Numerical simulation study on the distribution law of smoke flow velocity in horizontal tunnel fire

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Abstract. According to the fluid similarity theory, the simulation experiment system of mining tunnel fire is established. The grid division of experimental model roadway is carried on by GAMBIT software. By setting the boundary and initial conditions of smoke flow during fire period in FLUENT software, using RNG $k-\varepsilon$ two-equation turbulence model, energy equation and SIMPLE algorithm, the steady state numerical simulation of smoke flow velocity in mining tunnel is done to obtain the distribution law of smoke flow velocity in tunnel during fire period.

1. Introduction
The ashes and smoke produced by the forest and mine fire contains various toxic, harmful and corrosive components and dangerous consequences for the environment. In the case of mines, it can not only make the underground workers suffocation or poisoning, reduce the visibility of the operation environment, but also cause great difficulty on the safe evacuation of the affected population[1-4]. The study on flow characteristics of fire smoke in tunnel during fire period, especially the distribution law of smoke flow velocity, can provide theoretical guidance and technical support for accurately grasping the movement direction and diffusion degree of fire smoke, and also can reduce property losses and casualties to the maximum limit. Therefore, it is of great significance to control the fire development.

2. Establishment of the simulation experiment system of mining tunnel fire
According to the principle of fluid similarity, we choose the main transport crossheading, the auxiliary transport crossheading and two contact lanes that lay in the air intake system of Dingjialiang coal mine in Inner Mongolia as the prototype. And we make proper simplification by constructing the experimental model according to 1:20 proportion. In the experimental system, the length of the main transport crossheading and the auxiliary transport crossheading is all 8.35m. The length of two contact lanes is all 1m, the width of all the sections is 0.25m, the height of all the sections is 0.175m and the broken area is 0.045m$^2$.

Fourteen measuring sections are arranged in the experimental device. A temperature measuring point as well as a dynamic pressure measuring point is arranged on each measuring section. The wind
speed measurement point is in the center of the section and the temperature measuring point is 10mm top of the wind speed measuring point. The temperature measuring thermocouple and the dynamic pressure measuring pitot tube stretch into the tunnel from the reserved hole of roadway roof. We fill the gap between the reserved hole, the temperature measuring thermocouple and the dynamic pressure measuring pitot tube with plaster when testing [5-7]. The overall structure of the experimental system and the arrangement of measuring points are shown in Figure 1.

3. Numerical simulation of smoke flow velocity field in tunnel during fire period

3.1. Mesh division
The experimental model tunnels are meshed by using GAMBIT software which is a pre-processing CFD software of ANSYS Inc. Company in America, the grid of which are mainly hexahedral mesh units. Of course, the wedge grids also exit in the appropriate location. The mesh results are shown in Figure 2.

3.2. Setting of boundary conditions and the selection of calculation models
The divided grid model is import into FLUENT software which is CFD software of ANSYS Inc. Company in America. As the assumption, the fire source is put at the left entrance of the main transport crossheading when simulating the distribution situation of the velocity field of smoke flow in tunnel after the fire occurs. Inlet 1 is the velocity-inlet, the inlet material of which is the flue gas (the mixture of CO, CO₂ and air). The initial velocity of the tunnel entrance is 0.5 m/s and 2.5m/s (that is \( v_{in} = 0.5 \text{ m/s} \) and \( v_{in} = 2.5 \text{ m/s} \)). And the forward direction of velocity is X axis and temperature is 500K.
The exit condition outlet is set at the exit of the model tunnel, the boundary condition of which is the free flow (OUTFLOW). The roadway wall is set to WALL, with no slip and adiabatic, and the temperature is 283K. The roof and floor in tunnel are set as coal wall and both sides of tunnel are set as concrete wall. The RNG $k-\varepsilon$ two equation turbulence model is selected as the calculation model. The energy equation and the SIMPLE algorithm are also used [8-14]. The fire source in tunnel is set as the steady state heat source that can release heat steadily. The simulation time is set to “steady”.

3.3. Analysis of numerical simulation results

According to the different inlet velocity ($v_{in}$) of airflow in tunnel, a few pictures are selected from the FLUENT software for analysis, in which different cross sections are taken. The data are taken such as \(x=0.45m, 1.1m, 2.6m, 4.35m, 6.05m\) and \(7.75m\) on the X direction, which are the corresponding sections (from the first section to the twelfth section) of each measuring point in the experimental model. Also the data are taken such as \(y=0.125m, 0.8m\) and \(1.4m\) on the Y direction, that is, three cross sections are taken separately from the longitudinal direction of the main transport crossheading, the contact lane and the auxiliary transport crossheading in the experimental model[15-18]. At last, the data are taken such as \(z=0.025m\) and \(0.15m\) on the Z direction, that is, the sections which are on the bottom and the top of roadway are intercepted.

(1) Numerical simulation results of smoke velocity field when the inlet velocity is 0.5 m/s

Figure 3 shows the numerical simulation cloud images of velocity field of smoke flow in fire tunnel when the entrance velocity is 0.5m/s(that is \(v_{in}=0.5m/s\)). Figure 4 and figure 5 show the distribution curves of velocity field of smoke flow.

It can be seen from Figure 3 that the smoke flow velocity in tunnel changes when \(v_{in}=0.5m/s\), although the change range is small. During the top (\(z=0.15m\)) and the bottom (\(z=0.025m\)) of tunnel, the velocity increase at the top of main transport crossheading is faster than that of the bottom. The smoke flow velocity at the top of the main transport crossheading basically remains unchanged from the tunnel air inlet to the first contact lane intersection, but it rises suddenly at the intersection, and then gradually decreases from the intersection to the right side. The speed takes on symmetrical distribution in the intersection of the auxiliary transport crossheading along the channel and the first contact lane. The smoke flow velocity at the bottom of the main transport crossheading basically remains unchanged from the first contact lane intersection to the right side. But the smoke flow velocity slightly increases at multiple locations in the auxiliary transport crossheading.

In Figure 4, it can be observed that the velocity of smoke flow is gradually reduced from left to right on the center line of the main transport crossheading when \(v_{in}=0.5m/s\) and there is a fastest decline area in the intersection range (that is from 1.725 m to 1.825m along the X axis) between the main transport crossheading and the first contact lane, the decrease value of which comes to 0.27m/s. This phenomenon appears because that there is local resistance which can hinder the flow movement of smoke in the intersection point of the main channel and the first contact lane. So the velocity rate greatly decreases on that area. The smoke flow velocity change is not obvious on the center line of the auxiliary transport crossheading, which is substantially below 0.1m/s and only slowly rises in the intersection point of the main channel and the second contact lane (\(x=6.975m\)).

In Figure 5, it can be observed that the smoke flow velocity is very low on the center line of two contact lanes when \(v_{in}=0.5m/s\). The velocity rate of the first contact lane is about 0.1m/s and it is only about 0.05m/s in the second contact lane. This phenomenon shows that the two contact lanes are less affected by the roadway fire at this time and the fire smoke flow has not spread there.
Figure 3. Numerical simulation cloud images of velocity field of smoke flow in fire tunnel ($v_m=0.5\text{m/s}$).

Figure 4. Distribution curves of velocity field of smoke flow ($v_m=0.5\text{m/s}$) along the X axis on the centre line of the main transport crossheading and the auxiliary transport crossheading.

Figure 5. Distribution curves of velocity field of smoke flow ($v_m=0.5\text{m/s}$) along the Y axis on the centre line of two contact lanes.
(2) Numerical simulation results of smoke velocity field when the inlet velocity is 2.5 m/s

Figure 6 shows the numerical simulation cloud images of velocity field of smoke flow in fire tunnel when the entrance velocity is 2.5 m/s (that is \(v_{in}=2.5\) m/s). Figure 7 and Figure 8 show the distribution curves of the velocity field of smoke flow.

In Figure 6, it can be observed that the smoke flow velocity variation trend of the top and bottom of the tunnel is basically the same when \(v_{in}=2.5\) m/s. The smoke flow velocity gradually reduces from the left to the right in the main transport crossheading and only slightly increases at the intersection point of two contact lanes in the auxiliary transport crossheading. The smoke flow velocity at the exit of the tunnel is higher than that in the two contact lanes and the auxiliary transport crossheading, but lower than that at the entrance of the tunnel.

In Figure 7, it can be observed that the smoke flow velocity just declines fast in the intersection point of the two contact lanes on the center line of the main transport crossheading when \(v_{in}=2.5\) m/s, the decreasing amplitude of which is respectively up to 0.5 m/s and 0.45 m/s. The velocity changes little in the other parts of the main transport crossheading and it basically maintains at around 2 m/s. The smoke flow velocity increases fast in the intersection point of the two contact lanes on the center line of the auxiliary transport crossheading, the increasing amplitude of which is respectively up to 0.8 m/s and 0.9 m/s. The velocity changes little in the other parts of the auxiliary transport crossheading and it basically maintains at around 0.4 m/s. The smoke flow velocity on the centerline of the auxiliary crossheading is lower than that in the main transport crossheading.

In Figure 8, it can be observed that the trend of smoke flow velocity is basically consistent on the center line of two contact lanes when \(v_{in}=2.5\) m/s, which is all lower than 0.5 m/s. The smoke flow velocity just declines fast in the intersection point of the two contact lanes and the main transport crossheading \((y=0.25)\), the decreasing amplitude of which is respectively up to 2.35 m/s and 1.65 m/s. This phenomenon appears because that there is local resistance which can hinder the flow movement of smoke.

![Contours of Velocity](image)

**Figure 6.** Numerical simulation cloud images of velocity field of smoke flow in fire tunnel \((v_{in}=2.5\) m/s).
4. Conclusions

(1) It can be seen from these simulation charts from Figure 3 to Figure 8 that the change of smoke flow velocity in tunnel generally has the following rules after the fire happens, no matter how much the airflow entrance velocity value is: The velocity of smoke flow gradually reduces from left to right on the center line of the main transport crossheading. The velocity of smoke flow at the exit of the tunnel is higher than that in the two contact lanes and the auxiliary transport crossheading, but lower than that at the entrance of the tunnel. The velocity of smoke flow only increases slightly at the intersection point of two contact lanes in the auxiliary transport crossheading and it is unchanged in other places. The velocity distribution is basically consistent in two contact lanes. And the speed at the intersection point of two contact lanes and two transport crossheadings is significantly lower than that at the entrance and exit of the tunnel. This phenomenon appears because that there is local resistance at the intersection point and there is throttling effect during the tunnel fire, which can hinder the flow movement of smoke and reduce the smoke flow velocity.

(2) By comparing the experimental measurement results and numerical simulation results, the distribution law of smoke flow velocity during fire are basically the same, indicating that the numerical simulation model established according to the physical model is accurate and the boundary conditions and calculation parameters is reasonable and feasible.

Figure 7. Distribution curves of velocity field of smoke flow ($v_{in}=2.5\text{m/s}$) along the X axis on the centre line of the main transport crossheading and the auxiliary transport crossheading.

Figure 8. Distribution curves of velocity field of smoke flow ($v_{in}=2.5\text{m/s}$) along the Y axis on the centre line of two contact lanes.
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