

Temperature and Velocity Distributions within a Ceiling-jet along a Flat-ceilinged Horizontal Tunnel with Natural Ventilation

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ABSTRACT

The properties of a ceiling-jet propagating along a tunnel axis are fundamentally different from those under an unconfined ceiling because the ceiling-jet in a tunnel receives the effects of sidewall, ventilation and so on. A series of fire tests was conducted using a small-scale tunnel with rectangular cross-sectional shape, the dimensions of which are 10.0 m (L) \times 0.45 m (W) \times 0.75 m (H). Detailed measurements of the temperature and velocity within a steady fire-driven ceiling-jet running along the centre of the ceiling were conducted. Temperature and velocity distributions from the tunnel ceiling in the perpendicular direction showed different shapes in accordance with the distance from the fire source in a tranquil flow region. To clarify the characteristic of the distribution shape, the measured data and distance from the ceiling surface were normalised by dividing them by the maximum value and the ceiling-jet thickness, respectively, at each point where distributions were obtained. The normalised distributions were found to coalesce onto the same line, independent of the distance from the fire source. Correlations, which are easy-to-use and can be depicted with one graph, were proposed. The temperature rise at an arbitrary distance from the fire source in the tranquil flow region was calculated based on the correlation of temperature attenuation, considering the heat loss from not only the tunnel ceiling but also sidewalls. The value of the Stanton number was determined on the basis of the Reynolds analogy. For a coefficient of wall friction, a law of the wall was applied to the ceiling on the assumption of a smooth flat plate. Correlations for representing the variations of Richardson number and the ceiling-jet thickness along the tunnel axis in the tranquil flow region were also determined semi-empirically. Velocity was obtained with Richardson number, temperature rise and ceiling-jet thickness. The values of the coefficients included in the developed correlations for the temperature and velocity attenuation were determined using experimental results conducted in the small-scale tunnel.

KEYWORDS: Tunnel fire, ceiling-jet.

NOMENCLATURE

a, b	coefficients	$\Delta \bar{T}_x$	temperature rise at position x (K)
C_f	frictional factor (-)	$\Delta \bar{T}_{ref}$	temperature rise at which the density jump occurs (K)
c_p	constant pressure specific heat (J/(kg·K))	x_{ref}	distance from the centre of fire source to the position where the density jump occurs (-)
g	acceleration due to gravity (m/s ²)	U_w	wall temperature factor to control the fraction of wall temperature to the maximum ceiling temperature (-)
h_c	characteristic thickness of ceiling-jet (m)		
h_T	thickness of ceiling-jet derived from temperature distribution (m)		
h_V	thickness of ceiling-jet derived from velocity distribution (m)		
H	tunnel height (m)		

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l_b half width of tunnel (m)

Q heat release rate (kW)

Q^* dimensionless heat release rate (-)

$$Q^* = Q / (\rho_\infty c_p T_\infty g^{1/2} H^{5/2})$$

Ri Richardson number (-)

St Stanton number (-)

Pr Prandtl number (-)

V_x velocity at position x (m/s)

Greek

β coefficient of thermal expansion (1/K)

ρ density (kg/m³)

Subscripts

∞ ambient

Superscripts

— average values (top-hat distribution)

INTRUDUCTION

A tunnel is an indispensable artificial structure and can be defined as having an axially elongated length relative to the width and height of its cross-section. The properties of a ceiling-jet propagating along the ceiling of a tunnel with specific spatial characteristics are fundamentally different from those under an unconfined ceiling because the ceiling-jet in a tunnel is influenced by the sidewalls and differs depending on the presence or absence of forced ventilation.

Many studies have been carried out focusing on the temperature attenuation of the ceiling-jet that propagates along the tunnel axis in a horizontal tunnel with a smooth, flat ceiling under natural ventilation [1-3, 7]. There are some differences in treatment of heat loss in the tranquil region. For example, Delichatsios [7] considers the heat loss to the ceiling where the ceiling-jet comes into contact. Li et al. [1] consider the heat loss to both the ceiling and the sidewall that the ceiling-jet touches. However, in the model of Li et al., since the experimental values are substituted as the starting position of the tranquil region and its temperature rise, the treatment is not applicable to other shapes. There are only a few studies on velocity attenuation [4]. Empirical formulae to represent the velocity and temperature rise distributions within a quasi-steady fire-driven ceiling-jet in a direction perpendicular to the tunnel ceiling were developed by combining an exponential function and a cubic function with coordinate transformation [5-6]. It was verified that the correlation for the temperature distribution, which was derived based on the small-scale tunnel, is applicable by a comparison to large- and full-scale experimental results with similar aspect ratio of the rectangular cross-section. However, it is not confirmed whether these correlations can be applied, irrespective of the aspect ratio of the rectangular cross-section.

The objective of the current work was three-fold: first, to develop correlations that can describe temperature and velocity distribution in the ceiling-jet with one line; second, to develop a correlation for the temperature attenuation along the tunnel axis considering the starting position of the tranquil region and its temperature rise from theoretical considerations; and third, to examine the velocity attenuation which was obtained as a function of Richardson number, temperature rise and ceiling-jet thickness by comparison with experimental data.

EXPERIMENTAL PROCEDURE

A series of fire tests were conducted using a small-scale tunnel with a rectangular cross-sectional shape, the dimensions of which are 10.0 m (L) \times 0.45 m (W) \times 0.75 m (H). The tunnel ceiling and floor were built from calcium silicate and plywood. Both sidewalls were built using a transparent poly (methyl methacrylate) (PMMA) sheet and calcium silicate board.

Methanol was employed as a fuel. A fuel pan of 0.15 m \times 0.15 m in size made of 2 mm stainless steel was used to burn the methanol. The heat release rate was estimated from the mass loss rate and

the heat of combustion of the fuel under the assumption of complete combustion.

Detailed measurements of the temperature and velocity within a quasi-steady fire-driven ceiling-jet running along the centre of the ceiling were conducted. The temperatures perpendicular to the tunnel ceiling within the ceiling-jet were measured using thermocouple rakes consisting of K- and T-type thermocouples with a strand wire diameter of 0.2 mm. Thirteen thermocouples were installed in each rake, which was oriented from tunnel ceiling to the floor, at the distances of 5, 10, 20, 30, 40, 55, 70, 100, 140, 180, 230, 300, and 400 mm from the tunnel ceiling. Temperature distributions were obtained at twenty positions, which were 0.3, 0.35, 0.45, 0.50, 0.55, 0.60, 0.65, 0.7, 0.75, 0.8, 0.9, 1.0, 1.3, 1.5, 2.0, 2.5, 3.0, 3.5, 4.4, and 5.5 m from the centre of the fire source. The measured temperatures include the effect of the heat being radiated from the flames, as well as from the heated sidewalls and ceiling of the tunnel.

The velocities perpendicular to the tunnel ceiling, within the ceiling-jet running along the centre of the ceiling, were measured using a two-dimensional particle image velocimetry system (2D-PIV). The velocity distributions were obtained at fifteen positions: 0.3, 0.6, 0.7, 0.8, 0.9, 1.0, 1.3, 1.5, 2.0, 2.5, 3.0, 3.5, 4.0, 4.4, and 5.5 m from the centre of the fire source. The velocity was measured at least three or four times at each position. A pair of laser sheets pulsed every 0.1 s; the total duration required to acquire 167 pairs of velocity images was 16.7 s. The size of the measurement window was 250 mm x 340 mm. The time interval needed to obtain part of the velocity field image from a pair of velocity image snapshots varied depending on the distance from the fire source. The velocity data were obtained at approximately 3-mm intervals, using Koncerto software (Seika Corp.). Oil droplets, composed of bis(2-ethylhexyl) sebacate (mean particle size of 1 μm), were used as tracers.

RESULTS AND DISCUSSION

The tunnel has a rectangular cross-section with the width by the factor of 0.6 smaller than the height, $b/H = 0.3$. This aspect ratio is within the range in which theoretical models for ceiling-jets [1, 7] can be applied. Specifically, Li et al. [1] indicated that the valid range is $0.17 < b/H < 0.78$. Following Delichatsios [7], a ceiling-jet running in a beamed ceiling can be classified into three regions, corresponding to an axisymmetric radial ceiling-jet region, a one-dimensional shooting flow region, and a one-dimensional tranquil flow region as shown in Fig. 1. Both Delichatsios [7] and Li et al. [1] assumed that a density jump occurs after the ceiling-jet intersects the beam or sidewall of the corridor, and that the location of the density jump corresponds to the boundary between the shooting and the tranquil flow regions. In this study, we focused on the ceiling-jet properties in a one-dimensional tranquil flow region.

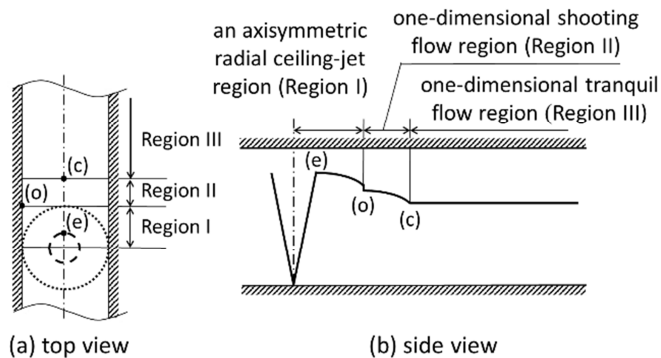


Fig. 1. Schematic diagram of ceiling-jet in horizontal tunnel.

Temperature and velocity distributions

Figure 2(a) shows the changes in vertical temperature distribution at each measurement position, starting at the tunnel ceiling and going to the floor. The temperature gradually rises with increasing distance from the ceiling and reaches its maximum. Thereafter, it declines very slowly from the distribution apex towards the floor. The temperature distribution shows a characteristic top-hat shape. Such distribution is almost independent of the distance from the fire source throughout the measurement range. In the case of the cross section with a width larger than the height, the temperature distribution shape changed from a convex distribution to a gentle decreasing distribution with increasing the distance from the fire source [6]. It was already confirmed that the cross-sectional shape has an effect on the temperature distribution in the tranquil flow region.

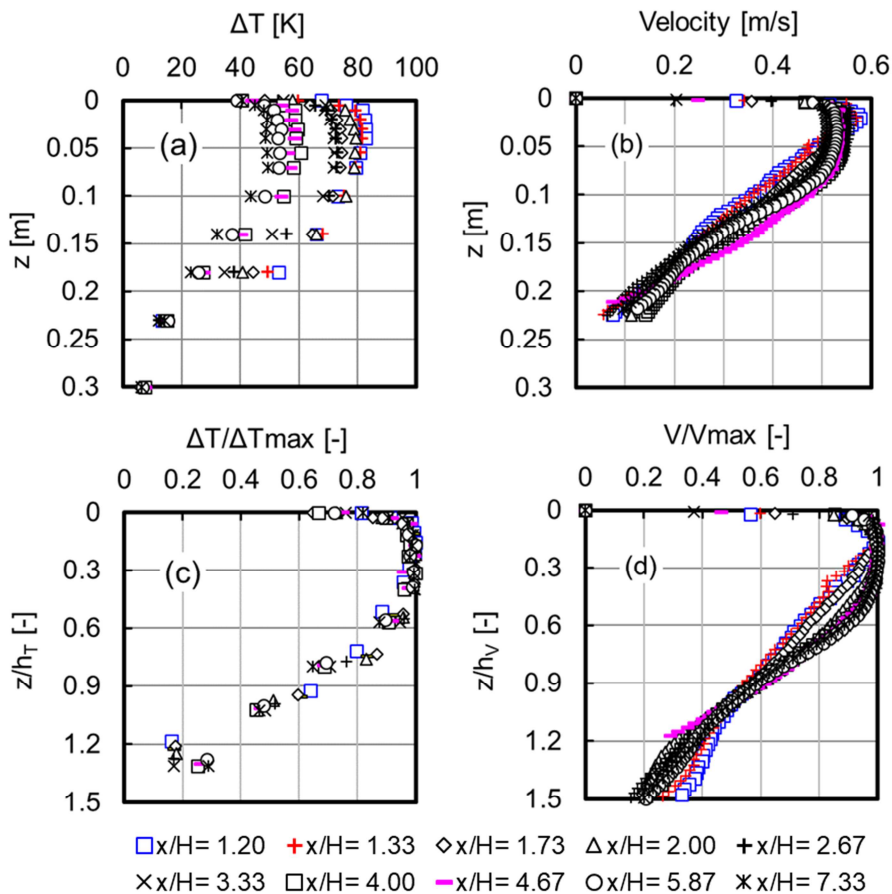


Fig. 2. Vertical distributions in the tranquil flow region. (a) Temperature distribution, (b) Normalised temperature distribution, (c) Velocity distribution, (d) Normalised velocity distribution.

Figure 2(b) shows vertical profiles of the streamwise velocity at measurement positions, which are divided into two major types. One shows a convex shape with the maximum velocity at the apex and velocity decreasing exponentially from the apex of the velocity distribution toward the tunnel floor. The other shows a top-hat type distribution in the region where the distance from the fire source is more than twice the tunnel height. This distribution shape remains vertically unchanged irrespective of the increase in the distance from the fire source and the velocity shows quite slow attenuation.

To clarify the characteristic of the temperature distribution shape along the tunnel axis in the tranquil flow region, the temperature rise and distance from the ceiling surface in the perpendicular direction were normalised by dividing them by the maximum temperature rise, ΔT_{\max} , and thermal thickness, h_T , respectively, at each point. The thermal thickness is defined as the distance from the ceiling surface to the point where the value drops to 1/2 of the maximum value at each position. The normalised temperature distributions are found to coalesce on to the same curve, independent of the distance from the fire source, as shown in Fig. 2(c).

The velocity distributions as a function of distance from the tunnel ceiling were also normalised by dividing them by the maximum velocity, V_{\max} , and velocity thickness, h_v , respectively, at each measurement point. The ceiling-jet thickness is derived from the velocity distribution and is defined as the distance from the ceiling surface to the point where the velocity drops to 1/2 of the maximum velocity at each position. As a result, the normalised velocity distributions are classified into two types of lines as the boundary of $x/H = 2$, as shown in Fig. 2(d). Therefore, it is reasonable to infer that the distribution shape in the range of $x/H < 2$ represents the distribution in the transition region from the shooting flow to the tranquil flow regime, whilst that in the range of $x/H > 2$ represents the distribution shape of the tranquil flow region.

In order to derive easy-to-use correlations for temperature and velocity distributions, a well-known profile method was applied. The vertical profiles of temperature rise and streamwise velocity are approximated by the following polynomial functions:

$$\frac{\Delta T}{\Delta T_{\max}} = C_{T1} \left(z/h_T \right)^{n_T} + C_{T2} \left(z/h_T \right)^{n_T+1} + C_{T3} \left(z/h_T \right)^{n_T+2} + C_{T4}, \quad (1)$$

$$\frac{V}{V_{\max}} = C_{V1} \left(z/h_T \right)^{n_v} + C_{V2} \left(z/h_T \right)^{n_v+1} + C_{V3} \left(z/h_T \right)^{n_v+2} + C_{V4}. \quad (2)$$

The values of the coefficients C_{T1} to C_{T4} and C_{V1} to C_{V4} as well as the exponents, n_T and n_v , are listed in Table 1. As for the velocity distributions, these values are determined using the data in the region where the distance from the fire source is more than twice the tunnel height. The resulting correlations for temperature and velocity distributions are shown in Figs. 3(a) and 3(b), respectively.

Table 1. Coefficients for temperature and velocity distributions

Temperature	C_{T1}	C_{T2}	C_{T3}	C_{T4}	n_T
	0.856	-1.464	0.359	0.75	0.522
Velocity	C_{V1}	C_{V2}	C_{V3}	C_{V4}	n_v
	1.72	-1.47	0.260	0	0.224

Oka et al. [6] have proposed empirical correlations for representing the distribution within the ceiling-jet, which were composed of two functions. One was an exponential function applied to the region where the data varied from tunnel ceiling surface to its maximum. The other was a cubic function with a coordinate transformation applied to the region from the apex of the distribution toward the tunnel floor. For comparison, these empirical correlations are also shown in Fig. 3. Because the distributions exhibit a top-hat shape, the fit by the existing empirical correlations outperforms that by Eqs. (1) and (2) in the region where the temperature and velocity gradually decrease from their maxima. However, the newly proposed correlations are superior in terms of practicality, since they can be described with the single formula.

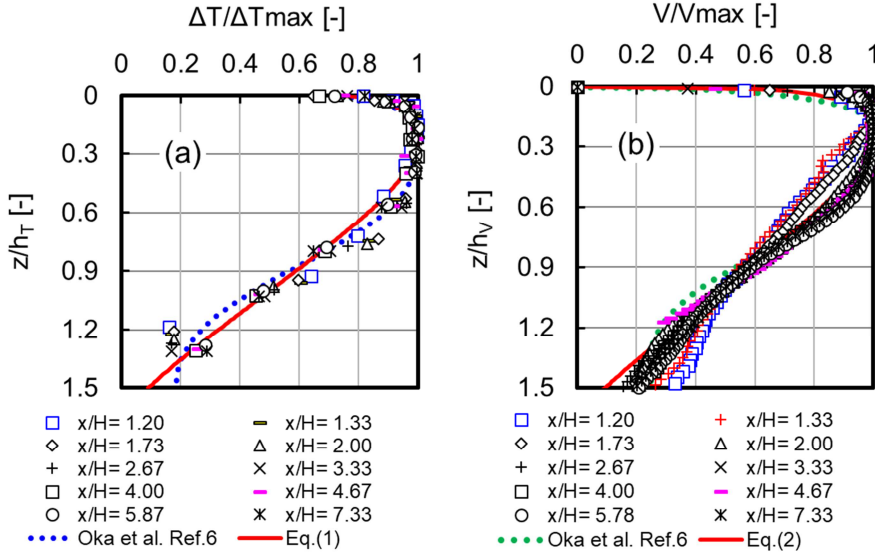


Fig. 3. Comparison of distributions in the tranquil flow region. (a) Temperature distribution, (b) Velocity distribution.

In order to use both the presented correlations, it is necessary to estimate the maximum temperature rise, maximum velocity, and ceiling-jet thickness at any distance from the fire source. These aspects are described in the following sections.

Simple model for temperature and velocity attenuation in the tranquil flow region

A simple correlation for estimating mean temperature rise attenuation, allowing for heat loss from not only ceiling but also sidewall in contacts with the ceiling-jet in the tranquil flow region, can be derived from the continuity and energy equation on the assumption of a uni-directional flow as

$$\frac{\Delta \bar{T}_x}{\Delta \bar{T}_{ref}} = \exp \left\{ -St \left(\frac{H}{h_c} + \frac{H}{l_b} \right) (1 - U_w) \left(\frac{x}{H} - \frac{x_{ref}}{H} \right) \right\}, \quad U_w = \frac{T_{wall} - T_{\infty}}{\bar{T} - T_{\infty}}, \quad (3)$$

where U_w is a wall temperature factor that controls the fraction of wall temperature to the maximum ceiling temperature. Hence, $U_w = 1$ means that $T_{wall} = \bar{T}$, namely adiabatic condition. In this paper U_w is set to 0.25 based on the literature [9]. $\Delta \bar{T}_x$ is the mean temperature rise at the position of x , which is calculated on the assumption of the top-hat type distribution from the ceiling surface to the ceiling-jet thickness.

The starting position of the tranquil flow region can be expressed by Eq. (4), and this corresponds to the position where the density jump occurs:

$$\frac{x_{ref}}{H} = a \left(\frac{h_c}{H} \right) + \left(\frac{l_b}{H} \right). \quad (4)$$

The mean temperature rise at the start position in the tranquil flow region can be estimated from a theoretical model [6] by:

$$\Delta \bar{T}_{ref} = 2^{-4/3} Q^{*2/3} T_{\infty} b \left(\frac{l_b}{H} \right)^{-1/3}. \quad (5)$$

Here the values of the coefficients a and b in Eqs. (4) and (5) will be determined later using the experimental data.

The mean velocity at the position x in the tranquil flow region can be expressed by:

$$\bar{V}_x = \sqrt{\frac{\bar{h}_c \bar{\nabla}}{Ri_x}}, \quad \bar{\nabla} = g \left(\frac{\Delta \bar{T}_x}{T_\infty} \right). \quad (6)$$

Thickness of ceiling-jet

The changes of the dimensionless ceiling-jet thickness, h_T/H and h_V/H , respectively derived from temperature and velocity distributions, as a function of the distance from the fire source position along the tunnel axis are shown in Fig. 4. The ceiling-jet thickness rapidly increases with an increase in the distance from the fire source in the shooting flow region, and then it remains almost constant in the tranquil flow region.

It can be seen in Fig. 4, that the two kinds of ceiling-jet thickness that are derived from the temperature and velocity distributions are not identical, and that the thickness derived from temperature is greater than that derived from velocity. The ceiling-jet thickness along the flat-ceilinged horizontal tunnel with natural ventilation can be expressed by Eqs. (7) and (8).

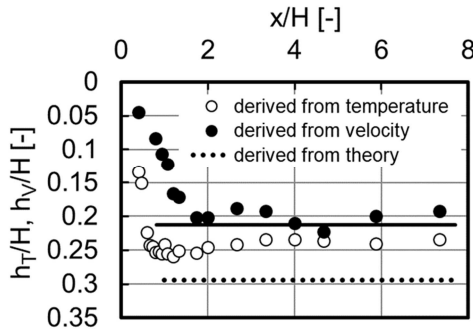


Fig. 4. Variation of ceiling-jet thickness with distance from the fire source.

$$\text{Temperature: } \frac{\bar{h}_T}{H} = 0.161 \left(\frac{l_b}{H} \right)^{-1/3}, \quad (7)$$

$$\text{Velocity: } \frac{\bar{h}_V}{H} = 0.135 \left(\frac{l_b}{H} \right)^{-1/3}, \quad (8)$$

where the values of the coefficients 0.161 and 0.135 are respectively determined from the corresponding experimental data.

In the calculation of x_{ref} , Ri , $\Delta \bar{T}_x$, and \bar{V}_x , the characteristic thickness of the ceiling-jet is necessary. The mean thickness obtained from the above two kinds of thicknesses is adopted as the characteristic thickness, which is plotted in the solid line in Fig. 4 and described by:

$$\text{Characteristic thickness: } \frac{\bar{h}_c}{H} = 0.1426 \left(\frac{l_b}{H} \right)^{-1/3}. \quad (9)$$

The theoretically obtained thickness in the tranquil flow region, which is plotted by the dotted line, is 1.38 times greater than the characteristic thickness. It is also correlates with the thickness at the start of the shooting flow region [6]. In this correlation, the constant a in Eq. (4) is included, so that the value of a is determined as 2.42 from the experimentally obtained thickness data at the start position of the shooting flow region and Eq. (9).

The position of x_{ref} is calculated using this value and we obtain $x_{ref}/H = 0.816$. The value of the constant b , which is included in Eq. (5), is determined as $7.01 (=1/0.1426)$ from Eq. (9) [6].

Determination of Stanton number and variation of Richardson number

Figure 5 shows the variation of Stanton number, St , along the tunnel axis. St is calculated based on the Reynolds analogy, which is expressed as $St_x = (C_{fx} / 2) / Pr^{2/3}$. Here, the friction factor, C_{fx} , is calculated from the wall shear stress, τ_{wall_x} , which is estimated on the assumption of the law of the wall for a smooth flat plate. St gradually increases with an increase in the distance from the fire source up to the boundary between the shooting flow region and the tranquil flow region. Then it remains almost constant in the tranquil flow region. Hence, $\overline{St} = 0.0172$ is adopted as a representative value in the tranquil flow region. This value is consistent with literature data; Vedman et al. [8] reported St for the ceiling-jet to be the range from 0.0127 to 0.0254.

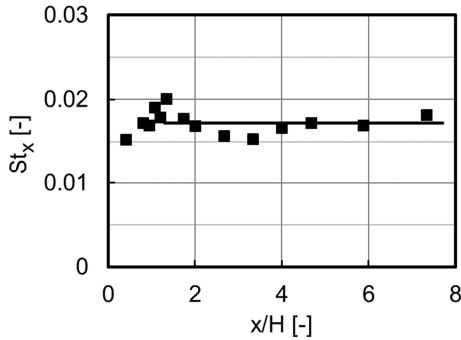


Fig. 5. Variation of Stanton number against distance from the fire source.

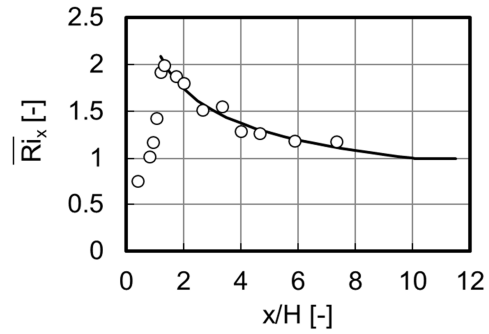


Fig. 6. Variation of Richardson number against distance from the fire source.

Figure 6 shows the variation of Richardson number, Ri , along the tunnel axis. After the occurrence of density jump, \overline{Ri}_x gradually approaches unity and can be represented empirically by:

$$\begin{aligned} \overline{Ri}_x &= 2.21 \left(\frac{x}{H} \right)^{-0.343}, & \frac{x_{ref}}{H} \leq \frac{x}{H} < 10.1, & \quad \overline{Ri}_x = \frac{g \beta \Delta \overline{T}_x \overline{h}_c}{\overline{V}_x^2} \\ \overline{Ri}_x &= 1, & \frac{x}{H} \geq 10.1 \end{aligned} \quad (10)$$

Temperature and velocity attenuations

By substituting the values of \overline{St} , \overline{h}_c , and x_{ref} into Eq. (3), the mean temperature attenuation along the tunnel axis in the tranquil flow region can be calculated. As shown in Fig. 7, a good agreement between the estimated values and the experimental results is confirmed. Specifically, the mean temperature rise at each given position was calculated using the reference

mean temperature rise $\Delta \bar{T}_{ref}$ at $x = x_{ref}$, which can be calculated from Eq. (5). By setting $b = 7.01$, the theoretically estimated temperature rise becomes 69.9 K, which is very close to the experimental value of 68.9 K.

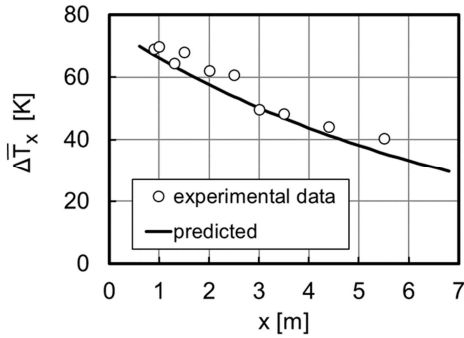


Fig. 7. Mean temperature attenuation in the tranquil flow region.

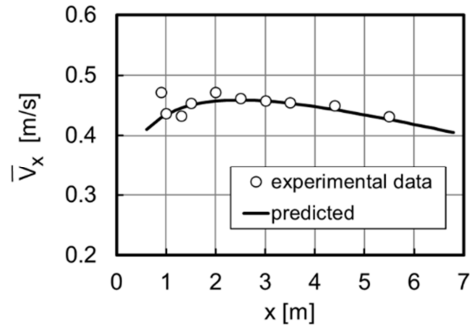


Fig. 8. Mean velocity attenuation in the tranquil flow region

Figure 8 shows the comparison of mean velocity attenuation along the tunnel axis in the tranquil flow region between measured and estimated velocities, which was calculated using Eq. (6). The mean velocity in the tranquil flow region shows similar variation and good agreement was confirmed. The relative error between measured and predicted values is 3.4 %. It was calculated from the following formula:

$$\text{Relative error} = \sqrt{\frac{1}{n} \sum_{i=1}^n (x_i - y_i)^2} \bigg/ \frac{1}{n} \sum_{i=1}^n y_i, \quad (11)$$

where x_i is the measured velocity and y_i is the calculated velocity.

In order to estimate the vertical distribution of temperature rise or velocity, within the ceiling-jet at any arbitrary position x using Eqs. (1) and (2), the maximum values are required. They can be calculated from $\Delta T_{x,\max} = \sqrt{2} \Delta \bar{T}_x$ and $V_{x,\max} = \sqrt{2} \bar{V}_x$, respectively.

CONCLUSIONS

The followings conclusions have been drawn from the results of a series of experiments on the quasi-steady fire-driven ceiling-jet running along the centre of the ceiling, in a flat-ceilinged horizontal tunnel with rectangular cross-sectional shape.

- To clarify the characteristic of the temperature and velocity distributions from the tunnel ceiling in the perpendicular direction in the tranquil flow region, the measured data and distance from the ceiling surface were normalised by dividing them by the maximum value and the ceiling-jet thickness, respectively, at all points where distributions were obtained. Normalised temperature and velocity distributions are found to coalesce onto the same curve without regard to the distance from the fire source. Correlations were developed by applying a profile method based on a polynomial function, which is easy-to-use and can be depicted with one formula. Coefficients included in these correlations were determined using experimental results.
- Temperature rise at an arbitrary distance from the fire source in the tranquil flow region can be calculated based on the correlation of temperature attenuation, considering the heat

loss from not only the tunnel ceiling, but also the sidewalls.

- Correlations were determined for representing the variations of Richardson number and the ceiling-jet thickness along the tunnel axis in the tranquil flow region. With these correlation equations, the ceiling-jet velocity could be calculated.
- The value of the Stanton number was obtained from measurement data, with the assumption that the Reynolds analogy and the law of the wall could be applied to the tranquil flow region of the ceiling-jet.

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