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Experimental investigation on the characteristics of buoyant plume movement in a stairwell with multiple openings

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ABSTRACT

A set of burning experiments were conducted in a 1/3 scale stairwell to investigate the characteristics of fire induced buoyant plume movement in a 12-storey stairwell with three vents. Results show that the temperature of fire plume generally decreases with height in the stairwell on the steady state, and the distribution of smoke temperature in stairwell is mainly determined by the heat release rate (HRR) of fire source. The variation trends of temperature and velocity profiles measured at the middle opening were used to determine the location of neutral plane, and the determined results were confirmed by the pictures of flow field (lightened by the laser sheet). Based on the temperature distribution in stairwell and theoretical analysis, the location of neutral plane in the stairwell was calculated and the results were in good agreements with experimental results. The location of the neutral plane was mainly affected by the height of the middle opening. For cases with the same middle opening, the heat release rate of fire source weakly affected the location of neutral plane. Based on experimental results, the discharge coefficient of the stairwell with three openings (0.41) was obtained.

1. Introduction

In the last decades, many skyscrapers have been constructed all over the world. Fire safety of these buildings has drawn public attention due to the occurrence of many catastrophic fires. Statistics showed that smoke and toxic gases, such as carbon monoxide, are the most fatal hazard to the people in fires [1,2]. Modern high rise buildings generally have vertical shafts, such as stairwells, elevator shafts, ventilating ducts and atriums [3,4]. When a fire occurs in a high rise building, hot smoke will spread from fire floor to other floors through these shafts in the building, threating the people's safety [5–9]. Such as The MGM Grand fire occurred in 1980 at the USA, killing 85 people, most of them located on the upper floor far from the fire source, killed by the toxic smoke [10], and the fire in Dong Du commercial building in 2000 at Luo Yang, killing 309 people, the fire broke out on the subbasement, most victims were on the fourth floor [11]. When smoke spread into the vertical shafts (stairwell, elevator well, pipe well), it can spread very fast if the stack effect forms. Stack effect is the phenomenon caused by pressure difference between the bottom and upper opening of the shaft, due to the temperature difference between the gas in the shaft and the air in the outer atmosphere. If average indoor temperature is higher than the outdoor one, the normal stack effect forms, air flows into the shaft from the bottom opening and flows out from the upper opening. However, if the air is hot outside, air flows into the shaft from the upper opening and flows out from the bottom opening. This is called reverse stack effect [12–14].

When fire induced smoke flowing into the stairwell, the temperature inside will be higher than outside, and the normal stack effect will form. Inside the stairwell, a horizontal plane exists where the pressure inside equals to the one outside, which is called the neutral plane. Below the neutral plane, the pressure inside a building is lower than the one outside, leading air to flow into the shaft from the opening below the neutral plane. Inversely, above the neutral plane, the pressure inside is higher than the one outside, and the smoke will flow out from the opening above the neutral plane, threatening the people on the upper floor. This is the reason that there are a lot of victims located on the upper floor far away from fire source in many fires.

A number of studies have been focused on the gas flow, pressure distribution and temperature distribution in vertical shafts in the last decades. Tamura [15] summarized the influence of stack effect on the characteristics of pressure distributions and fire induced smoke movement in high rise buildings and concluded that the distribution of openings influenced significantly the pressure distribution inside the vertical shaft. Chow and Zhao [16] discovered that the hydrostatic equations were suitable to calculate the pressure distribution in vertical shafts. Klote [17] assumed that the smoke temperature in vertical shafts is uniform and developed a computer program for estimating the location of the neutral plane. His results showed that the location of the neutral plane of vertical shaft with two openings depend weakly on air temperature but

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Nomenclature

C_D	discharge coefficient
$f_1(h)$	mass flow rate at the bottom opening (kg/s)
$f_2(h)$	mass flow rate at the middle opening (kg/s)
$f_3(h)$	mass flow rate at the top opening (kg/s)
$f(h)$	mass flow rate at the openings (kg/s)
H	height of the stairwell (m)
H_m	height of the middle opening (m)
H_x	height of the neutral plane (m)
N	constant presents the direction of flow (m)
P_{atm}	atmospheric pressure (pa)
Δp_1	pressure differences between inside and outside at the bottom opening (Pa)
Δp_2	pressure differences between inside and outside at the middle opening (Pa)
Δp_3	pressure differences between inside and outside at the top opening (Pa)
R	specific gas constant for air (J kg^{-1} k^{-1})
s_1	inflow area at the bottom opening (m^2)
s'_2	inflow area at the middle opening (m^2)
s''_2	outflow area at the middle opening (m^2)
s_3	outflow area at the top opening (m^2)
T_s	temperature of the fire plume (K)
T_0	temperature of the air (K)
v_1	velocity at the bottom opening (m/s)
v_2	velocity at the middle opening (m/s)
v_3	velocity at the top opening (m/s)

Greek symbols

θ	dimensionless temperature rise
ρ_0	density of air (kg/m^3)
ρ_s	density of buoyant plume (kg/m^3)

Subscript

1	bottom of stairwell
2	middle of stairwell
3	top of stairwell

strongly on size of openings. Zhang et al. [18] proposed one model for predicting the location of the neutral plane inside vertical shaft of a building under fire situation. In his model, the shaft space was divided into two zones, fire zone and inner space. The temperature was assumed uniform in each zone.

Many different models for predicting the neutral plane of the shaft have been proposed in previous studies. However, few studies have been focused on the fire induced smoke movement in stairwells. Sun [19] investigated the smoke movement in a full-scale six-storey stairwell and found that the smoke temperature in the stairwell generally decreased exponentially with height. Peppes et al. [20,21] studied the flows of mass and heat between the floors of the building connected with stairwell, and proposed formulas to predict the mass and heat flow rate. Ergin-Özkan et al. [22] conducted an experimental study on buoyancy driven flow between lower and upper compartments of a stairwell model with through flow via two small openings. Results showed significant influence of the opening size on the fluid flow and energy transfers within the stairwell. The smoke movement in stairwells is different with that in vertical shaft. The smoke is not only confined with the sidewalls but also the continuous treads. Therefore, the physical mechanisms of smoke spread in stairwells are more complex than that in vertical shafts without treads, such as lift shafts and ventilation shafts. Former studies mainly focused the vertical shafts with two openings [14,18,20–24]. However, in actual situation, especially in high rise buildings, the stairwell generally has more openings. In this paper, a set of experiments were conducted to study the influence of fire source and location of opening on the temperature distribution and the location of the neutral plane in stairwells with multiple openings.

2. Experimental setup

The experimental layer out is shown in Fig. 1. The dimension of the building model with 12 levels is 12.2 m high, 2.6 m long, and 1.5 m wide. The ground floor is 1.2 m high and the other floors are 1.0 m high. The left and front sidewalls of model are fire-resistant glass (12 mm thickness) for observation, and the other parts are constructed of steel plates with thickness of 2 mm. The cross-sections of stairwell, atria and room are respectively 1.5 m × 1.0 m, 0.8 m × 0.8 m, 0.8 m × 0.8 m Each floor has three doors with the size of 0.6 m (height) × 0.4 m (width). There is one top vent with size 0.6 m (height) × 0.7 m (width) on 12th floor. In experiment, the doors on the ground floor and the top vent on the 12th floor were always open and the three doors on the floor from the 2nd floor to the 11th floor were opened respectively in different cases.

As shown in Fig. 1, a column of 10 thermocouples (K-type) were arrayed in the vertical centerline of the stairwell. The interval of two thermocouples was 1 m. The lowest one was 2.05 m high, and the highest one was 11.05 m high. Four velocity probes were positioned at the door of the stairwell on the ground floor, and the interval of two probes was 15 cm. A column of 10 thermocouples (K-type) and four velocity probes were arrayed at the door of the stairwell on the middle opening, the interval of two thermocouples was 6 cm, and the interval of two velocity probes was 15 cm. The ambient temperature was about 16–20 °C.

As shown in Table 1, a total of 77 tests were carried out. A propane gas burner was used to simulate the fire source to provide steady heat release rate located at the center of the stairwell on the ground floor. The heat release rate of the fire was determined by multiplying the measured gas flow rate into the burner by the heat of combustion, which was taken as 46,350 kJ/kg for the propane fuel used in the study [25]. The amount of fuel fed to the burner was monitored using a rotameter with a 0–0.00069 m^3/s of air range for fires up to 40 kW and 0–0.0017 m^3/s of air range for fires greater than 40 kW. The gas burner is square with side length of 0.4 m. Seven different heat release rates were used with fire power from 12 kW to 94 kW, for a full scale equivalent using the scaling laws [26,27], these equated to fire power range from 184 kW to 1.5 MW. There was little yield of smoke particles during the combustion of propane at a well-ventilated condition. For the purpose of flow visualization, an ignited smoke cake (which is made from sulfur and saw foam) was placed over the fire source. The smoke particles generated by the smoke cake acted as tracers.

3. Results and discussion

3.1. Air velocity at the bottom opening

When a fire occurs, air enters into the stairwell through the three opened doors on the ground floor. As shown in Fig. 2, in the case when only the ground opening and top opening are open, fire-induced smoke moves upward in the stairwell and flows out from the top opening. When there are three openings in the stairwell, located on the ground floor, between the 2nd floor and 11th floor and on the top floor respectively, air will flow into the stairwell through the ground floor and smoke will flow out from the top vent. The flow patterns at the middle opening can be divided to three cases. As shown in Fig. 3(a), when the neutral plane is higher than the middle vent, air will flow into the stairwell from the middle