Fire Safety Journal 65 (2014) 41–52

Contents lists available at ScienceDirect

Fire Safety Journal

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

FIRE SAFETY JOURNAL

Temperature and velocity distributions of a ceiling jet along an inclined ceiling – Part 1: Approximation with exponential function

Yasushi Oka [a,*], Osamu Imazeki [b]

[a] Safety Management Course, Faculty of Environment and Information Sciences, Yokohama National University, 79-7 Tokiwadai, Hodogaya-ku, Yokohama, Kanagawa 240-8501, Japan
[b] I.T. Solutions Department, KAJIMA Corporation, 6-5-30 Akasaka, Minato-ku, Tokyo 107-8502, Japan

ARTICLE INFO

Available online 20 August 2013

Keywords:
Ceiling jet
Unconfined inclined ceiling
Velocity distribution
Temperature distribution
Exponential function

ABSTRACT

It is important to understand velocity and temperature distributions within a ceiling jet, because fire detectors operate within this region. Many researchers have worked positively to clarify ceiling jet properties by means of experimental and theoretical approaches, and sophisticated correlations have been developed to represent temperature and velocity distributions within the ceiling jet that flows under an unconfined, horizontal ceiling with smooth surface. Few studies focus on the ceiling jet that flows under an inclined ceiling. A series of pool fire tests are conducted using a smooth, unconfined model ceiling with varying inclination angles of up to 40°. Temperature distributions are measured using thermocouple rakes consisting of chromel–alumel with a strand wire diameter of 0.2 mm. Velocity distributions are also obtained using particle image velocimetry.

On the basis of the measured data, empirical formulae to represent temperature and velocity distributions are developed by applying an exponential function that decays monotonically with the distance from the ceiling surface, and coefficients included in these formulae are represented as a function of the inclination angle of the ceiling. To verify the applicability of the developed formulae to an actual fire, they are compared with the full-scale test data and show a good agreement.

1. Introduction

Early fire detection becomes a trigger for occupants to take actions for fire fighting or evacuation. Hence, it is essential to characterise the ceiling jet formed by a fire-induced buoyant plume, as most fire detectors and suppression devices are designed to operate within the ceiling jet.

Motevalli and Marks [1] have developed useful correlations, which were represented by the exponential function, to quantify temperature and velocity distributions within the ceiling jet generated by a steady. Cooper [2–4] has also proposed sophisticated relations, which are actually derived based on wall-jet theory, for temperature and velocity distributions. However, these correlations were developed based on data from a ceiling jet flowing under smooth, unconfined horizontal ceilings.

Therefore, the objective of this study is twofold. First, it aims to make clear experimentally the effect of the inclination angle on the temperature and velocity distributions along the steepest run in the upward direction. Second, it attempts to develop easy-to-use correlations to predict temperature and velocity distributions by taking into account the effect of the inclination angle of the ceiling.

2. Experimental procedure

A series of pool fire tests were conducted under a flat, unconfined ceiling with dimensions of 2.5 m (D) × 3.0 m (L). This suspended ceiling was made of two-ply calcium silicate boards and had a smooth surface finish. The thickness of the ceiling was 24 mm. The inclination angle could be varied up to 40° from the horizontal. 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 $H = 1.0$ m was used. The artificial floor was set around the fuel pool, the bottom of which was adjusted to the level of the artificial floor. The fuel pool was set on an electronic balance (LP34001S, Sartorius; accuracy: 0.1 g) to measure the mass loss of the fuel.

Two fuel pans, with dimensions of 0.15 m × 0.15 m and 0.285 m × 0.285 m, were used, both made from 2 mm thick stainless steel. The depth of each fuel pan was 30 mm. *n*-Heptane and methanol (Wako Pure Chemical Industries, Ltd.) were employed as fuels. The *n*-heptane was set afloat on an amount of water equal to that of the

---

[*] Corresponding author. Tel.: +81 45 339 3921.
E-mail address: y-oka@ynu.ac.jp (Y. Oka).

0379-7112/$ - see front matter © 2013 Elsevier Ltd. All rights reserved.
http://dx.doi.org/10.1016/j.firesaf.2013.07.009

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
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

α, β, γ, η	coefficients
ε	convergence test value
δT	thermal boundary layer thickness (m)
δV	momentum boundary layer thickness (m)
θ	inclination angle of the ceiling (deg)

Subscripts

down	downward
max	maximum
T	temperature
up	upward
V	velocity
∞	atmosphere

fuel to stabilise the burning rate. Methanol was placed directly in the fuel pan. The flame above the fuel did not touch the ceiling under the heat release rate conditions set in the test.

The ceiling jet temperature and velocity distributions perpendicular to the ceiling were measured as functions of the radial distance, r, or the upward distance, r_{up}, from the point where the vertical central axis of the fuel pool intercepted the ceiling. The temperature within the ceiling jet was measured at 13 positions (5, 10, 15, 20, 25, 35, 45, 65, 90, 115, 155, 195, 235 mm from the ceiling surface) with a rake of 0.2 mm chromel–alumel thermocouples. Experimental conditions for the temperature measurements are shown in Table 1.

Velocities were measured by the particle image velocimetry (PIV) method (FTR-PIV; Flowtech Research Inc.). A pair of laser sheets pulsed every 0.067 s (15 Hz), such that 100 pairs of velocity images were acquired in a total duration of 6.7 s. Two velocity components were obtained on the two-dimensional laser sheet cross-section. The measured velocity field was 180 mm × 130 mm and velocity data were obtained at 2 mm intervals. Smoke particles generated from the 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 the present experiment, the time interval required to obtain a velocity field image from a pair of velocity image snapshots varied between 600, 800, and 1000 μs, regardless of the radial distance from the plume impingement point and the ceiling inclination angle. Experimental conditions for the velocity measurements are shown in Table 2.

Data pertaining to the temperature and mass loss of the fuel were acquired at 1 s intervals with a data logger (MX110, Yokogawa), and were stored on a PC for further analysis. Data collection began 60 s before ignition of the fuel. Each test lasted for at least 6 min. Temperature rise and heat release rates are average values over 100 s during the quasi-steady state of the burning fuel. During each test, forced ventilation in the laboratory was blocked and all the doors of the test room were closed.

Table 1
Experimental conditions for temperature measurements.

Angle [deg]	H [m]	Measured locations, r_{up} [m]					HRR [kW]
		0.4	0.8	1.2	1.6	2.0	
0	1.0	0	0	0	0	0	9.8
5	1.0	0	0	0	0	0	10.3
10	1.0	0	0	0	0	0	10.1
20	1.0	0	0	0	0	0	9.8
40	1.0	0	0	0	0		9.6

3. Definition of parameters

The behaviour of the ceiling jet as a function of its position under quasi-steady state conditions is characterised as a function of the respective maximum values of the vertical distance from the ceiling, z, and the radial distance from the plume impingement point, r_{up} (i.e. $V(r_{up}, z)$ and $\Delta T(r_{up}, z)$). The ceiling jet momentum and thermal boundary layer thickness are denoted as δV_{max} and δT_{max}. They identify the region of the ceiling jet where the flow velocity and temperature vary from the wall no-slip conditions to the maximum values V_{max} and ΔT_{max}. Instead of being assigned at the measured maximum velocity and temperature rise, V_{max}, ΔT_{max}, and their positions were estimated based on a quadratic fit to data from three points – the measured maximum temperature and the two adjacent temperature measurements.

At distances beyond the boundary layer thickness, the ceiling jet flow behaves like a free jet and its growth may be defined by the half-Gaussian distribution. Here, the Gaussian momentum and thermal thicknesses, L_V and L_T, are obtained at each radial position and represented as a sum of the boundary layer thickness and the length from the maximum to the point where each value has decreased by $1/e$ of the maximum, as shown in the following equation:

$$L_T = \delta T_{max} + L_{\Delta T_{max}/e}, \quad L_V = \delta V_{max} + L_{V_{max}/e} \tag{1}$$

Table 2
Experimental conditions for velocity measurements.

Angle [deg]	H [m]	Measured locations, r_{up} [m]					HRR [kW]
		0.4	0.8	1.2	1.6	2.0	
0	1.5		0	0	0	0	24.8
5	1.0		0	0	0	0	9.9
10	1.0		0	0	0	0	9.9
	1.5	0	0	0	0	0	9.5
	1.5	0	0	0	0	0	45.6
20	1.0		0	0	0	0	10.2
	1.5	0	0	0	0	0	9.4
40	1.0		0	0	0		10.0