Numerical Simulation Study on the Laws of Smoke Backlayering of Fire in Level Roadway of Metal Mine

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Abstract. In order to study the law of smoke backflow in the middle of a metal mine fire, the FDS fire simulation software was used and the actual mine was used as the research background to establish a model including the middle section and the ramp. Set 6 kinds of fire source power of 5MW, 10MW, 15MW, 20MW, 25MW and 30MW, 1m/s, 1.5m/s, 2m/s, 2.5m/s and 3m/s 5 kinds of mid-range wind speed and 5%, 10%, 15% and 18% slopes are used to study the development rule of flue gas counterflow under different conditions. The results of the study show that the reverse flow range of the smoke flow in the middle section of different fire source powers can reach 8~30m, and the wind speed in the middle section has a significant effect on the suppression of the reverse flow of the flue gas. At the time, the length of fire smoke counterflow gradually decreased.

1. Introduction
With the continuous increase in the mining range and mining intensity of metal mines, the use of underground fuel oil equipment is increasing. Multiple large-scale shoveling equipment and other vehicles operating in the middle section of the concentrated production road increase the risk of mine fires. Due to the poor underground mining environment and the closed environment, the working faces of all roadways are very complex. Once a fire occurs, it will quickly spread. During the fire, smoke, high temperature, and toxic and harmful gases will be produced and cause serious harm to the workers under the mine \cite{1-2}.

In the field of roadway fire, scholars at home and abroad have done a lot of research \cite{3-10}, but few studies on the flue gas counterflow rule when fire occurs in middle and sloping roadway. Therefore, this paper takes the actual mine as the research object to simulate, so the middle and slope roadway models are established to study the influence of different fire source scale, wind speed and slope slope on the flue gas counterflow law when the diesel engine fires in the middle roadway. Formulate corresponding emergency plans when they occur.

2. Midcourse fire model establishment
2.1. Physical Model
The structure of level roadway is like Figure 1. There are two main laneways, one is the level roadway of the horizontal tunnel, the section size is 4.2m x 3.2m, the other is ramp, and the the section size 5.4m...
The air flows into the level roadway and continues downward respectively. The airflow of the level roadway flows through the stope, finally, enters the return-air at the boundary of the left ore body. Based on this, a FDS fire calculation model is established, as shown in Figure 2. In the model, the horizontal distance between the upper and lower ends of ramp and the intersection with the level roadway is 20m, and \( \beta \) is the slope of the ramp. The length of the level roadway is adjusted by the need of each influence factor, and the fire source is located in the middle position. The surrounding rock of the roadway is sandstone, and the specific parameters are shown in Table 1. A longitudinal section is arranged in the middle of the roadway model to record the longitudinal temperature changes in fire process.

![Figure 1. The structure of -630 level roadway.](image)

![Figure 2. Fire model diagram of level roadway.](image)

Table 1. Parameters of surrounding rock

| Thermophysical properties parameters |   |
|--------------------------------------|--|
| density(kg/m³)                       | 2620 |
| specific heat(kJ/kg·K)               | 0.84 |
| Thermal conductivity(W/(m·K))        | 2.2  |

The fire size, air velocity and ramp slope are respectively used as variables to simulate the law of the gas counter-current in the level roadway. When one factor is used as a variable, none of the other factors will change.

2.2. Grid setting and convergence verification

The grid size is given by the dimensionless expression
\[
D^* = \left( \frac{Q}{\rho_a c_p T_a \sqrt{g}} \right)^{2/5}
\]

(1)

Where \( D^* \) is fire characteristic diameter, m; \( Q \) is fire size, W; \( \rho_a \) is air density, kg/m; \( c_p \) is heat capacity at constant pressure, J/(kg·K); \( T_a \) is air initial temperature, K; \( g \) is acceleration of gravity, m/s². \( \delta x \) is the size of the mesh of the model. \( D^*/\delta x \) is flame characteristic size. When the value of \( D^*/\delta x \) is between 4 and 16, the simulation result is convergent.
To determine the grid size of the model, we set the fire size to 15MW and the middle air velocity to 2.5m/s. The temperature detector is set at every 0.5m between the roof above the fire source and the upper wind from the top of the fire source 10m to detect the flue gas temperature in different locations of the upper part of the fire source. The formula (1) calculates that the grid size should be between 0.172m and 0.689m. Therefore, this paper compares and analyzes the five different grid sizes of 0.2m, 0.3m, 0.4m, 0.5m and 0.6m. Figure 3 shows the temperature distribution between the roof above the fire source and the upper wind from the top of the fire source 10m. As the size of the grid decreases, the temperature curve tends to be uniform. The simulation results are closer of 0.2m, 0.3m and 0.4m. Considering the two factors of calculation accuracy and computation time, the grid size of the fire model is 0.3m.

2.3. **Fire source settings and initial conditions**

This paper simulates the fire situation when a diesel vehicle is on fire, so the combustible reaction type is heptane reaction, and the numerical simulation time is 300s. The initial temperature is 20°C, the initial pressure in the roadway is 101.325kPa, the air inlet at the upper end of the slope roadway, the incoming material is air, and the lower end of the roadway and the end of the middle roadway are free air outlets.

3. **Influence of fire size and air velocity on gas backlayering length in the level roadway**

3.1. **Condition setting**

(1) The influence of fire size. In the study of the effect of the fire size and air velocity on backlayering length in the level roadway, considering the actual situation and experience, the fire size is set to 5MW, 10MW, 15MW, 20MW, 25MW and 30MW respectively, and the other parameters are unchanged.

(2) The influence of air velocity on backlayering length in the level roadway. According to Fig. 2, the exit air velocity of the ramp is kept unchanged by 1.5m/s, and the air velocity in the level roadway is 1m/s, 1.5m/s, 2m/s, 2.5m/s and 3m/s respectively. The fire size of the level roadway is determined to be 15MW.

3.2. **Simulation results and analysis**

There is no specific size of the model in the analog image and the stable slice map generated by FDS. We can not accurately observe the backlayering length of the gas, so we directly enumerate the isotherm diagram after the Tecplot processing. When the fire size is 5MW, the isothermal diagram of reverse gas flow of the fire source and its upper part is shown in Figure 4, which reflects the temperature distribution of the fire. Figure 5 shows the enlarged temperature diagram, reflecting the early phase of the countercurrent gas. The isotherms of reverse gas flow in the early phases under different working
conditions are not listed here. Only the results of backlayering length and related parameters are listed in Table 2.

From the study of backlayering length of the fire gas in the roadway [13], it is found that the backlayering length is not only related to the fire size, but also related to the air density, heat capacity at constant pressure, the initial temperature of the environment, the height of the roadway and the air velocity. As the height of the roadway $H$ cannot fully reflect the geometric characteristics of the tunnel section, the hydraulic diameter of the roadway is used to replace the height of the roadway.

$$d = \frac{4A}{P} \quad (2)$$

Where $d$ is hydraulic diameter, m; $A$ is section area of roadway, $m^2$; $P$ is section perimeter, m.

**Figure 4.** Reverse gas flow isotherms.  **Figure 5.** Reverse gas flow isotherms in the early phase.

In order to study the influence of fire size on gas backlayering length, two dimensionless parameters $L/d$ and $Q^*/V^*$ are introduced, in which $L$ is the backlayering length; $Q^*$ is dimensionless fire size; $V^*$ is dimensionless wind velocity; $V$ is longitudinal wind velocity, m/s. The calculation formula is as follows:

$$Q^* = \frac{Q}{\rho_o C_p T_a g \frac{V^2}{2}} \quad (3)$$

$$V^* = \frac{V}{\sqrt{gd}} \quad (4)$$

The hydraulic diameter of the level roadway can be calculated as 3.63 m by formula (2). When the air velocity is 2.5 m/s, the $V^*=0.419$, $V^*V^*=0.07364$. 


Table 2. Related parameters of reverse gas flow under different fire size.

| Fire size | $L$ | $L/d$ | $Q^*/V^*$ |
|-----------|-----|------|-----------|
| 5 mw      | 8.6 | 2.369| 0.167     | 2.27     |
| 10 mw     | 9.05| 2.493| 0.335     | 4.54     |
| 15 mw     | 19.1| 5.26 | 0.502     | 6.82     |
| 20 mw     | 21.6| 5.95 | 0.669     | 9.09     |
| 25 mw     | 27.7| 7.63 | 0.836     | 11.36    |
| 30 mw     | 37.9| 10.44| 1.004     | 13.63    |

When the fire size is 15MW, the related parameters of reverse gas flow under different air velocity are shown in Table 3.

Table 3. Related parameters of reverse gas flow under different air velocity.

| air velocity | $L$ | $L/d$ | $Q^*$ | $Q^*/V^*$ |
|--------------|-----|------|-------|-----------|
| 1 m/s        | 126.3| 34.79| 0.0047 | 106.48    |
| 1.5 m/s      | 73.7 | 20.3 | 0.0159 | 31.55     |
| 2 m/s        | 38.3 | 10.55| 0.0377 | 13.31     |
| 2.5 m/s      | 19.1 | 5.26 | 0.0736 | 6.82      |
| 3 m/s        | 2.6  | 0.716| 0.1270 | 3.94      |

The results of the parametric relationship between the dimensionless parameters $L/d$ and $Q^*/V^*$ were plotted as scatter plots and the logarithmic fitting is performed, as shown in Figure 6, the fitting curvature $R^2=0.986$.

![Figure 6. The fitting curves of $L/d$ and $Q^*/V^*$.](image)

In summary, when the ramp slope is 18%, the middle section size is 4.2m×3.2m, the hydraulic diameter $d$ is 3.63m, and the air velocity and fire size are used as variables, the formula for the gas backlayering length of the level roadway fire is as follows:

$$\frac{L}{d} = 16.115 \ln\left(\frac{Q^*}{V^*} + 11.308\right) - 41.62$$
4. Influence of the ramp slope on gas backlayering length in the level roadway

In the model of figure 1, the air velocity and horizontal direction length remain unchanged, and the slope \( \beta \) of the ramp is set to 5\%, 10\%, 15\% and 18\% respectively. The air velocity at the lower end of sloping ramp is 1.5m/s, the air velocity in the level roadway is 2.5m/s, the fire size is fixed to 15MW. This model has been verified with the convergence of the grid set.

We set up a horizontal single roadway to compare the gas backlayering length of fire under different ramp slopes. The location of single roadway is from -140m to 0m, and the fire source is in the middle, that is, at 70m. The right end of the single roadway is a free opening, and the left end is the outlet of 2.5m/s. The wall surface and reaction of the roadway are not changed.

The gas backlayering length of the horizontal single roadway and the ramp of different slopes is shown in Table 4. \( L \) is the distance that the gas reverse flow along the direction of the roadway, the unit is m.

It can be seen from table 4 that with the increase of ramp slope, the gas backlayering length in the level roadway will decrease.

When the slope of the ramp is 5\% and 10\%, with the increase of slope, the trend of reducing the gas backlayering length are not obvious, other slopes are more obvious.

This is contrary to the conclusion that the gas backlayering length is positively correlated with the dip of the inclined single roadway. It is mainly due to the downward flow of ramps. In practice, considering the economic and safety of transportation, the slope range of ramp is generally 14\% to 17\%, which can play a role in reducing the gas reverse flow.

| \( \beta \) | \( L \) |
|---|---|
| 0   | 55.5 |
| 5\% | 34.6 |
| 10\%| 31.5 |
| 15\%| 29.1 |
| 18\%| 19.1 |

5. Conclusion

The fire source power, wind speed and slope gradient of the middle tunnel were changed respectively, and the laws and influencing factors of the middle section fire smoke were calculated and simulated. It can be seen from the calculation and simulation results that the mid-stage fire smoke under different conditions has a certain range of counterflow. main conclusion:

(1) The backflow range of the smoke flow of the middle section of different fire source powers can reach 8~30m; when the wind speed of the middle section is 1~3m/s, the backflow range of the smoke of a certain power source is several meters to more than 100 meters. It means that there is a fire within 30m of the middle entrance, and the flue gas easily enters the ramp countercurrent to expand the mine disaster. Therefore, the middle entrance has a certain range to strengthen vehicle management and prevent fires; the middle section wind speed has an obvious effect on suppressing the smoke backflow, so the middle section of normal production in case of fire, the wind shall not be stopped or reduced.

(2) The calculation simulation shows that for the downwardly ventilated slope, the slope has an effect on the reverse flow range of the fire smoke in the connected middle section. As the slope of the slope increases, the length of the middle section fire smoke reverse flow gradually decreases. Considering the economic safety of transportation in practice, the slope of the main ramp is about 16\%, which can play a role in reducing the smoke backflow.

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