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# Numerical Simulation Study on Fire Resistance and Thermal Roundabout Flow Phenomenon of the Tunnel Fire

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**Abstract:** Basing on thermodynamics and fluid mechanics, the viscous hindering effect of mine fire on fluid flow and throttling effect were analyzed in detail. Beyond that, fire resistance was classified according to various generation mechanisms. Fire resistance was composed of local resistance formed by barrier effect of flame and viscous frictional resistance formed by thermal plume. Numerical simulation experiments showed that the viscous resistance of the air flow becomes larger once a fire occurs in the tunnel, and it increases with the scale of fire. Throttling effect is influenced by fire scale and inlet airflow rate. It increases with the scale of fire and decreases with the increasing of inlet airflow rate. Study results have important practical significance for the simulation of the mine fire and the guidance of scientific disaster relief.

***Keywords:*** *Tunnel fire, Heat resistance, Throttling effect, Fluent, Reverse flow.*

## 1. Introduction

Research the temperature, poisonous and harmful gas distribution, and its effect on wind flow is important for disaster relief in the tunnel fire [1-3]. Affected by external and internal factors, mine ventilation system changes dynamically. When the well lane is on fire, physical properties and flow state of the air flow in the tunnel will change due to the influence of heat source. And then, it will affect the local network system and lead to the changes of its air flow [4-6]. The research of the influence of heat on the air flow is very important for the development of the mine fire plan and the development of the disaster relief work. In view of this problem, a lot of exploration and research have been carried out at home and abroad. By studying the influence of heat conduction and heat radiation on the temperature, density and static pressure of air flow, the influence factors of fire pressure are analyzed, and the mathematical description is carried out by Zhang Guoshu [7].

Detailed study was made on the thermal blocking of one-dimensional and two-dimensional fluid flow, and the thermal resistance coefficient of heat pipe flow is calculated and deduced by Guo Zengyuan [8]. Focused on throttling phenomenon, the concept of the thermal resistance was put forward and experimental study on its influence factors was carried out by Wang Deming [9]. Comprehensively considered heat's effect on viscosity and kinetic energy, relationships between thermal resistence and fire scale or inlet airflow rate were experimental studied by Cheng Xiaohu [10].

Under comprehensive consideration of the heat on the viscosity of the fluid and the fluid kinetic effects based on the function of, through experiments of thermal resistance, respectively, with the scale of fire and air velocity in the inlet size relationship. Li Zongxiang based on combustion and through the experiment, studied the relations among the wind speed fire area and fire area resistance [11].

The related research shows that the heat can not only directly change the density of the air flow in the tunnel and affect the gas flow state of the local ventilation system, but also lead to the generation of heat blocking phenomenon and affect the viscous resistance coefficient and kinetic energy of airflow. Related literatures have only done qualitative research and experimental analysis in thermal resistance and its influence factors, instead of making detailed analysis and research on its mechanism and related theory.

This paper will simplify gas flow in underground tunnel and study the mechanism of thermal roundabout flow phenomenon of thermal resistance and its mathematical description by numerical simulation, which provided theoretical basis for mine ventilation network solution.

## 2. Concept and related theory of thermal resistance

Under the influence of heat effect, the air temperature in the tunnel increases and the density of the air reduces, and the natural wind pressure formed is called fire pressure [12]. Fire pressure performs as ventilation resistance and ventilation power respectively when it is downward ventilation and upward ventilation.

Generation of fire pressure and its effect is not only related to the thermal power in the roadway, but also closely related to the elevation of the two ends of roadway. It is found in the experiment that the thermal power phenomenon, which is usually called throttling phenomenon, still exists even in the horizontal tunnel. In order to quantify the throttling phenomenon, the concept of thermal resistance was put forward combined with the actual situation.

### 2.1 Thermal resistance

Because of the viscous resistance only exists in the boundary layer, the turbulent flow resistance is mainly expressed as inertial resistance. Inertial resistance refers to the resistance caused by turbulent fluctuations in the process of turbulent flow [13]. Its size is affected by viscosity coefficient of the fluid and fluctuation intensity of the turbulence. Figure 1 is the schematic diagram of fire zoning in horizontal tunnel, where AB is the upwind of the fire area, BC is ignition area and CD is the downwind of the fire area. In this paper, the three regions are divided into the viscous coefficient enhancement area and the turbulent fluctuation enhancement area by the difference of the thermal leading factor.

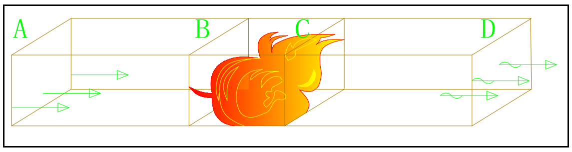


***Figure 1:*** *Schematic diagram of fire zoning in horizontal tunnel*

### 2.2. Viscous coefficient enhancement area

In the process of the airflow in the coal mine, the molecules are in the irregular thermal motion state. As shown in Figure 2, there is the exchange of molecular momentum in the vicinity two fluid micelles' boundary due to the molecular heat movement.

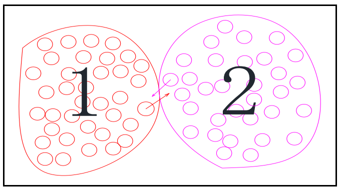


***Figure 2:*** *Schematic diagram of viscosity of fluid micelles*

Because translational and rotational speed of mass group 1 and mass group 2 are different, the average components of the internal molecular heat movement in the velocity direction are also different. If translational and rotational speed of mass group 1 is larger than that of mass group 2, molecules in mass group 1 will enter mass group 2 through thermal motion of molecule. Meanwhile, molecules in mass group 2 will enter mass group 1 carrying their momentum. Mass group 1 promotes rotation and translation of mass group 2, while mass group 2 impedes rotation and translation of mass group 1. This effect is expressed as viscosity between mass groups.

Under the influence of heat, the internal heat movement of the fluid increases, the molecular momentum exchange between the two mass groups becomes more frequent, the interaction force between the fluid mass and its viscosity increase.

According to the above analysis, the AB segment and CD segment mainly performed as increase of fluid viscosity under the thermal effect. However, the velocity changes of the fluid mass do not contribute to the increase of the flow resistance. In this paper, they are divided into a viscous coefficient enhancement area.

### 2.3. Turbulent fluctuation enhancement area

According to the standard model in fluid mechanics the turbulent motion can be decomposed into the mean flow pulsation in direction of flow and the turbulent flow in the other directions [14, 15]. The later' fluctuation intensity can be described by the Reynolds number quantity. When air flow passes through fire, hindered by flame, it can only flow around the flame, which is called thermal roundabout flow phenomenon. Under the influence of thermal roundabout flow phenomenon, the ventilation section decreases, the air flow velocity increases, and the flow velocity increases. With the increase of Reynolds number and fluctuating frequency of wind flow, ventilation resistance increase sharply. In this paper, we will call it the fluctuating frequency enhancement area.

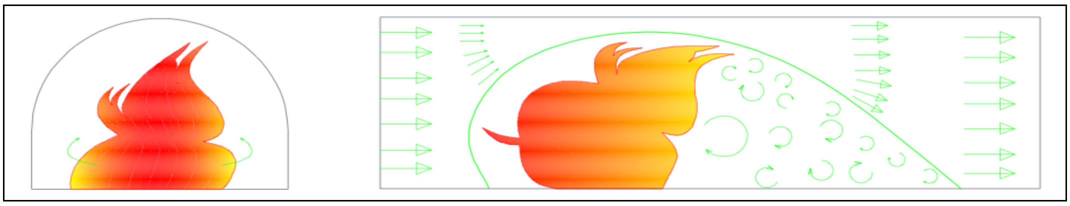

***Figure 3:*** *Schematic diagram of thermal roundabout flow*

In the District of fluctuating frequency enhancement, expansion force of plume will lead to smoke flowing inversely in the upwind side of fire source. While in the downwind side of fire source, vortex will be formed due to gravity, expansion force and detached phenomenon, which result in increase of local resistance. The comprehensive effect of reverse airflow and detached vortex phenomenon is the throttling phenomenon.

## 3. Basic hypothesis and numerical model

### 3.1. Basic hypotheses of the physical model of the horizontal tunnel

Mine fire can be divided into many different forms according to the accident location and fire source. Simulation of mine fire can't meet the specific conditions of fire. Therefore, using physical model as horizontal single lane, the PDF non-premixed combustion model was used to set up the certain mass flow gas phase fuel methane as fire source. Energy equation, radiation model, turbulence model were enabled. The influence of relaxation factor on the air flow, fuel source size, temperature and the distribution of the smoke movement are appropriately reduced when a fire occurs in tunnel. Because most of the tunnels in mines are horizontal tunnels, the typical horizontal single lane model is chosen to study development of the fire. The principles of model design are as follows:

Firstly, horizontal roadway was appropriate simplified as a section of the roadway with the width and height common values for mine roadway. Secondly, through the analysis of combustion characteristics and combustion model, when the fire occurred in the tunnel, flame area is very small relative to the roadway area. Therefore, to consider the most serious disaster when fire source was in the center of tunnel, the flame area was set as a cube with side length of 1m. The fire source was set for a certain mass flow of gaseous fuel methane, which can represent the fire source.

### 3.2. Establishment of physical model

The physical model of horizontal single lane is shown in Figure 4. A horizontal single lane with length of 100m and section of 16m$^2$ square was chosen as study object. Suppose the fire source is at the bottom of the midpoint, the flame area set for a certain quality flow of gas phase methane fuel and calculation of diameter of hydraulic boundary condition setting calculation for 4m.

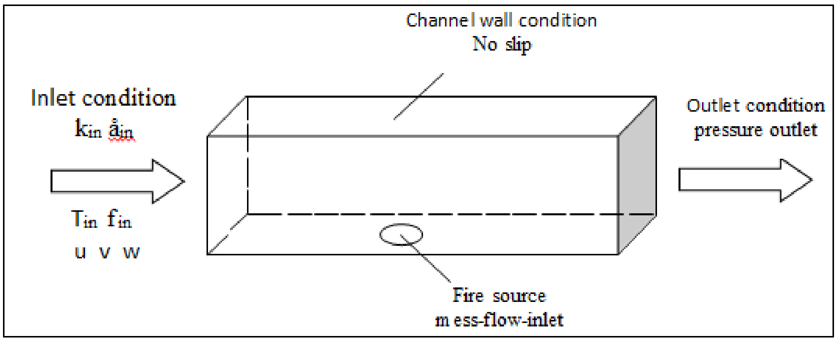


***Figure 4:*** *Level of single physical model of roadway*

### 3.3. The grid parameters

The phenomenon of smoke flow in the mine fire, the smoke flow in the tunnel longitudinal distribution gradient is relatively large, The change law of the source area and the space temperature and the gas flow in the process of the research, Therefore, when dividing horizontal single lane, due to the ratio of length and width of tunnel area is large and the fire source area is small comparing to the tunnel area, fire source area was local refined to achieve the accuracy of the calculation. Its grid number is 98000. The modeling of the roadway physical model and the division of the grid were preceded in the Fluent Gambit.

### 3.4. Setting of initial boundary conditions

The boundary conditions are defined as the solution conditions. Reasonably set up boundary conditions can not only make the calculation process converge fast, but also improve the accuracy of the results.

(1) Boundary conditions of roadway entrance

Inlet conditions was set as inlet velocity 1.2-1.8 m/s. Inlet temperature, inlet material, gauge pressure were set as 293K, air and 0 respectively. The turbulence model was set as standard k-å model and transmission model. Considering the effect of buoyancy, turbulence parameters k-å at the entrance can be calculated using the following equation:

$$k = 1.5 \times (\overline{\mu} \cdot \mathrm{I})^2 \tag{1}$$

$$\varepsilon = C_\mu{}^{3/4} \frac{k^{3/2}}{l} \tag{2}$$

Where, $\overline{\mu}$ is the average speed at the entrance. $C_\mu = 0.0845$.

l=0.07L. L is the equivalent hydraulic diameter (m) at the entrance,

I is turbulence intensity, which is the ratio of the square root of velocity fluctuation to the average velocity. I is low turbulence intensity when less than 1% and is high turbulence intensity when more than 10%. In this paper, I=3.5%.

(2) Boundary conditions of roadway export

When tunnel is on fire and do numerical simulation for combustion and smoke flow, boundary conditions of roadway export was set as fully developed export, where the parameters of the discrete grid of the section have no effect on the adjacent boundary parameters.

The outlet condition is defined as the pressure outlet, and the pressure value is obtained by the average pressure of each node in the internal grid. The modified pressure value form the last step is the initial pressure value of the next step in the discrete grid computing.

(3) The parameters of the roadway wall

Fluent numerical simulation can give certain characteristics to the tunnel walls. The default wall surface condition is no slip, that is, there is no tangential velocity along the wall. The actual speed of the wall is determined by the penetration rate of porous media. Wall penetration was not considered in the calculation of tunnel fire, that is to say the wall velocity is 0.

The calculation of enthalpy needs to know the temperature, fluid velocity, and fluid composition in wall temperature and enthalpy setting. Direct heat transfer between high temperature smoke flow and wall take place during mine fire period. Outer wall temperature is constant and the conduction coefficient of the tunnel wall is set as $2W/m^2K$.

The seepage flow between fluid chemical composition and the walls depends on the mass of the fluid component and the permeability of components in the permeability media. In this paper, it is supposed that there is no penetration between the smoke flow and the wall. So the diffusion coefficient is selected as the default value 0. Because the diffusion coefficient between the smoke flow and the wall is 0, the relationship between turbulent kinetic energy K and component C is as follows.

$$\left.\frac{\partial \Phi}{\partial n}\right|_{\Phi=k\cdot c}=0 \tag{3}$$

(4) Fire source treatment

As discussed in second chapter, when mine tunnel is on fire, the combustion, transportation and transmission process of gas-solid coupling are simplified in order to achieve fast convergence of numerical simulation. Huggett first proposed that the fuel consume every unit mass of oxygen will release a certain quantity of Joule heat. According to Huggett's theory, when consuming $0.3kg/m^2$ methane fuel per second, it will release $1.5MW/m^2$ heat. According to PDF theory in Fluent, the fuel is set as certain mass flow of gas phase $CH_4$ in this paper. Oxidant is the air flowed from ventilation inlet, that mass fraction of oxygen and nitrogen content is 23% and 77% respectively. When studying the change of temperature and smoke flow during the fire period, the combustion area is set as non-adiabatic combustion process, because of huge spread of heat transfer between the fire and wall. PDF non-premixed combustion model is used to simulate combustion area and the fire source is a burning flamelet. In most previous numerical simulation of the fire temperature and smoke flow distribution, fire source are set to a constant temperature area, which simplify the calculation of the temperature and smoke flow. But in the actual process of fire, flame will be influenced by air flow and flame will affect smoke plume. Therefore, in order to obtain more accurate results, it is necessary to consider the chemical reaction of the fire source area in the numerical simulation. The combustion reaction of the fire source is simplified to a simple and rapid chemical reaction. The model does not take into account the specific reaction mechanism; it is supposed that once the fuel encounter oxidant (oxygen), final product is produced in the rapid reaction. Fuel is set to a certain mass flow of gas phase methane.

## 4. Numerical simulation and results analysis

Aiming at different ventilation conditions and the scale of the fire when mine tunnel is on fire, the distribution of temperature, velocity and pressure in the tunnel are simulated.

When the initial flow field is set up in the tunnel fire model, the initial boundary conditions include the pressure level $1.01325x10^5$ pa, the inlet velocity of the wind, temperature boundary conditions 300K and wall no slip condition. Considering the influence of gravity, the acceleration values are set as $9.81m/s^2$.

(1) Inlet velocity set as 1.5m/s, various state parameters are simulated respectively 30s after tunnel is on fire, when fuel mass flow rate at fire source is 0.3kg/s, 0.2kg/s, 0.1kg/s and when the fire source is in the center of the tunnel bottom.

(2) Fuel mass flow rate set as 0.2kg/s (The scale of the fire is relatively serious.), various state parameters are simulated respectively 60s after tunnel is on fire, when inlet velocity is 1.2m/s, 1.5m/s, 1.8m/s and when the fire source is in the center of the tunnel bottom.

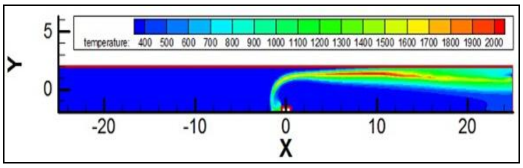


***Figure 5:*** *The temperature distribution when fuel consumption rate is 0.1 kg/s*

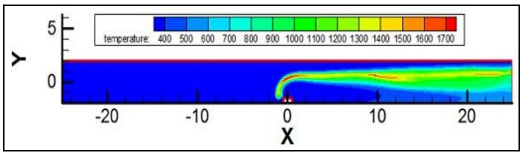


***Figure 6:*** *The temperature distribution when fuel consumption rate is 0.2 kg/s*

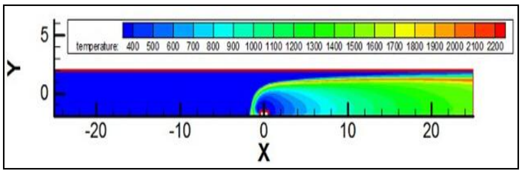


***Figure 7:*** *The temperature distribution when fuel consumption rate is 0.3 kg/s*

In the setting of the calculation model, semi implicit computation based on pressure coupled equations was selected as calculation method. Basic energy equation, RNG k-å two equation turbulence model that considering effects of buoyancy and P1 radiation model were selected. Then, PDF non-premixed combustion model was established to calculate.

When air flow rate is 1.8m/s and 30s after tunnel is on fire, temperature distribution of Z=2 face when fuel consumption rate is 0.1kg/s, 0.2kg/s, 0.3kg/s respectively is as shown from Figure 4.1 to Figure 4.3. When a fire occurs in a tunnel, the temperature of airflow in the ignition area and downwind were affected, while temperature of upwind air almost had no change. The maximum temperature of the air flow was 1700 K, 2000

K, 2200 K when fuel consumption rate was 0.1 kg/s, 0.2 kg/s, 0.3 kg/s respectively. The comparison analysis showed that the higher the fuel consumption rate is, the higher the air temperature is affected. High temperature plume was affected by buoyancy and gravity in vertical direction. Among them, thermal buoyancy and the flow velocity of the plume are positively related to the temperature of the plume. The degree plume affected by gravity is proportional to the density of the plume. The plume is obviously stratified by buoyancy force, which shows that the temperature of plume increases gradually in the vertical direction. When the fuel consumption rate is 0.1m/s or 0.2m/s, the concentration of plume generated by the combustion is relative small, which means the degree high temperature plume affected by gravity is small. On this occasion, the motion of plume is dominated by thermal buoyancy. When high temperature plume moves to the downwind side of the fire area, it rise continuously and diffuse to the roadway space on the whole. When the fuel consumption rate is 0.3m/s, the concentration of plume generated by the combustion is relative large, which means the degree high temperature plume affected by gravity is large. On this occasion, the motion of plume is dominated by thermal buoyancy and gravity. The plume with higher temperature moves upward under the influence of thermal buoyancy, the plume with lower temperature subsides under the action of gravity. During the subsidence, it is not only affected by shear force in the vertical direction, but also affected by shear force generated by thermal expansion in the horizontal direction. Then rotational movement of plume generates, so does the vortex. According to the analysis, the strength of the vortex should increase with temperature and concentration of the plume. That is to say, the strength of the vortex increases with fuel consumption rate.

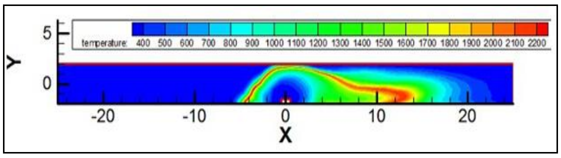


***Figure 8:*** *The temperature distribution when inlet wind speed is 1.2 m/s*

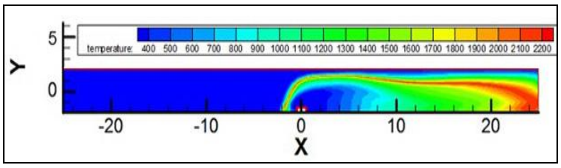


***Figure 9:*** *The temperature distribution when inlet wind speed is 1.5 m/s*

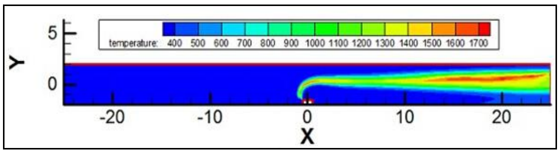


***Figure 10:*** *The temperature distribution when inlet wind speed is 1.8 m/s*

When fuel consumption rate is 0.1m/s and 30s after tunnel is on fire, temperature distribution of central plane when inlet wind speed is 1.2m/s, 1.5m/s, 1.8m/s respectively is as shown from Figure 4.4 to Figure 4.6. As shown in figures, distances of reverse flow is 5m and 2m respectively when air flow rate is 1.2m/s and 1.5m/s. When air flow rate is 1.8m/s, distances of reverse flow is less than 1m, fire spreads to downwind side. From the analysis, we can see that reverse flow phenomenon is obvious when air flow rate is relative small. When air flow rate is relative large, reverse flow phenomenon weaken or even disappear and the entire plume spread to downwind side.

## 5. Conclusions

(1) After the horizontal tunnel is on fires at the bottom, downwind side of fire source is totally affected by fire behavior. The temperature of plume increases with fuel consumption rate. Affected by thermal buoyancy and natural diffusion, the smoke flow stratifies in the vertical direction and move along air flow direction. Therefore, viscous resistance coefficient of plume in the downwind side becomes large and the viscous resistance enhanced area formed.

(2) When the fire intensity reaches a certain level (the fuel consumption rate increases to a certain value, the plume does rotational motion under the influence of gravity and thermal buoyancy. Vortex is then formed near the fire source and the vortex intensity increases with fire intensity.

(3) When airflow rate is relative small, there is reverse flow phenomenon in the upwind side of the fire source. As air flow rate increases, the distance of reverse flow gradually decreases. When the air flow rate increases to a certain value, the reverse plume on upwind side will disappear.

In conclusion, when the tunnel is on fire, roadway ventilation resistance is influence by fire intensity and the air flow rate at the entrance. Viscous resistance of wind increases with fire intensity. When fire intensity increases to a certain value, eddy will form on the downwind side of fire source and the intensity of vertex will increase with fire intensity. Airflow rate is directly related to reverse flow phenomenon. This phenomenon decreases as airflow rate increases.

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