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Diesel oil pool fire characteristic under natural ventilation conditions in tunnels with roof openings

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ABSTRACT

In order to research the fire characteristic under natural ventilation conditions in tunnels with roof openings, full-scale experiment of tunnel fire is designed and conducted. All the experimental data presented in this paper can be further applied for validation of numerical simulation models and reduced-scale experimental results. The physical model of tunnel with roof openings and the mathematical model of tunnel fire are presented in this paper. The tunnel fire under the same conditions as experiment is simulated using CFD software. From the results, it can be seen that most smoke is discharged directly off the tunnel through roof openings, so roof openings are favorable for exhausting smoke. But along with the decrease of smoke temperatures, some smoke may backflow and mix with the smoke-free layer below, which leads to fall in visibility and is unfavorable for personnel evacuation. So it is necessary to research more efficient ways for improving the smoke removal efficiency, such as early fire detection systems, adequate warning signs and setting tunnel cap.

1. Introduction

Tunnel fire is a hot concern around the world due to big fire disasters occurring in road or railway tunnels in recent years. The fires in the Tauern tunnel in Austria, the Mont Blanc tunnel joining France to Italy and the Channel tunnel joining the UK to France have highlighted the issue and shown the devastating effect of such fires, in terms of loss of life, damage to facilities and destruction of vehicles. The environment in the tunnel will be polluted by smoke particle and poisonous gases, such as carbon monoxide, produced by the fire. The smoke particles decrease the visibility range and induce that the evacuee cannot find their way out. Also, the toxic gases may directly harm and kill the evacuee. So fire protection and ventilation are now seen as the key elements in tunnel design and smoke characteristic in tunnel fires has been one of the main research topics [1].

Methods for analysis of smoke characteristic in tunnel fires are full-scale experiment, reduced-scale experiment and numerical simulation. Because a full-scale experiment can be assumed as a real situation, it provides the most useful data among these methods. However, it is high in cost, time-consuming and has a risk of fire. A reduced-scale experiment can have a flow characteristic like a real situation by application of a scaling law. But careful attention must be paid to the application of a scaling factor between the prototype and model otherwise reduced-scale experiment may fail to revert to a real situation. Numerical simulation can be analyzed repeatedly under various conditions. But it contains many assumptions. If experimental data are not provided for comparison, the numerical simulation results cannot be validated [2].

Apart from saving money in new tunnels with roof openings, natural ventilation could also be useful in the tunnels where installing a high-capacity mechanical ventilation system is difficult, especially for relatively short, shallow tunnels such as those found in urban areas. This tunnel is the first urban road tunnel to adopt natural ventilation with roof openings in China. Whether it can effectively exhaust smoke in real fires is still unknown. So it is necessary to validate its reliability by experiments. Although a number of fire experiments have been carried out in tunnels over the past few decades, those experiments were generally designed to investigate smoke control under forced ventilation conditions [3–4], rather than to study the smoke properties under natural ventilation conditions. One objective of this paper is to research the smoke characteristic under natural ventilation conditions in tunnel fire with roof openings by full-scale experiment. The other purpose is to assess the performance of CFD models comparing with experimental data under a difficult condition where roof openings affect the movement of smoke.

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Fig. 1. Interior photograph of tunnel configurations.

2. Description of fire scenario

2.1. Tunnel configuration

The tunnel is two-tube, one-directional on three lanes. Its northbound tunnel (experimental domain) is 12.35 m wide, 5.75 m high and 1410 m long. Roof openings distribute symmetrically on the mid-board between the two tubes and the cross-section of one roof opening is 3.0 m × 2.6 m. Four openings constitute one group with 0.8 m interval between two openings and between two groups the space is 8.8 m wide (see Figs. 1 and 2). Upon every opening, there is a beam, which is 0.8 m wide and 2 m high, near the top of tunnel. The velocity of natural wind outside the tunnel is 2–3 m/s. In the tunnel, the velocity of natural wind maintains 0.4–1.2 m/s and the average velocity is 0.95 m/s or so.

2.2. Heat release rate

This tunnel prohibits vehicles with dangerous chemicals or heavy goods from passing by. So the self-ignition of medium cars (about 5 MW) is the probable danger in the tunnel fires. Diesel oil added small amounts of gasoline (5–10%) were used as fuel [5]. Firstly, the pool fire (about 7.5 MW) was calibrated by oxygen consumption way in the lab ahead of full-scale experiments. The heat release rate of the pool fire was calculated from mass loss rates of the fuel, with the combustion heat to be 42,000 kJ/kg. The combustion efficiencies of the pool fire were measured and deduced in the large-space lab by the oxygen consumption way, combing with measurements of mass flow rate [6–8]. And then it is assumed that the same heat release rate is obtained with the same diesel oil pool in the tunnel configuration.

2.3. Fire source location

In many real fires of road tunnel, the fire originates near the sidewall [9], so the fire source is located at 3 m away from the exterior wall in this experiment. This tunnel adopts natural ventilation with roof openings, so the worst location for exhausting smoke is in the middle of the longest section without roof openings, at which the fire source location is set to study the worst case. The sketch map of fire source location is shown in Fig. 3. The plane layout of measurement system is shown in Fig. 4

2.4. Experimental results and analysis

After ignition, hot smoke rises driven by thermal buoyant force and entrains ambient cold air, forming smoke plume. Smoke plume impinges on the tunnel ceiling and then spreads upstream and downstream at the same time. In the early stage, an upper quiescent buoyant smoke layer is formed with a cold smoke-free layer below. After longer longitudinal propagation, the buoyancy becomes weaker with the decrease of temperature difference and then the head of hot current falls down and mixes with cooler air. The smoke front will halt when the buoyancy equals the applied force of longitudinal natural wind. When the new hot smoke is supplied from the fire source, the smoke front will continue to advance and then wander again under the effect of longitudinal natural wind. Arriving at the roof openings most smoke flow through the roof openings in the early stage, but along with the decrease of thermal pressure, smoke may flow back and mix with smoke-free air. When the new hot smoke from the fire source is supplied and thermal pressure is larger than wind pressure, smoke flows outside the tunnel through the roof openings again [10]. The detailed information of temperature field, smoke propagation and smoke sedimentation is described in the first test of Ref. [10].

3. Numerical simulation of tunnel fire

The cutting-edge technology for representing the complex phenomenon of fire and smoke propagation in the simulation space is computational fluid dynamics (CFD). This methodology solves the fundamental equations describing fluid flow: the time-dependent Navier–Stokes equations and the issues surrounding the heat transfer phenomena associated with fire. In addition, it is necessary

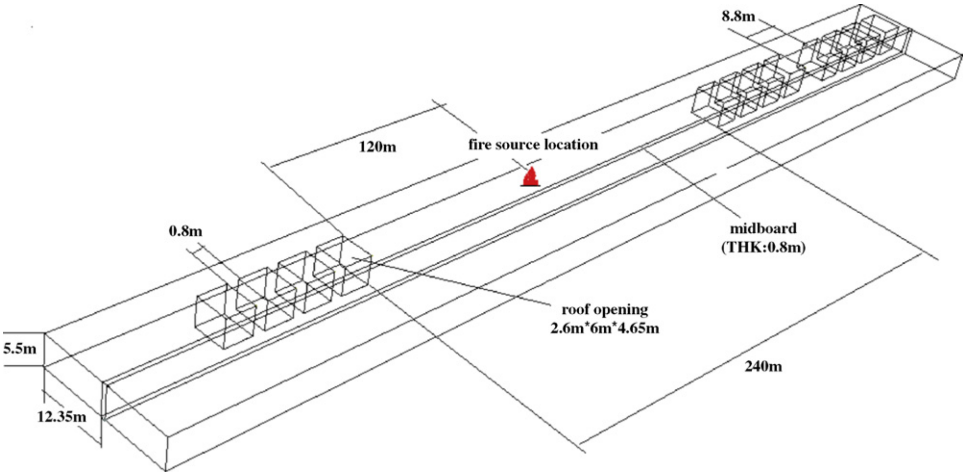

Fig. 2. Schematic illustration of tunnel configurations.