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Dimensionless analytical solutions for steady-state fire smoke spread through high-rise shaft

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ABSTRACT

Analytical solutions in terms of dimensionless numbers for the smoke spread through high-rise shafts during fires are essential to provide a fundamental understanding of smoke transport physics, which is a complex coupled heat and mass transfer problem. Existing solutions are often dimensional based on simplification of the problem such as assuming adiabatic conditions. In order to obtain the dimensionless analytical solutions, energy balance equation, mechanical energy equation and mass balance equation were established for smoke spread in high-rise buildings under both mechanical and natural venting conditions. Experiments were designed and conducted on two scaled shafts with different sizes and materials, and the measured results were compared to the dimensionless analytical solutions. It was found that the dimensionless analytical solutions could predict temperature profiles, mass flow rate and neutral plane level accurately. The effect of the adiabatic assumption on the accuracy was also discussed. For example, due to the adiabatic assumption, the error of the calculated mass flow rate required during mechanical venting to maintain a high-rise shaft smoke free was found to increase with a dimensionless number, ω, defined by the geometrical and thermal properties of the shaft.

1. Introduction

Fires in high-rise buildings are often disastrous, causing many injuries, fatalities and huge economic losses. Such notorious fires as the Winecoff Hotel fire at Atlanta, US (December 7, 1946) caused 119 deaths, and the MGM Grand Hotel fire at Las Vegas, NV (November 21, 1980) led to the deaths of 85 people and 600 injured [1]. A most recent high-rise fire, the 63-story Address Downtown Dubai Hotel fire, occurred on New Year's Eve of 2016, and continued to generate smoke on the next day even after the fire was put out [2,3]. Although luckily no deaths seem reported, the estimated repairs and business interruption exceeds $100 million dollars. Smoke generated from fires often spreads quickly throughout a building, often even faster than the fire itself, especially in a high-rise building, carrying toxic gases responsible for the majority of fatalities [4] with elevated temperatures causing spread damages of upholsteries and structures.

In typical high-rise buildings, about 95% or more of the upward movement of smoke attributes to the spreads through shafts [1], e.g. stairs, elevators, light wells, ventilation ducts. High-rise smoke control using pressurization systems becomes a popular option since the 1960s: by injecting clean air with mechanical fans into a shaft enclosure such that the pressure in the shaft is greater than the adjacent fire compartment, the pressurization systems are intended to prevent smoke leaking from its sources [5]. However, the pressurization systems have been found not to always work as expected, especially for high-rise shafts with strong stack effect, also known as chimney effect where shafts act like chimneys and smoke tends to spreads upwards due to buoyancy, and floor-to-floor variations in flow resistance [6]. It was estimated that 35% of pressurization systems might fail to function as intended [5]. A pressurization system often acts against the stack effect so its performance heavily relies on the strength of the stack effect, which could be subject to many variants, e.g. fire strengths and ambient weather conditions. An alternative approach is the use of shafts as smoke venting routes through which the smoke would be properly channeled to spread upwards, and eventually be exhausted at the top of the shafts to the outside of a building. Instead of fighting against the stack effect, this method of shaft smoke ventilation takes advantage of naturally-generated stack effect due to buoyancy, aided by mechanical fan systems when necessary, and thus gains much attentions lately.

These shaft smoke ventilation systems allow fire smoke to spread

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Nomenclature

A	area of opening (m^2)
A_c	cross-section area (m^2)
C_p	specific heat capacity of the smoke (J/(kg·K))
Fr	Froude number
H	height of the shaft (m)
f	dimensionless friction factor
h	heat transfer coefficient (W/(m^2·K))
$\dot{m}$	mass flow rate (kg/s)
p	pressure (Pa)
P	perimeter of the shaft (m)
R_t	thermal resistance between two sides of the shaft ((m^2·K)/W)
T	temperature (K)
v	velocity (m/s)
W	thickness of the shaft wall (m)
x	height of interests (m)

Greek letters

α	temperature attenuation coefficient
γ	relative smoke temperature at the top of the shaft
Δ	difference
η	dimensionless fire temperature
θ	normalized temperature
λ	thermal conductivity (W/(m·K))
ρ	density (kg/m^3)
ϕ	ratio of bottom opening area to top opening area
φ	relative height
ω	geometry and thermal factor
ψ	dimensionless mass flow rate

Subscripts

0	ground level, the height of $x = 0$
a	atmospheric
b	bottom
el	elevation in the shaft
H	height of the shaft
i	interior wall surface of the shaft
np	neutral plane
o	exterior wall surface of the shaft
sh	shaft
t	top
w	wall

through expectedly well-engineered routes of shafts so it is critical to understand the dynamic and thermal properties of the smoke along its route to the exit points, specifically smoke flow rates, smoke temperature and pressure distributions. Previous studies have been conducted using various experimental, mathematical and numerical techniques. Ji and Shi performed extensive experiments to investigate the transport characteristics of thermal plume in a ventilated stairwell with two or multiple openings [7–10]. Harmthy proposed a Fire Drainage System to remove the heat and induced convection smoke flow from a fire through a series of shafts to reduce the spread of fire from the region of fire source [5,11]. Design principles of this system were also introduced based on the assumption of constant gas temperature [11] but the heat transfer between the smoke and the shaft walls was not considered, i.e. under adiabatic conditions. Similar to the Fire Drainage System, the Beetham Tower system was developed to use an air inlet shaft to exhaust smoke from the fire floor aided by a mechanical fan system [5]. Klote studied the smoke ventilation control of stairwells in tall buildings by a tenability analysis based on computational fluid dynamics (CFD) and multi-zone network modeling. It was concluded that the stairwell smoke ventilation is a feasible approach [6]. Qi et al. [12] developed an analytical model of smoke movement in high-rise shafts. Different from other analytical models, heat transfer between smoke and the shaft boundaries was considered. Based on the analytical model, a hand calculation method and empirical equations were developed for the calculation of temperature distribution, mass flow rate and pressure inside the shaft [13,14].

However, most of the previous studies were conducted on specific buildings and shafts. As a result the generalization of the conclusions to other cases may need further verifications. Therefore, there exists a gap of research that the solutions to smoke flow rates, temperature and pressure distributions, preferably expressed in dimensionless analytical forms, should be developed for a better understanding of the thermal aerodynamics of shaft smoke ventilations. The dimensionless solutions could also benefit the research on the similitude and scale modeling analysis of a high-rise building, for which the sheer size of the structure often makes full-size tests impractical.

This paper reports the development of dimensionless analytical solutions of smoke spread in non-adiabatic high-rise shafts during fires. Conservation equations of thermal energy, mechanical energy, and mass were developed in dimensionless forms for both mechanical and natural smoke ventilations. A series of experiments were then conducted on two scaled shafts with different dimensions and materials, and used to validate the developed dimensionless analytical solutions by comparing temperature distribution, mass flow rate, pressure distributions, and neutral plane levels (*NPL*). As an example of demonstration, the dimensionless analytical solution developed in this study was applied to calculating the minimum mechanical venting rate required to maintain a full-size high-rise shaft free of smoke, and compared to the result if the conventional adiabatic assumption was used. The comparison helps to show the impact of the adiabatic assumption on the accuracy of the calculation.

2. Theory

Smoke spread inside high-rise shafts may be generalized by the schematic in Fig. 1. When mechanical smoke ventilation is used, a fan is installed at the top of the shaft. In comparison, the fan is replaced by an opening at the top for natural venting/ventilation of the smoke. The objective of this section is to develop dimensionless analytical solutions for these two venting systems, for which the following assumptions are used:

- A fire is located at the first floor of the building with a fire strength defined by the fire temperature.
- The outdoor air temperature and the building temperature at non-fire floors are constant.
- Specific heat capacity of the smoke, C_p, is constant.
- The smoke is assumed to be incompressible and viscous but thermally expansible satisfying the ideal gas law.
- No smoke leaks through shaft walls.
- Heat transfer coefficients (either due to convection or radiation) are constant and do not vary along the height of the shaft.
- The fire floor is not a large open space. Temperature of the fire floor is uniform and maintained at the fire smoke temperature [12].
- The smoke flow inside the shaft could be assumed as one-dimensional steady-state flow [8,12].
- The friction loss of the flow due to interior shaft wall is neglected [14].