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Global behaviors of enclosure fire and façade flame heights in normal and reduced atmospheric pressures at two altitudes

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ABSTRACT

Enclosure fire safety design and regulations are commonly specified for normal pressure conditions at sea level. There is need however to extend the design requirements for conditions in reduced pressure atmosphere such as city at high altitude, in which the corresponding fundamental behaviors should be clarified first. Experiments are designed and carried out in this work at two different altitudes (Hefei city: 50 m, 1 atm; Lhasa city: 3650 m, 0.64 atm) in a 0.4 m cubic fire enclosure with various window dimensions and an attached 1 m (wide) × 2.2 m (high) façade with and without an opposite facing wall. Gas temperature profiles inside the enclosure and façade flame heights are measured to find out their behavioral changes for these two pressures and to develop global correlations. It is found that, for a given fuel supply rate the gas temperature inside the enclosure is lower while the outside flame is higher in the reduced pressure atmosphere, owing to the lower fuel consumption inside the enclosure and air entrainment into the flame. The flame height (without a facing wall) normalized by a characteristic window length scale ℓ_1 can be well correlated with the dimensionless excess heat release rate, but being a bit higher due to lower entrainment or larger fluctuations at lower pressure, but can be accounted for globally by a correction factor of 0.8. In addition, the characteristic length scale ℓ_3 representing the horizontal projection of the flame is higher, and thus, the critical distance of the facing wall from the enclosure, at which interaction of the façade flame and the opposite facing wall starts, is larger at lower pressure. The relative higher façade flame height and the larger critical façade-to-facing-wall distance suggest that hazards of enclosure facade fires at low pressure (high altitude) are higher and it need more conservative regulations than those at standard pressure. By accounting for their behavioral changes, global models have been correlated for gas temperature inside the enclosure as well as façade flame height without and with an opposite facing wall applicable for these two atmospheric pressures. The present results and global correlations in both normal–and reduced pressure atmosphere provide fundaments of guideline for regulations extension to high altitude and are a significant supplement and improvement over previous results in literatures.

1. Introduction and background

Ejected flames from fully developed under-ventilated enclosure fires will cause the fire to spread to adjacent upper floors or spaces representing a serious risk for high rise buildings and in dense populated areas. Extensive works have been reported in the literatures to address this problem in quantifying the ejected flame characteristics, including the combustion condition inside the enclosure under which the flame ejects [1–6], flame height and temperature profile [7–16] as well as the effect of opposite facing wall [17,18]. However, no work has been reported for similar situations on façade flame height, as a critical quantity in above fire spread process, in a low pressure atmosphere at high altitudes such as in Tibet.

For façade flames without a facing wall, a series of new dimensionless parameters have been proposed and applied [12–17] to characterize the ejected façade flame height based on a length scale ℓ_1 and the excess heat release rate outside the enclosure $\dot{Q}_{ex}$:

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

with

$$\ell_1 = (AH^{1/2})^{2/5} \tag{1b}$$

where Z_f is mean flame height from the location of the neutral plane, ρ_∞ is air density, c_p is specific heat of air at constant pressure,

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Nomenclature

A	area of the window (m^2)
A_T	total exposed surface area of the enclosure (m^2)
C_p	specific heat of air at constant pressure
D	horizontal distance between the facade wall and facing wall (m)
g	gravitational acceleration (m/s^2)
H	height of the window (m)
ΔH_{ox}	heat release per mass of air consumed at normal conditions (3000 kJ/kg)
h_c	overall effective heat loss coefficient from the walls and the window of the enclosure (by convection and radiation) (kW/m^2 K)
$\dot{m}_a$	air inflow rate (kJ/s)
$\dot{m}_f$	fuel supply flow rate (kJ/s)
p	ambient air pressure
$\dot{Q}$	total heat release rate of the fire(kW)
$\dot{Q}_{ex}$	excess heat release rate (kW)
$\dot{Q}_{ex}^*$	dimensionless excess heat release rate
$\dot{Q}_{inside}$	heat release rate inside the compartment (kW)
R	ideal gas constant(8.31 J/(K mol)
T_∞	ambient temperature (K)
ΔT_f	the temperature rise between gas inside enclosure and ambient (K)
ΔT_g	the temperature rise above the ambient (K)
Z_f	mean flame height from the location of the neutral plane (m)
Greek symbols	
ρ_∞	ambient air density (kg/m^3)
ρ_f	the density of hot gas (kg/m^3)
Δ	difference between variables
α	entrainment coefficient
ℓ_1	characteristic length scale representing the exit condition of the enclosure, $\ell_1 = (AH^{1/2})^{2/5}$ (m)
ℓ_3	the distance of flames ejecting from the opening after which the flow turns from horizontal to vertical, $\ell_3 \propto (AH^{4/3})^{3/10}$ (m)

T_∞ is ambient temperature, g is acceleration of gravity. Moreover, $\dot{Q}_{ex}$ is the excess heat release rate due to the excess fuel burning outside the enclosure:

$$\dot{Q}_{ex} = \dot{Q} - \dot{Q}_{inside} \tag{2}$$

where $\dot{Q}$ is total combustion heat release rate of the fuel supplied (by a gaseous burner) and $\dot{Q}_{inside}$ is the heat released within the enclosure contributed by the fuel reaction with the fresh air flowing into the enclosure through an opening.

For façade flames with an opposite facing wall representing possible fire spread to adjacent buildings, Lee et al. [17,18] have found out that, in their reduced scale experiments, the gas temperature inside the enclosure is uniform and that the mean flame height elongates as the opposite facing wall approaches the façade. A particular characteristic length scale ℓ_3 is identified as an important design parameter representing the critical distance after which the ejected flow turns from horizontal to vertical. It is determined by the competition of momentum and buoyancy in the vicinity of the window, and is used to correlate the façade flame height in terms of the dimensionless excess heat release rates and the distance, D, between the two walls [17].

$$\frac{Z_f D^{2/3}}{\left(\frac{\dot{Q}_{ex}}{\rho_\infty c_p T_\infty g^{1/2}}\right)^{2/3}} = f\left(\frac{D}{\ell_3}\right) \tag{3}$$

where

$$\ell_3 \propto \left(\frac{\Delta T_g}{\Delta T_f}\right)^{1/2}\left(\frac{\rho_g}{\rho_\infty}\right)^{1/2}\left(1-\frac{1}{1+\left(\frac{\rho_\infty}{\rho_g}\right)^{1/3}}\right)(AH^{4/3})^{3/10} \tag{4}$$

This work addresses how the temperature fields inside the enclosures as well as the facade flames change with pressure with and without an opposite facing wall. Specifically it is found that relations for flame height such as in Eqs. (1a), (1b), (3), and (5) are not directly applicable because the magnitudes of the characteristic scales do change owing to changes in the entrainment and fluctuation at low pressure as have been exemplified by vertical temperature field of façade fire plume in the previous report [19]. In this paper, fire experiments are carried out further in the scale model measuring gas temperatures inside the enclosure, and ejected façade flame height at two altitudes for under-ventilated conditions. The effect of ambient atmospheric pressure change on temperature inside the enclosure with and without an opposite facing wall is clarified. Flame heights on the façade are subsequently non-dimensionally correlated and compared with each other and with previous results for global models utilizing the excess fuel heat release rate outside the enclosure and the appropriate characteristic length scales for the window exiting flow as well as opposite facing wall distance.

2. Experimental

Fig. 1 shows the scale model to study the gas temperature inside the enclosure and façade flame height out of the window at two different altitudes (*Hefei city:* 50 m, p = 1 atm; *Lhasa city:* 3650 m, p = 0.64 atm). More detailed information on the experimental facility can be found in [19]. The experimental facility consists of a fire enclosure, a façade wall attached to the enclosure window and an opposite facing wall. A porous propane gas burner (0.2 m square) is the fire source placed at the center flush with the enclosure floor. The total HRR of the fire is calculated from the fuel supply mass flow rate and the heat of combustion of the fuel as supported by previous experiments [12,14,15,17,19,20].

Two thermocouple trees having four thermocouples each are installed inside the fire enclosure as shown in Fig. 1. The two thermocouple (Type K, 0.5 mm, overall error less than 1 °C or 3% including due to radiation and that of the thermocouple itself) trees are positioned at the inner corner and the outer corner respectively, both being 0.05 m away from the inner wall surface. The lowest thermocouple is 20 cm above the enclosure floor and the vertical separation distance between the thermocouples was 5 cm. A CCD camera at 25 frames per second is employed from the side of the opening to capture the flames ejecting from the opening.

Two series of experiments are conducted for investigating the free façade flame behavior (as summarized in Table 1) and that constrained by an opposite facing wall (as summarized in Table 2). All cases represent under-ventilated conditions. However, In Lhasa, as the air density is smaller, the critical heat release rate inside the enclosure beyond which the façade flame emerged from the opening is lower. Thus, the heat release rates employed in the Lhasa experiments is lower. In the experiments, each test condition is repeated three times to assure reliability and repeatability.