows that the volume of the outburst hole at a gas pressure of 0.6 MPa is larger than that at 0.5 MPa, and the volume at a gas pressure of 0.5 MPa is larger than that at 0.4 MPa. This result indicates that the larger the gas pressure, the larger the coal hole volume is. The failure behavior is different from that of the roof rock, indicating that the gas pressure has a larger influence than the difference in the strength between the roof and coal. The volume of the hole in Group D is larger than that in Group B, indicating that if the other conditions are held constant, the higher the strength of the roof, the larger the volume of

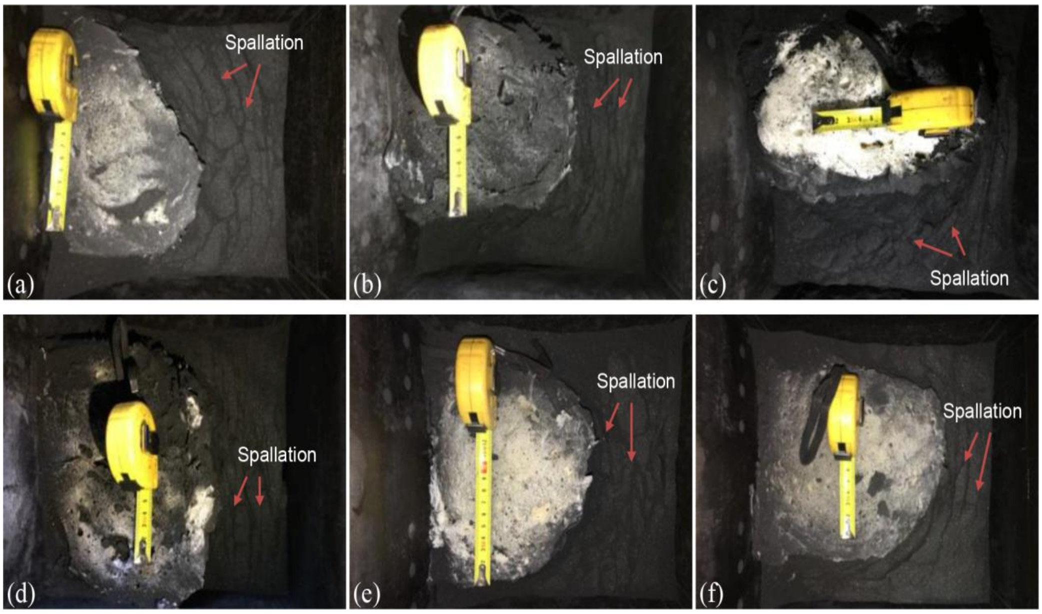

Fig. 6 Schematic diagram of the spallation characteristics of the coal body

Table 3 The thickness of the coal spallation for experiment groups

Number	Average thickness (cm)	Depth (cm)	Spallation thickness (cm)									
			D1	D2	D3	D4	D5	D6	D7	D8	D9	D10
a	1.1	16.5	2.0	1.3	0.7	0.6	1.4	0.6	1.6	0.5	0.3	2
	1.05	17.8	1.7	0.3	0.6	0.6	0.8	0.5	1.5	2	1.2	1.3
	1.4	20.8	1.4	0.9	1.5	2	1.5	1	1.6	-	-	-
b	1.5	16.8	2.0	1.2	1.3	1.5	-	-	-	-	-	-
	1.4	19	2.0	1.0	1.2	-	-	-	-	-	-	-
	1.08	24	2.2	0.8	1	1.5	0.8	0.7	1.2	0.8	0.7	1.1
c	1.58	13.7	1.5	2.4	1.6	0.8	-	-	-	-	-	-
	1.48	18.5	1.5	1.5	1.2	1.6	1.6	-	-	-	-	-
	1.4	20.5	1.5	1.5	1	1.2	1.3	1.9	-	-	-	-
d	0.81	16.8	1.0	1.3	0.7	0.5	0.8	0.4	0.6	1.2	-	-
	1.14	19.5	1.8	1.2	0.7	0.9	0.9	0.8	1.7	-	-	-
	0.95	23.3	0.5	1.5	0.5	0.8	1.2	0.9	0.8	1.4	-	-
e	1.57	15.7	1.5	1.7	1.5	-	-	-	-	-	-	-
	1.02	19.5	0.7	1.3	1.5	0.7	1.0	0.9	-	-	-	-
	1.4	20.7	1.5	1.5	2	1	1.2	1.5	1.1	-	-	-
f	1.95	15.2	2.3	1.9	1.9	1.7	-	-	-	-	-	-
	1.8	17.6	2.0	1.0	1.5	2.7	-	--	-	-	-	-
	1.14	20	1.5	1	1	1.5	1.5	0.5	1	-	-	-

the outburst hole is. The reason is that after the coal body is destroyed, the damage to the roof is more significant when the roof strength is low. If the roof has high strength, the failure of the roof consumes more energy, resulting in a relatively small amount of energy consumed by the failure of the coal body. Consequently, when the strength of the roof is high, the coal body suffers more destruction, and the volume of the outburst hole is large. The effect of the coal strength on the coal failure was assessed by comparing Group D with Group F and Group C with Group E. The results show that the volume of the outburst hole in Group C is larger than that in Group E, and the volume in Group D is smaller than that in Group F. These results highlight the importance of conducting failure tests of the coal-rock body rather than conventional physical simulation tests that only consider the failure of the coal body. When the gas pressure is high (such as in Group C and Group E at 0.6 MPa), the strength difference between the roof and coal body is larger than that at 0.5 MPa. In this case, the failure characteristics of the coal body are similar to those of a coal outburst;

therefore, the lower the coal strength, the larger the volume of the outburst hole is.

However, when the gas pressure is low (for example, Group D and Group F are at 0.5 MPa), the strength difference between the roof and the coal body is much smaller than that at 0.6 MPa. In this case, the failure of the coal body is more likely to destroy the coal-rock structure, and the failure characteristics are those of the rockburst-outburst coupling dynamic disaster. The smaller the strength difference between the rock and coal body, the larger the volume of the outburst hole is; this result is consistent with the failure behavior of the roof rock. These results demonstrate that it is impossible to obtain an accurate understanding of the mechanism of rockburst-outburst dynamic disasters by only exploring the failure characteristics of the gas-bearing coal body. The influence of the coal-rock composite structure has to be considered in the study of rockburst-outburst coupling dynamic disaster.
The model of the outburst hole filled with the polyurethane foam sealant was removed, and the model was placed on a table to obtain a side view and top view of the models (Fig. 5). The inset in the lower right corner of each photo is the top view of the hole model. Although the shapes of the holes are not the same under different conditions, they are generally irregular hemispherical or semi-conical. Unlike the holes caused by a typical outburst, some test holes do not exhibit the characteristics of a small mouth and large cavity, demonstrating the differences between rockburst-outburst coupling dynamic disaster and coal-gas outbursts.

2.3.3 The spallation failure characteristics of the coal

The coal seams filled with the polyurethane foam sealant in each test group were cleaned out, and the spall characteristics of the coal body in the third layer of each test group were compared, as shown in Fig. 6. The parts of the coal body that were peeled off but were not thrown out in all groups exhibit many arc-shaped cracks that are parallel to the outburst holes. There are many spherical shell-like spalls between the cracks, and the thickness of the spherical shell-like lobes is not the same. There are also some short cracks between the spalls. These short cracks are mostly concentrated in the coal body near the hole, indicating that the damage to the coal body is more extensive near the hole than far away from the hole. We obtained photos to conduct a quantitative assessment of the influence of the gas pressure, roof strength, and coal strength on the coal spall characteristics. After each layer was cleaned out, the depth of the outburst holes and the thickness of the cracks in each layer crack were measured, and the average thickness of the corresponding depth layer lobes was calculated, as shown in Table 3. It should be noted that D1-D10 represents the thickness of each spall from the edge of the outburst hole to the boundary of the chamber and from the first layer to the tenth layer.

Due to differences in the thickness of the cleaned coal seams in each group of experiments, the results in Table 3 and Fig. 6 are considered. A comparison of the test results of Groups A-C (Fig. 6 and Table 3) shows that when the other conditions are the same, the average thickness of the coal seam spalls does not decrease with an increase in the gas pressure. This is not consistent with the coal and gas outburst tests; in these tests, the higher the gas pressure difference, the stronger the tensile failure effect on the coal is, and the smaller the thickness of the spall is. This discrepancy may be attributed to the influence of the coal rock structure on the spalling behavior of the coal body. In Group D, the average thickness of the coal seam spalls is less than that of Group B. This result indicates that the roof strength also influences the coal seam spall characteristics. The coal body suffers more damage when the roof strength is higher, causing more spalls and resulting in the smaller average thickness. In Group C, the average thickness of the coal seam spalls is slightly greater than that of Group E. However, in Group D, the average thickness of the coal seam spalls is less than that of Group F. These results show that when the strength difference between the roof and the coal body is small, the lower the strength of the coal body, the more significant the destruction of the coal body is, resulting in a smaller average thickness of the coal seam spalls. However, when the strength difference between the roof and coal body is significant, different trends are observed that are not consistent with the coal and gas outburst without considering the influence of the roof. Overall, these results demonstrate that the influence of the coal-rock composite structure should be considered in the study of rockburst-outburst coupling dynamic disasters. More targeted research is needed in the future.

3. Discussion

3.1 The energy criterion of the rockburst-outburst coupling disaster

From an energy perspective, the occurrence of the rockburst-outburst dynamic disaster is a process of accumulating energy in the coal-rock body, which results in dynamic instability of the body when the accumulated energy exceeds the energy that the coal-rock body can store. In the coal-rock system, the energy includes the elastic energy of the coal and rock mass, the expansion energy of the free gas and adsorbed gas in the coal, the crushing energy of the coal body, and the damage fracture energy of the rock. The elastic strain energy per unit volume in a three-dimensional stress state can be derived from the generalized Hooke's theorem. The elastic energy of the coal and rock mass is expressed as follows (Tu *et al*. 2016):

$$U_r = \frac{1}{2E}\left[\sigma_1^2 + \sigma_2^2 + \sigma_3^2 - 2v\left(\sigma_1\sigma_2 + \sigma_2\sigma_3 + \sigma_1\sigma_3\right)\right] \quad (1)$$

$$U_c = \frac{1}{2E}\left[\sigma_1^2 + \sigma_2^2 + \sigma_3^2 - 2v\left(\sigma_1\sigma_2 + \sigma_2\sigma_3 + \sigma_1\sigma_3\right)\right] \quad (2)$$

where U_r and U_c are the elastic energy of the rock mass and coal mass, respectively. It should be noted here that from the above formula, the elastic energy of the coal body with a small elastic modulus is much larger than that of the rock body. However, unlike previous analyses of the coal-gas outburst energy, the occurrence of the rockburst-outburst coupling disaster is caused by the mutual induction and mutual coupling of the rockburst and coal-gas outburst. The energy release in the rock body or the coal body does not exist in isolation. Instead, both types of energy in the rock body or the coal body are released almost simultaneously and will affect each other. Therefore, both energies must be considered in the energy analysis of the coupling dynamic disaster induced by the instability of the gas-bearing coal-rock body. It has been shown in this work that the difference between the roof strength and coal strength of rockburst-outburst coupling dynamic disaster is not in the order of magnitude; therefore, the elastic energy of both bodies cannot be ignored.

The gas expansion energy consists of two parts: the expansion energy of the free gas W_f and the expansion energy of the adsorbed gas W_d that partially adsorbed gas is converted into free gas during coal deformation. The calculation formulas are (An *et al.* 2019):

$$W_f = \frac{RT\rho_c V_f}{V(n-1)}\left[\left(\frac{p_0}{p}\right)^{\frac{n-1}{n}} - 1\right] \tag{3}$$

$$W_d = \frac{\rho_c R T_0 a}{V(n-1)}\left\{\left[\frac{n}{3n-2}\left(\frac{p_0}{p}\right)^{\frac{n-1}{n}} - 1\right]\sqrt{p} + \frac{2(n-1)}{3n-2}\sqrt{p_0}\right\} \tag{4}$$

$$W_n = W_f + W_d \tag{5}$$

where, R is the gas constant, J/(mol·K); T is the absolute temperature after gas expansion, K; n is the variable process index; P_0 is the gas initial pressure, Pa; P is the pressure after gas expansion, Pa. V is the molar volume of gas in standard state, m^3/mol; V_f is the free gas content, m^3/t; ρ_c is the density of coal body, t/m^3; a is the gas content coefficient, $m^3/(t\cdot Pa^{0.5})$. According to dimensional analysis, the dimension of gas expansion energy is J/m^3.

After the occurrence of the coal-rock dynamic failure, the stress state of the coal rock fracture surface will change from a three-way to a one-way stress state in an instant. In this process, the energy consumed by the coal rock failure is the energy consumed by the coal rock fracture under unidirectional stress. Assuming that the ultimate energy consumption of the coal rock system is U_{fmin} (the energy required by the progressive failure of the layered energy storage structure or coal rock), then U_{fmin} can be expressed as follows,

$$U_{f\min} = \sigma_c^2 / 2E \tag{6}$$

or

$$U_{f\min} = \tau_c^2 / 2E \tag{7}$$

The crushing work of the coal body results in an increase in surface energy, which is directly proportional to the specific crushing work of the coal body and the newly added surface area. Numerous studies have shown that the crushing work per unit volume of coal body can be defined as follows (Cai and Wang 1988):

$$E_b = s_b w_b \rho_b \tag{8}$$

where s_b is the newly added specific surface area, cm^2/g; w_b is the specific work of coal crushing, cm^2/g; ρ_b is the density of coal.

The newly added specific surface area and the specific crushing work of the coal body are challenging to measure directly. Cai and Wang (1988) presented a rough range of the specific surface area (113-525 cm^2/g) obtained from an experimental study. Herein, for the convenience of calculation, the specific surface area of the coal is 100 cm^2/g; the relationship between the specific crushing work and the firmness coefficient is obtained as follows:

$$W_b = 10.43\times10^{-3} f \tag{9}$$

Therefore, the final expression of the crushing work can be simplified as follows:

$$E_b = 10.43\times10^{-3} f s_b \rho_b \tag{10}$$

In this paper, the sum of the elastic energy and gas expansion energy of the coal and rock mass in the coal-rock body is defined as the disaster start-up energy, and the energy required for the breaking of the coal body and rock body is defined as the disaster dissipation energy. If the disaster start-up energy is less than the dissipation energy, the system is considered to be in a stable state. Otherwise, the system is considered to be in an unstable state. If the two energies are equal, the system is in a critical state. In this case, the energy criterion of the rockburst-outburst coupling dynamic disaster induced by the instability of the gas-bearing coal-rock body is:

$$J_0 = \frac{\int_{V_{fc}}(U_c + W_f + W_d) + \int_{V_{fr}} U_r}{\int_{V_{fc}} E_b + \int_{V_{fr}} U_{f\min}} > 1 \tag{11}$$

where V_{fc} is the volume of broken coal body and V_{fr} is the damage volume of rock body. Based on the physical simulation test results, four groups with typical characteristics of coupling dynamic disaster were selected to calculate the various energies in the failure process of coal and rock. The results are shown in Table 4.

The energy calculation of the unit volume in Table 4 shows that in these four groups, the sum of the elastic energy per unit volume of the coal body and the internal gas energy is greater than the crushing work per unit volume of the coal body. The elastic energy per unit volume of the rock mass (roof) is greater than the fracture energy. It is evident from Eq. (11) that the sum of the elastic energy of the coal body and the internal gas energy in the volume of the broken coal body is higher than the crushing work of the coal body. Likewise, the elastic energy in the volume of the fractured rock mass (roof) is greater than the fracture energy. Therefore, the total disaster start-up energy of the coal-rock system is greater than the disaster dissipation energy, which verifies the rationality of the disaster energy criterion. It is worth noting from Table 4 that, according to the previous research on the energy criterion of coal-gas outbursts, if we only consider the energy accumulation and dissipation of the single coal body, the sum of gas energy in these four groups is also greater than the disaster dissipation energy. The result indicates that the four groups also meet

Table 4 Energy calculation of the rockburst-outburst coupling disaster

Number	U_r (MJ/m^3)	U_c (MJ/m^3)	W_f (MJ/m^3)	W_d (MJ/m^3)	E_b (MJ/m^3)	U_{fmin} (MJ/m^3)
a	1.696e^{-3}	2.188e^{-3}	0.1299	0.1504	0.2336	2.418e^{-4}
b	1.696e^{-3}	2.188e^{-3}	0.218	0.1069	0.2336	2.418e^{-4}
e	1.696e^{-3}	1.964e^{-3}	0.244	0.103	0.292	2.418e^{-4}
f	1.313e^{-3}	1.964e^{-3}	0.218	0.1069	0.292	3.001e^{-4}

the coal-gas outburst conditions. That is, the rockburst-outburst coupling disaster occurs when the gas and coal-rock system meets the energy instability condition. The occurrence of the disaster is induced by the interaction between the gas and the coal-rock structure. If we do not consider the coal-rock structure and only consider the coal body, the energy criterion of the coal-gas outburst cannot be determined accurately. The calculated energy is appropriate for coal-gas outbursts but cannot be used to explain the meaning of the rockburst-outburst coupling disaster. In an energy study of the rockburst-outburst coupling disaster, although the elastic energy of the coal body and the elastic energy of the roof are very small compared to the gas energy, the release of the gas energy will affect the stability of the coal-rock structure. In turn, the unstable coal-rock structure will also affect the release of gas energy. Therefore, in the energy criterion of the rockburst-outburst dynamic disaster, these two functions are indispensable, and this is not equivalent to ignoring the elastic energy of the roof in the study of coal-gas outbursts.

3.2 Gas-solid coupling mechanism of the rockburst-outburst coupling dynamic disaster

In this study, a gas-bearing coal-rock system that is located some distance from the working face is analyzed. Under the combined action of in-situ stress, gas pressure, and disturbance stress, the coal part of the gas-bearing coal-rock system close to the working face suffers plastic deformation and cracks as the mining operation proceeds. This region is the damaged area, but at this point, the system is still in a stable and balanced state.

As the mining operation advances, the coal body in the damaged area changes from a three-dimensional stress state to a two-dimensional stress state in which the confining pressure is unloaded radially, and the stress concentration expands in the vertical direction. Under the combined action of radial unloading and vertical stress concentration, the elastic modulus and the strength of the coal body decrease rapidly, increasing the elastic energy stored in the coal-rock system and decreasing the energy required for the breakage of the coal body. Moreover, during unloading, the stress of the coal wall in the unloading direction is significantly reduced. Therefore, the gas pressure inside the coal wall is much higher than the atmospheric pressure outside the coal wall. The high gas pressure gradient accelerates the crack propagation of the coal body, prompting rapid desorption and seepage of the adsorbed gas, which results in an increase in the effective stress of the coal body and tensile damage to the coal body. Under the combined influence of the decrease in the coal strength and the tension of the gas pressure gradient, the degree of damage to the coal body increases rapidly, and the cracks in this area rapidly extend and penetrate in the direction perpendicular to the maximum gas pressure gradient, resulting in spall damage. This damage promotes the rapid desorption and seepage of the adsorbed gas in a large area and accelerates the fracture of the coal layers. Due to the interaction of the changed gas flow state (gas field), the stress state (stress field), and the damage degree of the coal body (fracture field), the coal body in the damaged area will become unstable after reaching the ultimate compressive strength. Meanwhile, the roof rock above the unstable coal body may also have suffered significant damage, leading to bending and sinking. The sinking of the roof will affect the unstable coal body, which will break the unstable coal below. Finally, when the elastic energy and gas expansion energy of the coal-rock system are released rapidly simultaneously, the disaster start-up energy is greater than the disaster dissipation energy. Due to the interaction of the stress field and the gas field in the coal-rock structure, the rockburst-outburst dynamic disaster is induced as a result of the overall instability of the gas-bearing coal-rock system.

In the present work, fabricated briquette coal was used to represent raw coal, resulting in inevitable differences. However, we chose the appropriate stress based on previous experience to ensure that the properties of the fabricated briquette coal and raw coal were similar. Moreover, we also added a 5% aqueous solution containing polyvinyl alcohol to the fabricated briquette coal to ensure that the adsorption performance of the fabricated briquette coal was similar to that of the raw coal. Therefore, the results of this study provide reliable insights into the mechanism of rockburst-outburst dynamic disasters. Recent studies have shown that coal-gas systems activate chemical reactions under a mechanical load, resulting in the release of large amounts of gas due to unstable coal organic matter (COM) during coal outburst initiation (Rudakov and Sobolev 2019). However, due to the limitation of the experimental conditions, this factor was not considered in our work. More targeted research is needed in the future.

4. Conclusions

In the present work, the damage and failure characteristics of gas-bearing coal-rock structures were investigated in lab-scale physical simulation experiments. The energy criterion and gas-solid coupling mechanism of a rockburst-outburst dynamic disaster were obtained. The main conclusions are as follows:

(1) When a rockburst-outburst dynamic disaster occurs,

damage occurs not only to the coal body but also to the rock mass under certain conditions. The coal-rock structure should be considered in rockburst-outburst coupling dynamic disaster. The deformation degree of the roof is affected by the gas pressure and the difference in strength between the rock body and the coal body.

(2) In the six groups of experiments, the shapes of the coal outburst holes were all hemispherical or semi-tapered. When other conditions are consistent, the larger the gas pressure or the roof strength, the larger the coal hole volume is. In the case where the strength difference between the roof body and the coal body is small, the smaller the strength of the coal body, the smaller the coal hole is, and the smaller the average thickness of the coal spallation is. When other conditions are consistent, the coal spallation characteristics are more obvious and the average thickness is smaller when the roof strength is larger.

(3) An energy criterion of the rockburst-outburst coupling disaster in which the interaction of energy release of gas and structural instability of the coal-rock combination were taken into account was obtained as follows,

$$J_0 = \frac{\int_{V_{fc}} (U_c + W_f + W_d) + \int_{V_{fr}} U_r}{\int_{V_{fc}} E_b + \int_{V_{fr}} U_{f\min}} > 1$$

(4) According to the interaction between failure of the coal body and the rock body, considering the coupling law of the gas field, stress field and fracture field, the mechanism of gas-solid coupling instability induced rockburst-outburst coupling disaster in gas-bearing coal-rock combination system was clarified.

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Conflicts of interest

All the authors declare that they have no conflict of interest.

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