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Scale similarity on ceiling jet flow

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ABSTRACT

In this study, empirical formulae previously derived for describing the decrease in temperature rise, the decrease in velocity, the thermal boundary layer thickness, the momentum boundary layer thickness, the Gaussian thermal thickness, and the Gaussian momentum thickness of a ceiling jet flowing upward along the steepest run of an inclined ceiling were applied to a full-scale scenario. The coefficients in these formulae were determined through a series of pool fire tests conducted using a flat, unconfined model ceiling with dimensions of 2.5 m × 3.0 m, and fixed ceiling clearance of 1.0 m. To verify the applicability of the developed formulae to actual fires, another series of pool fire tests were conducted using a flat, unconfined full-scale ceiling with dimensions of 7.0 m × 14.0 m and a maximum ceiling clearance of 3.0 m. The proposed formulae were confirmed to be applicable to a full-scale scenario and to describe the ceiling jet flow accurately.

1. Introduction

A number of studies have been conducted on quantifying the flow a ceiling jet generated by the impingement of a fire plume into a horizontal ceiling. Alpert [1] has developed a generalized theory for predicting the velocities, temperature rises, and thicknesses of a steady fire-driven ceiling jet when the flame height is much less than the ceiling height above the burning fuel. Motevalli et al. [2] conducted small-scale experiments and developed relations between other parameters and the ceiling jet thickness. These relations are easy-to-use for quantifying physical parameters such as temperature rise, velocity, and thickness at a given position in a ceiling jet flow produced by a steady fire under a smooth, unconfined, horizontal ceiling.

In the present study, the focus is instead on upward ceiling jet flow behaviour along the steepest run of an unconfined, inclined ceiling. The associated temperature rise, velocity, thermal and momentum boundary layer thicknesses, and Gaussian thermal and momentum thicknesses of the flow in this situation are adopted as key parameters. Here, the thermal boundary layer thickness and momentum boundary layer thickness are defined as the distance between the ceiling surface and the point with maximum temperature or velocity, respectively. The Gaussian thermal thickness and momentum thickness are defined as the distance between the ceiling surface and the point where a decrease to $1/e$ of the maximum temperature or velocity, respectively, is observed.

Previously, empirical formulae were derived for these key parameters, taking account the influence of the angle of the ceiling [3–6]. These formulae described in the next section were derived from experimental data collected in tests using a small-scale, unconfined ceiling with dimensions of 2.5 m × 3.0 m and with an inclination angle varied between 0° and 40°. Along the vertical central axis of the fire plume, the distance between the bottom of the fuel pan and the inclined ceiling was fixed at 1.0 m. The flow properties of the resulting ceiling jet were measured with K type thermocouples with diameters of 0.2 mm, a bi-directional flow probe, and a particle image velocimetry (PIV) system.

However, the applicability of the developed formulae to full-scale situation needs to be confirmed. Accordingly, the purpose of the current study was to investigate the validity of these relations through two tests. The first replicated the experiments described above, and the second compared the resultant system of equations with a full-scale experimental model. The experimental setups and results for these two tests are presented below.

2. Empirical formulae of key parameters

An outline is first given of the empirical formulae describing the ceiling jet flow parameters. For the case that the flame does not touch the inclined ceiling, the following equations have been previously derived [3–6].

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Nomenclature

C_p	specific heat of air at constant pressure [kJ kg^{-1} K^{-1}]
e	Napier's constant
g	acceleration constant due to gravity [m s^{-2}]
H	ceiling clearance [m]
L_T	Gaussian thermal thickness [m]
L_V	Gaussian momentum thickness [m]
Q	heat release rate [kW]
Q_C	convective heat release rate [kW]
r	radial distance from the plume-impinged point [m]
V	ceiling jet velocity [m s^{-1}]
z	distance along ceiling surface normal [m]
T	temperature [°C]
ΔT	temperature rise [K]
Q^*	dimensionless heat release rate$=Q_C/(\rho_\infty C_p T_\infty g^{1/2} H^{5/2})$ [−]

Greek

ε	relative error
δT	thermal boundary layer thickness [m]
δV	momentum boundary layer thickness [m]
ρ	density [kg m^{-3}]
θ	inclination angle of the ceiling [°]

Subscripts

max	maximum
up	upward
∞	atmosphere

The decrease in the maximum temperature in the upward direction is

$$\left(\frac{\Delta T}{T_\infty}\right)\Big/\{Q^*(1+\sin\theta)\}^{2/3}=\left(0.1564+0.2798\frac{r_{up}\cos\theta}{H}\right)^{-4/3}, \tag{1}$$

where $0.1\le r_{up}\cos\theta/H\le 2.4$ and Q^* is calculated based on convective heat release rate.

The corresponding decrease in velocity in the upward direction is

$$\frac{V_{up}}{\sqrt{g(H+r_{up}\sin\theta)}}\Big/\{Q^*(1+\sin\theta)\}^{1/3}=\alpha\left(\frac{r_{up}\times\cos\theta}{H+r_{up}\sin\theta}\right)^{\beta}, \tag{2}$$

where for $r_{up}\cos\theta/(H+r_{up}\sin\theta)\le 0.357\Rightarrow\alpha=1.962,\ \beta=-0.197$, for $r_{up}\cos\theta/(H+r_{up}\sin\theta)>0.357\Rightarrow\alpha=0.841,\ \beta=-1.020$.

The thermal boundary layer thickness is

$$\delta T_{max}=\alpha_{T1}(r_{up})^{\beta_{T1}}, \tag{3}$$

where $\alpha_{T1}=0.0146-0.00207[1-\exp(-0.2017\times\theta)]$ and $\beta_{T1}=0.00418\times\theta+0.443$, for $0.4\le(r_{up}/H)\le 2.4$, $0^\circ\le\theta\le 40^\circ$ and the momentum boundary layer

$$\delta V_{max}=\alpha_{V1}(r_{up})^{\beta_{V1}}, \tag{4}$$

where $\alpha_{V1}=0.0118-0.00238[1-\exp(-0.0961\times\theta)]$ and $\beta_{V1}=-0.000411\times\theta+0.514$, for $0.4\le(r_{up}/H)\le 2.0$, $0^\circ\le\theta\le 40^\circ$.

The Gaussian momentum thickness is given by

$$\frac{L_V}{H}=\alpha_{V2}\left[1-\exp\left(\beta_{V2}\frac{r}{H}\right)\right], \tag{5}$$

where $\alpha_{V2}=0.00147\times\theta+0.110$ and $\beta_{V2}=-1.86+0.672\,[1-\exp(-0.0953\times\theta)]$, for $0.4\le(r_{up}/H)\le 2.0$, $0^\circ\le\theta\le 40^\circ$, and the Gaussian thermal thickness is

Gaussian thermal thickness

$$\frac{L_T}{H}=\alpha_{T2}\left[1-\exp\left(\beta_{T2}\frac{r}{H}\right)\right], \tag{6}$$

where $\alpha_{T2}=0.00254\times\theta+0.112$ and $\beta_{T2}=-2.91+2.20[1-\exp(-0.0662\times\theta)]$, for $0.4\le(r_{up}/H)\le 2.4$, $0^\circ\le\theta\le 40^\circ$.

3. Experimental procedures

3.1. Test I

A flat, unconfined ceiling with dimensions of 2.5 m × 3.0 m was used as shown in Fig. 1(a). This suspended ceiling was made of two-ply calcium silicate boards and had a smooth surface. The thickness of the ceiling was 24 mm. The inclination angle of the ceiling, θ, could be varied up to 40°. The distance along the vertical central axis of the fuel pool, from the surface of an artificial floor (2.4 m wide and 2.4 m long) to the point where the axis intercepts the ceiling, is called the ceiling clearance, H. A value of $H=1.5$ m was used. The artificial floor was set around the fuel pool, the bottom of which was adjusted to be flush with the level of the

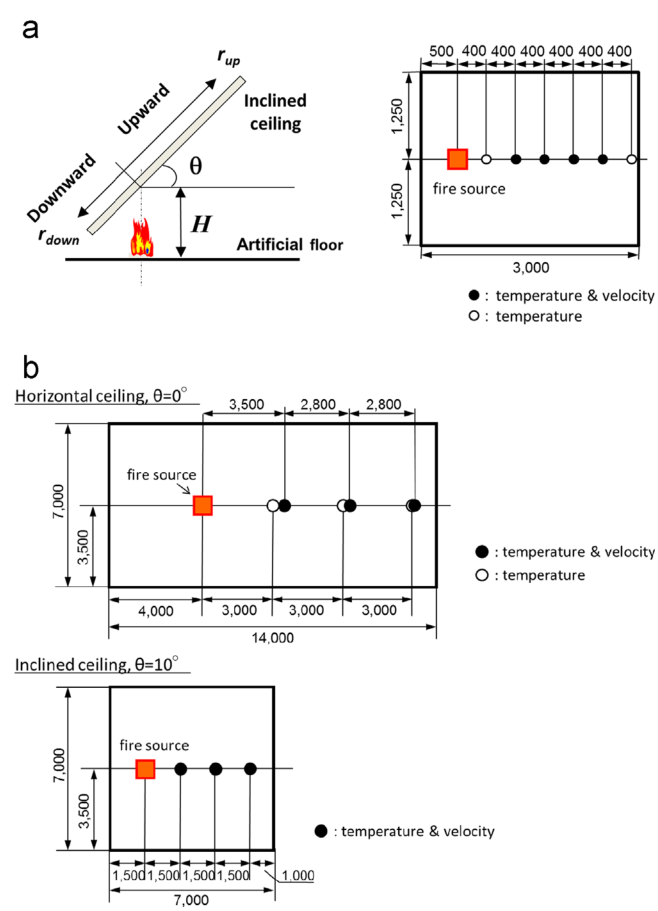

Fig. 1. Schematic diagram of experimental rig used in TEST I and TEST II and measuring positions of temperature and velocity. (a) TEST I (small-scale). (b) TEST II (full-scale).