Study on Fire Smoke Characteristic in Double-tube Road Tunnel with Complementary Ventilation System

Yonggang Fang1*, Jian Shen1, Jianrong Chen1, Jingyu Wang1, and Weiping Li1

1Zhejiang Provincial Institute of Communications Planning, Design & Research, Co., Ltd. Hangzhou, Zhejiang, 310030, China

*Corresponding author’s e-mail: fangyg@qq.com

Abstract. Complementary ventilation is a new and energy-saving mode put forward recently. In order to address safety concerns under fire situation, the fire simulation software FDS has been adopted to build a tunnel model with two tubes. The fire smoke spread rule, temperature field and visibility distribution in two tubes after fire are analysed. Results show that before closing the air valve in connect duct, a small volume of smoke spreads to the adjacent tube. Judging from temperature and visibility, the influence is limited; after closing the air valve, the adjacent tube is no longer affected by the fire tube. According to the personnel safety standards stated in the PIARC2005 Research Report, the complementary ventilation system can meet the requirements of tunnel safety operation in case of fire. Finally, a wet resonance grille dust removal device is proposed to prevent smoke from flowing into the adjacent tube.

1. Introduction

With the rapid development of China's economy, more and more highways have been constructed with increasing number of highway tunnels. On the other side, fire accidents in tunnels happen frequently. Due to the closed space, poor ventilation conditions, rapid spread of high temperature smoke, strong toxicity, and limited evacuation and rescue routes, it is prone to causing massive casualties and serious economic losses. For example, fire accidents in Mont Blanc tunnel(1999), which connects Italy and France, and St Gotthard tunnel(2001) of Switzerland caused a large number of casualties; In Jincheng, Shanxi, China, two trains carrying methanol collided in the Yanhou tunnel and resulted in serious fire accident, which lasts 73 hours, on March 1, 2014, caused 40 deaths, 12 injuries and 42 vehicles burned; On May 23, 2017, in Baoding, Hebei, the traffic accident happened in Futuyu No.5 tunnel and led to fierce explode, causing 12 deaths and 3 seriously injured.

Investigations show that more than 70% of casualties in fire accidents are caused by smoke, which means the smoke control of the extra-long highway tunnel fire is particularly critical. In recent years, scholars from China and abroad have carried out numerous researches on tunnel fire. Wu and Bakar[1] found that critical wind speed and fire power are related to tunnel section shape through a great deal of physical tests and simulation studies; Fumiaki Ura et al.[2], Wu et al.[3] utilised scale model tests to study the motion pattern and smoke exhaust efficiency with different ventilation modes and different longitudinal slopes; Wang et al.[4~5] combined scale model tests and the plume theory to predict maximum temperature of the tunnel dome, and obtained that the return length is less than 60m; Zhao [6], Fan et al.[7] used the CFD method to study the influence of chimney effect on the vertical spread and settlement of smoke; The World Road Association (PIARC) released the Fire and Smoke Control in Road Tunnels report in 2005, which proposed the following safety criteria for drivers and passengers in fire scenes, the thermal radiation flux should be lower than 2.0~2.5kW/m²; the air
temperature should not be higher than 80°C; the visibility at 2.0m of the characteristic height of human eye should not be shorter than 15m.

In order to reduce the tunnel ventilation system installation and operation power, Swiss scholar Berner proposed the concept of double-tube complementary ventilation for the extra-long road tunnels with uneven demand air volume. Taking Dabieshan tunnel of Hubei Province as a background sample, which was equipped with a complementary ventilation system, Hu[8], Wang[9] and Xia[10] adopted model tests and field measurements to study the distribution law of wind speed field, wind pressure field and pollutant concentration.

However, existed researches on complementary ventilation mainly focus on ventilation system design, demand air volume calculation, and operational feasibility. The safety of this new energy-saving ventilation mode in fire situations has not been systematically studied. Therefore, it is necessary to conduct further researches on fire and smoke characteristics in tunnels with complementary ventilation system. By observing the temperature field, visibility, speed field and other indicators, the spread characteristics and control laws of fire smoke in double-tube tunnels with complementary ventilation system has been studied.

2. Structure design of complementary ventilation duct
The basic principle of complementary ventilation is based on the longitudinal ventilation system. Two air ducts for air exchange are arranged at appropriate positions to connect uphill and downhill tubes to form an integral ventilation network. A considerable gap of air demand exists in uphill and downhill tubes. The low concentration air in the downhill tube is induced to dilute the high concentration air in the uphill tube, which ingeniously avoids constructing ventilation shafts equipped with high-power fans for uphill tube.

According to the structural design of complementary ventilation connecting air ducts such as Chenjiashan tunnel, Jingling tunnel of Hangzhou-Shaoxing-Taizhou Highway and Jinhuashan tunnel of Jiande-Jinhua highway, the longitudinal spacing of paired connecting air ducts is set as 50~100m in an antisymmetric layout, so as to ensure that the distance between the air supply outlet of one connecting air duct and the air suction outlet of another is not less than 50m, which is specified in Guidelines for Design of Highway Tunnel (hereinafter referred to as Guidelines). The air duct, with a clear width of 5m and a clear height of 4.5m, adopts side air suction and arch roof air supply. It is partially set as a variable cross-section according to equipment installation needs.

3. Fire analysis model and working condition settings
3.1. Analysis model
In order to study and evaluate the safety of the complementary ventilation mode under fire conditions, the fire 3D analysis model was built by FDS (Fire Dynamic Simulator) 6.0 software for simulation analysis. This software is a computational fluid dynamics software developed by the National Institute of Standards and Technology (NIST) and widely used in countries around the world. It uses large eddy simulation turbulence and effectively simplifies turbulence.

![Figure 1. Schematic diagram of simulation model](image-url)
In order to simulate the diffusion of fire smoke in a connecting air duct, the spacing of the connecting air duct is set as 50m in this study, and the ignition point is set at 30m upstream of the 2# connecting air duct, as shown in figure 1 and figure 2. In order to reduce the calculation load, the calculation range of right tube is 230m downstream of the fire origin and 20m upstream; the calculation range of left tube is 130m on the left side and 170m on the right side of the fire origin.

Flame characteristic length $D^*$ in the large eddy model of FDS software:

$$ D^* = \left( \frac{Q}{\rho_0 C_p T_0 g H} \right)^{2/5} $$

Where $Q$ is fire power (kW), according to the Guidelines, the design fire scale of Highway and Grade I road tunnel with a length more than 5km is 30MW; $\rho_0$ is air density (kg/m$^3$), which is 1.293kg/m$^3$; $C_p$ is air specific heat capacity (kJ·kg$^{-1}$·K$^{-1}$), which is 1.0 kJ·kg$^{-1}$·K$^{-1}$; $T_0$ is ambient temperature (K), which is 298.16K; $g$ is gravity acceleration (m/s$^2$), which is 9.8m/s$^2$.

The FDS requires $D^*/dx$ (grid size) to be between 4 and 16. Therefore, $D^* = 3.7$, which means $dx$ should be between 0.23m and 0.93m. In this model, $dx=0.5$m, and the total number of grids is 460,000.

3.2. Boundary conditions

The wind speed boundary is imposed at the entrance of two tubes. The initial wind speed is the traffic piston wind speed, which is about 6m/s according to calculation. After a fire occurs in one tube, the traffic flow quickly stagnates, then the normal ventilation mode is switched to the emergency ventilation mode, and it is assumed that the initial wind speed is gradually reduced to the critical wind speed within 120 seconds. The so-called critical wind speed is the minimum wind speed in the vertical smoke exhaust mode to prevent smoke backflow and threats to the upstream occupants, and is affected by many factors, such as the fire size, tunnel slope, fire size, fire locations, ventilation mode, structural characteristics, etc.

Using Wu and Baker formula to calculate the critical wind velocity of 30MW fire source, substituting the corresponding data, we can get:

$$ \bar{H} = 4A/P $$

$$ Q^* = \frac{Q}{\rho_0 C_p T_0 g H^{1/2}} $$

$$ \nu^* = \frac{\nu_{cr}}{\sqrt{gH}} $$

If $Q^* < 0.20$, $\nu^* = 0.40(0.20)^{-1/3} Q^{1/3}$; if $Q^* \geq 0.20$, $\nu^* = 0.40$.

Where $A$ is cross sectional area of tunnel (m$^2$); $P$ is tunnel’s hydraulic perimeter (m); $\bar{H}$ is tunnel hydraulic height (m); $Q^*$ is heat release rate (MW); other parameters are the same as formula (1). Therefore, the theoretical critical wind speed can be obtained, and it should meet the requirement of longitudinal smoke exhaust mode in the Guidelines when fire source power is 30MW, which is about 3~4m/s.
3.3. Working condition settings
At the same time, air valves are separately set in the two connecting air ducts. According to the linkage control requirements of the monitoring system and performance parameters of air valves, they can be shut off within 60s after fire occurrence. Considering the action time of the fire monitoring system, conservatively, in simulation analysis, the air valves are closed after 120s, and the air flow of two tubes is no longer connected. The fire source is placed in the center of the right tube. Wood with high smoke production rate and diesel oil are used as fuel. Smoke production rate is set at 5%, and total smoke production flow is about 80m\(^3\)/s.

4. Analysis of simulation results
In the center of two model tubes, temperature, concentration, velocity and visibility slices are set along the longitudinal direction to observe the movement of smoke. At the center line of two tubes and characteristic height of human eyes of 2.0m, a temperature measuring point is set every 5m to record the temperature distribution and change.

4.1. Characteristic analysis of smoke spread
In order to clearly show the spread of smoke under the influence of longitudinal wind speed when a fire occurs, Figure 3 shows the smoke spread process measured at 10s, 20s, 40s, 60s, 120s, 240s, 360s, 480s and 600s after a 30MW fire occurs.

![Figure 3. Schematic diagram of fire smoke spread](image)

After 10s, affected by the longitudinal wind speed from right to left in the fire tube, smoke mainly begins to spread rapidly to the downstream. The longitudinal velocity of 6m/s in the fire tube completely restrains smoke from spreading to the upstream, which is far more than the critical velocity of fire. Within 20s after the fire, smoke has spread 80m. Under the simultaneous of hot air pressure and longitudinal wind speed in the tube, smoke from the downstream of fire source spreads to the tube
very fast, and enters the 2# connecting air duct. Within 60 seconds, smoke has spread 200m. In the non-fire tube, due to the control of the longitudinal wind speed of 3m/s to the right, a small amount of smoke spreads to the upstream. The connecting air duct is closed at 200s, after which smoke cannot enter the non-fire tube from the fire tube along the duct. After 240s, 360s, 480s and 600s, most of smoke is concentrated in the fire tube, and part of it enters the connecting air duct and spreads to the non-fire tube. It can also be seen that only little smoke enters the non-fire tube. Because of strong longitudinal wind speed control, most smoke is concentrated in the downstream, little of which spreads to the upstream. It indicates that the longitudinal wind speed setting is effective and can ensure the safety of evacuation space of the upstream.

4.2. Temperature field analysis

Figure 4 shows the temperature field change within 10 minutes after the fire. In case of fire, there is a longitudinal wind speed of 6m/s in the fire tube, so the smoke spreads rapidly to the downstream and temperature rises rapidly. Due to the obstruction of longitudinal wind speed, the upstream of the fire tube has less smoke and lower concentration, so the temperature in the upstream is also lower. It can be seen from the figure 4 that there is a fire in the tube with longitudinal ventilation, smoke mainly concentrates in the downstream area, and a small amount enters the non-fire tube through the connecting air duct. A similar rule can be obtained from the previous analysis of smoke spread. The temperature in the upstream is lower than that in the downstream. Smoke spreads to the 2# connecting air duct, the temperature in it rises about 60°C, and local temperature reaches 120°C. Although there is some smoke entering non-fire tube, due to the influence of longitudinal wind speed, the temperature at 2.0m above the ground has no obvious change, and the maximum temperature is only 21°C.
Figure 5. Temperature curve at the height of 2.0m in the fire tube

Figure 5 shows the temperature distribution at 2.0m height of fire tube. It can be seen that after the fire, the temperature in the downstream of the fire source rises rapidly. At 90s, the temperature distribution reaches a stable state. Upstream temperature is maintained at 20°C, downstream temperature is maintained at about 50°C, and there is a temperature of more than 80°C in the range of about 50m.

Figure 6. Temperature curve at the height of 2.0m in adjacent tube

Figure 6 shows the temperature variation of each control point near the connecting air duct at a height of 2.0 m in the non-fire tube. It can be seen that the maximum temperature rise is less than 21°C, and the temperature of each measuring point quickly returns to room temperature after the air valve is closed. Therefore, from the temperature field analysis, the wind valve can be closed soon after fire, which can ensure that there is no obvious temperature rise in the adjacent non-fire tube.

4.3. Visibility analysis

Figure 7 shows the change of visibility during the simulation of longitudinal ventilation conditions and the 30MW fire happens in the middle of the tube. Visibility slices are set in both tubes, respectively, measured at 10s, 120s, 240s, 360s, 480s, and 600s. When a fire occurs in one tube, smoke spreads continuously in this tube due to the longitudinal ventilation speed of 6m/s. Visibility of the downstream decreases rapidly, and only a small amount decreases at the tunnel dome in the upstream of the fire source, which is the same as the rule of temperature field and smoke spread in the previous discussion. Smoke in the downstream of the fire source loses thermal driving force to form stable
stratification under actions of longitudinal wind, and visibility in the whole downstream is reduced, which is extremely harmful to the evacuation of downstream personnel. As the fire smoke continues to spread, it gradually passes through the connecting air duct to the adjacent non-fire tube. The visibility at 2.0m height in the non-fire tube is partially affected. In a short time, local visibility is reduced to about 15m, and maximum longitudinal length is about 150m. Visibility below 2.0m height (characteristic height of human sight) is almost unaffected and has little impact on driving.

![Figure 7. Diagram of fire smoke visibility](image)

5. Improvement measures
In order to prevent impact on driving safety of vehicles with higher cockpit, such as trailers, a wet resonance grille dust removal device (Figure 8) is adopted to prevent the smoke from flow into adjacent tube. This device consists of a spray system, a wet resonance grille dust removal system and a dewatering system. The basic principle is to force all the dusty airstreams to be washed through 3 water membranes, and smoke is left in the water while the clean air flow is discharged.

![Figure 8. Schematic diagram of wet resonance grille dust removal device](image)

6. Conclusions
The complementary ventilation system in double-tube tunnel requires further study due to lack of experience and corresponding fire safety concerns. A three-dimensional model of the extra-long tunnel with double tubes is established using the computational fluid dynamics software FDS. Based on the numerical simulation, propagation law, temperature field, visibility distribution impacted by fire smoke are studied. The results are as following:
(1) Due to the longitudinal critical wind speed in the tube, fire smoke spreads downstream quickly. Before the air valve in the connect duct is closed, a small volume of smoke spreads into the adjacent tube. However, a good stratification in the cross section has been seen, and smoke concentrates above 2m height (characteristic height of human eyes), which is recognised as the sight height of drivers and passengers.

(2) The maximum temperature in the adjacent non-fire tube is less than 21°C. After the air valve is closed, temperature of each measuring point quickly returns to room temperature.

(3) According to the visibility field, the local visibility of the adjacent tube is reduced to about 15m, and maximum longitudinal length is about 150m. Visibility under 2.0m road height is almost unaffected, causing little impact on driving.

(4) 120s after the fire, the air valve in the connect duct is closed quickly, and the non-fire tube will not be affected by the fire tube any longer.

(5) To shed safety inhibition thoroughly, a wet resonance grille dust removal device is proposed to avoid smoke flowing into adjacent non-fire tube.

In conclusion, in accordance with the personnel safety standards stated in PIARC 2005 report, the complementary ventilation mode can meet the safety operation requirements in case of fire.

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