Effect of Longitudinal Ventilation on Smoke Temperature below Utility Tunnel Ceiling

Z. P. BAI, Y. F. LI

***Abstract*—Utility tunnels are widely built in many cities. When an unexpected fire occurs in the electrical compartment of utility tunnel, the smoke temperature below the utility tunnel ceiling is one of the most important factors for thermal detection and alarm. In this paper, the smoke temperature distribution under the longitudinal ventilation in a utility tunnel fire accident is studied by combining experiment and numerical simulation. The main purpose of this paper is to study the smoke temperature distribution below the ceiling under the effect of longitudinal ventilation in a utility tunnel, and provide guidance for the installation of detector in case of fire. In addition, three important factors such as ventilation velocity, heat release rate and vertical position of fire source are considered respectively. The thermocouple trees are used to measure the temperature along the longitudinal direction of utility tunnel. Results show that the maximum temperature of the utility tunnel is directly above the fire source without longitudinal ventilation. What's more, with the ventilation velocity increases, the maximum temperature below the ceiling gradually moves to the downstream of the fire source in utility tunnel. Finally, a new correlation formula is proposed to predict the temperature distribution of smoke in utility tunnels on the basis of theoretical analysis. The longitudinal temperature distribution obtained by numerical simulation is in good agreement with the experimental tests. Therefore, the research in this paper is helpful to prevent utility tunnel fire and reduce people's property loss.**

***Index Terms*—Experimental study; Temperature distribution; utility tunnel; Ventilation**

I. INTRODUCTION

The utility tunnel is built in many cities all over the world, recently [1,2]. There are many cables in the electrical compartment of utility tunnel. The fire hazard of utility tunnel is high. In fact, fire prevention is very important in utility tunnel engineering. The fire accident affected the operation of the whole utility tunnel. What's more, the utility tunnel fire directly affects the normal life of thousands of people. Once there is a fire, it will cause huge property damage [3]. In addition, the smoke spread rapidly in the utility tunnel, and it soon filled the entire utility tunnel [1]. In order to detect fire accident in time and reduce property loss, it is necessary to install the temperature detector reasonably to detect fire in time and give alarm in time. It is worth noting that in case of fire in the electrical compartment of utility tunnel, the longitudinal ventilation will affect the temperature distribution below the ceiling. This is one of the important factors for fire detection and alarm.

There are many previous studies on the temperature distribution in the utility tunnel. These studies focused on the longitudinal ventilation without changing the vertical position of the fire source. Yan E et al. [4] used numerical simulation method to study the temperature distribution in the process of L-type utility tunnel fire. They focused on temperature distribution law in the L-type utility tunnel, when the heat release rate (HRR) was 250 kW, and mechanical ventilation velocity was 0.5 m/s. In addition, Zhao Y et al. [5] conducted a fire test study on the temperature distribution in a small scale cable tunnel. It was found that the temperature changes faster in an arc utility tunnel than 45 °. What's more, Liang K et al. [6] carried out the numerical simulation of cable fire. The ceiling temperature was analyzed in the T-shaped utility tunnel with HRR changes. Meanwhile, Xin et al. [7] studied the longitudinal and transverse distribution of temperature field in a tunnel during fire. They used the experimental equipment in a reduced-scale tunnel with a cross-section of 0.88 m×0.5 m, a length of 12 m and a variable ventilation velocity varying from 0 m/s to 5 m/s. It can be seen from the previous studies that most of the researches on utility tunnel fires draw on the experience of highway tunnel fires. Therefore, the smoke temperature distribution below the ceiling is an important part of utility tunnel fire alarm system. However, there is little research on the temperature distribution of smoke in the fire electrical compartment of utility tunnel with the change of the vertical position of the fire source, under the influence of different longitudinal ventilation velocity.

Under the condition of longitudinal utility tunnel ventilation, attention should be paid to the influence of different vertical positions of fire sources on the temperature distribution below the ceiling. Furthermore, it is very helpful to establish the prediction model of smoke temperature distribution in the utility tunnel fire detection and alarm system. However, there is no practical prediction model of smoke temperature in the electrical compartment of utility tunnel at present, especially with different vertical positions of fire sources under the influence of longitudinal ventilation. In addition, there are many previous studies on the prediction model of the maximum temperature of tunnel fire in the past. The classic maximum temperature prediction model of tunnel fire is proposed by Kurioka. Kurioka [8] proposed a model to

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predict the maximum smoke temperature beneath the ceiling based on the experiment of longitudinal ventilation in a reduced scale tunnel. The equations (1) - (3) as follows:

$$\frac{\Delta T_{max}}{\Delta T_a} = \gamma\left(\frac{Q^{*2/3}}{Fr^{1/3}}\right)^{\varepsilon}$$
$$\frac{Q^{*2/3}}{Fr^{1/3}} < 1.35, \gamma = 1.77, \varepsilon = 6/5 \quad (1)$$
$$\frac{Q^{*2/3}}{Fr^{1/3}} \geq 1.35, \gamma = 2.54, \varepsilon = 0$$

$$Q^* = \frac{Q}{\rho_0 c_p T_a g^{1/2} H_f^{5/2}} \quad (2)$$

$$Fr = \frac{v^2}{gH_f} \quad (3)$$

where, ΔT_{max} is maximum excess gas temperature beneath the ceiling (℃) ; ΔT_a is ambient temperature (℃); Q^* is dimensionless heat release rate of fire source; Fr is the Froude number; H_f is effective ceiling height in utility tunnel (m); g is the gravity acceleration, (m^2/s); ρ_0 is the density of smoke (kg/m^3); c_p is the specific heat capacity of hot smoke ($J/(kg \cdot ℃)$); Q is heat release rate of the fire (kW); v is longitudinal ventilation velocity (m/s); γ is coefficient parameter; ε is parameter.

However, the influence of longitudinal ventilation on the temperature distribution below the ceiling between tunnel fire and utility tunnel fire is different. The specific reasons are as follows. Firstly, there are wires and cables burning in the utility tunnel. The combustible in the tunnel is a car. Secondly, the geometry section size of the utility tunnel is different from that of the tunnel. Finally, the utility tunnel is 200 m long and divided into a fire compartment, but there is not include fire compartment in the tunnel. Therefore, the temperature characteristics of utility tunnel fire need further study. The longitudinal ventilation velocity, heat release rate and vertical position of fire shall be considered.

In this paper, the smoke temperature distribution in the utility tunnel is studied under the influence of longitudinal ventilation by changing the vertical position of the fire source. At the same time, the combustion of the cable in the utility tunnel is studied. The effects of ventilation velocity, heat release rate and vertical position of fire source are considered. The numerical simulation provides a supplement for further full-scale experimental tests. Through the temperature comparison between the numerical simulation and experimental test results, it shows that it has good consistency. In addition, a prediction model of smoke temperature distribution for utility tunnel fire detection and alarm is proposed. The influence of longitudinal ventilation on the temperature distribution and smoke propagation in the utility tunnel is studied. Finally, it provides guidance for the determination of the installation position of temperature detector in utility tunnel. Another contribution of this work is to enrich the experimental results of cable combustion in the electrical compartment of utility tunnel, which can be used to verify the numerical simulation test.

II. Method

The experimental tests were conducted in a full-scale utility tunnel. As shown in Figure 1, the utility tunnel is 15 m long, 2.6 m wide and 2.2 m high. There are 8 layers of cables laid in the utility tunnel. The cable spacing is 0.2 m. The cables are supported by brackets. The minimum support is 0.5 m from the floor of utility tunnel.

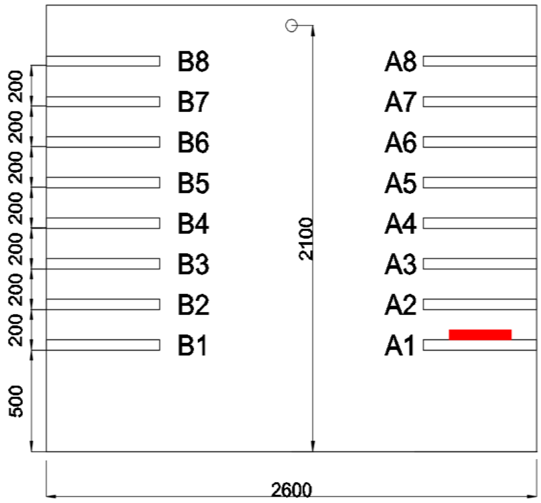

Figure 1. Cross-sectional view of the utility tunnel. (mm)

The cable consists of cable sheath and core material. As shown in Table 1, the performance of cable sheath and core material.

TABLE I
Parameters of Cable Materials

Material	Wire core	Sheath
Density (kg/m3)	8920	1380
Specific heat (kJ/(kg•K))	0.386	2.0
Thermal conductivity	300	0.42
Combustion heat (kJ/kg)	—	1.486E4

In the experiment, the utility tunnel floor and ceiling are made of concrete. The walls on both sides are made of fireproof materials [9]. The fuel is heptane as a source of ignition. The combustion object is a square pool with cross-sections of 0.33 m× 0.33 m and 0.6 m× 0.6 m. Heat release rates are 68 kW and 250 kW, respectively. In any case, the initial fuel thickness is 0.01 m. The equidistant thermocouples T1~T7 are placed in the center below the ceiling of the utility tunnel. The thermocouples T8 ~ T9 are arranged in a space of 2 m. And the first thermocouple in the thermocouple tree is 0.1 m away from the ceiling of the utility tunnel. The other thermocouples are arranged at an equal spacing of 0.20 m from the first thermocouple to bottom. Nine thermocouples are placed at every thermocouple tree.

The longitudinal ventilation velocity is controlled by the fan, which is arranged at the outlet of utility tunnel. The longitudinal ventilation velocity is measured by hot wire anemometer. The hot wire anemometer is located on the central line of the utility tunnel 2 m away from the fire source. As shown in Table 2, eight experimental conditions are carried out in this paper. In case 1, case 2 and case 3, HRR is 68 kW, longitudinal ventilation velocity is 0 m/s, 0.5 m/s and 1.0 m/s respectively. In case 3, case 4 and case 5, the vertical position of the fire source is A1, A4 and A8 respectively. In case 6, case 7 and case 8, HRR is 250 kW, longitudinal ventilation velocity is 0 m/s, 0.5 m/s and 1.0 m/s respectively.

TABLE 2
EXPERIMENTAL CONDITIONS

Case	Heat release rate (kW)	Size of oil (m)	Ventilation velocity (m/s)	Fire location
1	68	0.33×0.33	0	A1
2	68	0.33×0.33	0.5	A1
3	68	0.33×0.33	1.0	A1
4	68	0.33×0.33	1.0	A4
5	68	0.33×0.33	1.0	A8
6	250	0.60×0.60	0	A1
7	250	0.60×0.60	0.5	A1
8	250	0.60×0.60	1.0	A1

Numerical simulation is an effective method to predict thermal fluid phenomena [10-12]. The fire dynamics simulator (FDS) is a commonly used software in fire related research [13-15]. FDS is suitable for the study of smoke propagation and fire prevention in utility tunnel. Therefore, in order to compare the experimental results, the numerical simulation cases are in good agreement with the experimental test cases in the utility tunnel.

The numerical simulation conditions in this paper are similar to the experimental conditions. The size of the numerical model, the vertical position of the fire source, the characteristics of the fire source and the setting of the environment parameters are consistent with the experimental tests. Grid independence is very important in numerical simulation [16]. The element size is 0.1 m in the numerical simulation. In order to balance the expected accuracy and time cost, the simulation uses a 0.1 m cell size, which is similar to the work of Ji et al. [16] in tunnel fire simulation. The HRR is 68 kW and 250 kW, respectively. The ventilation velocity is 0 m/s, 0.5 m/s, 1.0 m/s, respectively. The vertical positions of fire sources are A1, A4 and A8, respectively. The wall is adiabatic. The inlet is set as an opening. The outlet is set to the ventilation velocity. In the experiment, the ambient temperature is 10 ℃.

III. RESULTS AND DISCUSSIONS

A. Effect of heat release rate

When the ventilation velocity is 0.5 m/s, the temperature distribution measured by the longitudinally arranged thermocouple when HRR is 68 kW and 250 kW, as shown in Figure 2. Figure 2 shows the measured values of ceiling temperature at different temperature measuring points and different heat release rates within 300 s.

In Figure 2, the closer to the fire source, the higher the temperature below the utility tunnel ceiling. The maximum temperature is 1 m below the utility tunnel ceiling from the fire source. At the same distance from the fire source, the maximum temperature upstream of the fire source is lower than the maximum temperature downstream of the fire source. With the distance from the downstream of the fire source increases, the temperature below the utility tunnel ceiling presents a downward trend. And the temperature decay rate gradually slows down. When the longitudinal ventilation velocity is 0.5m/s, the high temperature smoke moves to the downstream of the fire source. This is the reason that the maximum temperature is 1 m downstream of the fire source.

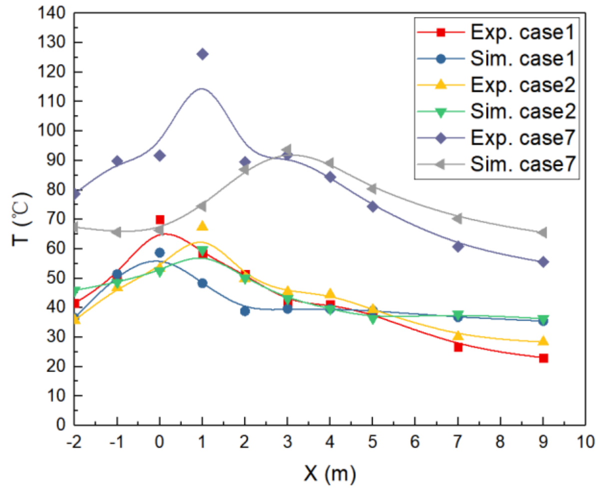

Figure 2. Temperature distributions below the utility tunnel ceiling with different heat release rates.

B Effect of fire location

When the longitudinal ventilation velocity is 1 m/s, the vertical position of fire source is located at A1, A4, and A8, respectively. The temperature is measured below the utility tunnel ceiling in the electric compartment of utility tunnel, when the vertical position of the fire source changes. Figure 3 shows the ceiling temperature below the utility tunnel measured longitudinally in case 3, case 4 and case 5, when the time of different temperature measurement points changes from 0 to 300 s.

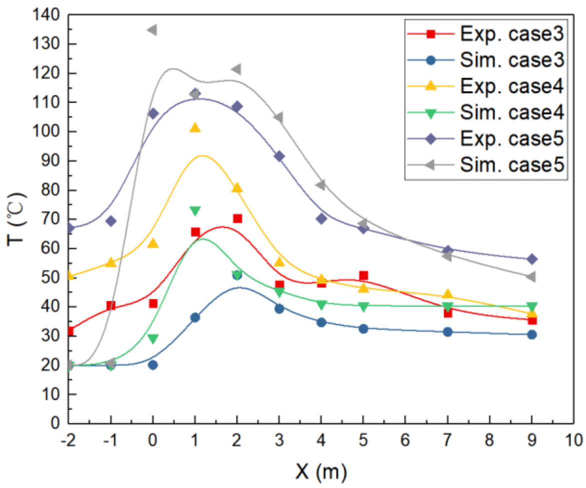

Figure 3. Temperatures measured along the utility tunnel ceiling in case 3, 4 and 5.

In Figure 3, the maximum temperature is 1 m downstream of the fire source at 300s. At the fire source, the smoke temperature is not the maximum. With the increase of the distance from the fire source, the smoke temperature gradually decreases along the longitudinal direction. And the temperature decay rate gradually slows down. The fire source is close to the ceiling of the utility tunnel, and the smoke temperature is high. The reason is that the vertical position of the fire source is close to the ceiling of utility tunnel, and the distance from ceiling of the utility tunnel to the fire source decreases gradually. Therefore, this causes the temperature to rise below the ceiling in the electrical compartment of utility tunnel.

C Effect of ventilation velocity

As shown in Figure 4, the influence of longitudinal ventilation velocity on the temperature distribution below the ceiling electric compartment of utility tunnel. When the heat release rate is 250 kW, the longitudinal ventilation velocity is 0m/s, 0.5m/s and 1.0m/s, respectively. With the change of longitudinal ventilation velocity, the temperature distribution in the utility tunnel is also different. In case 6 and case 8, at different temperature measuring points, when the time is 300 s, the ceiling temperature changes along the longitudinal direction.

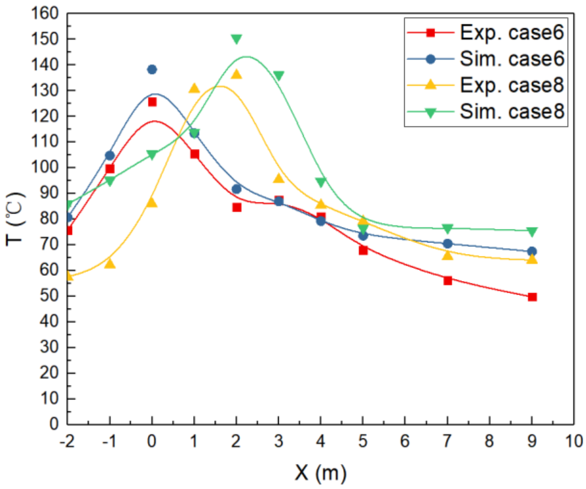

Figure 4. Temperatures measured along utility tunnel ceiling in case 6 and 8.

In Figure 4, the maximum ceiling temperature of the fire source in case 6 and case 8 is different. In case 6, the maximum temperature below the ceiling is 1 m downstream of the fire source. In case 8, the maximum temperature below the ceiling is 2 m downstream of the fire source. As the distance from the fire source increases, the maximum temperature below the ceiling in the upstream of the fire source decreases along the longitudinal direction. The temperature decay rate gradually slows down.

The longitudinal ventilation velocity is 0 m/s, and the temperature below the ceiling at the fire source location is the highest in the utility tunnel. With the increase of the longitudinal ventilation velocity, the smoke is blown to the downstream of the fire source by the ventilation. These causes the temperature of the downstream of the fire source to increase gradually. Another reason is that with the increase of the longitudinal ventilation velocity, it brings into a large amount of oxygen, which aggravates the combustion characteristics of the cables in the electrical compartment of the utility tunnel. When the longitudinal ventilation velocity is 1.0 m/s, the smoke moves strongly to the downstream of the fire source, resulting in the maximum temperature of the smoke at 2 m downstream of the fire source.

D Prediction model of temperature distribution

The heat release rate has an important influence on the smoke temperature distribution below the ceiling of utility tunnel [16-18]. As shown in Figure 5, the dimensionless longitudinal temperature distribution changes with the dimensionless distance from the fire source below the ceiling of electrical compartment in utility tunnel. It can be seen that in case 1, the experimental and numerical R-Square values are 0.97 and 0.92, respectively. In cases 1, 2 and 3, the heat release rate is 68 kW, the experiment R-Square value is very close to the numerical value. In case 6, case 7 and case 8, the heat release rate is 250 kW, the experiment R-Square value is basically the same as the numerical value.

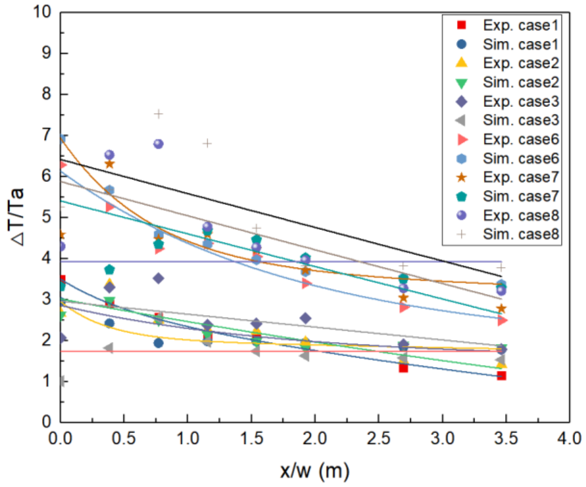

Figure 5. Non-dimensional longitudinal temperature distribution below the ceiling.

The prediction model of longitudinal temperature below the utility tunnel ceiling is proposed. The longitudinal temperature distribution obtained by numerical simulation is in good agreement with the experimental results. In conclusion, the temperature prediction model below the ceiling is derived as equation (4) in the utility tunnel fire.

$$\frac{\Delta T}{T_a} = A_1 \cdot \exp\left[-\frac{x/w}{a_1} \right] + A_2 \cdot \exp\left[-\frac{x/w}{a_2} \right] + A_3 \qquad (4)$$

where, ΔT is the temperature difference between utility tunnel and ambient temperature; T_a is ambient temperature (℃); a_1 is parameter; a_2 is parameter; x is distance from fire source (m); w is width of utility tunnel (m); A_1 is parameter; A_2 is parameter; A_3 is parameter.

IV. Conclusions

When a fire occurs in the electrical compartment of utility tunnel, the smoke temperature below the ceiling is an important factor for fire detection and alarm. In this paper, the distribution of smoke temperature with the longitudinal ventilation velocity in utility tunnel is studied by experiment and numerical simulation. Three important factors, ventilation velocity, heat release rate and fire source location, are considered. The main conclusions are as follows.

(1) The smoke temperature distribution is studied in the electrical compartment of utility tunnel by changing the heat release rate of the fire source. When the vertical position of the fire source is placed at A1, with the decrease of heat release rate, the maximum temperature below the ceiling of utility tunnel decreases.

(2) The closer the vertical position of the fire source is to the utility tunnel ceiling, the higher the temperature is below the utility tunnel ceiling. Under a given heat release rate, with the decrease of the distance between the vertical position of the fire source and the ceiling of the utility tunnel, the temperature attenuation rate of smoke below the ceiling of the

utility tunnel gradually decreases.

(3) The temperature distribution below the ceiling of utility tunnel is greatly affected by the longitudinal ventilation velocity. With the increase of longitudinal ventilation velocity, the position of maximum temperature below the ceiling of utility tunnel moves to the downstream of the fire source. The reason is that the longitudinal ventilation brings a lot of oxygen, which aggravates the combustion characteristics of the fire.

(4) This paper proposes a longitudinal temperature prediction model below the ceiling of utility tunnel. The longitudinal temperature distribution obtained by numerical simulation is in good agreement with the experimental tests. This paper has some guiding significance for the installation of temperature detection device in utility tunnel.

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