Research Article

Research on the Force Characteristics and Structural Optimization of Mine Antioutburst Door under the Influence of Coal and Gas Outburst Impact Airflow

Linchao Dai ^{1,2}, Haitao Sun ^{1,2}, Xusheng Zhao,^{1,2} Bo Wang,^{1,2} and Jie Cao^{1,2}

¹State Key Laboratory of the Gas Disaster Detecting, Preventing and Emergency Controlling, Chongqing 400037, China

²China Coal Technology and Engineering Group Chongqing Research Institute, Chongqing 400037, China

Correspondence should be addressed to Haitao Sun; dreamsht@163.com

Received 5 February 2021; Revised 11 March 2021; Accepted 16 March 2021; Published 31 March 2021

Academic Editor: Jiehao Wang

Copyright © 2021 Linchao Dai et al. This is an open access article distributed under the Creative Commons Attribution License, which permits unrestricted use, distribution, and reproduction in any medium, provided the original work is properly cited.

In order to deeply explore the destructive effect of the impulsive airflow on the mine antioutburst door when coal and gas outbursts occur in underground coal mines, a large-scale coal and gas outburst dynamic effect simulation experiment device is used to carry out the coal and gas outburst disaster simulation experiment. The impact load and deformation characteristics of the antioutburst door under the impact airflow during coal and gas outburst are analyzed, and the experimental results are discussed in depth through numerical simulation analysis and field example analysis. Based on this, the internal and external causes of the damage of the antioutburst door on the coal mine site are analyzed, the key technologies that need to be solved in the design of the antioutburst door's disaster resistance are studied, and the overall design of the structure optimization design of the antioutburst door is proposed. The research results show that after coal and gas outburst, the pressure on the antioutburst door will rise and fall, and the fluctuation will be greater. Under the same installation position, the farther the antioutburst door is from the protruding point, the less pressure it bears. In the middle and late stages of the outburst, intermittent negative pressure of the gas at the antioutburst door appeared. The key technologies for the design of the antioutburst door and its disaster resistance mainly include that strengthen theoretical and experimental research on the formation mechanism of outburst shock waves in mines, the interaction mechanism between disaster shock loads and dampers, and the magnitude of disaster expected shock loads; optimize the structure of the antioutburst door size, the width of the contact surface between the air door and the door wall, the stress distribution of the air door under impact load, the design of the safety hole, and the locking device; and improve the disaster monitoring and alarm capabilities of the antioutburst door and collect changes in antioutburst door pressure in real time. The research results provide a theoretical basis and technical support for the optimization of the antishock performance of underground antioutburst doors in coal mines and have important practical significance for improving the disaster resistance of the ventilation system.

1. Introduction

The antioutburst door is one of the basic safety facilities in coal and gas outburst mines and an important guarantee for the safe production in mines [1–3]. When a serious coal and gas outburst disaster occurs underground, the antioutburst door near the disaster site should have disaster protection capabilities to reduce the scope of disasters, prevent harmful substances such as gas, carbon monoxide, coal dust, or impact gases from entering other areas outside the antioutburst door, and reduce the possibility of secondary disas-

ters [4–7]. However, due to the lack of professional disaster prevention structural design theory and technical support, the disaster resistance of many mine antisurge doors is still poor. When directly facing the severe impact of the disaster shock wave, the antioutburst door often produces large plastic deformation, which causes partial or overall fracture displacement or thrown out, thereby failing to meet the needs of disaster protection. For example, on November 21, 2009, a coal (rock) and gas outburst was occurred in the No.15 coal seam of Heilongjiang Xinxing Coal Mine at 1:37, and then, the outburst gas flowed back to the second level, and the

gas explosion occurred at 2:19, causing 108 deaths. This is because when coal and gas outburst occurs, the high-pressure gas flow and broken coal (rock) will quickly spray from the coal wall to the stope or roadway space, producing a more destructive impact airflow and shock wave. And it results in the deformation and damage of ventilating facilities such as air doors, wind windows, and air ducts, resulting in air flow turbulence and secondary disasters [8]. Therefore, it is very necessary to optimize the structure and improve the performance of the mine antioutburst doors near the work area with outstanding hazards from the perspective of prominent disaster protection design.

The existing mine antioutburst doors are mostly focused on the analysis of the deformation laws under the action of gas explosions, and there are few studies on the impact deformation laws of the antioutburst doors in the process of protruding disasters [9–13]. Because the shock wave generated by coal and gas outburst has different characteristics from the shock wave of gas explosion, scholars have carried out research on the deformation characteristics of the antioutburst door under the action of the outburst impact airflow through theoretical analysis and numerical simulation. In 1991, Tian [14] comprehensively used the principles of gas dynamics, thermodynamics, and material mechanics, and according to the conditions and characteristics of coal and gas outbursts, discussed the force analysis and strength design of the mine antioutburst door, and obtained the corresponding calculation formula. In 2009, Cheng et al. [15] used numerical simulation methods to study the damage characteristics of antioutburst doors after coal and gas outbursts, clarified the reflected overpressure acting on the door during outbursts, gave its calculation formula, and obtained similar simulation experiments. Based on the antioutburst door pressure data, the ANSYS software was used to simulate the damage characteristics of the antioutburst door. In 2013, Miao [16] established a statically indeterminate structure model under the impact load of a mine antioutburst door based on the structural characteristics of the antioutburst door. In 2017, Dai et al. [17] used numerical simulation methods to study the static and dynamic characteristics of steel antioutburst doors under the action of gas outburst. In 2020, Xu et al. [1] used the LS-DYNA software to numerically simulate the damage of the air door under the impact load and obtained the static characteristics of the Q460 steel antioutburst door.

At the same time, through the optimized design of the structure, the impact resistance of the coal mine antioutburst door can be greatly improved under the same material conditions, or when the same impact resistance is required, the material of the air door can be saved, and the use efficiency of the material can be improved [18]. The impact resistance of the antisurge door is not only reflected in the strength of the material but also restricted by many factors such as the impact load characteristics, the structural characteristics of the air door, the structural accessories, and the connection points [19]. Even if the same material is used, due to the anisotropy of the material and the different requirements of different structures on the bearing capacity of the material, the bearing capacity of different structures and even different

areas of the same structure are different. In practical applications, on the one hand, the form of the load-bearing structure should be considered, and specific structures and materials should be selected according to the site use to meet the functional requirements. On the other hand, the material should be maximized, improve the efficiency of the material, and optimize the overall performance of the structure. Therefore, by carrying out coal and gas outburst disaster simulation experiments, analyzing the impact load and deformation characteristics of the antioutburst door under the impact of the outburst process, and discussing the structural optimization of the antioutflow door, it has important practical significance for improving the disaster resistance of the ventilation system.

2. Analysis of the Dynamic Effect of Coal and Gas Outburst and the Impact Load Law of the Antioutburst Door

At present, in the field of coal and gas outburst dynamic effect research, through the joint efforts of many experts and scholars, basic research work has obtained preliminary results, theoretical research, numerical analysis, experimental research, and field analysis, and other research methods are becoming more mature, and theoretical systems are also being formed [20–33]. To solve the problem of disaster prevention design of the antioutburst door, we must first understand the characteristics of the dynamic effect in the process of coal and gas outburst and the law of the bearing pressure change of the antioutburst door. This paper mainly uses three methods, including laboratory experiment, numerical analysis, and field case analysis, to study the characteristics of the dynamic effects of coal and gas outbursts.

2.1. Laboratory Experiment. In order to obtain the impact pressure change law of the outburst impact airflow on the remote antioutburst door, a large-scale coal and gas outburst dynamic effect simulation experiment device [34–36] is used to carry out the coal and gas outburst disaster simulation experiment. The simulation test device for dynamic effect of coal and gas outburst is shown in Figure 1. In order to collect the data at the antisurge door, gas pressure sensors are installed near the antioutburst doors A and B, respectively. The installation position of the air door is shown in Figure 2. And the raw coal samples of the N2808 working face in the M8 coal seam of Chongqing Yuyang Coal Mine are selected as the experimental materials. The M8 coal seam is a coal and gas outburst coal seam. The gas content of the coal seam is $15.08\sim 29.4\text{ m}^3/\text{t}$, the gas pressure is $2.24\sim 4.87\text{ MPa}$, the permeability coefficient of the coal seam is $21.2\text{ m}^2/(\text{MPa}\cdot\text{d})$, the failure type is Type V, and the initial gas emission velocity is $22\sim 43$. This experimental container has a volume of 1.8 m^3 , a coal particle of 1.5 t in it, an inflation pressure of 0.3 MPa , a protrusion diameter of 0.2 m , and a roadway cross-sectional dimension of $0.3\text{ m}\times 0.3\text{ m}$, and it is sealed by a double blasting disc. Figure 3 shows the gas pressure change curve at the antioutburst doors A and B during the protruding process.

FIGURE 1: The simulation test device for dynamic effect of coal and gas outburst: (1) bursting disc, (2) pressure\temperature\concentration sensor, (3) multifunction data acquisition controller, (4) display and operating platform, (5) controller, (6) gas cylinder, and (7) vacuum pump.

FIGURE 2: Schematic diagram of the experimental system and the position of the simulated antioutburst door.

From Figure 3, the peak gas pressures at antioutburst doors A and B are 0.0148 MPa and 0.0133 MPa, respectively. If this experiment is estimated and compared with a similar geometric length ratio of 1/10 [37, 38], it is equivalent to the following outburst conditions on site: (1) The volume of the outburst hole is 1800 m³, there are 1500 t loose coal particles in it, and the gas pressure is 0.3 MPa. The actual conditions are similar to that when a large number of coal particles accumulate in the middle and late stages of the extra large outburst, and the desorption gas pressure is reduced to 0.3 MPa. (2) The antioutburst door of the protruding opening is 2 m, and the cross-sectional dimension of the rectangular roadway is 3 m × 3 m. (3) The distance between the antioutburst doors A and B from the projecting point is 235 m and 285 m, respectively.

The following laws can be obtained from the change trend of the antioutburst door pressure: (1) The antioutburst door has a rising and falling process with pressure, the decay speed is slower than the rising speed, and the fluctuation is higher. (2) Under the same installation position, the pressure of the antioutburst door is inversely proportional to the dis-

tance of the protruding point, that is, the farther the antioutburst door is from the protruding point, the less pressure it bears. (3) In the middle and late stages of the outburst, intermittent negative pressure of gas at the antioutburst door appeared.

2.2. Numerical Analysis. In order to obtain the change law of the antioutburst door pressure under more prominent parameter states, the Fluent software was used to numerically analyze the antioutburst door pressure change law under different state parameters. The numerical analysis model uses a two-dimensional simplified model. In order to reflect the different orientation of the antioutburst door relative to the protruding opening, the roadway area adopts the upper and lower branches, and the ratio of the size of the upper and lower branch model to the size of the experimental device is 1 : 1. The three points A, B, and C in Figure 2 can be used as the protruding fluid outlet and the installation point of the antioutburst door, which can simulate the influence of the different positions of the antioutburst door on the pressure of the air door on site and experiment. This paper

FIGURE 3: The gas pressure change law at antioutbursts A and B.

mainly studies the situation that point C is the exit boundary; points A and B are the antioutburst doors.

This numerical model assumes that the pore pressure change equation is:

$$p_{\text{inlet}}(t) = \frac{p_0}{\exp(A \cdot \sin(\pi/8) \cdot t)} \quad (0 < t < 4), \quad (1)$$

where p_{inlet} is the pore pressure, MPa; p_0 is the initial pressure, MPa; t is the time, s; and A is the undetermined coefficient. When the pore pressure attenuates from 1.0 MPa to 0.1 MPa, the process time is 4 s, and $A = 2.3$ at this time.

The simulation calculation adopts the mixture two-phase flow model. Consider the compressibility of the gas phase medium, set it to an ideal state, and the gas viscosity is 1.37×10^{-5} kg/m·s, the density of the solid phase medium is 1200 kg/m³, and the viscosity is 1.72×10^{-5} kg/m·s.

For an outburst impact process (monotonous attenuation of the hole pressure), during the initial period of the outburst, the pressures of the antioutbursts A and B show a small high-frequency oscillation attenuation trend, which is mainly affected by the air shock wave and the critical state of the two-phase flow. It presents a trend of attenuation of large-scale low-frequency oscillations, which is mainly affected by changes in two-phase flow motion parameters. After the last

peak pressure, the antioutburst pressure gradually decreases, and negative pressure may appear at the end. When the volume fraction of solid phase changes between 0.1 and 0.5, the pressure change trend of antioutbursts A and B is basically the same. Taking the solid phase volume fraction $\Theta = 0.2$ as an example, the pressure change trend of antioutbursts A and B during the highlighting process is shown in Figure 4.

According to the numerical simulation results in Figure 4, when the volume fraction of solid phase $\Theta = 0.2$, the maximum static pressure of antioutburst doors A and B is 0.240 MPa and 0.239 MPa, so the maximum pressure of antioutburst doors A and B is 0.140 MPa and 0.139 MPa (relative to atmospheric pressure), and the maximum pressure occurs approximately in the middle of the outburst ($t = 1.6$ s). After that, the antioutburst door pressure gradually decreases and starts to enter a negative pressure state at $t = 3.7$ s. When $t = 4.0$ s, the negative pressure of the antioutburst door A is -0.0058 MPa, and anti-outburst door B is -0.0046 MPa. When the negative pressure state appears, it means that at the entrance of the roadway branch, the flow of the two-phase flow toward the outlet is greater than the flow of the two-phase flow out of the outburst.

2.3. Field Case Analysis. At 0:01 on June 11, 2014, an extra large coal and gas outburst accident occurred at the working face of 1601 air return way 2# connecting lane in Xinhua

FIGURE 4: The static pressure change of antioutbursts door A and B in condition of exit C ($\Theta = 0.2$).

FIGURE 5: Schematic diagram of the 6.11 outburst accident site in Liuzhi Xinhua Coal Mine, Guizhou.

Coal Mine, Liuzhi Mining Area, Guizhou (as shown in Figure 5).

The amount of outburst coal (rock) in the accident was 1010t, and the total gas emission was about 120,000 m³. The accident damaged two pairs of antioutburst doors at the opening of No.2 connecting lane in 101 gas lane at 22 m and 31 m. Among them, the outer antioutburst door of 101 gas lane, the door wall was destroyed, the air door was thrown out by the protruding airflow, and the inner antioutburst door was destroyed. The top of the blower door was washed out, and the protruding power effect on site was very significant, as shown in Figure 6.

After the accident, the pulverized coal-gas two-phase flow rushed down the No.2 connecting lane into the 101 gas lane and diverted the flow at the connection point of the No.2 connecting lane and the 101 gas lane and generated the two pairs of antioutburst doors installed in the 101 gas lane. The impact causes the antioutburst door to be destroyed under the action of gas shock wave, two-phase hydrostatic pressure, and dynamic pressure. In the initial stage of the outburst launch, the impact force of the outburst airflow is weak, and a large amount of coal particles accumulate under the inner antioutburst door, which indirectly protects the door leaf structure of the inner antioutburst door. The high-strength impact airflow behind can only impact the top of the inner antioutburst door. After the top of the inner antioutburst door is damaged, the impact air directly impacts

the outer antioutburst door, causing the outer antioutburst door to be thrown out as a whole.

3. Analysis of the Failure Reason of the Antioutburst Door

3.1. External Cause Analysis of Failure. The impact of the pulverized coal-gas two-phase fluid during the outburst is the main external cause of the damage of the antioutburst door. The magnitude and change of the impact energy are related to the outburst strength, the two-phase fluid movement state, the physical and mechanical properties of the coal seam, the gas pressure and content, roadway conditions, and other factors [39]. According to the above experimental analysis, numerical analysis, and field example analysis results, the external factors that cause the failure of the antioutburst door during the coal and gas outburst mainly include the following three situations:

- (1) The gas pressure generated at the antioutburst door during the protruding process is higher than the ultimate load that the antioutburst door structure can withstand

The gas pressure generated at the antioutburst door during the high-speed flow of pulverized coal-gas two-phase flow along the roadway space is the main external force

(a) The inside antioutburst door at 101 gas lane

(b) The outside antioutburst door at 101 gas lane

FIGURE 6: The damaged air doors in scene of accident.

influencing factor for the impact load and damage of the antiburst door. In the process of coal and gas outburst, the formation of gas shock pressure at the antioutburst door is closely related to the energy size, change law of the outburst fluid, and roadway environment. When the gas energy of the protruding hole is high, the two-phase flow ejected by it will violently compress the gas in the roadway when it migrates in the roadway space to produce a very destructive gas shock wave. Its destructiveness mainly depends on the wave front pressure and acting time of the shock wave [20, 23, 39].

The impact pressure generated during the protruding process poses a huge threat to the antioutburst door. Due to the large cross section of the antioutburst door, even if a shock wave with a wave front pressure of 0.001 MPa acts on the antioutburst door, the force per square meter area must reach 1000 N. Taking the data in Figure 3 as an example, the experimental simulation area of antioutburst door is 0.09 m^2 , and the force on antioutburst doors A and B will reach 12.60 kN and 12.51 kN, respectively. At this time, the ability of the antioutburst door to resist damage is very important.

- (2) The negative pressure generated by the high-speed moving fluid at the antioutburst door during the protruding process. The antioutburst door opens by itself when the structure is intact, causing the safety protection function to fail

When the impact pressure difference on both sides of the antioutburst door is positive, the antioutburst door is automatically closed. At this time, if the gas impact pressure is less than the ultimate bearing capacity of the antioutburst door structure, the anti-outburst door structure will not fail. Conversely, when the impact pressure difference on both sides of the antioutburst door is negative, if the locking device is not designed, the antioutburst door will automatically open under the action of the negative pressure difference. At this time, the opened antioutburst door loses its safety protection function, and the gas flow will pass through the antioutburst door smoothly and flow back to the ventilation system after protruding.

- (3) The interval impact frequency of the pulse wave or airflow generated by the protruding “resonance” with the forced vibration frequency of the antioutburst door so that the deformation of the anti-outburst door structure is greater than the limit deformation of the antioutburst door

The so-called resonance refers to the phenomenon that when the system is forced to vibrate under external excitation, if the frequency of the external excitation is close to the system frequency, the amplitude of the forced vibration may reach a very large value. Due to the limitation of coal destruction speed or fluid critical state, the ejection process of coal-gas two-phase flow during outburst is mostly a pulsed impact process. This phenomenon is recorded in most large outburst accidents. On November 4, 1977, there was a text record in the actual measurement of coal and gas outburst in Zhongliangshan [39]: “The first impact sound occurred at 1.5s after the sound of the vibrating gun, and then there were three more impact sounds at 2.5s, 3.5s, and 4.0s. An impact sound was heard at 23.5s.” This test shows that there is indeed a time interval between the impact of two-phase flow in the process of highlighting, and the interval time of multiple impact processes is different.

HDGEO_5552949 In addition, the abnormal disturbance of external factors such as particle deposition, turning, and roadway cross-section changes during the two-phase flow will also cause fluctuations in the gas pressure at the antioutburst door. After the antioutburst door is impacted by an airflow or two-phase flow, it will be in a forced vibration state, and its amplitude is related to the impact load and the physical characteristics of the antioutburst door [40, 41]. During the vibration process, when the next airflow or two-phase flow arrives, if the vibration direction of the antioutburst door is exactly the same as the impact load direction, the antioutburst door deformation after the impact load will be greater than the deformation caused by the impact load in the static state of the antioutburst door. Multiple such impacts will cause the deformation of the antioutburst door to become larger and larger. When the final deformation of the antioutburst

door exceeds the limit it can bear, the antioutburst door structure will be damaged.

3.2. Internal Cause Analysis of Failure. In addition to external influencing factors such as disaster shock waves, the damage of mine antioutburst door also has internal factors that have not fully considered the requirements of disaster prevention design in its own design and installation. The main manifestations are as follows:

- (1) When designing the antioutburst door, the research on the disaster mechanism of various mine disasters such as coal and gas outburst and rock burst is not perfect. There are relatively few research results on the formation mechanism of shock waves, the change law of airflow parameters in the tunnel network, and related simulation experiments after disasters, which makes the mine antioutburst door strength design without accurate theoretical basis and experimental data support, and it is easy to cause design deviations
- (2) Many mines have not paid full attention to the disaster protection function of the antioutburst door, and the site installation is relatively random, lack of the basic research and professional structural design, and cannot maximize the impact resistance of the material
- (3) Due to the lack of relevant theoretical support, no professional standards related to the impact resistance of mine air doors have been established so far. The existing industry standard (MT 1066-2008) only stipulates the technical conditions such as the installation location, quantity, strength, management, and removal of the antioutburst reverse door. There is no specific requirement for the impact resistance structure of the antioutburst door, and the impact resistance design of the mine antioutburst door lacks relevant regulations and industry standards to regulate
- (4) The design and installation of on-site mine vents often pay more attention to the strength design of the door leaf and door wall, while ignoring the strength design of the door leaf and door wall connection accessories, resulting in insufficient overall strength of the vent. It can also be seen from some accident cases that after the disaster, the antioutburst doors of many mine vents were thrown out as a whole, and the material of the antioutburst doors was not damaged. Instead, it is directly separated from the weaker connection between the door leaf and the door wall, causing the overall structure to fail
- (5) The location and number of on-site antioutburst doors did not consider the requirements of disaster prevention design. When antioutburst doors are arranged near locations where impact disasters are likely to occur, wrong designs such as short-distance placement and insufficient strength often

occur on site, making the antioutburst doors vulnerable to disaster shock waves

4. Key Technologies for Structural Optimization of the Antioutburst Door

The disaster prevention design of mine antioutburst doors mainly involves multiple technical details such as the location and number of air doors, disaster resistance strength, installation dimensions, and bearing structure. In general, the focus includes the following three technical issues:

4.1. Disaster Mechanism of Coal and Gas Outburst. The influencing factors of the dynamic effects of coal and gas outburst disasters are more complex, including coal seam parameters, outburst pore parameters, coal destruction speed, mine pressure, and roadway parameters. The formation and propagation of the protruding shock wave run through the entire protruding process, the action time is longer, and the impact energy is in a fluctuating attenuation state. Therefore, in the future, relevant experimental research and field applications should be strengthened to promote the integration of various research results to form a more mature theory and technical system so that the research results can be applied to the field more accurately and efficiently to ensure mine production safety.

For mine disasters with known locations, the maximum impact strength and impact characteristics of disaster shock waves can be estimated or calculated theoretically through the study of disaster mechanism. Then, according to the propagation and attenuation law of shock wave in the tunnel, the expected maximum shock intensity of the antioutburst door at different locations is obtained. When it is possible to adjust the distance between the disaster location and the antioutburst door, the impact load of the antioutburst door can be reduced by increasing the distance. When the installation location of the antioutburst door cannot be changed, the anti-impact performance of the antioutburst door can be designed according to the expected maximum impact load of the antioutburst door, and the parameters such as the installation quantity and installation strength of the antioutburst door can be determined.

4.2. The Bearing Structure of the Antioutburst Door. The overall structure of the antioutburst door mainly includes door leaf, door wall, and connection accessories. Its overall load-bearing capacity is mainly related to material characteristics, installation dimensions, supporting structure, etc. At present, the structural unit of the antioutburst door in a coal mine is shown in Figure 7. In Figure 7, A' is a fixed hinge support, A and B are the simple supports, q is the impact load, a is the width of the air door AA' contact surface, b is the width of the BC contact surface, and l is the pass width.

When the antioutburst door is not subjected to an impact load, the contact mode with the AA' , BC , and the door wall is surface contact. And when the antioutburst door is subjected to an impact load and deforms, the surface contact with the AA' and BC becomes a point contact with three fulcrums A' , A , and B .

FIGURE 7: The structural unit of the antioutburst door.

The bending deflection of the antioutburst door under impact load is one of the important indexes affecting the stability of the antioutburst door. In order to prevent the antioutburst door from bending deformation and damage, it is necessary to ensure that the bending deflection of the antioutburst door under impact load is less than its limit value. The expression of bending deflection is as follows:

$$f = \frac{ql^4}{EI} \cdot g\left(\frac{a}{l}, \frac{b}{l}\right), \quad (2)$$

where f is the bending deflection, EI is the bending stiffness, q is the impact load, l is the pass width, and $g(a/l, b/l)$ is the expressions about a and b .

It can be seen from formula (2) that the bending deflection value f is mainly related to the a and b values, q , l , and EI . Therefore, in order to improve the carrying capacity of the overall structure of the antioutburst door, improvements need to be made from the following aspects:

4.2.1. Control the Load of the Antioutburst Door (q). The impact load of the antioutburst door (q) is mainly determined by the gas impact energy when the disaster shock wave reaches the antioutburst door. After the installation position of the antioutburst door is determined, if the residual energy of the expected disaster shock wave is still higher than the design strength of the antioutburst door, adding a safety hole (different from the wind window) at the appropriate position of the door leaf can be considered. The size of the safety hole is determined according to the impact load. The opening pressure of the safety hole is preset, and when the pressure of the antioutburst door does not threaten its structural strength, the safety hole is in a sealed state. When the pressure of the antioutburst door is greater than the preset pressure of the safety hole, the safety hole is automatically opened to relieve the pressure, and the safety hole is automatically closed after the force of the air flow on the safety hole is less than the preset pressure.

Under the peak pressure, if the gas pressure is greater than the maximum bearing load of the structure, the safety hole is opened to relieve the pressure. At this time, the air in the tunnel space flows out from the safety hole at first, and after the peak pressure, the safety hole will automatically close. From the data analysis in Figure 3, it can be found that the peak pressure range at the antioutburst door is very small, and in this case, the opening of the safety hole will not cause the prominent disaster airflow to pass through the antioutburst door. The preset opening pressure of the safety hole can be comprehensively determined according to the structural strength of the antioutburst door and the risk assess-

ment results of the outburst coal seam so that the safety hole not only meets the safety protection requirements of the antioutburst door structure but also does not cause disaster gas backflow.

4.2.2. Minimize the Passage Width (l). The deflection of the structural unit (f) is proportional to the 4th power of the passing width (l^4). When other conditions are the same, the greater the passage width (l), the greater the deflection (f). In the case of meeting basic requirements, reducing the passage width (l) as much as possible can also reduce the deformation of the antioutburst door and improve the impact resistance of the antioutburst door. Therefore, when the antioutburst door is designed and installed, the deflection deformation can be reduced by reducing the passage area, and the impact resistance can be improved.

4.2.3. Improve the Bending Stiffness of the Antioutburst Door (EI). Increasing the bending stiffness of the antioutburst door (EI) can also reduce the deflection and deformation of the antioutburst door. One method is to change the material of the main body of the antioutburst door and use a material with strong impact resistance (such as steel plate) as the main material of the antioutburst door. Another method is to improve the structure of the antioutburst door, by appropriately increasing the thickness of the antioutburst door or the surface ribbed plate to increase the bending stiffness. At present, the most commonly used measure in underground mines is the surface ribbed plate. On the premise of meeting the requirements for controlling prominent disasters, the latter method should be preferred.

4.2.4. Reduce the Concentrated Stress of AA' Area. According to field survey data, the contact width between door leaf and door wall of most mine antioutburst door structures (values a and b in Figure 7) is very small. When the antioutburst door is subjected to an impact load, the AA' area (including the fulcrum) will bear a large concentrated stress, which is the most dangerous area for the deformation and damage of the antioutburst door. Taking into account the deflection deformation, material properties, and stress state of the antioutburst door, the width of the contact surface (a) between the antioutburst door and the door wall can be appropriately increased to reduce the supporting reaction force at points A and A' , thereby reducing the concentrated stress of the AB area and improve the overall strength of the antioutburst door.

In addition to the above measures, in order to reduce the concentrated stress in the AA' area, elastic materials can be added on the contact surface between the door leaf and the

FIGURE 8: The overall design idea of the antioutburst door.

door wall. The elastic material can produce elastic deformation to adjust the displacement of the A and B fulcrums, thereby changing the contact state of the A and B fulcrums, so as to reduce the regional concentrated stress.

4.2.5. Enhance the Strength of the Door Leaf and Door Wall Connection Accessories and Increase the Locking Device. For the connection between the door leaf and the door wall, many antioutburst doors on site adopt the method of installing the hinge seat at two points up and down. This connection method will also cause concentrated stress at the two connection points. When the antioutburst door is subjected to a large impact load, it is prone to damage at the connecting hinge seat. This conclusion has been confirmed by experiments [42]. Meanwhile, according to the analysis of the external cause of the antioutburst door failure, a locking device should be installed to prevent the antioutburst door from opening under negative pressure.

4.3. Data Collection and Feedback of the Antioutburst Door. At present, most of the mine antioutburst door are not equipped with pressure data acquisition sensors and corresponding alarm devices. It is impossible to grasp the safety status of the vents in real time and the pressure of the vents during disasters. Therefore, the research on the propagation and destruction of disaster shock waves is mostly theoretical analysis and simulation experimental research, and the field data is extremely lacking so that many theoretical research results cannot be verified and corrected by field data. In view of the current situation, it is recommended that data acquisition devices such as impact pressure sensors, gas concentration sensors, and corresponding alarm devices should be installed at the same time when the antioutburst door is designed and installed in the future. Once an abnormal situ-

ation occurs downhole, the data acquisition device will record and collect antioutburst door status data at any time. On the one hand, the collected data can be used as a reference for emergency response measures when disasters occur underground. On the other hand, on-site feedback data can also be used to revise and improve theoretical results, continuously improve the mine's awareness of disasters and accidents, and help prevent similar disasters from happening again.

5. Overall Design of Antioutburst Door Structure Optimization

Based on the above analysis, the mine antioutburst door can be designed for disaster prevention according to the following procedures and steps, as shown in Figure 8. The optimization of the mine antioutburst door structure is a link of the entire mine safety protection system. In actual application, the optimization of the mine antioutburst door structure needs to be based on the overall construction plan of the mine or mining area and the disaster protection system and comprehensively consider and compare the feasibility and practicability of various aspects such as technology, economy, safety, and other aspects. And the relevant technical details will be selected and adjusted accordingly.

6. Conclusions

In this paper, a large-scale coal and gas outburst dynamic effect simulation experiment device developed independently is used to carry out a coal and gas outburst disaster simulation experiment. Combining numerical analysis and field case analysis, the impact load and deformation characteristics of the antioutburst door under the impact of air flow

during coal and gas outburst are obtained. In addition, the internal and external causes of the damage of the antioutburst door on the coal mine site are analyzed, and the key technologies that need to be solved in the design of the antioutburst capacity of the antioutburst door and the optimization design ideas of the mine antioutburst door structure are proposed. The following conclusions are mainly obtained:

- (1) Under the condition of gas pressure 0.3 MPa, the peak gas pressures at antioutburst doors A and B are 0.0148 MPa and 0.0133 MPa, respectively. After the outburst, the antioutburst door withstands the pressure rise and fall, and the fluctuation is greater. Under the same installation position, the farther the antioutburst door is from the protruding point, the lower the pressure. And in the middle and late stages of the outburst, intermittent negative pressure of the gas at the antioutburst door appeared
- (2) The key technologies for the design of the antioutburst door and its disaster resistance mainly include: ① strengthen theoretical and experimental research on the formation mechanism of outburst shock waves in mines, the interaction mechanism between disaster shock loads and dampers, and the magnitude of disaster expected shock loads; ② optimize the structure of the antioutburst door size, the width of the contact surface between the air door and the door wall, the stress distribution of the air door under impact load, the design of the safety hole, and the locking device; and ③ improve the disaster monitoring and alarm capabilities of the antioutburst door and collect changes in antioutburst door pressure in real time
- (3) The optimization of the mine antioutburst door structure needs to be based on the overall construction plan of the mine or mining area and the disaster protection system and comprehensively consider and compare the feasibility and practicability of various aspects such as technology, economy, safety, and other aspects, and then, the corresponding technical details are selected and adjusted

Data Availability

The data used to support the findings of this study are included within the article.

Disclosure

The funding sponsors had no role in the design of the study; in the collection, analyses, or interpretation of data; in the writing of the manuscript; and in the decision to publish the results.

Conflicts of Interest

The authors declare no conflict of interest.

Authors' Contributions

All the authors listed have approved the manuscript that is enclosed. The manuscript is approved by all authors for publication.

Acknowledgments

This work is financially supported by the National Natural Science Foundation of China (51974358, 51874348, 51774319), the Science and Technology Project of Chongqing Jiulongpo District (2020-02-008-Y), the Natural Science Foundation of Chongqing (cstc2019jcyj-msxm2231), the Chongqing Science Fund for Distinguished Young Scholars (cstc2019jcyjX0019), and the Science and Technology Innovation and Entrepreneurship Fund of China Coal Technology Engineering Group (2019-TD-QN040) which are gratefully acknowledged.

References

- [1] B. Z. Xu and X. J. Li, "Research on damage failure of outburst prevention air door under outburst shock wave," *Journal of Safety Science and Technology*, vol. 16, no. 8, pp. 113–118, 2020.
- [2] D. X. Xing, "The layout and management of reversed outburst-prevention air door in coal and gas outburst mine," *Mining Safety & Environmental Protection*, vol. 39, no. 2, pp. 77–79, 2012.
- [3] D. T. Bao, X. Z. Zhou, Z. B. Wang, and B. Wang, "The appropriate allocation and optimization choice of air door," *Coal Mine Safety*, vol. 40, no. 9, pp. 42–44, 2009.
- [4] C. L. Zhang, E. Y. Wang, J. Xu, and S. J. Peng, "A new method for coal and gas outburst prediction and prevention based on the fragmentation of ejected coal," *Fuel*, vol. 287, article 119493, 2021.
- [5] J. Y. Lin, Y. J. Zuo, K. Zhang et al., "Coal and gas outburst affected by law of small fault instability during working face advance," *Geofluids*, vol. 2020, Article ID 8880091, 12 pages, 2020.
- [6] A. Fisne and O. Esen, "Coal and gas outburst hazard in Zonguldak Coal Basin of Turkey, and association with geological parameters," *Natural Hazards*, vol. 74, no. 3, pp. 1363–1390, 2014.
- [7] S. X. Zhou, P. Li, and M. G. Qin, "Research and application of permanent outburstproof door for encased structures," *Safety in Coal Mines*, vol. 50, no. 4, pp. 145–148, 2019.
- [8] D. J. Ma, Z. H. Li, Y. L. Yang, Y. B. Tang, and M. M. Jiang, "Research on coal and gas outburst accident of Xinxing coal mine based on shock wave theory," *Journal of Safety Science and Technology*, vol. 8, no. 8, pp. 69–73, 2012.
- [9] T. Dong, H. Q. Wang, W. Tao, S. Q. Chen, and T. Wu, "Destruction to ventilation system from mine explosion and its hazards," *Journal of Hunan University of Science & Technology (Natural Science)*, vol. 27, no. 3, pp. 5–9, 2012.
- [10] F. M. Zhu, L. Yu, and Y. Yang, "Application of intelligent explosion-proof emergency air door system in outburst coal," *Safety in Coal Mines*, vol. 47, no. 2, pp. 102–105, 2016.
- [11] Y. M. Shu, J. H. Sun, C. R. Wei, and X. W. Zhang, "Study of automatic air door of porous leaking pressure barrier

- explosion of mine,” *Coal Mine Machinery*, vol. 32, no. 3, pp. 132–134, 2011.
- [12] J. H. Sun, J. L. Zhao, and C. R. Wei, “The porous-leak-pressure barrier explosion of the automatic air-door that is used in the mine,” *China Mining Magazine*, vol. 20, no. 3, pp. 105–108, 2011.
 - [13] D. J. Miao and D. H. Chang, “Deformation characteristics and new pressure-resistance constructing technology of air door,” *Journal of Shandong University of Science and Technology (Natural Science)*, vol. 35, no. 1, pp. 38–43, 2016.
 - [14] R. J. Tian, “Force analysis and strength design of mine anti-outburst door,” *Safety in Coal Mines*, vol. 2, pp. 4–10, 1991.
 - [15] W. M. Cheng, G. Wang, G. Zhou, and L. J. Chen, “Numerical simulation of outburst prevention air door destruction by coal and gas outbursts,” *Journal of Chongqing University (Natural Science)*, vol. 32, no. 3, pp. 314–318, 2009.
 - [16] F. T. Miao, “Impact deformation characteristics and structural optimization of mine air door,” *Mining Safety and Environmental Protection*, vol. 40, no. 2, pp. 28–30, 2013.
 - [17] S. H. Dai, Z. T. Wang, and Y. Xu, “Static and dynamic analysis of safety of steel outburst prevention air door,” *China Safety Science Journal*, vol. 27, no. 12, pp. 74–79, 2017.
 - [18] L. X. Qian, *Optimization Design of Engineering Structure*, Science Press, Beijing, 2011.
 - [19] X. B. Meng and H. Yang, “Design of automatic blockade and anti-headwind device for outburst reverse air door in coal and gas outburst mine,” *China Energy and Environmental Protection*, vol. 41, no. 7, pp. 155–157, 2019.
 - [20] S. Z. Yang and R. L. Zhang, “Research on injuries due to shock wave and gas flow from coal and gas outburst,” *China Safety Science Journal*, vol. 22, no. 11, pp. 62–66, 2012.
 - [21] L. C. Dai, Y. B. Liu, J. Cao et al., “A Study on the energy condition and quantitative analysis of the occurrence of a coal and gas outburst,” *Shock and Vibration*, vol. 2019, Article ID 8651353, 13 pages, 2019.
 - [22] T. R. Ma, H. Xu, C. B. Guo, X. H. Fu, W. Q. Liu, and R. Yang, “A discrete fracture modeling approach for analysis of coalbed methane and water flow in a fractured coal reservoir,” *Geofluids*, vol. 2020, Article ID 8845348, 15 pages, 2020.
 - [23] J. F. Zhang, K. Wang, and C. P. Wei, “Formation and propagation of shock waves during coal and gas outbursts,” *Journal of Mining & Safety Engineering*, vol. 27, no. 1, pp. 67–71, 2010.
 - [24] L. Chen, J. Y. Qiao, and Y. S. Ding, “A model of one-dimensional coal and gas outburst wave,” *Scientia Sinica (Physica, Mechanica & Astronomica)*, vol. 44, no. 1, pp. 68–78, 2014.
 - [25] J. Xu, D. Liu, S. J. Peng, W. J. Zhou, and M. J. Cheng, “Coal and gas outburst analogous test under the different diameter of exposed coal seam surface,” *Journal of China Coal Society*, vol. 38, no. 1, pp. 9–14, 2013.
 - [26] J. P. Tang, Y. S. Pan, and S. L. Yang, “Experimental study of coal and gas outburst under tridimensional stresses,” *Chinese Journal of Rock Mechanics and Engineering*, vol. 32, no. 5, pp. 960–965, 2013.
 - [27] A. T. Zhou, K. Wang, L. Wang, F. Du, and Z. L. Li, “Numerical simulation for propagation characteristics of shock wave and gas flow induced by outburst intensity,” *International Journal of Mining Science and Technology*, vol. 25, no. 1, pp. 107–112, 2015.
 - [28] A. T. Zhou, L. P. Fan, K. Wang, and D. Elsworth, “Multiscale modeling of shock wave propagation induced by coal and gas outbursts,” *Process Safety and Environmental Protection*, vol. 125, pp. 164–171, 2019.
 - [29] K. Gao, Z. G. Liu, and J. Liu, “Effect of gas on coal and gas outburst induced by rock cross-cut tectonic soft coal uncovering,” *China Safety Science Journal*, vol. 25, no. 3, pp. 102–106, 2015.
 - [30] C. W. Li, W. Yang, S. Y. Wei, T. Li, and L. L. Chi, “Experimental research of influence scope of disaster gas after coal and gas outburst,” *Journal of China Coal Society*, vol. 39, no. 3, pp. 478–485, 2014.
 - [31] C. L. Zhang, J. Xu, G. Z. Yin, S. J. Peng, Q. X. Li, and Y. X. Chen, “A novel large-scale multifunctional apparatus to study the disaster dynamics and gas flow mechanism in coal mines,” *Rock Mechanics and Rock Engineering*, vol. 52, no. 8, pp. 2889–2898, 2019.
 - [32] X. G. Kong, E. Y. Wang, S. G. Li, H. F. Lin, Z. B. Zhang, and Y. Q. Ju, “Dynamic mechanical characteristics and fracture mechanism of gas-bearing coal based on SHPB experiments,” *Theoretical and Applied Fracture Mechanics*, vol. 105, article 102395, 2020.
 - [33] A. T. Zhou, M. Zhang, K. Wang, X. Zhang, and T. F. Feng, “Quantitative study on gas dynamic characteristics of two-phase gas-solid flow in coal and gas outbursts,” *Process Safety and Environmental Protection*, vol. 139, pp. 251–261, 2020.
 - [34] J. Cao, H. T. Sun, L. C. Dai, D. L. Sun, B. Wang, and F. T. Miao, “Simulation research on dynamic effect of coal and gas outburst,” *Journal of China University of Mining & Technology*, vol. 47, no. 1, pp. 113–120+154, 2018.
 - [35] D. L. Sun, J. Cao, F. T. Miao et al., “Migration law of outburst coal and gas in roadway,” *Journal of China Coal Society*, vol. 43, no. 10, pp. 2773–2779, 2018.
 - [36] J. Cao, L. C. Dai, H. T. Sun et al., “Experimental study of the impact of gas adsorption on coal and gas outburst dynamic effects,” *Process Safety and Environmental Protection*, vol. 128, pp. 158–166, 2019.
 - [37] S. T. Zhang, *Research on Similarity of Material and System for Coal and Gas Outburst Simulation Test*, Anhui University of Science and Technology, Huainan, 2015.
 - [38] L. C. Dai, S. T. Zhang, and J. Cao, “Research on geometric parameters of coal and gas outburst similar model,” *Coal Mine Safety*, vol. 49, no. 8, pp. 194–197, 2018.
 - [39] Q. T. Hu and G. C. Wen, *The Mechanical Mechanism of Coal and Gas Outburst*, Science Press, Beijing, 2013.
 - [40] R. S. Zhang, Z. H. Zhang, and Z. M. Gu, *Architectural Structure Vibration Computation and Anti-Vibration Measures*, Metallurgical Industry Press, Beijing, 2010.
 - [41] Y. Z. Guo and Z. H. Zhou, *Theoretical Mechanics*, Tsinghua University Press, Beijing, 2014.
 - [42] L. Liao and W. S. Su, “Tests of FM reversed outburst-prevention air door,” *Coal Engineer*, vol. 25, pp. 26–28, 1998.