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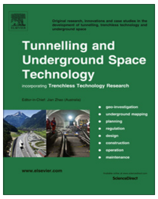

Possibility of using roof openings for natural ventilation in a shallow urban road tunnel

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ABSTRACT

Naturally ventilated urban vehicular tunnels with multiple roof openings have increased in China. Unnecessary gas (polluted air or fire smoke) are expected to be exhausted out through openings. Whether its safety standards can be satisfied or not still needs to be verified. In this paper, a safe CO concentration was firstly discussed, and a heat risk level of very high to extreme up to 46 °C was given. Secondly, a real 1410 m tunnel was proposed, and a 1/10 scale model tunnel was reproduced. Ambient winds of 0.95 m/s in prototype and 0.3 m/s in model were considered. Under normal traffic test, a track circuit was constructed with model vehicles moving on it to form traffic wind, and once the air velocity was larger than 0.31 m/s, the airflows were found to be not relevant to the Reynolds number. The traffic winds were weakened by openings. For three of all tested traffic, the actual air velocities were larger than the required ones, so its air qualities were satisfied. In firing test, two sets of burning experiments were conducted with which the heat release rates (HRR) were 8.35 kW and 13.7 kW. Large amounts of smoke were exhausted out of openings, and the high-temperature was not significant. Full-scale numerical simulations were carried out to verify the experimental results respectively using Fluent 6.0 for normal traffic and FDS 4.07 for firing. The simulations were compared well with the experiments. Further FDS simulations show that the openings' mass flow rates are influenced little by ambient temperature; with the increasing length of the buried section, much smoke accumulate inside leading to a high temperature; having 4–5 openings in one shaft group is oversize in the actual engineering design.

1. Introduction

The number of shallow buried urban vehicular tunnels with multiple roof/shaft openings has recently increased in large Chinese cities to reduce traffic congestion. These tunnels consist of two tubes, and each tube is unidirectional. Examples of such tunnels include the Xianmen, Tongjimen, and Mofanlu tunnels in Nanjing city and the Honxing tunnel in Chengdu city. Most of these tunnels are longer than 1000 m, and the height between bottom and top of the openings is approximately 4 m. Multiple roof openings are intended to exhaust unnecessary gas (polluted air or smoke) via natural ventilation; thus, these tunnels are not equipped with conventional longitudinal ventilators. This new strategy often conflicts with the current code in the *Specifications for Design of Ventilation and Lighting of Highway Tunnel* (JTJ026.1-1999), which requires that mechanical ventilation must be used when the product of tunnel length and traffic volume exceeds 2000 km-cars/h. The local administrative department and fire protection institutions pay considerable attention and are concerned with this ventilation. The tunnel air quality and smoke control of mechanical systems has been extensively studied, but natural ventilation systems have not been studied to this extent (Bari and Naser, 2010; Ferkl and Meinsma, 2007; Chen et al., 2013; Li et al., 2010; Ingason and Li, 2010; Maele and Merci, 2008). Nevertheless, Modic (1998, 2003) identified the allowable limit length as 3000 m when using only tunnel portals without roof openings for natural ventilation under a certain traffic volume and vehicle speed, and some studies (Prajongsan and Sharples, 2012; Li and Chow, 2003; Merci and Van Maele, 2008; Gao et al., 2012) revealed that roof openings can play a role in effectively strengthening natural ventilation. Furthermore, Ding et al. (2004) verified the possibility of controlling the ratio of the skylight to door areas for both natural ventilation and smoke control in an atrium.

In normal traffic, airflow mainly results from the piston effect due to the moving vehicles (Naser and Murad, 2002). The complex and unsteady piston effect is more evident in a one-way tunnel than that in a two-way tunnel due to the opposing traffic (Chen

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et al., 1998; Gonzalez, 2014). Tong et al. (2014) surveyed on the Xianmen, Tongjimen, and Mofanlu tunnels with roof openings and two other tunnels without roof openings for comparison. It found out that the vehicle speeds changed between 10 and 60 km/h; the traffic winds were during 1.1–5.7 m/s; the vehicle speed positively correlated with the traffic wind, but the traffic winds were weakened by roof openings. Sambolek (2004) conducted model testing of road tunnel ventilation in normal traffic conditions, and demonstrated that the functioning of a tunnel ventilation system could be successfully investigated with a physical model.

In case of a fire, the gases begin to flow out when they reach the bottom of the openings (Karlsson and Quintiere, 2000). In recent years, Ji (Ji et al., 2013a,b; Fan et al., 2014) studied the influences of the cross-sectional area and aspect ratio of the shaft and the shaft arrangement on natural ventilation during a fire. He suggested that the cross-sections of single shaft openings in actual engineering designs tend to be too large, and the shaft could exhaust more smoke and avoid the plug-holing effect for different heat release rates when it was at the critical plug-holing height (Ji et al., 2012, 2013a,b).

Small-scale experimental models are mainly used to validate numerical models when predicting building ventilation performance, and the Computational Fluid Dynamics (CFD) models are most popular for this purpose (Maele and Merci, 2008; Merci and Van Maele, 2008; Gao et al., 2012; Ding et al., 2004; Ji et al., 2013a,b; Chen, 2009). In this study, two of these models are employed to confirm the technical possibility of using the same openings for both natural ventilation and smoke control in a real urban road tunnel.

2. Standards on health and fire safety

In the environment with petrol engine emission, CO is one of the major vehicular pollutants. If the CO concentration is kept within an acceptable level, other pollutants, e.g., SO_2 and CO_2, will also be kept within acceptable levels (Chow and Chan, 2003). The pollutant removal process can be achieved by dilution of the indoor air. Assuming the indoor air is thoroughly mixed and the concentrations are stable, the required air velocity u_{req} (m/s) can then be calculated as the following (Vedavarz et al., 2007):

$$u_{req} = \frac{m_{CO}}{\rho_{air} \times A_r \times (\delta_{co,req} - \delta_{co,out}) \times \rho_{CO}} \tag{1}$$

where m_{CO} (mg/s) is the total CO vehicle emission; $\delta_{co,req}$ (ppm) is the required steady state concentration; $\delta_{co,out}$ (ppm) is the steady outdoor concentration; ρ_{air} (kg/m^3) and ρ_{CO} (kg/m^3) are the air density and the CO density, respectively; A_r (m^2) is the tunnel cross-sectional area, then $u_{req} * \rho_{air} * A_r$ is the required ventilation rate for dilution of the tunnel air. When the actual air velocity $u_{act} \geqslant u_{req}$, the concentration of pollutants are just in allowable limits, or not. The CO vehicle emission m_{CO} (mg/s) can be calculated as the following (Ministry of Communications of PRC, 1999):

$$m_{CO} = m_{o,CO} \cdot f_d \cdot f_a \cdot f_h \cdot f_v \cdot L \cdot N / 3.6 \times 10^6 \tag{2}$$

where $m_{o,CO}$ (mg/km veh) is the mean CO emission factor, and it has been decreased to be 1000 for a private small car in China (Guo et al., 2008); f_h, f_v, f_a and f_d are the factors of tunnel altitude, tunnel slope, traffic density and traffic condition, the first three items can all be assumed to be 1 here, but the smaller the vehicle speed, the larger the f_d (Ministry of Communications of PRC, 1999); L (m) is the tunnel length; N (vehicle/h) is the traffic flow. CO is also one of the poisonous gases found in fire smoke, and one of the major causes of death in a fire is inhalation of smoke, especially the CO. The standards applicable to CO can be derived from various authorities: the Hong Kong Environment Protection Department (EPD) (1995) recommends a safe CO level of 100 ppm for 5 min; the World Health Organization (WHO) (2010) allows 87 ppm for 15 min; the United States National Ambient Air Quality Standard (NAAQS) (2015) allows 35 ppm for 1 h; the United States Occupational Safety and Health Administration (OSHA) (2015) gives a safe CO limit of 50 ppm. Since the exposure time for CO in tunnels is normally short, the short-term exposure limit is the point of interest.

In performance-based fire design, thermal radiation is indeed to be considered besides smoke temperature and smoke layer interface height. The human tolerance limit for radiant heat is 2.5 kW/m^2, at which the smoke temperature is about 180–200 °C (Cooper, 1984, 1983). Because there are a lot of particles in the fire smoke, refraction and reflection due to particles would weaken the radiation spread greatly. So, smoke temperature in occupied-zone is often used to determine the effects of radiation, and it is easy and direct. The OSHA (2015) gives a heat risk level of very high to extreme if greater than 46 °C. A safe smoke layer interface height can be considered to be higher than 1.8 m above the ground which basically equals to the human body height.

3. Prototype tunnel

The tunnel used in this study closely resembles the southbound Xianmen one-way tunnel. It is 1410 m long, 12 m wide and 6 m tall and has three lanes. Multiple shafts with each being 8 m long, 3 m wide and 4 m tall are built, and their top openings are parallel to the ground outside. Three equally spaced girders are built inside each shaft to support its structure, as shown in Fig. 1. 5–6 shafts comprise a shaft group at an interval of 8 m. A total of 4 shaft groups are included, thus the tunnel is divided into 5 buried sections, as shown in Fig. 2. Private small cars represent 93% of all the traffic flow (Tong et al., 2014).

4. Model experiments

4.1. Similarity methods

The first and essential condition is that there should be geometrical similarity between the model and the prototype, as shown in Eq. (3):

$$\frac{l_m}{l_p} = \lambda_l \tag{3}$$

where l (m) is the geometric dimension; λ_l is the dimensionless geometric proportion. The subscript 'p' and 'm' represent the full and the model scale parameters respectively. It should be noted that complete geometrical similarity also includes micro-geometric similarity, i.e. roughness similarity. Unfortunately, roughness similarity

Fig. 1. Scene of the bottom of shafts inside tunnel Xianmen.