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Study on the smoke movement and downstream temperature distribution in a sloping tunnel with one closed portal

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ABSTRACT

In this paper, downstream temperature distribution and smoke movement were investigated in a slopping tunnel with one ended-portal, experimentally and numerically. A series of experimental and simulation tests were conducted in a 1:10 small scale model tunnel. According to the results, two typical behaviors of smoke movement were found out: 1) the fire plume tended to incline towards the end wall in the tunnel with or without slope when the fire was located near the end wall. Moreover, for the tunnel with slope, the inclination was more severe as slope became larger. 2) when the fire occurs in an inclined tunnel, the interface of smoke layer downstream the fire is parallel to the horizontal level. During the smoke propagation, a clear stratification could be observed. Results also indicated that the dispersion of smoke would be more confined when the tunnel slope increased. By conducting a series of simulation cases, we carried out an empirical model to predict the downstream temperature distribution beneath tunnel ceiling, taking into consideration the sealing condition, tunnel slope and heat release rate. The prediction model revealed that the downstream maximum temperature decreased as the distance to fire source increased. Meanwhile, it followed an exponential decrease to 0.694 power of heat release rate and subjected to an exponential decrease when the tunnel slope increased.

1. Introduction

For many years, tunnel fire has been a concern due to its enormous damage to the tunnel construction and threat to people's life. Owing to the narrow cross-section and relatively closed environment, the toxic gases produced by the fire are not easy to discharge outside the tunnel. Generally, there are two main strategies for smoke control in tunnel fires, that is, natural and mechanical ventilation. By comparing these two strategies, natural ventilation has advantages in low investment and failure rate because there is no extra equipment. Otherwise, the smoke control effect under natural ventilation will be affected by many uncertain factors, including ambient temperature, wind direction, etc. In contrast, mechanical ventilation method will be less affected, though it has relatively higher investment and failure rate, according to the fan, valves and sensors' error.

In a ventilated tunnel, previous studies have paid a lot of attention on the temperature and toxic gases distribution [1–4]. In a compartment fire, Alpert [5] proposed that the maximum temperature rise ΔT_{max} was related to the heat release rate Q and the room height H. The maximum temperature rise ΔT_{max} could be generated as Eq. (1) only when the distance between fire and any vertical wall nearby was not less than 1.8 times of room height H.

$$\Delta T_{max} = 16.9\frac{Q^{2/3}}{H^{5/3}} \quad (1)$$

However, in the constructions with narrow cross section, like tunnels, the distance between the vertical wall and the fire source is more likely to be less than 1.8 times of tunnel height. The prediction model proposed by Alpert should be validated. Besides, several methods, including longitudinal ventilation [6], semi-transverse [7], transverse ventilation [8] and air curtain [9], have been adopted in tunnel fires in order to prevent smoke from propagation and reduce the fire risk effectively. Longitudinal ventilation, particularly, is the most prevalent one and its attributes includes relatively lower investment and convenience of equipment. In a horizontal tunnel, taking the longitudinal ventilation into consideration, Kurioka [10] conducted experimental tests in a 1:10 scale model tunnel. An empirical formula was put forward

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Nomenclature

ΔT_{max}	Maximum temperature rise (K)
Q	Heat release rate (kW)
H	Tunnel height (m)
T_a	Ambient temperature (K)
Q^*	Dimensionless heat release rate
F_r	Froude number
ρ_a	Air density (kg/m^3)
C_p	Heat capacity of air (kJ/kg·K)
g	Gravitational acceleration (m/s^2)
H_d	Distance from burning surface to tunnel ceiling (m)
V	Longitudinal velocity (m/s)
b_f	Radius of the fire source
V^*	Dimensionless longitudinal velocity
ΔT	Temperature rise (K)
ΔT_x	Temperature rise at x (K)
θ	Inclination angle (°)
ΔH_c	Specify heat of combustion (kJ/g)
$\dot{V}$	Burning rate (g/s)
D^*	Character length of fire source (m)
δ_x	Mesh size (m)
r	Distance between the fire source to the end wall (m)
d	Distance between the measuring point and fire source (m)
$T_{max,d}$	Maximum temperature at measuring point (K)
$\Delta T_{max,d}$	Maximum temperature rise at different d (K)

Greek symbols

γ	Coefficient in Eq. (2)
ε	Coefficient in Eq. (2)
K_1	Coefficient in Eq. (7)
K_2	Coefficient in Eq. (7)
K	Coefficient in Eq. (8)
χ	Combustion efficiency
α	Coefficient in Eq. (17)
β	Coefficient in Eq. (17)
ϕ	Tunnel slope in percentage
a	Coefficient in fitting line
b	Coefficient in fitting line
$\overline{a}$	Average value of a
$\overline{b}$	Average value of b

Table 1
A list of scaling correlation for the model scale enclosures.

Physical quantities	Scaling correlation
Length (m)	$L_m/L_f = \lambda_L = 1/10$
Temperature (k)	$T_m/T_f = 1$
Pressure (Pa)	$P_m/P_f = 1$
Velocity (m/s)	$V_m/V_f = \lambda_L{}^{1/2} = (1/10)^{1/2}$
Heat release rate (kW)	$Q_m/Q_f = \lambda_L^{5/2} = (1/10)^{5/2}$
Time (s)	$t_m/t_f = \lambda_L^{1/2} = (1/10)^{1/2}$

to estimate the maximum temperature beneath ceiling and it was expressed in Eq. (2)

$$\frac{\Delta T_{max}}{T_a} = \gamma\left(\frac{Q^{*2/3}}{F_r{}^{1/3}}\right)^{\varepsilon} \tag{2}$$

Where T_a is the ambient temperature, Q^* is the dimensionless heat release rate given by Eq. (3):

$$Q^* = \frac{Q}{\rho_a C_p T_a \sqrt{g} H_d^{5/2}} \tag{3}$$

Where ρ_a is the ambient density, C_p is the heat capacity of air, g is the

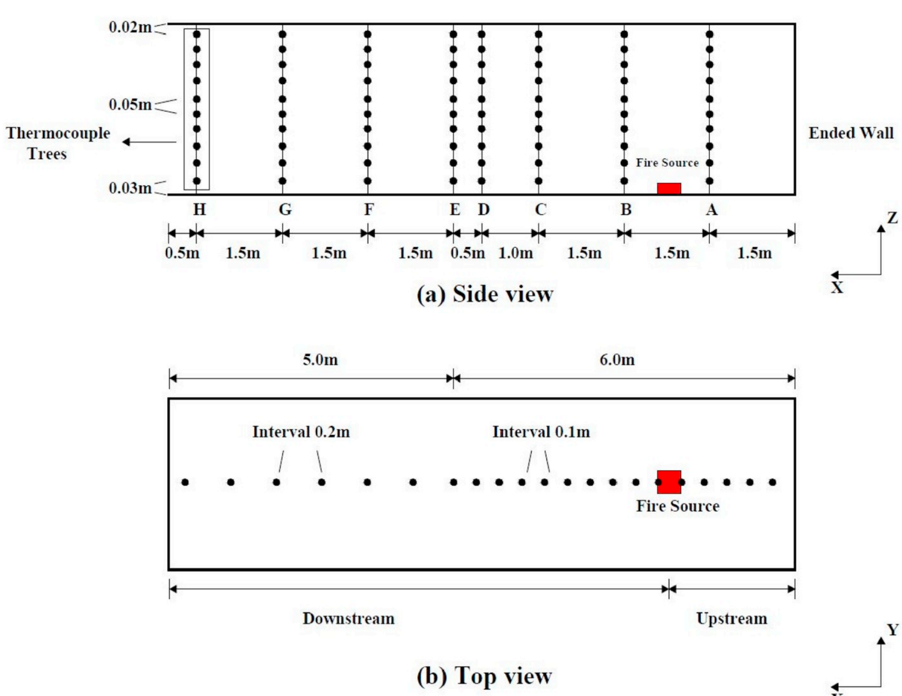

Fig. 1. Sketch of the experimental model.