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Cite as: AIP Advances **11**, 075223 (2021); https://doi.org/10.1063/5.0052080
Submitted: 29 March 2021 • Accepted: 09 July 2021 • Published Online: 23 July 2021

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ABSTRACT

This study was conducted to analyze the influence of outburst power from coal and gas on mine ventilation systems in order to avoid damage from secondary disasters to mine ventilation systems. Through the outburst dynamic experiment of a simple ventilation network system, the unsteady movement characteristics of mine air flow under the combined action of gas outburst source flow and fan ventilation are studied. In this study, the "11.8" coal and gas outburst accident that occurred in the Qunli Coal Mine was simulated numerically. The TF1M simulation program was used to analyze the entire process of the diffuse flow of the countercurrent and outburst gas in the mine ventilation system as well as the dynamic change process of the natural wind pressure in each stage. The results indicate that the power of the outburst source causes the ventilation system to run against the current, the gas in the air intake system of the mine exceeds the limit, and the airflow disturbance of the mine ventilation system is influenced by natural gas pressure and fan pressure. The air pressure of the fan cannot change the rate of air flow but can reduce the time of air flow disorder and promote the gas discharge in the ventilation system. In a word, the research achievements do have important theoretical and practical significance for disaster prevention and aid in outburst mine as well as effectively preventing the occurrence of secondary disasters.

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I. INTRODUCTION

Coal and gas outburst is one of the most serious disasters in coal mine production. The coal powder and high-concentration gas produced by the outburst can cause casualties and property losses, as well as damage the mine ventilation system.[1–5] Considerable research has been conducted on coal and gas outburst, including the coal and gas outburst mechanism,[6–10] outburst simulation experiments,[11–16] and risk identification and early warning of typical dynamic disasters in coal mines,[17–20] and significant progress has been made in this direction. In recent years, many coal and gas outburst accidents have occurred in China. For example, in 2011, 43 people died in the "11.10" coal and gas outburst accident in Sizhuang Coal Mine, Shizong County, Qujing City; in 2009, a gas explosion accident caused by the "11.21" coal and gas outburst in Xinxing Coal Mine of Hegang branch of China Longmei Group Co. Ltd. caused 108 deaths;[21] and in 2004, 148 people died in the gas explosion accident caused by the "10.20" coal mine and gas outburst in Daping Coal Mine of Zhengzhou Coal Group. This makes people realize the importance and urgency of research on the "secondary disaster" associated with coal and gas outbursts where the range and degree of harm are more serious.[22–24] Therefore, it is necessary to study the processes of outburst gas flow and a coal-gas two-phase flow in mine network systems.[25–30] Yang studied the diffusion and migration laws of outburst gas in a ventilation system and simulated the ventilation network under an unsteady state.[25] The author combined the two to establish a calculation model for the wind network and gas distribution under the unsteady state and on this basis developed a set of online identification and emergency decision-making software to simulate coal and gas outbursts in mines. Li *et al.*[26,27] developed a simulation program called TF1M for a mine ventilation system based on the active wind network theory and numerically simulated the entire process of a coal and gas outburst. Sun used a self-developed experimental device for simulating the coal and gas outburst to carry out the experiment on a two-phase gas–solid flow.[28] Zhou studied the influence of the four factors on the

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gas-dynamic characteristics of a two-phase flow.[29] Sun established the mathematical model of the movement of the outburst coal in the roadway by combining the suspension motion mechanism and the conservation of energy.[30]

However, because of the complexity of the behavior of the ventilation system at the timing of the coal and gas outburst disaster, this paper mainly studied the influence of the gas on the ventilation flow in the roadway after the outburst. The interaction between the coal powder and the gas was not considered in the research process. At present, there are few studies on the change of the state parameters of the disaster gas in the process of the coal and gas outburst, and the study on the ventilation system under the combined action of the source power of the disaster gas outburst and the ventilation power is relatively deficient. Here, we study the dynamics of gas outburst and the process of gas migration, the influence of gas flow on mine ventilation systems, and the law of propagation of disaster gases during the disaster period to realize a dynamic identification and judgment of the scope and danger degree of the accident within a short period after the occurrence of a local accident and to take rapid emergency measures before the occurrence of a secondary disaster to avoid the secondary disasters caused by greater loss of property and human casualties.

II. THEORY OF GAS CONVECTION AND DIFFUSION IN MINE

The diffusion of harmful gases, including the propagation of concentrated harmful gases or the source section of a multi-section compound structure, in a mine tunnel can be described by the convection–diffusion equation and solved using a numerical method.[31,32] The convection–diffusion equation describes the one-dimensional spatial distribution of gas concentration with time, and the finite-difference method is used to address the problem of gas migration in the tunnel.[33–35] For the convenience of calculation, the convection–diffusion equation can be simplified as a one-dimensional equation to describe the unsteady process of gas migration and diffusion in the tunnel,[36]

$$\frac{\partial C}{\partial \tau} + u_x \frac{\partial C}{\partial x} = E_x \frac{\partial^2 C}{\partial x^2} + W, \tag{1}$$

where C is the mass concentration of the gas, kg/m^3; W is the quantity of gas generated by the wall resolution in the unit volume space per unit time, kg/(m^3 s); τ is the time, s; u_x is the longitudinal average velocity of the roadway, m/s; and E_x is the longitudinal mechanical dispersion coefficient of the harmful gas in the roadway, m^2/s.

III. EXPERIMENTAL STUDY OF UNSTEADY DYNAMIC FLOW OF GAS OUTBURST PIPELINE NETWORK

A dynamic experiment of the gas outburst pipeline network is conducted to study the influence of the gas outburst dynamic on the mine airflow.[27] An experimental schematic of the gas outburst power pipeline network is shown in Fig. 1. The inner diameter of the pipeline network is 60 mm, the total length is 48 m, the fan provides out-drawn ventilation, and the prominent source is replaced by a high-power aeromodeling engine, which can produce 1.5 kg of thrust. This thrust acts as the "super power" for the experimental pipeline network. A complete experimental recording system of

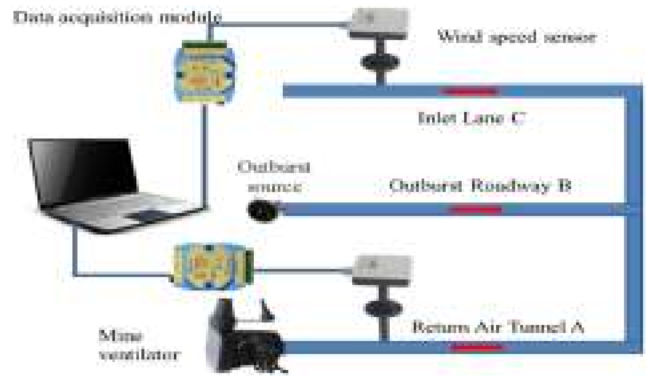

FIG. 1. Schematic of the experiment.

the air flow measurement, data acquisition, and storage comprises a wind speed transmitter, a pressure difference transmitter, a data acquisition module, and a host computer. The three pipelines represent the mine air-inlet tunnel, air return tunnel, and outburst accident tunnel, respectively. The key point of this experiment is the unsteady process of the gas outburst power acting on the ventilation system.

This paper presents the experimental results of the engine with different protrusion intensities at Shift 1 and Shift 2. The mathematical model of the experiment is established using a computer program, and the process of the experiment is numerically simulated. When the protruding source fan is in Gear 1 (i.e., when the protruding power is small), the air flow in the air-inlet lane C stops, and

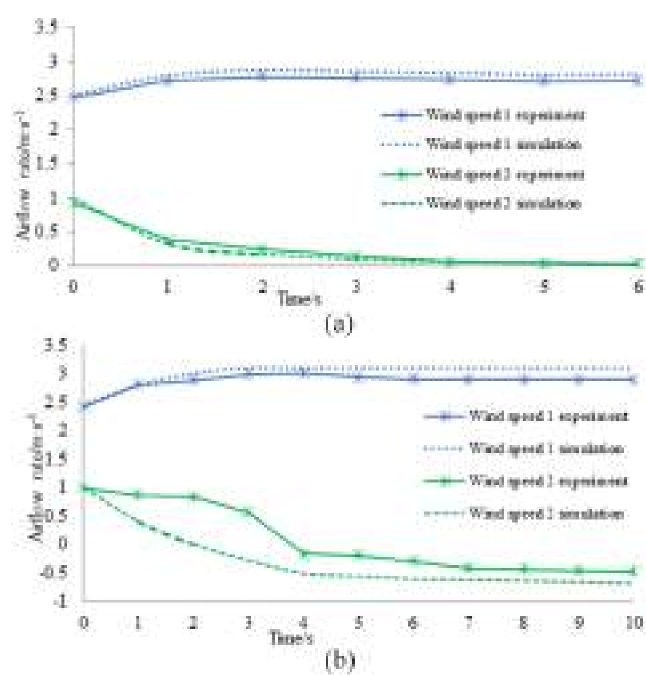

FIG. 2. Variation in air flow in the pipeline network under stress. (a) Wind flow stagnation and (b) airflow reversal.

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when the protruding source fan is in Gear 2 (i.e., when the protruding power is large), the air flow reverses because of the protruding strength. In both cases, the air volume of the Return Air Lane A increases first and then decreases due to the inertia of air flow. As shown in Figs. 2(a) and 2(b), the numerical simulation results agree with the experimental results, where the outburst force affects the ventilation system considerably and makes the air flow in the inlet shaft decrease or counter-flow and increase the air flow in the return shaft.

IV. NUMERICAL SIMULATION ANALYSIS OF THE INFLUENCE OF GAS OUTBURST POWER ON THE STABILITY OF MINE VENTILATION SYSTEM

A. General situation of "11.8" coal and gas outburst accident in Qunli Coal Mine

Nayong, Nijiazhai Qunli Coal Mine, is located in southwest of Nayong County, Guizhou Province, and an administrative territorial entity under the jurisdiction of Yangchang town, Nayong County. At 13:43 on November 8, 2007, a serious accident of coal (rock) and gas outburst occurred in the mine at the temporary water sump heading the mine face. The depth of the outburst point was 331 m, and 37 283 M3 gas was emitted in the coal (rock) and gas outburst accident, resulting in 35 deaths, 2 serious injuries, 5 minor injuries, and 12.61×10^6 yuan of direct economic losses. After the accident, the gas countercurrent phenomenon occurred underground and the gas wave spread to the whole mine; according to the data obtained from the monitoring system, from 13:43 onward, the underground gas concentration sensors began to break or exceed the limit one after another, the gas concentration in the total return air lane of the mine after 105 h to November 12 at 22:45 before reducing to the level before the accident.

B. Initial condition setting for simulation of mine ventilation system disaster process during gas outburst

The outburst countercurrent is caused by the propagation of a compressible gas at high pressure from the outburst source, which is a very complex problem and belongs to the category of aerodynamics. To analyze this problem, the solution must be simplified and described in sections on the premise that the impact of the outburst on the mine ventilation system in a large-scale mine complex network system is the research objective, the compressibility of gas from outburst sources in small-scale local outburst sites is ignored, and the air is incompressible. The flow rate of the gas outburst source in coal mine accidents can be approximately estimated using the outburst time and observation record of gas concentration in the mine. It is difficult to directly measure the pressure and change in outburst force in the actual outburst source in the coal mine; thus, the gas flow from the outburst source is adopted as the outburst source.[37,38]

In this paper, the ventilation system in the Qunli Coal Mine was constructed using the TF1M simulation program for the mine ventilation system developed by the Matlab software. The TF1M program has the advantages of excellent visual display and better operability. The simulation of the 3D mine ventilation system and the description of the ventilation system in the disaster period were realized. This simulation program could be used to calculate and simulate the time of the disastrous accident in the global mine tunnel network. Here, the active ventilation network theory, the mine ventilation network solution theory, the external gas convection and diffusion theory, and other related mine expertise and scientific solution methods were combined.

According to the actual production experience, the time of coal and gas outburst is relatively short and the gas emission quantity is huge; however, there is partial air in the tunnel and the highest gas volume fraction is set to 99%. According to the above theory and the model of nonuniform outburst source, the model of coal and gas outburst is simulated, the peak gas emission amount of the gas outburst source is set to 334.264 m^3, the total simulated gas outburst amount is set to 37 283 m^3, the gas emission intensity is set to 8.17×10^{-4} m^3/s, the external air leakage is set to 2.18 m^3/s, the residual source intensity after the outburst is 0.2 m^3/s, and the total simulated time is 60 min.

C. Analysis of simulation results

The dynamic gas migration process in the mine ventilation system after the coal and gas outburst in Qunli Coal Mine is simulated using TF1M, and the influence of the outburst gas on the mine ventilation system and the change in its air flow after the outburst are analyzed.[26,27,37] A diagram of the mine ventilation system in Qunli Coal Mine is shown in Fig. 3.

Under the strong driving force of the outburst source, the gas diffuses and flows to the whole mine ventilation system from the center of the outburst site, filling the main roadway with gas, and the reverse flow occurs along the main inlet roadway, as well as in the mine air-inlet route and air-inlet shaft. The gas distribution in the mine ventilation system is shown in Fig. 4. Under the action of outburst power, the gas diffuses to the last 2122 return wind inclined lane of the outburst accident. When the coal and gas outburst accident is simulated at the 35th second, the gas outburst emission is the largest, the gas diffuses rapidly in the local loop near the outburst site, and the gas concentration in the local loop is higher. When the simulation reaches the 100th second, the main adit is filled with

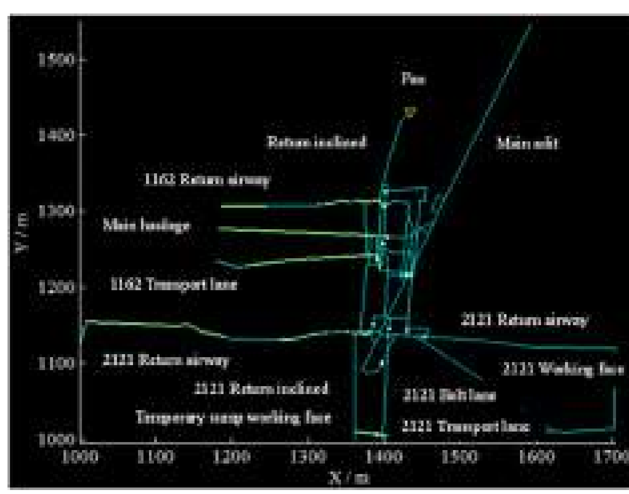

FIG. 3. Mine ventilation system of Qunli Coal Mine.

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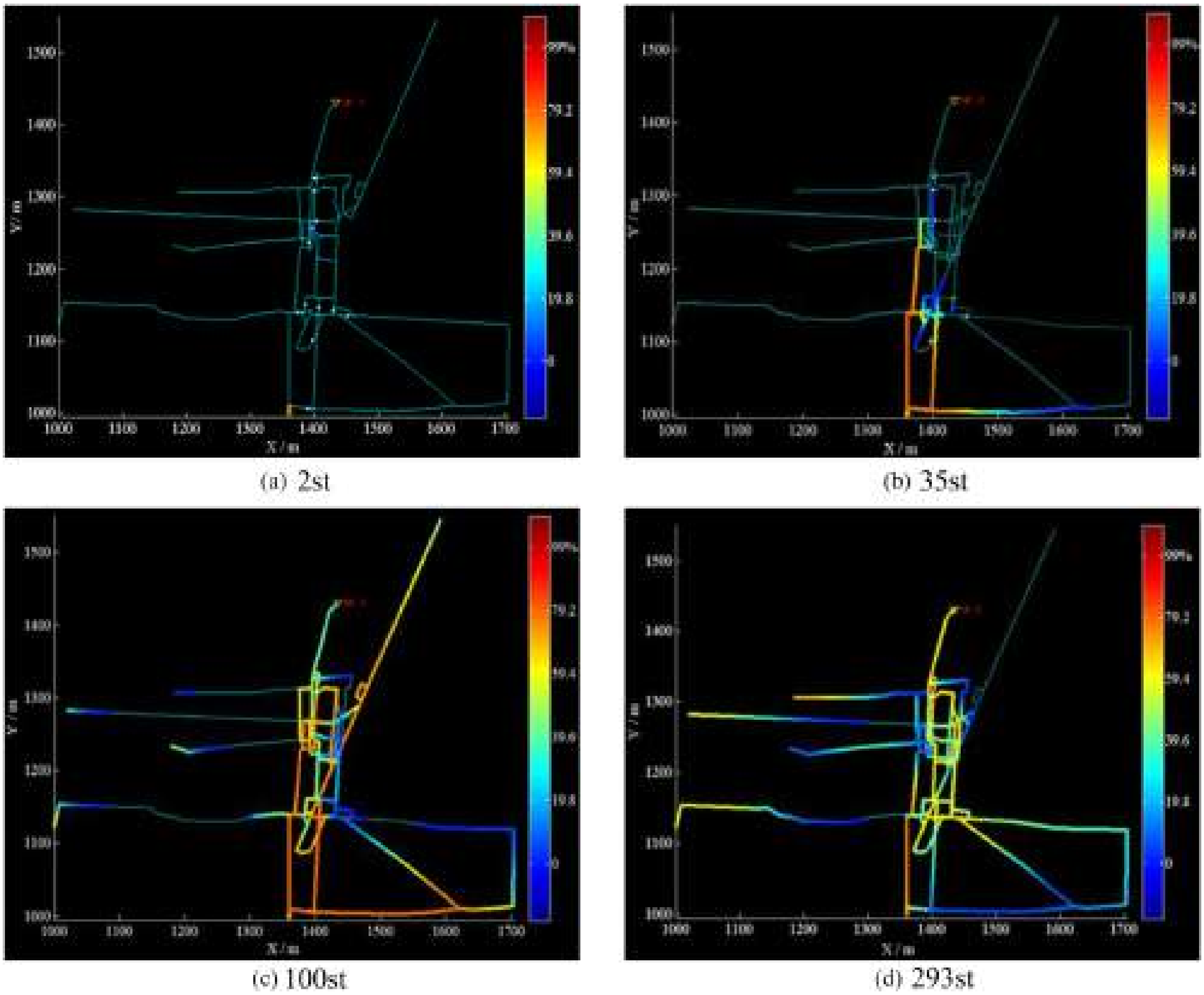

FIG. 4. Distribution map of the gas concentration in the ventilation system during the catastrophic period.

the outburst gas countercurrent. The strong power of the gas outburst causes the fan to fail, the explosion-proof door of the main adit opens, and the gas flows against the inlet shaft and rushes out of the ground. The natural wind pressure of the positive gas is formed in this process, and the natural wind pressure of the gas is helpful for the air flow of the mine ventilation system. Under the combined action of gas natural wind pressure and gas outburst power, the area affected by the gas gradually, as well as the air flow rate in the mine air-inlet tunnel, increases. When the process of coal and gas outburst ends and the outburst power disappears, the emission intensity of the gas outburst source can be neglected. At the 293rd second, the gas diffusion fills the 1162 Return Air Lane and 2122 Return Air Lane. The natural wind pressure of the gas causes the gas volume fraction to decrease gradually, the direction of air flow remains the same as that of the normal ventilation, and the local air flow reverses in the mine ventilation system. The mine is almost filled with gas; oxygen content drops; and harmful gases such as methane and carbon dioxide almost fill the entire space. The gas diffuses in the mine tunnel, causes an explosion, causes the underground personnel to be poisoned to death, and affects the entire ventilation network security. This also explains why the "11.8" accident in Qunli Coal Mine killed 35 workers, which were distributed in the most prominent location of the 2121 backdraft inclined lane and 2121 face constitute a local loop.

After the simulation, the fan is set open, the blast door is closed, and the operation of the mine ventilation system returns to normal. Under the action of fan air pressure, the gas is introduced into the return air tunnel through the shortest route and the gas in the tunnel

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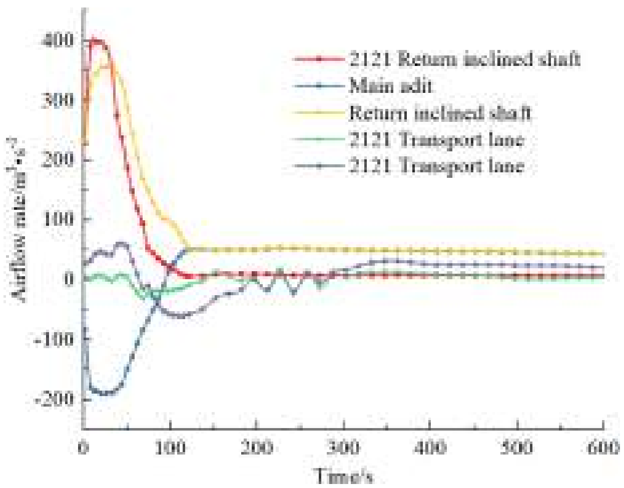

FIG. 5. Variation curve of the air flow rate with time in the ventilation system during the catastrophic period.

is discharged outside the mine ventilation system. Due to the ventilation system tunnel height difference and gas accumulation, the gas natural wind pressure still exists. Irrespective of whether a dynamic phenomenon occurs before the gas natural wind pressure, the gas natural wind pressure influences the air flow in the roadway, generating an air flow turbulence in the roadway. Gas makes the air flow disordered, which will carry on the flow with the gas, causing a complex change in the gas distribution. The redistributed gas may have a new effect on the airflow and further disturb the airflow.

As shown in Fig. 5, the time-dependent air flow curves of the 2121 belt roadway, 2121 transport roadway, 2121 return air inclined shaft, main adit, and return air inclined shaft are obtained by simulating the disaster process of the coal and gas outburst. After the outburst, the power of gas outburst reverses the gas flow in the main adit and creates negative air volume; the intensity of the gas outburst source first increases and then decreases, and the air quantity of the main adit first decreases and then increases to the maximum value of the countercurrent. With a decrease in the intensity of the gas outburst source, when the fan resumes working, the gas natural air pressure and fan pressure are combined to gradually stabilize the air flow. Under the combined action of natural gas pressure and fan pressure, the air flow in the return air tunnel increases gradually, forming over-flow, and that in the return air inclined shaft increases. With the attenuation of the outburst power, after increasing to the maximum value, the fan stops working and the air flow in the return air tunnel is attenuated under the effect of natural gas pressure, whereas the main adit and return air tunnel have the same air flow. The 2121 return air inclined shaft is the return air tunnel closest to the outburst point. The air flow of this tunnel changes earlier than the return air inclined shaft and the change is the same as that in the return air inclined shaft. Wind turbulence occurs in the 2121 Belt Roadway and 2121 transport roadway, and the direction and volume of wind flow change. The negative value of air flow represents the countercurrent, which occurs in the 2121 belt roadway, 2121 haulage roadway, and main adit.

During the simulation process, four gas monitoring points are set up to record the change in the gas volume fraction during the disaster. Gas Monitoring Point 1 is located near the return air outlet with coordinates (1422, 1419, 1635), Gas Monitoring Point 2 is located near the air-inlet substation with coordinates (1471, 1297, 1563), Gas Monitoring Point 3 is located under Gas Monitoring Point 1 with coordinates (1404, 1358, 1625), and Gas Monitoring Point 4 is located on the 2121 face at coordinates (1703, 1014, 1493). The variation curves of the gas concentration at the four monitoring points in the disaster process of coal and gas outburst are shown in Fig. 6.

After the coal and gas outburst, considerable gush gas diffuses along the air flow to the ventilation system of the entire mine and is discharged into the total return air tunnel. If the gas concentration curves of the Monitoring Points 3 and 1 are located in the same return air tunnel, the gas concentration increases first and then decreases. The time required to reach specific locations is determined by the speed of wind in the return air tunnel after the outburst and the distance between each specific location and the outburst location. As shown in Fig. 6, in the process of coal and gas outburst, at the same time, the gas concentration of Monitoring Point 1 in the same tunnel is lower than that of Monitoring Point 3. The gas diffuses first to Gas Monitoring Point 3 and then to Gas Monitoring Point 1. With the end of the outburst, the fan resumes working,

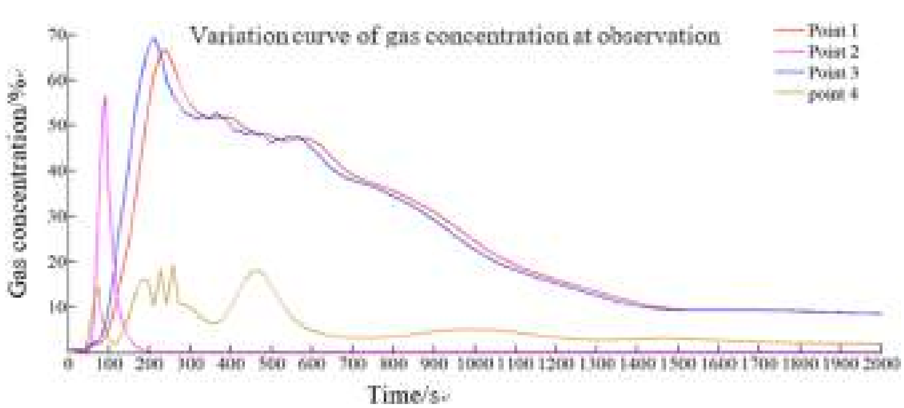

FIG. 6. Variation curves of gas concentrations in the disaster process.

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the airflow in the roadway is affected by the natural gas pressure and fan pressure, and the gas concentration gradually decreases. Finally, Gas Monitoring Points 1 and 3 have the same concentration. Gas Monitoring Point 2 is located in the main adit, where the gas flows to the main adit against the fresh air flow, resulting in a "countercurrent." With the fresh air entering the main adit, the gas concentration decreases; thus, the gas increases first, then decreases, and finally approaches zero. Gas Monitoring Point 4 is located in the 2121 working face. In the process of coal and gas outburst, the air flow in the local circuit is disordered. The air flow in the roadway is affected by the natural gas pressure, and the effect of natural gas pressure is relatively complex. During the whole process, the gas concentration of the observation point changes repeatedly, showing a downward trend, and there is still gas accumulation at the end of the simulation.

D. Influence of fan pressure on airflow reversal caused by natural gas pressure

After the ventilation is resumed, the gas power disappears and the gas begins to flow back along with the fan pressure, entering the stage of return flow. For the complex large-scale mine, the natural air pressure of the gas produced by the outburst accident was lower than that of the ventilator. With the flow of gas, its volume fraction changes continuously. However, the natural wind pressure of the gas generated by the gas left in the roadway continuously interferes with, and affects, the work of the main fans, forming wind pressure confrontation and hindering ventilation. The phenomenon of air flow disorder still appears in the local circuits. To analyze the influence of different fan pressures on the mine ventilation system, the fan pressure can be changed by changing the fan rotation when other parameters are consistent. Table I shows the ventilation system and the basic parameters of the fan when the fan pressure is changed for numerical simulation, including fan revolution, fan pressure, coal and gas outburst, initial air volume, natural air pressure, and minimum air volume. The influence of different fan pressures on the mine ventilation system is investigated through many simulation calculations. The time-dependent curve of the main adit's wind speed under different fan pressures is shown in Fig. 7. At different speeds, there is little difference in the wind speed curve of the main flat tunnel. The wind speed decreases first and then gradually returns to normal ventilation after reducing to the minimum air volume. The main adit reverses the air flow, and the minimum air flow is

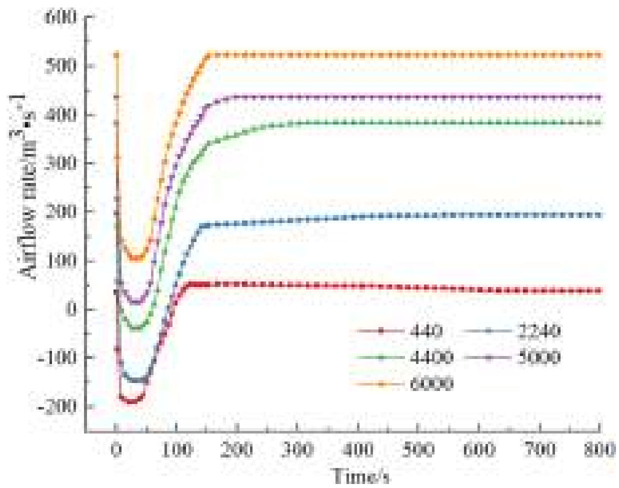

FIG. 7. Variation curve of wind speed with time in the main adit under different fan pressures.

negative at revolutions of 440, 2240, and 4400 rpm. It is increasingly difficult to reverse the inlet air flow with an increase in the fan speed and fan pressure. When the fan pressure reaches a certain degree, the reverse phenomenon of the main adit air flow no longer occurs. At the same time, the increase in fan pressure increases the minimum air volume of the main adit. The wind pressure of the fan has very little effect on the rate of air flow reduction but affects the recovery of the air flow in the roadway. The higher the wind pressure of the fan, the shorter is the duration of the air flow turbulence and the shorter is the time required for the roadway to return to normal ventilation. This shows that the change in fan pressure influences the duration of air turbulence. The higher the fan pressure, the higher is the initial air volume of each roadway in the mine ventilation system. As the increase in fan pressure increases the initial air volume of each roadway, the increase in fan pressure prevents the reversal of air flow. Table I shows that when normal ventilation is resumed, the air volume of the main adit is larger than the initial air volume because the natural air pressure of the gas still exists in the mine ventilation system.

In summary, the increase in fan pressure has the most obvious effect on the air turbulence caused by gas air pressure, according to

TABLE I. Basic parameters under different fan revolutions.

Nos.	1	2	3	4	5
Fan revolution (rpm)	440	2240	4400	5 000	6 000
Fan pressure (Pa)	64.68	2270.79	8705.79	11 113.70	15 603.60
Volume of coal and gas outburst (m^3)			37 283		
Time for normal ventilation to resume (s)	1052	602	302	212	167
Initial air volume (m^3/s)	39.27	197.92	387.72	440.22	527.35
Natural wind pressure (Pa)	3.12	16.88	61.44	78.26	109.74
Return air volume to normal ventilation (m^3/s)	36.99	194.01	383.99	436.63	523.80
Minimum air volume (m^3/s)	−190.79	−146.41	−38.53	15.63	105.4

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which the time required by the air flow to return to normal ventilation is evidently reduced. With an increase in the fan pressure, the initial air velocity of each roadway in the mine increases. Although the change in air velocity caused by natural gas air pressure is not obvious, the initial air velocity is larger and the risk of airflow stopping or reversing in mine shafts is reduced. The faster the gas is discharged, the lower is the risk of gas disaster and the lower is the time of gas natural wind pressure acting on the mine air flow, in favor of airflow and gas concentration to restore to the normal level as soon as possible. Therefore, in the design of mine ventilation, the capacity of the mine ventilator should be improved as far as possible within the economic reasonable range and the allowance should be considered when selecting the main ventilator to deal with the ventilation during the disaster period.

V. CONCLUSIONS

(1) After the coal and gas outburst, the mine ventilation system is affected by the outburst source power and the natural gas pressure. The natural wind pressure of the gas plays a leading role in the late period of the outburst and the natural wind pressure of the gas makes the gas diffuse with the wind flow in the mine roadway. The influence time is long and the disaster area is enlarged.

(2) In this paper, the TF1M program was used to simulate the diffusion of the gas after the outburst in the whole mine. It was reasonable to analyze the direct dynamic influence of the gas outburst on the ventilation system and the influence of the natural wind pressure of the gas.

(3) With an increase in fan pressure, the recovery time of the airflow in the roadway is shortened, the ability of gas drainage from the mine ventilation system is enhanced, and the possibility of secondary disasters, such as gas explosion in the mine, is reduced. When the wind pressure of the fan is large, it can prevent the air flow reversal; the increase in the fan pressure can increase the initial wind speed of the roadway and reduce the time required by the air flow to return to normal; however, an increase in the fan pressure cannot significantly change the change rate of the air flow speed.

ACKNOWLEDGMENTS

This research was supported by the National Natural Science Foundation of China (Grant No. 51774170).

DATA AVAILABILITY

The data that support the findings of this study are available from the corresponding author upon reasonable request.

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