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Facade flame height ejected from an opening of fire compartment under external wind

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ABSTRACT

This paper presents an experimental study and analysis on the facade flame height ejected from an opening of fire compartment under external wind. Experiments are carried out in a reduced-scale model consisting of a cubic fire compartment with a vertical facade wall. An opening is designed at the center of one sidewall of the fire compartment at the facade side and subjected to external wind (normal to the opening) provided by a wind tunnel. The facade flame heights are measured by a CCD camera for five different openings at various fuel supply heat release rates and wind speeds. It is found that the facade flame height decreases with increasing external wind speed. A scaling analysis is performed to interpret this behavior based on the change of air entrainment into the flame from both the facing-facade and parallel-facade directions caused by the external wind flow. A global model incorporating the external wind speed, the two characteristic length scales of the opening as well as the dimensionless excess heat release rate is developed for describing the facade flame height of various conditions. The proposed model correlates the experimental data well.

1. Introduction

Facade flames ejected from an opening (such as a window) from room fires in high-rise buildings could pose great threat to upper floors resulting in catastrophic loss. Started by Yokoi [1] in 1960, many researchers have investigated this behavior. Those works focused on the key parameters including temperature profiles [2–6], facade flame heights [7–13] as well as heat flux/radiation intensity [8,9,11,14–18] during the past decades. Among these characteristics, the facade flame height is one of the most crucial parameters, as it determines the possible direct ignition of the combustible in the floor above the opening.

Recently, Lee and Delichatsios [7–9] carried out a series of reduced-scale experiments and proposed following non-dimensional formula to describe the facade flame height from opening of compartment fires:

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

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

where Z_f is the mean flame height (of 50% intermittency) above the neutral plane of the opening, ℓ_1 is the characteristic length scale representing the opening dimensions (A and H are the area and height of the opening, respectively), ρ_∞ is ambient air density, C_p is specific heat of ambient air at constant pressure, T_∞ is ambient air temperature, g is acceleration of gravity. The dimensionless excess heat release rate $\dot{Q}_{ex}^*$ is defined in terms of the excess heat release rate $\dot{Q}_{ex}$, which is the difference between the total heat release rate $\dot{Q}$ and the heat released inside the compartment for under-ventilated fires $\dot{Q}_{inside}$ [8,9]:

$$\dot{Q}_{ex}^* = \frac{\dot{Q}_{ex}}{\rho_\infty C_p T_\infty \sqrt{g}\ell_1^{5/2}} = \frac{\dot{Q} - \dot{Q}_{inside}}{\rho_\infty C_p T_\infty \sqrt{g}\ell_1^{5/2}} \tag{3}$$

Later, Lee and Delichatsios [8,9] developed a model taking the facade flame from a compartment fire as a fire standing at the level of the neutral plane of the opening with a heat release rate of $\dot{Q}_{ex}$ generated by a rectangular source having the side dimensions as ℓ_1 (representing the opening dimension, parallel to facade) and ℓ_2 (representing the horizontal projection distance of the flames outside the opening, normal to facade), where ℓ_2 is also dependent on the opening dimensions and expressed as:

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

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Nomenclature

A	area of the opening (m^2)
$A\sqrt{H}$	ventilation factor of the opening ($m^{2.5}$)
C_p	specific heat of air at constant pressure (kJ/(kg·K))
g	acceleration of gravity (9.8 m/s^2)
H	height of the opening (m)
I	flame intermittency index
K	global non-dimensional correction factor
$\dot{m}_{front}$	air entrainment from the front direction (kg/s)
$\dot{m}_{side}$	air entrainment from the side direction (kg/s)
$\dot{Q}$	total heat release rate (kW)
$\dot{Q}_{critical}$	critical heat release rate for flame ejection (kW)
$\dot{Q}_{inside}$	heat released inside the compartment, $\dot{Q}_{inside}=\dot{Q}_{critical}$ (kW)
$\dot{Q}_{ex}$	excess heat release rate, $\dot{Q}_{ex}=\dot{Q}-\dot{Q}_{inside}$ (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 air temperature (K)
U_W	external wind speed (m/s)
W	width of the opening (m)
Z_f	flame height (m)
$Z_{f,0}$	flame height without external wind (m)

Greek symbols

α	a coefficient to describe the external wind effect on air entrainment
ℓ_1	characteristic length scale of the opening, $\ell_1=(A\sqrt{H})^{2/5}$ (m)
ℓ_2	characteristic length scale of the opening, $\ell_2=(AH^2)^{1/4}$ (m)
$\tilde{\ell}$	characteristic air entrainment length scale (m)
$\tilde{\ell}_W$	characteristic air entrainment length scale under external wind (m)
ρ_∞	density of air (kg/m^3)

Subscripts

ex	excess
f	flame
∞	ambient condition

Concerning the effects of external boundary conditions on the air entrainment of the facade flame and thus the flame height, Lee and Delichatsios [17] investigated the constraint effect of an opposite facing wall (opposite to the opening of the compartment facade), which was later extended to sub-atmospheric pressure condition (64 kPa; Lhasa-Tibet) [10]. Moreover, Tang et al. [11] revealed the flame height evolution with a sloping facing wall constraint at various angles. Hu and coworkers [12,13,18] studied side walls (at the two sides of the opening with various separation distance and lengths) constraint effect on the facade flame characteristics, and a global non-dimensional model for facade flame height was proposed based on the analysis of air entrainment change. Hu et al. [19] further studied the merging behavior of the two facade flames from two parallel openings. What's more, Asimakopoulou and coworkers [20] evaluated a broad range of empirical correlations and widely employed methodologies for the estimation of externally venting flame characteristics. However, there is still no work reported in the literature about the facade flame height evolution under external wind; meanwhile it is common for high-rise building fires.

So in this paper, a series of experiments are carried out to study the facade flame height ejected from an opening of a fire compartment under external wind. The experimental results are then analyzed with a non-dimensional correlation proposed. Following the introduction, the experimental setup is depicted in section 2, the experimental results are presented and correlated in section 3, and finally the conclusions are summarized in section 4.

2. Experiments

Fig. 1 illustrates the experimental design. A reduced-scale experimental model consisting of a fire compartment with a vertical facade wall is located at the outlet portal of a wind tunnel. The fire compartment is cubic with dimensions of 0.4 m and the inner wall is lined with 3 mm

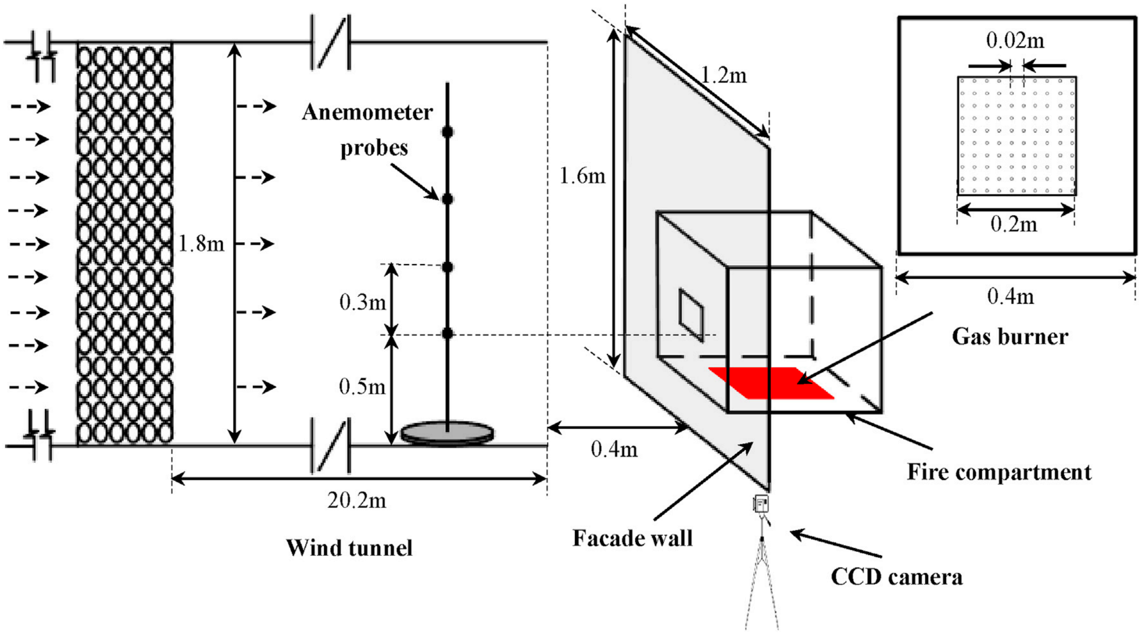

Fig. 1. Experimental setup.