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Influence of relative location of two openings on fire and smoke behaviors in stairwell with a compartment

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ABSTRACT

Opening conditions in stairwells will affect the fire and smoke behaviors in connected compartments and stairwells in high-rise buildings. A series of experiments was conducted to investigate the influences of relative location of two openings on fire behaviors in the adjacent compartment and smoke flow characteristics in the stairwell. In the experiments either the lowest (1st floor) or the highest (12th floor) vent in the stairwell was maintained open while one of the other vents was opened to create different ventilation conditions. The results show that when the 12th floor vent was opened the large pool fires might lead to ghosting flames. The burning rate per unit area in these experiments can be divided into four stages which are the early steady burning, the boiling burning, the ghosting flame and the decaying stages. Thus the experiments without ghosting flame involve only three stages. The burning rates at the boiling burning stage are 3.7 ~ 9.7 times of the burning rates at the early steady burning stage. A parameter λ taking into account the burning rate in open space is introduced to determine the control mechanism of combustion. The smoke flow pattern in the stairwell is dominated by respective the stack effect when the 1st floor vent was opened and the turbulent mixing when the 12th floor vent was opened. Although the maximum temperature distributions at the stairwell centerline decline exponentially with height, different smoke flow patterns result in different distribution trends.

1. Introduction

In recent years, the increasing high-rise building fires have caused numerous casualties, such as the high-rise residential building fire in Shanghai, 2010, leading to 58 fatalities [1]. Usually there are many vertical shafts in high-rise buildings, such as stairwells, elevator wells, ventilation ducts and even tall atrium can be regarded as shafts. The hot smoke might spread rapidly to other floors through these shafts during fires [2–4]. Statistics have shown that smoke is the most hazardous threat to the occupants and most of fatalities were caused by the hot and toxic smoke in building fires [5]. Therefore, it is worthwhile studying the fire and smoke behaviors in the shafts, especially the stairwells due to their egress path function during fires.

For stairwells with large height-to-width ratio, two mechanisms are primarily responsible for the internal buoyant flow [6]. The first one is stack effect induced by pressure difference generated by the density difference of hot and cold airs respectively inside and outside of the stairwell. The stack effect is normally formed when the indoor temperature is higher than the outdoor temperature and the fresh air flows into the stairwell from the lower opening and smoke flows out from the upper opening. On the contrary, the reverse stack effect forces the air to flow at an opposite direction [2,7,8]. As reported by Qi et al. [9], fire-induced smoke may arrive at higher levels easily via the vertical shafts driven by stack effect. The second mechanism is the turbulent mixing which relates to the Rayleigh-Taylor mixing process and leads to a rapid mixing between the upper layer of cold gas and lower layer of hot gas [6].

A large amount of researches have accounted for the two mechanisms separately over the past decade [3]. The previous studies on stack effect have mostly focused on its impacts on the crucial properties with respect to building fires such as the neutral plane [2,10,11] and gas temperature [2,12,13]. Klote [10] developed a computer program to estimate the neutral plane height by assuming uniform gas temperature in shafts. Zhang et al. [11] indicated that the Klote model was only suitable for fire-free condition, thus they further developed a two-zone model to determine the location of neutral plane. Li et al. [2] conducted theoretical analysis and experimental study on the location of neutral plane in

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stairwells with multiple openings and suggested that the neutral plane height depended on the middle opening location rather than the heat release rate (HRR). Benedict [12] reported that the temperature in a shaft would reach steady state under constant HRR. Xu [13] concluded that temperatures in a shaft at quasi steady state decreased exponentially with height. Furthermore, Ergin-Özkan [14] studied the effect of opening size on the flow behaviors and energy transfers in a stairwell via two fixed openings. Compared to lots of studies on stack effect, less attention has been paid to the turbulent mixing. Cannon and Zukoski [15] demonstrated that the turbulent diffusivity coefficient was a function of density gradient, gravity and construction of the shaft. Shi et al. [3] pointed out that both stack effect and turbulent mixing are primarily responsible for the vertical movement of hot smoke in stairwells. Shi et al. [3] carried out small-scale experiments and claimed that the turbulent mixing plays a significant role in smoke movement at early steady burning stage while the stack effect becomes dominant at the later stages.

The former researches indicate that opening conditions in stairwells have great impact on both stack effect and turbulent mixing processes, thus further affect fire behaviors and smoke movement. Nevertheless, the previous studies have mainly focused on the conditions where the bottom vent was maintained opened while the top vent was either opened or closed. Little effort has been put with respect to the effect of relative location of two openings on the fire development process. Therefore the current work is conducted to study the effect of relative location of two openings on the fire and smoke behaviors. The comprehensive impact of fire-induced stack effect and turbulent mixing on flame shape and smoke temperature in the stairwell is investigated. The scope of current study is to help engineers and researchers to obtain deepened insights into the fire and smoke behaviors in high-rise building fires.

2. Experimental setup

The experiments were conducted in a 1/3-scale stairwell model with 12 floors. Froude modeling was applied to build up the physical model, which has been regarded as an effective way to study the fire and smoke behaviors. The dimensional relationships between the fluid dynamics variables were derived from first principles by Morgan et al. [16] and also reported in NFPA 92B [17]. By maintaining the Froude number constant, the relationships can be simplified to obtain the required scaling laws [18,19] which are

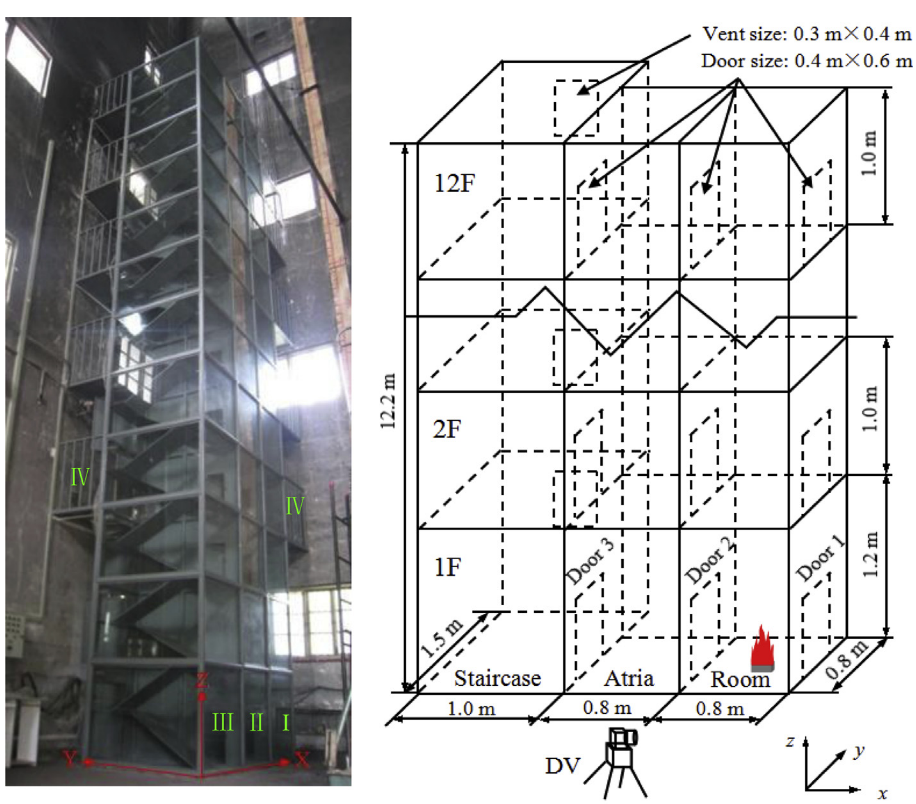
$$\frac{Q_m}{Q_f} = \left(\frac{L_m}{L_f}\right)^{5/2} \tag{1}$$

$$T_m = T_f \tag{2}$$

$$\frac{V_m}{V_f} = \left(\frac{L_m}{L_f}\right)^{1/2} \tag{3}$$

where, Q is the heat release rate (HRR), T is the temperature, V is the velocity, L denotes the model size and L_m/L_f is the similarity ratio. The subscript 'f' and 'm' denote the full and model scale parameters respectively.

Fig. 1 shows the experimental setup. The model consists of rooms (I), atria (II), a staircase with continuous steps (III) and operating platforms (IV) [20], as shown in Fig. 1a. Fig. 1b illustrates



(a) Picture of the scaled model **(b) Simplified schematic of the scaled model**

Fig. 1. Experimental rig.