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Flame height and temperature profile of window ejected thermal plume from compartment fire without facade wall

Xiepeng Sun, Longhua Hu*, Fei Ren, Kaizhi Hu

State Key Laboratory of Fire Science, University of Science and Technology of China, Hefei, Anhui, China

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ABSTRACT

This paper investigates experimentally the flame height and temperature profile of window ejected thermal plume from compartment fire without facade wall. The previous works and correlations on these characteristics of such thermal plume mainly concern the condition with a facade wall, where the air entrainment of the thermal plume from the side of the facade wall is restricted. However, such entrainment constraint effect does not exist when the fire occurs at the top floor of the building noting that there is no facade above the top floor, for which scenario the flame height and temperature profile of the thermal plume characteristics have not been quantified in the literature. In this work, comprehensive experiments were carried out by employing a reduced-scale model (1:8), consisting of a 0.4 m cubic fire compartment with six different window openings corresponding to various ventilation factors ($A\sqrt{H}$). A propane square porous burner was set as fire source with various fuel mass flow meters and hence heat release rate. All the tests were designed as un-ventilated condition that stable flame was observed outside the window. The flame height outside the window was recorded through a CCD camera from the side view. The temperature profiles of the ejected fire plume outside the window were measured by the thermocouple arrays (7 rows, 7 columns) located above the top of the compartment. These measured quantities without the facade wall were compared from those with a facade wall. Results showed that the flame height can be still well correlated non-dimensionally by the excess fuel heat release rate and the characteristic length scale ($\ell_1 = (A\sqrt{H})^{2/5}$) of the window. However, the flame height with a facade wall was higher, being 1.31 times of those without a facade wall. This difference was physically quantified by the air entrainment change due to constraint effect from the facade wall. The radial temperature profile in the ejected thermal fire plume at various height can be globally represented by the Gaussian function ($\frac{T_{z,x} - T_\infty}{T_{z,max} - T_\infty} = e^{\left[-\beta\left(\frac{x-x_m}{\mathrm{FWHM}}\right)^2\right]}$) with and without facade wall, where the value of β was found to be $2\ln 2$. These quantifications and correlations on window-ejected thermal plume characteristics without a facade wall, providing a significant supplementary over previous works focusing on condition with the facade wall, will be an important addition for the estimation of such thermal plume characteristics and its thermal impacts. This work, providing experimental data and correlations on window ejected thermal plume characteristics from compartment fire at the top level of the building without the effect of facade wall, will be an important supplementary over previous knowledge focusing on the scenario with the effect of facade wall.

1. Introduction

Compartment fire and thermal plume characteristics is one of the very important topics of thermal science [e.g., [1–3]]. A thermal fire plume is observed to eject out of the window when the fire inside the compartment reaches un-ventilated condition. The thermal characteristics of this window-ejected fire plume, such as flame height and temperature profiles which will pose serious adverse thermal impact on the facade, have received focused attention in the past decades.

The early work investigating this phenomena was carried out by Yokoi [4]. Later, Webster et al. [5,6], Seigel [7], Thomas [8], Law [9] and Oleszkiewicz [10] studied the facade flame height ejected from the compartment and quantified its evolution with window dimensions and heat release rates. Recently, Lee and Delichatsios [11–13], based on scaling analysis, proposed two characteristic lengths ($\ell_1 = (A\sqrt{H})^{2/5}$ and $\ell_2 = (AH^2)^{1/4}$) according to the dimensions of the window to characterize the facade thermal fire plume characteristics. The flame height was found to be well correlated non-dimensionally with excess

* Corresponding author. State Key Laboratory of Fire Science, University of Science and Technology of China, Hefei, Anhui, 230026, China.
E-mail address: hlh@ustc.edu.cn (L. Hu).

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Nomenclature

A	area of the window opening [m^2]
C_p	specific heat of air at constant pressure [J·kg^{-1}·K^{-1}]
g	acceleration of gravity [9.8 m·s^{-2}]
H	height of the window [m]
$I_{intermittency}$	flame intermittency index [-]
$\dot{Q}_{total}$	total heat release rate [kW]
$\dot{Q}_{ex}$	excess heat release rate outside the window, $\dot{Q}_{ex} = \dot{Q}_{total} - 1500A\sqrt{H}$ [kW]
$\dot{Q}_{ex}$	dimensionless excess heat release rate [-]
$\Delta T_{z,\max}$	temperature rise above ambient at the height of Z [K]
$T_{x,z}$	temperature at the certain height of Z and radical distance of x [K]
T_∞	ambient temperature [K]
W	width of the window [m]
x	horizontal coordinate base on the different coordinate system [m]
x_m	horizontal coordinate for the peak temperature [m]
Z	vertical height above the top of the compartment [m]
Z_n	neutral plane height at the window [m]
$Z_{f,w}$	flame height with facade wall [m]
$Z_{f,n}$	flame height with no facade [m]

Greek symbols

ℓ_1	characteristic length of the window, $\ell_1 = (A\sqrt{H})^{2/5}$ [m]
ℓ_2	characteristic length of the window, $\ell_2 = (AH^2)^{1/4}$ [m]
β	parameter of Gaussian function in Eq. (4) [-]

heat release rate outside the window:

$$\frac{Z_f}{\ell_1} = fcn(\dot{Q}_{ex}^*) = fcn\left(\frac{\dot{Q}_{ex}}{\rho_\infty C_p T_\infty \sqrt{g}\,\ell_1{}^{5/2}}\right) \quad (1)$$

where Z_f is flame height above the neutral plane (0.4 H) of the window, ρ_∞ is air density, C_p is specific heat of air at constant pressure, T_∞ is ambient temperature, g is acceleration of gravity, and $\dot{Q}_{ex}$ is the excess heat release rate due to the burning excess fuel outside the compartment defined as $\dot{Q}_{ext} = \dot{Q}_{total} - 1500A\sqrt{H}$. Later, based on the theory proposed by Lee [11–13], Lu et al. [14] and Tang et al. [15] further quantified the facade flame height with air entrainment constraints by the side walls at the two sides of the opening, or by a slopping facing wall. Besides the flame height, another basic characteristic of such facade fire plume is the temperature profile [16,17]. Himoto [16] and Tang [17] et al. measured the radial temperature profile, which is closely related to the entrainment and diffusion of facade thermal fire plume. Such radical temperature profile might be able to be represented, which is similar to that of a free fire plume [18], by Gaussian function.

However, for the previous works [1–17], such thermal plume is mainly consider as attaching to the facade wall when the compartment on fire is not at the upper levels or near the top of the building. The physics is that the facade wall will pose significant constraint effect on the air entrainment, and hence its thermal characteristics of the thermal plume. However, the fire can also happen at the top level of the building then eject out through the window. Under this condition, the entrainment constraint effect due to the facade wall on the thermal plume does not exist noting that there is no facade above the top floor. By far, there is still no work reported yet to quantify the flame height and radical temperature profile of window-ejected thermal fire plume under this no-facade condition, despite of that physically the air entrainment will be significantly different from those with a facade wall.

So, in this work, comprehensive experiments were carried out to measure the flame height and radical temperature profile of window-ejected thermal plume from compartment fire of various window dimensions and heat release rates without facade wall, and compare it with those revealed previously with the facade wall. The previous correlations and functions proposed with facade wall were extended to the no-facade condition. Following the introduction, the experimental setup and measurement were described in Section 2, the results and analysis in Section 3 and the conclusions are summarized in Section 4.

2. Experiments

2.1. Experimental setup

Fig. 1 shows the experimental model and setup. A 0.4 m cubic compartment was designed to simulate the burning compartment, whose inner surface is lined with 5 mm thickness ceramic fiber boards (density: 285 kg/m^3, thermal conductivity: 0.18 W/(m·K), specific heat: 1390 J/(kg·K)) for thermal insulation. A square porous propane gas burner with side dimension of 0.2 m, with top surface flushed with the compartment floor, was set as fire source. The fuel supply rate and the heat release rate were controlled through the mass flowmeter (accuracy: 0.1 SLPM, Standard Liter Per Minute).

A thermocouple (K-type; diameter: 0.5 mm) array, consisting of 49 thermocouples (7 rows, 7 columns) with a horizontal interval of 5 cm and a vertical interval of 15 cm, was set up to measure the temperature profile of ejected thermal fire plume outside the window. The lowest row of the thermocouple array was set to flush with the upper edge of the compartment. Fig. 1(a) and (b) show the coordinate system and the

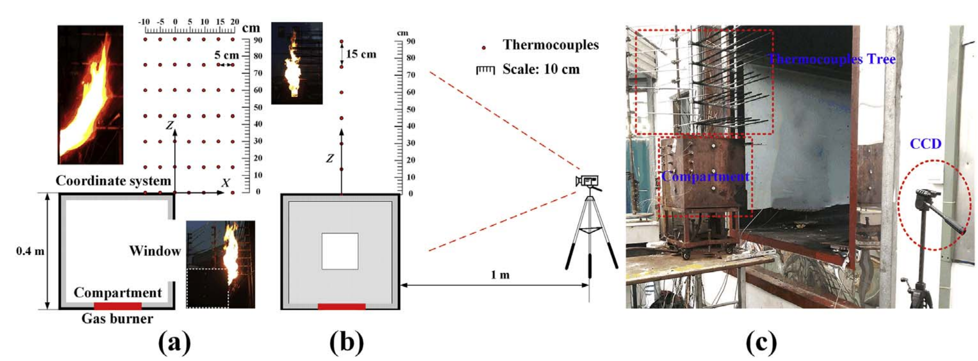

Fig. 1. Schematic of experimental design: (a) side view; (b) front view; and (c) overall view.