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Research Paper

A mathematical model for burning rate of n-heptane pool fires under external wind conditions in long passage connected to a shaft

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HIGHLIGHTS

- A set of burning experiments was conducted in a long passage connected to a shaft.
- The competitive effect led by external wind and stack effect was investigated.
- The effects of external wind on the fuel burning rate were analyzed.
- The influence of external wind on the temperature field in the shaft was analyzed.
- The average temperature rise inside the shaft with burning rate was well correlated.

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ABSTRACT

A set of experiments was conducted to study the influence of external wind on burning rates of n-heptane pool fires in a long passage connected to a shaft. The competitive effect led by the external wind and the stack effect induced by fire significantly influenced the burning rate of n-heptane pools. Results show that there is one critical wind velocity for certain pool size. While the external wind velocity is lower than the critical velocity, the burning rate at the quasi-steady stage does not change with the wind velocity. As the external wind velocity approaches the critical velocity, the burning rate at the quasi-steady stage decreases as the heat feedback from the boundaries is significantly reduced. Once the external wind velocity exceeds the critical velocity, the burning rate increases with wind velocity, and under the same wind velocity its value is approximately 2 times of the one in open space. Moreover, it is found that the average temperature rise inside the shaft has strong linear correlation with burning rate while the stack effect takes place, otherwise it remains as the ambient temperature.

1. Introduction

The fire safety of high rise buildings has drawn public attentions due to the occurrences of many catastrophic fires [1–4]. Statistics have shown that smoke and toxic gases are the most fatal factors in fires, which travels through the vertical shafts in high-rise buildings and causes about 85% of victims in building fires [5–7]. During fires, when stack effect takes place, the fire-induced smoke enters the vertical shafts, which is driven by the air density difference between the exterior and interior spaces of building or shaft [8]. The air flow induced by the stack effect may influence the fire behaviors and smoke movements and thus the burning rate of fire source and temperature distribution inside building. Meanwhile, the high-rise buildings are usually immersed in a windy environment [9] which will significantly affect the fire and smoke behaviors inside the buildings. Therefore, it is worth studying the fire behaviors under simultaneous external wind and stack effect for better understanding the mechanism and building design.

Many works have been carried out to study the stack effect and temperature distribution in vertical shafts during building fires [10–19]. Marshall [10,11] studied the smoke movement in staircases and shafts and obtained a simple empirical equation to predict the air entrainment. Mercier and Jaluria [14] experimentally studied the fire-induced smoke in open vertical enclosures and obtained detailed information on the flow pattern. Sun et al. [15] studied the influence of stack effect on buoyant plume temperature using a scaled 12-layer stairwell. Yang et al. [19] developed a model to predict vertical distributions of temperature and pressure, mass inflow rate and neutral plane location in a shaft during stack effect.

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Nomenclature

Q	heat release rate (kW)
$\dot{m}$	burning rate (g s^{-1})
Q^*	non-dimensional heat release rate
C_p	specific heat of air at ambient pressure (kJ kg^{-1} K^{-1})
T	absolute temperature (K)
g	acceleration of gravity (ms^{-2})
L	pool length (m)
H	height of the passage (m)
U	air supplying velocity (ms^{-1})
U	non-dimensional air supplying velocity
C_w	wind pressure coefficient
V	external wind velocity (ms^{-1})
A	area of top window (m^2)
h	height (m)
w	width of shaft (m)
l	length of top window (m)
V^*	non-dimensional external wind velocity
$\dot{m}''$	burning rate per unit area of pool fire in open space (g s^{-1} m^{-2})
$\dot{m}''_\infty$	burning rate per unit area for an infinite diameter pool (g s^{-1} m^{-2})
D	equivalent diameter (m)
S	pool area (m^2)
$\dot{m}''_V$	burning rate per unit area in open space under cross wind condition (g s^{-1} m^{-2})
$\Delta\dot{m}''_V$	burning rate per unit area enhancement due to cross wind (g s^{-1} m^{-2})
$\dot{m}''_{Vp}$	burning rate per unit area in the passage (g s^{-1} m^{-2})
$\dot{m}''_{VU}$	burning rate per unit area under critical velocity in open space (g s^{-1} m^{-2})
ΔT	temperature rise (K)

Greek symbols

η	combustion efficiency
$\Delta\zeta$	heat of combustion (MJ kg^{-1})
ρ	density (kg m^{-3})
κ	extinction-absorption coefficient of the flame (m^{-1})
β	mean beam length corrector

Subscript

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

On the other hand, there has been a considerable amount of researches on the effect of external wind on pool fires and compartment fires[20–27]. Blinov et al. [20] experimentally investigated the burning rates of circular pools ranging from 15 to 50 cm in diameter with cross wind velocity up to 25 m/s. Their results showed that the burning rates of fuels (diesel, kerosene, gasoline) monotonically increased with wind velocity and eventually approached an asymptotic limit except for the one of heavy fuel oil remaining constant. Roh et al. [22] investigated the effect of longitudinal ventilation velocity (0–1.68 m/s) on the burning rate of n-heptane pool fires in a tunnel and found that the increase of ventilation velocity enhanced the burning rates due to the excessive oxygen supply. Huang et al. [25] conducted experiments in a reduced-scale compartment to study the fire growth process in compartments under external wind conditions. Chen et al. [26,27] experimentally studied the wind effect on compartment fire in cross ventilation condition and found that the ambient wind enhanced the fire severity and reduced the time to flashover.

In the literature, studies were carried out for the respective effect of external wind and stack effect on fire behaviors and smoke movement. However, in reality, their combined effect should not be ignored [22,25], which need more in depth investigations. The stack effect is strongly affected by fire size (burning rate), which can overcome the external wind forces lower than a critical value. To perform a proper fire design, the burning rate and temperature distribution inside the building have to be determined, which have not been reported previously. This paper presents the burning rate and temperature distribution inside the shaft successive to the previous flame data and a new theoretical model based on dimensional analysis is proposed to determine the burning rate and temperature inside the shaft.

2. Experiments

The experimental facility consists of wind screen machine, shaft and long horizontal passage, as shown in Fig. 1. The wind screen machine is used to supply the external wind and its height is adjustable from 0 to 3.8 m. The 1/6 scale model shaft with 6 floors is 3.0 m high, 0.75 m long and 0.5 m wide and each floor is 0.5 m high. The horizontal passage is 2.0 m long, 0.5 m high and 0.5 m wide. Each floor of the shaft has a window with the size of 0.3 m in height and 0.4 m in width. There are two doors at the two ends of the passage, connecting respectively the ambient environment and the shaft. The two doors are both 0.35 m high and 0.3 m wide. One sidewall of the passage was made of 4 mm thick fire-resistant glass for observation, and the other walls were made of steel plate with 8 mm thick fireboard as the inner lining.

Sixteen K-type thermocouples with 1 mm diameter were positioned at the vertical centerline of the shaft at elevations of 0.1 m, 0.2 m, 0.4 m, 0.6 m, 0.8 m, 1.0 m, 1.2 m, 1.4 m, 1.6 m, 1.8 m, 2.0 m, 2.2 m, 2.4 m, 2.6 m, 2.8 m, 2.9 m, respectively. Four thermocouples and velocity measuring points were set 5 cm away from the door 1 outside of the passage, with the height of 0.05 m, 0.10 m, 0.20 m and 0.30 m. The locations of thermocouples and velocity measuring points are shown in Fig. 2.

The fuel pans are square with side lengths of 7 cm, 10 cm, 14 cm. The fuel pan located in the passage was about 5 cm above the ground and 20 cm away from door 1. *N*-heptane was used as the fuel. The fuel pans are made of steel. The clear height of the fuel pan is 4 cm and the initial thickness of the fuel in the pan was set as 3 cm, as shown in Fig. 2. The fuel mass was measured using an electronic balance with a resolution of 0.1 g. A digital camera (DV) with a frequency of 50 frames per second located in front of the passage was used to record the transient flame shapes of pool fires. During the experiments, door 1, door 2 and the 6th floor window (labeled as "top window" in following text) were opened and the other windows were closed. The ambient temperature was about 303 K. Before each experiment, the wind screen machine was turned on for certain amount of time to obtain a steady wind flow in the shaft. The external wind velocity varies from 0 to 1.51 m/s.

3. Results and discussion

3.1. Burning rate

The fire scenarios in our experiments can be categorized into three types. Fig. 3 illustrates the flame behaviors in cases with pool size of 10 cm × 10 cm. The first type has no external wind thus the