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Ambient wind effect on combustion characteristics in compartment with simultaneous door and window opened

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ABSTRACT

The work in this paper is to clarify and quantify the effect of ambient wind on compartment fires. Under ambient wind conditions, a set of experiments were conducted in a compartment with a window and a door at the opposite walls. The effect of ambient wind on flame behavior, airflow characteristic, temperature distribution and mass loss rate (MLR) was investigated. Results show that at low wind velocities the air flows into the compartment from lower part of the door while hot gases and flame flow out from the window and upper part of the door. For the wind velocity being equal to the velocity at the transitional phase, the flame can no longer flow out of the window. At high wind velocities, the flame spilled out from the door. An optimistic opening distance is determined for a theoretical model from the literature predicting the critical velocity for opposing wind force with downward flow. Moreover to predict the MLR, the heat feedback is taken into account by involving the compartment temperature in a modified model with wind velocity and the make-up air at the door. Involving ambient wind and the make-up air at the door, a new characteristic length l is proposed using theoretical analysis, which is related to the amount of make-up air at the door. The characteristic length l can be used to estimate wind effects on fuel mass loss rate and it reflects that increasing the wind velocity would push the flame flowing out from the door and restrains the air entrainment at the door way thus reduces the MLR.

1. Introduction

Ambient wind affects air exchange rate in the buildings [1,2]. During fires, ambient wind might flow into the compartment from broken windows and doors, and it plays an important role on the combustion characteristics. For instance, the ambient wind may deflect the flame, which increases the possibility of fire spreading to other floors or adjacent buildings [3,4]. Besides, Strong wind may influence smoke movement and smoke extraction efficiency [5].

Compartment fire has been studied for decades as an important fundamental topic in fire and combustion research. Researches on compartment fire started with single opening models. In such a configuration, fresh air will be drawn into the compartment and hot gases will be driven by buoyancy to escape the compartment through the same opening. Flames will spill out when the inflow air is not sufficient for burning. This condition is termed as an under-ventilated fire [6]. For the under-ventilated conditions, the heat released inside the compartment depends on the amount of air flowing in [6]. Gas temperatures are regarded as uniform inside the compartment and a correlation for predicting the gas temperature was proposed by Delichatsios [6], which was compared to the well-known MQH (McCaffrey, Quintiere & Harkleroad) correlation. On the other hand, the flame spilling out of the opening, so called window flame, will release a significant amount of heat outside the compartment. Himoto et al. [7] modeled the trajectory of window flame with special care on the flow attachment and found whether the flow attached to the adjacent wall depended on the pressure difference between the by-wall region and the ambient region. Yokoi [8] used circle radius of r_o to represent the outflow of hot gas at opening, which also determines the temperature distribution of window flame. Instead of using r_o, Lee et al. [9] proposed two length scales, l_1 denoting the convective flow and l_2 denoting the competition of inert force and buoyancy at the window. They found that the new length scales provided better predictions of the window flame temperature than Yokoi's.

In reality, there could be more than one opening in a compartment. The flow patterns of gases moving in and out will be different from the compartments with only one opening. Merci and Vandevelde [10] found that air flows into the compartment from the wall vent enhanced the burning inside the compartment. When there

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are two opposite openings at the side walls, the fresh air is drawn into the compartment through the lower part of both openings and the external flame spilled out from the upper part of both openings, which is called as cross ventilation condition. Kumar and Naveen [11] found that the temperatures in cross ventilation condition are higher than those with single vent for larger fire size. They proposed a simple mathematical model, CALTREE, to predict temperatures [12], which can be used in compartments under both single ventilation and cross-ventilation conditions. Utiskul et al. [13] investigated the heptane pool fire behaviors in a compartment with dual openings at different height and showed that the extinction depends on heating as well as oxygen concentration. The effect of multiple ceiling vents on flow characteristics in enclosure has been studied numerically by Harish and Venkatasubbaiah [14]. They found the volume flow rates through the two ceiling vents showed a significant variation depending on the location of vent. However, the wind effect was not covered in the above studies.

Wind velocity increases from zero at the ground to certain level related to altitude [15] and most fires burned under wind condition. A few researches were conducted on fires subjected to ambient wind and the used experimental configurations vary from simple to complex. Empirical models were proposed by Oka et al. [16] to predict the apparent flame height and the flame tilt angle. Besides, Oka et al. [17] developed a correlation of temperature rise and velocity along the inclined fire plume in crosswinds. Furthermore, Welker et al. [3] found that the burning rate of gasoline pool fire increased with cross wind velocity linearly when the wind velocity was relatively low. Woods et al. [18] found the burning rate demonstrated a 2.5 times monotonic increase, invariance, nonmonotonic response to increasing cross wind velocity with intermediate-sized square pools. The nonmonotonic burning rate response corresponded to the flame separating from the trailing edge of the pool.

The effect of ambient wind on compartment fire is much more complicated than that on unconfined fires. Chen et al. [5] and Huang et al. [19] experimentally observed that the ambient wind has two contradictory effects on compartment fire: (I) enhancing fire severity by supplying more oxygen and (II) suppressing the fire by heat removal and dilution of combustible gases. Besides, as mentioned above, air entrainment conditions of the fire plume and flow patterns of inflow and outflow vary with different opening configurations in the compartment. Wind effects on the compartment fire are different correspondingly. For the compartment with openings at the roof, Sadrizadeh et al. [20] found increasing the vertical ventilation flow rate will lead to the airflow less efficient fully mixed. The numerical simulation by Meroney [21] revealed how external wind deflects and changes the fire plume properties in an atrium. For the compartment with two openings, under cross ventilation conditions, the bidirectional flow would change to unidirectional flow as the wind velocity increases. Chen et al. [5] deduced the critical wind velocity theoretically and verified it experimentally. Huang et al. [19] found the dimensionless temperature of ejected flame was slightly lower than the results from Yokoi's experiments without wind. For the compartment with two openings at different vertical levels at the opposite walls, the wind blowing into the compartment from the lower opening reinforces fire-induced thermal buoyancy and the entrainment of the fire [22]. Poreh and Trebukov [23] studied the wind effects on smoke motion theoretically and Himoto et al. [24] developed a set of expressions for flame temperature rise incorporating the dimensionless heat release rate.

Once the fire breaks out in the compartment with two openings, the wind blows into the compartment from the higher opening and contradicts with fire-induced thermal buoyancy inside of the compartment. The flow characteristics depend on the competition of these two forces. Harish and Venkatasubbaiah [25] studied forced ventilation through upper dual enclosure doorway with varying fire source locations and identified the critical ventilation velocity that prevents the spreading of thermal plume from doorway opening by Large Eddy Simulations. In order to study effects of wind, buoyancy and thermal expansion on a room fire with natural ventilation, a dimensionless system function was derived from conservation of enthalpy by Chow et al. [26] and solved under different heat release rates. The ambient wind through the window plays a crucial role in affecting fire behavior and smoke would then spread following airflow pattern inside the building. Since toxic gases such as carbon monoxide poses threat to human safety and environment, it is essential to investigate the influence of ambient winds on building fire dynamics. The present paper aims to determine the flow characteristics in this fire scenario experimentally. Moreover, the combination effect of wind and heat feedback on fuel mass loss rate is also taken into account. The research examines the experimental data on (a) the characteristics of combustion and airflow patterns due to different wind velocities; (b) gas temperatures inside the compartment; (c) fuel mass loss rate. The results will lead to a better understanding of wind effect on compartment fire and be beneficial for the safety design of buildings.

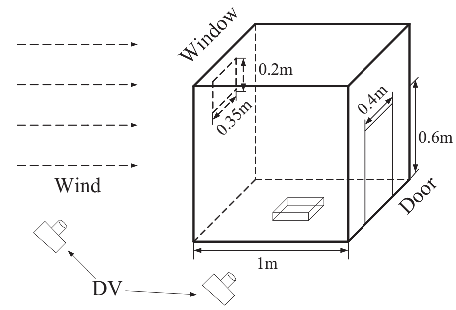

Fig. 1. Schematic of experimental apparatus.

2. Experimental setup

Experiments were performed in a reduced scale model (1:3) as shown in Fig. 1 in which the compartment is a 1 m cube with 0.02 m thick ceramic fiber boards as thermal insulated inner lining. The window is 0.2 m high by 0.35 m wide and the door is 0.6 m high by 0.4 m wide at the opposite walls of the compartment. The sizes are 1/3 scaled correspondingly and determined based on the sizes of the window and door of full and small scale model in [5,11,27–29]. The wind screen machine is installed 0.4 m away from the window, providing a steady airflow of 0–3 m/s. Four hot-wire anemometers (Kanomax, KA12) with measurement error less than 2% [30] are placed at the window to measure the wind velocity. Four velocity probes are removed during the burning process.

The temperatures inside the compartment are measured using K-type fine wire thermocouples with a diameter of 1 mm and response time less than 1 s. As shown in Fig. 2, three thermocouples (D1–D3) were installed at the centerline of the door. The distances of the thermocouples from the bottom of the compartment are 0.03 m, 0.3 m and 0.57 m, as shown in Fig. 1. To measure the temperature underneath the ceiling, nine thermocouples are installed 4 cm beneath the ceiling of the compartment symmetrically. Meanwhile 3 thermocouple trees are positioned at the center plane of the compartment near the window (WT), at the center (MT), near the door (DT). The distances from the bottom of the thermocouples are 0.12 m, 0.4 m, 0.68 m, 0.96 m, respectively.

A number of factors are identified to influence thermocouple readings in fires, such as diameter and response time of the thermocouple, radiative heat exchange between walls, gases and flames [31]. It has been found that the radiation error significantly affects the measured temperature using thermocouples. The thermocouple measurement error depends on the combination of the