International Journal of Thermal Sciences 89 (2015) 264–271

Contents lists available at ScienceDirect

International Journal of Thermal Sciences

journal homepage: www.elsevier.com/locate/ijts

Transport characteristics of thermal plume driven by turbulent mixing in stairwell

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ARTICLE INFO

Article history:
Received 17 May 2014
Received in revised form
17 November 2014
Accepted 17 November 2014
Available online 11 December 2014

Keywords:
Turbulent mixing
Thermal plume
Transport characteristics
Shaft
Stairwell

ABSTRACT

A set of experiments was conducted to study the transport characteristics of thermal plume driven by turbulent mixing in a 1/3 scale stairwell with single opening. The opening location was varied at the stairwell height direction to obtain different air supply conditions. When the thermal plume moves upwardly in the vertical stairwell, the interface between the upper cold layer and the lower hot layer is unstable. The gravitational instability leads to the turbulent mixing in the two layers. The location of the thermal plume front is determined using the temperature increases at different measuring points. Based on the dimensional analysis, the plume front location can be expressed as a function of time and effective gravitational acceleration. The velocity of thermal plume in stairwell is lower than those in hollow shafts, resulting from the block and cooling effects of stair steps. The comparison of the experimental and calculated plume front locations shows good agreement with the maximum error less than 20%. The results could improve the understanding of thermal plume movement driven by turbulent mixing in stairwells.

1. Introduction

Disastrous high-rise building fires, which occurred frequently in recent decades, have drawn more and more public attentions to the fire safety in high-rise buildings. During fires, large amount of smoke and toxic gases will be produced threating the occupants [1]. A notable example is the MGM Grand Hotel fire in Las Vegas in 1980 [2] where 85 fatalities were identified. Moreover, the statistics have shown that the fire-induced smoke is the most fatal threat in building fires, and about 85% of fatalities were caused by the hot and toxic smoke [3–5].

There are many vertical shafts in high-rise buildings, such as stairwells, elevators shafts, ventilating ducts and electric cable shafts. These shafts will become the potential paths of smoke spread during fires. There are two mechanisms mainly responsible for vertical motion of thermal plume in vertical shafts, i.e. turbulent mixing and stack effect [6].

Stack effect is the air movement driven by the air density difference between the exterior and the interior building spaces [7,8]. Many previous studies [9–19] have been conducted on the fire-induced smoke movement driven by stack effect in vertical shafts, including the neutral plane position [13,14], rising characteristics of thermal plumes [15,16], distribution of pressure and temperature [17,18].

When thermal plume moves upwards in shafts without stack effect, it is mainly driven by the turbulent mixing related to the Rayleigh-Taylor mixing process [20–24]. In the shafts, the thermal plume fills out the whole cross-section of shaft and causes a hot layer with low density gases. The interface between the colder-denser upper layer and the hotter-lighter lower layer is unstable. The gravitational instability will lead to a mixing between the two layers [6]. The process is different from the rising of thermal plume in open space driven by the buoyancy. Limited work has been conducted on the process of turbulent mixing. Zukoski [6] studied the turbulent mixing process using the salt-water experiment and proposed an empirical model to predict the relationship between rise time and height of the disturbance front. Cooper [25] further investigated the turbulent mixing in shafts with large height-to-span ratios, a set of equations was developed to simulate the combined buoyancy and ventilation driven flow through long vertical shafts. The equations were validated using Zukoski's [6] and Cannon's experimental results [22,23]. Benedict [26] studied the mixing process experimentally and found that the location of initial front was expected to be a function of density ratio, channel

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http://dx.doi.org/10.1016/j.ijthermalsci.2014.11.009

width, gravity and time. Kumar et al. [27] numerically studied the unsteady, laminar, buoyant flow through a horizontal rectangular vent connecting two large enclosures. They found that a plume rose steadily into the upper chamber, forcing the colder fluid to move along the sidewalls. Harish et al. [1] numerically investigated the fire-induced turbulent flow characteristics in a tall vertical shaft connected to an adjacent rectangular compartment. They found that the flow patterns in vertical shaft represented multi-recirculating convective cells with effective turbulent mixing due to buoyancy, which revealed that plume transport were different from room fires. Shi et al. [28] found that the turbulent mixing affects hot smoke movement strongly before the stack effect takes place in a 1/3 scale stairwell. Ji et al. [16] conducted burning experiments in a small scale stairwell with an opening at the first floor and found that the rise time of thermal plume is inversely proportional to the 1/3 power of the heat release rate. Li et al. [29] took the convective heat transfer through the sidewalls into consideration and proposed a new model to describe the one-dimensional turbulent mixing process in closed vertical shafts.

In previous studies, the experiments on the smoke movement induced by the turbulent mixing were conducted in shafts with only one opening at the bottom. If the opening height increases, the different amount of ambient air flowing into the stairwell will influences the combustion process and turbulent mixing movement of fire-induced smoke. However, the effect of the opening height on the upward movement of smoke in stairwells has not been addressed previously. In this paper, a set of experiments was conducted to investigate the influence of changing opening height on the rising characteristics of thermal plume induced by the turbulent mixing.

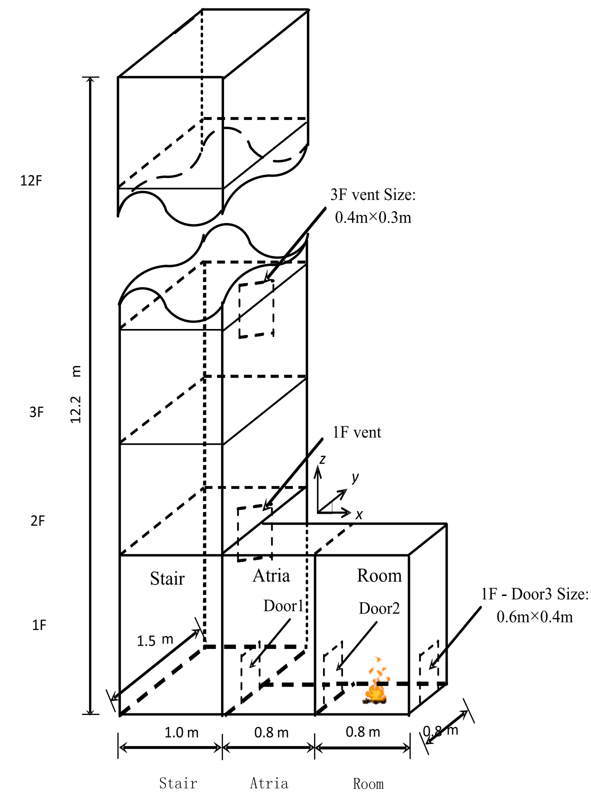

Fig. 1. Schematic of 1/3 scaled stairwell building model.

2. Experimental arrangement

The experiments were conducted in a 1/3-scale stairwell model [30] with 12 floors. A sketch of the experimental rig is shown in Fig. 1. As shown in Fig. 1, the ground floor is 1.2 m high and the other floors are 1.0 m high. The cross-sections of stairwell, atria and compartment are 1.5 m × 1.0 m, 0.8 m × 0.8 m and 0.8 m × 0.8 m, respectively. The first floor has three doors with a size of 0.6 m high by 0.4 m wide connecting the stairwell, atria and compartment. Most of the experimental rig was made of 2 mm thick steel plate apart from the left and front sidewalls which were made of 12 mm thick fire-resistant glass for observation purpose. The 8 mm thick fireboard was used as the inner lining in the fire compartment and atria for thermal insulation.

Twenty-four K-type fine wire thermocouples were set at the centerline of the stairwell, as shown in Fig. 2. The response time of the thermocouple is 1 s. The uncertainty of these thermocouples was within 1.5 °C per 100 °C. Heptane pool fires were used as fire sources which were located at the center of the compartment on the ground floor. The side length of square pool was respective 10 cm, 15 cm and 20 cm and the depth was 4 cm. The initial thickness of fuel in the pool was 2 cm for each experiment. The mass of burning pool fires was recorded by a digital electronic balance with a resolution of 0.01 g. The ambient temperature was 15 °C–17 °C.

In the experiments, Door 1 was always open and Door 3 remained closed. There is a vent at each floor with a size of 0.4 m high by 0.3 m wide. The vent located at the 1st, 3rd, 6th and 9th floor in the stairwell was open respectively in different cases. 12 cases were carried out as shown in Table 1. Typical cases were repeated once and the repeatability of the measured temperature was determined to be less than 11%, which indicates that the repeatability was good. More details can be seen in Ref. [31].

3. Results and discussion

3.1. Rising characteristics of the smoke plume

In the cases with the vent opened at the 1st floor, the oxygen is sufficient for combustion. In the cases with the open vent at respective 3rd, 6th or 9th floor, the fresh air enters the stairwell via the vent and moves downwardly along the stairwell while the hot smoke moves upwardly, resulting in a counter flow and insufficient oxygen in the fire room. The temperatures at the vertical centerline of the stairwell versus time are shown in Fig. 3. Only twelve out of 24 thermocouples are shown in Fig. 3 due to the readability reason. From Fig. 3, in the cases with the same vent open, the peak values of thermocouples increase with pool sizes. In all the cases, the maximum temperature measured by the thermocouple tree has always taken place at 1.05 m high instead of the lowest point at 0.45 m high and then the vertical temperatures decrease with increasing height. The temperature at 0.45 m remained at the ambient temperature at the early stage in all cases. At the early stage, the smoke plume flows out of the fire room and enters into the stairwell with a tilted angle. Under the impact of continuous steps in the stairwell, smoke moves upward spirally [29]. The measuring point at 0.45 m high is lower than the upper edge of the Door 2 (0.6 m high) and may not has any contact with the smoke plume at the early stage therefore the measured temperature is relatively low. In the region higher than 1.05 m, the smoke temperature decreases significantly with the increasing height, resulting from the cooling effect of the steps and walls in the staircase and the mixing with cold air.

For the same pool size, time histories of the temperatures vary slightly in the cases with different open vent height. Taking cases with 20 cm pool as an example, when the vent at the 1st, 3rd, 6th and 9th floor is open respectively, as shown in Fig. 3c, f, i and l, the