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Effect of blockage-induced near wake flow on fire properties in a longitudinally ventilated tunnel

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ABSTRACT

Effect of blockage-induced near wake flow on fire properties in a longitudinally ventilated tunnel was studied. Numerical simulation was conducted in a tunnel under longitudinal ventilation velocity in the range of 1.0–4.0 m/s. Vehicular blockage was positioned in the upstream of the fire source, with four kinds of blockage ratios (0.24, 0.40, 0.56, 0.72). Temperature contours were used to describe the fire plume region in the tunnel with longitudinal ventilation. It is found that the fire flame goes five stages and transits leaning direction from downstream to upstream of the fire with increasing blockage ratio and ventilation velocity, behaving differently from that in just a longitudinally ventilated tunnel without vehicular blockage. With the increasing ventilation velocity and blockage ratio, the vertical temperature 5 m downstream of the fire decreases and temperature difference in the vertical direction gradually weakens. However, in the upstream 2.5 m from the fire, after the temperature tending to be uniform in the vertical direction, it is high in the middle height and low at the top and bottom. At ventilation velocity larger than 2.5 m/s, the temperature beneath the tunnel ceiling decreases with the increasing blockage ratio downstream of the fire, while there is increase in the upstream. A new expression with the factor blockage ratio included is proposed to predict the maximum temperature beneath the tunnel ceiling, showing good agreement with simulation data.

1. Introduction

Tunnel fires, as a significant threat to tunnel safety, have attracted extensive research attention. Fire flame and the characteristics of the fire-induced smoke flow such as the maximum temperature, the longitudinal temperature distribution beneath the tunnel ceiling, the smoke back-layering length and the critical velocity of the longitudinal ventilation, have become the focus of research to fully understand tunnel fires [1–30].

Kurioka et al. [1] conducted a series of small-scale experiments and proposed an empirical equation to predict the maximum temperature of smoke layer beneath tunnel ceiling with longitudinal forced ventilation:

$$\frac{\Delta T_{\max}}{T_a} = \gamma\left(\frac{\dot{Q}^{*2/3}}{Fr^{1/3}}\right)^{\varepsilon}$$
$$\dot{Q}^{*2/3}/Fr^{1/3} < 1.35,\ \gamma = 1.77,\ \varepsilon = 6/5$$
$$1.35 \le \dot{Q}^{*2/3}/Fr^{1/3},\ \gamma = 2.54,\ \varepsilon = 0 \quad (1)$$

where $\dot{Q}^*$is the dimensionless heat release rate of the fire source and defined as:

$$\dot{Q}^* = \frac{Q}{\rho_a c_p T_a g^{1/2} H_d^{5/2}} \quad (2)$$

Fr is the Froude number and defined as,

$$Fr = \frac{u^2}{gH_d} \quad (3)$$

where ρ_a is the density of the ambient air, T_a is the ambient temperature, H_d is the distance from the surface of the fire source to the tunnel ceiling, and u is the longitudinal ventilation in the tunnel.

Li et al. [19] proposed a model to predict the maximum temperature based on theoretical analysis and small-scale experiments. In Li's model, the maximum temperature was presented in two regions:

$$\Delta T_{\max} = \begin{cases} \dfrac{\dot{Q}}{ur^{1/3}H_d^{5/3}}, & u' > 0.19 \\ 17.5\dfrac{\dot{Q}^{2/3}}{H_d^{5/3}}, & u' \le 0.19 \end{cases} \quad (4)$$

where

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Nomenclature

c_p	specific heat at constant pressure (kJ/(kg·K))
D^*	characteristic fire diameter (m)
Fr	Froude number
g	gravitational acceleration (m/s^2)
H_d	vertical distance between the surface of the fire source and the tunnel ceiling (m)
$\dot{Q}$	heat release rate (kW)
$\dot{Q}^*$	dimensionless heat release rate
$\dot{Q}_c$	convective heat release rate (kW)
r	radius of fire source (m)
u	longitudinal ventilation velocity (m/s)
u'	dimensionless ventilation velocity
u^*	characteristic plume velocity (m/s)
$\Delta T_{\max}$	maximum temperature rise under the tunnel ceiling (K)
T_a	ambient temperature (K)
δx	mesh size (m)
ϕ	blockage ratio
ρ_a	density of ambient (kg/m^3)

$$u' = \frac{u}{u^*} \tag{5}$$

$$u^* = \left(\frac{\dot{Q}_c g}{r\rho_a c_p T_a}\right)^{1/3} \tag{6}$$

where r is the radius of the fire source and $\dot{Q}_c$ is the convective heat release rate of fire source.

Wang et al. [20] conducted studies on the maximum temperature beneath ceiling for a tunnel fire with vertical shafts, and a model by considering the effect of shaft geometry and arrangement was proposed to predict the maximum temperature.

Delichatsios [25] studied the temperature distribution of smoke flow under a beamed ceiling and proposed an exponential expression for temperature distribution along the beamed ceiling. The temperature distribution of hot gas under the ceiling when smoke is issued from a fire compartment into a corridor was studied by Evers and Waterhouse [26], and an exponential expression was proposed. Li studied the temperature distribution of fire-induced flow beneath tunnel ceiling under natural ventilation and forced longitudinal ventilation, and presented corresponding correlations [27,28]. Gong et al. [29] carried out theoretical study and scale experiments to study the longitudinal smoke temperature distribution in tunnel fires and proposed an equation by considering thermal radiation, air entrainment and heat convection.

The above studies mainly consider the fire scenario when there is no vehicular blockage in the tunnel. Considering the causes for tunnel fires over the years, it can be found that the railway and subway tunnel fires are mainly started by short-circuit of electrical equipment, while the road tunnel fires is mainly caused by rear-end accidents. So, vehicle usually exists, acting as a blockage in tunnel fires. Longitudinal ventilation system is usually adopted as a strategy to prevent smoke in case of a tunnel fire. Therefore, when longitudinal ventilation is applied and vehicular blockage exists in the tunnel, there will be wind flow past around the vehicular blockage.

Studies have been conducted to address the characteristics of wind flow passing a square cylinder such as a blockage in a large space [31–38]. When wind flow passes around a square cylinder, a near wake flow region will be formed right behind the blockage. The structure of the near wake is characterized by a recirculation region, and such recirculation region is characterized by low mean velocity and high turbulence relative to the approaching forced flow. If a fire is just located in the near wake flow region, there will be pulling forces in two opposite directions acting on the fire flame due to the existence of the recirculation region. The leaning direction of the fire flame depends on the interaction of these two pulling forces, which has been investigated in the work of Hu et al. [39]. They carried out a series of experiments to

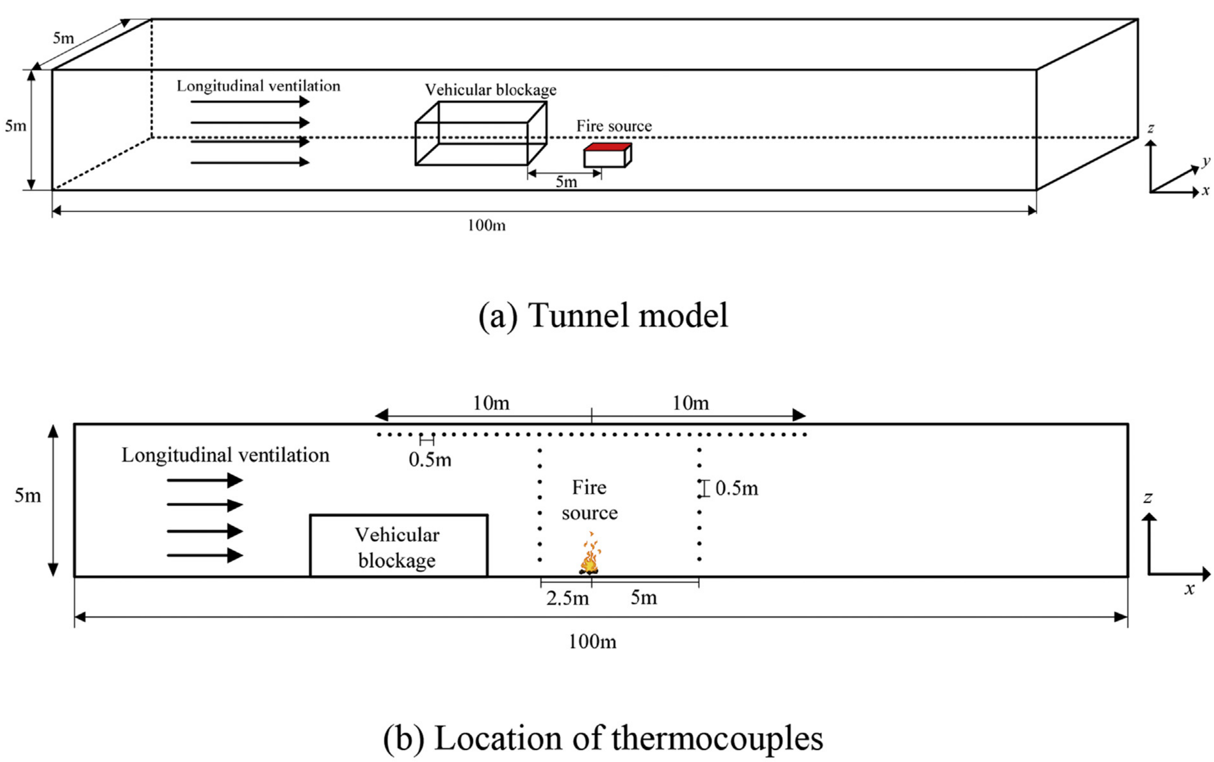

Fig. 1. Schematic view of the numerical tunnel model and the measuring setup.