A numerical study of the low-temperature zone in tunnel fires with strong longitudinal ventilation

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Abstract. In this paper, a numerical study was conducted to study the low-temperature zone induced by the strong longitudinal ventilation in tunnel fires by using Fire Dynamics Simulator (FDS). Six different longitudinal ventilation velocities at a range of 2m/s to 6m/s, two different heat release rates (5MW and 8MW) and two tunnel widths (5m and 10m) were considered in the simulations. Results showed that the bifurcation flow formed with the increasing of longitudinal velocity, and there would be a low-temperature zone. The low-temperature zone, results from comprehensive effect of inertia force and thermal buoyancy, expands with the enhancement of longitudinal ventilation. A prediction model was proposed and it revealed that the length of low-temperature zone is in proportion to the -0.44 power of \( Q^*/V^3 \).

Keywords: low-temperature zone, wall fire, longitudinal ventilation, bifurcation flow

1. Introduction

Nowadays, traffic tunnel plays a significant role in urban cities, attribute to its advantages in alleviating the traffic pressure. Due to its special structure, fire protection and smoke control in tunnels has been attached great attention. A remarkable feature of tunnel fire is that the hot smoke will be produced continuously and difficult to exhaust timely. The poisonous smoke at a high temperature is a huge threat for the personnel safety. In fact, many methods or ventilation modes have been proposed to exhaust the smoke, such as longitudinal ventilation, transverse ventilation and semi-transverse ventilation. Particularly, longitudinal ventilation is the most prevalent mode owing to its relatively lower investment.

In a longitudinal ventilated tunnel, the ventilation velocity should be large enough to prevent smoke from propagating to the uphill, then the smoke is able to be discharged from the downstream portal.
Therefore, the critical velocity, defined as the minimum ventilation velocity when the back-layering length equals to zero, should be primarily concerned in longitudinal ventilated tunnel fires. In general, the critical velocity is presumed as the lower limit of longitudinal ventilation. But the upper limit, which is also necessary for the design of longitudinal ventilation, has not attracted enough attention.

Previous studies indicated that the bifurcation flow would occur when the longitudinal ventilation velocity approach a certain value. Thereafter, the smoke flow will be divided into two branches and tend to move along the sidewall, which is quite different from the condition that the longitudinal ventilation is relatively small. As shown in Figure 1, a clear view of bifurcation flow and the low temperature zone is well observed.

![Figure 1. A schematic diagram of Bifurcation flow (top view)](image)

Researchers have confirmed the existence of this phenomenon and given a certain theoretical explanation in their studies [1-5]. Zhong et al. [1] pointed out that the exhaust efficiency of the shafts will be seriously affected if the vertical shafts located in the low-temperature zone. Wu [3] carried out a series of numerical simulation in an arch tunnel and concluded that the smoke would be separated at the top of tunnel in a V shape and formed a central low temperature zone when the longitudinal velocity was strong. Zhong et al [4] indicated that the bifurcation flow would increase the disturbance of the smoke flow and hinder the formation of a stable smoke layer. In addition, Zhong et al [5] conducted a series of reduced-scale experiments. Results showed that the dimensionless critical velocity of bifurcation flow is 1.48 times of dimensionless critical velocity of preventing smoke back-layering.

Note that to figure out the mechanism of bifurcation flow is of great significance in smoke control. Meanwhile, the bifurcation flow pattern is likely to be different when the fire position changes. However, previous researches rarely concerned about it. In fact, when the fire breaks out at the sidewall, bifurcation flow would still exist and the trajectory of smoke flow will be different from the situation that fire was located at centre.

In this paper, a series of numerical simulation has been carried out to study the characteristic of bifurcation flow with wall fire, taking different widths of tunnel into consideration. The length of low-temperature zone was calculated under different circumstances and a prediction model has been put forward.

2. Theoretical analysis

Bifurcation flow is related to many factors, like heat release rate, tunnel geometry and the ambient environment parameters. Therefore, the length of the low-temperature (L) will be affected by these factors, width (W) and height (H) of the tunnel, the ventilation velocity (V), heat release rate of fire (Q), the ambient temperature (T_a), density of air (ρ_a), the acceleration of gravity (g) and the constant pressure specific heat capacity of air (C_p). The relationship between these quantities can be expressed as:

\[ f(L, W, H, V, Q, T_a, \rho_a, g, C_p) = 0 \]  

(1)

Mass, time, length and temperature were selected as the basic dimensions, and W, V, ρ_a, C_p were chosen as the basic parameters. Hence that there will be five dimensionless quantities as follow:

\[ \pi_1 = \frac{L}{W}, \pi_2 = \frac{Q}{\rho_a W^2 V^3}, \pi_3 = \frac{C_p T_a}{W^2}, \pi_4 = \frac{gW}{V^2}, \pi_5 = \frac{H}{W} \]  

(2)
According to the arithmetic rules of dimensional analysis, the length of low-temperature zone can be expressed as:

\[
\frac{L}{H} = f\left(\frac{Q^*}{V^*^3}\right)
\]

Where \( Q^* = \frac{Q}{C_pT_0a\rho g^{1/2}W^{5/2}} \), \( V^* = \frac{V}{(gW)^{1/2}} \).

3. Numerical modelling

3.1 Fire Dynamics Simulator

Fire Dynamics Simulator (FDS) was developed by the US National Institute of Standards and Technology (NIST). As an open source code for studying smoke propagation laws and fire protection researches, FDS has been widely used in fire science researches related to fire science and engineering practice. NIST has made many updates and improvements for FDS since its first release in 2000. Many verification and validation works are also released with the publication of FDS. In the field of tunnel fire research, the reliability and efficiency has been verified by many studies.

3.2 Physical model and fire scenario analysis

Taking rectangular tunnel as the research object, the typical single-line tunnel with width of 5m and double-line tunnel with width of 10m were built in the simulation model. Figure 2 shows a clear view of the physical model.

![Figure 2. Three views of model sketch](image)

Both of double-line tunnel (left) and single line tunnel (right) were 250m long and 5 m high. As exhibited in Figure 2, three strings of thermocouples were installed inside tunnel (A, B, C) to record the longitudinal temperature distribution. Series B was located at the centre line of the tunnel, Series A and series C are 0.2 m away from the two side walls. All the thermocouples are equipped 0.2m beneath the ceiling, and each string of thermocouple has 401 measuring points. In addition, the first measuring point is 10m away from the fire centre at the longitudinal direction. The interval of 201 measuring points near the fire is 0.2m while the remaining 200 points is 0.5m. In this paper, the fire source was located near the side wall of the tunnel and 100m away from the left end. Heptane was obtained as the fuel source and its heat release rate was set as 5MW and 8MW, respectively. The fire source was set in rectangle shape with dimension of 2m(length) \( \times \) 2m(width). The material of the tunnel construction, including walls, ceiling and floors was specified as “CONCRETE”. The tunnel portal was set as “SUPPLY”.
and the exit was set as “OPEN”. For the “SUPPLY” vent, the velocity ranges from 2m/s to 6m/s. In sum, all the fire scenarios are listed in Table 1, in which the length of low-temperature zone (L) also included.

| Case | HRR (kW) | W (m) | V (m/s) | L (m) | Case | HRR (kW) | W (m) | V (m/s) | L (m) |
|------|----------|-------|---------|-------|------|----------|-------|---------|-------|
| 1    | 5000     | 5     | 2       | -     | 13   | 8000     | 5     | 2       | -     |
| 2    | 5000     | 5     | 3       | 32.8  | 14   | 8000     | 5     | 3       | 30.9  |
| 3    | 5000     | 5     | 4       | 59.6  | 15   | 8000     | 5     | 4       | 43.5  |
| 4    | 5000     | 5     | 5       | 64.4  | 16   | 8000     | 5     | 5       | 52.8  |
| 5    | 5000     | 5     | 5.5     | 75.2  | 17   | 8000     | 5     | 5.5     | 62.   |
| 6    | 5000     | 5     | 6       | 89.1  | 18   | 8000     | 5     | 6       | 66.5  |
| 7    | 5000     | 10    | 2       | -     | 19   | 8000     | 10    | 2       | -     |
| 8    | 5000     | 10    | 3       | 44.4  | 20   | 8000     | 10    | 3       | 44.8  |
| 9    | 5000     | 10    | 3.5     | 56.2  | 21   | 8000     | 10    | 4       | 58    |
| 10   | 5000     | 10    | 4       | 67    | 22   | 8000     | 10    | 4.5     | 68.4  |
| 11   | 5000     | 10    | 5       | 98.4  | 23   | 8000     | 10    | 5       | 95.1  |
| 12   | 5000     | 10    | 6       | *     | 24   | 8000     | 10    | 6       | 107   |

Note: "-" indicates no low-temperature zone, "**" indicates out of the measurement range

3.3 Grid independence

The mesh cell is the basic unit of numerical calculation, the size is a key parameter that determines the accuracy of calculation results. In theory, smaller mesh size can get more accurate calculation results, but it requires higher demands on the computer and takes more time. A non-dimensional expression $D^*/\delta_x$ was proposed by the FDS user’s guide to assess the grid resolution. The characteristic fire diameter $D^*$ could be calculated as follow:

$$D^* = \left( \frac{Q}{\rho_a c_p T_a g^{1/2}} \right)^{2/5}$$

(4)

The suggested value of $D^*/\delta_x$ ranges from 4 to 16. Therefore, the calculated value of grid size for the current study supposed to located among 0.11m-0.44m. In this paper, the longitudinal temperature distribution in the tunnel was selected to compare simulation results of six different mesh sizes with 0.1m, 0.125m, 0.16m, 0.2m, 0.3m and 0.4m, as shown in Figure 3. The results showed that there is
slight difference among the mesh size with 0.16m, 0.125m and 0.1m. Hence that the grid size of 0.16m was employed in this paper.

4. Results and discussion

4.1 The process of smoke dispersion

Taking 5MW fire as an example, Figure 4 shows the smoke dispersion patterns in the model tunnel with different longitudinal ventilation of 2m/s and 4m/s. In the process of smoke dispersion, after smoke plume impinging the tunnel ceiling, ceiling jet would be generated. At a relatively small velocity, the inertia force is not strong enough to prevent smoke from flowing upstream. Therefore, the back-layering of smoke is observed. In this condition, the smoke fills the ceiling downstream, which can be seen clearly in Figure 4 (a) and (c). At a strong velocity, the back-layering would completely disappear and form an envelope region along the side wall. The envelope region surrounded by smoke is defined as low-temperature zone, which is much clearer in Figure 4 (d).

![Figure 4](image_url)

(a)Single line, 2m/s
(b)Single line, 4m/s
(c)Double line, 2m/s
(d)Double line, 4m/s

Figure 4. Smoke dispersion at different longitudinal velocity (top view)

4.2 The length of the low-temperature zone

Figure 5 shows the temperature distribution of series A and series C while the ventilation velocity is 4m/s. The maximum value of Series A is the location where the smoke impinges the ceiling. And the point of intersection of Series A and Series C can be the end of bifurcation. Thus, the distance between
the position of the maximum temperature of Series A and the position where two lines converge can be considered as the length of low-temperature zone.

Based on Table 1 mentioned above, the results of simulation can be arranged as Figure 6. By fitting the data to the analysis, the relationship between $\frac{L}{H}$ and $\frac{Q^*}{V^*}$ can be expressed as Equation (5):

$$\frac{L}{H} = 7.20 \left( \frac{Q^*}{V^*} \right)^{-0.44}$$

$$\text{(5)}$$

5. Conclusion

In this paper, the law of smoke propagation under strong longitudinal ventilation in tunnel wall fire was studied, and the phenomenon of smoke bifurcation was investigated. Results showed that the smoke flow structure was much different from the condition that fire located at centre. Taking different heat release rates of fire source, longitudinal velocity and tunnel width into consideration, a prediction model of low-temperature zone has been put forward. This model is conducive to the further understanding of the phenomenon of bifurcation flow, and can provide a certain reference for the longitudinal design.

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