fire

Technical Note

Feasibility Analysis of Cross Passage Ventilation and Smoke Control in Extra-Long Submarine Tunnel

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Abstract: Longitudinal ventilation fans in extra-long submarine tunnels are usually arranged at both ends of the tunnel limited by the tunnel cross section, which is usually hindered by insufficient power caused by extra-long ventilation distances. In this paper, the conception of a ventilation mode is proposed that services the tunnel and cross passages, to provide auxiliary air supply to the main tunnel. Two critical factors have been analyzed on the premise of evacuation safety, which combine to affect the ventilation efficiency in the case of an accident inside the tunnel, these are: air volume within the service tunnel, and cross passage open numbers. FDS simulation software is used to simulate the tunnel model; consider the number of cross passages from one to four; and simulate the service tunnel airflow velocity of 0.7 m/s, 0.75 m/s, 0.85 m/s, 1.0 m/s and 1.3 m/s. The results show that when 1.3 m/s wind speed is applied at both ends of the service tunnel, and three cross passages are operated, 20 MW of fire smoke within the accident tunnel can be effectively controlled; additionally, the wind speed in the cross passage will not hinder the evacuation. The simulation results are verified by ventilation network calculation.

Keywords: extra-long submarine tunnel; smoke control; cross passage; ventilation network

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1. Introduction

In recent years, the extra-long railway tunnel has made travel easier, but also introduces new challenges with regards to safety management [1,2]. When fire breaks out inside a tunnel, poison gas and heat accumulate within the long and narrow space in a short period of time, posing a threat to life [3,4]. Over past decades, tunnel ventilation [5–7] and smoke control [8,9] has been investigated by many researchers, which has proved effective for eliminating back-layering and protecting personnel evacuation. Providing a certain flow velocity from one side of the fire source [10,11], or exhausting smoke through the shaft and flue [12,13], is expected to weaken the fire risk; however, there are still many challenges with long-distance ventilation, including smoke exhaust, evacuation, and emergency rescue. For long-distance ventilation, airflow produced by fans will encounter great resistance within the tunnel and it is hard to form a stable air flow, which may easily cause a disaster, due to the obstructed ventilation.

Tunnel ventilation systems, which provide fresh air to tunnels [14–16], are classified as transverse, semi-transverse and longitudinal. Of these, a longitudinal ventilation system equipped with jet fans is the most widely used, owing to lower costs and easier implementation. Using this ventilation mode, wind flow runs for dozens of kilometers against the wall friction; therefore, a large number of fans are required to provide enough air flow to withstand the huge ventilation loss. Unfortunately, due to the limitation of space within the tunnel, jet fans can only be arranged at both ends of the tunnel, which easily forms a local ultra-high wind pressure, threatening both human and traffic safety. In addition, such an arrangement will also present further train and personnel traffic safety issues, such as excessive ventilation pressure at the end of the tunnel.

Feng et al. [17] studied the smoke control of a subway tunnel fire, and its influencing factors, by use of CFD numerical simulation and full-scale cold-smoke experiment. It was found that the ventilation velocity through the cross passage increased with the shorter distance between train and cross passage. As the fire location was closer to the cross passage, a lower critical velocity was needed for smoke control. Hou et al. [18] carried out research on the critical velocity in a tunnel cross passage through theoretical analysis, full-scale experiment, and numerical simulation. Their results show that when the train blockage is considered in the fire tunnel, the ventilation speed in the cross passage exceeds critical velocity. In the research of Li et al. [19], critical velocity in the cross passage was related to the fireproof door height, fire load and ventilation velocity. They also proposed the dimensionless prediction model of critical velocity in the cross passage, based on their experimental results. Guo et al. [20] used the ventilation network calculation to study wind pressure and measure the tunnel section velocity, exploring tunnel ventilation energy saving technology. Optimal energy saving was proven to reach 43%, which could be applied to practical projects.

Overall, previous studies mainly focused on the critical velocity of fire smoke control in accident tunnels or cross passages, but few studies focused on the design parameters of ventilation systems using cross passages for smoke control, which is worth investigating.

In this paper, a new combination ventilation mode is designed for extra-long tunnels, which adopts longitudinal ventilation of the passenger tunnel, together with auxiliary ventilation in cross passage driven by pressurization of the service tunnel. The twin-tube complementary ventilation system is commonly used in tunnels, because of the advantage of significant reductions in total air volume, and total ventilation power consumption of the two tunnels [21–23]. We will attempt, therefore, to explore the cross passage, which is used as an important part of the ventilation and exhaust system, providing airflow in the case of an accident within extra-long tunnels.

2. Theory and Calculation

2.1. Longitudinal Ventilation Critical Velocity

If a fire occurred in a tunnel under longitudinal ventilation, the critical velocity is defined as the minimum longitudinal airflow velocity, which can limit smoke flow to one side of the fire source. Li et al. [8] carried out a model experiment of tunnel fire to investigate the movement and control of smoke, based on previous research [24]. A set of modified formulas for critical longitudinal velocity can be expressed as:

$$V_c = V_c^* \sqrt{gH} \tag{1}$$

$$V_c^* = \begin{cases} 0.81 Q^{*1/3} & , \quad Q^* \leq 0.15 \\ 0.43 & , \quad Q^* > 0.15 \end{cases} \tag{2}$$

$$Q^* = \frac{Q}{\rho_0 c_p T_0 g^{1/2} H^{5/2}} \tag{3}$$

where V_c is critical velocity, (m/s); V_c^* is dimensionless critical velocity; Q is heat release rate, (kW); Q^* is dimensionless heat release rate; g is gravitational acceleration, (m/s^2); H is tunnel height, (m); ρ_0 is ambient density, (kg/m^3); c_p is thermal capacity of air, (kJ/kg K); T_0 is ambient temperature, (K).

2.2. Ventilation Parameters

Several factors should be fully considered in ventilation and smoke control in tunnels, such as the pressure of ventilation fans, on-way resistance, local resistance, and fire wind pressure. Among these, fire wind pressure p_f [25], on-way resistance p_λ and local resistance

p_ξ are regarded as ventilation resistance in the design and calculation of the ventilation system, which can be expressed, respectively, as:

$$p_\lambda = \sum_{i=1}^{n} \lambda_i \frac{L_i}{D_i} \frac{\rho}{2} v_i^2 \tag{4}$$

$$p_\xi = \sum_{i=1}^{n} \xi_i \frac{\rho}{2} v_i^2 \tag{5}$$

The ventilation system in the tunnel satisfies the conservation of energy:

$$p_v + p_f + p_\lambda + p_\xi = \frac{1}{2} \rho v_i^2 \tag{6}$$

In order to meet the requirements of smoke control, the average wind velocity v_f at the fire location should exceed the critical longitudinal velocity v_c [8]:

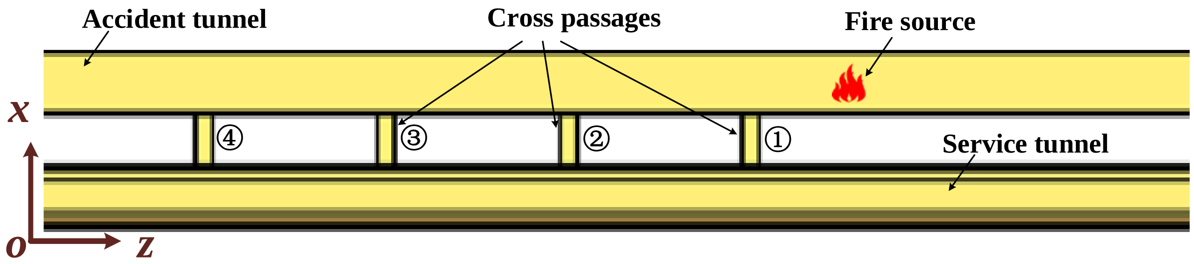
$$v_f \geq v_c \tag{7}$$

where p_λ is on-way resistance, (Pa); p_ξ is local resistance, (Pa); p_v is ventilation pressure, (Pa); p_f is fire wind pressure, (Pa); λ is frictional resistant coefficient; ξ is local resistance coefficient; v_i is airflow velocity, (m/s); v_f is airflow velocity of fire source location, (m/s).

3. Numerical Simulation

3.1. Model Design

In this paper, FDS (Version 6.5.3) codes are used for simulating smoke movement induced by fire [26], which is developed by NIST. The fire tunnel model is based on the Qiongzhou Strait shield tunnel in southern China, which consists of two main tunnels, one service tunnel and multiple cross passages, with a total length of 21 km. To simplify the model, three modules of the tunnel are considered: one main tunnel with a horseshoe section area of 55 m^2 and height of 8.5 m; one service tunnel with a section area of 42.8 m^2; and the cross passages. The total length of the tunnel model is 600 m. The ventilation section covers the whole section of the tunnel, as shown in Figure 1. The section shape is the ventilation space section. A series of temperature and velocity measuring points are arranged at a height of 2 m inside the main tunnel, service tunnel and cross passages, with 1 m interval longitudinally; the velocity and temperature slices are set along the tunnel plotted in Figure 1b. For a high-speed railway tunnel, the heat release rate of 20 MW for train fires is recommended by the 'Code for Design on Rescue Engineering for Disaster Prevention and Evacuation of Railway Tunnel' (TB 10020-2017) [27], which is selected for modeling.



(a) Top view

Figure 1. *Cont.*

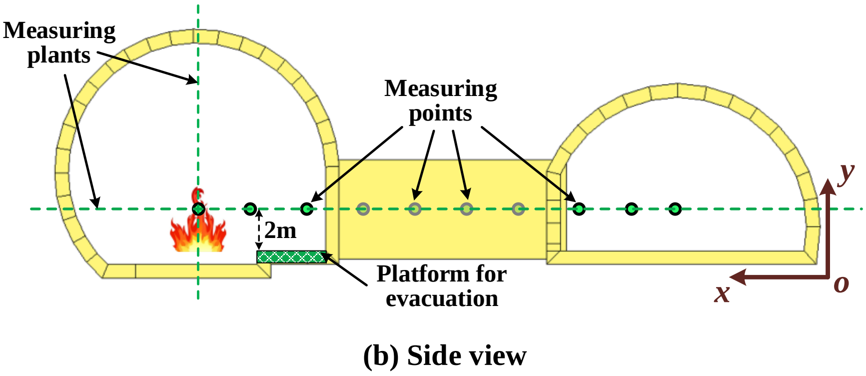


Figure 1. Simulation model: (**a**) Top view; (**b**) Side view.

3.2. Simulated Conditions

Two groups of simulation scenarios are designed, as summarized in Table 1. The first group establishes the model by changing the number of cross passages (CP) from one to four. The interval of cross passages is 50 m, with the cross-sectional area of 12 m^2 and a width × height of 4 m × 3 m. The velocity of longitudinal ventilation generated in an accident tunnel is 2 m/s; the airflow velocity at both ends of the service tunnel is 1.3 m/s. The other group has five conditions, with different ventilation velocities in the service tunnel, set as: 0.70, 0.75, 0.85, 1.00 and 1.30 m/s. Three cross passages remain open. Other parameter conditions are consistent with the first group.

Table 1. Simulated conditions.

Cases No.	Fire Source Location (m)	CP.1 Location (m)	CP.2 Location (m)	CP.3 Location (m)	CP.4 Location (m)	Velocity of Accident Tunnel (m/s)	Velocity of Service Tunnel (m/s)
a01	310	300	–	–	–	2	1.30
a02	310	300	250	–	–	2	1.30
a03	310	300	250	200	–	2	1.30
a04	310	300	250	200	150	2	1.30
b01	310	300	250	200	–	2	0.70
b02	310	300	250	200	–	2	0.75
b03	310	300	250	200	–	2	0.85
b04	310	300	250	200	–	2	1.00
b05/a03	310	300	250	200	–	2	1.30

The fire source is located at 310 m inside the accident tunnel, with a heat release rate of 20 MW, set to reach the maximum value within 1 s, then maintained during the simulation for up to 500 s. Air flow in the service tunnel enters the accident tunnel through cross passages, to raise the longitudinal ventilation velocity to critical velocity. As smoke movement would reach a quasi-steady state after 300 s, the average values from 450 s to 500 s is considered as quasi-steady state data for investigation.

3.3. Grid Sensitivity Analysis

As the gird size is crucial for the reliability of numerical simulation, we chose the value range $D^*/16$ to $D^*/4$, which has been widely used for assessing grid resolution for sensitivity analysis. Here, D^* can be calculated by [26]:

$$D^* = \left(\frac{Q}{\rho_\infty c_p T_\infty \sqrt{g}} \right)^{2/5} \tag{8}$$

A grid size of between 0.2 m and 0.8 m is considered suitable for simulation. In order to obtain a reasonable and accurate mesh size, we took five grid sizes of 0.40 m, 0.50 m, 0.60 m, 0.70 m and 0.80 m, for the numerical simulation stability analysis. The longitudinal ventilation velocity in the tunnel is 3.0 m/s and the fire load is 20 MW. As shown in Figure 2, when the mesh size is less than 0.5 m, the simulation results obtained stability and repeatability, while the CPU time of 0.4 m took 23 h more than 0.5 m (computer configuration: i7-7700, 16 GB RAM). In order to save storage space and computing time, we employed 0.5 m as the mesh size of the numerical simulation model.

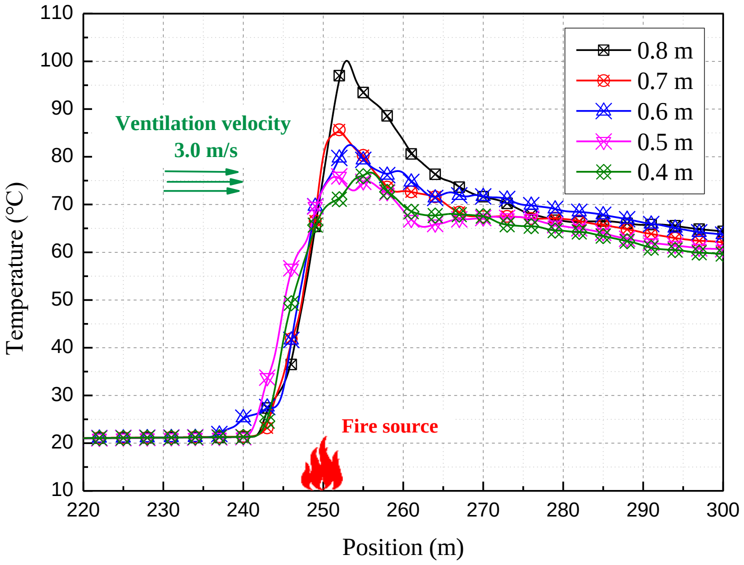


Figure 2. Temperature distribution with different grid sizes.

4. Result and Discussion

4.1. Optimum Number of Cross Passages Open

When a fire occurs in the main tunnel, 2 m/s longitudinal ventilation will be provided, and 1.3 m/s pressurized wind speed will be applied at both ends of the service tunnel. With the number of cross passages open increasing from one to four, the variation of airflow is detected in Figure 3. When only one cross passage is open, the upstream ventilation velocity in the accident tunnel is stable at about 2 m/s, while airflow speed at the intersection of the cross passage and accident tunnel reaches 12 m/s. In addition, the longitudinal ventilation velocity of the main tunnel downstream maintains at 4.7 m/s. As shown in Figure 3a,b–d, the longitudinal wind speed from the tunnel entrance to the first cross passage is basically stable, as the number of cross passages increases. However, velocity is unstable at the intersection of channels, due to chaotic turbulence, gradually stabilizing at 4.5~4.7 m/s when reaching downstream.

In this paper, cross passages are used for the evacuation of people, as well as ventilation. In order to prevent fire smoke from spreading into cross passages, the wind speed in passages has been stipulated to be between 1.5 m/s to 8 m/s by TB 10068-2010 [28]. In fact, as airflow velocity in the cross passage exceeds 5 m/s, evacuation efficiency will be negatively affected; therefore, it is necessary to optimize the number of cross passages open when addressing the issue of smoke control. After simulation, when one cross passage is open, velocity exceeded 8 m/s. When two cross passages are open, the velocity was between 4 m/s and 7 m/s. Average wind speed reached from 1.5 m/s to 5 m/s when CP1, CP2 and CP3 were open. With all four cross passages open, average wind speed in CP3 and CP4 are less than 1.5 m/s, which does not satisfy the safety evacuation requirement. Therefore, when a fire occurs in a tunnel, the three cross passages closest to upstream of the fire source should be open for smoke control.

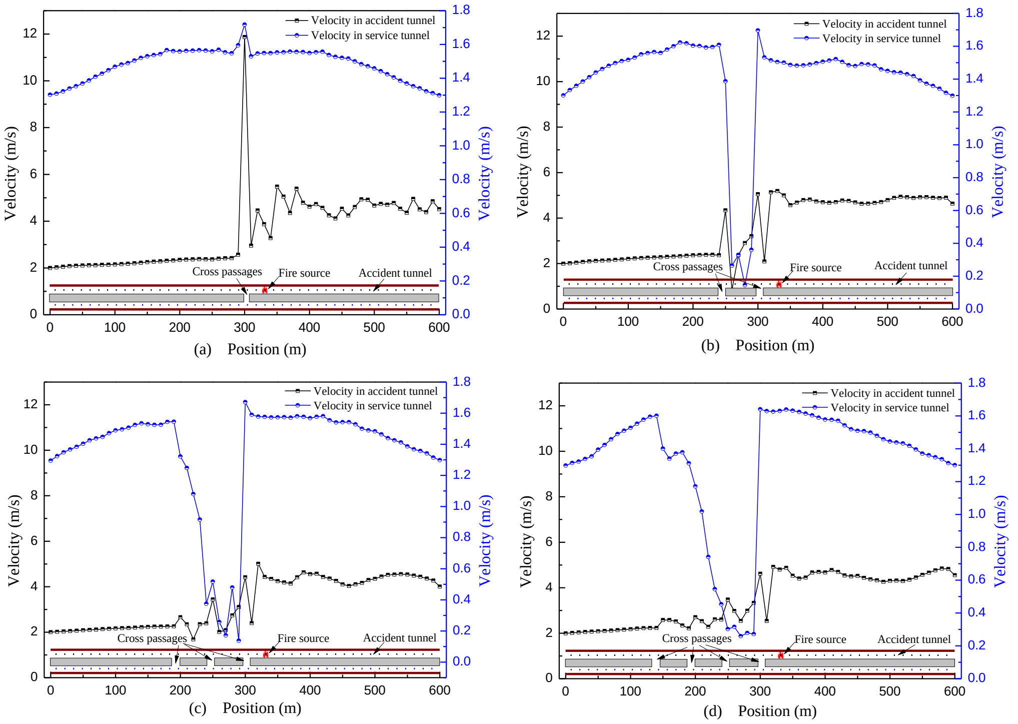


Figure 3. Velocity distribution with different numbers of cross passages open: (**a**) One cross passage open; (**b**) Two cross passages open; (**c**) Three cross passages open; (**d**) Four cross passages open.

4.2. Optimum Ventilation Quantity of Service Channel

The distribution of smoke movement and airflow velocity, with three cross passages open, were analyzed at ventilation velocities of 0.7 m/s, 0.75 m/s, 0.85 m/s, 1.0 m/s and 1.3 m/s, at both ends of the service tunnel. Figure 4 compares the accident tunnel velocities at a height of 2 m, under a service tunnel wind speed from 0.7 m/s to 1.3 m/s. As reflected in the figures, velocities near the fire source increased with service tunnel wind speed; velocities in the cross passages were all less than 8 m/s, under different working conditions. Of note, the average wind speed in some cross passages was less than 1.5 m/s in airflow velocity conditions of 0.7 m/s, 0.75 m/s and 0.85 m/s; therefore, it is necessary to reconsider tunnel ventilation design systems, in order to ensure the effectiveness of fire smoke control in tunnel ventilation.

4.3. Ventilation Network Verification

In tunnel ventilation systems, network calculation can capture overall mean flow parameters, such as velocity and pressure, with a one-dimensional flow regime [29]. Two typical concepts, node and branch, will be discussed. Both tunnels and cross passages are characterized as branches, while the intersection point of branches are described as nodes. Figure 5 shows typical tunnels with a three cross passage ventilation network, which includes a main loop, ten nodes and fourteen branches.

The ventilation airflow at the mth node in tunnels follows the mass balance Equation (9), and the pressure balance equation for the nth branch can be represented as Equation (10). The on-way resistance and local resistance will meet Equations (4) and (5), respectively. In addition, fire exists as resistance in branch and its wind pressure is set at 5 Pa [25].

$$\sum M_m = 0 \tag{9}$$

$$\sum p_n = 0 \tag{10}$$

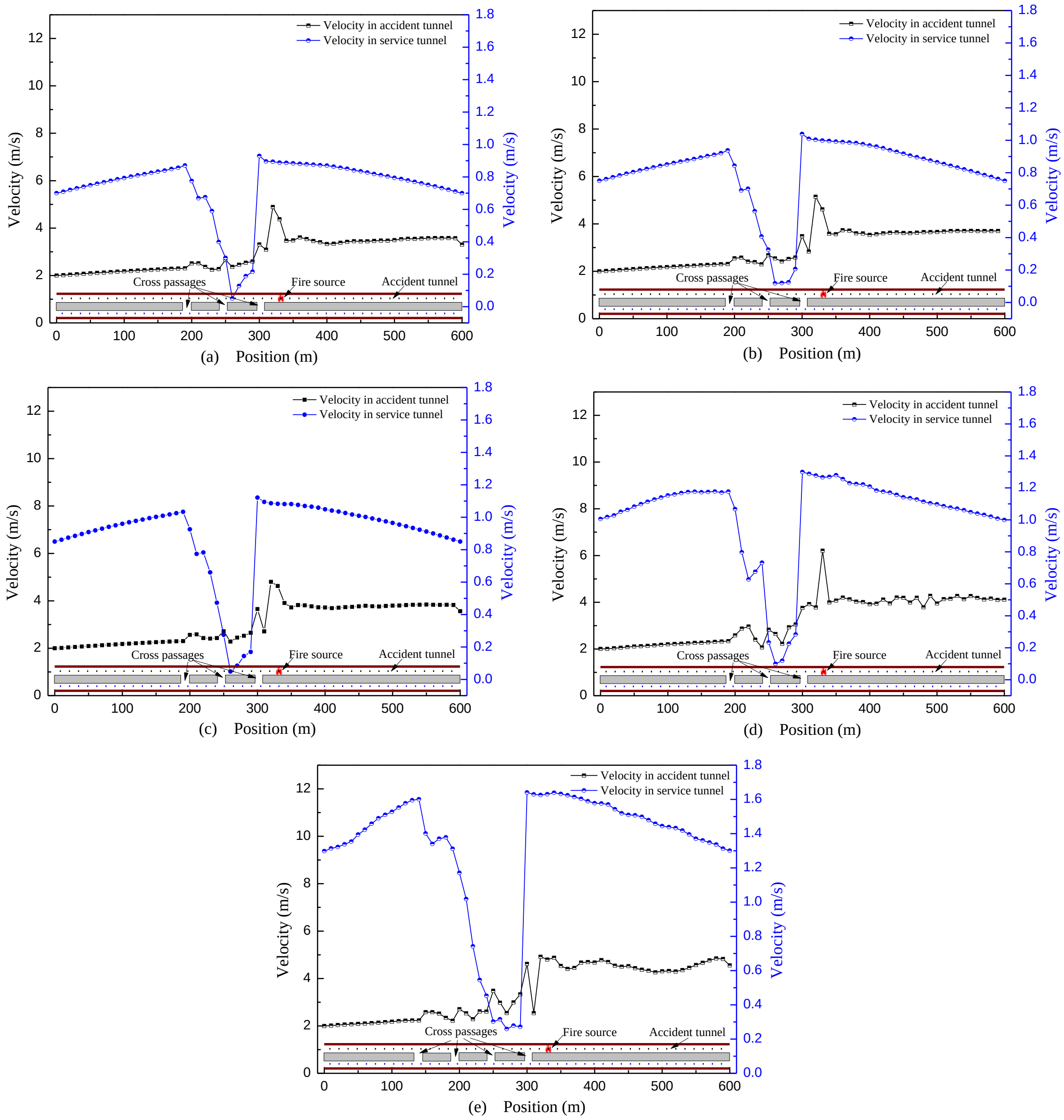


Figure 4. Velocities in both accident tunnel and service tunnel: The velocity at both ends of service tunnel is (**a**) 0.70 m/s; (**b**) 0.75 m/s; (**c**) 0.80 m/s; (**d**) 1.00 m/s; (**e**) 1.30 m/s.

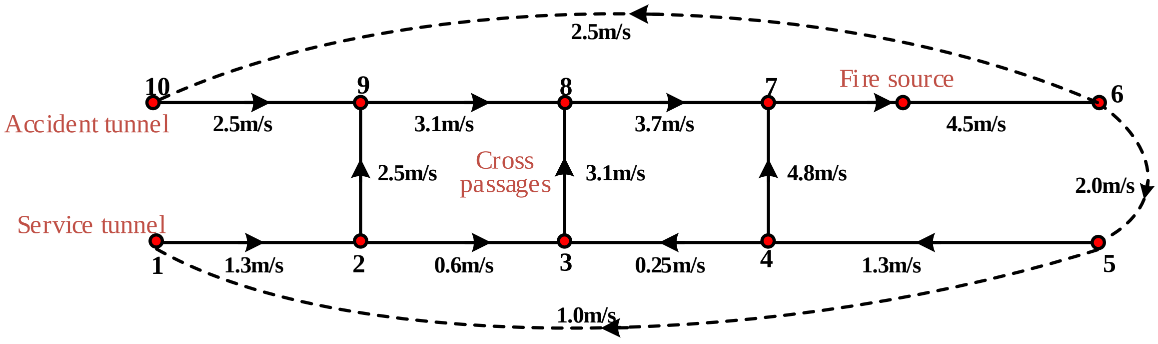


Figure 5. Calculation result of ventilation network.

Figure 5 represents the calculation results and data of the ventilation network. At both ends of the accident tunnel, ventilation pressure of 210 Pa is applied in the same direction, and ventilation pressure of 135 Pa with opposite direction is set in the service tunnel. The ventilation volume of the CP.1, CP.2 and CP.3 are 29.9 m^3, 36.9 m^3 and 45.5 m^3, respectively; the average airflow velocity are 2.5 m/s, 3.1 m/s and 4.8 m/s. The fire source is located in the 10th branch, with ventilation velocity of 4.5 m/s, exceeding the longitudinal critical velocity of 3.5 m/s. The calculation results of the ventilation network agree with the numerical simulation. Therefore, it is feasible to use the service tunnel to pressurize ventilation through three open cross passages, in order to limit smoke movement in the case of a 20 MW fire in the main tunnel.

5. Conclusions

In this paper, a ventilation mode with service tunnel and cross passages for auxiliary air supply and smoke control was studied using FDS simulation. The study proposed a ventilation and smoke exhaust scheme, and solved the problem of longitudinal ventilation in extra-long submarine tunnels. Our main conclusions are as follows:

(1) In the case of a 20 MW fire, the longitudinal ventilation velocity of 2 m/s will be applied in the accident tunnel, and the airflow speed of 1.3 m/s will be supplied at both ends of the service tunnel, together with three cross passages open to provide airflow, which can effectively control the fire smoke and improve the human evacuation.

(2) A ventilation network model is established according to the design parameters of extra-long tunnels. The calculation results show that the longitudinal wind speed at the fire source reaches 4.5 m/s, exceeding the critical velocity for smoke control of 3.5 m/s, which is in accordance with the numerical simulation results. In theory, cross passage pressurized air supply technology is proved feasible.

It should be noted that the distance between cross passages, and the angle between cross passages with main tunnel, will influence ventilation efficiency. Therefore, further experiments and simulations are needed, and parameters should be extended in order to investigate the optimum ventilation scheme. In this paper, design parameters are closely related to the tunnel structure, which are not necessarily applicable to other projects. With regards to ventilation design, the methods and ideas highlighted in this paper are significant; perhaps other tunnels need similar structural models and calculation conditions.

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