Research Article

The Airflow Reversal Law in Ventilation System after Coal and Gas Outburst in Tunneling Roadway

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Considering the coal and gas outburst phenomenon in the mining space, this paper analyzes the main characteristics of coal and gas outburst accidents, defines the outburst airflow reversal degree, and constructs a simplified topology graph of tunneling ventilation system, while the air door is not destroyed. Using the numerical simulation method, this paper elaborates on the relationship between the outburst pressure and airflow reversal degree. The results indicate that the inlet pressure increases to 264 hPa and the outlet pressure increases to 289 hPa when the outburst pressure increases from 1 hPa to 1 MPa, and the relative variation coefficient of pressure decreases from 1501.5 to 1.62 in the inlet of return airway and decreases from 2002 to 1.65 in the outlet of return airway. Furthermore, the air velocity decreases from -1.38 to -284.44 m/s in the inlet and increases from 3.10 to 297.38 m/s in the outlet. Moreover, the gas concentration of the inlet and outlet in return airway increases rapidly with the increase of outburst pressure. When the outburst pressure is greater than 0.15 MPa, the gas concentration will be over 98% in tunneling ventilation system. This paper also finds out a cubic polynomial relationship existing between the reversal degree and the outburst pressure. It provides the prediction of coal and gas outburst and serves as a guidance in case mine ventilation disturbances occur.

1. Introduction

The coal and gas outburst is a phenomenon where a large amount of coal and gas is ejected into the mining space almost immediately [1, 2]. In an outburst accident, the high pressure often injures people in underground roadway [3]. Furthermore, coal and gas outburst destroys equipment, such as the ventilation facilities, making airflow disorder in mine ventilation system easier to occur. More seriously, it causes secondary disasters, such as the gas explosion accident [4, 5] and the coal dust explosion accident. Generally speaking, there are two ways of transmission after an outburst accident—one is the shock wave and the other is gas pressure [6, 7]. The pressure of outburst gas is the main reason in mine airflow disorder after the outburst power fades away.

After a disaster happens, an effective ventilation system can help avoid secondary disasters caused by airflow reversal and, at the same time, safeguard the disaster relief work. Currently, some researchers have studied the reverse flow

and turbulence of airflow in the overall mine tunnel ventilation system during the disaster period. Firstly, the underground roadway space is regarded as the flow field. When the flow field after gas outburst is disturbed by the shock waves, the huge energy and pressure involved in the process of the gas outburst as well as the influence the operating parameters of the ventilation system pose on roadway airflow are studied [8]. Then, the model of outburst source was established to study the unsteady flow and distribution of gas after gas outburst. By using the outburst disaster simulation software, the outburst danger area is determined. Combining with the automatic control system of the air door, the gas in the return airway is controlled [9]. At the same time, the gas migration model of the mine ventilation system was established, and it was concluded that the mine ventilation system would experience the gas reversal states, the natural flow states, and the gas flow states after the occurrence of gas outburst accident [10]. Finally, through the case of the gas outburst accident, the main influencing factors of airflow reversal in the upwind roadway are studied; that is, the

airflow is easily reserved if the height difference of the roadway is large, and the impact scope of gas outburst accident expanded if the gas reversal time was short [11].

The safety and stability of mine ventilation system usually referring to the airflow direction are stable and the air velocity does not exceed the limit when the ventilation system is disturbed. They reflect the antidisturbance capability of the ventilation system. Through establishing a mathematical model of unsteady gas flow and studying the flow variation law induced by the gas outburst, it was found that ventilation pressure is the main factor affecting airflow reversal [7]. Then FLUENT software was used to study the influence of the direction of gas flow in inclined roadway on gas distribution and accumulation [12]. The results show that the downward ventilation is beneficial to the combination of gas and air. The greater the air speed is or the smaller the roadway angle is, the smaller the possibility of gas accumulation is; the transient model of airflow stability induced by gas accumulation was established, and it was found that the main reason for airflow disorder is the air pressure of gas accumulation [13]. Furthermore, methane buoyancy [14], shock wave, and main fan pressure [15] could cause the flow to stall or reverse. The dynamic simulation of gas migration in coal and gas outburst can be realized with the help of the mine ventilation network software during the disaster period [16]. Combined with laws between outburst gas and max impact power of ventilation structures, as well as the reasonable location of air door [17], the destructiveness of gas outburst to the damper [18] provides a theoretical basis for the stable operation of ventilation system.

In summary, the outburst gas is prone to air disorder and airflow reverse. However, the transmission law of outburst gas is a complex problem in ventilation system, which has many influence factors of ventilation parameters, such as the length of underground roadway, the air resistance, and the air pressure, as well as the complexity of ventilation network [19, 20]. There is little research on the process of outburst air disorder and airflow reversal law, as well as its quantitative analysis and evaluation.

This paper uses the numerical simulation method to study the airflow variation law of the tunneling ventilation system under different outburst pressure conditions. It provides the basis for monitoring and early warning before the disaster, ventilation decision-making during the disaster, and ventilation management during the disaster relief, which is of great significance for the prediction and prevention of coal and gas outburst accidents.

2. Gas Outburst and Airflow Reversal

2.1. Principle of Outburst Gas Flow. The airflow is an unstable state after the coal and gas outburst accident. The air pressure and air velocity changes were accompanied with plenty of the outburst gas, which obeys the energy conservation equation, the mass conservation equation, and the momentum conservation equation.

In a gas outburst, the gas concentration is suddenly rising with a large amount of gas entering into the roadway

in a short time, and the air pressure of roadway is redistributed in ventilation system. Furthermore, the air pressure of the upwind and leeward side increases; in particular, the airflow would be reversed when the air pressure at the upwind side is lower than the outburst pressure.

2.2. Main Factors of Gas Outburst. The outburst intensity, the outburst position, and the physical conditions of roadway are main factors in a gas outburst.

Outburst intensity represents the scale of an outburst accident, which refers to the amount of coal and rock thrown into the roadway and the amount of ejected gas. According to the amount of outburst coal and rock, the outburst accident is divided into small outburst accident (<100 t), medium outburst accident (<500 t), large outburst accident (<1000 t), and extra-large outburst accident (≥ 1000 t).

Outburst position refers to the place where the outburst accident occurs. The outburst gas can be faster exhausted to the ground if the outburst position is closer to the air exhausted shaft. So reducing the air resistance of the return airway and increasing the intake airway are two main methods to decrease the impact of outburst accident on ventilation system.

The characteristics of roadway are determined by the physical conditions, such as the section and length of the roadway. Specifically, the outburst gas is easy to exhaust in the large section or the shorter length of roadway.

2.3. Airflow Reversal Degree. The outburst airflow reversal degree is defined as the ratio of the air quantity variation of the roadway after gas outburst and the original air quantity, which represents the airflow variation of a roadway affected by the gas outburst accident. It can be calculated by the following equation:

$$\varphi = \frac{Q_i - Q_0}{Q_0}, \quad (1)$$

where φ is the outburst airflow reversal degree; Q_i is the air quantity of the roadway after gas outburst, m^3/s ; Q_0 is the original air quantity.

A positive value means that the outburst airflow is consistent with the original airflow, and a negative one means that the airflow is reversed.

3. Ventilation System of Tunneling Roadway

3.1. Composition of Tunneling Ventilation System. The ventilation system in tunneling roadway is composed of tunneling roadway, heading face, auxiliary fan, and air duct, as shown in Figure 1. Most of the gas outburst accident occurs in the heading face [21].

The forced ventilation style is adopted in tunneling roadway ventilation, which has the advantages of small air leakage and large air supply. The fresh air is transported from the intake airway to the heading face through the auxiliary fan and air duct, and the polluted air enters the return airway through the tunneling roadway. The air door obstructs the air, and the air duct needs to pass through the

FIGURE 1: Sketch map of ventilation system in tunneling roadway.

air door. The blue arrow in Figure 1 indicates the airflow direction of the fresh air, and the red one indicates the polluted air.

3.2. Airflow Reversal of Tunneling Ventilation System. Suppose that P_i represents the gauge total pressure in position i , the magnitude of air pressure is $P_{20} > P_{21} > P_{22}$, $P_{10} > P_{11} > P_{12} > P_{13}$, and $P_{11} > P_{31} > P_{21}$ in the tunneling ventilation system shown in Figure 1.

In a gas outburst, P_{12} rises rapidly with the high pressure released by the outburst gas. When it reaches Point 21, one part of the gas attacks the air door, and the other part directly flows into the return airway. If $P_{21} > P_{20}$, the gas will flow in the opposite direction from Point 21 to Point 20. If the air door is destroyed, the gas reaches the intake airway. The flow direction depends on the magnitude of air pressure of Points 10, 12, and 13. With the exhaustion of outburst energy, the mine ventilation system reaches a new equilibrium state.

3.3. Simplification of Tunneling Ventilation System. A ventilation facility usually has two states, a destroyed state and a normal state, in a gas outburst. The air door plays an important role in the accident, especially the safety of air door, which directly affects the scope of gas outburst. At present, it is particularly difficult to destroy the antioutburst air door in a gas outburst accident as a better shock-resistant capability. So, the air migration is more significant in the return airway after gas outburst.

The tunneling ventilation system can be simplified in Figure 2 in a normal state. There are 4 branches, the return airways (P_{20} – P_{21} and P_{21} – P_{22}), the tunneling roadway (P_{12} – P_{21}), and the auxiliary fan (P_{11} – P_{12}).

3.4. Calculation of Ventilation Parameters of Tunneling Ventilation System. Suppose that both sectional areas of the return airway and tunneling roadway are 15 m^2 , the friction resistance coefficient is 100×10^{-4} , the inlet air quantity of return airway Q_{20} is $40 \text{ m}^3/\text{s}$, and the air quantity of auxiliary

FIGURE 2: Simplified ventilation network of tunneling roadway.

fan Q_{fan} is $9 \text{ m}^3/\text{s}$. Then the outlet of return airway Q_{21} is $49 \text{ m}^3/\text{s}$. According to the relationship between the air resistance and the friction resistance coefficient of the roadway,

$$R = \frac{LU\alpha}{S^3}, \quad (2)$$

where R represents the air resistance, kg/m^7 ; L represents the length of roadway, m ; α represents the friction resistance coefficient, kg/m^3 ; U represents the perimeter of roadway section, m ; S represents the sectional area of the roadway, m^2 .

In equation (2), the air resistance of return airway $R_{20} = R_{21} = 0.0032 \text{ kg}/\text{m}^7$, and the tunneling roadway from the air duct outlet to the return airway $R_{12} = 0.00576 \text{ kg}/\text{m}^7$. Assuming that the operation pressure is the standard atmospheric pressure (101.35 hPa), the gauge total pressure at the inlet of return airway $P_{20} = 6 \text{ Pa}$, and the node pressure $P_{22} = -14 \text{ Pa}$.

4. Modeling of Gas Outburst in Tunneling Roadway

4.1. Model Assumptions

- (1) Assuming that there is no heat transfer and no chemical reaction in the airflow, the gas flow process in the roadway is isothermal; then the gas compression factor and friction coefficient are constants.
- (2) The airflow expansion coefficient of wall and the local resistance loss of equipment and pipeline are 0.
- (3) The gas outburst source, the gas emission, and external sources in the pipeline network are not considered temporarily.
- (4) The error of uneven distribution of flow field in tunnel caused by transient is ignored.

4.2. Physical Model and Meshing. The intersection of the tunneling roadway and return airway is the key position of this model. The airflow direction is determined by calculating the ventilation parameters. The physical model and its physical parameters are shown in Figure 3.

In Figure 3, the length of tunneling roadway is 500 m, and the length of return airway is 500 m, including 250 m at the upwind side of the intersection and 250 m at the downward side. The section area is 15 m^2 , the width is 5 m, and the height is 3 m. The length of the air duct is 450 m, the radius is 0.5 m, its outlet is 50 m from the heading face, and the center of air duct is 1 m from the roof and 1 m from the roadway.

The physical model is divided with Tet/Hybrid elements and TGrid type, the spacing is 0.5 m, and the mesh quantity is 608110. The meshing is shown in Figure 3.

4.3. Mathematical Model. The boundary conditions of the model are shown in Table 1.

In Table 1, the physical model area is fluid type, and the pressure of operation condition is 101.35 hPa. The inlet boundary condition of return airway and outburst position is pressure inlet, the initial gauge total pressure is calculated by equation (2), and the result is shown in Table 1. The species of inlet of return airway is 20% oxygen and 80% nitrogen, and the outburst position is 100% CH_4 .

The inlet boundary condition of the air duct is velocity inlet, and the species is 20% oxygen and 80% nitrogen. The outlet of return airway is pressure outlet.

Turbulent flow is a common flow phenomenon in most engineering problems. FLUENT software provides standard $k-\epsilon$, RNG $k-\epsilon$, and realizable $k-\epsilon$ models. The realizable $k-\epsilon$ model has good performance for solving the adverse pressure gradient and vortex problems.

The pressure-based type, the absolute velocity formulation, and pressure-velocity coupling algorithm are used to solve the problem. Further, adopting SIMPLE scheme to calculate the mathematical model, it computes the mass conservation and obtains the pressure field by the mutual correction of pressure and velocity.

A reasonable accuracy is an important parameter to ensure the convergence of the model. The convergence residual is 10^{-6} in this model and the number of iterations is 1000, so the calculation will be finished when the residuals of each variable were less than 10^{-6} or when the iterations reach 1000. Furthermore, the convergence of the calculation results can be dynamically monitored by checking the iterative residuals of each variable.

5. Results and Discussion

5.1. Distribution Laws of Ventilation Parameters. Using Fluent software, the flow field distributions of outburst gas in tunneling ventilation when the outburst pressure is 0.1001 MPa, 0.1005 MPa, 0.101 MPa, 0.105 MPa, 0.11 MPa, 0.15 MPa, 0.2 MPa, 0.5 MPa, 0.74 MPa, 1 MPa, and 5 MPa are obtained, respectively. Data from the simulation results are extracted and the cloud charts of air pressure, air velocity, and gas concentration under different outburst pressure conditions are drawn, as shown in Figures 4(a)~4(k). The cloud chart of air pressure is the plane where the height equals 1 m ($z = 1$). The two contour maps of velocity and gas concentration above are the outlet of return air roadway, and the two contour maps below are the inlet of the return airway.

The outburst gas is the external energy source into the tunneling ventilation system after the gas outburst accident. From Figure 4, with the increase of outburst pressure, the air pressure is rapidly rising in the heading face. Then, a high-pressure zone instantly formed; it makes all of the inlet and outlet in return airway into relative low pressure areas. As the outburst pressure is higher than the inlet of return airway, the outburst gas can overcome the air resistance loss of the return airway, and then the airflow will be reversed.

The data of velocity magnitude, CH_4 concentration, and total pressure of inlet and outlet of the return airway extracted from simulation results are shown in Table 2. All parameters are taken as the maximum value on the plane.

As shown in Table 2, the inlet velocity and CH_4 concentration are less than the outlet velocity and CH_4 concentration with the increase of outburst pressure. Before the outburst pressure is 0.1001 MPa, the absolute pressure at the inlet is less than the absolute pressure at the outlet, and the other states are opposite.

Defining the relative variation coefficient is the quotient of the relative change rate of air pressure and the relative change rate of the outburst gas pressure, which is calculated as shown in Figure 5. Moreover, the variation law of inlet and outlet pressure in return airway with outburst pressure is also shown in Figure 5.

From Figure 5, there is a gradually decreasing relationship between inlet and outlet of return airway and the outburst pressure. With the increase of the outburst pressure (from 1 hPa to 1 MPa), the inlet pressure increases to 264 hPa and the outlet pressure increases to 289 hPa. The relative variation coefficient of pressure in the inlet of return airway decreases from 1501.5 to 1.62, and the outlet decreases from 2002 to 1.65. Then, the gas emission rates of inlet and outlet in return airway are calculated. The variation

FIGURE 3: Physical model and its meshing.

TABLE 1: Boundary conditions.

Boundary category	Location	Boundary type	Species	Gauge total pressure
Inlet boundary	Inlet of return airway	Pressure inlet	$O_2 = 20\%$, $N_2 = 80\%$	6 Pa
	Outburst	Pressure inlet	$CH_4 = 100\%$	(1, 5, 10, 50, 100, 500) hPa; (0.1, 0.4, 0.64, 0.9, 4.9) MPa
Outlet boundary	Air duct outlet	Velocity inlet	$O_2 = 20\%$, $N_2 = 80\%$	-14 Pa
	Outlet of return airway	Pressure outlet

FIGURE 4: Continued.

FIGURE 4: Continued.

FIGURE 4: Cloud charts of ventilation parameters under different outburst pressures in heading roadway. (a) 0.1001 MPa. (b) 0.1005 MPa. (c) 0.101 MPa. (d) 0.105 MPa. (e) 0.11 MPa. (f) 0.15 MPa. (g) 0.2 MPa. (h) 0.5 MPa. (i) 0.74 MPa. (j) 1 MPa. (k) 5 MPa.

of gas concentration and gas emission rate with outburst pressure are shown in Figure 6.

As shown in Figure 6, the gas concentration of the inlet and outlet in return airway increases rapidly with the increase of outburst pressure. When the outburst pressure is greater than 0.15 MPa, the gas concentration exceeds 98% in tunneling ventilation system. Furthermore, the gas emission also increases due to the high concentration of outburst gas. It can reach $2.5 \times 10^5 \text{ m}^3/\text{min}$, while the outburst pressure was 1 MPa of inlet and outlet of return airway. Because the air velocity of the outlet of return airway is greater than the inlet and the pressure is lower than inlet, the gas concentration and gas emission of the outlet are greater than those of the inlet.

5.2. Airflow Disturbance Law of Roadway Intersection.

The intersection of tunneling roadway and return airway is the confluence point of airflow, and it is the key position of tunneling ventilation system. The pathline of air velocity at 1 m ($z = 1 \text{ m}$) is drawn in Figure 7. Figure 7(a) shows the conditions of no outburst, and Figures 7(b) to 7(l) are the different outburst pressures from 0.1001 MPa to 5 MPa.

Figure 7 shows that, before the occurrence of gas outburst accident, the pathline of windward return airway and the intersection are relatively gentle. There is merely a small vortex in the upwind return airway. After the occurrence of

gas outburst accident, the pathline vortex appears in both the windward and the upwind sides of the return airway. In addition, the range and intensity of vortex are larger with the increase of outburst gas pressure. Because the leeward return airway cannot exhaust the outburst gas in time, the gas migrated in reverse direction along the windward return airway. Then the airflow reversal phenomenon emerges.

5.3. Airflow Reversal Law of Return Airway. According to the air velocity of the inlet and outlet of return airway, the variation curve of inlet and outlet air velocity of return airway with outburst pressure is shown in Figure 8.

Airflow reversion will seriously affect the safety and stability of ventilation system, especially in the intake airway. Figure 8 shows that when the outburst pressure increases from 1 hPa to 1 MPa, the air velocity of the inlet decreases from -1.38 to -284.44 m/s , and the air velocity of the outlet increases from 3.10 to 297.38 m/s . A negative sign indicates the opposite direction of airflow. The airflow reversal quantity has an important impact on the ventilation system. Calculating the airflow reversal degree in each state, the relationship between outburst airflow pressure and airflow reversal degree is drawn in Figure 9.

Form Figure 9, the airflow reversal degree of the inlet of return airway decreases from -1.29 to -265.8 when the outburst pressure increases from 1 hPa to 1 MPa. It is a cubic

TABLE 2: Ventilation parameters of inlet and outlet in return airway.

Outburst pressure (MPa)	Inlet			Outlet		
	Velocity magnitude (ms^{-1})	CH_4 (%)	Pressure (Pa)	Velocity magnitude (ms^{-1})	CH_4 (%)	Pressure (Pa)
0	1.07	0	6	1.62	0	-12
0.1001	-1.38	78.89	7	3.10	77.93	-11
0.1005	-4.65	90.64	13	5.72	90.67	-3
0.101	-7.00	92.63	22	7.91	93.58	7
0.105	-16.72	95.67	99	17.72	97.27	90
0.11	-24.15	96.68	198	25.36	97.82	198
0.15	-55.75	97.99	1025	58.07	98.5	1092
0.2	-80.07	98.29	2104	83.49	98.66	2271
0.5	-170.00	98.67	9450	177.54	98.84	10305
0.74	-226.95	98.75	16829	236.41	98.88	18275
1	-284.44	98.80	26422	297.38	98.99	28914
5	-2142.67	98.97	1496880	2255.34	98.99	1659410

FIGURE 5: Variation law of inlet and outlet pressure in return airway.

FIGURE 6: Variation of gas concentration and gas emission rate with outburst pressure.

FIGURE 7: Ventilation pathline of tunneling roadway intersection.

FIGURE 8: Variation curve of inlet and outlet air velocity with outburst pressure.

FIGURE 9: Relationship between airflow reversal degree and outburst airflow pressure.

polynomial relationship between airflow reversal degree and outburst airflow pressure. The correlation coefficient is 0.99932.

6. Conclusions

This paper analyzes the main characteristics of coal and gas outburst accidents, proposes the degree of outburst airflow reversal, and studies the principle of airflow reversal in the tunneling ventilation system. Then, ventilation parameters are calculated by the simplified topology diagram of the tunneling ventilation system, and the airflow reversal model of tunneling ventilation system under different conditions is established. The main results are as follows.

The inlet pressure increases to 264 hPa and the outlet pressure increases to 289 hPa, while the outburst pressure increases from 1 hPa to 1 MPa. Furthermore, the relative variation coefficient of pressure in the inlet of return airway

decreases from 1501.5 to 1.62, and the outlet decreases from 2002 to 1.65. The air velocity of the inlet decreases from -1.38 to -284.44 m/s, and the air velocity of the outlet increases from 3.10 to 297.38 m/s.

The gas concentration of the inlet and outlet increases rapidly in return airway with the increase of outburst pressure. When the outburst pressure is greater than 0.15 MPa, the gas concentration exceeds 98% in tunneling ventilation system; and there is a cubic polynomial relationship between airflow reversal degree and outburst pressure.

Data Availability

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

Conflicts of Interest

The authors declare that they have no conflicts of interest.

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