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An experimental study on critical velocity in sloping tunnel with longitudinal ventilation under fire

Liang Yi [a,b,*], Qiqi Xu [a], Zhisheng Xu [a], Dexing Wu [c]

[a] Institute of Disaster Prevention Science and Safety Technology, Central South University, Changsha, Hunan, China
[b] Key Laboratory of Gas and Fire Prevention of Henan Province, Henan Polytechnic University, Jiaozuo, Henan, China
[c] Zhejiang Provincial Institute of Communications Planning, Design and Research, Hangzhou, Zhejiang, China

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ABSTRACT

Experiments based on Froude scaling law were conducted in a 1/10 reduced-scale model tunnel to investigate the effect of slope on critical velocity in tunnel with longitudinal ventilation under fire. Methanol pool fire was used as the fire source. Smoke movement in the model tunnel with different combination of tunnel slope (−3%, −1.8%, −1%, 0%, 1%, 1.8% and 3%) and longitudinal ventilation velocity was studied. The longitudinal distribution of temperature and velocity were measured. Critical longitudinal ventilation velocity for arresting smoke back flowing in the model tunnel was investigated. Critical velocity in horizontal tunnel obtained in this study was used to compare with that of previous studies. The experimental results agreed well with the model proposed by Wu and Bakar. Correlation between the critical velocity and the slope of the tunnel is proposed based on the experiment results. As the tunnel slope increases from downhill to uphill, critical velocity decreases nearly at a rate independent of the heat release rate of the fire source. The correlation proposed in this studied agrees well with the equation adopted in the Subway Environment Simulation Computer Program (SES). However, it has some discrepancy with the expressions proposed by Atkinson and Ko et al. based on their experimental results. The cause of the discrepancy is attributed to different configuration of the experiments.

1. Introduction

Tunnel is an important part of modern transportation system and fire is regarded as the main enemy of tunnel safety. Lots of tunnel fire events showed that with an effective ventilation system, loss of properties and human lives might be significantly reduced. Different ventilation and exhaust systems have been applied in tunnels around the world. In China, road tunnels longer than 1.5 km are required for installation of ventilation and extraction system for fire protection purpose (Ministry of Transport, 2000). A large proportion of tunnels in China are equipped with longitudinal ventilation systems. An unidirectional wind flow will be formed in the tunnel with longitudinal ventilation system, smoke will be blown downstream out of tunnel and fresh air will be drawn in by jet or exhaust fans. Back-layering is often observed in tunnel with longitudinal ventilation under fire and it is harmful for the upstream passengers who are hindered by the fire from egressing forward. As velocity of longitudinal ventilation increases, length of back-layering will decrease. When the back-layering length drops to zero, the corresponding longitudinal ventilation velocity is defined as critical velocity.

Temperature distribution along the tunnel ceiling under fire is important to evaluate damage to the lining of the tunnel by fire, which has been widely studied (Hu et al., 2003, 2013b; Kurioka et al., 2003; Li et al., 2011, 2012b; Chen et al., 2013). Critical velocity is another key design parameter of tunnel ventilation system. It is determined by factors including geometrical configuration of tunnel, heat release rate of fire, position of fire source, ambient conditions, etc. A great deal of theoretical, numerical and experimental studies on critical velocity can be found in the literatures (Thomas, 1968; Danziger and Kennedy, 1982; Oka and Atkinson, 1995; Wu and Bakar, 2000; Kunsch, 2002; Hwang and Edwards, 2005; Lee and Ryou, 2005; Hu et al., 2005, 2008; Roh et al., 2007a,b; Li et al., 2010; Kang, 2010; Ko et al., 2010; Tang et al., 2013). Expressions for calculating critical velocity were proposed by Thomas, etc. (Thomas, 1968; Danziger and Kennedy, 1982; Oka and Atkinson, 1995; Wu and Bakar, 2000; Kunsch, 2002; Roh et al., 2007a,b). The expressions are of great value for reference in tunnel ventilation systems design.

* Corresponding author at: Institute of Disaster Prevention Science and Safety Technology, Central South University, Changsha, Hunan, China. Tel./fax: +86 731 82656625.

E-mail address: yiliang@mail.csu.edu.cn (L. Yi).

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Actually, most tunnels have slopes which might significantly affect smoke movement under fire due to buoyancy and stack effect. Study on smoke movement in sloping tunnels can also be found in the literatures (Atkinson and Wu, 1996; Hwang and Edwards, 2005; Ballesteros-Tajadura et al., 2006; Palazzi et al., 2009; Chow et al., 2010; Ko et al., 2010; Li et al., 2012a; Hu et al., 2013a). The slope of the tunnel will affect the critical velocity as well. Critical velocity might be higher for downhill slope and smaller for uphill slope than that in horizontal tunnel due to the effect of buoyancy. Empirical correlations between critical velocity and tunnel slope were proposed by Atkinson and Wu (Atkinson and Wu, 1996) and Ko (Ko et al., 2010) based on experimental results.

A model tunnel was built recently (Yi et al., 2013) with which experiments on tunnel ventilation and smoke extraction were carried out in succession. In this paper, a series of experiments were carried out in the model tunnel with different tunnel slopes. Effect of tunnel slope on critical velocity will be discussed based on the experiment results.

2. Scaling law

For turbulent buoyancy-driven flow generated by a fire, general characteristic of flow does not depend on the scale (McCaffrey and Quintiere, 1977). Therefore, experimental studied can be performed with reduced-scale model on smoke movement in fire situation based on Froude modeling. In Froude modeling, the Froude number, which is the ratio of inertia force to gravitational force, should be preserved (Quintiere, 1989).

$$Fr = \frac{v_c^2}{g l_c} \tag{1}$$

where g, v_c and l_c are the gravitational acceleration, the characteristic velocity and characteristic length, respectively. The scaling relationships for velocity (U) and heat release rate ($\dot{Q}$) in Froude modeling are (Quintiere, 1989):

$$\frac{U_M}{U_F} = \left(\frac{L_M}{L_F}\right)^{1/2} \tag{2}$$

$$\frac{\dot{Q}_M}{\dot{Q}_F} = \left(\frac{L_M}{L_F}\right)^{5/2} \tag{3}$$

where L is the characteristic length, and subscript M and F refer to model and full-scale, respectively.

3. Experimental installation

Experiments were carried out in a 1:10 scale model tunnel. The model tunnel is arched, 52.5 m long with cross-sectional area of about 0.65 m^2. The tunnel is made up of 21 sections, as shown in Fig. 1. Each section is 2.5 m long and labeled as L10, L9,...,L2, L1, Fire, R1, R2,...,R9, R10, respectively. Slope of the model tunnel can be set from −3% to 3% by adjusting the heights of the brackets beneath the model tunnel. Longitudinal ventilation velocity up to 1.8 m/s is provided in the model tunnel by an axial flow fan with adjustable volume flux installed at the entrance of the tunnel.

Methanol pool fire is located in the center of the floor of the middle section (Fire section). Two types of square fuel trays are used in the experiments. Sizes of the square fuel trays are 475 mm × 475 mm and 600 mm × 600 mm respectively.

51 K-type thermocouples (diameter of 0.5 mm) with accuracy of ±0.5 °C are fixed 1 cm under the ceiling of the model tunnel to measure the longitudinal distribution of temperature. The interval between 2 adjacent thermocouples is 1 m, as shown in Fig. 1. Distribution of velocity in four sections (V-Section1 to V-Section4) is measured by pitots. Positions of the measure points are shown in Fig. 1.

14 groups of tests with different tunnel slope and fire size were carried out in this study, as listed in Table 1. Longitudinal ventilation velocity was calibrated before each test group. All the experiments were carried out in an indoor environment to reduce the effect of wind. The ambient temperature of each test varied from 4 to 18 °C.

4. Results and discussion

Heat release rate of the fire is calibrated using mass lost rate method. Mass of the fuel and fuel tray was measured by an electronic balance. Mass loss rate of the methanol at steady burning stage is deduced from the variation of the mass of the fire source over time using linear fit. For methanol pool fire (size of 600 mm × 600 mm) burning in the model tunnel, required longitudinal ventilation velocity for complete combustion is less than 0.06 m/s, which was quite easy to be satisfied in the experiments. Therefore the combustion efficiency of methanol is taken as 1.0 (Yi et al., 2013). For fire source with the fuel tray of 475 mm × 475 mm, the heat release rate is calibrated varying from 86 kW to 99 kW. The average, 92 kW, is then regarded as the heat release rate of the fire in all the tests with the fuel tray of 475 mm × 475 mm. For fire source with the fuel tray of 600 mm × 600 mm, the heat release rate is calibrated varying from 148 kW to 166 kW. The average, 156 kW, is taken as the heat release rate of the fire in all the tests with the fuel tray of 600 mm × 600 mm. Fire kept burning for about 15 min in each test. Burning and flow reached a nearly steady stage at about 4 min after ignition and operation of the ventilation fan (fan was turned on at about 30 s after ignition in each test). Temperature and velocity data measured in the model tunnel during the time interval from 300 s to 600 s after ignition are averaged and taken as the values in the steady stage.

Temperature of gas beneath the ceiling of the model tunnel was measured in each test. Typical distribution of temperature beneath the ceiling along the model tunnel is shown in Fig. 2. With longitudinal ventilation, the temperature distribution is asymmetric, average gas temperature in the downstream region is much higher than that in the upstream region. Based on the longitudinal temperature profiles in each test, back-layering length can be obtained. Considering the effect of radiation on the thermocouples, front of the back-layering smoke is located upstream from the fire where the temperature of gas under the ceiling is 5 °C over the ambient. It is clearly demonstrated that the back-layering length of smoke decreases with the increase of longitudinal ventilation velocity, as shown in Fig. 2. When the back-layering length drops to zero, the corresponding velocity of longitudinal ventilation is regarded as the critical velocity. However, it is hard to control the ventilation velocity to make the back-layering length of smoke decrease exactly to zero due to the pulse of the gas flow and effect of environmental wind. The critical velocities are therefore expressed as a small range of velocity in this study. The upper bound of the velocity range is the minimum longitudinal ventilation velocity under which the back-layering length is less than zero, and the lower bound of the velocity range is the maximum longitudinal ventilation velocity under which the back-layering length is greater than zero in all the experiments. The accurate critical velocity then should be a value between the lower bound and the upper bound. To obtain the lower bound and upper bound of the critical velocity range, several values of longitudinal ventilation velocity near the critical velocity were selected for each test group, and each