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Temperature distribution within a ceiling jet propagating in an inclined flat-ceilinged tunnel with natural ventilation

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ABSTRACT

In this study, we conducted detailed measurements of the temperature distribution within a steady fire-driven ceiling jet, formed in a tunnel with a rectangular cross-section. We then compared the measured temperature distributions with those for an unconfined smooth-ceiling jet flow, and estimated the relative errors between them. The results showed that the temperature distribution in a horizontal tunnel exhibits a greater bulge than that of a ceiling jet under an unconfined ceiling and varied from a bulging shape to an exponential shape as the tunnel inclination increased. We propose a new correlation for representing the temperature distribution, which takes the tunnel inclination into account, and which consists of an exponential function and a cubic function with a coordinated transformation.

1. Introduction

Tunnels are indispensable to the high-speed mass transit networks that carry goods and passengers. In terms of spatial characteristics, a tunnel can be defined as having an axially elongated length relative to the width and height of its cross-section. Unfortunately, significant and fatal accidental tunnel fires occur on an annual basis [1]. Such fires could potentially become much worse in the future as new, longer tunnels are constructed and as traffic densities increase. The behaviour of a fire in a tunnel, as represented by the flame shape, hot current flow, and other parameters, differs from that of a building fire given the structural factors and the effect of ventilation.

Based on previous data obtained in full-scale [2–5] and small-scale [6–9] experiments, as well as from numerical calculations [10,11], researchers have developed easy-to-use correlations between the maximum ceiling gas temperature and its position [12–14], the critical velocity [15–19], the temperature reduction along the tunnel axis [20–23], and the backlayering length [24,25].

Most studies of tunnel fires have been conducted in a horizontal tunnel. However, the ramps that connect the surface to underground tunnels, which tend to be constructed at considerable depths to make the best use of the underground space in urban areas, are, by necessity, steeply sloped. Therefore, the temperature distribution within the ceiling jet flow in these inclined tunnels will be different from that of a ceiling jet in a horizontal tunnel and also from that under an unconfined inclined ceiling. Previous studies have focused on the temperature distribution within a ceiling jet flowing under an unconfined horizontal or inclined flat ceiling [26–29]. However, the extent to which these correlations are applicable to tunnels in which the side walls disrupt the radial expansion of the ceiling jet has not yet been clarified.

For this study, our objective was to accurately and systematically measure the temperature distribution in the ceiling jet that propagates along the tunnel axis in an inclined tunnel and to develop a correlation to represent the temperature distribution as a function of the inclination of the tunnel.

2. Experimental procedure

We conducted a series of fire tests in a test room with interior dimensions of 13.2 m (L) × 7.5 m (W) × 6.0 m (H). A model tunnel having a rectangular cross-section with dimensions of 10.0 m (L) × 0.75 m (W) × 0.45 m (H) was constructed, as shown in Fig. 1(a). We constructed the tunnel ceiling using 12 mm calcium silicate boards with a smooth surface finish. The sidewalls were 10-mm transparent poly(methyl methacrylate) (PMMA) board, which would allow us to observe the hot current flow and fresh air backflow. For the floor, we used 9.5-mm plywood, except for the area around the fire source, for which we used 12-mm calcium silicate board. Both ends of the tunnel were left completely open

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Nomenclature

a, b	Coefficients in Eq. (3) representing the temperature distribution defined by a cubic function
H	Tunnel height [m]
L_T	Thermal thickness [m]
$L\_\Delta T_{\max}$	Distance from the centre of the fire source to the point at which the maximum gas temperature arises
Q_C	Convective heat release rate [kW]
Q_t	Total heat release rate [kW]
x	Distance along the tunnel axis from the point at which $\Delta T_{\max\_\mathrm{ceiling}}$ the maximum ceiling gas temperature appears [m]
z	Distance perpendicular to the ceiling from tunnel ceiling surface [m]
z_{apex}	Distance from the point at which the apex of the temperature distribution appears perpendicular to the tunnel ceiling
ΔT	Temperature rise [K]
$\Delta T_{\max}$	Maximum temperature rise at the apex of temperature distribution in perpendicular direction to tunnel ceiling [K]
$\Delta T_{\max\_\mathrm{ceiling}}$	Maximum ceiling gas temperature measured 10 mm below the tunnel ceiling [K]
Q_c^*	Dimensionless heat release rate [-],$=Q_c/(\rho_\infty C_p T_\infty g^{1/2} H^{5/2})$

Greek

α, β, γ, η	Coefficients in Eq. (2) representing the temperature distribution defined by an exponential function
ε	Relative error
θ	Inclination angle of tunnel [°]

Subscripts

c	Ceiling
∞	Atmosphere

to enable the unrestricted flow of both the hot gas flowing out of the tunnel and the fresh air being drawn into the tunnel. The inclination was set to 0°, 3°, 5°, 8°, and 10°.

We used two fuels in this study: methanol and liquefied petroleum gas (LPG), with propane being the major component of the latter. To burn the methanol, we used two fuel pans made of 2-mm stainless steel, one measuring 0.10 m × 0.10 m and the other 0.15 m × 0.15 m. Both pans were 30 mm deep. The fuel pool was rested on an electric balance (LP 8200 S, Sartorius; precision: 0.01 g) to allow us to measure the mass loss. For the experiment using LPG, the fuel was supplied to a diffusion gas burner through a mass flow controller (M100B, MKS Instruments). We used a gas burner measuring 0.1 m × 0.1 m that we filled with fine porous aggregate. The fuel pan and gas burner setups in the inclined tunnel are shown in Fig. 1(b). For the methanol, the fuel pan was separated from the electric balance by a stand and the surface of the fuel pan was kept horizontal. We provided a small hole for the support strut that passed under the fuel pan. For the experiment using liquefied propane gas, we set up the square porous burner such that its top surface was at the same level as the tunnel floor.

We estimated the heat release rates from the mass loss or flow rate and the heat resulting from the combustion of the fuel, based on the values calculated by assuming complete combustion. It is generally believed that the source of the driving force of the ceiling jet is the convective component of the total heat of combustion. Then, we used the convective heat release rate to analyse the experimental data. We assumed the convective heat resulting from the combustion of the methanol and LPG to be 16.1 and 31.2 MJ/kg, respectively, and the heat of combustion to be 19.1 and 43.7 MJ/kg, respectively [30].

We suspended fifty-seven thermocouples 10 mm below the centre line of the tunnel ceiling, as shown in Fig. 1(c). We installed thirty copper-constantan (T-type) thermocouples at points between −0.6 m and −3.5 m, relative to the centre of the fire source, at 0.1 m intervals. We also installed fourteen chromel-alumel (K-type) thermocouples at points between −0.5 m and +0.55 m, specifically at −0.5, −0.4, −0.3, −0.2, −0.1, 0, 0.05, 0.1, 0.15, 0.2, 0.25, 0.3, 0.4, and 0.55 m. In the range from +0.9 m to 6.3 m, we installed thirteen T-type thermocouples at 0.9, 1.35, 0.8, 2.25, 2.7, 3.15, 3.6, 4.05, 4.4, 4.95, 5.4, 5.85, and 6.3 m. The strand wire diameter of the thermocouples was 0.2 mm.

We measured the ceiling jet temperature distribution along the centre plane, perpendicular to the tunnel ceiling, using thermocouple rakes with K- and T-type thermocouples. The K-type thermocouples were set in the near field of the fire source, while the T-type thermocouples were set in the far field. Each thermocouple rake had twelve thermocouples and was oriented relative to the tunnel ceiling as shown in Fig. 1(d). We positioned the thermocouples at points 5, 10, 20, 30, 40, 55, 70, 100, 140, 180, 230, and 300 mm from the tunnel ceiling. We performed the temperature measurements twice under the same conditions but with two different thermocouple rake settings. For the first rake, denoted as “rake-1,” we set the thermocouples at 0.75, 1.5, 3.5, and 5.5 m from the centre of the fire source. For the second rake, denoted as “rake-2,” we set the thermocouples at 1.0, 2.0, 3.0, and 4.4 m from the centre.

The measured temperatures include the effect of the heat being radiated from the flames as well as that from the heated sides and ceiling of the tunnel. We recorded the temperature and fuel mass loss data at 1 s intervals by using a data logger (MX110, Yokogawa), and stored this data on a PC for further analysis. Data collection was started 60 s before the fuel was ignited. We ran each test for at least 10 min. During these tests, we shut down the forced ventilation in the laboratory and closed all the doors to the test room.

3. Results and discussion

3.1. Heat release rate

Table 1 lists the results obtained for the heat release rate. The repeatability or variability of the experiments was within ±7%, as regards the heat release rate of the fire. To calculate the heat release rate of the methanol, we used the Douglas-Avakian numerical differentiation method. We performed the calculation using the data obtained during the quasi-steady state existing 420–520 s after ignition. For the LPG fire, the heat release rate was adjusted to two different values of 4.48 kW and 8.89 kW. Applying this to a full-scale tunnel with a height of 7 m, the heat release rate range of 3.40–8.89 kW in this experiment would correspond to a range of 3.2–8.5 MW, as determined using Froude modelling. This approximates to the values that would be generated by a passenger vehicle fire.