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An experimental investigation of burning behaviour of liquid pool fire in corridor-like enclosures

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ABSTRACT

This work aims to investigate the burning behavior of a liquid fuel pool fire in a corridor-like enclosure and to identify the key factors influencing fire development. A series of experiments is conducted in a medium-scale corridor-facade configuration using ethanol pool fires. A new fuel supply system has been developed to keep the fuel level constant to minimize lip effects. The influence of fuel surface area and ventilation factor on the fire development is also investigated. Experimental measurements consist of mass loss, heat release rate, temperatures and heat fluxes inside the corridor. Experimental results indicate that in corridor-like enclosures the fuel burning rate in ventilation-controlled conditions corresponds to about 2/3 of that observed in cubic-like enclosures. The fuel burning rate varies as the temperature distribution in the enclosure changes from uniform, in cubic-like enclosures, to layered, in corridors. The ventilation coefficient value used for the calculation of the inflow rate in corridor-like enclosures during post-flashover conditions is found to decrease with an increase of the ventilation factor.

KEYWORDS:

corridor, pool fire, ventilation factor, fuel burning rate, fuel pan size

INTRODUCTION

Substantial research has been conducted on fire characteristics in typical residential cubic-like compartments [1], [2], [3], but there is still limited data on the development of fires in other geometries, even though it has been demonstrated that the geometry of an enclosure affects significantly fire development [4]. Investigation of enclosure fires occurring in modern constructions that differ from typical cubic-like enclosures (e.g. long corridors, tunnels etc.) is thus essential [2], [3]. Studies [3], [5] have indicated the need to further progress knowledge related to the understanding of the physics of fire growth in corridor-like enclosures and the mechanisms that eventually may lead to fire spread to adjacent floors or buildings.

For under-ventilated compartment fires, the mass flow rate of the air entering the compartment is a key parameter in determining the maximum heat release rate inside the compartment. The air mass flow rate entering the compartment (\dot{m}_a) can be estimated using the ventilation factor, $A_o H_o^{1/2}$ [1, 2], where A_o and H_o are the area and height of the opening respectively. Kawagoe [1] applied the Bernoulli equation to calculate the air inflow through a single moderate opening when under-ventilated conditions prevail and found that \dot{m}_a is proportional to $A_o H_o^{1/2}$, as shown in Equation (1), assuming uniform temperature distribution in the interior of a cubic enclosure [1]. The proportional constant C is referred to as the ventilation coefficient and takes values of 0.45 [1] or 0.5 [2] for cubic enclosures with moderate openings. Delichatsios et al. [3] proposed a correction for the expression of \dot{m}_a for cubic enclosures, Equation (2), by subtracting Equation (1) by $0.5 \dot{m}_T$, where \dot{m}_T is the burning rate of fuel. It has been shown in [2], [4], [6] that the geometry of the enclosure has a significant effect on the burning rate of fuel in enclosure fires. Kawagoe [1] proposed that in rectangular configurations, \dot{m}_T , under ventilation-controlled conditions, can be attained by multiplying $A_o H_o^{1/2}$ by 0.1, Equation (3). However, limited information exists regarding corridor-like configurations.

$$\dot{m}_a = C \times A_o H_o^{1/2} \quad (1)$$

$$\dot{m}_a = 0.5 A_o H_o^{1/2} - 0.5 \dot{m}_T \quad (2)$$

$$\dot{m}_T = 0.1 A_o H_o^{1/2} \quad (3)$$

The present research aims at investigating the differences in terms of fire development and burning behaviour between cubic- and corridor-like enclosures. Most of previous work in corridor-like enclosures [e.g., 6, 7, 8] has been performed using gaseous burners, with which the fuel supply rate must be pre-defined, therefore the interaction between the hot gases and the burning rate cannot be accounted for. In this work, a more realistic fire source is employed by using liquid pool fires. Two fuel pan sizes of constant fuel surface level and various opening sizes were used to investigate the influence of fuel surface area and ventilation factor on the burning rate and fire development.

EXPERIMENTAL SETUP

Corridor-like enclosure and façade configuration

The tests were conducted in a corridor-like enclosure having internal dimensions 3 m x 0.5 m x 0.5 m. The enclosure was constructed using six 0.5 m x 0.5 m cubic boxes and a 1.8 m x 1 m façade was attached to the front box, Box A, as indicated in Fig. 1, which shows a schematic drawing (side view) of the experimental configuration, depicting also the locations of the measurement devices. Opening dimensions, located in Box A, vary for each test case as summarized in Table 1.

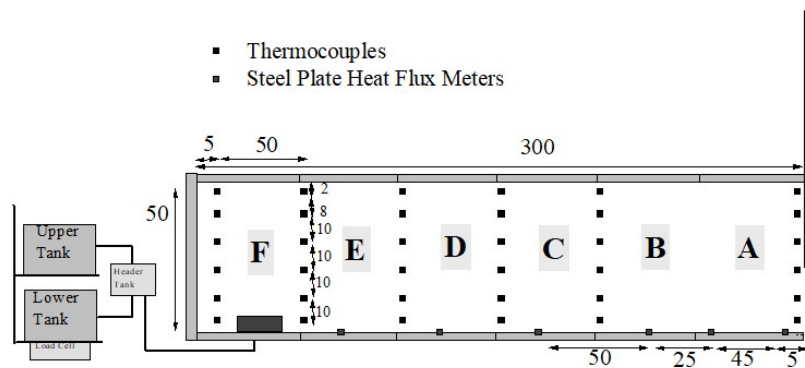


Fig. 1. Fire test configuration and experimental setup.

Fuel Delivery, Sensors and Data Acquisition System

In contrast to previous works using gaseous fuels in corridor-like enclosures [7], [8], ethanol pool fire is employed in this work to simulate more realistic fuel sources. A level maintenance system is designed to keep a constant fuel level (10 mm from the pan's rim) to minimize lip effects [9] and to establish steady-state conditions within the enclosure. Fuel is driven by gravity from the upper tank to the header tank as shown in Figure 1, with any excess fuel flushed to the lower tank. The fuel supply mechanism is placed on a balance with a maximum load of 36 kg and ± 0.2 g accuracy. Two stainless steel circular pans, 0.06 m high and 0.2 or 0.3 m in diameter, representing the radiative heat transfer regime [10], are used. A water-cooling circuit wrapped around the pan helps retain constant pan temperature to reduce conductive heat losses and thus to retain constant burning rates [11], [12]. Small pebbles are placed inside the pan to suppress convective motion in the liquid and excess boiling of the fuel on the surface [13]. The burner is placed on the floor at the center of Box F. A total of thirty-six K-type thermocouples with a bead diameter of 1.5 mm are used to monitor gas temperatures inside the enclosure at every 6 s [6], [7], with six thermocouples positioned in each Box 5 cm from the side wall at 2, 10, 20, 30, 40 and 48 cm above the floor as shown in Figure 1. Six steel plate heat flux meters are located in the centerline at the floor level of the corridor-like enclosure [14]. The whole experimental set-up is placed under a 3 x 3 m² hood to measure heat release rate (*HRR*), production of CO, CO₂ and smoke. Footage from CCD cameras are used for visually determining flames emerging through the opening as discussed in [15].

Experiments

In total, sixteen different cases are investigated in the present work, excluding repeatability tests for each case. Table 1 summarizes all the experiment cases presented in this work. The effect of ventilation is investigated by altering the dimensions of the opening. Eight different door-like openings are used in the current study, with their dimensions shown in Table 1.

Table 1 Opening and pan dimensions of the test cases studied.

Test	Opening size (m x m)	Pan diam. (m)	Test	Opening size (m x m)	Pan diam. (m)
BC20W10H10	0.10 x 0.10	0.2	BC30W10H10	0.10 x 0.10	0.3
BC20W15H15	0.15 x 0.15		BC30W15H15	0.15 x 0.15	
BC20W10H25	0.10 x 0.25		BC30W10H25	0.10 x 0.25	
BC20W20H20	0.20 x 0.20		BC30W20H20	0.20 x 0.20	
BC20W25H25	0.25 x 0.25		BC30W25H25	0.25 x 0.25	
BC20W30H30	0.30 x 0.30		BC30W30H30	0.30 x 0.30	
BC20W50H25	0.50 x 0.25		BC30W50H25	0.50 x 0.25	
BC20W50H50	0.50 x 0.50		BC30W50H50	0.50 x 0.50	

RESULTS AND DISCUSSION

Effect of pan size

Significant differences in the burning behaviour are observed with different fuel pan sizes. To demonstrate the main characteristic stages regarding the fire growth, the temporal evolution of measured \dot{HRR} , \dot{Q}_{exp} , and theoretical \dot{HRR} , \dot{Q}_{th} , are plotted in Fig. 2 for two characteristic test cases, namely BC30W30H30 and BC20W30H30. The theoretical \dot{HRR} , \dot{Q}_{th} , is calculated using Equation (4) based on the mass loss rate, as measured by the load cell and the heat of combustion, ΔH_c , of ethanol (26.78 MJ/kg). The maximum \dot{HRR} in stoichiometric conditions inside an enclosure, $\dot{Q}_{st,in}$, is calculated by multiplying \dot{m}_a by the heat released by complete combustion of 1kg oxygen, which for most fuels is found approximately equal to 3000 kJ/kg [2].

$$\dot{Q}_{th} = \dot{m}_T \Delta H_c \quad (4)$$

$$\dot{Q}_{st,in} = 3000 \times \dot{m}_a \quad (5)$$

As shown in Fig. 2, the fire behaviour is characterized by three distinct phases (*Regions I, II and III* as illustrated in the figures) appearing in succession. *Region I* corresponds to the fuel-controlled period (growth period), where the combustion efficiency is close to unity and thus \dot{Q}_{exp} and \dot{Q}_{th} are almost equal. In the case with the smaller pan, *Region I* period is substantially prolonged. This prolongation can be attributed to the radiation feedback to the fuel surface from the flame and the surroundings, which is less and results in smaller burning rates. During *Region II*, fire gradually becomes ventilation-controlled and \dot{Q}_{exp} reaches a plateau until flames ejects through the opening. In test cases with large openings (e.g. W25xD25, W30xD30, W50xD25 and W50xD50), during this period, \dot{Q}_{exp} is found to be less than $\dot{Q}_{st,in}$ indicating reduced air flow rate into the compartment. Flames ejection indicates the beginning of *Region III*, where sustained external burning is

observed. In *Region III*, \dot{Q}_{exp} continues to increase until a plateau is formed indicating that steady state conditions are established. Similar trends in *HRR* as depicted in Fig. 2 are generally observed in other test cases.

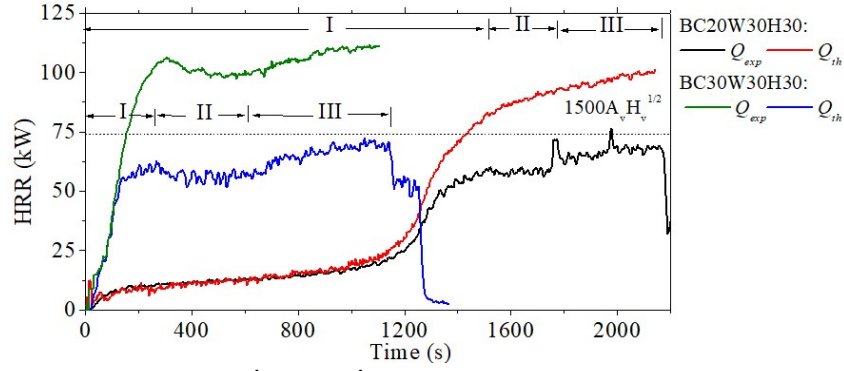


Fig. 2. Temporal evolution of \dot{Q}_{exp} and \dot{Q}_{th} for test cases BC30W30H30 and BC20W30H30.

To explain the difference in the *HRR*, gas temperature histories for test cases BC20W30H30 and BC30W30H30 are depicted in Fig. 3. During *Region I*, maximum temperatures are observed in Box F at the rear of the corridor as the fire is still fuel-controlled. For the case BC30W30H30, gas temperatures increase at much higher rates as a result of higher *HRR* and the duration of this region is much shorter compared to BC20W30H30. During *Region II*, maximum temperature is observed in Box E indicating that flames detach from the burner and gradually migrate towards the opening where oxygen availability is increased. At the same time, temperature in Box F decreases reaching a plateau, indicating steady-state conditions. In *Region III*, flames fill the upper layer of the corridor and appear to be anchored in Box E extending towards the opening, and eventually emerges from the opening when the *HRR* becomes sufficiently large.

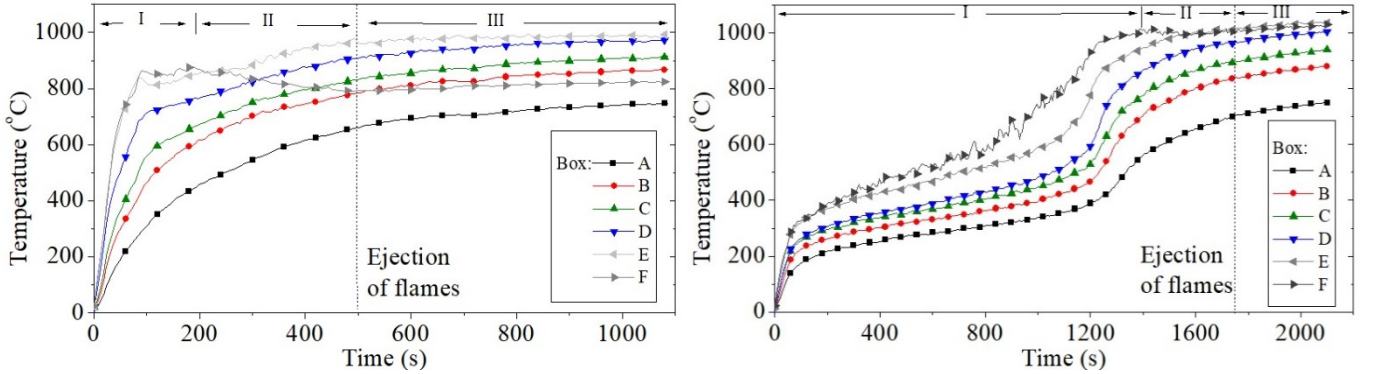


Fig. 3. Upper hot gas layer temperatures at each Box for BC30W30H30 (left) and BC20W30H30 (right).

Effect of ventilation factor

To examine the effect of the ventilation factor on the burning rate, Fig. 4 plots \dot{m}_T against $A_o H_o^{1/2}$ both normalized by the fuel surface area for all test cases when the steady state condition is achieved. Additional data for cubic enclosures [16] are also included for comparison. Values of \dot{m}_T are taken as the average of those at steady state conditions in Region III. As the ventilation factor increases, the normalized burning rate, \dot{m}_T/A_f , also increases until reaching a maximum value corresponding to the transition from ventilation- to fuel-controlled conditions, observed at about $A_o H_o^{1/2}/A_f=2$. A further increase in the opening factor results in a decrease in, \dot{m}_T/A_f , as the fire becomes fuel-controlled and finally, \dot{m}_T/A_f approaches the free-burn burning rate. It is worth noting that the data for the cases with the smallest opening factor (W10xH10) is not include in Fig. 4, because the air flow rate is too limited in these cases to sustain burning and the fire was self-extinguished after a few minutes. The trend between \dot{m}_T/A_f and $A_o H_o^{1/2}/A_f$ found in this work follows those obtained for cubic enclosures [1], [3]. Using experimental data from [1], [3] and [16] for different fuels, Delichatsios [3] found that the slope of the ventilation-controlled regime for cubic enclosures is 0.1, Equation (6). The present data indicate that in corridor-like enclosure a linear relation between \dot{m}_T/A_f and $A_o H_o^{1/2}/A_f$ still exists, as shown in Fig. 4. However, the proportional constant is found to be 0.067, Equation (7), which is about 2/3 of the one observed in cubic-like enclosures.

$$\frac{\dot{m}_T}{A_f} = 0.1 \frac{A_o H_o^{1/2}}{A_f} \quad (6)$$

$$\frac{\dot{m}_T}{A_f} = 0.067 \frac{A_o H_o^{1/2}}{A_f} \quad (7)$$

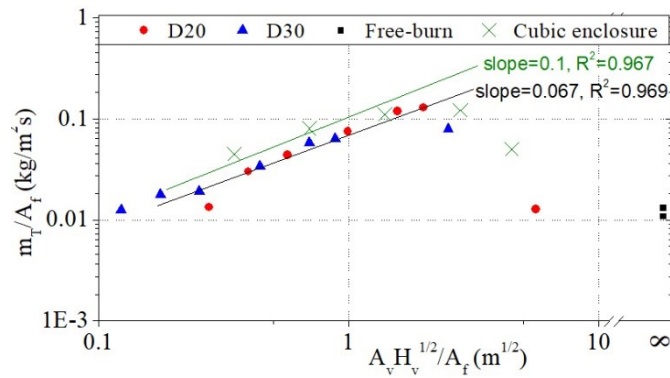


Fig. 4. Normalized values of \dot{m}_f against $A_o H_o^{1/2}$ for cubic-[16] and corridor-like enclosures in *Regime III*.

The current results are in accordance with previous experimental studies in corridors [3] [4], [17], [18] demonstrating that the burning rate in corridor-like enclosures is less than that in cubic-like enclosures under ventilation-controlled conditions. This difference was attributed to a decrease of the air inflow rate or the ventilation coefficient, C , in corridor-like enclosures [4] and [19]. The typical values for C are 0.45 [1] or 0.5 [2], which have been deduced during post-flashover conditions in cubic enclosures with single moderate opening. Thomas et al. [4] and Yii et al. [19] examined the effects of opening dimensions on the air flow rate and concluded that assuming a constant C value overestimates the air inflow rate, especially when the opening width is the same as the full width of the enclosure. Yii et al. [19] also showed that for large openings air entrainment dominates the vent flows. During *Region II*, all combustion takes place inside the enclosure. The ventilation coefficient can be calculated from the measured HRR in *Region II* as $C = \dot{Q}_{exp} / 3000 A_o H_o^{1/2}$ with the assumption that all oxygen is consumed in the enclosure in this region. This assumption is reasonable as (i) the *HRR* in this region is nearly constant and (ii) external burning occurs after the end of this region. Figure 5 shows the calculated C values for all test cases. It is found that C decreases with a decrease in the ventilation factor, which is in accordance to previous analysis of post-flashover fires [4], [19] indicating that \dot{m}_f in long enclosures (e.g. corridors) is less than in rectangular enclosures with the same opening geometry.

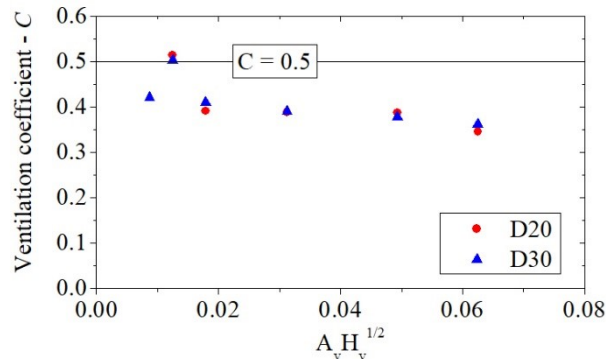


Fig. 5. Ventilation coefficient C for each test case against $A_o H_o^{1/2}$.

CONCLUSIONS

An series of medium-scale fire tests was performed using a liquid pool fire located at the rear of a corridor-like enclosure. Two pan sizes and eight opening sizes (thus ventilation factors) were used. The main conclusions of this work are:

1. For most cases, three distinct burning regions (*Region I*, *II* and *III*) have been observed, corresponding respectively to fuel-controlled, ventilation-controlled and steady-state burning. The duration of each regions depends on both the pan size and ventilation factor. In *Region II*, the heat release rate is nearly constant. The transition from *Region II* to *III* is indicated by the flame emerging from the opening. In *Region III*, the *HRR* continues to increase until a steady state is established.
2. For the cases when ventilation-controlled conditions are achieved, the normalized steady state mass burning rate, \dot{m}_f / A_f , is found to increases linearly with the normalized ventilation factor, $A_o H_o^{1/2} / A_f$, which is consistent with previous findings with cubic-like enclosures. However the proportional constant is found to be about 2/3 of that observed in cubic-like enclosures.

3. The effect of opening size on the air flow rate into the corridor was also examined, and the ventilation coefficient, C , for corridor-like enclosures during post-flashover conditions was found to decrease with an increase of the ventilation factor. These results are supported by the temperature measurements which show that the temperature in a corridor-like enclosure is not uniform even after ventilation-conditions are established. The temperature difference between the top and bottom locations increases with an increase in the ventilation factor.
4. The present work provides a framework towards the understanding the physics of the fire growth in corridors-shaped structures but future experiments should aim at further investigating the effect of corridor geometry (e.g. investigation of different aspect ratios and geometrical configurations), fuel type and positions within the enclosure. More detailed information regarding velocity distribution, gas and smoke concentration at the interior would further enhance the understanding of the phenomena involved.

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