International Journal of Heat and Mass Transfer 70 (2014) 578–585

Contents lists available at ScienceDirect

International Journal of Heat and Mass Transfer

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

Experimental analysis of low air pressure influences on fire plumes

Zhihui Zhou [a,c], Yao Wei [b], Haihang Li [a], Richard Yuen [c], Wang Jian [a,*]

[a] State Key Laboratory of Fire Science, University of Science and Technology of China, Hefei 230027, PR China
[b] LHD, Institute of Mechanics, Chinese Academy of Sciences, Beijing 100190, PR China
[c] Department of Civil and Architectural Engineering, City University of Hong Kong, Hong Kong 999077, PR China

ARTICLE INFO

Article history:
Received 8 July 2013
Received in revised form 31 October 2013
Accepted 13 November 2013
Available online 8 December 2013

Keywords:
Low air pressure
Burning rate
Dimensionless heat release
Fire plume

ABSTRACT

To examine the pressure effect on burning rate, flame height and axial temperature distribution of diffusion fires, experimental measurement and theoretical analysis on circular n-Heptane fires with serial sizes were conducted at two altitudes, i.e. 100.8 kPa (in a sea-level city Hefei) and 64.3 kPa (in a Tibetan city Lhasa). From the results, the mean burning rate at quasi-steady stage and boiling stage consistently implied that the exponent α ($\dot{m}'' \underset{D}{\sim} P^{\alpha}$) varies for different heat transfer domination stages, i.e. $\alpha \leqslant 0$ for conductive stage and $\alpha = 2/3$ for convective stage. Analysis shows that the flame height, the axial flame and plume temperatures are all well correlated with the dimensionless heat release rate $Q \sim Q/(PD^{5/2})$, with the correlation coefficients derived from the current low-pressure measurements. Analysis shows that the flame height and the plume temperature increase with the pressure rise as a power function of pressure for the same pool size.

Contents

1. Introduction

Altitude tests have confirmed that low air pressure plays significant effects on mass burning rate ($\dot{m}$), or fire load Q. Earlier European standard EN54 fire tests at four altitudes between 420 and 3000 m (97–71 kPa) pointed out that mass transfer flux $\dot{m}'' \underset{D}{\sim} P^{\alpha}$ (the symbol $\underset{D}{\sim}$ denotes the proportional relationship for the same burner size D), with P the pressure and $\alpha \approx 1.3$ [1]. Since the building of a high-altitude fire in Lhasa (3658 m/64.3 kPa) of Tibet, a series of fire tests with different experimental parameters have been conducted. Li et al. [2] firstly reported the experimental results on n-Heptane and wood crib fires in Hefei (50 m/100.8 kPa) and Lhasa, and verified the correlation obtained by Wiser et al. [1]. Hu et al. [3] conducted n-Heptane fire tests in Dangxiong (4350 m/5.91 kPa) and Lhasa, and suggested that $\dot{m}'' \sim fcn\,(D, P)$, with D the pool diameter. Fang et al. [4,5] summarized the data from square pool fires with different sizes (D = 4–33 cm), and obtained $\dot{m}'' \underset{D}{\sim} P^{\alpha}$, where α is related to the flame heat feedback terms. Rectangular ethanol and n-Heptane fires tested in Hefei and Lhasa by Tu et al. [6] indicated that $\dot{m}'' \underset{D}{\sim} P$ under radiation-controlled condition. Cardboard box fires of different sizes specified by federal aviation administration (FAA) minimum performance standard (MPS) [7] were tested in Hefei and Lhasa by Niu and Yao et al. [8,9], where it is found that mass burning rate and radiative heat flux decrease while plume temperature increases under lower pressure.

* Corresponding author. Tel.: +86 551 63606463; fax: +86 551 6360643.
E-mail address: wangj@ustc.edu.cn (W. Jian).

0017-9310/$ - see front matter © 2013 Elsevier Ltd. All rights reserved.
http://dx.doi.org/10.1016/j.ijheatmasstransfer.2013.11.042

Nomenclature

A_f	flame surface area (m^2)
c_p	specific heat (J/kg K)
D	burner diameter (m)
f_v	soot volume fraction
g	acceleration of gravity (m/s^2)
h	heat transfer coefficient (k W/m^2 K)
H_c	heat of combustion (kJ/g)
k	thermal conductivity (k W/m K)
$\dot{m}$	burning rate (g/s)
$\dot{m}''$	burning intensity (g/m^2 s)
L_m	mean bean length (m)
R_l	fuel regression rate (m/s)
P	ambient pressure (kPa)
Q	heat release rate (kW)
Q^*	dimensionless heat release rate (–)
$\dot{q}''$	Heat flux (k W/m^2)
r	stoichiometric mass rate, air to fuel (–)
t	time (s)
T	temperature (K)
T_s	fuel surface temperature (K)
X_r	radiant fraction (–)
V_f	flame volume (m^3)
z	axial height (m)
z^*	characteristic flame length (–)
z_0	virtual origin (m)
z_f	flame height (m)
κ	effective absorption coefficient (m^{-1})
ρ_∞	air density (kg/m^3)
σ	Stefan–Boltzmann constant (W/m^2 K^4)

Subscripts

f	flame
h	Hefei
l	Lhasa
r	radiative
s	liquid surface
st	quasi-steady phase
bl	boiling phase
∞	ambient

Theoretical modeling approach has been used to correlate the fire plume parameters with total heat release rate Q and pool size D based on experimental data at standard pressure. Thomas [10] derived a dimensionless relationship for flame height, i.e. $z_f/D \sim fcn\ (Q^2/gD^5)$. McCaffrey [11] identified the three distinct regimes by the correlations of axial velocity and axial temperature with scaled axial height in a buoyant methane diffusion flame on a 0.3 m square porous burner. Zukoski introduced the concept of dimensionless heat release rate ($Q^* = Q/(\rho_\infty c_p T_\infty \sqrt{g}D^{5/2})$) and dimensionless flame height to describe diffusion flames and plumes in a unified way [12,13]. A model for correlating measurements of virtual origins for finite axisymmetric sources was proposed by Heskestad, with which mean flame height can be well predicted [14–17]. Quintiere formulated the behavior of fire plumes by a set of unified correlations, which included another important factor, radiation fraction (X_r) [18].

Fang et al. recorded the change in the axial temperature with $z/Q^{2/5}$ for n-Heptane and ethanol fires at high altitude, without consideration of the varied air density aroused by pressure [4]. Yin et al. investigated the altitude influence on small pool fires with a pressure chamber of 3 m × 2 m × 2 m, and pointed out the importance of low air pressure influence on Q^*, as $Q^* \underset{D}{\sim} Q/\rho_\infty \underset{P}{\sim} Q/P$, with which the dimensionless fire plume temperature ($(T - T_\infty)/T_\infty$) is correlated with the pressure to the power of −2/3 [19].

In order to unify the air pressure influences on fire plumes, a series of circular pool fires with different sizes were tested in Hefei and Lhasa. The combustion characteristics of fire plumes, such as mass burning rate, flame height and axial temperature distribution were measured to establish a unified analysis of air pressure influences upon fire plume. The classical theoretical modelings and their simplified forms will be discussed and compared to verify their applicability under low air pressure.

2. Experimental setup

The experiments were conducted in Hefei and Lhasa, respectively under the condition of similar ambient temperatures and humidities (Hefei: 15 ± 2 °C, 45% ± 5%; Lhasa: 15 ± 3 °C, 40% ± 4%). Fig. 1 shows the schematic diagram of experimental setup.

Five different sizes of circular pans were adopted, with the diameters of 6, 8, 10, 12, and 14 cm, respectively. The burners were constructed by steel, with 2 cm in depth and 0.32 ± 0.01 cm in thickness. Electronic scale (METTLER TOLEDO, XP 10002S) with the resolution of 0.1 g was used to record the mass loss of fuel during burning. A 30 cm × 30 cm insulation board was placed on the top of scale to shield the high temperature. To minimize the effect of soot deposition on temperature measurement, the thinner K-type armored thermocouples with diameter of 0.5 mm [19] and response time less than 1 s were adopted. An array of 14 thermocouples was located vertically along the axis of the burner. The lower eight thermocouples were spaced 5 cm between each other, and the upper six ones were spaced 10 cm. The temperature measurements reported in this study were the direct thermocouple readings without radiation correction which may yield an uncertainty less than 10% [20] depending largely on the level of soot radiation. The boiling of liquid fuel was monitored by a high-resolution CCD camera. Another 25-fps video camera (Sony, HDR-XR160E) was place 1.5 m away from the fire axis to record flame images.

In the experiments, n-Heptane was selected as the tested fuel with industrial purity above 99% (impurity contents: volatile ⩽0.05%, water ⩽0.05%, unsaturated compounds in Br+ ⩽0.032%),

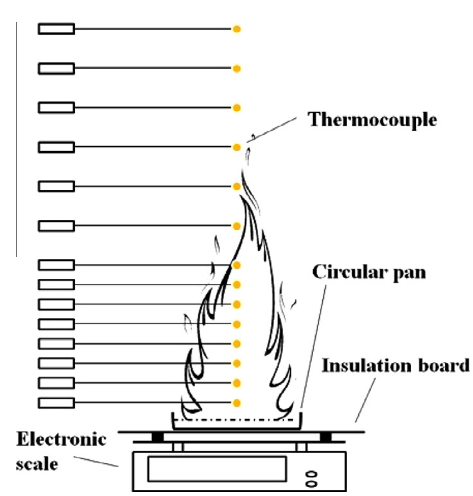

Fig. 1. Schematic diagram of experimental setup.