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TECHNICAL NOTE

A New Experimental Apparatus for Coal and Gas Outburst Simulation

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1 Introduction

Instantaneous coal and gas outbursts are dynamic underground mining phenomena in which coal and gas are suddenly and violently ejected from a coal face (Shepherd et al. 1981). Since March 22, 1843, when the first recorded coal and gas outburst happened in the Isaac mine, Zeroual coalfield, France (Lama and Bodziony 1998), experts have conducted extensive investigations on these outbursts. However, understanding and predicting such a disaster has achieved only limited progress in the intervening years (Chen 2011).

Field data of coal and gas outbursts are rarely captured; thus, experts from different countries have worked on mathematical models or explored the mechanisms for coal and gas outbursts (Litwiniszyn 1985; He and Zhou 1994; Frid 1997; Beamish and Crosdale 1998; Valliappan and Zhang 1999; Li 2001; Cao et al. 2001, 2003; Alexeev et al. 2004; Xu et al. 2006; Aguado and Nicieza 2007; Wold et al. 2008; Zhang and Lowndes 2010; Chen 2011; Xue et al. 2011). For example, a porous rock is composed of a skeleton and pores. Its skeleton is made up of solid particles and its pores form a system of capillaries filled with gaseous substances. This model of a porous medium suggests a domino effect that leads to a catastrophic failure, or outburst, of the coal. The occurrence of an outburst depends on the local stress state, gas content, and physicomechanical properties of the coal. Such models or mechanisms lack sufficient experimental evidence. Coal and gas outbursts are so devastating that field trials are almost impossible. An alternative is to simulate the dynamic phenomenon of a coal and gas outburst in the laboratory with a specially designed apparatus.

Some efforts have been made to develop an experimental apparatus for coal and gas outburst simulations (Meng et al. 1996; Guo et al. 2000; Cai 2004). However, their designs for the apparatus had some limitations, such as using small coal samples and simulating only horizontal coal seams. A key limitation is that all outburst caverns are manually opened. These limitations may significantly affect the experimental results. For instance, a smaller coal sample may have a greater boundary effect. Outburst accidents occur more frequently in dip coal seams, especially in rock cross-cut coal uncovering, which refers to the excavation process of rock cutting just before the exposure of the coal seam. Manually opening the outburst cavern may be too slow. This may reduce the intensity of coal and gas outbursts in the tests. In addition, the current apparatus cannot simulate the local concentration of stress in front of the coal face because it can only apply a uniformly distributed load on coal samples through a single loading plate. Finally, the current apparatus cannot simulate gas infiltration from the entire cross-section because the coal samples only have a single inflatable hole.

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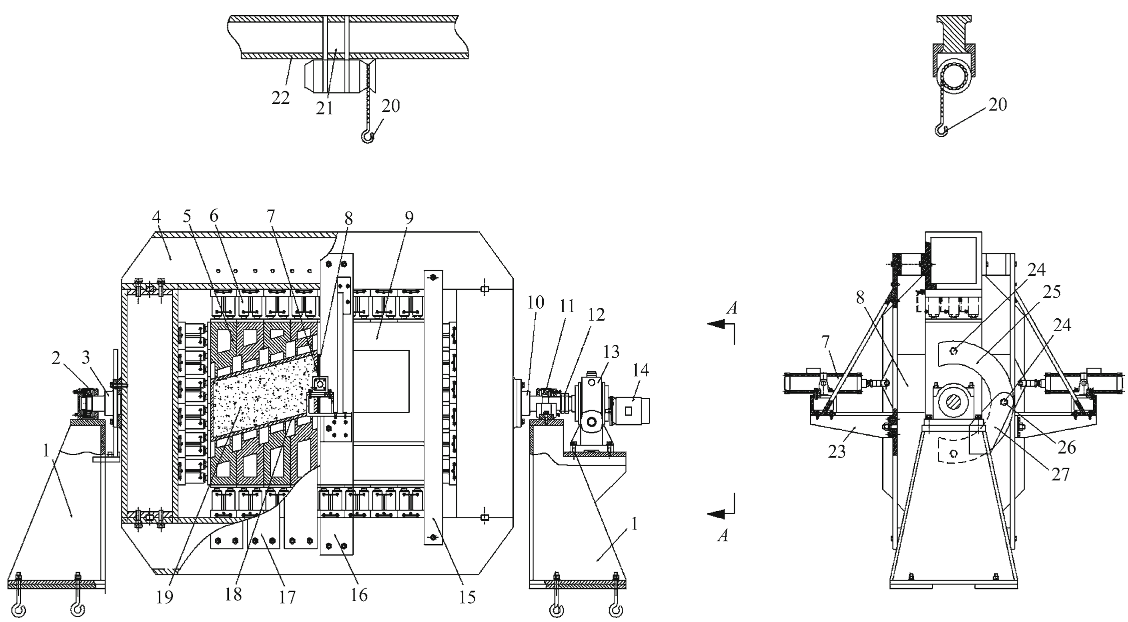
Researchers at Chongqing University have developed a large-scale coal and gas outburst simulation experimental apparatus to avoid the above-mentioned limitations. The apparatus, described in this paper, can accommodate large coal samples with different coal seam dip angles and outburst intensities under different geo-stresses and gas pressures. Both uniform and non-uniform loading distributions can be applied to coal samples. Such a loading system can simulate the local concentration of stresses. This paper will describe the design principles, structures, and key technologies used in this apparatus. Some preliminary results are obtained to check its capability, reliability, and accuracy.

2 Main Components and Design of the Apparatus

The coal and gas outburst simulation experimental apparatus consists of the coal sample cell, fast coal uncovering component, load carrying frame, loading system, rotation mechanism, main bracket, and attachments (see Fig. 1). Its load carrying frame can rotate 360° and be locked in either horizontal or vertical positions. The rotation mechanism provides a convenient installation of the coal sample cell. The cells have five different dip angles to simulate outbursts, which usually occur in rock cross-cut coal uncovering of inclined coal seams. The metal foam (see Fig. 2e) lets gas pass uniformly through the specimen and prevents direct contact between coal samples and the inflation port. This foam filters coal from gas and brings the simulation of gas sources in underground coal seams closer to actual field conditions. This apparatus can apply either uniformly or non-uniformly distributed loads on coal samples. Such a loading system can simulate local stress concentrations ahead of the coal face. Manual opening of the outburst cavern is replaced by an automatically controlled fast coal uncovering component, which speeds up the opening process. Finally, high-speed video cameras facilitate data recording for the coal and gas outburst process.

This apparatus can monitor or measure the following parameters: outburst intensity, temperature of the coal sample before and during the outburst, critical gas pressure and geo-stress at outburst, and crushing and separation of the coal samples under different conditions. These



(a) front view **(b)** side view (A-A)

1-main bracket; 2-left bearing block; 3-left shaft; 4-load carrying frame; 5-upper dowel bar ; 6-hydraulic jack; 7-pneumatic cylinder; 8-sealing plate of outburst cavern; 9-support block; 10-right shaft; 11- right bearing block; 12-coupling; 13-reducer; 14-stepper motor; 15-fixed beam; 16- support beam of pneumatic cylinder; 17-seal beam; 18-coal sample cell; 19-coal sample; 20-hook; 21-electric hoist; 22-rails; 23-pneumatic cylinder bracket; 24-positioning screw holes; 25-positioning adjustment ring; 26-positioning lug screw hole; 27-positioning lug

Fig. 1 Structure of the experimental apparatus for coal and gas outburst simulation

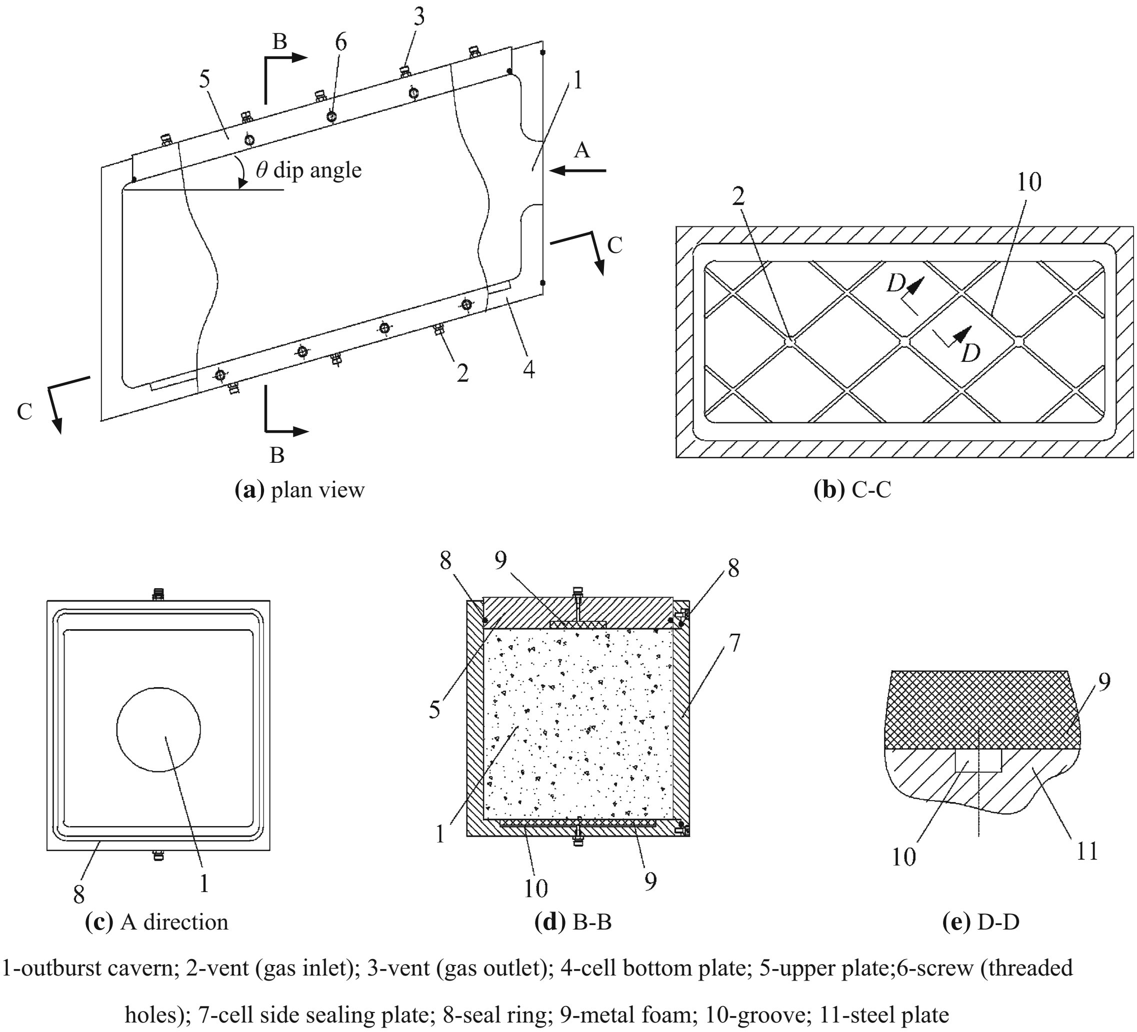


Fig. 2 Structure of the coal sample cell

parameters provide quantitative data to understand the mechanism of coal and gas outbursts. They can be used for the development of new theories on coal and gas outbursts.

2.1 Coal Sample Cell and Gas Pressure Detector

This apparatus has five sets of coal sample cells. One cell can simulate one coal seam dip angle of 0°, 15°, 30°, 45°, and anti-45° in coal and gas outburst experiments. The cell dimensions are 570 mm × 320 mm × 385 mm. All cells are made from welded Q235 steel plate (30 mm in thickness) and have a circular cavern on the outburst side where the coal samples can erupt under external forces. For a sample cell, the up side is movable and the other five sides are welded together. The movable side is fixed by screws during installation. The sample cell has an open side, which is located on the right of Fig. 2a; namely, it is the side of "1-outburst cavern". Figure 2 shows the structure of a typical coal sample cell with a dip angle of 15°. In order to investigate the impact of uncovering dimensions on coal and gas outbursts in rock cross-cut coal uncovering, each set has cells with circular caverns of diameter 30, 60, and 100 mm, respectively. These caverns are designed with conical, 65° inner tapers. Further, 5-mm-deep criss-cross mesh grooves are engraved on the bottom plate of each cell (see Fig. 2b). On each groove, a 15-mm-thick, high-strength stainless steel foam with small pores is welded to isolate the gas inlet from the coal sample (see Fig. 2d, e). The stainless steel acts as a filter for coal dust from gas. It ensures that pulverized coal stays away from the groove and the gas inlets. The coal does not clog the inlet channel. During the gas intake process, gas first flows from three inlet holes on the bottom plate into the groove and then infiltrates through the stainless steel foam into the coal sample. This design simulates gas infiltration through the entire cross-section. Therefore, the cell of this apparatus does not only simulate the excavation of an inclined coal seam effectively, but it also models any possible outburst.

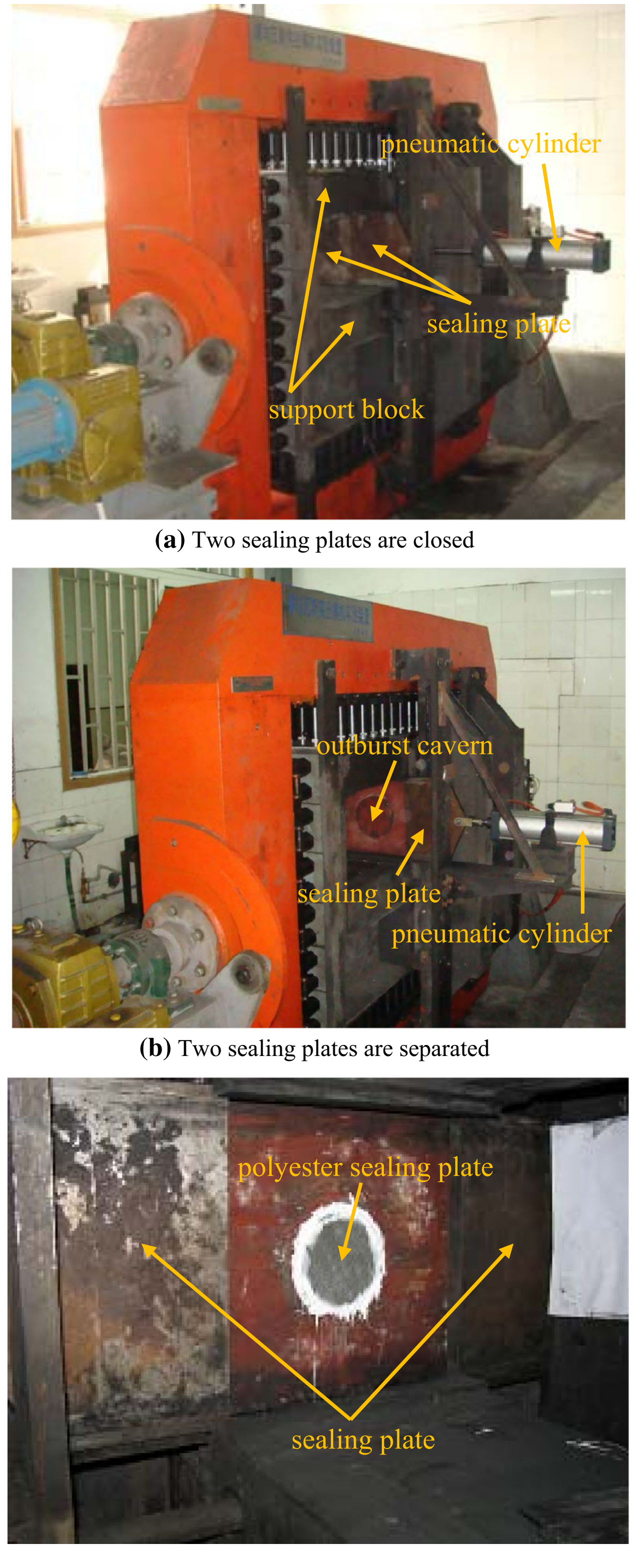
Five vents are installed uniformly on the upper plate of each cell (see Fig. 2a) to detect the temperature change of the coal sample and the gas pressure distribution within the sample before and during the outburst. A pressure gauge with a capacity of 4 MPa is connected to the vents to detect the change of gas pressure during the test. Temperature sensors can be embedded in the vents to measure the temperature of the coal seam. These data are recorded with MaxTest-Load test control software, which was specially developed for this apparatus.

2.2 Fast Coal Uncovering Component

The fast coal uncovering component consists of an air compressor, pneumatic cylinder, support beam, bracket, and sealing plates for the outburst cavern. Sealing plates for the outburst cavern have two parts located at one end of the sample cell. The two parts can move oppositely along the cell side so as to block or open the outburst cavern. A polyester sealing plate is settled on the cavern (see Fig. 3). It is noted that all of the following equipment or devices were manufactured or provided by Xi'an Langjie Testing Equipment Co., Ltd. Particularly, the air compressor is Type Y132S2-2 and the automatic air pressure switch is Type GYD20–20/C, with pressure ranging from 0.6 to 1.5 MPa. The pneumatic cylinder is Type KKP-15, with pressure ranging from 0.05 to 0.80 MPa. The sealing plates for the outburst cavern are 28 mm thick and have a maximum stroke of 170 mm for each plate. The two plates have surface machining accuracies of less than 0.01 mm. Each sealing plate is connected to one pneumatic cylinder via a piston rod. During the test, the air compressor supplies a predetermined pressure to the pneumatic cylinder. The pneumatic cylinder drives the sealing plates with the piston rods. The sealing plates can move aside at high speed (fully opened within 1 s), quickly opening the outburst cavern (see Fig. 3). This process is equivalent to the abrupt collapse of the stress wall that hinders the outburst, and abruptly relieves the stress on the coal sample. Other similar apparatus manually opens the outburst cavern. Such a manual operation lengthens the opening duration and affects the intensity of the outburst. This apparatus solves this slow-opening problem by implementing mechanical controls for the opening process, dynamically and vividly simulating the outburst during rock cross-cut coal uncovering.

2.3 Loading System

The loading system consists of hydraulic jacks, a servo hydraulic station, computers, the MaxTest-Load test control software, and sensors for monitoring and measuring the experimental data. The entire test process can be automatically controlled for secure and reliable measurements.



(a) Two sealing plates are closed

(b) Two sealing plates are separated

(c) Outburst cavern is sealed by polyester sealing plate

Fig. 3 Sealing of the outburst cavern

MaxTest-Load controls the output power of the hydraulic jacks and measures the test data. The maximum force of a single set of jacks is 300 kN, and the maximum stroke of the jack piston rod is 100 mm. Four sets of jacks (Nos. 1, 2, 3, and 4) are used to apply load onto the coal sample cell. The jack plate is a 400 mm × 200 mm × 20 mm block. MaxTest-Load can control the output of each hydraulic jack through programming, so a non-uniform distribution of loading can be applied. This solves the problem of only a uniformly distributed load applied by previous similar apparatus. The current apparatus can simulate the local stress concentration ahead of the coal face caused by underground mining activity.

2.4 Rotation Mechanism

A rotation mechanism is designed for the convenient installation of a coal specimen. The rotation mechanism consists of a stepper motor, reducer, bearings, couplings, positioning lug, and positioning regulating ring. The reducer used in this mechanism is Type WPEDKA, a secondary worm and gear reducer. The stepper motor is YE2100L1-4, and its brake moment is 30 Nm. The load carrying frame can rotate 360° when the driving force of the stepper motor is decelerated by the reducer, and the motor drives the rotation bearing via couplings. Screw holes are on both the positioning adjusting ring and positioning lug. For convenient loading, the load carrying frame is kept horizontal during the installation of a coal sample. This can be done by aligning the positioning lug screw hole with the middle screw hole on the ring. After installation, the load carrying frame is rotated to the vertical direction and kept vertical during the testing process (see Fig. 1b). The rotation mechanism allows the frame to lock in either the horizontal or the vertical position. This is convenient for the installation of a coal sample but has no influence on the position during the test.

3 Performance Check on the Apparatus

3.1 Accuracy Check on the Loading System

The accuracy of the loading system is checked by comparing the MaxTest-Load software readings with the real output of the hydraulic jacks. The check instrument is a grade 0.3 standard dynamometer, model EHB-600B. The maximum force of the apparatus is 600 kN. The dynamometer was fixed to the carrying frame, and each hydraulic jack was set to eight levels of force in turn (30, 50, 80, 100, 150, 200, 250, and 300 kN) by the MaxTest-Load software. The output of each jack at each level was checked by the dynamometer. Each reading was measured three times and averaged. The output data of jacks displayed in the MaxTest-Load software were compared with the values measured by the dynamometer to calculate the accuracy of the hydraulic jacks. As an example, hydraulic jacks in the servo loading system had full-scale errors that were an average of 0.25 % (the minimum is 0.06 % and the maximum is 0.56 %) for the first set and an average of 0.10 % (the minimum is 0.02 % and the maximum is 0.21 %) for the second set. These accuracies can meet the requirements of the experimental loadings.

3.2 Repeatability Check on the Coal and Gas Outburst Apparatus

3.2.1 Experimental Preparation

As a result of tectonic action, underground coal is usually fractured and weak. A large raw coal specimen is difficult to obtain. Moreover, even if a large raw coal specimen is obtained, the repeatability of experiments and the ability to compare experimental results are poor (Jasinge et al. 2009, 2011; Ranjith et al. 2010). Briquette specimens and raw coal specimens deform similarly and have good consistency in deformation. The most important is that briquette specimens have good repeatability (Chen et al. 2013). Therefore, this study used briquette specimens in the tests.

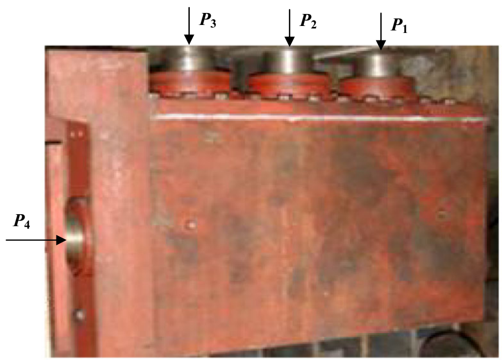
Coal samples are taken from Coal Seam #7 of Chongqing Datong No. 1 Mine in China. This coal seam has experienced many coal and gas outbursts. The coal is crushed, screened, and compacted into rectangular parallelepiped coal briquettes. The coal seam is horizontal, so the 0° dip angle coal seam cell is chosen. The briquette is the same size as the cell, 570 mm × 320 mm × 385 mm. As shown in Fig. 4, P_1, P_2, and P_3 are loaded with 2.0 MPa, but P_4 is loaded with 1.4 MPa. The coal samples were taken from a depth of about 400 m. The gas pressure at this depth is approximately 1.0 MPa. Therefore, the gas pressure is set at 1.0 MPa and 99.99 % pure methane gas is used.

3.2.2 Experimental Results and Analysis

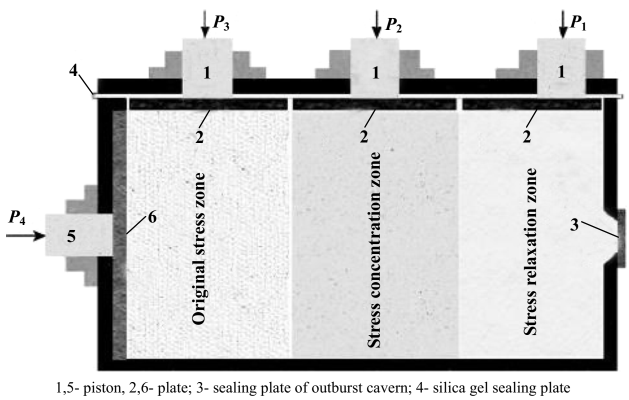
A total of six coal and gas outburst tests were carried out under the same conditions, i.e., the same gas pressure, load, and coal sample size, to check the repeatability of the tests. Samples weighed 88.61 ± 0.83 kg. The absolute outburst intensity, which refers to the mass of ejected coal, was 16.98 ± 0.04 kg and the relative outburst intensity, which is the ratio of ejected coal mass to the total coal sample mass, was 19.12 ± 0.15 %. These results demonstrated the good repeatability of this apparatus. It can be used in coal and gas outburst simulation tests.

These tests also observed the following details:

1. The intensity of the coal and gas outbursts measured by this apparatus is relatively great. Most of the coal



(a) Photo of loading conditions



(b) Schematic of loading conditions

Fig. 4 Loading conditions

sample was ejected a few meters away. Several smaller coal particles were ejected even farther away.

2. Pulverized coals are distinctly sorted by the outburst. Larger coal particles are near the outburst cavern, while the smaller ones are far away from the outburst cavern.
3. Under the same conditions, the amount of outburst coal, the hole shape, the sound of outburst, and the spray distances of coal particles in each test showed little differences.

3.3 Effect of Non-Uniform Loading Distribution on Coal and Gas Outbursts

Geo-stress is one of the main factors affecting coal and gas outbursts. In underground coal mining, geo-stress is non-uniform and three zones usually form in front of the coal working face (Zou et al. 1999; Barla et al. 2011; Yin et al. 2015): the stress relaxation zone, the stress concentration zone, and the original stress zone. The stress relaxation zone is the zone of stress reduction relative to its original stress. The stress concentration zone is the zone of stress intensity relative to its original stress. The original stress zone is the zone where stress is essentially unaffected by the mining activity. This section will investigate the effect of geo-stress in the stress concentration zone on coal and gas outbursts. In these tests, the loading pressure P_2 was set at 1.8, 2.7, and 3.6 MPa, respectively, while $P_1 = 0.6$ MPa, $P_3 = 1.8$ MPa, and the horizontal stress $P_4 = 2.4$ MPa. The gas pressure was 1.0 MPa. As shown in Fig. 5, the absolute outburst intensity and the relative outburst intensity of coal and gas outbursts increased with the geo-stress in the stress concentration zone. Therefore, higher geo-stress has a higher probability of coal and gas outbursts.

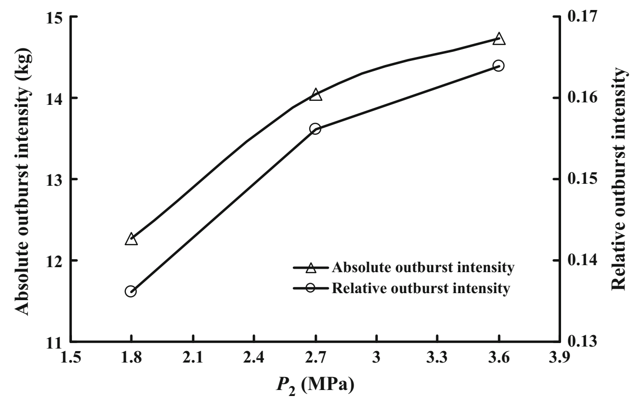


Fig. 5 Effect of geo-stress in the stress concentration zone on the absolute outburst intensity and the relative outburst intensity

3.4 Gas Pressure Effect on Coal and Gas Outbursts

Gas energy may be the main driving force for the development of a coal and gas outburst (Valliappan and Zhang 1999; Yin et al. 2013). This section investigates the effect of gas pressures on coal and gas outbursts. In these tests, $P_1 = P_2 = P_3 = 4.0$ MPa and $P_4 = 2.4$ MPa. The gas pressure was set at 0.5, 1.0, and 1.5 MPa, respectively. Figure 6 shows the effect of gas pressure on the absolute outburst intensity and the relative outburst intensity. Coal and gas outbursts do not happen when the gas pressure is at or below 0.5 MPa. The absolute outburst intensity and the relative outburst intensity increased with the increase of gas pressure. These experimental results showed that a gas pressure threshold between 0.5 and 1.0 MPa exists for coal and gas outbursts in these tests. When the gas pressure is greater than this threshold, the outburst intensity increased with the increase of gas pressure.

3.5 Moisture Effect on Coal and Gas Outbursts

This section investigates the impact of moisture content on the intensity of coal and gas outbursts and reveals the mechanism of risk control through injecting water into the coal seam.

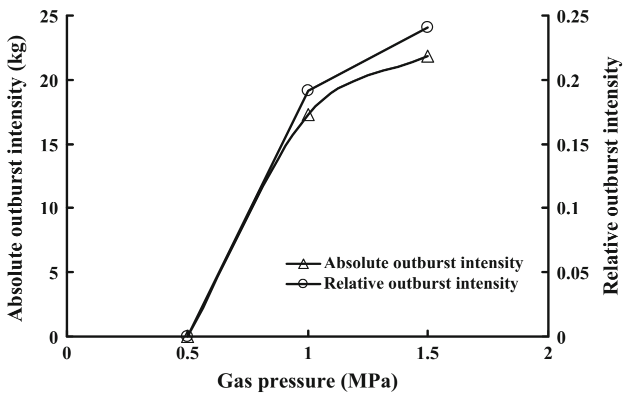


Fig. 6 Effect of gas pressure on the absolute outburst intensity and the relative outburst intensity

3.5.1 Experimental Program

To accurately measure the impact of moisture content on the intensity of coal and gas outbursts, this study involved three groups of tests. Each group had samples with moisture contents of 5, 10, and 15 %, and the samples were tested twice. The settings for the coal samples, load, and gas pressure are the same as those in the repeatability check of the section entitled "Repeatability Check on Coal and Gas Outburst Apparatus". The final intensity of the coal and gas outbursts in each group is the average of the two results.

3.5.2 Experimental Results and Analyses

The effect of moisture content is measured from the ejection size and the intensity of the coal and gas outburst. Figure 7 is a video screenshot at the moment when coal and gas burst out of the cavern. Higher moisture content corresponds to smaller coal outburst volume. The outburst coal pattern is wide and intense at 5 % moisture content. The shape and size of the coal pattern at 10 % moisture content is smaller than those at 5 % moisture content. When the moisture content reaches 15 %, the ejected coal pattern is a thin column.

The changes in the absolute outburst intensity and the relative outburst intensity with moisture content are shown in Fig. 8. The two curves indicate that the absolute outburst intensity and the relative outburst intensity tend to decrease with the increase of moisture content. A similar phenomenon was observed by Yin et al. (2012), who noted that the effective permeability of gas in a coal seam decreases with the increase of moisture content. Moisture weakens the initially released energy due to gas expansion during coal uncovering. This reduction of gas expansion energy which may trigger a coal and gas outburst thus decreases the potential of outburst disaster. This observation is also

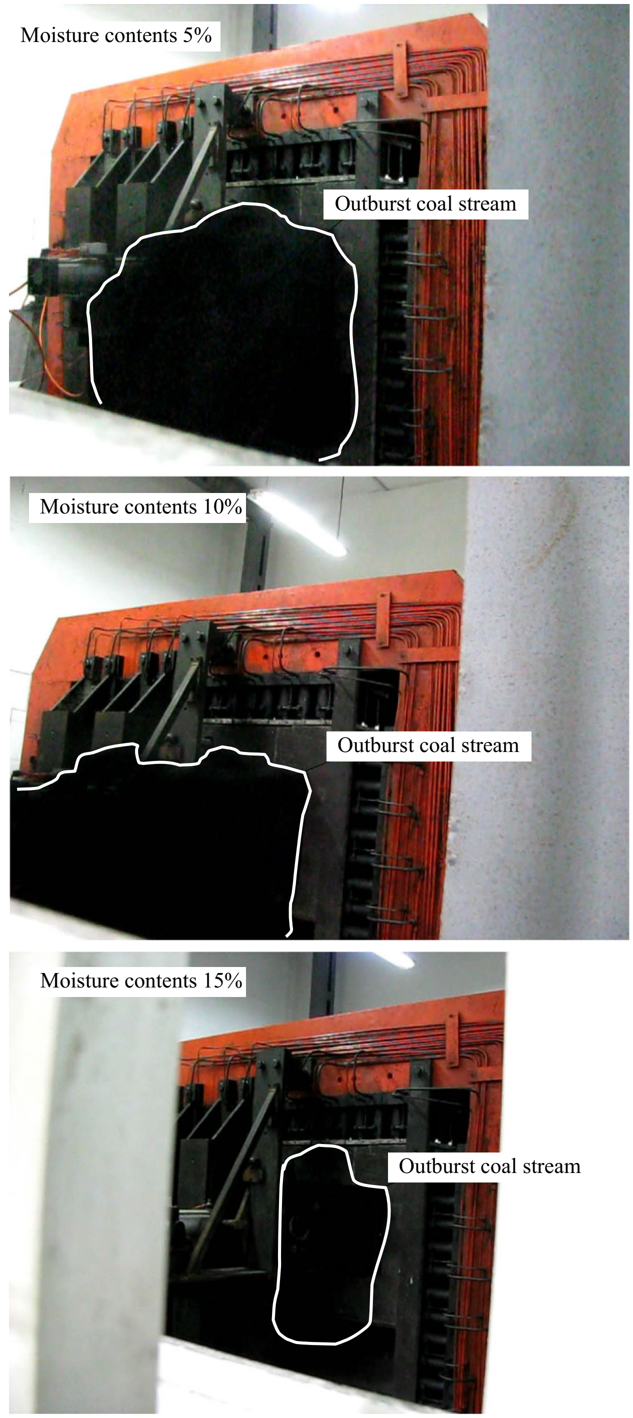


Fig. 7 Video screenshot at the moment of coal and gas outburst from the cavern

consistent with the site observations by Aguado and Nicieza (2007). Their site observations showed that outburst risk can be reduced by injecting water into a coal seam. Therefore, the moisture content has a significant impact on the absolute outburst intensity of coal and gas outbursts.

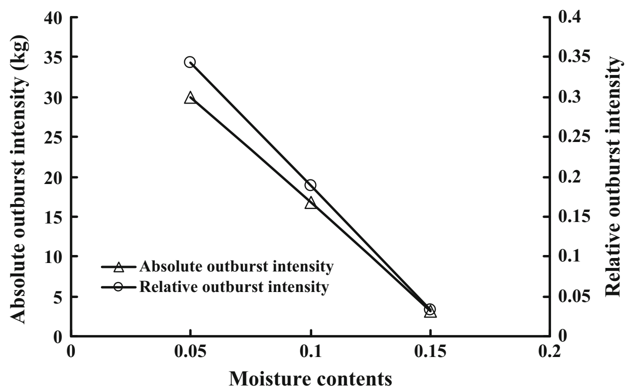


Fig. 8 Impact of moisture content on the absolute outburst intensity and the relative outburst intensity

4 Conclusion

This article presents a new experimental apparatus for coal and gas outburst simulation. Its reliability, repeatability, and accuracy were checked by means of simulation tests on a coal seam from the Chongqing Datong No. 1 Mine in China. The impacts of geo-stress, gas pressure, and coal moisture content on coal and gas outbursts were investigated to check the performance of the apparatus. From these tests and verifications, the following understandings and conclusions are drawn.

This apparatus is reliable and accurate for coal and gas outburst simulation tests. It can be used for large-sized coal samples at different coal seam dip angles. Geo-stress and gas pressure can be independently assigned and a non-uniform distribution of loadings can be applied to simulate the local stress concentration ahead of the coal face. Automatically opening the outburst cavern can largely reduce the disturbance from the coal excavation component. High-speed video cameras facilitate data recording.

It is difficult for an experimental apparatus to simulate real coal and gas outburst conditions. This experimental apparatus has a number of improvements over others, but still has some limitations. For example, this apparatus can only apply one-directional active loading for horizontal stress. For any other direction, the apparatus can only provide full constraint at zero displacement. In addition, this apparatus cannot monitor the deformation of the coal sample. Lastly, the gas sealing system can only provide a maximum pressure of 2 MPa; thus, this apparatus cannot simulate the case of gas pressure over 2 MPa. These limitations are good topics for future improvements.

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