Numerical analysis of natural gas pressure during coal and gas outbursts

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Abstract
Any disturbance in the ventilation system of a mine during a coal and gas outburst can lead to secondary disasters. This is because, on the one hand, the expansion power of the outburst source makes the airflow in the ventilation system countercurrent, causing the gas in this system to exceed the allowable limit. On the other hand, the airflow density changes because of the outburst and the consequent airflow mixing in the mine roadway, thereby changing the natural wind pressure. From this, the concept of natural gas wind pressure is proposed, and a calculation method for this pressure in a 3D model mine ventilation system is derived. For the “11.10” major coal and gas outburst that occurred in Shizhuang Coal Mine in Qujing, Yunnan Province, the entire process of the countercurrent and gas dispersion flow in the main and auxiliary shafts is analyzed using the TF1M 3D simulation program, including the dynamic change in the natural wind pressure in the mine in each stage. The simulation shows that during the gas outburst period, the natural gas pressure of the countercurrent circuit is greater than that of the main fan. Between 140 s and 225 s following the outburst, the natural wind pressure once overcomes the fan pressure and reverses the airflow in the 1824 transport roadway, and the gas is withdrawn from the 1727 service point. Evidently, the natural pressure of the gas produced by the outburst affects the mine ventilation system. In the event of a coal and gas outburst in a private village coal mine, if the natural gas wind pressure can be reasonably utilized and the main fan stopped or the entire mine reversed in time, casualties may be minimized. Scholars studying coal and gas outburst mines should pay attention to mine airflow disorder due to the varying natural gas wind pressure when an outburst occurs and perform simulation drills of the outburst beforehand. Thus, a scientific emergency management plan for mine disaster prevention and reduction can be formulated.

KEYWORDS
3D ventilation network with sources, airflow disorder, coal and gas outburst, gas natural ventilation pressure
1 | INTRODUCTION

Coal and gas outbursts that occur in coal mines are extremely complex dynamic disasters, threatening the safety of coal production. Scholars and engineers from various countries have studied the mechanism of such outbursts from the aspects of outburst conditions, outburst source dynamics, and energy impact. The dynamic disaster mechanism has been studied by conducting experimental physical simulation tests, and simulation test devices for outbursts with different characteristics have been developed. Outburst simulation experiments have also been carried out using 3D simulation test platforms. Further, a new theoretical system was studied to comprehensively improve risk judgment and early warning ability for typical dynamic disasters occurring in coal mines. The prevention and control technology for coal and gas outbursts has been significantly improved, and the prediction and prevention technology is being continuously developed. However, existing technical methods cannot completely prevent outbursts. There have been numerous coal and gas outbursts in China’s coal mines in the past 10 years, with a significant number of casualties due to secondary gas suffocation or gas explosion following an outburst. For example, in 2011, 43 people were killed in a coal and gas outburst at a private coal mine in Shizong County, Qujing. In 2009, 108 people died in a gas explosion due to an outburst at Xinxing Coal Mine, Hegang Branch of China Longmei Group. In 2004, 148 people died in a gas explosion due to “10.20” coal and gas outburst in Daping Coal Mine of Zhengmei Group. These tragic accidents are a reminder of the importance and urgency of studying “secondary disasters” resulting from a coal and gas outburst, that is, the gas flow process in the mine system network.

Secondary disasters following an outburst mainly occur due to the change in the outburst power in the mine ventilation system, that is, the airflow in the ventilation system becomes disordered, making it difficult to predict the direction and concentration of the outburst gas flow in the ventilation network system. In the event of an outburst, the direct expansion power of the outburst gas makes the airflow in the ventilation system countercurrent. The outstanding gas and airflow mixing change the airflow density of the roadway constantly, and the natural wind pressure of the mine system or local area varies, which is called the natural gas wind pressure. The change in the natural gas wind pressure due to gas outbursts was first reported in Ref. 26 As special power sources of the mine ventilation system during the outburst period, the outburst power and natural gas wind pressure directly or indirectly alter the original airflow operation of the ventilation system and make the airflow disorderly. The outburst and its effect on the ventilation system may lead to asphyxiation accidents and gas explosions, making the outburst even more serious in terms of its scale and extent of damage. Therefore, considering the scale of a mine, it is important to understand and control the turbulence in its ventilation system and the natural gas pressure following an outburst. Yang studied the diffusion and migration rule of outburst gas in a ventilation system and simulated a ventilation network under an unsteady state. Combining the two, a solution model of the air network was proposed considering the unsteady state and gas distribution. On this basis, an online identification and emergency-assistance decision-making software was developed to prevent coal and gas outbursts.

The key to solving the gas outburst problem in mine ventilation systems during the disaster period is the expression of the outburst source point in the ventilation system. Li proposed the concept of an active air network in 2010 and found a breakthrough point for solving this problem. Based on the theory of an active wind network, a computer simulation program TF1M (3D) was developed to describe the outburst process in a mine ventilation system, and the process description and deduction of the outburst were realized. Because of the complexity of the mine ventilation system during the catastrophic period, the effect of the two-phase coal powder/gas flow and the gas analysis of the coal powder are ignored. Studies focused on the influence of natural gas pressure on the airflow after the disaster, without considering the gas pressure formation process and whether there is a dynamic phenomenon before this formation. The dynamic emission characteristic of the gas in the outburst process is an important parameter determining the influence range of the gas in the roadway; however, it is difficult to measure the dynamic change directly. Typically, after a coal and gas outburst, the underground power supply is cut off because of the high gas concentration in the tunnel, and it is difficult to fully monitor the change in the gas concentration. Moreover, the time required for manual monitoring is considerable, the accuracy is low, and the risk is relatively high. Therefore, the measured gas emission data during coal and gas outbursts are typically inadequate.

Studies on secondary disasters due to coal and gas outbursts are limited in terms of the flow process of the outburst gas in the mine network system and the superposition of the outburst gas flow and ventilation dynamic force. In the past, the passive air network theory has been used to simulate gas outbursts. In this study, the gas diffusion after an outburst in the entire mine was simulated using the active air network theory, and the direct dynamic effect of the gas outburst on the ventilation system and the combined effect of the natural gas pressure were considered. Combined with an actual example of an outburst that occurred in Shizong County Coal Mine, Qujing City, Yunnan Province, this study analyzed the gas migration process and the law of disaster evolution in the entire mine network area during the outburst period. Based on the theory of an active ventilation network, mathematical models of the unsteady airflow movement and gas movement
in the mine during the outburst were established. A simulation program was used to simulate the dynamic change process in the ventilation network during the outburst period. We describe the movement process of the gas in the mine network area; analyze the occurrence, characteristics, and laws of air turbulence due to the natural gas wind pressure; and study the influence of natural gas wind pressure on the mine ventilation system. This study provides new insights into the disordered nature of the airflow in mine ventilation systems during gas outbursts and a technical support for emergency rescue and preplanning.

2 | THREE-DIMENSIONAL MODEL OF SOURCE-CONTAINING VENTILATION NETWORK AND MASS-ENERGY BALANCE EQUATION FOR GAS OUTBURSTS IN COAL MINES

2.1 | Air volume-wind pressure balance equation for source-containing ventilation network

The wind sources in an active wind network can be divided into branch and nodal based on the generation method and location. For example, the gas emission in coal roadways is a typical branch wind source (weak source), whereas a gas outburst is a nodal wind source (strong source). In coal mines, branch and nodal air sources often appear simultaneously.30 The mass balance equation for an active wind network (considering the quality source and sink terms) is as follows:

\[
AM = A^*W + D
\]

\[
A = \begin{bmatrix}
  a_{11} & a_{12} & \cdots & a_{1n} \\
  a_{21} & a_{22} & \cdots & a_{2n} \\
  \vdots & \vdots & \ddots & \vdots \\
  a_{m-1,1} & a_{m-1,2} & \cdots & a_{m-1,n}
\end{bmatrix}
\]

\[
M = \begin{bmatrix}
  M_1 \\
  M_2 \\
  \vdots \\
  M_n
\end{bmatrix}
\]

\[
W = \begin{bmatrix}
  W_1 \\
  W_2 \\
  \vdots \\
  W_n
\end{bmatrix}
\]

\[
D = \begin{bmatrix}
  D_1 \\
  D_2 \\
  \vdots \\
  D_m
\end{bmatrix}
\]

When the branch weak source is ignored or when the branch strong source can be directly converted to a node wind source, we have:

\[
\sum_{j=1}^{n}a_{ij}M_j = D_i, \quad (i = 1, 2, 3, \ldots, m - 1)
\]

(2)

From Equation (1), the expression is complete in the form of the equation. Therefore, in a broad sense, the active wind network (network) is the general form of the network, and the ordinary network (homogeneous equation) is only a special case of the general form.

The key theory to solve the gas outburst source problem in the mine tunnel system is the active network.27 The wind pressure balance equation in an active wind network containing the gas outburst source is as follows:

\[
BH = BH_f + BP_e
\]

(4)

where B is the basic loop matrix; H is the wind pressure vector, Pa; \(P_e = [P_{ej}]_{n \times 1}\) is the position pressure difference vector, where \(P_e\) is the position pressure difference of the j branch, Pa.

\[
P_{ej} = g \int_{Z_{j,1}}^{Z_{j,2}} \rho_j dz
\]

(5)

where \(\rho_j\) is the airflow density of branch j, kg/m³; \(Z_{j,1}\) and \(Z_{j,2}\) are the elevations of the start and end nodes of branch j, m, respectively, which are inputted during mine 3D modeling; \(\rho_{j,a}\) is the average airflow density of branch j, kg/m³, n is the number of branches.

2.2 | Mine natural gas wind pressure and gas transport dispersion equation

The natural wind pressure refers to the algebraic sum of the pressure differences in each branch in a loop of the active wind network. The gas concentration at each point of the mine tunnel during the gas outburst period varies dynamically. If the influence of temperature is ignored, the density
of the gas relative to air under standard atmospheric pressure is 0.554. The relationship between the gas concentration and the density at the differential node $i$ in the branch airflow is as follows:

$$\rho_{ij} = \rho_{i,d} (1 - 0.446 c_{ji})$$

where $\rho_{i,d}$ is the density of the airflow at branch $j$, kg/m$^3$; $c_{ji}$ is the gas volume percentage concentration of the airflow at node $i$ in the $j$th branch, \%.

During the gas outburst period, the density of the gas flow or gas-containing wind flow is significantly lower than that of the normal wind flow, thereby causing a relatively significant change in the natural wind pressure on a circuit $s$. The natural gas wind pressure on circuit $s$ is as follows:

$$h_{es} = \sum_{j=1}^{n} b_{s,j} (p'_{es,j} - p_{es})$$

where $p'_{es,j}$ is the potential pressure difference of the branch $j$ during the catastrophic period, Pa, and $b_{s,j}$ represents the elements of the basic loop matrix.

During the gas outburst and catastrophic period, the airflow in the mine airflow system and the gas flow and dispersion are unstable. For branch $j$ in the wind network, the airflow and gas concentration and mass transfer equations can be expressed as follows:

$$\begin{align*}
\frac{\partial \rho_j}{\partial t} + \rho_j \frac{\partial v_j}{\partial x} &= 0, \\
\frac{\partial c_j}{\partial t} + v_j \frac{\partial c_j}{\partial x} &= E_x \frac{\partial^2 c_j}{\partial x^2} + W_j,
\end{align*}$$

where $v_j$ is the wind speed in the branch $j$, m/s; $t$ is the time variable, s; $c_j$ is the gas concentration in the wind flow in the $j$th branch, \%; $E_x$ is the gas mechanical dispersion coefficient, m$^2$/s.

In each step of the time cycle, the gas concentration at each node in the network is continuously updated and calculated. Each node in the network constitutes the starting point and boundary value of the downstream branch, and the gas concentration at each node is formed by the upstream branch confluence. Thus, the gas concentration (external source gas) after mixing at the $m$th node can be expressed as follows:

$$c_m = \frac{\sum_{k=1}^{J_m} Q_k c_k + W_k}{\sum_{k=1}^{J_m} Q_k + w_k},$$

where $k$ represents the inflow branch of node $m$; $J_m$ is the number of inflow branches of node $m$; $c_m$ is the inflow-mixed concentration of node $m$ (boundary value); $c_k$ is the concentration of the external source gas in the $k$th branch; $W_k$ is the external gas in the $k$th branch The source strength.

Gas outburst sources have two types of boundary conditions (flow rate). If the gas outburst source is given as a node source, the gas concentration boundary condition for the outburst source is as follows:

$$c_{i_{out}} = C_s$$

where $C_s$ is the gas volume fraction concentration of the prominent source, \%.

### 2.3 Description of the process and source

The process of coal and gas outbursts can be broadly divided into outburst dynamic wave propagation and outburst (gas flow and coal flow) propagation. The propagation speed of dynamic waves is the highest, close to the speed of sound, followed by gas flow, and finally coal flow. The protruding sound is heard first, followed by the gas flow, and finally the coal flow; the coal flow is particle size sorting, and the bulk is at the end, the pulverized coal spreads farthest, even reaching the wellhead along with the gas flow. Outburst coal flow can form packing in the accident roadway, and outburst coal flow can fill the accident roadway, which has a certain impact on the subsequent appearance of gas outbursts.

After the outburst coal flow fills the accident roadway, a large wind resistance is formed therein. The coal filling of the roadway constitutes a blocking section from the outburst source gas jet hole to the free space roadway. The greater the gas flow, the greater the resistance. This makes the gas that is rapidly desorbed by the collapsed coal in the outburst source trapped in the outburst source cave, forming a high-pressure gas cavity; the high-pressure gas in the cavity continues to be squeezed out from the outburst source coal flow blocking section. When the intensity of the outburst source is high and the gas pressure in the tunnel is too high, the flow of the roadway stuffing coal will continue to occur, thereby increasing the distance of the roadway stuffing coal until the pushing pressure and movement resistance reach a balance. There are two reasons for stopping the movement of landfilled coal in roadways. One is that the moving distance of the landfilled coal in the roadway is too long, and the pushing resistance is too high to achieve a balance between the thrust and resistance. The other is that the intensity of the gas outburst is attenuated, and the amount of desorption gas in the source is weakened, because of which the outburst power is insufficient to overcome the coal flow resistance.

The high-pressure gas in the outburst source tunnel is extruded through the coal flow buried roadway (blocking section), resulting in particle size separation in the packed coal section. The most evident feature is that the outburst gas flow rushing out of the packed coal section entrains a large amount of coal dust, and a higher-pressure gas can also cause internal displacement of the packed coal section during the extrusion process of the packed coal section. This type of dislocation is orderly. Large particles become small particles in the sieve.
leading to particle size distribution sorting recombination, eventually forming a layered particle size distribution structure from large particles to small particles.

After the high-pressure gas passes through the coal flow to fill the roadway, an outburst gas flow is formed in the free space roadway. In terms of the time, the outflow time of the protruding gas flow entering the free space roadway lags behind the completion time of the protruding action; the protruding gas flow flows at a high speed and emits a whistling sound, which produces a strong impetus to all obstacles, which is an important disaster characteristic. Prominent gas migration and diffusion in the complex mine roadway network may cause secondary suffocation or gas explosion accidents. Here, this is used as the main parameter in simulating the ventilation system during the catastrophic period.

2.4 Treatment of mechanical boundary conditions for outburst sources

As shown in Figure 1, as a node source in the network, the mechanical boundary conditions of the gas outburst source can be described by the pressure under type 1 boundary conditions and the flow rate under type 2 boundary conditions. It is difficult to obtain the outburst pressure in the mine, so the mechanical boundary condition of the gas outburst source is described by the second boundary condition. If a gas outburst occurs at node $s$ of the wind network, and the gas flow rate $D_s(\tau)$ of the outburst source is a function of time $\tau$, the outburst source is:

$$D|_{ins} = D_s(\tau)$$  \hspace{1cm} (12)

where $s$ denotes the node where the outburst source is located; $D_s(\tau)$ denotes the flow rate of the outburst source, m$^3$/s.

Large amounts of pulverized coal and gas were injected during the hydraulic piercing test. A single-hole coal injection can reach several tons to dozens of tons, and the gas injection can reach thousands or tens of thousands of cubic meters. The jet hole during hydraulic punching can be considered a small protrusion. Therefore, studying the hydraulic punching and spraying processes will help deepen our understanding of the occurrence and development of coal and gas outbursts. The gas flow of an outburst source is a nonuniform source, and the pulsation process is neglected. Generally, the gas flow of the outburst source increases rapidly to the peak value and then decreases gradually, as shown in Figure 2.

The flow boundary condition can be estimated from the observed data of the gas concentration and total quantity. The total amount of gas outburst can be expressed as follows:

$$V_0 = \int_{\tau_0}^{\infty} D_s(\tau) \, d\tau$$  \hspace{1cm} (13)

where $D_s(\tau)$ is a function of the source intensity on the node $s$ of the air network, m$^3$/s, which is a key parameter in the active air network, and $\tau_0$ is the time at which the gas outburst occurred, s. The gas quantity $V_0$ of the gas outburst is known, and $D_s(\tau)$ is determined according to the outburst change model.

3 SIMULATION OF MINE VENTILATION SYSTEM DURING COAL AND GAS OUTBURSTS

3.1 Coal and gas outburst case description

At 6:30 on 10 November 2011, a coal and gas outburst occurred at the Sizhuang Coal Mine in Shizong County, Qujing City, killing 43 people. Sizhuang Coal Mine is a private small-scale mine with coal and gas outburst mines and inclined shaft development. The approved production capacity is 90,000 tons/a. The accident occurred at the 1747 heading face, which had eight people working on duty. After the accident, the gas wave broke out and reached the 1727 inspection and repair point. The inspection and repair point had 35 workers and 43 people in total. All of them were trapped. The amount of outburst coal was more than 1000 tons, and the total amount of outburst gas was approximately 58,000 m$^3$, which indicates that this outburst was a major one. During the rescue after the incident, the gas concentration in the tunnel was still as high as 55%. At the time of the outburst, the driving distance of the 1747 roadway of the No. 2 auxiliary shaft reached 100 m. After the outburst, the roadway of the No. 2 auxiliary shaft 180 m in length from the well head was narrow, and there was more clogged cinder. The 181 m long roadway was filled with coal, and the thickness of at least 207 m roadway was between 0.4 m and 0.7 m, as shown in Figure 3.

3.2 Construction of mine ventilation system model

The mine ventilation system simulation program TF1M (3D) developed and compiled in the MATLAB system was used to construct the ventilation system of a private village coal mine. As shown in Figure 4, the mine is equipped with a central boundary ventilation method. The ventilation system is fed by
the No. 2 auxiliary shaft and the main inclined shaft. The return air from the air shaft in the south wing (i.e., 1# air shaft in Figure 4) adopts the extraction ventilation method. A KJ-90 safety monitoring system was installed in the mine, and a methane sensor was installed at the exit of the 1727 inspection point. The simulation adopts a BD-II-6-No18 fan, the speed of 1# air shaft fan was 340 r/min, the air volume was 37.9 m³/s, the external air leakage volume was 2.18 m³/s, the wind pressure was 211.23 Pa, and the natural wind pressure was −32.63 Pa. In the branches shown in the figure, the combination of symbols “○” and “·” is used to express the direction of wind flow, where “·” represents the front of the wind flow direction, and “○” represents the back of the wind flow direction; the higher the wind speed, the greater the distance between the two. The wind flow and wind speed in the figure are separated by commas, the unit of air volume is m³/s, and the unit of wind speed is m/s.

### 3.3 Basic assumptions of the model

Theoretically, the outburst power transmission in the mine tunnel system can be calculated at the speed of sound. The propagation time of the power change is approximately a few seconds or tens of seconds. In terms of the time, the outburst power propagation is short-lived relative to the flow process of the outburst gas flow. Therefore, the propagation time of the protruding power in the mine can be ignored, and the “protruding impact dynamic effect” is ignored in the simulation. When a coal and gas outburst occurs, a short-term high pressure is formed in the outburst hole, which is sprayed into the tunnel in a two-phase flow. For the entire mine ventilation system, the outburst tunnel does not occupy the mainstream section, and the two-phase flow of the coal and gas in the outburst tunnel is ignored. The outburst coal flow stopped after filling and excavating the 1747 roadway, 181 m into the lower section of the No. 2 auxiliary shaft. During the simulation, the accumulated coal section was automatically adjusted to a large wind resistance by the program; the gas outburst source in the complicated dynamic process in the local outburst incident was simplified. A (storm) high-flow boundary condition was applied, that is, the second type of boundary condition.

### 3.4 Simulation results and analysis

TF1M 3D is used to simulate the dynamic change process of the coal and gas outburst, including the flow, velocity, pressure, gas concentration distribution of each branch of the mine.
network domain, as well as the changes in the working conditions, and the natural wind pressure of each loop. Figures 5-7 show the simulation results. The numerical simulation results in Figure 5 show that when the coal and gas outburst is in the 86th s, the mine ventilation system has a countercurrent flow, and the gas flow velocity in the outburst roadway is as high as 54.25 m/s. The original No. 2 auxiliary shaft and the main inclined shaft have occurred to varying degrees. The
countercurrent air volumes are 322.88 m$^3$/s and 72.44 m$^3$/s, respectively. Table 1 lists the air volume changes in the typical roadways before and after coal and gas outbursts.

The simulation results in Figures 6 and 7 show the entire process of gas flow change during the coal and gas outburst. When the coal and gas outburst occurred in the 1747 driving face, the outburst gas directly flowed upstream along the No. 2 auxiliary shaft until it filled the entire No. 2 auxiliary shaft roadway. Under the action of the ventilator, the protruding gas enters the 1727 maintenance work area with the wind flow through the depot and is discharged from the south air shaft. During the period of prominent catastrophe, there were nine loops in the 3D wind network of the Sizhuang Mine, varying the natural wind pressure to different degrees, from the main air intake shaft to the main disaster-causing lane (via 26 nodes) to the south return air shaft. The loop that has the highest natural wind pressure and plays a key role in the mine ventilation is the main loop that highlights the catastrophe; the natural gas wind pressure in the main loop is the natural gas wind pressure of the mine. The simulation showed that at

**FIGURE 6** Simulation diagram of mine ventilation system in gas outburst period
85.8 s, when the gas filled the No. 2 auxiliary well, the natural gas wind pressure reached −390.04 Pa, which was in the countercurrent direction and much higher than the fan wind pressure. In the 140-225 s period, the natural wind pressure once overcame the wind pressure of the ventilator, causing the air flow in the 1824 transportation lane to flow back. The gas flowed back from the 1727 inspection point and completely discharged from the No. 2 auxiliary shaft. Thereafter, the ventilator overcomes the natural wind pressure to maintain the gas discharge process.

During the outburst process, the natural wind pressure in the circuit of the No. 2 auxiliary shaft and the return air shaft changes significantly, as shown in curve 1 in Figure 8. As the gas accumulation in the mine decreases, the natural wind pressure gradually decreases. Figure 9 shows the gas concentration change process at the return airport (26 nodes) and the No. 2 auxiliary wellhead (1 node) at the 1727 inspection point during the gas outburst process.

Since the safety monitoring system was unable to obtain useful and more detailed data to directly support the simulation, it could not record high gas concentrations and validate the simulation data. Nevertheless, the description of the accident by people on-site is consistent with the simulation, that is, it has been verified macroscopically. In addition, the process of

**FIGURE 7** Gas Drainage process of mine ventilation system after gas outburst

**TABLE 1** Air volume changes in the wellbore before and after the outburst

| Mine roadway name     | Air flow before coal and gas outburst (m³/s) | Air flow after coal and gas outburst (m³/s) | Change in air flow     |
|-----------------------|---------------------------------------------|--------------------------------------------|-----------------------|
| No. 2 auxiliary well  | 29.56                                       | −322.88                                    | adverse current       |
| Main inclined shaft   | 7.69                                        | −72.44                                     | adverse current       |
| South return air shaft| 37.25                                       | 117.96                                     | down-flow             |
coal and gas occurrence and migration is a typical open complex system, so it is difficult to simulate and describe the actual process. Li Zongxiang\textsuperscript{23,24} used the development simulation program TF1M (3D) to simulate and analyze the gas outbursts that occurred in the Chongqing Songzao Coal Power Plant and Daping Coal Mine of Zhengmei Group. The feasibility of applying this simulation to the program was verified.

4 | ANALYSIS OF THE FUNCTION OF NATURAL GAS PRESSURE IN THE OUTBURST PERIOD

In the mine accident, 11 people died at the return air outlet (26 nodes) of the 1727 inspection point, six people died at the air inlet, and two people died at the return air shaft. As shown in Figure 9, when the gas concentration in the coal mine shaft reaches 43\% and the oxygen concentration is below 12\%, people will die of hypoxia and suffocation. The high concentration gas that can cause suffocation lasts for more than 255 s at the coal mine shaft (26 nodes), and the gas concentration near the 26 nodes is high enough to cause death. This shows that the gas flows back into the 1727 inspection point area under the action of the fan.

Following the gas outburst, if the coal mine workers can timely reverse the wind or stop the operation of the ventilator based on the actual conditions of the mine, it is possible to minimize the casualties in the 1727 working face by utilizing the natural gas wind pressure generated when the outburst countercurrent gas fills the No. 2 auxiliary well to discharge the outburst gas from this well.

As the natural gas wind pressure is relatively high, anti-wind measures must consider the influence of the natural gas wind pressure. To prevent the anti-wind power and natural gas wind pressure from offsetting each other, the best way is to add the two in the same direction, so that the gas can be discharged from the mine as soon as possible. To study the effect of natural gas pressure, only the case of stopping the fan is considered. Under the effect of natural gas pressure (no fan power), when the outburst power disappears, the gas begins to subside. In this process, the natural wind pressure continues to act in a direction opposite to the original ventilation after the outburst power disappears (the natural gas pressure is negative), see the curve 2 in Figure 8. The natural wind pressure does not disappear until the gas is completely discharged. Under these conditions, the maximum gas concentration at the 1727 inspection point is 10\%, which is not high enough to cause death.

The formation and function of the natural gas wind pressure in the outburst mine are directly related to the mine ventilation system and outburst source scale and characteristics. After the outburst, the working of the fan is ensured, and the mine ventilation system under the power of the fan is conducive to the quick discharge of the outburst gas, and the action time of the natural gas wind pressure is reduced. Contrary to the specific conditions of a private village mine, timely counter-wind and use of mine gas natural pressure ventilation can help prevent the outburst from further expanding. In this accident, the outburst gas was discharged from the south air shaft and was drawn to the working area, such as the 1727 maintenance point, where the personnel were concentrated. This made the disaster more severe. At the same time, the ventilator needed to overcome the strong natural gas pressure and reduced the efficiency of the ventilator, high concentration gas cannot be discharged in a short time, so that 1727 overhaul points and other working face gas long-term detention, personnel asphyxiation. If fan operation is stopped or timely anti-wind measures are taken, the natural gas pressure ventilation can be conducive to the rapid discharge.

Wang Kai\textsuperscript{30} analyzed experimentally that when high concentrations of methane accumulate in an inclined roadway, the difference between methane and air can cause airflow in a downward-ventilated roadway to reverse. This is in good
agreement with the law of gas migration and diffusion and the effect of natural gas pressure after outburst described in this paper.

5 | Conclusions

1. Based on a 3D model of a nonuniform gas outburst source and the mass-energy balance equation, the TF1M 3D program was used to simulate the gas outburst in a mine. The simulation results were consistent with the typical characteristics of coal and gas accidents. The gas outburst movement in the ventilation system could be divided into three stages: outburst counterflow, natural flow, and down-flow. This led to a disturbance in the mine ventilation system.

2. The natural gas pressure is an important power source in mine ventilation systems during an outburst, as it affects the movement of the gas in the mine ventilation system after an outburst. The natural gas pressure changes constantly with the operation state of the gas in the mine ventilation system, which makes the result of the action of this dynamic force complicated and the trend difficult to predict. It must be described and evaluated using a network fluid simulation technology depending on the specific mine conditions. Theoretical simulation showed that the natural gas pressure can be used to reduce or avoid the accident to a certain extent in the event of a coal and gas outburst. Therefore, it is important for mines that are prone to coal and gas outbursts to strengthen the application of simulation technology and gain disaster experience.

3. In the case of Shizhuang mine accident, the gas was discharged directly from the No. 2 auxiliary shaft of the air inlet by countercurrent movement, and in the natural flow stage, the gas was discharged along the air inlet shaft. If ventilation were continued or resumed at this time, the entire ventilation system would have been driven by the ventilator and the gas in the incoming air would have entered the working area with a large number of personnel, which is not conducive to the evacuation of personnel. If anti-ventilation was used before the ventilation was resumed, and the gas continued to be discharged along the inlet shaft by blowing the air into the tunnel by the extraction fan, the workers in the mine could have been evacuated to the ground along the return shaft or other disaster-avoiding route.

4. Through a simulation program, this study deduced a coal and gas outburst in Shizhuang Coal Mine and analyzed the law of gas movement and the influence of natural gas wind pressure on the stability of the mine ventilation system. To make the calculations feasible, some simplified assumptions were made, and the results of the natural gas wind pressure in the disaster period should be further verified using an experimental method.

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