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Wind effects on flame projection probability from a compartment with opposing openings

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ABSTRACT

This paper investigates flame projection probability from a compartment with opposing openings under assisting wind environment. The effect of external wind on the flow conditions at the door, hot gas velocity at the window and flame projection probability was investigated. Results showed that when the external wind is absent or at low wind velocities, bidirectional flow can be seen at the door. With the increment of the wind velocity, the bidirectional flow will become unidirectional at low fuel supply rate. At high wind velocities, the unidirectional flow can be seen at the door regardless of the fuel supply rate. Correlations for hot gas velocity at the window are formulated based on the mass conservation of the flow in the compartment. The calculated results have a good agreement with the experimental data. Due to fluctuations of the gases ejected from the window, flames eject from the compartment intermittently. The intermittent characteristic of flame ejecting from the compartment is influenced by the temperature and velocity of the hot gas velocity at the window. The model to predict flame projection probability is modified based on previous study without external wind.

1. Introduction

As an important fundamental topic in fire and combustion research, compartment fire phenomena have been studied for decades. Fire spill plume is an important phenomenon in compartment fires. When a fire inside a compartment develops to be at its most vigorous stage, flames would be ejected from the opening after the failure of window glass to form spill plume [1]. In high-rise building fires, flames ejected from windows can spread to upper floors along the facade wall, leading to disastrous loss of human lives and properties. A notable example is the MGM Grand Hotel fire in 1980 [2], where 68 victims were identified at the upper floors far away from the ground fire floor. Additionally, the New York “Black Sunday Fire” in 2005 resulted in the death of two firefighters and serious injuries on the other floors [3].

The behavior of the spill plume has drawn wide attention in fire community. Prahl and Emmons [4], Nakaya et al. [5] and Steckler et al. [6] studied fire induced flow behavior through an opening of a compartment. Wang and Quintiere [7] established a model attempting to include the effect of fire entrainment and vent mixing. When the fires are at under-ventilated condition, Steckler et al. [8], Kawagoe [9], and Lee at al. [10] verified theoretically and experimentally that the heat released inside the compartment depends on the amount of air consumed inside the enclosure, which is proportioned to the ventilation factor. Yokoi [11], Ohmiya et al. [12] and Lee et al. [13,14] proposed characteristic length scales, representing equivalent burner providing unburned gas of the spill flame, to describe the temperature profile, heat flux profile, and length of the fire spill plume. Himoto [1] formulated a model to predict the trajectory of window flame. Limit work has been conducted to study the fluctuation and oscillation of the spill plume. An oscillatory phenomenon was observed in the compartment with dual opening or single opening for floor fires but not for wall fires [15]. Takeda [15] considered the oscillation was the symmetrical puffing of ventilation. Hu et al. [16] has studied statistical characterization of intermittent flame ejecting behavior of compartment fires with an opening. A simple mathematical model quantifies the ejection probability as a function of normalized excess heat release rate and opening factor parameter. But the external wind was absent.

Buildings are usually in a windy environment, especially high-rise buildings. Wind velocity increases from zero at the ground to certain level related to altitude [17]. Kerber and Madryzkowski found that untenable conditions occurred quicker when fires were wind driven [18]. Wind effects on the compartment fire are different with the relative location of opening configurations. When the external wind blows into the compartment from the window and hot gases flow out from the door, the wind force opposes the buoyancy, so called “opposing wind force” [19]. On the other hand, when external wind

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Nomenclature

a	coefficient in Eq. (16).
A_d	door area (m^2)
A_w	window area and (m^2)
b	coefficient in Eq. (16).
C_d	discharge coefficient
c_p	specific capacity of gas (kJ/kg/K)
F_b	buoyancy force of hot gases
F_h	horizontal inertia force
Fr	Froude number
H_n	neutral plane height at the door (m)
h_o	neutral plane height at the door without wind (m)
h_d	door height (m)
h_w	height from the lower to the upper edge of the window (m)
L	the model size (m)
l_1	length scale related to air inflow mass flow rates with bidirectional flow at the door (m)
l_1'	length scale related to air inflow mass flow rates with unidirectional flow at the door (m)
m	mass loss rate (kg/s)
m_a	air inflow mass flow rate (kg/s)
m_{sd}	hot gas mass flow rate at the door (kg/s)
m_{sw}	hot gas mass flow rate at the window (kg/s)
P	flame projection probability
Q	heat release rate (kW)
Q_{conv}	the convective heat flow rate at the window (kW)
$Q_{conv,l}$	lower critical value of the convective heat flow rate at the window (kW)
R_h	hydraulic diameter of the window (m)
T	temperature (K)
T_s	temperature beneath the ceiling (K)
T_o	ambient temperature (K)
ΔT	temperature difference between T_s and T_o (K)
T_{sw}	hot gas temperature at the window (K)
T_{od}	air temperature at the door (K)
v	velocity (m/s)
v_o	wind velocity (m/s)
v_s	gas velocity at the window (m/s)
w	door width (m)

Greek symbols

α	coefficient in Eq. (12) and Eq. (14).
ρ_o	air density (kg/m^3)
ρ_{od}	air density at the door (kg/m^3)
ρ_s	hot gas density, g is the gravity acceleration (kg/m^3)
ρ_{sw}	hot gas density at the window (kg/m^3)

blows into the compartment from the door and hot gases flow out from the window, the blowing wind reinforces the buoyancy-induced flow and the air entrainment inside the compartment therefore it is called as "assisting wind force" [19]. And, the principle of "assisting wind force" has been used in positive pressure ventilation, helping firefighters to gain control of a fire. When the fan is setup outside of the structure entrance, combustion gases will be forced to flow out of the compartment through the opened window by the fan flow [20]. If the fire apartment has a high pressure relative to the outside due to an imposed wind, the flame will "pulse" out of the window to balance the overpressure [21]. The intermittent characteristic of flame ejecting from the compartment will be influenced by the external wind.

In this paper, we present an experimental study on the intermittent characteristic of flame ejecting from the compartment with simultaneous door and window opened on opposite walls under assisting wind environment. The research examines the experimental data on (a) the direction of the flow at the door (b) hot gas velocity at the window (c) flame projection probability. The results will lead to a better understanding of the effect of an assisting wind on the intermittency of the flame ejected from the compartment and be beneficial for the firefighters with the rescue.

2. Experimental details

Fig. 1 shows the experimental setup. The small-scale model with a scale ratio of 1:4 was built up based on Froude modeling which is widely used in compartment fire research [16,22,23]. Froude modeling does not account for radiation and the heat transfer mechanisms were predominantly convection [24]. By holding the Froude number constant, the relationships can be simplified to obtain the required scaling laws, which are $\frac{Q_m}{Q_f}=\left(\frac{L_m}{L_f}\right)^{5/2}$, $\frac{m_m}{m_f}=\left(\frac{L_m}{L_f}\right)^{5/2}$, $\frac{v_m}{v_f}=\left(\frac{L_m}{L_f}\right)^{1/2}$ and $\frac{T_m}{T_f}=\left(\frac{L_m}{L_f}\right)^{0}$ [25,26]. Where Q is the heat release rate, m is the mass loss rate, v is the velocity, T is the temperature, L denotes the model size, L_m/L_f is the similarity ratio. The subscript 'f' and 'm' represent the full and model scale parameters respectively. The model compartment was located at the outlet of a wind tunnel [27]. The wind tunnel can provide a steady air flow with a velocity varying from 0 to 15 m/s while 0–3 m/s at an increasing step of 0.6 m/s were used for the current experiments. For a full scale equivalent with the scaling laws [25,26], the wind velocity ranges from 0 to 6 m/s. Two hot-wire anemometers were vertically set to calibrate the wind velocity 1 m before it enters the compartment from the door.

As shown in Fig. 1a, the model compartment was cubic with a side length of 0.8 m and it was attached to a vertical facade wall of 3 m (H)×2 m (W). The compartment consisted of a steel frame lined with 2.5 cm thick fiberboards. The top edge of the window is 0.75 m high. The window size was 0.2 m wide by 0.2 m tall and the door was 0.4 m high by 0.3 m wide in opposing compartment walls. A 0.24 m square porous gas burner was used with propane as the fuel. The fuel supply rate was controlled by a flow meter ranging from 1.6 to 6 m^3/h. The heat of combustion of propane was 46.45 kJ/g [28] and complete combustion was assumed in the estimation of heat release rate. The heat release rate (HRR) in the experiments ranged from 39 kW to 146 kW. For a full scale equivalent with the scaling laws [25,26], HRR ranges from 1.2 to 4.7 MW. The conditions used for each experiment are listed in Table 1. To determine repeatability, each experiment was repeated three times.

K-type thermocouples with 1 mm diameter wire were used for temperature measurements. The measuring errors of thermocouples associated with radiation were estimated using Luo's correlation [29]. The errors were estimated to be less than 10% using Luo's correlation [30,31]. Nine thermocouples were installed 4 cm beneath the compartment ceiling, as shown in Fig. 1b. As shown in Figs. 1c, 8 thermocouples and 3 thermocouples were installed at the centerlines of the door and window respectively. The distances of thermocouples were located at heights of 0.08 m, 0.16 m, 0.2 m, 0.24 m, 0.28 m, 0.32 m and 0.36 m from the bottom of the door while the distances of thermocouples were located at heights of 0.04 m, 0.1 m, and 0.16 m from the bottom of the window. Three pitot tubes were used at the centerline of the window. Based on the study of McCaffrey and Heskestad [32], the errors in the velocity measured by the pitot tubes were about 7%. They were mounted at 0.04 m, 0.1 m, and 0.16 m above the lower edge of the window.

A video camera at 25 frames per second was employed from the side of the window to capture the flame behaviors outside the window, as shown in Fig. 1a.