Study on the Length of the Near -Fire Source Area in Long and Narrow Space

Z. P. BAI, Y. F. LI

Abstract—**This paper studies the fire spread in horizontal long and narrow space with urban tunnels as the background. The length of the near-fire source area is a key factor to study tunnel fire with hybrid field-network simulation method. The length is influenced by the temperature difference in the cross section and the rate of temperature difference in long and narrow space with different tunnel widths and heat release rates. The theoretical analysis and numerical simulation methods are used to consider the influence of long and narrow space's width, heat release rate, effective ceiling height and the distance from fire source on the smoke propagation. The results show that the length of the near-fire source area are basically affected by the cross-sectional area of the long and narrow space and the heat release rate. For the type t^2 ultra-fast fire model, when the heat release rate is 15MW and the length of the near-fire source area is 115m, the smoke flow can be fully developed. Finally, this paper proposes a prediction model for estimating the length of the near-fire source area.**

Index Terms—**Numerical simulation, Long and narrow space, Fire, Smoke propagation**

I. INTRODUCTION

When fire occurs in the long and narrow space represented by urban tunnels, it is great dangerous with low visibility [1]. When a fire accident occurs in the long and narrow space, the smoke is difficult to spread vertically upwards, however, it can only be discharged from the vents at both ends [2]. Therefore, the smoke tends to spread along the longitudinal direction of the long and narrow space. These brings inconvenience for people to the evacuation and rescue. Generally, a small fire in long and narrow space can cause huge disasters, which results in the temperature rise and the smoke propagation [3]. In case of fire, with the ventilation velocity and heat release rate varies, the temperature field in the long and narrow space is changed, and the temperature distribution is also be shifted with the passage of time [4].

All the previous studies are focused on the fire characteristics in tunnels by numerical simulation methods [5]. For example, Woodburn and Britter [6,7] carried out a numerical simulation on 360 m long longitudinal ventilation in tunnels. Their results agreed well with the experimental tests. Vaquelin and Wu [8] and van Maele and Merci [9] found that the critical ventilation velocity was related to the tunnel width with the Computational Fluid Dynamics (CFD). The Fire Dynamics Simulator (FDS), developed by the National Institute of Standards and Technology (NIST), has solved the problems about smoke propagation and heat transfer in fire [10]. FDS is a good tool for studying fire characteristics. However, for long and narrow space simulation, a large number of grid needs to be established, and the calculation time is long. The reasonable solution to the ventilation and smoke control condition of long and narrow space is to adopt the hybrid field-network simulation method. The length of the near-fire source area is a key factor to study tunnel fire with hybrid field-network simulation method. However, it is not commonly used in the numerical simulation of smoke propagation in long and narrow space. Therefore, it is great significance to study the length of the near-fire source area in the long and narrow space for the alarm, fire evacuation, fire fighting, and the formulation of ventilation and smoke extraction schemes.

A series of fire experimental tests in urban tunnels has increased significantly over the past few years in the wake of deadly tunnel fires in Europe. Unlike small-scale [11] and large-scale trials, such as those were conducted in Zwenberg (Austria), Ofenegg(Switzerland), or Finland [12], Memorial tunnel experimental test indicated that it was consistent with the experimental measurement results in the far field of fire source [13]. However, the result is not accurate in the near-fire source area. Chow [14] and Hu et al. [15] applied the CFAST model to describe the growth and evolution of fires in highway tunnels. Hu et al. used experimental and numerical tests to study the maximum smoke temperature under the ceiling of tunnel fire. In addition, they also made a sensitivity analysis on the influence of grid size and iteration times on required computing time and result accuracy [16]. The simplified model proposed by Hu et al. [15,16] is similar to the method put forward by Stefopoulos and Damigos [17], is easy to test the design of the accident ventilation system. In a conclusion, in previous studies, CFD simulation method can be used to better analyze the law of fluid motion [18-21]. Overall, a prediction model for the length of near-fire source area has not been put forward to study the law of smoke flow with the hybrid field-network simulation method.

Therefore, this paper studies the length of near-fire source area in long and narrow space using theoretical analysis and numerical simulation methods. The theoretical analysis and numerical simulation methods are applied to use the hybrid field-network simulation method. The purpose is to accurately grasp the development law of smoke from the transition phase to the one-dimensional spread phase. It can provide a guidance for the quantitative study of smoke flow characteristics in each phase. The results showed that the length of the near-fire source area was mainly affected by four factors in long and narrow space. The four factors are the

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width of long and narrow space, the heat release rate, the effective ceiling height and the distance from the fire source. In addition, a prediction model is proposed for quantitative study of smoke characteristics.

II. METHOD

A. Physical Model and Fire Scenario

Referring to the size of many domestic and foreign urban tunnels, a long and narrow space model is established, according to the relevant codes of urban tunnel construction in China and United States [15-17]. As shown in Figure 1, numerical simulation is carried out for the long and narrow space with 500 m long. W = 9.0 m; H = 3.8 m. E = 0.5 m. In which, W, H and L represents the tunnel width, height and length, respectively.

Fig. 1. Cross-section of long and narrow spaces

According to the length of the long and narrow space, the location of the fire source has the greatest effect on the fire was selected for numerical simulation. Reasonable selection of heat release rate has an important influence on simulation results [15]. Therefore, the heat release rate is selected as 5MW, 15MW and 20MW based on the existing research results, which are respectively applied to the fire scenario of small cars, minibuses and large buses. The fire source was placed in the longitudinal centerline of the long and narrow space, with 250 m far from the inlet and outlet on both ends.

B. Theoretical Analysis and Numerical Study

FDS software is used to simulate the long and narrow space model, in which the temperature and ventilation velocity are calculated. The model takes 5MW, 15MW and 20MW as the heat release rates. The inlet and outlet boundaries are both open. The wall boundary is set to "CONCRETE". The calculation formula of characteristic diameter D* of fire source is as follows [22]:

$$D^* = \left(\frac{Q}{\rho_\infty c_p T_\infty \sqrt{g}}\right) \tag{1}$$

where, D^* is the fire characteristic diameter, m; Q is heat release rate of fire source, kW; ρ_∞ is ambient air density, kg/m3; c_p is constant pressure specific heat, $J/(kg\cdot K)$. T_∞ is ambient air temperature, K; g is acceleration of gravity, m^2/s. $T_\infty = 293K$; $g = 9.81\,m^2/s$; $\rho_\infty = 1.204 kg/m^3$; $c_p = 1.005 J/(kg\cdot K)$; $P = 0Pa$ [19].

According to relevant literature [23-26], the length of the near-fire source area is calculated in the horizontal long and narrow space. As shown in equations (2) - (8). In this case, the derivation process of the length of the near-fire source region can be written as follows:

$$L''_d = \frac{L'_d}{L'_c} = \frac{L_d/H_e}{L_c/H_e} \tag{2}$$

$$L''_d = 1.866\exp(-0.624\cdot(2d/W)) \tag{3}$$

$$L'_c = 12.33\cdot(Q_1)^{2/3} \tag{4}$$

Then, the dimensionless of heat release rate is expressed as in equation (5).

$$Q_1 = \frac{Q}{\rho_\infty c_p T_\infty \sqrt{g} H_e^{5/2}} \tag{5}$$

$$\frac{L_d}{L_c} = 1.866\exp(-0.624\cdot(2d/W)) \tag{6}$$

Therefore, the length of near-fire field source area in long and narrow space is expressed as in equation (8).

$$L_c = 0.115\cdot Q^{2/3}\cdot H_e^{-2/3} \tag{7}$$

$$L_d = 0.215\exp(-0.624\cdot(2d/W))Q^{2/3}\cdot H_e^{-2/3} \tag{8}$$

where, L'_c is the dimensionless length of the near field of fire source. Q_1 is dimensionless heat release rate of fire source. H_e is effective ceiling height (the height of the oil surface from the ceiling, m). L''_d is dimensionless length of near field of fire source area, W is the long and narrow space width, m; d is location of fire source, m; L_d is length of the near field of fire source, when the lateral position of the fire source changes , m; L_c is length of the near field of fire source, m.

In this paper, FDS is used to numerically simulate the smoke propagation in the long and narrow space. In this case, the calculation model is performed as the k-ε model. The SIMPLE algorithm is used to solve the coupling problems between mass and momentum conservation equations [24,25]. Length of the near field of fire source is calculated with the numerical simulation results. The length of the near-fire source area is a key factor to study tunnel fire with hybrid field-network simulation method. A prediction model for the length of near-fire source area has been put forward in order to study the law of smoke propagation.

III. RESULTS AND DISCUSSIONS

Under mechanical ventilation, the critical ventilation velocity in the upstream of the fire source intensify the mixing of the air layer in the downstream. It contributes to the rapid and full development of the downstream flow field. However, the distance is longer to reach a stable state under windless case in the horizontal long and narrow space. Therefore, it is more reliable to confirm the length of the near-fire source area by studying the stable situation position of the smoke layer in the long and narrow space with windless case. The accuracy requirements of parameter interaction of boundary conditions can be met in the hybrid field-network model.

A. The Basis for Determining The Length of NF in Natural Diffusion of Smoke

The main basis for determining the length of the near-fire source area is the law of parameter the cross-section average temperature and the temperature change rate.

The average temperature of the cross section takes into account the average values of 9 measuring points at different heights and widths. The main reason for using the cross-section temperature change rate is to reflect the longitudinal temperature attenuation rate along the long and narrow space by considering the variation of the maximum temperature differences of different sections [21-26]. The temperature change rate is shown in equation (9).

$$\varepsilon = \frac{T_{high} - T_{low}}{T_{high}} \tag{9}$$

where, T_{high} is maximum temperature of cross section, K; T_{low} is the minimum temperature, K.

The heat release rate is 15MW, which is calculated according to equation (8). As shown in Figure 2, the length of the near-fire source area increases with the width of the long and narrow space increases. The length of near-fire source area keeps constant after a certain distance from fire source. When the width of the long and narrow space is 9 m and the effective ceiling height is 3.8 m, the position where the width has a significant influence on its temperature difference value is within 87 m from the fire source. While the distance is far from 87 m, the temperature change trend is relatively flat.

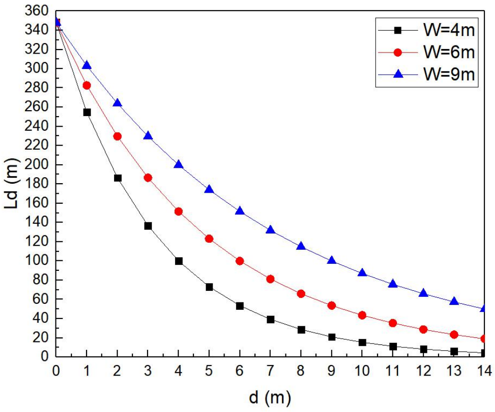

Fig. 2. The influence of space width.

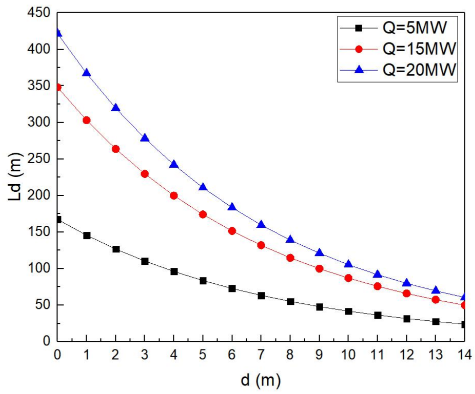

Fig. 3. The influence of heat release rate of fire.

As shown in Figure 3, the length of the near-fire source increases with the increase of the heat release rate. When the heat release rate is less than 5MW, the change of the length of the near-fire source area is slowly. When the heat release rate is 20MW, the length of the near-fire source area changes rapidly. When the width is 9 m and the effective ceiling height is 3.8 m, the area where the heat release rate is 20MW exerts a significant influence on the temperature difference value in the long and narrow space is within 320 m from the fire source. While the temperature change trend is relatively small when beyond 320 m.

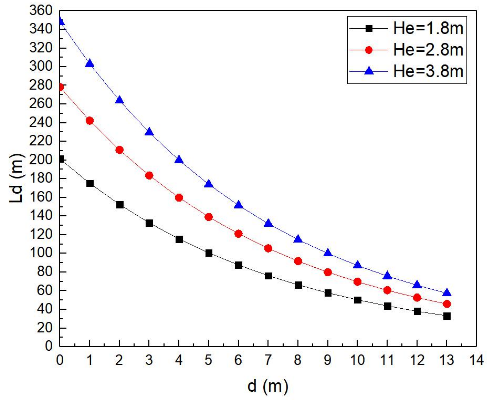

Fig. 4. The influence of effective ceiling height.

As shown in Figures 4 and 5, the length of the near-fire source area is positive correlation with the effective ceiling height, but is negative correlation with the distance from the fire source in the long and narrow space. In conclusion, when the heat release rate is fixed, reducing the effective ceiling height extend the horizontal diffusion distance of smoke, further expand the ceiling smoke temperature, and then increase the length of the near-fire source area.

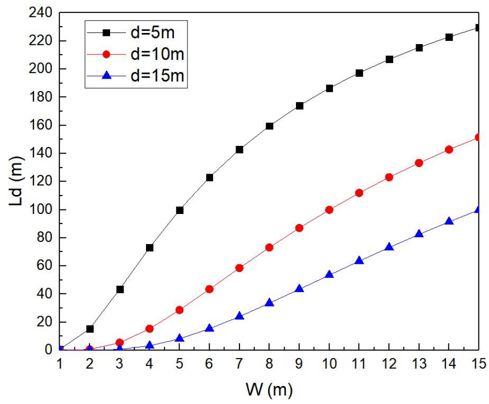

Fig. 5. The influence of distance form fire source.

B. Average Temperature Difference and Temperature Change Rate in Fire Source

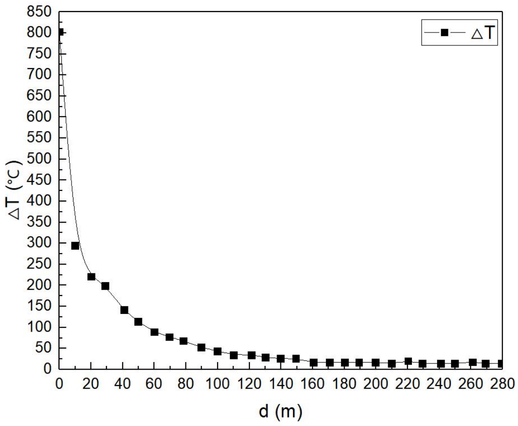

Fig. 6. Average temperature difference in fire source.

A horizontally long and narrow space model is established according to the determined dimensions, with W is 9 m, H_e is 3.8 m, and the heat release rate is 15 MW. Figures 6 and 7 respectively show the temperature changes on cross-sections with different distances downstream of the fire source. d is the distance from fire source; ΔT is the section temperature value between average temperature and ambient temperature; ε is the temperature gradient.

Figure 6 shows that the temperature difference varies with the distance from fire source. The length near-field of fire source is within 25 m where the temperature difference affected greatly. The distance from fire source beyond 100 m, the temperature difference has little change with distance, while it exceeds 115 m, the temperature difference value is basically constant.

It can be found from the temperature change rate shown in Figure 7. When heat release rate is 5 MW, the temperature change rate is nearly 40% when the distance from fire source is 115 m. The temperature change rate is consistent with the results of average temperature and temperature difference value. It indicates that when the distance from fire source is more than 115 m in the downstream, the smoke flow state has been fully developed in the simulated conditions.

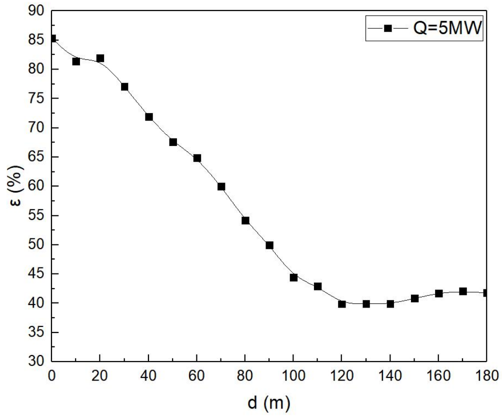

Fig. 7. Temperature change rate in fire source.

The longitudinal temperature gradient decay rate decreases gradually, and the descent speed decreases. Although the distance from fire source barely affect the temperature gradient of the fire source region, the characteristic diameter of flame and the length of horizontal flame both increase as the rising of the heat release rate. Therefore, the influence of the heat release rate increases. Near the field of fire source, the smoke temperature is not only affected by the wall surface of the long and narrow space and the ambient air temperature, but also it is influenced by the radiation and convection of fire source. When the smoke spreads to a certain distance, the smoke temperature is hardly influenced by the heat release rate, and it enters a stable decay stage.

C. Comparison with Previous Studies

Kurioka et al. [26] and Fan et al. [27] proposed a model for predicting longitudinal temperature distribution in tunnels. This paper proposes the longitudinal temperature distribution model needs to be verified. Fan et al. [27] carried out smoke temperature distribution tests on 1/6 scale for a tunnel with the length of 6m, width of 2m and height of 0.88m. As shown in Figure 7, the comparison between the longitudinal temperature distribution obtained by the prediction model equation (8) and the experimental data conducted by Fan et al. [27] agrees well. In conclusion, in the horizontal long and narrow space, the average temperature difference between the cross-section temperature inside the space and the temperature outside the space gradually decreases as the the distance from the fire source increases.

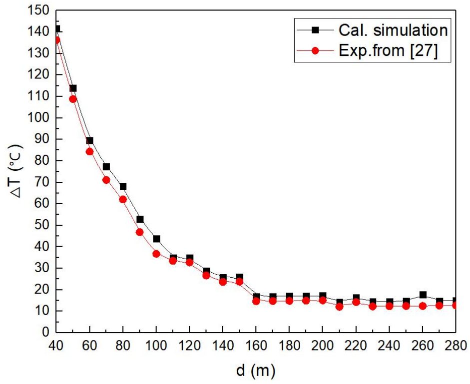

Fig. 8. Temperature change rate in fire source.

In this paper, the length of the near-fire source area are affected by four factors in the horizontal long and narrow space. Four factors are space width, the effective ceiling height, heat release rate and distance from fire source. The length of the near-fire source area is a key factor to study tunnel fire with hybrid field-network simulation method. By numerical simulation, the length prediction model of near-fire source area are proposed in this paper (for example equation 8). It is very important to study the smoke propagation with the hybrid field-network simulation method.

IV. Conclusions

In this paper, the length of near-fire source area prediction model is proposed in the long and narrow space. The length basically reveals the law of smoke propagation from the transition stage to the starting position of the one-dimensional spread stage. The theoretical analysis and numerical simulation methods are applied to study the influencing factors of the interface in the hybrid field-network simulation. This paper provides a theoretical basis for quantitative study of smoke propagation characteristics with the hybrid field-network simulation method. The conclusions are as follows:

Firstly, the length of near-fire source area is affected by four factors: the width, heat release rate, effective ceiling height and distance from fire source. The length of the near-fire source area is positively correlation with the width, heat release rate and the effective ceiling height, however, it is in negative correlation with the distance from the fire source.

Secondly, the width of the long and narrow space and heat release rate have effect on smoke propagation. For the t^2 ultra-fast fire with heat release rate is 15MW, the average temperature difference and the temperature change rate are basically constant at 115 m downstream of the fire source in the state of nature ventilation. The length of the near-fire source area is 115 m, which can satisfy the full development of the smoke with hybrid field-network method under different conditions.

Finally, the comparison between the smoke temperature distribution law obtained from the prediction model equation (8) and the experimental data of Fan et al. [27] have good agreement. In future studies, it is necessary to carry out more experiments to study the length of the near-fire source area of the fire conditions in the long and narrow space in combination with its slope.

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