International Journal of Heat and Mass Transfer 115 (2017) 706–716

Contents lists available at ScienceDirect

International Journal of Heat and Mass Transfer

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

Froude-Stanton modeling of heat and mass transfer in large vertical spaces of high-rise buildings

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ARTICLE INFO

Article history:
Received 6 June 2017
Received in revised form 19 July 2017
Accepted 11 August 2017

Keywords:
Scale modeling
Heat and mass transfer
Froude
Stanton
High-rise buildings

ABSTRACT

Understanding physics of heat and mass transfer inside large vertical spaces is a major challenge for high-rise fire safety. Due to the size of a high-rise building, experimental studies based on sub-scaled models play an important role in high-rise heat and mass transfer research. Froude modeling method is probably the most common approach for sub-scaling. However, Froude modeling has been found incapable of obtaining accurate temperature predictions from the sub-scaled experiments, especially near building boundaries where there exists significant heat transfer between smoke and the boundaries. In this paper, a new modeling method, Froude-Stanton modeling, is developed for both mechanically-driven and naturally-driven thermal smoke spreads, in which heat transfer is taken into consideration in the energy balance equation. The flow resistance of the internal shaft structure is also considered using a lumped method. To verify the new method, series of experiments were conducted on three shafts with different sizes and material using both Froude and Froude-Stanton methods. The results, including temperature profile, relative neutral plane level and thermal smoke flow rate, are compared between the two modeling methods, and it was found that the new Froude-Stanton modeling method is more accurate.

1. Introduction

According to the definition of National Fire Protection Association (NFPA), high-rise buildings are defined as buildings higher than 23 m [1] (roughly seven stories) while buildings higher than 150 m are often referred to as skyscrapers [2]. High-rise buildings have been a solution to the economic growth in highly populated metropolitans limited by land shortages, increasingly becoming a major indicator of economic prosperity around the world. It was reported that by July 2016, there are 43 skyscrapers in Toronto and 315 skyscrapers in Hong Kong [3]. The proper functioning of these huge man-made modern structures heavily rely on tall vertical spaces inside, i.e. shafts, more generally, or shaft-like spaces, for example, elevators and stairwells, and super tall and thin atria for utilizing natural lights/ventilations for energy conservation and human comfort concerns, e.g. the atrium in a 135-m-high building of Australia, and the 435-m-high building of China as shown in Fig. 1. Among all the technical hurdles for engineers setting up these high-rises, one of the major challenges is the fire protection in these buildings, especially in the tall and vertical shafts, where fire-generated smoke laden with toxic gases could spread far from fire origins deep throughout the buildings driven mostly by stack effect, endangering people's lives and causing property damages. Stack effect is the air/smoke movement through the vertical spaces due to a difference in air temperature and resultant air density between indoors and outdoors. The greater the temperature difference and the height of the structure, the greater the stack effect. The impact of the stack effect on the vertical smoke spread is also closely related to the internal flow resistance in the shaft. Statistics have shown that about more than 95% of the upward movement of fire smoke in high-rise buildings is through the large vertical spaces [4], which is a complicated coupled heat and mass transfer phenomena [5].

Many previous studies have been focused on the fire smoke spread inside large vertical spaces in buildings using computer modeling, such as computational fluid dynamics (CFD) [8,9], and/or sub-scaled experiments. Froude modeling, in which the Froude number is conserved between sub-scale and full-size models, is probably one of the most common approaches to modeling building fire protection. This scaling law was used by previous experiments, e.g. smoke movement in a corridor [10,11], a compartment [12] and an atrium [13]. Ding et al. [14] conducted a 1/25 scale experiment of a full-size building based on Froude modeling to collect measurement data for the validations of their CFD analysis of using the existing HVAC system for fire smoke controls.

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http://dx.doi.org/10.1016/j.ijheatmasstransfer.2017.08.030
0017-9310/

Nomenclature

A	cross section area of the shaft (m^2)
C_d	discharge coefficient
C_p	specific heat capacity of the smoke (J/(kg K))
D	characteristic length (m)
Fr	Froude number
Fr'	modified Froude number
g	acceleration of gravity (m/s^2)
h	heat transfer coefficient (W/(m^2 K))
H	height of the large vertical spaces (m)
m	model
$\dot{m}$	mass flow rate (kg/s)
NPL	neutral plane level
Q	heat release rate (kW)
p	pressure (Pa)
P	perimeter of the shaft (m)
R_t	thermal resistance between two sides of the shaft ((m^2 K)/W)
St	Stanton number
St'	modified Stanton number
T	temperature (K)
v	velocity (m/s)
W	thickness of the shaft wall (m)
x	height of interests (m)

Greek symbols

α	temperature attenuation coefficient
a^*	a constant of fitting smoke temperatures [24]
β	a constant of fitting smoke temperatures [24]
Δ	difference
γ	relative smoke temperature at the top of the shaft
η	normalized fire temperature
λ	thermal conductivity, W/(m K)
θ	normalized temperature
ρ	density (kg/m^3)
φ	relative height

Subscripts

0	ground level, the height of $x = 0$
a	atmospheric
b	bottom opening
f	fire; full scale
$horz$	horizontal
H	height of the shaft
np	neutral pressure
t	top opening
sh	shaft
i	interior wall surface of the shaft
o	exterior wall surface of the shaft

To investigate the hot smoke spreading in an atrium from an adjacent compartment fire, Harrison used Froude modeling in a 1/10 scale building model. The experimental results were also used to validate their CFD simulations [15]. Quintiere applied the scale modeling technique to investigate the performance of the smoke control system during an actual fire incident in the atrium of a department store so that a design flaw of the smoke control system was identified: the inlet air of the smoke pressurization system was so high to mix the fire smoke in the atrium, and spreading it throughout the whole space store [16]. Ji et al. built a 1/3 scale high-rise building model based on Froude modeling and conducted extensive tests on the effect of staircase ventilations on the smoke flow and heat transfer inside the heated room at the middle floor [17], and on the combustion conditions in the compartment connected to the staircase [18]. Chen et al. presented a mathematical model for predicting vertical temperature distributions in ventilation shaft. To validate the mathematical model, experiments were conducted on a 1/4 scale shaft, which was designed using Froude modeling [19]. However, Ding, Ji and Chen et al. did not verify Froude modeling in their chimney and stairwell shafts.

Meanwhile, it has been well recognized that Froude modeling is appropriate for scenarios that the smoke temperature is relatively lower near the walls and the heat transfer between smoke and the wall is not important [20]. Otherwise, Froude modeling may fail and lead to inaccurate temperature predictions. Using Froude modeling, Carey compared the temperatures at different locations between a full-size compartment and its 1/8 scale model, and found that the error varied with the distance from the fire origin and could be up to 50%, which, as he pointed out, was due to the fact that Froude modeling neglects heat transfer between the smoke and the walls [21]. Chow carried out a series of experiments of natural smoke filling process in a 27-m full-scale atrium and a 1/26.5 scale model. It was found that there existed significant deviations of temperatures measured in the full-size and the sub-scale model due to the negligence of heat transfer from the hot smoke to the surroundings by Froude modeling. Therefore, they suggested further examinations of the scaling law of using Froude modeling [22]. Due to the lack of appropriate scaling method that considers heat transfer, Froude modeling is still widely used to design small scale shafts in the researches though there exists heat loss to the shaft wall, such as the researches in the articles [19,23,24]. Some studies have been conducted on the scaling model that considers heat transfer through the wall for compartment fires but not high-rise fires. Andreozzi designed two different scale compartments by Froude modeling with the consideration of wall conduction, and modeled the compartments fires in CFD. It was found that temperature differences between the full and scaled models become larger when it approaches to the wall, which indicates that heat convection at the wall surface needs to be taken into account [25]. Lassus et al. developed a scaling method for a compartment

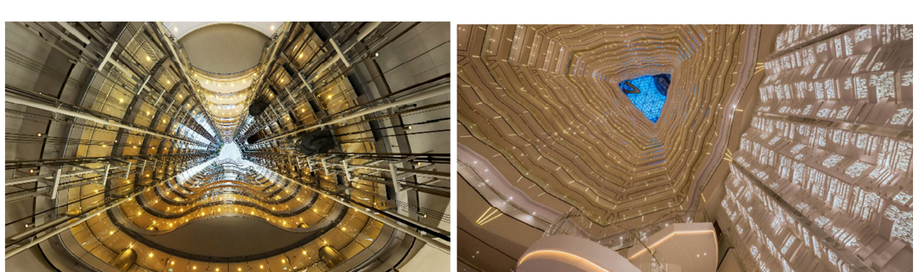

Fig. 1. Upward views in an atrium in a high-rise building of Australia [6] (left), and in a high-rise building of China [7] (right).