Fire Safety Journal 55 (2013) 97–105

Contents lists available at SciVerse ScienceDirect

Fire Safety Journal

journal homepage: www.elsevier.com/locate/firesaf

Temperature and velocity properties of a ceiling jet impinging on an unconfined inclined ceiling

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ARTICLE INFO

Article history:
Received 4 June 2010
Received in revised form
25 August 2012
Accepted 19 October 2012
Available online 21 November 2012

Keywords:
Ceiling jet
Temperature rise and velocity profiles
Inclined unconfined ceiling
Froude number
Richardson number

ABSTRACT

Understanding the characteristics of ceiling jet flow is important because most fire detectors and suppression devices are designed to operate within the ceiling jet; the increases in temperature and smoke concentration within the ceiling jet become trigger occupants to begin fire-fighting action or to evacuation. A series of pool fire tests was conducted using a flat, unconfined model ceiling with dimensions of 2.5 m $(D) \times 3.0$ m (L) and changing the ceiling inclination angle of up to 40°. A single ceiling height is used. Two fire heat release rates were used to evaluate the effects: one with and the other without the flame tip touching the inclined ceiling under a steady-state condition. Maximum temperature and its position were determined based on the measurement using a rake consisting of 0.2-mm-diameter chromel–alumel thermocouples. The maximum velocity and its position were obtained by the particle image velocimetry method. These data were compared with the velocities obtained using a bi-directional flow probe and the relationship between them was clarified. Empirical formulae for the temperature rise and velocity versus the radial distance from the plume impingement point along the steepest run in the upward direction were developed considering the effect of the inclination angle. Variations in the Froude number and the Richardson number with radial distance were clarified with and without the flame tip touching the inclined ceiling.

1. Introduction

To improve upon the design, appropriate positioning, and sensitivity of fire detectors and/or sprinklers, and to predict their response time, it is necessary to understand the characteristics of ceiling jet flows, particularly their velocities and gas temperature rise. Indeed, most fire detectors and suppression devices in buildings are designed to operate within ceiling jets, and the temperature rise and smoke concentration within ceiling jets trigger these devices, initiating fire fighting or evacuation efforts by building occupants.

Many researchers [1–4] have developed easy-to-use correlations based on experimental and theoretical approaches to predict the temperature rise and velocity of ceiling jets at given radial positions below smooth, unconfined horizontal ceilings. Such correlations are available for both steady and time-dependent fires and are widely used in hazard analysis. However, some previous studies [5–7,11,17] have reported on the ceiling jet flow produced by a steady fire source along an inclined smoothed ceiling.

The current study has three objectives. First, we experimentally characterise the behaviour of the hot current flow along the inclined ceiling. Second, we elucidate the decreases in temperature and velocity that occur along the steepest run in the upward direction. Third, we develop an empirical formula that takes into account the effect of the inclined ceiling as a tool for hazard analysis.

2. Experimental procedures

Fig. 1 shows the schematic diagram of the experimental setup. A flat, unconfined ceiling with dimensions of 2.5 m $(D) \times 3.0$ m (L) was used. This suspended ceiling was composed of 12-mm-thick two-ply calcium silicate boards and had a smooth surface finish. Five inclination angle were evaluated: 0°, 5°, 10°, 20°, and 40°. The distance along the vertical centreline 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 centreline intercepts with the ceiling was referred to as the ceiling clearance, H. A single ceiling height of 1.0 m was used. The artificial floor was set around the fuel pool, and the bottom of the fuel pool was adjusted to the level of the artificial floor. The fuel pool rested on an electric balance (model LP34001S, Sartorius; accuracy: 0.1 g) for mass loss measurement.

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0379-7112/$ - see front matter
http://dx.doi.org/10.1016/j.firesaf.2012.10.019

Nomenclature

C_p	specific heat of air at constant pressure [kJ kg^{-1} K^{-1}]
E	entrainment function [–]
Fr	Froude number [–]
g	acceleration constant due to gravity [m s^{-2}]
H	distance between the ceiling and the fire source [m]
L	travelling distance, $L=H+r_{up}$ [m]
L_T	Gaussian thermal thickness [m]
r	radial distance from the plume impingement point to the inclined ceiling [m]
Q_C	convective heat release rate [kW]
Q_T	total heat release rate [kW]
Q^*	dimensionless heat release rate, $Q_C/\left(\rho_\infty C_p T_\infty g^{1/2} H^{5/2}\right)$ [–]
Q^{**}	dimensionless heat release rate, $Q_T/\left(\rho_\infty C_p T_\infty g^{1/2} H^{5/2}\right)$ [–]
V	ceiling jet velocity [m s^{-1}]
Ri	Richardson number [–]
T	temperature [°C]
T_∞	ambient temperature [°C]
ΔT	temperature rise, $T-T_\infty$ [K]
ρ_∞	density at ambient temperature [kg m^{-3}]
ρ	density [kg m^{-3}]
$\Delta\rho$	density difference [kg m^{-3}]
α	coefficient [–]
β	coefficient [–]
θ	inclination angle of the ceiling [°]

Subscript

max	maximum
measured	measured
up	upward direction

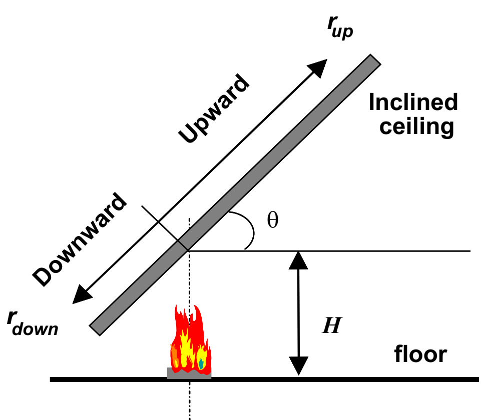

Fig. 1. Experimental setup.

We used two kinds of fuel pans, with dimensions of 0.15 × 0.15 m, and 0.285 × 0.285 m, made of 2-mm-thick stainless steel. The depth of the pan was 30 mm. *n*-Heptane (Wako Pure Chemical Industries, Ltd., 99%) was employed as a fuel; an equal amount of water was added to enhance the steady burning of *n*-heptane.

The convective heat release rate was estimated from the weight loss and the heat of fuel combustion and it corresponded to the value calculated by assuming complete combustion. The convective heats of combustion of *n*-heptane and methanol were assumed to be 27.6 kJ g^{-1} and 16.1 kJ g^{-1}, respectively [8]. The value of convective heat of combustion of methanol was used in arranging the data of You and Feath's [9].

Ceiling gas temperatures produced by a steady fire source to the perpendicular direction to the inclined ceiling run passing through the inclined ceiling centre were measured using chromel–alumel thermocouples with wire diameter of 0.20 mm. These thermocouples were installed at 10 points as shown in Fig. 2.

Velocities were measured using bi-directional flow probes that were produced based on the blueprint of a probe developed by McCaffrey and Heskestad [10] and also by the particle image velocimetry method as shown in Fig. 3 (FTR-PIV, Flowtech Research Inc.). The temperature and velocity of the ceiling jet were systematically measured, as given in Table 1.

In the PIV system employed in this study, a pair of laser sheet was emitted every 0.067 s (15 Hz), corresponding to a total measurement time of 6.7 s to obtain 100 pair velocity images. The velocity field measured by PIV was 130 × 180 mm; as a matter of course, this measured velocity field depends on the accuracy of the measured value, and velocity data were obtained at 2-mm intervals. The time interval to obtain a part of the velocity field image from a pair of snapshots of the velocity image varied with the distance along the steepest run from the plume impingement point and inclination angle of the ceiling; four intervals were used: 600 μs, 800 μs, 1000 μs, and 1200 μs. Smoke particle generated by the combustion of *n*-heptane was used as a tracer particle.

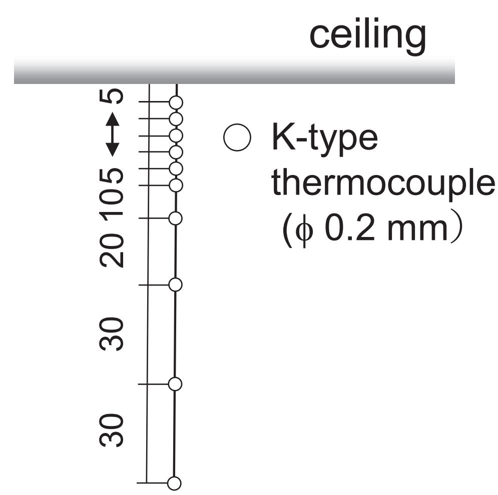

Fig. 2. Schematic of the ceiling jet and its characteristic parameters.

Table 1
Test variables, measurement method, and measurement points.

Angle [°]	Measurement points, r_{up} [m]							
	0.4	0.65	0.8	1.2	1.45	1.6	2.0	2.4
0	X	O	X	X	O	X	X	O
5	O		O	O		O	O	O
10	X		X	X		X	X	O
20	X		X	X		X	X	O
40	X		X	X		X	O	

O: Temperature X: Temperature and PIV velocity.