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Experimental investigation on the rising characteristics of the fire-induced buoyant plume in stairwells

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ABSTRACT

A set of burning experiments were conducted in a 1/3 scale stairwell to investigate the rising characteristics of fire-induced buoyant plumes in stairwells. Results show that the time for the front of a buoyant plume to reach a given height from a fire source is inversely proportional to the 1/3 power of the heat release rate and proportional to the 1.203 and 2.129 power of the height in the stairwell with top vent open and closed, respectively. The relations between dimensionless rise-time of fire plume front and dimensionless rise-height in stairwells are proposed to predict rise time of fire plume fronts. The vertical distribution of temperature in the stairwell with top vent open at steady state was investigated and results show that the attenuation coefficient is inversely proportional to the mass flow rate in the stairwell. Discharge coefficient of the stairwell was calculated based on the air velocity at the openings of the stairwell and the temperature distribution in the stairwell. The average value of discharge coefficients is 0.23, indicating larger resistance to influence the rising of fire plume in the stairwell due to the block of the stairwell treads.

1. Introduction

Many skyscrapers have been constructed in china with the economic development. With the increasing of high-rise buildings, the number of high-rise building fires increased and caused many disasters, such as the fire in a residential building on Jiaozhou road in Shanghai in 2010, killing 58 people [1]. Statistics showed that more than 80 percent deaths in fire were caused by toxic gases, such as carbon monoxide [2–5]. Therefore, in case of fire, it is very important to control the spreading of smoke. There are many vertical wells in high-rise buildings, such as elevator wells and stairwells. These wells may be paths for smoke spread in case of fires. When the smoke enters into the wells, it can spread very fast if the stack effect forms and threat the safety of upper residents. The stack effect can suck more fresh air to the fire room, and may make small fire become larger quickly [6–8]. Therefore, the study on smoke motion in these wells may benefit the current design of smoke management system and complement the current codes on high rise buildings.

Two physical mechanisms are primarily responsible for vertical motion of buoyant gas within a vertical shaft [9]. The first mechanism is the stack effect [10] which results from the difference in density between inside gas and atmosphere air. The second mechanism is turbulent mixing process [9,11], which is related to the Rayleigh–Taylor mixing process. Recently, a number of researchers have investigated the smoke motion in vertical shafts. Marshall [8,12] experimentally studied air entrainment and smoke motion in open shaft and stairwell, and developed one empirical model for predicting air entrainment. Cannon and Zukoski [13] studied the turbulent mixing in one closed shaft and developed one relationship between smoke rise time and the ratio of initial density difference between fluids inside and outside of the shaft. Water/salt-water experiments were conducted to verified the model. Cooper [11] further investigated the turbulent mixing in room configurations with large height-to-span ratios, and developed model equations to simulate smoke movement. These equations were verified by comparisons between solutions and previously published data from unsteady experiments in long vertical tubes. Tanaka et al. [14] conducted experiments to investigate the rise time of fire-induced buoyant plumes in the free space and in vertical shafts. Sun [15] developed a theoretical model for predicting buoyant plume rise in a vertical shaft, and conducted small scale experiments and corresponding CFD simulations to validate the theoretical model.

However, few studies have been focused on the buoyant plume rise in stairwells. Sun [15] conducted experiments and CFD simulations to investigate the smoke movement in a full-scale six-storey stairwell and concluded that the smoke flow moved upward in circular patterns and the smoke temperature decreased exponentially with height in the stairwell. Peppes et al. [16,17] experimentally and numerically studied the flows of mass and heat

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Nomenclature

A	horizontal section area (m^2)
C_D	discharge coefficient
C_p	specific heat of air at constant pressure (kJ/kg K)
D	characteristic length (m)
g	acceleration due to gravity (m/s^2)
h	convective heat transfer coefficient (W/m^2 K)
ΔH	heat of combustion (kJ/g)
H	height of the shaft (m)
L	non-dimensional travel height
$\dot{m}_{shaft}$	mass flow rate in shaft (kg/s)
$\dot{m}_{stairwell}$	mass flow rate in stairwell(kg/s)
Δm	mass loss rate (g/s)
P_{atm}	atmospheric pressure (Pa)
ΔP_a	pressure difference between the neutral pressure level and the lower opening (Pa)
ΔP_b	pressure difference between the neutral pressure level and the higher opening (Pa)
Q	heat release rate (kW)
R	specific gas constant for air (J/kg K)
s_a	area of the open at the bottom of the stairwell (m^2)
s_b	area of the open at the top of the stairwell (m^2)
t	travel time (s)
T	temperature of the fire plume (K)
T_0	temperature of the air (K)
v_a	averaged velocity of flow into the stairwell (m/s)
v_b	velocity of the buoyant plume flow (m/s)
z	distance from the fire source (m)

Greek symbols

β	attenuation coefficient
λ	combustion efficiency
θ	dimensionless temperature rise
ρ_a	density of air flow into the stairwell (kg/m^3)
ρ_b	density of buoyant plume (kg/m^3)
ρ_0	density of air (kg/m^3)

Subscript

a	bottom of stairwell
b	top of stairwell
f	full-scale stairwell
m	model stairwell

between the floors of the building. Ergin-Özkan et al. [18] 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. Qin et al. [19] numerically investigated smoke movement and ambient airflow in a stairwell. Results showed that under different fire scenarios, there were fairly distinct layers of hot smoke and ambient air and the heat release rate had a remarkable effect on distributions of smoke temperature, velocity and oxygen concentration.

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. A set of experiments were conducted to study the rise characteristics of smoke in one stairwell model. Based on the experiment results, formulas to predict rise time of fire plume fronts in stairwell were proposed, which may be benefit the current design of smoke management system in a high-rise building. The vertical distribution of temperature in the stairwell with top vent open at steady state was investigated and discharge coefficient of the stairwell was calculated based on the temperature distribution in the stairwell and the air velocity at the openings of the stairwell, which may give benefit for people to further understanding the smoke spread in stairwell.

2. Experiments

The approach of physical scale modeling is well established and has been used in many researches of smoke movement in fire scenario [20–23]. The idea of applying similar model to fire research was first proposed by Thomas et al. [24], after the development and improvement of the later scholars [25,26], the approach of physical scale modeling has evolved into an effective way to study the phenomenon of fire and smoke. Measurements in this study are made of temperature, velocity and the mass loss rate. To ensure that the results can be extrapolated to full scale, the Froude modeling was applied with the requirements for the equivalent flows fully turbulent on both full and model scale [24]. Turbulent flow is typically achieved for flows with Reynolds numbers ⩾4000 [27]. In these experiments the Reynolds number of the smoke plume within shaft was determined, with values ranging from approximate 5000 to 20000, indicating the series of experiments using physical scale model in this study is appropriate. The dimensional relationships between the fluid dynamics variables were derived from first principles by Morgan et al. [28] and also included in NFPA 92B [26]. By holding the Froude number constant, the relationships can be simplified to obtain the required scaling laws:

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

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

$$T_m = T_f \quad (3)$$

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

Fig. 1 shows the 1/3 scale physical scale model which can simulate a fire in a stairwell. The dimension of the building model with 12 levels is 12.2 m high, 1.5 m long and 1.0 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 ground floor has a door with the size of 0.53 m (height) × 0.655 m (width). The 12th floor has a door with the size of 0.835 m (height) × 0.645 m (width). The oil pan was position on one platform located on the stairwell treads, at height of 0.6 m.

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 is 2.05 m high, and