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Experimental investigation on window ejected facade flame heights with different constraint side wall lengths and global correlation

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A B S T R A C T

This paper presents an experimental investigation on the effect of side wall length (normal to the facade direction) on the ejected facade flame height from a window of an under-ventilated compartment fire. The ejected facade flames are recorded by a CCD camera with various side wall lengths L at different side wall separation distances D. Results show that, as the length of the side wall increases, the change in behavior of the flame height can be categorized into two regimes: (1) the flame-entrainment-controlled regime in which flame height increases with side wall length for "(half) axisymmetric fire" but independent of side wall length for "wall fire"; and (2) the combustion-efficiency-controlled regime where the flame heights for both these two fire types decrease with side wall length due to decrease of the combustion efficiency inside the fire room, for $L = 3D$ or greater. A global parameter K is then proposed based on scaling analysis for the air entrainment of the flame with side wall length, in relation to characteristic length scales ℓ_1 and ℓ_2 of the window, which well collapse the experimental data for different window dimensions, side wall lengths and separation distances.

1. Introduction

Flames are usually observed to eject from windows along the facade in a fully-developed under-ventilated compartment fire, which cause fire spread to upper floors resulting in catastrophic loss of life and property. Yokoi [1] examined this phenomenon in 1960 and the temperature profile outside the fire compartment was quantified by Seigel [2], Thomas [3] and Sun [4] for different surrounding conditions. The model of temperature profile, radiation intensity, flame height, and the heat flux upon the facade wall was built later [5–8]. More recently, works on the virtual origin [9], temperature profile [9,10], intermittency behavior [11], as well as plume behaviors [12–14] have been addressed by Hu et al.

Physically, the window flame height is determined by the amount of excess fuel ejected outside the window which cannot be consumed by the air flowing into the room through the window, as well as the entrainment intensity of ambient fresh air into the ejected flame to further consume the excess fuel outside the window. For a free facade window flame in which buoyancy is the only dominating factor, Delichatsios et al. [15–18] has proposed non-dimensional models of the flame ejecting behavior based on the dimensionless heat release rate $\dot{Q}^*_{ex}$ as well as the characteristic length scales of the window as:

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

$$\ell_1 = (A\sqrt{H})^{2/5} \tag{2}$$

where $\dot{Q}_{ex}$ is the excess heat release rate due to the burning of excess fuel outside the window estimated and verified through experiments [17] as:

$$\dot{Q}_{ex} = \dot{Q} - \dot{Q}_{inside} = \dot{Q} - 1500A\sqrt{H} \quad kW \tag{3}$$

This value is derived theoretically from the air inflow rate through the window and the heat of combustion of the oxygen in the air flow at stoichiometric ratio. The reliability of this formula has been justified and been commonly used extensively in previous works [9–13,15,18–20].

Furthermore, Lee et al. [15,17] have proposed that the flame flowing outside the window can be depicted as a fire generated by a rectangular source having side dimensions ℓ_1 and ℓ_2 at the level of the neutral plane of the room window and providing a heat release rate of $\dot{Q}_{ex}$, whereℓ_1 is defined by Eq. (2) and ℓ_2 represents the competition of momentum to buoyancy of ejected flame at the window,

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Nomenclature

A	area of the opening (m^2)
A_T	total exposed surface area of the compartment (m^2)
$A\sqrt{H}$	ventilation factor ($m^{2.5}$)
C_p	specific heat (kJ/kg/K)
D	separation distance of the two side walls (m)
g	acceleration of gravity (m/s^2)
h_c	total heat loss coefficient from enclosure ($kW/m^2/K$)
H	height of the opening (m)
I	flame intermittency index
K	global non-dimensional factor accounting for side wall effect on facade flame height
L	length of the side wall (m)
$\dot{m}$	entrainment amount (kg/s)
$\dot{Q}$	heat release rate (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_∞	ambient temperature (K)
$\dot{V}$	volume flow rate (m^3/h)
Z_0	mean flame height without side walls (m)
$Z(D, L)$	mean flame height with side walls at distance of D and length L (m)

Greek symbols

α	entrainment coefficient
ℓ_1	characteristic length scale, $\ell_1 = (A\sqrt{H})^{2/5}$ (m)
ℓ_2	characteristic length scale, $\ell_2 = (AH^2)^{1/4}$(m)
ℓ_3	characteristic length scale, $\ell_3 = (AH^{4/3})^{3/10}$ (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

$$\ell_2 = (AH^2)^{1/4} \tag{4}$$

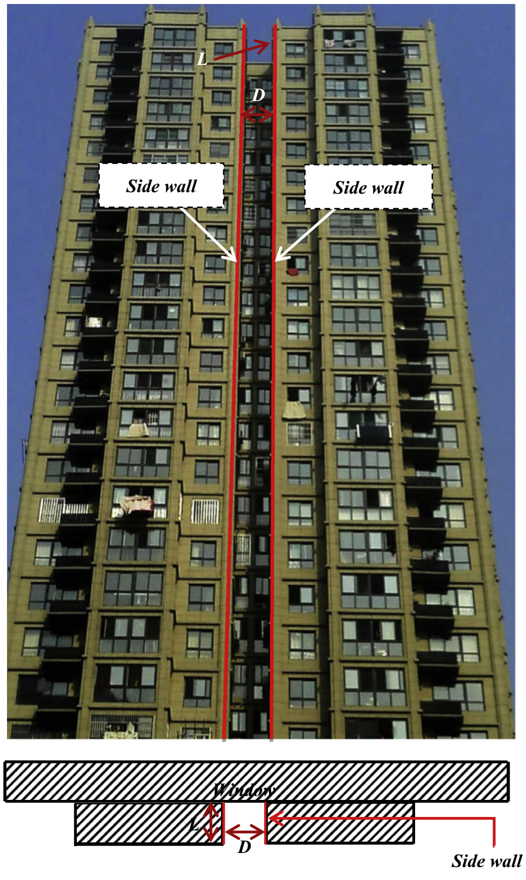
Additionally, constraint effect, due to opposite facing wall, on facade flame height has also been investigated by Lee and Delichatsios [21,22], where a length scale ℓ_3 [$=(AH^{4/3})^{3/10}$] is proposed, indicating the critical distance from the facing wall to the facade wall, below which the flame height starts to increase.

Another kind of entrainment constraint boundary effect, which is due to the presence of side walls beside the window, also exists in practice as exemplified in Fig. 1. A narrow channel is formed by the two parallel side walls constructed vertically beside the window, and will influence the window-ejected flame behavior considerably (e.g. 2010s Busan high-rise building fire). The window ejected flame was observed to be remarkably high in the narrow vertical channel formed by the two parallel side walls. However, investigations on this issue seem to be still very limited, with available literature mostly focusing on the effect of side walls on the ejected fire plume temperature distribution [e.g. 23–25]. In our recent work, it has been shown that the presence of side walls and their separation distance (in the direction parallel to the facade) will strongly block the entrainment of fresh air from side direction into the flame and thus influence the flame height [27]. It is found that for small flames behaving like a “wall fire” ($\dot{Q}^*_{ex} \leqslant 1.3$), the mean flame height is nearly irrelevant to the separation distance of side walls; but for relative larger flames behaving like a “(half) axisymmetric fire” ($\dot{Q}^*_{ex} > 1.3$), the flame height increases with the decreases in side wall distance. A global non-dimensional factor K has been brought forward to account for the effect of the side wall separation distance on the flame height as:

$$K = \frac{Z_D}{Z_0} = \left\{\frac{\ell_1 \cdot [1 + 2\lambda(\ell_2/\ell_1 - \ell_2/D)]}{\ell_1 + 2\lambda\ell_2}\right\}^{-1} = \frac{\ell_1 + 2\lambda\ell_2}{\ell_1 \cdot \left[1 + 2\lambda\left(\frac{\ell_2}{\ell_1} - \frac{\ell_2}{D}\right)\right]} \tag{5}$$

However, how the side wall length (in the direction normal to facade) affects the entrainment and thus the flame height has not been accounted and still needs to be quantified, which is also an important parameter in building design (Fig. 1).

In this paper, a series of experiments are conducted in a reduced-scale cubic room model of size 0.4 m having a vertical facade wall attached at the window and two side walls located at both sides of the window symmetrically. By changing the length (in the direction normal to the facade) of the side walls at different wall separation distances (in the direction parallel to the facade), the flame heights for different window geometries are recorded by a CCD camera. The effect of side wall length on the flame height has been correlated and further included into the parameter K to develop a more general global model.



(top view)

Fig. 1. Typical photo of facade side wall design in buildings.