Prediction of Smoke Back-layering Length and Critical Velocity in a Utility Tunnel

Z. P. BAI, Y. F. LI

***Abstract*—The prediction smoke back-layering length and critical velocity in the event of a fire in a utility tunnel are studied. In this paper, the method of numerical simulation is used to study the combustion characteristics of the cable tray in a utility tunnel. The prediction of smoke back-layering length is related to factors such as heat release rate, longitudinal ventilation velocity, and fire source location. The smoke back-layering length is determined by the temperature record. The temperature measurement is made by thermocouple tree in the utility tunnel. Results show that the dimensionless critical velocity has a certain influence on the dimensionless heat release rate in utility tunnel. The numerical simulation results show that there is an exponential relationship between the dimensionless smoke back-layering length with two fire locations (locations A and C) in the utility tunnel. This paper proposes a method for predicting the smoke back-layering length based on the correlation of numerical simulation data. In two fire locations (locations A and C), the numerical simulation data of the smoke back-layering length has a good correlation with the results of the Li model. The main contribution of this paper is to prevent the smoke propagation in utility tunnels and provide technical guidance. Therefore, this paper has certain guiding significance for the smoke propagation below the ceiling of the electric compartment in utility tunnel.**

***Index Terms*—Back-layering length; Critical velocity; utility tunnel; Ventilation**

I. INTRODUCTION

In recent years, utility tunnels have been built in many cities [1][2]. However, there are many cables in the electric compartment of utility tunnel. These cables can easily cause a fire at the junction. The smoke from the cable fire spread rapidly in utility tunnel [1]. The fire caused huge economic losses to the utility tunnel [3].

Many previous studies have focused on the fire protection of cable tunnels. Cable fire is one of the most important fire factors in utility tunnel fires. Many researchers have studied the fire hazard of cables. Using small-scale models and numerical simulation methods, some characteristics of utility tunnel fire are studied. Thibert E et al. [4] used a cone calorimeter to test the burning characteristics of the cable.

Manuscript received Oct 25, 2019. This work is supported by Beijing Natural Science Foundation（8172006）.

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The study found that the burning performance of flame retardant cables with different types is difficult to predict. The heating value of the cable has a certain regularity. F.E. Baker [5] built a cable tunnel test environment according to the actual construction size (length 9. 14 m × width 2. 13 m × height 2.13 m). The cables actually used should be arranged horizontally according to the actual installation situation, and the fire test should be carried out. They got the flame retardant data for utility tunnel cables. These data show that a large amount of smoke and flame spread after the cable burns. Yan E et al. [6] used numerical simulation methods to study the temperature field of fire accidents in the L-shaped utility tunnel. Zhao Y et al. [7] studied the temperature distribution in a small-scale cable tunnel through the fire experiments. The results showed that the temperature increased rapidly in the arc utility tunnel area above 45 ° . Liang K et al. [8] conducted cable fires through numerical simulation. The maximum temperature below the ceiling of T-shaped utility tunnel with different heat release rates (HRRs) was analyzed. Huang X et al. [9] studied vertical cable tray fires in confined compartments. The temperature prediction model was studied. This model was used to evaluate the fire hazard of cables in nuclear power plants. Plumecocq W [10] proposed a semi-empirical model of the horizontal cable tray fire in nuclear power plant. Beji T et al. [11] used numerical simulation method to study the fire of cable trays. The heat release rate (HRR) is underestimated when using the cone calorimetry (CC) data.

However, there are few studies on the reverse flow of smoke in utility tunnels at home and abroad. The reverse flow of smoke leads to the appearance of smoke back-layering length. When the reverse flow of smoke disappears, the longitudinal ventilation velocity is the critical ventilation velocity. There are few studies on the back-layering length of smoke in utility tunnels. Meanwhile, the smoke back-layering length and critical velocity in tunnels have been studied. Thomas [12,13] defined the critical Froude number as follows:

$$Fr_c = \frac{\Delta\rho g H}{\rho_0 V_c^2} \tag{1}$$

where, Fr_c is critical Froude number; $\Delta\rho$ is density difference, kg/m^3; g is the gravity acceleration, m^2/s; H is tunnel height, m; ρ_0 is the ambient density, kg/m^3; V_c is critical velocity, m/s.

Thomas proposed that the critical Froude number is close to 1, when the smoke reverse flow disappears. The equation (2) was proposed to predict the critical velocity was expressed as follows:

$$V_c = \left(\frac{gQ_c H}{\rho_0 c_p T_f A}\right)^{1/3} \tag{2}$$

where, T_f is gas temperature, K; A is the tunnel cross-sectional area, m^2. Q_c is convective heat release rate, kW.

Kennedy [14] proposed an equation (3) based on the similar theory.

$$V_c = K_g \left(\frac{gQ_c H}{\rho_0 c_p T_f A Fr_c}\right)^{1/3} \tag{3}$$

where, $T_f = \frac{Q_c}{\rho_0 c_p A V_c} + T_0$

where, T_0 is ambient temperature, K.

Li Y. Z. [15] proposed the smoke back-layering length by giving the equation (4).

$$l^* = \begin{cases} 18.5\ln(0.81Q^{*1/3}/V^*), Q^* \le 0.15 \\ 18.5\ln(0.43/V^*), Q^* > 0.15 \end{cases} \tag{4}$$

where, l^* is dimensionless smoke back-layering length; V^* is dimensional ventilation velocity; Q^* is dimensionless heat release rate.

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

where, Q is total heat release rate, kW.

The dimensionless longitudinal ventilation velocity is shown as equation (6).

$$V^* = \frac{V}{\sqrt{gH}} \tag{6}$$

There have been many previous studies on the smoke back-layering length in tunnels in the past. Meanwhile, the longitudinal ventilation critical velocity has also been widely studied in tunnel fires. These parameters are of great significance to the fire prevention in utility tunnels. The model of smoke back-layering length and critical velocity of longitudinal ventilation is established in tunnels. There are some differences between tunnel and utility tunnel. On one hand, cables are placed in utility tunnels, but they are not in tunnels. On the other hand, cars cause fire in tunnels, but they are not in utility tunnels. Thus, the phenomenon of smoke reverse flow in utility tunnel fire and tunnel fire is completely different. Therefore, it is necessary to study the smoke back-layering length and critical velocity of longitudinal ventilation in utility tunnel fire under the influence of different factors.

In order to provide guidance for the installation of fire detector and smoke detector, this paper studies the smoke back-layering length and critical velocity of longitudinal ventilation in cable fire of utility tunnel. In view of the above problems, a full-scale model is used to simulate the fire in the utility tunnel. There are three important factors such as heat release rate, longitudinal ventilation velocity and fire source location changed, respectively. The temperature change of each measuring point is recorded in the utility tunnel. The temperature measurement data are analyzed. In this paper, under the influence of three important factors, the smoke back-layering length and critical velocity of longitudinal ventilation in the smoke propagation model at the initial stage of utility tunnel fire are derived. This paper provides basic guidance for the research of fire protection technology of utility tunnel.

II. METHOD

As shown in Figure 1, the numerical simulation is carried out in a full-scale utility tunnel. The utility tunnel is 2.6 m wide, 2.2 m tall and 100 m long. That is to say, the utility tunnel is 2.6 m in Y direction. The utility tunnel is 2.2 m in Z direction. The utility tunnel length is 100 m in the X direction. The floor, walls and ceiling are made of concrete [16]. The interior is laid with 8 layer cables side by side. Eight layer cables are installed on both sides of the electrical compartment in the utility tunnel. In order to facilitate calculation, a section of utility tunnel is selected for test. Most of the numerical simulations are carried out in a full-scale utility tunnel. The fire source has two locations, one is located at the center line of the fire source, and the other is close to the utility tunnel wall. As shown in Figure 1, the fire source is located in the cross section diagram of the utility tunnel at the central location C. As shown in Figure 2, the fire source is located on one side of the utility tunnel wall below the cable trays.

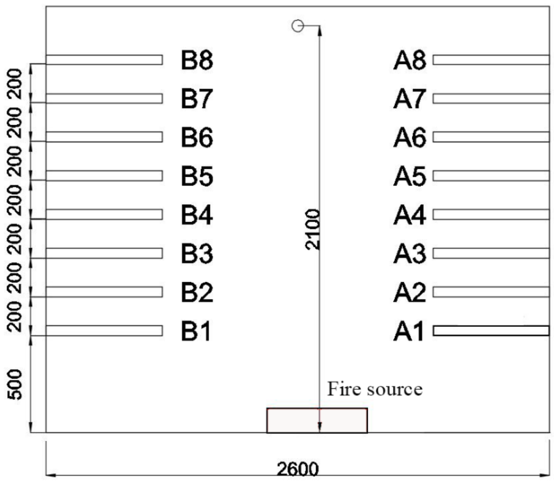

Fig. 1. Cross-sectional view of the utility tunnel with fire located at centerline C.

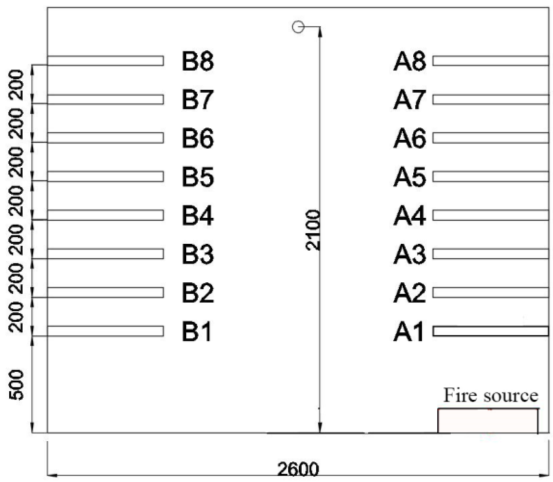

Fig. 2. Cross-sectional view of the utility tunnel with fire located at one side A.

It is not easy to test the fire in utility tunnel. In the past, computational fluid dynamics (CFD) simulation method was used to analyze the motion law of fluid [17,18]. Fire dynamics simulator (FDS) is [19] developed by NIST, which is used to simulate the fire scene of utility tunnel. FDS is a very good tool to evaluate the smoke propagation in tunnel fire [20].

There are two openings on both sides of the electric compartment of the utility tunnel. These openings are used for longitudinal ventilation. The cable spacing is 0.2 m. The cables are supported by brackets. The lowest bracket is 0.5 m from the floor of the utility tunnel. The cable is made of copper core rubber insulation material in the utility tunnel. The performance of cable sheath and core material is shown in Table 1.

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

The fire source fuel is heptane. The smoke back-layering length is measured by K-type stainless steel-sheathed thermocouples below the utility tunnel ceiling. The thermocouples are 10 mm from the utility tunnel ceiling. The thermocouples are arranged in the upstream 49 m from the fire source to 49 m downstream in the utility tunnel. The interval of thermocouples is 0.5 m along the longitudinal direction of the utility tunnel. The critical velocity of longitudinal ventilation is calculated, when the phenomenon of smoke reverse flow disappears.

The changing conditions are heat release rate and longitudinal ventilation velocity. The longitudinal ventilation velocity can be changed by setting different parameters. The heat release rate of the fire source is determined according to the fire of different scales in the utility tunnel. The ventilation velocity is calculated according to the critical velocity of ventilation under different heat release rates. There are 16 cases in the numerical simulation test. The cases are shown in Table 2. The fire source of case 1 ~ 8 is located at side A. In cases 9 ~ 16, the fire source is placed at center line C.

TABLE 2
EXPERIMENTAL CONDITIONS

Case	HRR (kW)	Fire source	Ventilation velocity (m/s)				
1	250	A	0.4	0.6	0.8	1.0	1.1
2	500		0.6	0.8	1.0	1.1	1.2
3	800		0.8	0.9	1.0	1.1	1.2
4	1000		0.7	0.9	1.1	1.3	1.4
5	1500		0.9	1.1	1.2	1.3	1.4
6	2000		1.0	1.2	1.4	1.5	1.6
7	2500		1.0	1.2	1.4	1.5	1.6
8	3000		1.1	1.3	1.5	1.6	1.7
9	250	C	0.4	0.6	0.8	0.9	1.0
10	500		0.6	0.8	0.9	1.0	1.1
11	800		0.7	0.9	1.0	1.1	1.2
12	1000		0.7	0.9	1.1	1.2	1.3
13	1500		0.9	1.0	1.1	1.3	1.5
14	2000		1.0	1.2	1.3	1.4	1.6
15	2500		1.0	1.2	1.4	1.5	1.6
16	3000		1.1	1.3	1.5	1.6	1.7

III. Results And Discussions

A. *The smoke back-layering length*

Figures 3 and 4 respectively study the effect of longitudinal ventilation velocity and heat release rate on the smoke back-layering length in utility tunnel in case of fire at the central line position and one side. The results show that the smoke back-layering length varies significantly with the longitudinal ventilation velocity. However, the relationship between the smoke back-layering length and the longitudinal ventilation velocity is not linear. With the longitudinal ventilation velocity decreases, the smoke back-layering length increases rapidly. Figures 3 and 4 also show that the smoke back-layering length depends on the heat release rate. When the heat release rate of fire source is less than 3000 W, the smoke back-layering length increases with the increase of the heat release rate.

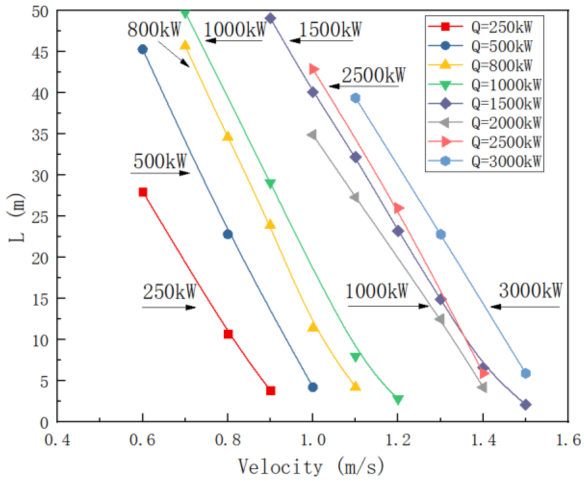

Fig. 3. The smoke back-layering length the utility tunnel with fire located at center line C.

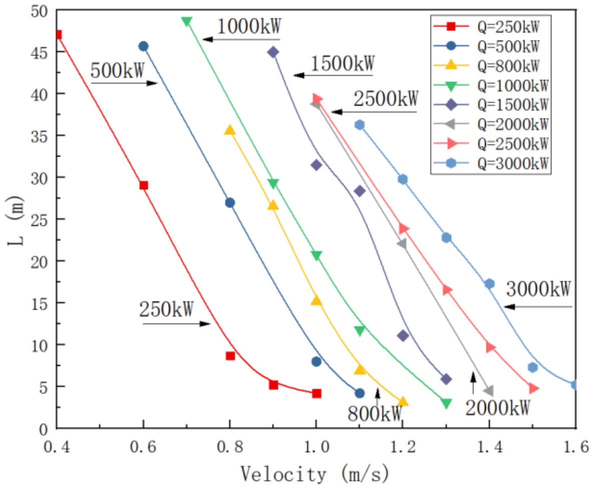

Fig. 4. The smoke back-layering length the utility tunnel with fire located at side A.

B. *Dimensionless critical velocity*

As shown in Figure 5, dimensionless critical ventilation velocity is positively correlated with dimensionless heat release rate of the utility tunnel fire.

When the fire source is located at position C in the utility tunnel, the dimensionless critical ventilation velocity is shown in equation (7). The correlation coefficient of equation (7) is 0.943.

$$V^* = 0.49 \cdot Q^{*1/3} + 0.09 \tag{7}$$

where, Q^* is dimensionless heat release rate of the fire; V^* is the dimensionless critical ventilation velocity.

When the fire source is located at side A in the utility tunnel, the dimensionless critical ventilation velocity is shown in equation (8). The correlation coefficient of equation (8) is 0.948.

$$V^* = 0.42 \cdot Q^{*1/3} + 0.13 \tag{8}$$

where, Q^* is dimensionless heat release rate of the fire; V^* is the dimensionless critical ventilation velocity.

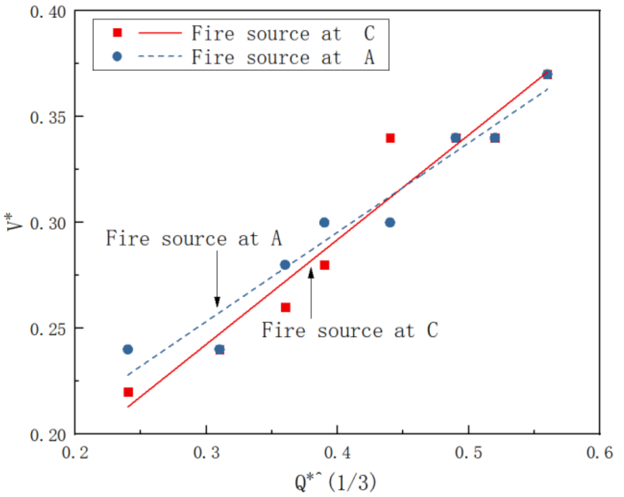

Fig. 5. The dimensionless critical ventilation velocity in the utility tunnel.

C. Dimensionless smoke back-layering length

The dimensional analysis method is used to further analyze the numerical simulation results. Figure 6 shows that when fire source is placed at center line C location, the dimensionless smoke back-layering length increases with the increase of heat release rate, and it decreases with the increase of longitudinal ventilation velocity. Obviously, the variable of heat release rate and longitudinal ventilation velocity correlates well with the dimensionless smoke back-layering length. As the heat release rate increases, the smoke back-layering layers increases.

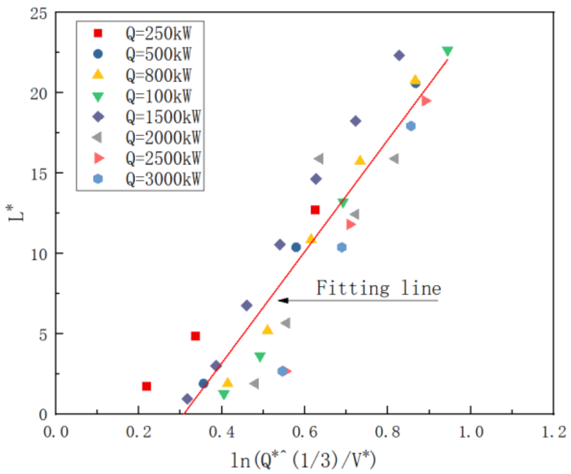

Fig. 6. Correlation of dimensionless smoke back-layering length with variable of $\ln(Q^{*}\wedge(1/3)/V^{*})$ when fire source at center line C location.

When the fire source is placed at the center line, the numerical simulation data of the smoke back-layering length can be correlated into a general form. The dimensionless smoke back-layering length is shown in equation (9). The correlation coefficient of equation (9) is 0.950.

$$l^* = 34.72 \cdot \ln(Q^{*(1/3)} / V^*) - 10.71 \tag{9}$$

As shown in Figure 7, when the fire source is on side A, the dimensionless smoke back-layering length increases with the increase of heat release rate, but decreases with the increase of longitudinal ventilation velocity. As the heat release rate increases, the smoke back-layering length increases. The dimensionless smoke back-layering length is shown in equation (10). The correlation coefficient of equation (10) is 0 .942.

$$l^* = 28.63 \cdot \ln(Q^{*(1/3)} / V^*) - 7.50 \tag{10}$$

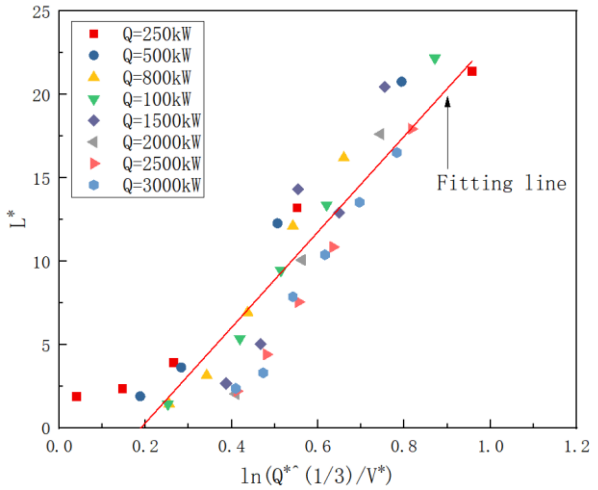

Fig. 7. Correlation of dimensionless smoke back-layering length with variable of $\ln(Q^{*}\wedge(1/3)/V^{*})$ when fire source located at side A.

D. Comparison between smoke back-layering length and the Li model

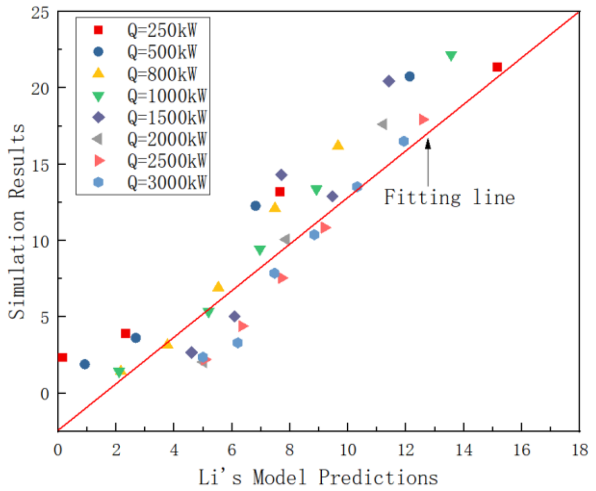

Fig. 8. The comparison between back-layering lengths of simulations results and Li's model predictions when fire source located at side A.

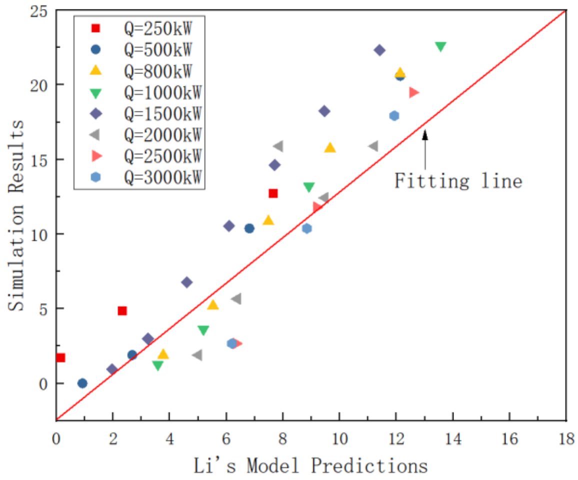

Fig. 9. The comparison between smoke back-layering length of simulation results and Li's model predictions when fire source located at center line C.

Figure 8 shows the comparison of the smoke back-layering between the numerical simulation results and the Li model [15] when the fire source is on the A side. It is shown that the numerical simulation is in good agreement with the Li model [15]. The proposed equation (10) can deal with almost all the data of numerical simulation results.

Figure 9 shows the comparison of the smoke back-layering between the numerical simulation with the Li model [15] when the fire source is placed at position C. It can be seen that the numerical simulation test is in good agreement with the Li model [15]. And the proposed equation (9) could solve almost all cases in the numerical simulation results.

IV. Conclusions

In this paper, the numerical simulation method is used to study the cable fire in a utility tunnel. The prediction smoke back-layering length and critical velocity with different longitudinal ventilation velocity are studied in utility tunnel . Three important factors are considered, which are longitudinal ventilation velocity, heat release rate and fire source location. These three important factors affect the smoke back-layering length and critical velocity of ventilation in the electric compartment of utility tunnel. In this paper, the main conclusions are as follows.

(1) This paper proposes the prediction model can predict the critical velocity well when fire source placed at two locations (locations A and C) in utility tunnel.

(2) The smoke back-layering length is related to the ratio of longitudinal ventilation velocity. It can be seen that fire source located at two locations (locations A and C), the dimensionless smoke back-layering length increases with the increase of heat release rate, and decreases with the increase of longitudinal ventilation velocity in utility tunnel .

(3) This paper proposes a prediction model of smoke back-layering length based on numerical simulation results. In addition, the numerical simulation results of the smoke back-layering length are compared with those of the Li model. It is noted that the numerical simulation experiment is in good agreement with the Li model at two locations of fire sources.

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