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# Critical velocity and backlayering distance in tunnel fires with longitudinal ventilation taking thermal properties of wall materials into consideration

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ABSTRACT

A set of tunnel fire experiments using a 1:20 scale model tunnel was conducted taking into account the scaling of heat conduction through the tunnel walls. The critical velocity and backlayering distance measured in the tunnel fire experiments were compared with other reference data to examine the effect of the thermal properties of the tunnel walls on these two parameters. In this paper, we present new correlations for estimating the critical velocity and backlayering distance, and discuss the difference between our correlations and the previous ones from the viewpoint of the thermal properties of the tunnel wall materials.

## 1. Introduction

When a fire occurs in a tunnel, the thermal fumes produced by the fire obstruct efforts of the tunnel users to find refuge, due to the large amounts of soot and toxic gas in the thermal fumes which deprive them of visibility and fresh air. The ventilation systems play an important role in securing a safe refuge environment for tunnel users in a tunnel fire.

Normally, the longitudinal ventilation system is adopted to prevent the backlayering of thermal fumes produced by a fire in a unidirectional expressway tunnel. This ventilation system protects the refuge environment from smoke pollution upstream from a fire by creating a longitudinal wind to blow into the tunnel. Extensive research on the effectiveness of longitudinal ventilation systems has been carried out on the following related topics: the backlayering distance and critical velocity for preventing backlayering smoke (Weng et al., 2015; Li et al., 2010; Wu and Bakar, 2000; Oka and Atkinson, 1995; Thomas, 1968), temperature distribution under the ceiling (Li et al., 2012), the effect of the degree of tunnel incline (Chow et al., 2015; Yi et al., 2014), the effect of the aspect ratio on the temperature distribution and critical velocity (Liu et al., 2016; Lee and Ryou, 2005), the effect of blockage by vehicle congestion (Zhang et al., 2016; Gannouni and Maad, 2015), and critical velocity for multi fire sources (Heidarinejad et al., 2016; Tsai et al., 2010).

In many of these conventional studies, model-scale fire experiments based on the Froude similarity law have been carried out, however, the scaling of heat conduction through the tunnel walls, which is important for accurately estimating the critical velocity and backlayering distance, has been not often considered in these conventional studies using a model-scale tunnel (Minehiro et al., 2012). To fill in this research gap, we built a 1:20 scale model tunnel made of autoclaved lightweight aerated concrete (ALC) board. ALC is chosen as its thermal properties are closest to those of concrete when modeling equivalent thermal characteristics under 1:20 scale conditions to full scale. In this study, we conducted a set of tunnel fire experiments considering scaling of thermal properties of the tunnel walls, and apprised the effect of the thermal properties of the tunnel walls on the critical velocity and backlayering distance in a tunnel fire.

## 2. Experimental apparatus

Fig. 1 shows a schematic drawing of the 1:20 scale model tunnel. The tunnel cross section was rectangular with an aspect ratio of two. Table 1 lists the scaling correlations based on Froude's scaling law used for our fire experiments (Ingason et al., 2015). The model tunnel was 10 m long (corresponding to 200 m in full scale), 0.25 m high (5 m in full scale), and 0.5 m wide (10 m in full scale). ALC board was used as a suitable wall material for the model tunnel. The distance from the center of the fire source to the upstream inlet was 5 m. The longitudinal ventilation wind blew into the tunnel by drawing in air from the outlet using a mechanical ventilation fan. A propane gas porous bed burner having a 90 mm diameter was used as the fire source. The mass flow rate of propane gas consumed by the burner was measured by a mass flow meter. K-type thermocouples with a diameter of 0.1 mm were

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**Nomenclature**

| | |
|---|---|
| $A$ | cross-sectional area of the tunnel (m$^2$) |
| $AR$ | aspect ratio $AR = W/H$ (–) |
| $c_p$ | specific heat at constant pressure (kJ/kg K) |
| $c$ | specific heat at constant volume (kJ/kg K) |
| $g$ | gravitational acceleration (m/s$^2$) |
| $H$ | tunnel height (m) |
| $\overline{H}$ | hydraulic tunnel height (m) |
| $\Delta H$ | lower calorific value (kJ/kg) |
| $h$ | heat transfer coefficient (kW/m$^2$ K) |
| $I$ | thermal inertia (W$^2$·s/K$^2$ m$^4$) |
| $k$ | thermal conductivity (W/m K) |
| $L_b$ | backlayering distance (m) |
| $l$ | characteristic length (m) |
| $\dot{m}$ | average mass flow rate (kg/s) |
| $Q$ | heat release rate (kW) |
| $q$ | heat flux (kW/m$^2$) |
| $S$ | tunnel perimeter (m) |
| $T$ | temperature (K) |
| $V$ | ventilation velocity (m/s) |
| $V_c$ | critical velocity (m/s) |
| $W$ | tunnel width (m) |

*Greek*

| | |
|---|---|
| $\alpha$ | thermal diffusivity (m$^2$/s) |
| $\chi$ | combustion efficiency (-) |
| $\gamma$ | scale ratio (-) |
| $\rho$ | density (kg/m$^3$) |

*subscripts*

| | |
|---|---|
| $f$ | full-scale |
| $m$ | model-scale |
| $s$ | solid material |
| $w$ | wall surface |
| 0 | ambient condition |

*superscripts*

| | |
|---|---|
| $*$ | dimensionless parameter |

installed along the centerline at 0.1 m intervals, and 5 mm directly below the ceiling of the tunnel. The data on the temperature and propane gas mass flow rate was measured by a data logger at 1 s intervals. Two hot-wire anemometers were installed at two locations on the cross section 3.2 m upstream from the fire source to measure the longitudinal wind velocity. The longitudinal ventilation velocities at the two locations were measured at 10 s intervals, and evaluated as the averaged ventilation velocity on the cross section of the tunnel.

The uncertainty analysis of the measurement is discussed here. The bias limits are defined as a half of the measuring precision. These limits for the mass flow meter, the K-type thermocouple and the anemometer, used in this study, were estimated as $\pm 3.5 \times 10^{-6}$ kg/s, $\pm$ 1 K, $\pm$ 0.01 m/s, respectively. The values of precision indexes of parameters measured were significantly less than the values of the bias limits of these instruments. Consequently, measurement uncertainties of parameters measured were dominated by the bias limits of these instruments. As a result, measurement uncertainties of the mass flow meter, the K-type thermocouple and the anemometer were approximately $\pm 3.5 \times 10^{-6}$ kg/s, $\pm$ 1 K, $\pm$ 0.01 m/s, respectively.

## 3. Experimental procedure and conditions

Preheating of the tunnel fire for 25 min (corresponding to 112 min in full scale as per the scaling law given in Table 1) was performed by running the fire source without measurement so that the heat-absorbing

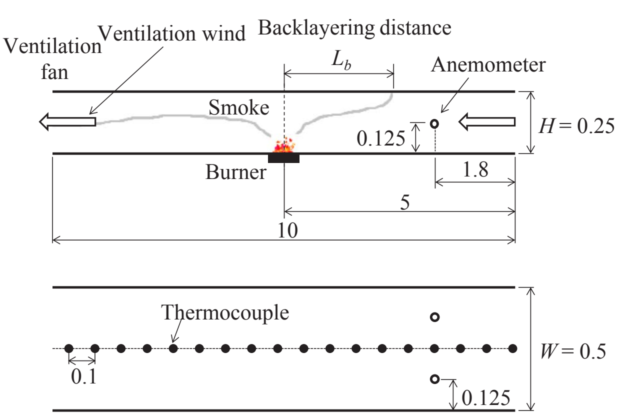


**Fig. 1.** Schematic of the 1:20 scale model tunnel made of ALC board. (unit: m).

condition of the tunnel walls would reach a quasi-steady state. After the preheating, the mass flow rate of the propane gas, temperature distribution on the centerline under the ceiling, and longitudinal wind velocity were measured for 10 min, and evaluated as the average 10 min values in the fire experiment. The heat release rate of the fire source was estimated based on the following equation.

$$Q = \chi \dot{m} \Delta H \tag{1}$$

where $\dot{m}$, $\Delta H$, and $\chi$, are the average mass flow rate of the propane gas, the lower calorific value of propane gas ($\Delta H = 46 \times 10^3$ kJ/kg), and the combustion efficiency ($\chi = 0.95$) (DiNenno, 2002), respectively. The distribution of the rise in temperature measured by the thermocouples was used for evaluating the backlayering distance.

Table 2 lists 40 items of experimental conditions and primary measured data. The critical velocity, $V_c$, with standard deviation was estimated by the least squares method. The dimensionless heat release rate, $Q^*$, and the dimensionless longitudinal velocity, $V^*$, in Table 2 were defined as follows:

$$Q^* = \frac{Q}{\rho_0 T_0 c_p \sqrt{g}\,\overline{H}^{5/2}} \tag{2}$$

$$V^* = \frac{V}{\sqrt{g\overline{H}}} \tag{3}$$

$$\overline{H} = \frac{4A}{S} \tag{4}$$

where the product of the ambient temperature and density is $\rho_0 T_0 = 353$ [kg K/m$^3$], the specific heat of air at constant pressure is $c_p = 1.005$ [kJ/(kg K)], and gravitational acceleration is $g = 9.81$ [m/s$^2$]. Moreover, the hydraulic tunnel height, $\overline{H}$, was defined as the ratio of four times the cross-sectional area, $A$ [m$^2$], to the tunnel perimeter wall, $S$ [m], as shown in Eq. (4), and was used as the characteristic

**Table 1**
Scaling correlations used for the fire experiment.

| Type of unit | Scaling |
|---|---|
| Heat release rate $Q$ (kW) | $Q_f = \gamma^{5/2} Q_m$ |
| Velocity $V$ (m/s) | $V_f = \gamma^{1/2} V_m$ |
| Time $t$ (s) | $t_f = \gamma^{1/2} t_m$ |
| Length $L$ (m) | $L_f = \gamma L_m$ |
| Temperature $T$ (K) | $T_f = T_m$ |