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Deflection characteristic of flame with the airflow induced by stack effect

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ABSTRACT

A set of experiments was conducted in a small scale high-rise building model with 12 floors to study the deflection characteristic of flame with the airflow induced by the stack effect. The results show that the position of the open window influences the location of the neutral plane, which determines the airflow velocity induced by the stack effect, and a correlation is proposed for their relationship. The airflow has a significant impact on the burning rate. The stack effect would cause a separation of flame base from the pan at the windward side, resulting in the exposure of part of the fuel surface to the cold air. The dimensionless flame height (H_f/D) and length (L_f/D) of leaned heptane flame are proportional to 1/4 power of the dimensionless heat release rate (Q^*). The temperature rise (ΔT) at the continuous flame zone is lower under the stack effect than that of a free burning case at open space due to the cooling of airflow. The flame of pool fire is stretched and the lengths of continuous and intermittent flame zones are much greater than those obtained at the open space. The ratio of $L/Q^{2/5}$ in the intermittent flame zone ranges from 0.12 to 0.25 in the current research whereas it ranges from 0.08 to 0.2 at the open space.

1. Introduction

In recent years, many high-rise buildings have been constructed in the world. The fire safety of high-rise buildings has drawn a lot of public attention due to the occurrences of many catastrophic fires [1]. A notable example is the MGM Grand Hotel fire in 1980 [2], where 85 people died, including 68 victims identified at the upperfloors far away from the ground fire floor. When the fire occurs in a high-rise building, the fire-induced thermal plume may flow into vertical shafts, such as stairwells, elevator shafts, and could be driven by the turbulent mixing [3,4] or stack effect [5,6] to spread from the fire floor to the other floors. Statistics have shown that about 85% of fatalities are caused by the toxic smoke and the fire-induced smoke is the most fatal threat in building fires [7]. Usually, the stack effect [5,6] is induced by the pressure difference generated by the density difference of hot and cold air respectively inside and outside of the building, and could accelerate the fire-induced thermal plume movement in the vertical shafts and significantly affect the fire behavior.

Many studies have been conducted on the stack effect in building staircases and shafts in the past decades, including the thermal plume movement [8], the neutral plane position [1,5], rising characteristics of thermal plumes [9,10] and temperature distributions [11,12]. However, little work has been focused on the effects of stack effect on the flame behavior in the fire compartment. Sun [8] found that the flame inclined towards the staircase due to the stack effect in experiments. However, he did not explore the flame behavior in depth. Satoh et al. [13] investigated the effect of the low-inlet position on the flame inclination of a propane gas fire located at the floor center in a shaft. They found the dimensionless flame shape was well correlated to the 2/3 power of dimensnsionless heat release rate modified with a Froude number [13]. Later, a simple model which gives the estimation of the attacking door jet velocity induced by stack effect on a flame was presented [14]. But compared to the staircases and shafts, there are more combustible materials in the compartments adjacent to the staircases. Fires are more likely to occur correspondingly. Under the stack effect, large amount of fresh air will be sucked into the fire compartment, providing excessive oxygen to combustion and the flame would be stretched, increasing the likelihood of fire spread. For the methanol pool fire, Shi et al. [15] found that the flame tilting angle influenced by the air flow induced by stack effect increases

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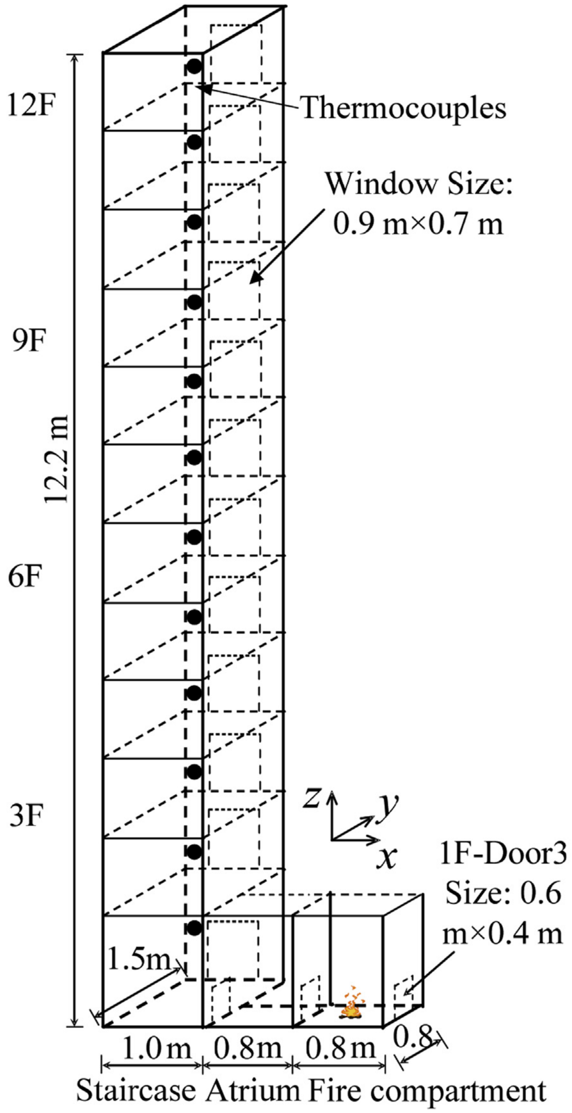
with Ri^{-1}. The velocity of the induced air flow is proportional to 1/3 power of the heat release rate [15].

In previous studies, the distance between the top and bottom opening were kept the same. But the positions of the open window in staircases will affect the severity of stack effect. After a strong stack effect is formed, a large amount of fresh air is sucked into the fire compartment. The flame is stretched, increasing the risk of flame spreading in the building. In this study, the position of the open window is changed on the 3rd, 6th and 9th floor in the staircase respectively. A set of experiments [16] was conducted to study the impact of different strength of stack effect on the flame behavior of pool fires in the compartment adjacent to a staircase. The research examines the experimental data on (a) burning rate of the heptane pool fire (b) velocity of the airflow induced by the stack effect (c) shape and temperature of the leaned flame. The results will lead to a better understanding of the fire behavior under stack effect with different strength. It provides a guide for fire detector installation and is beneficial for the safety design of buildings.

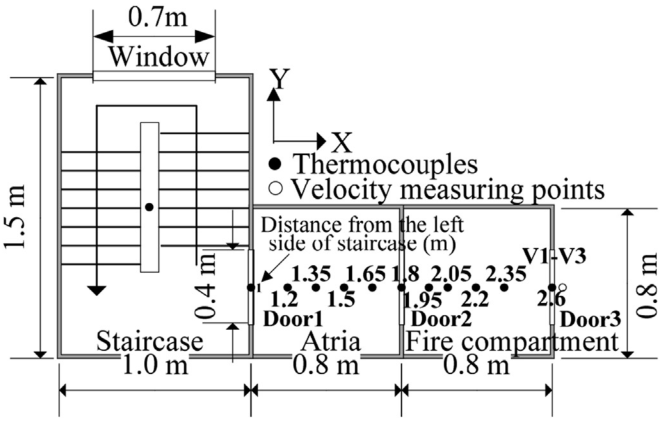
2. Experiments

Experiments in full scale are expensive that limit the numbers of tests. With reduced-scale experiments, more tests may be carried out [17]. To ensure that the results can be extrapolated to full scale, Froude modeling was applied to build up the model which is widely used in fire research [18–20]. For a perfect scaling, all of numbers, e.g. the Froude number, the Reynolds number and the Richardson number, should keep the same in the model scale as in the full scale. But in most cases it is not possible. It is often enough to focus on the Froude number. By holding the Froude number constant, the scaling laws are $\frac{Q_m}{Q_f}=\left(\frac{L_m}{L_f}\right)^{5/2}$, $\frac{m_m}{m_f}=\left(\frac{L_m}{L_f}\right)^{5/2}$, $\frac{u_m}{u_f}=\left(\frac{L_m}{L_f}\right)^{1/2}$ and $\frac{T_m}{T_f}=\left(\frac{L_m}{L_f}\right)^{0}$. Where Q is the heat release rate, m is the mass loss rate, u 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. Froude modeling does not account for conduction and radiation therefore the heat transfer mechanisms were predominantly convection [21].

The experiments were conducted based on one type of multi-storey buildings in China. In the multi-storey building, the stairwell is in the center of it and the residents are on both sides of the stairwell. There are always electric bicycles and bicycles storing under the stair step in the 1st floor. The electric bicycle may be on fire when it was charging. The 1/3 scaled building model consists of a staircase with solid ceiling, an atrium and a fire compartment as shown in Fig. 1. The model is 12.2 m high, 2.6 m long and 1.5 m wide. The staircase has 12 floors. The ground floor is 1.2 m high and the other floors are 1.0 m high. The cross-sections of staircase, atrium and fire compartment are respective 1.5 m × 1.0 m, 0.8 m × 0.8 m, 0.8 m × 0.8 m. There is a window at the back wall of the staircase in each floor with a size of 0.9 m high by 0.7 m wide. The first floor has three doors with a size of 0.6 m high by 0.4 m wide connecting the staircase, atrium and fire compartment. Most of the model is made of 2 mm thick steel plate apart from the left and front sidewalls which are made of 12 mm thick fire-resistant glass for experimental observation. The 8 mm thick fireboard is used as the inner lining in the fire compartment and atrium for thermal insulation.



(a) building structure diagram



(b) top view

Fig. 1. Schematic of 1/3 scaled staircase building model.

As shown in Fig. 1, a column of twelve 1 mm K-type thermocouples were arrayed in the vertical centerline of the stairwell. The interval of two thermocouples was 1 m. The lowest one is 1.05 m high. Fifty-five thermocouples and three velocity probes of hot-