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Influence of the external wind on flame shapes of n-heptane pool fires in long passage connected to a shaft

Jie Ji [a,b,*], Xiangyong Yuan [a], Kaiyuan Li [a], Jinhua Sun [a]

[a] State Key Laboratory of Fire Science, University of Science and Technology of China, Hefei, Anhui 230026, PR China
[b] Institute of Advanced Technology, University of Science and Technology of China, Hefei, Anhui 230088, PR China

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ABSTRACT

A set of experiments was conducted to study the influence of external wind on flame shapes of n-heptane pool fires in a long passage connected to a shaft. The competitive effect led by external wind and stack effect was investigated. Results show that for certain pool size, there is a critical wind velocity. When the wind velocity is lower than the critical value, the flame tilts towards the outdoor at early stage. The tilting angle gradually decreases and the flame eventually tilts towards the shaft due to the stack effect. A dynamic equilibrium among the inertial force induced by stack effect and the buoyancy induced by fire is established. At this stage, the flame tilting angle towards the shaft is approximately 71° which is surprisingly independent of the pool size and the external wind velocity. The mean flame length gradually decreases with increasing wind velocity and reaches a minimum when the external wind velocity approaches the critical value. When the wind velocity is higher than the critical value, the flame remains tilting towards the outdoor during the whole experiment and the flame tilt angle and the mean flame length at the quasi-steady stage increase with the wind velocity. A non-dimensional number *R*, denoting the ratio of horizontal inertial force generated by external wind to vertical buoyancy force causing the stack effect, is proposed to determine the flame tilting direction and its critical value is determined as 0.041 based on the experimental data.

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1. Introduction

Statistics have shown [1] that smoke and toxic gases, such as carbon monoxide, are the most fatal factors in fire accidents, and about 85% of victims in building fires were caused by hot and toxic smoke. There are a lot of vertical shafts in high-rise buildings, such as stairwells, elevator shafts and ventilation ducts. During fires, when the fire-induced smoke enters these vertical shafts, the strong stack effect may be formed. Stack effect is the mechanism of air movement caused by the pressure difference generated from the density difference of hot and cold airs respectively inside and outside of the building [2]. In previous studies, lots of works have been conducted to study the stack effect in building fires. Sun et al. [3,4] experimentally studied the influence of stack effect on the fuel burning rate, the entrainment rate and the plume temperature using small-scale and full-scale experiments. Shi et al. [5,6] studied the influence of stack effect on fire behaviors in the compartment connected to a stairwell. They concluded that the flame tilting angle correlated linearly with the Richardson number and the velocity of air flow into fire room was proportional to 1/3 power of the heat release rate. Ji et al. [7] experimentally investigated the smoke rise time, vertical temperature distributions and discharge coefficient in stairwells with open and closed top windows. Qi et al. [8] developed an analytical model on the coupled heat and mass transfer of fire smoke through the vertical shafts of high-rise buildings and presented a hand calculation method to solve the coupled problem. Yang et al. [9] numerically studied the smoke movement and smoke temperature field in a 20-storey residential building fire.

Buildings are usually in a windy environment [3]. The wind pressure might affect the fire dynamics and smoke behaviors in the buildings. Poreh and Trebukov [10] analyzed the wind effect on the motion of buoyant smoke in a compartment with two openings at the opposite walls while the windward one was set at lower elevation than the leeward one. The air flow direction is certainly unidirectional in this case. Chen et al. [11,12] experimentally studied the wind effect on compartment fires in cross wind conditions. They developed an equation with critical wind speed to predict the direction of smoke movement and found that the

* Corresponding author at: State Key Laboratory of Fire Science, University of Science and Technology of China, Hefei, Anhui 230026, PR China. Fax: +86 551 63606430.

E-mail address: jijie232@ustc.edu.cn (J. Ji).

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Nomenclature

T	absolute temperature (K)
h	convective heat transfer coefficient (W/(m^2 K)); height (m)
k	thermal conductivity (W/(m K))
D	thermocouple diameter (m)
g	acceleration of gravity (m/s^2)
w	width of shaft (m)
l	length of top window (m)
C_w	wind pressure coefficient
V_{wind}	wind velocity (m/s)
A	area of top window (m^2)
Nu	Nusselt number
Re	Reynolds number
Pr	Prandtl number
ΔP	pressure difference (Pa)

Greek symbols

σ	Stefan-Boltzmann constant (W/(m^2 K^4))
ζ	surface emissivity
ρ	density (kg/m^3)
$\Delta\rho$	density difference (kg/m^3)

Subscript

th	thermocouple
s	hot smoke
g	thermal gas
0	ambient air
i	the i-th part
n	the shaft is divided into n parts along the direction of height

ambient wind enhanced the fire severity and reduced the time to flashover. In these studies, fires were only investigated in one compartment. However, in real building fires, it is very common that the external wind acts on one or more openings of vertical shaft in buildings and then influences the flow field in the shafts and the fire behaviors in the adjacent spaces. Generally, the external wind is existent before fire occurs and the velocity of air flow is almost constant. It was found that external wind could have two opposing effects on the compartment fire. One is enhancing fire severity by supplying more oxygen whereas the other one is suppressing the fire by heat removal and combustible gases dilution [13]. Which one of these two opposing effects dominates the combustion process depends on the wind velocity for certain fire size. Tao et al. [14] experimentally studied the effects of oblique air flow on the burning rates of square ethanol pool fires in an inclined wind tunnel. Woods et al. [15] experimentally studied the effects of a transverse air flow on the burning rate of square and rectangular methanol pools. Hu et al. [16] investigated the flame tilt angle of hydrocarbon pool fires in a cross air. On the other hand, the velocity of air flow drawn into the fire compartment is directly related to the strength of the stack effect. The coupled influence of stack effect and external wind on fire plume behaviors is very complicated. However, little attention has been focused on this topic.

In this paper, a set of small scale experiments was conducted to study the interactive effect of external wind and stack effect on fire plume behaviors in a passage connected to a vertical shaft. The results may help researchers and engineers to better understand the fire behaviors under specific circumstance.

Following this introduction, there will be three more sections. Section 2 introduces the experimental facility, measurement setup and conditions. Section 3 presents the experimental outcomes and the corresponding discussions. The last section summarizes the major findings and conclusions of the paper.

2. Experiments

Experiments based on Froude modeling were conducted in a facility which consists of a wind screen machine, a vertical shaft and a long horizontal passage, as shown in Fig. 1. Froude modeling is a research method which scales the actual fires down to model sizes for research purpose by maintaining Froude number constant [17]. The dimensional relationships between the fluid dynamics variables were derived from first principles by Morgan et al. [18] and also mentioned in NFPA 92B [19]. Thomas et al. [20] examined smoke flows in models with differing scales with the results providing temperature measurements consistent with the predictions made using the scaling laws. By holding the Froude number constant, the relationships can be simplified to obtain the required scaling laws. In this research, the scale laws become $\dot{Q}_c \propto L^{5/2}$; $\dot{m} \propto L^{5/2}$; $u \propto L^{1/2}$ and $T \propto L^0$. As the scaling laws of Froude modeling do not apply to conductive and radiative heat transfer processes, it is actually assumed that the heat transfer mechanisms in this research work were predominantly convective [21].

The 1/6 scale building model with 6 floors is 3.0 m high thus each floor is 0.5 m high. The horizontal cross-section of shaft is 0.75 m × 0.5 m. The long horizontal passage is 2.0 m long, 0.5 m wide and 0.5 m high. Each floor has a single window with a size of 0.3 m (height) × 0.4 m (width). There is one door at each end of the horizontal passage, connecting the passage with ambient environment and shaft, respectively. The door sizes are 0.35 m (height) × 0.3 m (width). The front sidewall of the horizontal passage was made of the fire-resistant glass (4 mm thickness) for

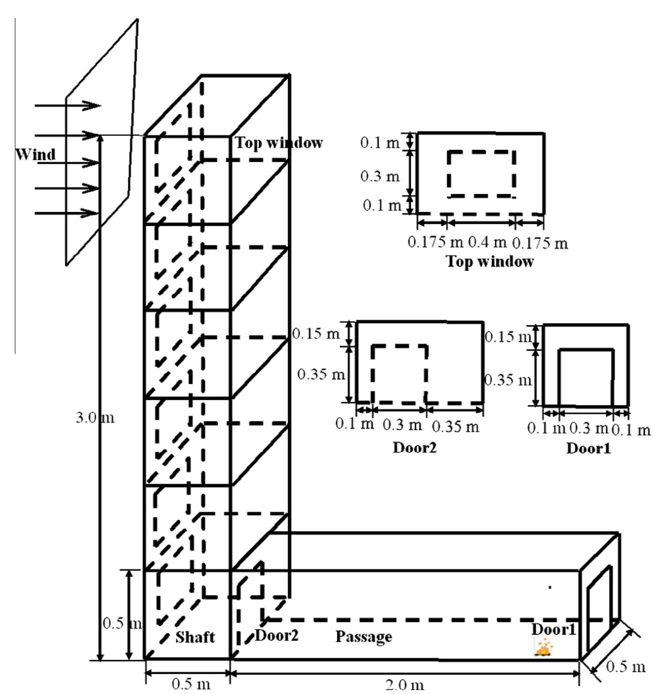

Fig. 1. Schematic of 6-layer-shaft configuration.

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