The Smoke Spread Rule under Different Longitudinal Wind Speed in the Case of Fire in a Blocked Tunnel

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Abstract. In recent years the development of the field of underground transportation is entering a new era. At the same time the loss caused by the tunnel fire is also incalculable. In the case of fire, its complex interior, less entrances and exits, and long evacuation routes bring great difficulties to the evacuation of people, often causing significant casualties and property losses. In this paper, FDS will be used to study the smoke spreading law of the tunnel with train blockage in terms of no mechanical ventilation and different ventilation speeds in different fire source locations. The results show that the critical wind speed of the tunnel with train blockage is lower than that of the tunnel without train blockage.

1. Introduction
With the rapid development of China's economy, the transportation has entered the era of rapid development. Vigorously developing underground transportation has become an effective way to relieve the pressure of ground transportation [1-3]. The characteristics of large traffic volume, fast speed and deep underground make fire become one of the major factors threatening the safety of underground traffic [4, 5]. As shown in Figure 1 once there is a fire and the loss is huge especially in the case of traffic jam. China's railway operation, construction in progress and railway tunnels under design and planning are shown in Figure 1 and Figure 2 by the end of 2018. It is estimated that the total number of railway tunnels put into operation in China will reach 17000, and the total length will exceed 20000 km by the end of 2020. Therefore the influence of blockage on the critical wind speed and the temperature characteristics of tunnel fire are the main research hotspot at present [6]. Thomas first proposed the method of longitudinal ventilation to control flue gas counter current [7, 8]. Oka and Atkinson carried out a small-scale tunnel fire experiment and studied the critical wind speed in a horizontal tunnel [9]. Wu and Bakar found that Oka's critical wind speed calculation model can not fully consider the influence of most tunnel sections on critical wind speed [10]. In view of the existence of train blocking in the tunnel and the ignition point located at different positions of the train, FDS software will be used to study the smoke spread law under different longitudinal ventilation speed conditions in this paper.
2. Theoretical calculation of critical wind speed

A large number of tunnel fire physical tests and calculation simulation have proved that there is a critical wind speed in ventilation and smoke exhaust, that is when the longitudinal wind speed is greater than or equal to the critical wind speed the smoke will only spread in one direction for a tunnel with longitudinal ventilation. The relationship between the longitudinal wind speed and smoke diffusion is shown in Figure 3.

Scholars at home and abroad have done a lot of research on the theoretical calculation of critical wind speed and achieved a lot of substantive results, among which the representative ones are:

- Thomas proposed dimensionless critical wind speed based on Froude

\[ V_c = k \left( \frac{gQH}{\rho C_p T_a A} \right)^{1/3} \]  

(1)

- Hesselden et al. Obtained from large-scale experiments and Froude dimensionless numbers

\[ V_{cr} = 0.61K_g \left( \frac{gHQ}{\rho C_p AT_f} \right)^{1/3} \]

(2)

\[ T_f = \frac{Q}{\rho C_p AV_{cr}} + T_0 \]

(3)

- Wu and others obtained by building fire models with different cross-section shapes and introducing hydraulic diameter of tunnel for the first time

\[
V_c^* = \begin{cases} 
0.4 \left( \frac{Q^*}{0.2} \right)^{1/3} & Q^* \leq 0.2 \\
0.4 & Q^* > 0.2 
\end{cases}
\]

\[ \frac{Q^*}{\rho C_p T_g} \frac{V_c^*}{\sqrt{gH}} = \frac{A}{\rho}, \quad H = \frac{A}{\rho} \]  

(4)

The critical wind speed of 7.5 MW fire source is calculated by heselden formula, which is
substituted into the corresponding section data of the section tunnel (saddle tunnel width 5.4m, height 5.2m) and \( V_C = 2.3m/s \). The critical wind speed of 7.5mw fire source is calculated by Wu and Baker, which is substituted into the corresponding section data of the section tunnel, and \( V_C = 2.5m/s \). Based on the above theoretical formula the critical wind speed is about 2.5m/s when there is a fire in the middle of the tunnel.

3. Numerical model

The tunnel between wengjiao road and Maqing road of Xiamen Rail Transit Line 2 is taken as the research object and the smoke diffusion and temperature field distribution in the tunnel are calculated by the numerical calculation software FDS in case of fire in this paper. By changing the location of the fire source, the longitudinal ventilation wind speed and other simulation conditions, the smoke distribution is found under the different working condition. In this paper 1.85M is taken as the critical height. According to relevant data 66℃ and 250 ppm CO concentration are taken as safety standards at critical height. The lower surface of the fire source is attached to the top of the train, and the heat release rate of the fire source is unchanged (7.5MW). The model is shown in Figure 4.

![Model under blocking](image)

The monitoring points are placed at the tunnel ceiling and critical height. The simulated saddle shaped tunnel is 400m in length, 5.4m in width and 5.2m in height. The 400m section tunnel is divided into 20 sections by numerical simulation. Each section is 20m and the total number of grids is 115200 with grid size of 0.5m × 0.5m × 0.5m. The train is a standard B-type train with120m in length, 2.8m in width and 3.5m in height. Fire source size is 3.0m × 1.0m × 0.1M. Initial conditions: the ambient temperature is 20 ℃; the atmospheric pressure is 101325.0pa; the oxygen content in the environment is 23%; the carbon dioxide content is 0.06%; the volume fraction of the initial flue gas is 0ppm; the acceleration of gravity is 9.8m/s2; the air density is 1.21kg/m³; the specific heat capacity of the air at constant pressure is 1.005kj/kg · K; and the impact of the traffic piston wind on the flue gas and temperature in the tunnel is not considered after the fire ;it is assumed that the intensity of fire source is constant and the influence of tunnel indicator light and cable on air flow is ignored. Boundary conditions: (1) set the tunnel entrance (x = 0) as the supply surface to provide different longitudinal wind speed; set the tunnel exit (x = 400) as the open surface. (2) The tunnel wall material is unified as concrete and the train material is set as alloy.

3.1 smoke spread law with fire source in the middle of train

(1) Calculation results under the condition of no ventilation

| Time  | Smoke Spread |
|-------|--------------|
| T=100s| ![Image](image) |
| T=250s| ![Image](image) |
| T=500s| ![Image](image) |
| T=1000s| ![Image](image) |

**Figure 5. Tunnel fire smoke spread (main view)**

The smoke spreads to both ends of the tunnel and then air is continuously sucked in, the smoke layer sinks, the thickness of the smoke layer increases when fire occurs for about 280s according to figure 5.
The smoke on both sides of the fire source presents symmetrical spread.

Figure 6 shows the change of temperature profile on the longitudinal axis line of the tunnel at different combustion times. It can be seen from the figure that the temperature of the tunnel ceiling is significantly higher than the temperature of the middle and lower part of the tunnel when the heat release rate reaches a stable state and the highest temperature in the tunnel maintain stability (about 1000 °C) which appears directly above the fire source when the fire source burns for 250s. The high temperature area is mainly on the roof of the train.

Figures 7 and 8 show the variation of smoke characteristics at the most unfavorable measuring points of the tunnel (all critical heights). The tunnel temperature suddenly increases after 200s of fire and reaching the most unfavorable situation after 600s. The CO concentration measured in the train is 0 under the condition of no ventilation because the train is set as a solid body with thermal insulation material. The average temperature at both ends is lower than 25°C and the volume fraction of CO is no more than 25 ppm since it is far away from the fire source.

(2) Calculation results under different longitudinal ventilation speeds
The longitudinal ventilation is often used to control the flow of smoke and ensure the safe evacuation of people once the train fires in the actual tunnel, therefore the smoke diffusion rule can be studied under the condition of the longitudinal ventilation speed of 1.4m/s, 1.7m/s and 2.0m/s respectively when there is blocking.
It can be seen from Figure 9 that there is flue gas temperature in the tunnel ceiling (upstream of the fire source) when the longitudinal wind speed is 1.4 m/s and 1.7 m/s because the critical wind speed is not reached. The flue gas composition at the critical height in the upstream direction of the fire source is 0 basically because the flue gas composition in the upstream of the fire source is less and both of them are located in the tunnel ceiling position. Affected by the longitudinal wind there are a lot of smoke in the downstream of the fire source but the maximum volume fraction of CO at the critical height of the tunnel is only 13 ppm due to the effect of longitudinal wind and vehicle blocking, which does not exceed the tolerance limit of human body. The temperature of smoke at the upstream of the fire source is normal temperature under the simulation condition of longitudinal wind speed of 2.0 m/s so this wind speed is the critical wind speed under the condition and the CO concentration decreased with the increase of longitudinal wind.

3.2 smoke spread law with fire source at front end of train

(1) Calculation results under the condition of no ventilation

Figures 10 and 11 show the variation of smoke characteristics at the most unfavorable measuring points of the tunnel (all critical heights). It can be seen from the figure that the flue gas composition of the tunnel reaches the most unfavorable situation at 800s. The temperature change trend at the critical height is small and maintained at about 30 °C basically. The volume fraction of CO at the critical height changes greatly but the maximum is not more than 35 ppm.
Fig 10. Temperature change curve

Fig 11. Change rule of CO concentration

(2) Calculation results under different longitudinal ventilation speeds

(a) Ceiling temperature at 1.0m/s
(b) Critical height CO volume fraction at 1.0m/s

(c) Ceiling temperature at 1.2m/s
(d) Critical height CO volume fraction at 1.2m/s

(e) Ceiling temperature at 1.4m/s
(f) Critical height CO volume fraction at 1.4m/s

Fig 12. Change of smoke characteristics under different longitudinal wind speed
As shown in Figure 12 the reverse flow degree of flue gas in the tunnel ceiling upstream of the fire source decreases gradually when the longitudinal wind speed changes from 1.0m/s to 1.4m/s. The temperature of the tunnel ceiling upstream of the fire source is the initial temperature when the wind speed is 1.4m/s, which indicates that 1.4m/s is the critical wind speed under the simulated working condition. Due to the less smoke settlement in the fire the smoke concentration at the critical height is low and it does not reach the tolerance limit of human body in a short time. When the fire source is located at the front of the train and there is no mechanical ventilation the numerical simulation result is just the opposite of that when the fire source is located at the end of the train, and when the longitudinal ventilation in the opposite direction is added the numerical simulation result is exactly the same as that when the fire source is located at the end of the train.

4. Conclusion
Where the fire source is located in the middle of the train the smoke generated by the fire source basically presents a symmetrical distribution and the smoke volume at the critical height is low under the condition of no mechanical wind, which is less dangerous for evacuees. The critical wind speed is about 2.0m/s when the fire source is located in the middle of the train, which is significantly lower than that in the case of no blockage (2.5m / s), indicating that the tunnel will reduce the critical wind speed when there is blockage.
Where the fire source is located at the front of the train the smoke generated by the fire source basically presents a symmetrical distribution and the flue gas concentration basically remains unchanged under the condition of no mechanical wind in the beginning, and the critical wind speed is about 1.4m/s, which is much smaller than when the fire source is in the middle of the train. The high temperature area in the tunnel is mainly concentrated in the roof of the train no matter where the fire source is and the maximum temperature is up to 1000℃. The temperature and flue gas concentration at the critical height are relatively small within 1000s without mechanical ventilation, which does not reach the tolerance limit of human body.
Compared with no mechanical ventilation, the longitudinal ventilation makes the CO concentration in the tunnel greatly low and the CO concentration also shows a decreasing trend with the increase of the longitudinal wind speed.

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**Acknowledgments**

The study is financially supported by Open Project of Key Laboratory of Fire-fighting and Rescue Technology of the Ministry of Public Security under Grant No. KF201809.