Study of the effectiveness of water mist curtain in blocking fire-induced smoke in tunnel by means of CFD simulations

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Abstract. Tunnel fire smoke control is an important issue in the area of tunnel fire safety. Inspired by fire compartmentation in buildings, it is worth investigating whether a tunnel can be partitioned by a water mist system into a fire zone and safety zones. If so, people can move from the fire zone into a safe zone through the water mist system. Obviously, an essential question is to examine to what extent the fire-induced heat and smoke can be blocked by the water mist system. Thus, in present paper, CFD simulations were conducted to investigated the effectiveness of water mist systems on blocking fire-induced heat and smoke in a full-scale tunnel. We mainly focus on the impact of nozzle combination on smoke blocking effect. Simulation results show that the entrainment caused by the water mist system plays the main role on blocking fire-induced smoke, and the nozzle combination has small impact on heat blocking effect. Based on the momentum balance of the water mist system and ceiling jet smoke flow, a correlation of total water flow rate of the water mist system and fire heat release rate was proposed.

1 Introduction

In recent years, the interest for fire safety issues in tunnels has increased dramatically due to a significant increase in number of tunnels worldwide and due to numerous catastrophic tunnel fires[1]. Due to the relatively limited cross-sectional area in tunnels, hot smoke can spread rapidly, e.g., downstream with the traffic flow or due to longitudinal ventilation. Consequently, people downstream of the fire may be exposed to high temperatures and toxic gases, especially in urban tunnels that are likely to clog during rush hours. Inspired by fire compartmentation in buildings[2,3], it is worth investigating whether a tunnel can be partitioned by a water system into a fire zone and safety zones. If so, people can move from the fire zone into a safe zone through the water system. Obviously, an essential question is to examine to what extent the fire-induced heat and smoke can be blocked by the water system. So far, there is still a lack of investigation of using water systems as a curtain to prevent smoke and heat spreading in tunnel, and there are no clear design specifications[4-12]. Therefore, it is of great importance to study the effectiveness of water systems with respect to blocking smoke and heat in tunnels.

2 Numerical study of applying a water spray system in a full-scale tunnel

2.1 Tunnel geometry and characterization of water spray under normal working pressure

The dimensions of the full-scale tunnel refer to a city cross-river tunnel (see Figure 1). The smoke exhaust and the evacuation channel in case of fire are placed underneath the ceiling and the floor. Thus, the simulation domain refers to...
the red rectangle with 4.5 m height and 7 m width. The whole length of the tunnel is about 3 km and the modeling length of the tunnel is 160 m, with the fire source located 25 m away from the tunnel entrance. Thermocouples are set at two different heights along the tunnel: \( z = 4.4 \) m and \( z = 2.2 \) m. Figure 1 and show the position of thermocouples. The dimensions of the fire are \( 2 \) m \( \times \) \( 2 \) m \( \times \) \( 0.5 \) m (red rectangle in Figure 1). The water spray system is positioned 70 m away from the fire (blue triangle in Figure 1). The characterization of the water droplets produced by a new type of nozzle is performed beforehand. The orifice of the nozzle is 2.5 mm. The water working pressure is 5 MPa with 7.1 l/min water flow rate and 160 μm mean droplet diameter. Heat release rate was set to 5 MW which represents a small car on fire.

Fig. 1. Sketch of vertical section of modeling tunnel (red rectangle indicates the fire, blue triangle indicates the water sprays, and orange circle indicates thermocouples)

Fig. 2. Temperature fields in the vertical mid-plane (x = 3.5 m) for Test A, Test B, Test C, Test D and Test M (from top to bottom). Values have been averaged over the steady state period (150 s - 200 s).

Fig. 3. Temperature evolution at positions 5 (close to the fire source), 6 (in between the fire source and the water sprays) and 8 and 10 (downstream of the water sprays) for Tests A, B, C, D. Positions 5 and 6 are located upstream the water spray system, position 9 and 10 are placed downstream the water spray system. The dashed line in the figures indicates the activation of the water spray system. As the smoke passed though water sprays, temperatures downstream water sprays are higher than the ambient temperature shown in Figure 3. Temperature differences are small among those tests. In general, the impact of the nozzle arrangement on the temperature inside tunnel is small, but the upward flow in between the water sprays is stronger with more nozzles per row.

3 Study of the correlation between heat release rate and water flow rate

The main idea of this section is to discuss the correlation between fire HRR values and water flow rate of water spray system. As we present in previous chapter, the entrainment from water sprays is crucial to blocking fire-induced smoke and heat. It was deduced that when the entrainment caused by the WMS is higher enough than the momentum of fire-induced smoke, the designed WMS is sufficient to prevent smoke spreading. Thus, the comparison of the momentum of water sprays and the momentum of ceiling jet flow is investigated to evaluate the effectiveness of smoke blocking effect of water sprays. Suppose that the entrainment of water sprays increased linearly with the increasing number of nozzles. Figure 4 is the sketch of the interaction between ceiling jet flow and water sprays.
3.1 Momentum of ceiling jet flow

As shown in Figure 4, the momentum of ceiling jet flow can be calculated as follows:

\[ M_{\text{smoke}} = xh \rho_{\text{smoke}} v_{\text{smoke}}^2 \]  

(1)

where:
- \( M_{\text{smoke}} \): horizontal velocity of smoke (m/s)
- \( x \): width of tunnel (m)
- \( h \): smoke thickness (m)
- \( \rho_{\text{smoke}} \): smoke density (kg/m\(^3\))
- \( Q_c^* \): dimensionless heat release rate, \( Q_c^* = Q_c / (\rho_{\infty} C_p T_{\infty} g H^2) \) (-)

3.2 Momentum of the water spray system

The entrainment induced by water droplets is not easy to calculate. A simple method can be used to calculate the momentum of the water flow from a nozzle head:

\[ M_{\text{water}} = \frac{v_{\text{water}}^2}{2 \sigma \rho_{\text{water}}} \]  

(3)

As we state in the previous section, for a HRR of 1 MW, the WMS can block the fire-induced smoke effectively when the number of nozzles is set to 6 \( \times 4 = 24 \). Figure 5 shows the number of nozzles (momentum of water mist system) corresponding to heat release rates (momentum of ceiling jet flow). The starting value is 1 MW with 24 nozzles (6 \( \times \) 4) which is discussed in section 5.2.4. The red dots are the numbers of nozzles that based on calculation and the blue line indicates the numbers imposed in FDS simulations, the difference is due to the number of nozzles show be integer multiples of 6 (number of nozzles per one row). Due to this, the number of nozzles used in the simulations is higher than obtained from the theoretical analysis.

4 Conclusions
In this paper, we mainly focus on applying water sprays in a full-scale tunnel to block fire-induced smoke. The characteristics of the water droplets under a working pressure of 5 MPa were determined beforehand. Investigation of impact of the nozzle combinations, with the same total water flow rate, on temperature and flow fields shows that the combination of nozzles has a slight impact on temperatures downstream, but the upward flow and the entrainment are more significant with more nozzles installed in one row (higher coverage of water mist). The study of the distance between two nozzle rows also indicates that the temperatures downstream the water spray system are not affected by this distance. The entrainment caused by the water spray system plays the main role on blocking fire-induced smoke. Based on the momentum balance of the water mist system and ceiling jet smoke flow, the correlation of total water flow rate of water mist system and ceiling jet smoke flow was investigated. The momentum of the water mist system was taken as the sum of all the momentums per nozzle, while the momentum of the ceiling jet flow was calculated as the product of the mass flow rate of the ceiling jet flow and its maximum velocity. The total water flow rate (number of nozzles) is proportional to the 2/3 power of the heat release rate (supposing that the thickness of the smoke layer changes only slightly from 1 MW to 3 MW), as illustrated by simulation results for 5 different values of HRR.

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