Experimental Study on Dynamic Evolution Mechanism during Coal and Gas Outburst

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Abstract: Coal and gas outburst is one of the most serious disasters in coal mining. To research the outburst evolution mechanism, we used the multi-field coupled coal mine dynamic disaster large-scale test system for simulating coal and gas outburst. In the present study, the evolution characteristics of gas pressure, temperature, and coal body stress during the outburst process were explored. Experiment results show that (1) the coal seam gas pressure decreased faster where the position is closer to the outburst, and the spherical shell-shaped outburst wave front formed in the coal seam propagated rapidly from the outburst outlet to the inside; (2) during the process of coal and gas outburst, the elastic energy of coal body released instantly, which slightly increased the temperature and then the gas desorption absorbed the heat, thereby slowly dropping the temperature; (3) after the outburst, coal and gas released the pressure, and the stress inside of the coal body decreased. The reduction of stress around the outburst hole was the most obvious.

Keywords: coal and gas outburst, gas, temperature, in-situ stress

Coal and gas outburst is a complicated dynamic disaster in coal mine production. It can throw considerable coal and gas from coal wall to roadway or stope space in a short time and cause serious casualties and huge property losses. Its occurrence has the characteristics of burst and is destructive, rendering its on-the-spot monitoring difficult. Therefore, the research method of simulating coal and gas outburst in a laboratory employing test equipment is favored by most researchers [1-9]. Since the 1950s, a 1D outburst simulation experiment was conducted in the former Soviet Union; the results showed that a large gas pressure gradient was required for the coal to be broken and ejected. B.B [10] conducted the physical simulation test of gas outburst and obtained the curve of gas pressure drop. Starting in the early 1960s, researchers in Japan performed similar tests and continued to improve their equipment, eventually including in-situ stress and gas pressure. Shiping [11] used the coal shock tube to conduct experiments for simulating the outburst phenomenon when the coal was uncovered in Shimen. After considerable field data were collected and sorted out, some domestic scholars also performed physical simulation experiments. Jiang [12] used 1D experimental equipment to simulate the outburst. Meng [13] developed a device that can conduct 2D simulation experiment research. He found that two failure forms of coal sample cracking and outburst commonly exist in the process of gas outburst. Ju [14, 15] used axial pressure confining pressure to simulate ground stress and pore pressure for simulating gas pressure and successfully performed gas outburst test. Cai [16] developed a device, which can conduct 3D simulation tests of coal and gas outburst, and obtained the mathematical relationship model...
between parameters such as strength stress of coal under gas pressure and outburst strength using experimental data. Given the abovementioned test equipment structure, equipment size and other aspects still have some deficiencies. Therefore, on the basis of previous studies, Xu [17] developed a large coal and gas outburst simulation test bed and investigated the relationship between parameters such as coal particle size and water content under gas pressure and outburst strength. However, these studies fail to elaborate on the gas pressure temperature and the stress state of coal during the dynamic evolution of gas outburst. To make up for this deficiency, the present study used the independent research and development of Chongqing University of multi-field coupling large-scale simulation test system and the dynamic disaster in coal mine in mining under the condition of outstanding physical simulation experiment on the basis of the data obtained from the analysis in the process of the prominent evolution law of temperature and stress fields of the gas field. Doing so further explored the coal and gas outburst mechanism to provide certain database.

1. Test device and test method

1.1 Test equipment
The size of the sample box is 1050 mm × 410 mm × 410 mm. Raw coal of this size is difficult to prepare. Such raw coal is crushed and screened, and then the briquette is made according to previous research results. The coal sample is taken from a coal and gas outburst mine in Jiangxi Province. The moisture content of the prepared coal sample is 4%, the forming pressure is 7 MPa, and the stable time of forming pressure is 1 H. The sensors are arranged in batches while being formed. After the coal sample forming and sensor arrangement are complete, the test piece box is placed into the test bench (Fig. 1).

![Fig. 1 Multi-field coupling test system for dynamic disaster in coal mine](image)

1.2 Model coordinate system
To conduct a quantitative analysis of the test results, a space rectangular coordinate system is established with the lower left corner of the test piece as the origin; four sections, five vertical planes, and five levels are defined inside the test piece. Among them, the plane perpendicular to the Z axis is the section, from left to right is the first to the fourth section; the plane perpendicular to the Y axis is the vertical plane, from back to front is the first vertical plane to the fifth vertical plane; the plane perpendicular to the X axis is the layer, from bottom to top is the first to the fifth vertical plane. During the test, nine stress sensors are arranged on each section or layer; 28 gas pressure sensors and 11 temperature sensors are arranged, and the specific positions distributed in the coal body are shown in Fig. 2 in which the green dot indicates that pressure and temperature sensors are at this position.
1.3 Test program

The disturbance of coal mining results in the formation of three stress zones in front of the mining work, that is, original stress zone, stress concentration zone, and pressure relief zone. During the test, the maximum principal stress, the minimum principal stress, and the intermediate principal stress correspond to the directions of $\sigma_1$, $\sigma_3$, and $\sigma_2$, respectively. As illustrated in Fig. 2(a), the stress in the direction of maximum and minimum main stress is provided by four hydraulic cylinders on the side of the box; the middle main stress is provided by one cylinder at the end of the box. In conclusion, $\sigma_{11}$, $\sigma_{2}$, and $\sigma_{31}$ all exert the stress in the original stress area, whereas $\sigma_{12}$, $\sigma_{32}$, $\sigma_{13}$, and $\sigma_{33}$ exert the stress in zones 1 and 2 of stress concentration. Moreover, $\sigma_{14}$ and $\sigma_{34}$ exert the stress in the relief zone. The design stress concentration coefficient is 2.0, and the lateral pressure coefficient is 0.6. The specific stress value of each indenter can be obtained by calculation. During the experiment, CO2 is selected as the outburst gas. The coal seam with a depth of 1000 m is selected for simulation, and the similarity ratio of 12 is taken. The test gas pressure is 1 MPa, and the original ground stress of the coal body is 2.0 MPa. Table 1 presents the parameters of the specific test scheme.

| K  | $\sigma_{1}$/MPa | $\sigma_{2}$/MPa | $\sigma_{3}$/MPa | $\sigma_{11}$/MPa | $\sigma_{12}$/MPa | $\sigma_{13}$/MPa | $\sigma_{14}$/MPa | $\sigma_{31}$/MPa | $\sigma_{32}$/MPa | $\sigma_{33}$/MPa | $\sigma_{34}$/MPa | P/MPa | D/mm |
|----|------------------|------------------|------------------|---------------|------------------|------------------|------------------|---------------|------------------|------------------|------------------|-------|------|
| 2.0| 2.0              | 3.0              | 4.0              | 1.0           | 2.0              | 1.2              | 1.8              | 2.4           | 0.6              | 1.0              | 30                |

2. Experimental results and discussion
2.1 Evolution of test control parameters
The process of gas outburst is powered by ground stress and gas pressure. Therefore, the stress on coal body and gas pressure in coal body are defined as the test control parameters. To explain the evolution characteristics of the control parameters during the test process, the stress and gas pressure evolution curves of each region during the whole test process are presented, as displayed in Fig. 3. The test process according to the change of the ground stress of phases is shown in Fig. 3(c). Main stages: (1) Segment OA (0–2 h) is the vacuum stage, which aims to eliminate the air without the stress load of coal under the condition of vacuum, so that the coal specimen can result in full gas adsorption; the vacuum pressure is 0.09 MPa. (2) Section AB (2–2.5 h) is the stress loading stage where the coal body is in a vacuum state. First, the minimum principal stress direction and the intermediate principal stress are loaded to 10 KN to ensure that no gap exists between the box body and the reaction frame. (3) Section BC (2.5–7 h) is the stress and stable stage, the stable period in the previous step load stress value, and the coal specimen into carbon dioxide gas, about over 1 h or so, gas pressure to the expected value, then close the cylinders, as gas adsorption, gas pressure, to about 1 h later, again opened into gas cylinders. (4) Due to the long adsorption time of the gas in Section CD (7–7.5 h), if the test is operated for a long time, then it causes oil leakage and other faults. Therefore, the pressure unloading should be conducted, and the testing machine must be shut down in approximately seven hours from the beginning of calculation. (5) Section DE (7.5–49 h) is the cyclic gas-filled adsorption stage in which the ground stress is unloaded, and the gas cylinder is opened every 4 h for inflation. (6) In Segment EF (49–49.5 h), the stress loading stage is highlighted. In this stage, the stress values in the three directions are loaded again to the predetermined value of the test. After the target value is reached, the gas cylinder is opened to inflate the box body. (7) Section FG (49.5–51.5 h) is the stress stability stage, during which the stress value in all directions is stabilized, and the gas cylinder is kept open to ensure the full saturation of the gas adsorption on the coal specimen. (8) Section GH (after 51.5 h) is the protrusion stage. After the stress is stabilized for two hours, the cylinder is closed, and the protrusion is opened to achieve the protrusion. The stress is unloaded after the protrusion stops, and the testing machine is shut down.

2.2 3D dynamic visualization analysis of gas pressure field
After the outburst, the coal dust is collected and weighed. A total of 12.84 kg of pulverized coal is ejected in this test. The relative outburst intensity is 5.33%. By opening the cover plate of the box body, the data of the prominent hole can be obtained. With the prominent mouth as the center of the ball, it is roughly half ellipsoid with a width of 258 mm and a height of 328 mm. Through calculation, its volume is approximately 5.9*10^-3 m³. The evolution law of axial gas pressure with time during outburst is shown in Fig. 4, which illustrates that the measuring point P1 of the sensor closest to the outburst rapidly decreases from 1.00 MPa to 0.44 MPa within 0.2 s, with a decrease of approximately 56%. Subsequently, the gas pressure increases to 0.56 MPa, with a recovery of approximately 27%. Immediately after, it rapidly drops to 0.23 MPa again within 0.3 s and stabilizes at approximately 0.23 MPa within 0.2 s at the beginning of 0.6 s. It continues to decrease, and the slight phenomenon of rising gas pressure occurs in the following time. Finally, the gas pressure approaches the atmospheric pressure in approximately 10 s. At the
end of the protrusion, only weak air flow comes out, and the coal powder is no longer ejected from the protrusion. According to the analysis, due to the large amount of destruction of the coal body in the early stage of the outburst and its limited section, the coal powder that cannot be ejected in time blocks the outburst, thus forming a relatively closed space inside the coal body. Meanwhile, the gas desorbed from the rear coal body continues to flood into the position, leading to the phenomenon of rising gas pressure in the hole. That is, the occurrence of coal and gas outburst pulse phenomenon.

From the pressure monitoring data P10 at the center of the second section, the gas pressure drop rate at this position is close to that at the center of the first section, both of which decrease to the level of atmospheric pressure after approximately 10 s. However, the specific gas pressure drop process at the two positions is quite different. During the protrusion process, P10 does not rebound; specifically, the pressure drops to approximately 0.4 MPa within 0.54 s from the protrusion time. Subsequently, an inflection point occurs, with the decline rate greatly reduced. The analysis shows that the measuring point of P10 is located in the stress concentration area, and the outburst hole does not extend to this area, leading to the presence of a certain thickness of coal in the PU pipe of the sensor pressure guide and the outburst hole, which acts as a buffer against the fluctuation caused by the gas pressure upheaval. Therefore, the gas pressure reduction process at this position is relatively smooth. After observing the two measuring points in the original stress area, similar conclusions can be drawn, which are not repeated here.

Fig. 4 Curves of gas pressure change with middle axis

In the actual process of coal and gas outburst, the gas flow inside the coal body is a radial flow with the center of the outburst. To understand the change of gas pressure in coal during the occurrence and development of gas outburst intuitively, investigating the 3D flow state of gas is necessary. To obtain the results of 3D flow, the gas pressure distribution is presented in the form of 3D slice diagram with the help of MATLAB data processing software. First, interpolation is conducted for the measured gas pressure data on the basis of the 3D coordinate values of each sensor. After the interpolation results are synthesized, grid data function is used to interpolate again, and slice function is used to draw the 3D slice graph of air pressure.
Fig. 5 Evolution of pressure distribution over time in coal

Fig. 5 displays the pressure section diagram at different moments during the development of coal and gas outburst, and the protrusion coordinates are (205, 205, 1050). The figure also shows that at $t = 0$ s, the outburst has not yet occurred, and the entire coal body is in an adsorption equilibrium state with the gas pressure being the same everywhere, all at 1 MPa. After the outburst is opened, coal and gas outburst occurs immediately. At the moment of $t = 0.2$ s, gas pressure at the exit of the outburst decreases rapidly, and an ellipsoidal isobaric surface is formed with the outburst as the focus, whereas the gas pressure in the deep part of the coal body has a small variation range. When $t = 1.0$ s, the gas pressure on the main longitudinal plane and the upper part of the first section decrease to less than 0.5 MPa. As the bulge continues to develop, the isobaric surface of the ellipsoid continues to move deep into the coal, and the rear desorption gas continues to replenish the bulge. As the protrusion continues to develop, the isobaric surface of the ellipsoid continues to move to the depth of the coal body, and the gas desorbed from the rear continuously supplements the gas consumed during the protrusion process. Finally, after the exhaust of the gas in the chamber, the protrusion stops, and the evident isobaric surface is no longer shown in the section diagram.

2.3 Spatial and temporal evolution of coal body temperature

In the development process of coal and gas outburst, physical phenomena, such as coal fracture, gas desorption, movement and friction between coal powder and coal wall, and coal particles exist, which can all cause the change of coal body temperature. To further study the outburst mechanism, monitoring the data of coal body temperature change is necessary. To achieve this purpose, pt1000 temperature sensors are embedded layer by layer in the forming process of the coal specimen. However, some temperature sensors are damaged by huge stress changes in the protruding process. In this test, only the temperature data of measuring points T5, T7, T8, T9, and T11 are obtained. Fig. 6(b) illustrates the temperature evolution curve of the outburst and gas desorption process. After outburst, the temperature in the coal decreases rapidly due to a large amount of gas desorption. After a period of approximately 100 s, the rate of decline decreases, and the final temperature change is approximately $-8.00$°C. By comparing T5, T8, and T11 on the same axis, as shown in Fig. 6(c), the rate of temperature change in the coal body decreases gradually with the increase of the distance between the temperature and the outburst. However, the final temperature of the three positions tends to be the same after 400 s with the increase of desorption. In conclusion, the decrease of temperature is mainly caused by gas desorption and expansion. After outburst, a large amount of gas adsorbed by coal is quickly desorbed as free gas, thus absorbing a large amount of heat. The gas desorbed can also absorb a large amount of heat when expanding. As time goes on, heat transfer also occurs inside the
coal, making the temperature of the whole coal specimen consistent. As illustrated in Fig. 6(d), the analysis of the temperature change during the protruding development shows that on the central axis, a small rise occurs before the temperature drops. T11 and T10 far from the outburst increase by 2.1°C and 1.13°C, respectively. Measuring point T5 close to the outburst shows a little upward trend, whereas measuring point T8 increases by approximately 0.15°C. According to the analysis, a certain amount of elastic strain energy accumulated inside the coal body before the outburst, whereas a large number of cracks are rapidly formed in the coal body after the outburst. During the expansion process, the crack tip rises in temperature due to the release of elastic energy. However, near the protrusion, the temperature change caused by gas desorption occupies a dominant position due to the large amount of coal being thrown out. Therefore, no temperature rise occurs.

2.4 Spacetime evolution of the crustal stress state on the coal body

After the outburst, the stress and pressure in the coal body drop rapidly, but the change trend and change amount in different areas have their own characteristics, as displayed in Fig. 7, which also shows the curve of the stress in the coal seam and the pressure at the center of the corresponding area changing with time during the outburst.
Fig. 7 Evolution curve of coal seam stress and gas pressure during outburst

As presented in Fig. 7(a), the stress in the coal body and the gas pressure in the pressure relief area drop rapidly after outburst. In 0.1 s, the gas pressure $P_1$ drops from 1.00 MPa to 0.4 MPa; the maximum main stress $\sigma_{14}$ in the area drops from 0.60 MPa to 0.43 MPa, with the reduction amount of 28%; the minimum main stress $\sigma_{34}$ drops from 0.36 MPa to 0.34 MPa, with the reduction amount of approximately 5%. This analysis indicates that the pressure drop in the direction of the maximum principal stress is large, along which a large number of coal bodies are thrown out, resulting in the development of the outburst holes in this direction. Therefore, the bearing capacity of the coal body in the pressure relief area along the direction of $\sigma_{14}$ is greatly weakened. However, some coal bodies remain along the direction of $\sigma_{34}$, which also has a certain bearing capacity. Therefore, the stress value in the direction of the minimum principal stress decreases slightly. In the next 1.5 s, $P_1$ continues to decrease to approximately 0.04 MPa, the minimum principal stress $\sigma_{34}$ decreases to 0.19 MPa, and the maximum principal stress $\sigma_{14}$ tends to be stable at approximately 0.42 MPa. Based on the analysis of this phenomenon, during this period, the outburst holes continue to expand but mainly develop to the depth of the coal body and the direction of the minimum principal stress; thus, $\sigma_{34}$ changes greatly. Subsequently, the pulse phenomenon occurs, $P_1$ rises to 0.2 MPa, and the minimum principal stress rises to 0.05 MPa. This phenomenon also shows that the accumulation of gas energy in the hole aggravates the roof damage, making the coal and gas outburst further destructive. Finally, the process of coal and gas outburst is over, the stress in the coal body is basically stable, the maximum principal stress is stable at 0.07 MPa, and the minimum principal stress is stable at 0.03 MPa. However, the coal body in the pressure relief area has no bearing capacity at this stage due to the presence of outburst holes.

The histogram of the change of the coal seam stress during the outburst process is shown in Fig. 8, and the change situation is observed vividly. Fig. 8 illustrates that after the occurrence of the outburst, the change rules of the maximum principal stress and the minimum principal stress directions in each stress area are roughly similar, and the changes from large to small are: pressure relief area > stress concentration area > original stress area 1 > original stress area 2. The analysis of this phenomenon indicates that the formation of prominent holes in the pressure relief area is possible. Thus, after the occurrence of the outburst, the stress changes at the same time because the stress concentration area is the closest to the outburst hole, the
pressure variation in the stress concentration area is large, and the bearing capacity of the coal body in this area is greatly affected. Original stress zones 1 and 2 are far away from the protruding hole and have less influence. Both zones are also affected by the rear intermediate principal stress.

3. Conclusion
1) During the development of gas outburst, the closer the gas pressure is to the outburst, the faster the gas pressure drops, and the pressure rises in the outburst hole. The outburst wave front formed in the coal body during the outburst development can be observed directly by using the 3D barometric section diagram drawn by data processing software.
2) In the process of gas outburst, the temperature in the coal body decreases, and the maximum variation is −8°C. Finally, the temperature in the whole coal body tends to be consistent. In some places, the temperature rises before it drops.
3) Coal and gas outburst is a process of pressure relief. After the outburst, the stress in each region in the coal body decreases. According to the descending order, the stress concentration area > is in the pressure relief area, > is in the original stress 1 area, > is in the original stress 2 area.

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References:
[1] Huang Weixin, Liu Dunwen and Xia Ming. Study of meso-mechanism of coal and gas outburst[J]. Chinese Journal of Rock Mechanics and Engineering. 2017, 36(02):429-436.
[2] Li Hui, Feng Zengchao, Zhao Dong, et al. Simulation experiments and mechanism analysis of coal and gas outbursts under 3D stresses[J]. Journal of Mining & Safety Engineering. 2018, 35(02):422-428.
[3] Li Shucai, Li Qingchuan, Wang Hanpeng, et al. A large-scale three-dimensional coal and gas outburst quantitative physical modeling system[J]. Journal of China Coal Society. 2018, 43(51):121-129.
[4] Liu Yejiao, Yuan Liang, Xue Junhua, et al. Laboratory Experiments and Numerical Simulation on Coal and Gas Outbursts[J]. Industry and Mine Automation. 2018, 44(02):43-50.
[5] Xu Jiang, Luo Xiaohang, Zhang Chaolin, et al. Study on Gas Pressure Visualization During Coal and Gas Outburst Based on Matlab[J]. Safety in Coal Mines. 2018, 49(06):1-4.
[6] Zhang Chaolin, Peng Shoujian, Xu Jiang, et al. Temporospatial evolution of gas pressure during coal and gas outburst[J]. Rock and Soil Mechanics. 2017, 38(01):81-90.
[7] Zhang Chaolin, Xu Jiang, Peng Shoujian, et al. Advances and prospects in physical simulation of coal and gas outburst[J]. COAL GEOLOGY & EXPLORATION. 2018, 46(04):28-34.
[8] Zhu Likai, Yang Tianhong, Xu Tao, et al. Explore the mechanism of ground stress and gas pressure in coal-gas outburst[J]. Journal of Mining & Safety Engineering. 2018, 35(05):1038-1044.
[9] Hu Weijia. Theoretical and experimental research for gas –pulverized coal iMPactive dynamic effect after outburst[D]. Beijing: China University of Mining & Technology, Beijing, 2013.
[10] B.B.Huoduote.(Translated by Song Shizhao, Wang Youan ), Coal and gas outburst[M]. Beijing: China Industry press, 1966.
[11] ShiPing Zengzhi. Discussion on theory and model of the mechanism of coal and gas...
outburst[J], The 21st Camp of International Seminar of Coal Safety, 1985

[12] Jiang Chenglin, Yua Qixiang. Spherical Shell Losing Stability of Coal and Gas Outbursts and Prevention technique [M]. Xuzhou: China University of Mining and Technology Press, 1998

[13] Meng Xiangyue, Ding Yangsheng, Chen Li et al. 2D Simulation Test of Coal and Gas Outburst [J]. Journal of China Coal Society, 1996, 21(1): 57-62.

[14] Tang Jupeng, Pan Yishan and Yang Shenlin. Experimental study on coal and gas outburst under three-dimensional stress [J]. Chinese Journal of Rock Mechanics and Engineering. 2013, 32(05): 960-965.

[15] Tang Jupeng, Yang Shenlin, Wang Yalin et al. Deep coal and gas outburst test under ground stress and gas pressure [J]. Rock and Soil Mechanics. 2014, 35(10): 2769-2774.

[16] Cai Chenggong. Experimental study on 3D simulation of coal and gas outbursts [J]. Journal of China Coal Society. 2004, 19(1): 66-69.

[17] Xu Jiang, Tao Yunqi, Ying Guangzhi et al. Development and application of coal and gas outburst simulation test device [J]. Chinese Journal of Rock Mechanics and Engineering, 2008, 27(11): 2353-2362