Fire Safety Journal 70 (2014) 14–22

Contents lists available at ScienceDirect

Fire Safety Journal

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

Heat flux profile upon building facade with side walls due to window ejected fire plume: An experimental investigation and global correlation

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ARTICLE INFO

Article history:
Received 15 July 2013
Received in revised form
18 July 2014
Accepted 16 August 2014
Available online 30 September 2014

Keywords:
Heat flux profile
Building facade
Side wall separation distance
Compartment fire
Window ejected fire plume

ABSTRACT

This paper investigates the heat flux profile upon building facade with side wall constraints due to ejected fire plumes from a window of an under-ventilated compartment fire. A reduced-scale model (1:8), consisting of a cubic fire compartment with a facade wall attached and two side walls located symmetrically at both sides of the window is developed. The window dimensions and the side wall distances are changed in experiments, representing different ventilations and constraints on fire plume entrainment. Five heat flux gauges are employed in measurement of vertical heat flux profile upon the facade wall. Results show that with the decrease in separation distance of side walls, the heat flux increases for small windows where dimensionless excess heat release rate $\dot{Q}^*_{ex} \geq 1.3$ ("(half) axisymmetric fire" regime), meanwhile shows weak dependency on side wall separation distance for large windows where $\dot{Q}^*_{ex} < 1.3$ ("wall fire" regime). A new global formula is proposed to characterize the vertical profile of heat flux based on Lee's model without side walls as further modified by a parameter K in relation to the separation distance of side walls and characteristic length scales of the window. Experimental data for different windows and side wall separation distances are well collapsed by the proposed formula.

1. Introduction

In high-rise building fires flame can be observed to eject from the window of a room after flashover and then spread to upper floors, leading to catastrophic loss of casualties and properties. Behaviors of facade fire plume ejected out of the window over the building facade have received focused attentions in the last decades [1–17]. One of the most important parameters is the heat flux upon the building facade wall due to the exposure of ejected fire plumes which directly determines damage to the thermal insulation materials as well as the vertical fire spread along the building facade. Some of most relevant previous works on heat flux upon building facade due to such window ejected fire plume is reviewed below.

A series of full-scale experiments with different window dimensions and fire heat release rates have been conducted in early years by Oleszkiewicz [6]. The magnitudes of heat flux upon facade wall as well as the effect of facing wall and eaves on the heat flux profiles and the radiation and convection fraction are also qualitatively discussed. More recently, through reduced-scale experiments [12], Ohmiya et al. have found that the heat flux profile upon facade wall is determined by the facade flame height as well as the heat accumulation in the vicinity of the window, or more specifically excess fuel amount and window dimensions as:

$$\frac{\dot{q}''_t \times Z_f}{\dot{Q}_{conv,plume}/W} = fcn\left(\frac{Z}{Z_f}, \frac{W}{H}\right) \quad (1)$$

where $\dot{q}''_t$ is the total heat flux to the facade, W and H are the width and height of the opening, Z and Z_f are the vertical position on the facade and mean flame height from the neutral plane of the opening respectively. The neutral plane is calculated to be about $0.4H$ [22] above the bottom of the window. $\dot{Q}_{conv,plume}$ is defined as total heat released outside the compartment window, including convective heat flowed out of the window and that released by external combustion of excess fuel outside the window:

$$\dot{Q}_{conv,plume} = \left(\dot{m}_f + 0.5AH^{1/2}\right) \times C_p \times (T_{encl} - T_a) + \dot{Q}_{ex} \quad (2)$$

Furthermore, Delichatsios and Lee [18–23] have replaced the term $\dot{Q}_{conv,plume}$ by excess heat release rate $\dot{Q}_{ex}$ in above model. New characteristic length scales ℓ_1 and ℓ_2 have also been proposed to

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http://dx.doi.org/10.1016/j.firesaf.2014.08.001
0379-7112/

Nomenclature

A	area of the opening (m^2)
$A\sqrt{H}$	ventilation factor (m$^{5/2}$)
C_p	specific heat (kJ/kg/K)
d	distance of opposite facing wall to facade (m)
D	separation Distance of the two side walls (m)
g	acceleration of gravity (m/s^2)
H	height of the opening (m)
h_c	total heat loss coefficient from enclosure (kW/m^2 K)
K	global non-dimensional factor accounting for side wall effect on facade flame height
$\dot{q}''_t$	total heat flux to the facade wall (kW/m^2)
$\dot{Q}$	heat release rate (kW)
$\dot{Q}_{conv,plume}$	total heat released outside the enclosure (kW)
$\dot{Q}_{ex}$	excess heat release rate, $\dot{Q}_{ex}=\dot{Q}-1500A\sqrt{H}$ (kW)
$\dot{Q}^*_{ex}$	non-dimensional excess heat release rate, $\dot{Q}^*_{ex}=\frac{\dot{Q}_{ex}}{\rho_\infty C_p T_\infty\sqrt{g}\ell_1^{5/2}}$
T_a	temperature of ambient air (K)
T_{encl}	temperature inside the enclosure (K)
T_∞	ambient temperature (K)
ΔT	temperature rise (K)
$\dot{V}$	volume flow rate (m^3/h)
W	width of the opening (m)
Z	vertical position on the facade wall above the neutral plane (m)
Z_f	mean flame height (m)
$Z_{f,0}$	mean flame height without side walls (m)
$Z_{f,D}$	mean flame height with side walls at distance of D (m)

Greek symbols

α	slope of data in Figs. 3 and 7
Δ	difference between variables
ℓ_1	characteristic length scale, $\ell_1=\left(A\sqrt{H}\right)^{2/5}$ (m)
ℓ_2	characteristic length scale, $\ell_2=\left(AH^2\right)^{1/4}$ (m)
ℓ_3	characteristic length scale, $\ell_3=\left(AH^{4/3}\right)^{3/10}$ (m)
λ	a coefficient to describe the difference between entrainment strength from side and that from front
ρ_∞	density of air (kg/m^3)

Subscripts

ex	excess
∞	ambient condition

address the window dimension effect. They have proposed the following new non-dimensional formula,

$$\frac{\dot{q}''_t\times Z_f}{\dot{Q}_{ex}/\ell_1}=fcn\left(\frac{Z}{Z_f},\frac{Z_f}{\ell_1},\frac{\ell_1}{\ell_2}\right) \quad (3)$$

where $\ell_1=\left(A\sqrt{H}\right)^{2/5}$, $\ell_2=\left(AH^2\right)^{1/4}$ [19–22], and as the heat release rate inside an under-ventilated room fire is $1500A\sqrt{H}$ (kW), which gives:

$$\dot{Q}_{ex}=\dot{Q}-1500A\sqrt{H}\ \text{kW} \quad (4)$$

Considering the flame height Z_f is the function of non-dimensional excess heat release rate $Z_f/\ell_1=fcn\left(\dot{Q}^*_{ex}\right)=fcn\left(\dot{Q}_{ex}/\rho_\infty C_p T_\infty\sqrt{g}\ell_1^{5/2}\right)$, and the fact of small difference between the two length scales ℓ_1 and ℓ_2, the model is then further simplified as [20,22]:

$$\frac{\dot{q}''_t\times Z_f}{\dot{Q}_{ex}/\ell_1}\times e^{0.6(H/\ell_1)}=fcn\left(\frac{Z}{Z_f}\right) \quad (5)$$

where the pattern $e^{0.6(H/\ell_1)}$ is introduced as an empirical correction factor showing different window shapes. In this model, the heat flux profile is divided into three regimes based on the normalized height factor Z/Z_f. For continuous flame regime where $Z/Z_f<0.8$, heat flux remains relatively constant as dominated by flame radiation. However, on the other hand, when $Z/Z_f\geq 0.8$, the heat flux starts to decrease vertically where the heat flux is dominated by radiation together with convection. The region of $Z/Z_f>1.3$ is defined as the buoyant plume regime above the flame tip, where the heat is transferred to the facade wall only by convection from the facade buoyant plume.

The above studies are for the condition of a free window fire plume without boundary constraints. Additionally, Delichatsios and Lee [21] have investigated the constraint effect of an opposite facing wall (representing the facade of another opposite nearby building) on the heat flux profile upon the facade. With the decrease in the distance between the opposite facing wall and facade wall, heat flux profile on the facade wall increases as a result of the increase of facade flame height due to the constraint effect of the opposite facing wall on fresh air entrainment of the facade fire plume. The model of Eq. (5) is further remedied to include the factor of the distance between the facade and the opposite facing wall:

$$\frac{\dot{q}''_t\times Z_f}{\dot{Q}_{ex}/D}\times \exp[0.6(\ell_1/\ell_3)^{5.5}]=fcn\left(\frac{Z}{Z_f}\right)\quad \text{for}\quad D<\ell_3$$
$$\frac{\dot{q}''_t\times Z_f}{\dot{Q}_{ex}/\ell_3}\times \exp[0.6(\ell_1/\ell_3)^{5.5}]=fcn\left(\frac{Z}{Z_f}\right)\quad \text{for}\quad D\geq\ell_3 \quad (6)$$

in which a new characteristic length scale $\ell_3=\left(AH^{4/3}\right)^{3/10}$ is proposed, representing the critical distance from the opposite facing wall to the facade wall, below which the constraint on entrainment has to be taken into account, meanwhile the term $\exp\left[0.6(\ell_1/\ell_3)^{5.5}\right]$ is also introduced as an empirical correction factor addressing the window dimension effect.

However, there still remains another boundary constraint on such facade window fire plume behaviors. For example, in the fire event of a high-rise building in Busan City of Korea in 2010, it has been observed the external fire spreads very fast vertically along the facade to upper floors, in which the narrow vertical channel formed by two side walls constructed on the facade beside the window is deemed to contribute to such faster facade fire spread. This suggests another kind of boundary constraint condition (due to side walls beside the window) to be considered, as it also influences the buoyant entrainment of the facade fire plume and hence its parameter profiles. However, the studies on such kind of constraint condition are still very limited. The study in [24] just shows that the presence of side walls are irrelevant to the critical heat release rate inside the compartment ($1500A\sqrt{H}$, in kW [25]). Lu et al. [26], based on series of small-scale experiments, have recently found that for larger flames with relative stronger horizontal momentum behaving like a "(half) axisymmetric fire" ($\dot{Q}^*_{ex}>1.3$), the flame height increases with the decreases in the side wall separation distance and a global model is proposed to address such behavior. But still none work has been reported to address the side wall constraint effect on the heat flux profile