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Temperature and velocity distributions of a ceiling jet along an inclined ceiling—Part 2: Approximation based on cubic function and coordinate transformation

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ABSTRACT

Motevalli and Marks and Cooper have represented temperature and velocity distributions at a given radial distance within a ceiling jet that flows under a flat, unconfined ceiling by applying either an exponential function or a trigonometric function, respectively. In representing the distribution of the ceiling jet that flows along an inclined ceiling, the authors developed modified correlations to represent temperature and velocity distribution by applying an exponential function based on data from a series of pool fire tests conducted under a flat, unconfined ceiling with dimensions of 2.5 m (D) × 3.0 m (L) and with a change in the angle of inclination of the ceiling reaching 40°. The reproducibility of the apex position of the distribution predicted by the proposed correlations is improved except in the region of attenuation from the apex of the distribution, whose curve has a concavo-convex shape. Therefore, alternative correlations were developed by applying a cubic function and the coordinate transformation taking into account the angle of inclination of the ceiling. The resultant correlations were verified by making a comparison with the full-scale test data, and they showed good correspondence with the data.

1. Introduction

During a fire, the fire plume rises directly above the burning fuel and impinges on the ceiling. Then, the hot gases in the plume turn and form a horizontal flow under the ceiling that moves away from the fire source. The fire detectors (both heat and smoke) and sprinklers installed near the ceiling surface become immersed in the hot gas layer. In order to reduce the fire damage, to contain it in a local area, and to select an effective installation location and detection level for operation, the knowledge of the temperature and the velocity distribution of the ceiling jet is required.

To understand the temperature and velocity distributions within a ceiling jet that flows under a flat, unconfined ceiling, Motevalli and Marks [1] have represented them by applying an exponential function. Cooper [2–4] assumed them to have quadratic shapes, with maximum velocity and temperature at $z=0.23\delta$, and have represented them by applying a trigonometric function.

The present authors have previously also developed correlations to represent temperature and velocity distributions within a ceiling jet that flows under an inclined unconfined ceiling [5] after referring to the method that Motevalli and Marks [1] have employed. These developed correlations, which are applicable to an angle of inclination of up to 40°, were described by an exponential function, and included coefficients were represented as a function of the angle of inclination of the ceiling. The reproducibility of the apex position of the distribution predicted by proposed correlations is improved. However, there is a room to improve the reproducibility of the attenuation from the apex of distribution, whose curve has a concavo-convex shape, by using the developed exponential function [5].

Therefore, the objective of this study is to develop alternative correlations for predicting temperature and velocity distributions by taking into account the effect of the angle of inclination.

2. Experimental procedure

The outline of the 'small-scale' and the 'large-scale' tests to get the data is described. Please refer to Ref. [6] for details of experimental conditions.

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Nomenclature

e	Napier's constant
$f(x_i)$	predicted value at x_i
H	ceiling clearance [m]
L_T	Gaussian thermal thickness [m]
L_V	Gaussian momentum thickness [m]
n	number of experimental data
Q	heat release rate [kW]
r	radial distance from the impingement of the plume on the ceiling [m]
ΔT	temperature rise [K]
y_i	measured data
$\bar{y}$	mean of measured data
z	distance normal to ceiling surface [m]

Greek

$\alpha, \beta, \gamma, \eta$ coefficient

δ	effective depth of ceiling jet, i.e. $V(\delta)=1/2V_{max}$ according to the definition by Cooper
ε	convergence test value
δT	thermal boundary layer thickness [m]
δV	momentum boundary layer thickness [m]
θ	angle of inclination of the ceiling [°]

Subscripts

down	downward
max	maximum
T	temperature
up	upward
V	velocity

In small-scale test, a flat, unconfined ceiling with dimensions of 2.5 m (D) × 3.0 m (L) was used. This suspended ceiling had a smooth surface finish. The inclination angle could be varied up to 40° from the horizontal. A single ceiling height of 1.0 m was used. An artificial floor (2.4 m wide and 2.4 m long) was set around the fuel pool and the bottom of fuel pool was adjusted to the level of the artificial floor. *n*-Heptane and methanol were employed as fuels and heat release rate changes from 9.5 to 47.4 kW. The flame above the fuel did not touch the ceiling. The ceiling jet temperature and velocity distributions perpendicular to the ceiling were measured as functions of the radial distance from the point where the vertical central axis of the fuel pool intercepted the ceiling. The temperature within the ceiling jet was measured at 6 points, r=0.4, 0.8, 1.2, 1.6, 2.0, and 2.4 m with a rake of 0.2 mm chromel–alumel thermocouples. Velocities were measured at r=0.8, 1.2, 1.6, and 2.0 m by the particle image velocimetry (PIV) system (FTR-PIV; Flowtech Research Inc.). A pair of laser sheets pulsed every 0.067 s (15 Hz). Two velocity components on the two-dimensional laser sheet cross section were acquired. The measured velocity field was 180 mm × 130 mm and velocity data were obtained at 2 mm intervals. Smoke particles generated from *n*-heptane were used as a tracer. The average velocity field was calculated from 100 pairs of velocity field images taken in the quasi-steady state of the burning fuel.

In large-scale test, two unconfined ceilings were employed: a horizontal ceiling with dimensions of 14.0 m × 7.0 m and an inclined ceiling with dimensions of 7.0 m × 7.0 m. Both ceilings were constructed of plasterboard and had a smooth finish. A series of pool fire tests were conducted by changing the heat release rate from 20.5 to 146.6 kW and the ceiling height. The inclination angle of the ceiling was set at 0 or 10°. Temperature and velocity distributions perpendicular to the ceiling within a ceiling jet produced by a steady fire were measured as a function of radial distance. The thermocouple rakes were positioned at three points, r=3.0, 6.0, and 9.0 m or at 3.5, 6.3, and 9.1 m for the horizontal ceiling, and r_{up}=1.5, 3.0, and 4.5 m for the inclined ceiling. Velocities were also measured at three points, r=3.5, 6.3, and 9.1 m for the horizontal ceiling, and r_{up}=1.5, 3.0, and 4.5 m for the inclined ceiling with a PIV system. The velocity were obtained by using Koncerto software (Seika Corp.). A pair of laser sheets pulsed every 0.5 s (2 Hz), such that the total duration to acquire 100 pairs of velocity images was 50 s. Two velocity components on the two-dimensional laser sheet cross section were acquired. The measured velocity field was 400 mm × 500 mm and velocity data were obtained at 6 mm intervals. Oil droplets composed of di(2-ethylhexyl) sebacate (mean particle size of 1 μm) were used as a tracer.

3. Proposal for a prediction equation for temperature or velocity distribution

3.1. Deviation in the case of the prediction equation

It is difficult to approximately reproduce the attenuation properties in areas of uneven decrease, as shown by the concavo-convex shape in the region of slow decrease from the maximum temperature rise (such as those shown in Figs. 1 and 2), with correlations based on the exponential function given in Eqs. (1)–(3). These

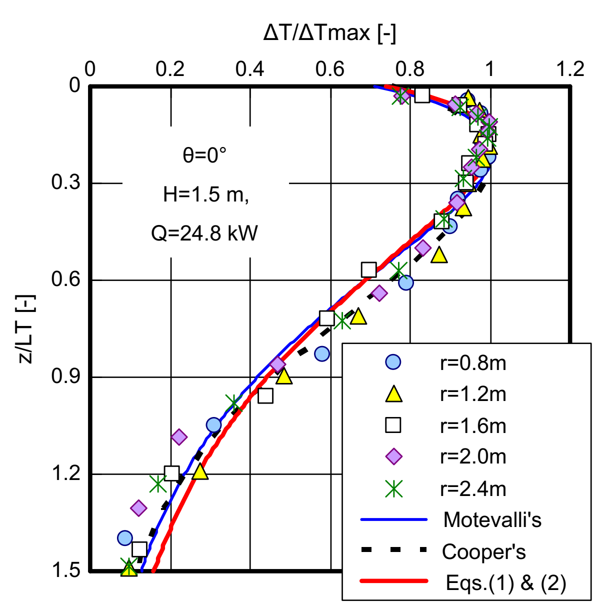

Fig. 1. Typical temperature distribution of ceiling jet at θ=0° obtained in small-scale tests.