Experimental Thermal and Fluid Science 79 (2016) 118–125

Contents lists available at ScienceDirect

Experimental Thermal and Fluid Science

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

Vertical temperature distributions in ventilation shafts during a fire

Yanqiu Chen [a], Xiaodong Zhou [a], Zhijian Fu [a,b,c], Taolin Zhang [a], Bei Cao [a], Lizhong Yang [a,d,*]

[a] State Key Laboratory of Fire Science, University of Science and Technology of China, Hefei, Anhui 230026, China
[b] School of Transportation and Logistics, Southwest Jiaotong University, Chengdu, Sichuan 610031, China
[c] National United Engineering Laboratory of Integrated and Intelligent Transportation, Southwest Jiaotong University, Chengdu, Sichuan 610031, China
[d] Collaborative Innovation Center for Urban Public Safety, Hefei, Anhui 230026, China

ARTICLE INFO

Article history:
Received 12 January 2016
Received in revised form 12 April 2016
Accepted 6 July 2016
Available online 7 July 2016

Keywords:
Ventilation shaft
Fire
Temperature distribution
Heat exchange
Wall
Exhaust rate

ABSTRACT

As fire smoke spreads in shafts, the affected area experiences a significant rise in temperature. Thus, calculating temperature distributions is of vital importance in understanding smoke motion in shafts during a building fire. Generally, the smoke temperature in a ventilation shaft is mainly affected in two ways: (i) heat exchange occurs between smoke flow and shaft walls, and (ii) a part of smoke is exhausted out of shafts from the top due to ventilation and another part of smoke is driven into the shaft from the bottom. However, these factors were usually ignored or partly considered in previous studies. This paper presents a mathematical model for predicting vertical temperature distributions in ventilation shafts. In this model, the influence of both shaft walls and ventilation is considered. A series of validation experiments were conducted under various exhaust rates. The experimental data agreed well with calculated results from the model: the mean error was around 1.62 °C.

1. Introduction

Vertical shafts are very common structures in buildings, which influence smoke motion considerably during a fire. Understanding fire smoke motion in shafts is of vital importance in developing efficient smoke control systems. As fire smoke spreads in shafts, the affected area experiences a significant rise in temperature. Thus, calculating temperature distributions is of vital importance in understanding smoke motion in shafts during a building fire. Generally, shafts were constructed in three forms: (1) traditional shafts which are hollow inside, such as atriums and ventilation shafts; (2) shafts consisted with a series of partly connected spaces, such as evacuation staircases [1–3]; and (3) shafts with moving objects inside, such as elevator shafts [4,5]. Based on different forms, lots of numerical [1,2,5–7] and experimental [8,9] models have been developed to describe thermal behavior of smoke. Specifically, the first form has the most basic structure and it has been researched most frequently, which is also the form discussed in this paper. A lot of classical theories were developed based on this form, including the stack effect [10] and the zone model [11].

- Stack effect is a phenomenon resulted from temperature difference inside and outside of the shaft [10]. Driven by thermal buoyant force, hot smoke rises up and flows out from the top of the shaft, while cold air flows in from the bottom. This phenomenon was validated through experimental vertical temperatures profiles inside and outside of shafts [12], and employed to describe the smoke motion in designed fires [6,13].
- The height-to-span ratio is usually employed to describe structure characteristics of shafts [14], which could be calculated from height/width. For shafts with small height-to-span ratios, zone model is a common approach to analyze evolving distribution of smoke, through dividing the smoke into two layers: the high temperature layer and the low temperature layer. Based on zone model, natural smoke filling process and spill plume development were predicted through a series of numerical programs, such as NIST FDS codes [15,16], CFAST codes [17,18], plume equations [19], and the equations proposed by Tanaka and co-workers [20,21]. The mathematical results were compared to validation experiments, and they agreed well [22,23]. However, in shafts with large height-to-span ratios, this approach may not satisfy the requirements.

These two classical theories mentioned above were based on temperature difference between inside and outside of shaft, or between the upper layer and the low layer. In order to understand and describe the classical theories more accurately, it is very

---

* Corresponding author at: State Key Laboratory of Fire Science, University of Science and Technology of China, Hefei, Anhui 230026, China.

E-mail address: yanglz@ustc.edu.cn (L. Yang).

http://dx.doi.org/10.1016/j.expthermflusci.2016.07.007
0894-1777/

Nomenclature

C_p	specific heat [J/(kg·K)]
u	vertical velocity [m/s]
h_s	heat transfer coefficient [W/(m^2·K)]
h	height of shafts [m]
z	elevation [m]
m	mass [kg]
D	characteristic diameter of shafts [m]
L	characteristic length of heat sources [m]
T	temperature [°C]
Q	heat [J]
$\dot{Q}$	heat release rate [W]
$\dot{Q}^*$	dimensionless heat release rate [–]
q	exhaust rate [m^3/s]
f	frequency [%]
t	time [s]

Greek symbols

ρ	density [kg/m^3]

Subscripts

∞	ambient
W	wall
V	variation
0	bottom ($z = 0$)
h	top ($z = h$)
N	the Nth smoke element
$N + 1$	the ($N + 1$)th smoke element
P	experimental platform
R	real fire
max	maximum

necessary to develop a more precise method to calculate temperature distributions.

Specifically, some shafts are designed for ventilation and smoke exhausting in buildings [6,24–27]. In this form of shafts, a part of smoke is exhaust out and another part of smoke is driven in, which makes the smoke motion and temperature distributions in the shafts more complex. Generally, in a ventilation shaft, temperature distributions are affected by two factors:

(1) Heat exchange. As the smoke rises in a shaft, heat exchange occurs between smoke and shaft walls. Some investigators [28,29] have realized the influence of this heat exchange on smoke temperatures. They developed theoretical models to predict temperature distributions in vertical shafts and validated them through experiments.

(2) Ventilation. In ventilation shafts, a part of smoke is exhaust out from the top of shafts and another part of smoke is driven into the shafts from the fire region. To obtain the effect of ventilation on temperature distributions, studies were carried out under various operation status of exhaust fans [24,25,30]. However, in almost all the previous studies, people only discussed the influence of ventilation on average temperatures [24] instead of the temperature distributions as a function of elevation.

Both of the two factors are important in determining temperature distributions in ventilation shafts. However, they were usually ignored or partly considered in almost all the previous studies [24–26,28–30]. In this paper, a new mathematical model was put forward to describe the vertical temperature distributions in ventilation shafts, where the influence of both shaft walls and ventilation was considered. A series of validation experiments were conducted under various operation statuses of exhaust fans, and the experimental data were compared to the results calculated from the mathematical model. In some papers [31,32], the influence of both shaft walls and ventilation were also considered at the sometime. The main difference between them and this paper was the condition of ventilation: this paper additionally analyzed the temperature distributions when the exhaust rate varied while the area of the ventilation opening remained the same.

2. Mathematical model

As fire smoke rises in a shaft, heat exchange occurs between the hot fire smoke and cold shaft walls. In almost all the previous studies [6,9,10,12,13,28,33,34], the temperature of shaft walls was usually described with the ambient temperature. However, in reality, the wall temperature is always higher than the ambient temperature as the walls can be heat up by flame or smoke in a fire. In the mathematical model proposed in this paper, influence of the heat exchange was considered. To simplify the heat transfer process and analysis, we assumed the vertical velocity and density of smoke were uniform in the shaft [6,9,10,12,13,23,28,30,33–35]. According to some literatures [31,32], smoke temperatures in shafts ranged within 100 °C when the shaft height was within 50 m. When temperature rises 100 °C, the density of dry air at standard atmospheric pressure decreases less than 0.3 kg/m^3. This difference in density could be neglected. For higher shafts, the change of density cannot be neglected. In this condition, this model may not be applicable. Smoke in the shaft was divided into a series of continuous elements in the vertical direction. As a part of hot smoke may not be exhausted out of the ventilation shaft immediately, heat would accumulated at the higher positions. Without considering heat accumulation, heat transfer process for one smoke element is displayed in Fig. 1.

where Q_V is the heat variation of one smoke element, T_N and T_{N+1} are respectively the temperature for the Nth and the ($N + 1$)th smoke element, u is vertical velocity, z is elevation. Since the accumulation of heat was not involved in the heat transfer process in the ventilation shaft, this model is only applicable when the shaft has one or several openings, for example, slits around doors which connect shafts and front chambers.

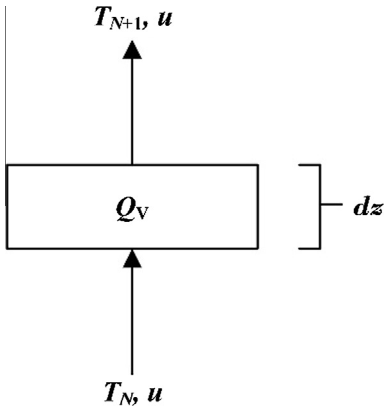

Fig. 1. Vertical heat transfer process for one smoke element in ventilation shafts.