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Vault temperature of vehicle fires in large cross-section road tunnel

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ABSTRACT: On the basis of CFD models, the simulation analysis of a lorry and car fire in large cross-section road tunnel was carried out in this paper. The vault temperature was simulated and compared with the value calculated by correlative empirical equation. The corresponding results would be contributed to provide effective technique for the fire protection measures of the major structure of road tunnel.

1 INTRODUCTION

Large scale tunnel fires often caused considerable material damage, not only to vehicles, but also to the tunnel facilities as well. The damage was brought about by the massive development of heat and aggressive combustion gases, which led to enormous difficulties to reconstruction of tunnel. In order to provide the road tunnel with effective fire protection measures, it is important to predict the vault temperature in different road tunnel fire scenarios. There were some experiments on testing the structure characteristics under fire. But most of them were tested by following the standard temperature-time curve (Yasuda et al., 2004). Very few data are available on maximum smoke temperature under the tunnel ceiling with different ceiling heights, longitudinal ventilation velocities and fire intensities. Based on CFD models, the simulation analysis of a lorry and car fire in large cross-section road tunnel was carried out in this paper. The vault temperature was simulated and compared with the value calculated by correlative empirical equation. The corresponding results would be contributed to provide effective technique for the fire protection measures of the major structure of road tunnel.

2 DESIGN OF FIRE SCENARIO FOR CFD

2.1 Brief introduction of FDS

In these simulations, FDS (Fire Dynamics Simulator) 4.06 which was released by NIST (National Institute of Standards and Technology, USA) was used. FDS is a Computational Fluid Dynamics (CFD) model with LES (Large Eddy Simulation) of fire-driven fluid flow. The model solves numerically a form of the Navier-Stokes equations appropriate for low-speed, thermally-driven flow with an emphasis on smoke and heat transport from fires. The partial derivatives of

the conservation equations of mass, momentum and energy are approximated as finite differences, and the solution is updated in time on a three-dimensional, rectilinear grid. Thermal radiation is computed using a finite volume technique on the same grid as the flow solver.

2.2 Simulation scenarios of tunnel fire

In this paper, CFD simulation of the maximum vault temperature was conducted by FDS (4.06) in different fire scenarios with constant longitudinal ventilation velocity set as 3 m/s. The simulation length of the model which was three-driveway large cross-section road tunnel with diameter of 15 m was 100 m, as shown in Figure 1. The Heat Release Rate (HRR) of the fire

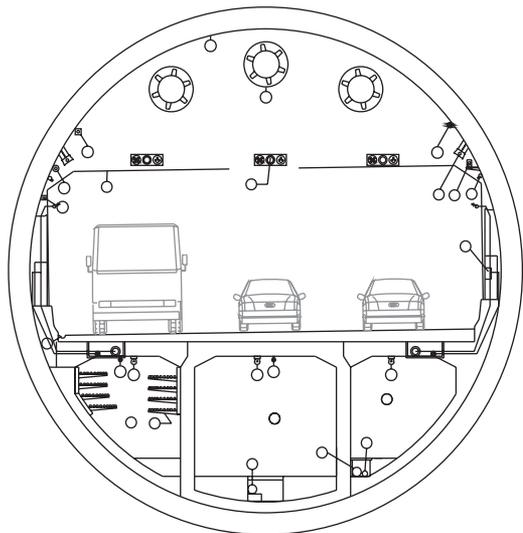


Figure 1. Cross-section of road tunnel.

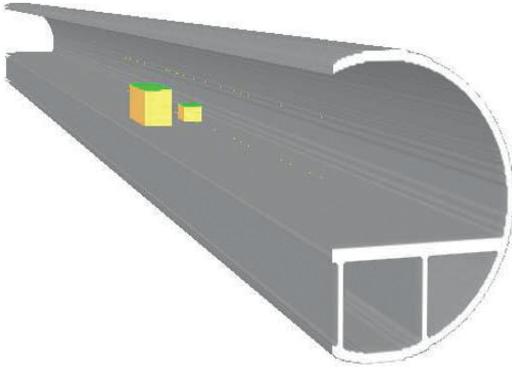


Figure 2. CFD analysis model in scenario 1.

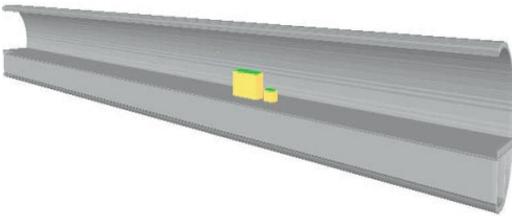


Figure 3. CFD analysis model in scenario 2.

source was based on the EUREKA project conclusion, which was completed by nine Europe countries in antiquated road tunnel. The fire position was located at 37 m from the upstream ventilation cross-section and 63 m from the downstream ventilation cross-section. In this simulation, the car was ignited by the lorry and the design scenarios include: scenario 1: the car in the flank of the lorry; scenario 2: the car downstream the lorry. In these two scenarios, the spacing between the car and the lorry was 2 m, as shown in Figures 2 and 3.

In the simulation process, the lorry firstly burned and for about 220s the car was ignited by the lorry which received more heat radiant flux than its critical value of 16 kw/m^2 . The maximum HRR of the lorry and the car was 20 MW and 5 MW separately. The total HHR generated by these two vehicles was shown in Figure 4.

3 DESIGN OF FIRE SCENARIO FOR CFD

3.1 HRR curve

As shown in Figure 4, HRR curves in these two scenarios were constructed. The relative position of the lorry and the car had less influence on total HHR. During the simulation, the HHR was approximately 23 MW and less than the algebra sum of 25 MW which was calculated by the HHR of these two vehicles respectively.

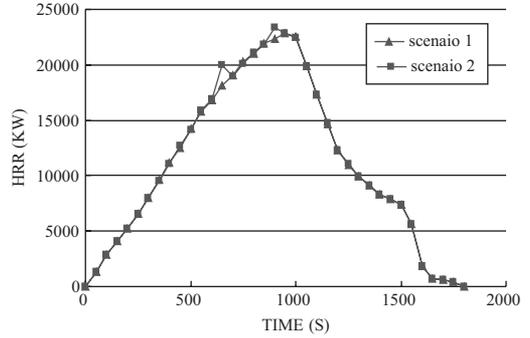


Figure 4. Heat release rate of fire source in scenario 1, 2.

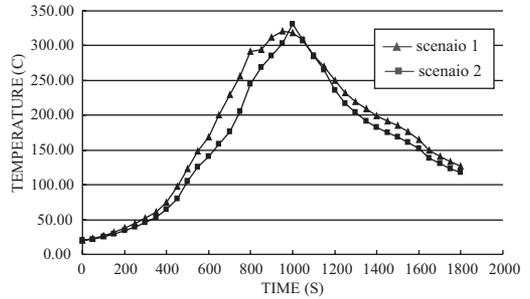


Figure 5. Vault temperature-time curves in scenario 1, 2.

3.2 Vault temperature-time curve

As shown in Figure 5, the vault temperature reached the maximum value of 321°C at the position of 4 m downstream from the fire source after 941 s in scenario 1 and achieved 331°C at the position of 5 m downstream from the fire source after 980 s in scenario 2. The vault temperature-time curves were basically of superposition in these two scenarios with the same ventilation velocity of 3 m/s and geometry properties. It was indicated that the relative position of these two vehicles had less influence on vault temperature curve.

As shown in Figures 6 and 7, because of large cross-section of the road tunnel and relatively smaller HRR value of the fire source, the simulated vault temperature was not much high. On the other hand, under the longitudinal ventilation velocity of 3 m/s, the fire flames were sloped towards downstream far from the vault, so it attenuated the environmental temperature and made less contribution to vault temperature.

3.3 Comparative analysis of vault temperature

An empirical equation which was derived to predict the maximum smoke temperature under the tunnel ceiling is presented as follows (Kurioka et al., 2003):

$$\frac{\Delta T_{\max}}{T_a} = \gamma \left(\frac{Q'^{2/3}}{Fr^{1/3}} \right)^\epsilon \quad (1)$$

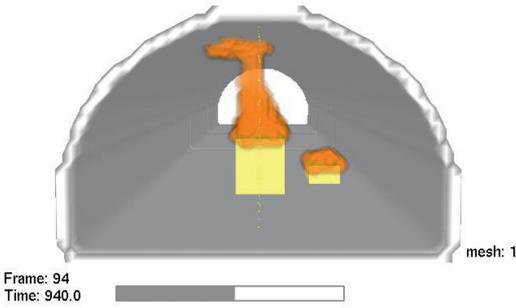


Figure 6. Fire flames in scenario 1 after 940s.

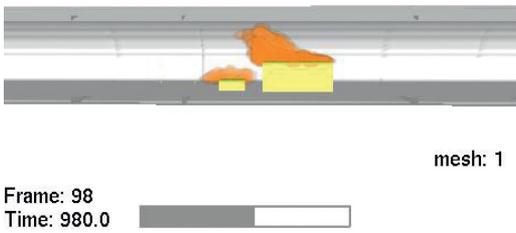


Figure 7. Fire flames in scenario 2 after 980s.

$$Q' = Q / (\rho_a C_p T_a g^{1/2} H_d^{5/2}) \quad (2)$$

$$Fr = u^2 / (g H_d) \quad (3)$$

$$Q'^{2/3} / Fr^{1/3} < 1.35, \gamma = 1.77, \varepsilon = 6/5 \quad (4)$$

$$1.35 \leq Q'^{2/3} / Fr^{1/3}, \gamma = 2.54, \varepsilon = 0 \quad (5)$$

where Q = heat release rate of the fire, kW; Q' = dimensionless heat release rate; Fr = dimensionless Froude number; γ, ε = experimental constant; C_p = specific heat capacity of air at constant pressure, $\text{kJ kg}^{-1} \text{K}^{-1}$; ρ_a = ambient air density, kg m^{-3} ; T_a = ambient air temperature in tunnel, K; ΔT_{max} = maximum excess temperature of smoke under the tunnel ceiling, K; u = representative longitudinal ventilation velocity, m s^{-1} ; g = acceleration due to gravity, ms^{-2} ; H_d = height from the surface of fire source to tunnel ceiling, m.

For validating the availability of equation (1) to the vault temperature in large cross-section road tunnel fires, three other scenarios were introduced to the simulation analysis, including: (1) scenario 3: car fire; (2) scenario 4: passenger car/lorry; (3) scenario 5: heavy goods vehicle. The heat release rates of the fire source were also in accordance with the EUREKA project conclusion, as shown in Figure 8. The fire flames in scenario 3, 4, 5 were shown in Figure 9, 10, 11 respectively.

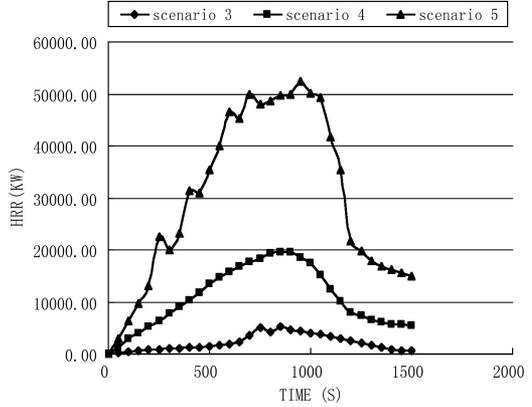


Figure 8. Heat release rate of fire source in scenario 3, 4, 5.

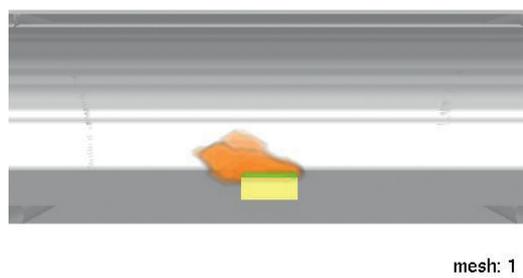


Figure 9. Fire flames in scenario 3 after 940s.

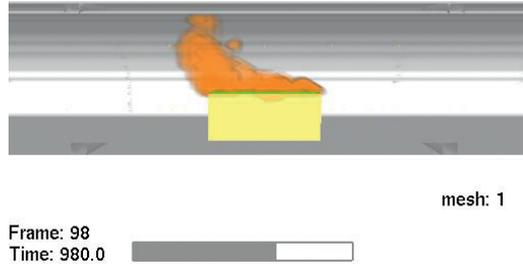


Figure 10. Fire flames in scenario 4 after 980s.

The vault temperature reached the maximum value at the position of 4 m downstream from the fire source in scenario 3, 4, 5 with the same longitudinal ventilation velocity of 3 m/s. The simulation results and empirical equation value of the vault temperature in these scenarios were shown in Figure 12 and Table 1.

As shown in Figure 13 and Table 1, there were rather differences between the simulation results and

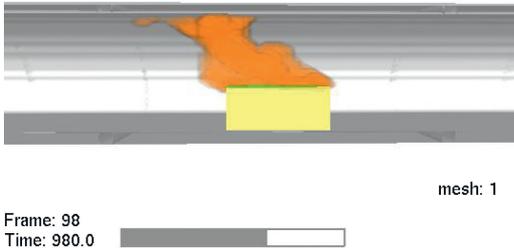


Figure 11. Fire flames in scenario 5 after 980s.

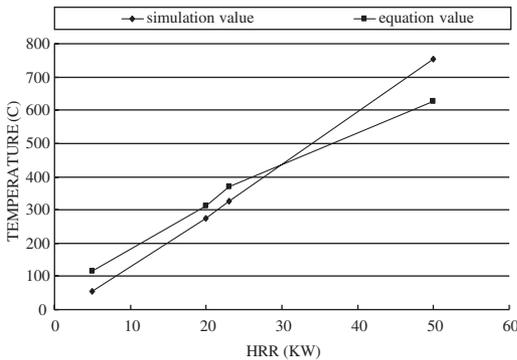


Figure 12. The simulation value and the equation value of vault temperature in different scenarios.

Table 1. The simulation value and the equation value of vault temperature in different scenarios.

Scenario	3 (5 MW)	4 (20 MW)	1, 2 (23 MW)	5 (50 MW)
Sv	54	275	(321 + 331)/2 = 326	753
Ev	116	312	369	628
Re	53.4%	11.9%	11.7%	16.6%

Sv = simulation value; Ev = equation value; Re = relative error.

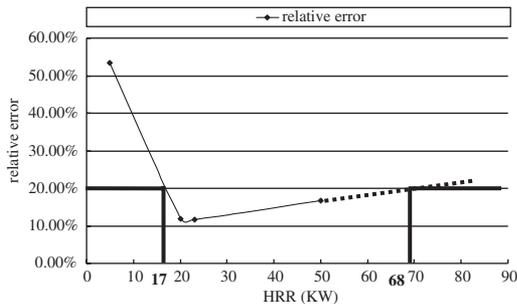


Figure 13. The relative error among the simulation value and the equation value of vault temperature in different scenarios.

the empirical equation values of the vault temperature. The relative error exceeded 20% for the HRR which were less than 17 MW and greater than 68 MW. It should be mentioned that for small scale fire, such as HRR of 5 MW, the relative error approached 53.4%. Therefore, much more simulation analysis and practical tests need to be carried out. On the other hand, it was suggested that the empirical equation could be further improved to be applicable for small scale fire in large cross-section road tunnel. Perhaps some other factors had to be considered during the calculation of vault temperature, involving different kinds of ventilation conditions and geometrical properties of the road tunnel.

4 CONCLUSION

1. As for lorry and car fires in large cross-section road tunnel and under longitudinal ventilation velocity of 3 m/s, the relative position of vehicles had less influence on total HRR which was approximately 23 MW and less than the algebra sum of 25 MW.
2. Owing to large cross-section of the road tunnel, small scale vehicle fire and longitudinal ventilation velocity of 3 m/s, the simulated vault temperature was not very high.
3. In connection with the calculation of the vault temperature, there was limitation to the related empirical equation. The relative error which was between the simulation analysis results and the empirical equation value exceeded 20% for the HRR less than 17 MW and greater than 68 MW. Obviously it should be further improved especially for small-scale fire of the road tunnel.

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