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Merging behavior of facade flames ejected from two windows of an under-ventilated compartment fire

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Abstract

This paper investigates the merging behavior of flames ejected from two parallel windows of an under-ventilated compartment fire using a LPG gas burner. A reduced-scale model (about 1:4) of a compartment fire with a facade wall has been constructed where the window dimensions and the separation distance between them varied during the experiments. The flames ejected from the windows were recorded by a CCD camera. The excess heat release of the fuel burning outside the windows was high enough to produce flames controlled by three-dimensional entrainment. Temperatures inside the compartment, the flame merging probability, the distance from neutral plane to flame lowest merging point, and the height of the facade flames before and during merging were measured. The temperature measurements inside the under-ventilated compartment fires do not change with total heat release rate or the window separation distance, thus indicating that the same heat is produced inside the compartments. The flame merging probability and the flame merging point distance are normalized and well correlated using the facade flame height for completely non-merging flames and the separation distance between the windows. Finally, the facade flame height normalized by the facade flame height for completely non-merging flames is well correlated with the ratio of surface of the air entrained between the windows as the separation distance changes divided by the total surface area from all sides available for entrainment. For the present case this ratio is a function of the ratio of the flame merging point distance over the facade flame height for completely non-merging flames which is finally used for the correlation of merging flame heights.

Keywords: Compartment fire; Two parallel windows; Flame merging probability; Flame merging point distance; Flame height

1. Introduction

Flames ejected from the windows from under ventilated room fires in high rise buildings can spread to upper floors along the facade wall, leading to disastrous loss of human lives and

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properties. The behavior of facade flames can be characterized by the temperature profile, the radiation intensity, the heat fluxes as well as the flame height, on which much attention has been drawn.

Started by Yokoi [1] in 1960, research on facade flames has been extensively expanded especially in the last tens of years to characterize all the facts of facade flames [1–10]. Typically, facade flames involve the combustion of unburned fuel ejected from the fire compartment. Recently, based on this basic mechanism and the geometry of the window, the normalized facade flame height above the neutral plane for 50% intermittency, Z_f/ℓ_1, has been established in [5–7]:

$$\frac{Z_f}{\ell_1} = fcn(\dot{Q}^*_{ex}) = fcn\left(\frac{\dot{Q}_{ex}}{\rho_\infty C_p T_\infty \sqrt{g}\ell_1^{5/2}}\right) = fcn\left(\frac{\dot{Q} - 1500A\sqrt{H}}{\rho_\infty C_p T_\infty \sqrt{g}\ell_1^{5/2}}\right) \quad (1a)$$

$$\ell_1 = (A\sqrt{H})^{2/5} \quad (1b)$$

where $\dot{Q}_{ex}$ is the dimensionless excess heat release rate owing to the combustion of excess fuel outside the window normalized by the air density ρ_∞, the specific heat of air at constant pressure C_p, the ambient temperature T_∞, the acceleration of gravity g and the characteristic length scale representing the window dimensions ℓ_1 (A and H are the area and height of the window, respectively). Note that the excess heat release rate $\dot{Q}_{ex}$ is the difference between the total heat release rate $\dot{Q}$ and the heat $\dot{Q}_{inside} = 1500A\sqrt{H}$ in kW released inside the compartment.

It has also been shown that the flame height in Eq. (1a) depends on the 2/3 power of the dimensionless excess heat release rate $\dot{Q}^*_{ex}$ when $\dot{Q}_{ex}$ <1.3 ("two-dimensional flame") and on the 2/5 power of the dimensionless excess heat release rate when $\dot{Q}^*_{ex}$ >1.3 ("three-dimensional flame") [5,7]. In addition, Lee [7] depicts the facade flame from a compartment fire as a fire standing at the level of the neutral plane of the window with a heat release rate of $\dot{Q}_{ex}$ generated by a rectangular source having side dimensions as ℓ_1 (representing the window dimensions, parallel to facade wall) and ℓ_2 (representing the horizontal extension of the flames outside the window, normal to facade wall), where ℓ_2 is also depends on the window dimensions:

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

Extensive additional work using this modeling approach [8–16] has verified its applicability for a compartment with a single window. This works examines facade flames from a compartment fire having two windows which is common in modern high rise buildings especially concentrating for the first time on the merging behavior of the flames issuing from each window as the heat release rate inside the compartment, the excess heat release rate and the separation window distance vary. We note that merging of fires has been previously examined for jet and pool fire configurations [17–23].

So, in this paper, a series of experiments for under-ventilated fires are presented and analyzed for facade flames in a reduced-scale cubic room of size 0.8 m having two window type openings. Specifically, the flame merging probability, the flame merging point distance and the facade flame height are measured by CCD camera and correlated for different separation distances and sizes of the windows. The details of the experiments are described in the second section, followed by the experimental results, discussion and correlations. Finally, the last section summarizes the major findings of this work.

2. Experimental setup

As shown in Fig. 1, a ceramic-inner-lined cubic fire compartment of 0.8 m attached to a vertical facade wall of 5 m (H) × 3 m (W) was established as experimental rig. Two sets of parallel windows of the same size are located symmetrically from the center of the facade wall. Each set has window sizes of 0.25 m (H) × 0.125 m (W) and 0.30 m (H) × 0.15 m (W), whereas the separation distance of the two windows varied by 0.05 m intervals in the experiments as listed in Table 1.

LPG (Liquefied Petroleum Gas) was the fuel used to provide a steady fuel supply controlled by a flow meter into a porous gas burner in the center of the fire compartment. The total Heat Release Rate (HRR) is then acquired using the heat of combustion of the fuel and the flow rate of the gas with combustion efficiency estimated to be about 0.9 [7]. All the experimental scenarios listed in Table 1 are set up and maintained to be under-ventilated when the flames are ejected from the window [14]. The height of the ejected flames at the facade captured by a CCD camera at 25 frames per second is calculated by applying the OTSU [24] method in image processing. The experimental conditions are summarized in Table 1 for different window sizes, separation distances, the total HRR inside the fire compartment and the normalized excess heat release rate (see Eq. (1)). In addition, two thermocouple trees inside the compartment measured the gas temperatures in order to check whether the heat release rate inside the compartment changed with the separation distance between the windows.

3. Results and analysis

In the following sections we present and correlate by dimensionless analysis the flame merging