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Maximum temperature beneath the ceiling in tunnel fires with combination of ceiling mechanical smoke extraction and longitudinal ventilation

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ABSTRACT

This paper experimentally investigated the maximum temperature of smoke flow under the ceiling with the combined effect of ceiling mechanical exhaust system and longitudinal ventilation. Experiments were carried out in a tunnel model with dimensions of 66 m × 1.5 m × 1.3 m (length × width × height). The longitudinal ventilation wind speed was set by 0–1.2 m/s, while the ceiling extraction velocity was 0–2.2 m/s with the fire heat release rate of 30–50 kW. Smoke temperature beneath the tunnel ceiling was measured by K-type thermocouples. The experimental results showed that the ceiling mechanical exhaust system will affect the smoke control, due to the interactions between induced ambient air flow near the ceiling mechanical exhaust vent and longitudinal ventilation. The actual longitudinal air flow velocity would decrease with the ceiling extraction velocity increased, when the fire source was placed downstream of the ceiling extraction vent. The maximum smoke temperature beneath the tunnel ceiling decreased linearly with the ceiling extraction velocity without longitudinal ventilation. A modified model was put forward to predict the maximum temperature of smoke flow beneath the ceiling with combined effect of ceiling single point extraction and longitudinal ventilation in tunnel fires.

1. Introduction

Recently, there was a rapid growth of transportation demand and this will lead to a sharp rise in traffic tunnel construction. However, the growing number of tunnels also brings more safety risks (Heidarinejad et al., 2016; Shaw et al., 2016; Meng et al., 2014). Fire accident was a major disaster in the construction and operation of tunnels (Chen et al., 2016; Yang et al., 2017). With the increasing of tunnel length, traffic volume and the complexity of transport goods, the probability of tunnel fire risks also increased. Due to the special narrow and confined structure characteristics of tunnel, smoke was the main concern parameter, which will affect the personnel evacuation, because most of the casualties were caused by toxic smoke (Bari and Naser, 2005). The high temperature smoke can not only bring serious threat to people's life (Haack, 2002; Migoya et al., 2011; Barbato et al., 2014), but also can cause serious thermal damage to tunnel structure, and even collapse.

In recent years, many researches were conducted to investigate the fire and smoke characteristics (Oka and Oka, 2016; Oka et al., 2016; Ingason et al., 2012; Zhong et al., 2013; Kashef et al., 2013; Vuilleumier et al., 2002; Harish and Venkatasubbaiah, 2014; Weng et al., 2014; Fan et al., 2015, 2017; Liu et al., 2016; Yi et al., 2015; Wang et al., 2017; Tian et al., 2017) in tunnels to guide the design of the tunnel structure. For instance, the maximum smoke temperature beneath ceiling (Kurioka et al., 2003; Hu et al., 2006, 2013; Ji et al., 2011; Li et al., 2011; Li and Ingason, 2012; Wang et al., 2015) as it closely related to the damage degree of tunnel lining in fire. As known from many previous works, the smoke temperature of tunnel fire was influenced by many factors, such as the longitudinal ventilation velocity (Li et al., 2010; Tang et al., 2013; Guo and Zhang, 2014; Tang et al., 2014; Soufien and Rejeb, 2015; Yang and Chuah, 2017), the geometry size of the tunnel (Chow et al., 2010; Caliendo et al., 2013; Huo et al., 2015), vehicle blocking (Hu et al., 2013; Gannouni and Maad, 2015; Tang et al., 2017) and mechanical smoke exhaust system (Tong et al., 2009; Li et al., 2014; Wang et al., 2015; Liang et al., 2017). Kurioka et al. (2003) proposed a model to predict the maximum smoke temperature under the tunnel ceiling based on model scale experiments. Hu et al. (2006) verified the reliability of Kurioka's model by full-scale experiment and numerical simulation. And he also (2013) conducted experiment to study the influence of blockage (vehicle) on tunnel ceiling smoke temperature, and proposed a non-dimensional global model of maximum smoke temperature beneath ceiling with blockage (vehicle) at different distance from fire source in a longitudinal ventilated tunnel. Li et al. (2011), Li and Ingason (2012) considered the effect of fire heat release rate, longitudinal ventilation velocities and tunnel geometries

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Nomenclature

c_p	thermal capacity of air (kJ/(kg K))
g	gravitational acceleration (m/s^2)
H_d	effective tunnel height (m)
$\dot{Q}$	total heat release rate (kW)
$\dot{Q}_c$	convective heat release rate (kW)
$\dot{Q}_m$	heat release rate of the model test (kW)
$\dot{Q}_r$	real equivalent heat release rate (kW)
r	radius of fires (m)
T_a	ambient air temperature in tunnel (K)
T_{max}	maximum smoke temperature (K)
u	longitudinal ventilation velocity (m/s)
u'	dimensionless longitudinal ventilation velocity
V	ceiling extraction velocity (m/s)
V^*	dimensionless ceiling extraction velocity

Greek symbols

ρ_a	ambient density (kg/m^3)
$\triangle$	difference between variables

on the maximum excess gas temperature beneath the ceiling in large tunnel fires, and derived a model based on the analysis on the plume entrainment physics, just as shown in Eq. (1):

$$\Delta T_{\max} = \begin{cases} \frac{\dot{Q}}{ur^{1/3}H_d^{5/3}} & u' > 0.19 \\ 17.5\frac{\dot{Q}^{2/3}}{H_d^{5/3}} & u' \leqslant 0.19 \end{cases} \tag{1}$$

where

$$u' = \frac{u}{u^*} \tag{2}$$

$$u^* = \left(\frac{\dot{Q}_c g}{r\rho_a c_p T_a}\right)^{1/3} \tag{3}$$

where $\dot{Q}$ was the total heat release rate (kW), u was the longitudinal ventilation velocity (m/s), r is the radius of fire (m), H_d was the effective tunnel height (m), $\dot{Q}_c$ was the convective heat release rate (kW), g was the gravity acceleration (m/s^2), ρ_a was the ambient density (kg/m^3), c_p was the thermal capacity of air (kJ/(kg·K))and T_a was the ambient air temperature in a tunnel (K).

However, these previous studies mainly focused on the effect of natural ventilation or longitudinal ventilation on smoke temperature. To date, no experimental study has been presented the evolution characteristics of maximum temperature beneath the ceiling in tunnel fires with combination of ceiling mechanical smoke extraction and longitudinal ventilation. In recent years, with the development of smoke control technology, the ventilation strategy combining longitudinal ventilation with ceiling mechanical smoke extraction was more widely applied for long and large tunnel in the case of fire accident, such as Cangling tunnel in Zhejiang province of China; Yangzijiang tunnel et al. For the study of the combining ventilation method, Chen et al. (2013, 2015) and Hu et al. (2014) studied the smoke temperature decay coefficient and smoke back-layering length with the mechanical ceiling extraction vent located the upstream of fire source. It should be noted that, when the fire source was located downstream of the ceiling extraction vent, the longitudinal ventilation needs to pass through the ceiling extraction vent to reach the fire source. When the longitudinal ventilation approached the fire source, it was affected by the ceiling extraction system, and the decay degree of smoke temperature was related with the ceiling extraction velocities.

In this paper, a series of experiments were conducted to study the effect of longitudinal ventilation and ceiling extraction velocities on the smoke maximum temperature in the tunnel, when the fire source located at downstream of the ceiling extraction vent, and the corresponding characterization models were proposed.

2. Experimental

The experiments were conducted in a small-scale (about 1/6 of the full scale) tunnel model (Tang et al., 2016) with dimensions of 66 m × 1.5 m × 1.3 m (length × width × height) as shown in Fig. 1.

In the experiments, a burner with dimensions of 0.3 m (length) × 0.3 m (width) was used as the fire source. Liquefied petroleum gas (LPG) was supplied as the fuel and controlled by the mass flow meter. The top surface of the burner was 15 cm from the tunnel floor. The burner was placed on the central of the tunnel, and 1 m downstream of the extraction vent and the fire source at the bottom of the pad was high 10 cm. Smoke temperature was measured by K-type thermocouples with a diameter of 0.05 cm. The thermocouples were installed 1 cm below the ceiling of the tunnel with an interval of 0.5 m. Taking the ceiling extraction opening as origin, 10 K-type thermocouples were placed 5 m in the upstream and 30 K-type thermocouples were placed 15 m downstream. In the experiments, there were six different longitudinal ventilation velocities: 0 m/s, 0.3 m/s, 0.5 m/s, 0.8 m/s, 1.0 m/s, 1.2 m/s, and six ceiling extraction velocities: 0 m/s, 0.5 m/s, 1 m/s, 1.5 m/s, 2 m/s, 2.2 m/s. The fire heat release rates (HRR) were set as 30 kW, 40 kW and 50 kW. The real equivalent heat release rate ranges from 2.6 MW to 4.4 MW based on Froude modeling ($\dot{Q}_m = \dot{Q}_r(1/6)^{5/2}$), $\dot{Q}_m$ was the heat release rate of the model test and $\dot{Q}_r$ was the real equivalent heat release rate.). As the general fire scale of the small car was 2.5 MW, thus this paper intended to study the smoke maximum temperature when a fire occurs in a small passenger car in the tunnel. All the experimental conditions were summarized in Table 1. Each test was repeated three times and the average value was taken. In the experiment, ambient temperature was 24 ± 4 °C.

3. Results and discussion

In Fig. 2, the experimental results of the smoke maximum temperature varied with longitudinal ventilation velocity and fire heat release rate without ceiling extraction (namely ceiling extraction velocity

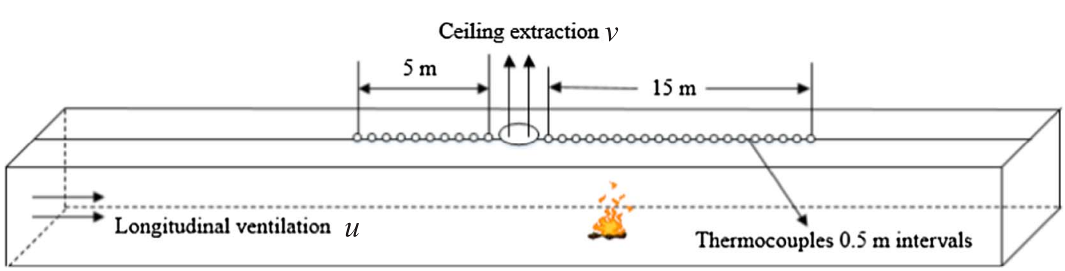

Fig. 1. Schematic diagram of model-scale tunnel.

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