Experimental study of burning behavior of liquid pool fires in a corridor-like enclosures

EXPERIMENTAL STUDY OF BURNING BEHAVIOURS OF LIQUID POOL FIRES IN A CORRIDOR-LIKE ENCLOSURE

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Abstract

This work investigates experimentally the burning behaviour of ethanol pool fires in a corridor-like enclosure, maintaining the fuel surface at a constant height. More than 60 experiments were performed in a three metre long corridor-like enclosure having a cross section 0.5m x 0.5m and a façade extended over the front panel of the enclosure. The scope of this work is to investigate the influence of three parameters, namely ventilation factor, pan size and location of the pool fire source, on the burning behaviour of the liquid pool fires. Therefore, eight opening dimensions, two pan sizes and two pan locations were examined. An extensive sensor network has been used to monitor the temporal variation of several important physical parameters, such as mass loss and heat release rate, temperatures and heat fluxes inside the corridor and on the façade, gases and smoke production outside the enclosure. Videos were also recorded by CCD camera facing the façade to determine the height of the external flame. Results show that in under-ventilated conditions the mass loss rate was found to decrease by 1/3 in corridor enclosures compared to rectangular enclosures. It is also found that the size and location of the pan have a significant influence on the burning behaviour. When the pan is located away from the opening of the enclosure an increased HRR was reported when compared to cases with pans located at the proximity of the opening, owing to the formation of the hot gas layer and the increased radiation feedback from the enclosure's walls to the fuel surface. Combustion efficiency was found to decrease by decreasing the dimensions of the opening. The obtained extensive set of experimental data of the current study can also be used to validate CFD models.

1. INTRODUCTION

It is widely recognised that fire spread in enclosures is influenced by many factors [1], such as the geometry of enclosure, size and location of the openings, fuel characteristics (type, size, location), enclosure wall material properties and environmental conditions. Though typical living spaces are represented by rectangular enclosure geometries, there are supplementary constructions of different geometries. One of the most common is a corridor-like enclosure geometry representing tunnels, offices and various transportation means geometries such as aeroplanes, trains etc. So, it is essential to ensure fire safety in such configurations to avoid potential cost in human lives and economy.

For fires in enclosures, Kawagoe [2] firstly introduced the concept of the ventilation factor, $AH^{1/2}$, where A and H are respectively the area and the height of the opening. He found that the mass flow rate of the incoming air, $\dot{m}_a$, through opening in cubic enclosures can be calculated as:

$$\dot{m}_a=0.5AH^{1/2} \tag{1}$$

Kawagoe [2] further proposed that in compartment configurations the burning rate, $\dot{m}_T$, of pool fire under ventilation-controlled conditions is correlated with the ventilation factor as:

$$\dot{m}_T = 0.1AH^{1/2} \qquad (2)$$

Delichatsios et al. [3] proposed based on non-dimensional relations of mass and energy balance a correction to the mass flow rate of incoming air, by subtracting Equation (1) by $0.5\dot{m}_T$.

The dependence of the burning rate on the ventilation factor was further discussed in [3] and is depicted in Figure 1. In the ventilation-controlled regime, the burning rate increases linearly with the ventilation factor. After a critical opening factor, corresponding to the transition from ventilation- to fuel-controlled fires, the burning rate decreases and eventually, with a further increase in the opening factor, reaches the steady burning rate corresponding to the free-burn regime.

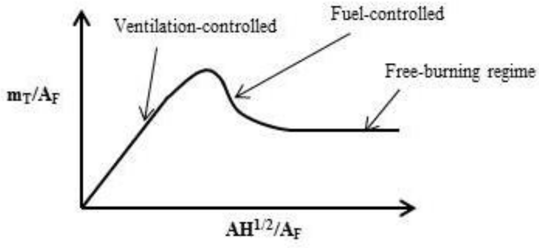

Figure 1. Expected behaviour of mass pyrolysis rates for varying ventilation factors where both co-ordinates are normalised by the fuel area.

Whilst fires in nearly cubic configurations are common in literature and thus many data can be used for analysis [3], limited information exists regarding corridor-like configurations. Some studies [4], [5] have shown that the geometry of the enclosure has a significant effect on the burning rate and burning behaviour of enclosure fires. Thomas and Bennetts [4] found that the mass loss rate of fuel in long enclosures is less than in wide enclosures having the same opening geometry. Delichatsios et al. [3] based on the data of Miyazaki and Watanabe [6], found that the constant in Equation (2) for a corridor-like enclosure is 0.025, compared to 0.1 for a cubic-like enclosure, although it was noted by the authors that more data is needed in corridor-like enclosures for validating this correlation. The difference between the two configurations was attributed to the difference in temperature distribution inside the enclosure.

For enclosure fires, researchers found that the location of the fire also affects the burning characteristics. Parkes and Fleischmann [7] studied the impact of the location of a heptane pool fire in a reduced-scale of an ISO room [8]. They stated that the location of fire can have a pronounced effect on the burning of pool fires, as the pan was moved progressively from the front to the rear of the compartment. Heat release rate (HRR) was also found to be a function of fire location. Similar findings were also reported by Beji [9], who used the same experimental rig as in this work but with a gaseous burner. He found that when the burner was at the rear of the corridor the HRR became steady reaching a plateau, indicating burning in stoichiometric conditions, for a few minutes. As proposed by many authors [1], [3], HRR in stoichiometric conditions inside an enclosure is given in Equation (3) and is calculated by the mass flow rate of incoming air, given in Equation (1), and the heat released by the complete consumption of the oxygen entraining the enclosure which for most fuels is found to be approximately equal to 3000kJ/kg. Then flames moved towards the opening, with HRR increasing rapidly up to the time they came out of the corridor through the opening indicating the fully developed regime. When the fire source was close to the opening that plateau was not observed, as flames being close to the opening ejected from it after a short period. In this case more oxygen reaches the fire source resulting a more efficient combustion. Similar findings are also noted in previous works using the same experimental rig, all using gaseous burners [5], [10].

$$HRR_{st,in}=3000x0.5AH^{1/2} \quad (3)$$

To the best knowledge of the authors, despite considerable work that has been carried out on pool fires in open conditions [11]-[22] or in cubic-like enclosure [2], [7], [23] and fires in corridor enclosures [3]-[6], [9], [10], no study has been conducted for constant level liquid fuel surface pool fires in corridor-like enclosures. Thus, not much information on burning behaviour of liquid pool fires under steady state conditions in corridor enclosures are currently available. The aim of the present paper is to fill this knowledge gap by presenting an experimental study on the burning behaviours of constant level liquid pool fires in a reduced-scale corridor-like enclosure, investigating the period when steady-state conditions are established at the interior of the enclosure. The effects of the burner size, opening size and burner location were examined. In total, 32 experimental cases were investigated including two burner sizes, eight opening sizes and two burner locations. Experimental measurements include gas temperatures inside the enclosure, HRR, mass burning rate, heat flux on the floor inside the enclosure and on the façade, and concentration of CO, CO_2 and smoke.

2. EXPERIMENTAL DETAILS

2.1. Corridor-like and Façade Experimental Rig

A corridor-like enclosure was used in the present study, with dimensions 3 m long × 0.5 m wide × 0.5 m high. The enclosure was constructed by 6 cubic boxes. As illustrated in Figure 2, Box A was close to the opening and Box F at the rear of the enclosure. The walls of the enclosure were lined with two different wall materials, consisting of a high temperature resistant board of 40 mm thickness (Unifrax LD) used as inner insulation wall and a 12 mm MDF board at the exterior side. A façade, 1.8 m high × 1 m wide, is extended over Box A, constructed using the same 40 mm thick insulation material and 12 mm MDF board. The same experimental rig was used by other researchers in the authors' group [5], [9] and [10].

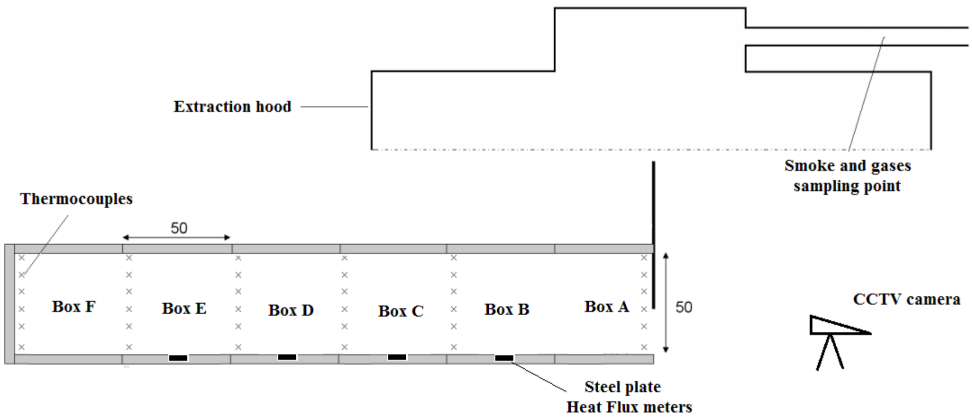

Figure 2. Side view of the experimental layout including instrumentation.

2.2. Parameters Investigated

The effect of ventilation was investigated by performing a parametric study by altering the dimensions of the opening. In total, eight different door-like openings were used in the front panel, with their dimensions shown in Table 1 along with the stoichiometric (maximum ventilation controlled) HRR calculated based on Equation 3.

Table 1. Opening dimensions and ventilation factors of the openings studied.

Width (W) x Height (H) (dimensions in cm)	Ventilation Factor ($AH^{1/2}$) ($m^{3/2}$)	$HRR_{st, in}$ (kW)
10 x 10	0.0032	4.8
15 x 15	0.0087	13.1
10 x 25	0.0125	18.8
20 x 20	0.0179	26.7
25 x 25	0.0313	46.5
30 x 30	0.0493	73.5
50 x 25	0.0625	93.8
50 x 50	0.1767	265.1

Two circular pans with diameters of 20 and 30 cm and a height of 6 cm were constructed using stainless steel. A water-cooling circuit was wrapped around the pan for keeping the wall's temperature cooled. Small pebbles were also placed inside the pans to reduce excess boiling of the fuel on the surface. Two different configurations were investigated in order to study the influence of pan's location to burning behaviour. Thus, the burner was placed on the floor at the centre of either front box (Box A) or the rear box (Box F). Ethanol was used as fuel and its level inside the pan was kept constant at 10mm from rim during burning for minimising the lip effect and helping steady-state conditions being established inside the enclosure. The fuel supply system used in the present study is shown in Figure 3. Fuel is driven by gravity from the upper tank to the header tank. Applying the communicating vessels principle, a copper tube connects the header tank and the bottom of the pan, with excess fuel in the header tank flushed to the lower tank.

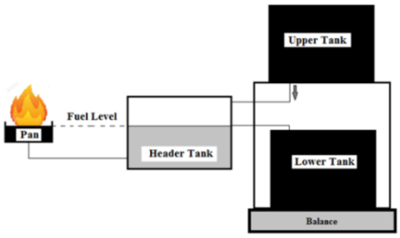

Figure 3. Fuel delivery and level maintenance system.

2.3. Experimental Instrumentation

Gas temperatures inside the enclosure were measured using K-type thermocouples of 1.5 mm diameter. A total of 36 thermocouples were placed inside the enclosure, 5 cm from the side wall, acquiring data every 6 s. Six thermocouples were vertically distributed in each box as illustrated in Figure 2, being 2, 10, 20, 30, 40 and 48 cm from the floor of the enclosure.

Heat fluxes were measured using steel plate flux meters (see Figure 2) [5] on the floor of the enclosure, in the middle of each box, and on the façade of the enclosure. Two Gardon gauge flux meters were also used on the façade for validating and comparing measurements from the steel plate flux meters. Positions of measurements on the façade can be found in [5], [9].

The whole fuel supply was placed on a balance with a maximum load of 36 kg and 0.2 g accuracy. Mass was recorded every 3 s. The whole set-up was placed under a 3x3 m^2 1MW hood, which allows measurements of HRR, production of CO, CO_2 and smoke every 3 s. A

CCD camera (JVC KY-F55B) was placed in front of the corridor facing the opening. Images, composed of 768 × 512 pixels, extracted from the videos for determining the height of flames emerging from the opening, using the method discussed in [24].

2.4. Experiments Conducted

In total, 32 different cases were investigated in the present work, with more than 60 experiments conducted. In order to uniquely identify each of the 32 different cases based on the location, the size of the pan and the opening dimensions, each case was given a unique name which starts with the location of the pan (either FR for front box or BC for rear box location), followed by the size of the pan (20 for the 20 cm diameter pan or 30 for the 30 cm diameter pan) and ended with the opening dimensions W x H. For example, the case having the 30 cm pan at the rear box and the 25 x 25 opening will be referred to as BC30W25xH25.
To ensure repeatability, duplicated tests were conducted for each case. For comparison purpose, tests in open conditions were also conducted for both pans (referred as free-burn cases). Table 2 summarises all the experiment cases presented in this work.

Table 2. Cases studied in present work.

Pan Location	Pan Diameter	Opening
FRONT BOX (Box A)	20 cm	All 8 different openings
	30 cm	All 8 different openings
REAR BOX (Box F)	20 cm	All 8 different openings
	30 cm	All 8 different openings
Free-burn	20 cm	N.A.
	30 cm	

Before each experiment, calibration of HRR measurement on the hood was carried out. Fuel was ignited in the middle of the pan using a lighter. For most of the tests, the fire has reached the steady-state according to HRR measurement. The tests were allowed to run a few minutes after the fire reaches the steady state in order to calculate the average results. There are however a few cases, in which no steady state was achieved because the HRR became excessively high and the test has to be terminated in order not to damage the walls of the corridor. No experiment was run for more than 45 mins.

3. EXPERIMENTAL RESULTS AND DISCUSSION

3.1. Repeatability and Free-burn Experiments

In order to ensure the repeatability of the tests, at least two experiments were conducted for each case. Figure 4 shows a comparison of the HRR measured in the hood of two repeated experiments conducted for the same test case FR20W50xH50. It is clearly depicted that the trends of the two experiments are almost identical indicating good repeatability.

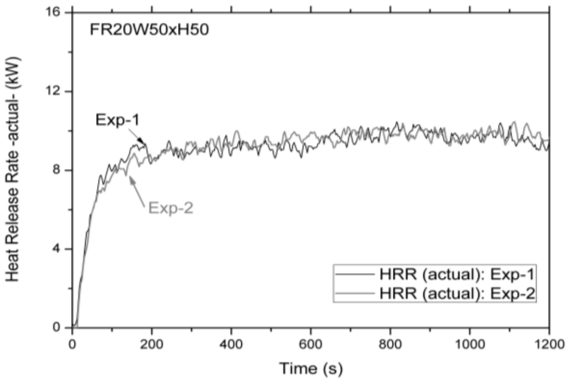

Figure 4. HRR measured in the hood for two experiments of the FR20W50xH50 case.

Before experiments conducted in the corridor-like enclosure, free-burn ethanol pool fire experiments were conducted to examine if the fuel delivery and level maintenance system works properly. The theoretical maximum HRR, calculated by the mass loss rate multiplied by the heat of combustion of ethanol (ΔH=26.78 MJ/kg), for the 30cm diameter pan is compared with the experimentally measured using oxygen calorimetry in the hood as shown in Figure 5. After the initial growth period, the burning rate became steady. The average burning rate of the steady-state period was calculated 0.93 g/s. Very good agreement of the two measurements is observed which was expected in open conditions. The average combustion efficiency during the steady-state period is found to be 0.97, which is calculated by dividing the measured HRR using oxygen calorimetry by the theoretical HRR calculated by multiplying the mass loss rate by the heat of combustion of ethanol. Regarding the 20 cm pan, the average burning rate calculated 0.34 g/s with the combustion efficiency 0.97.

The burning rates of both pans are in accordance with other ethanol experimental results found in literature [14], [16-20] following the trend proposed in [11] for the regression rate (mm/min) over pool diameter (m) as shown in Figure 6. The trend in Figure 6 shows the three regimes of flow in quiescent conditions based on pool diameter, namely laminar, transitional and turbulent flow [11].

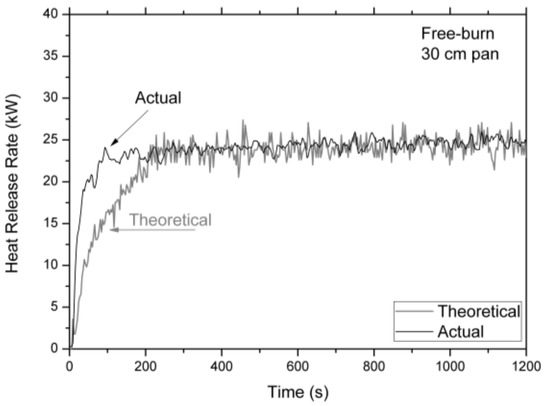

Figure 5. Actual and theoretical HRR profiles over time for the 30 cm pan burning in open conditions.

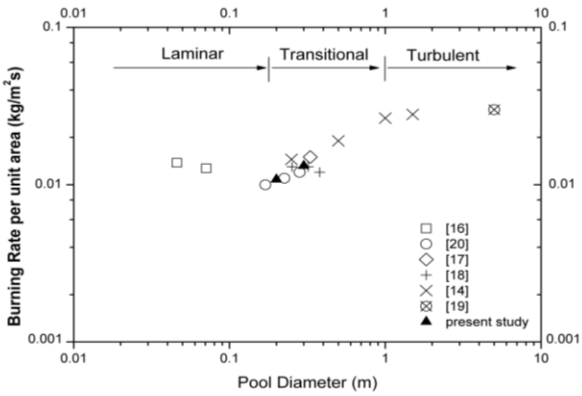

Figure 6. Mass loss rate per unit area in relation to pool diameter for free-burn ethanol experiments.

3.2. Burning Behaviour

Figure 7 plots the mass pyrolysis rate deduced for all the tests conducted in this work against the ventilation factor, both normalised by the total fuel surface area. The data shown in the plot are extracted for the period when steady conditions were established in the enclosure. Additionally, data extracted from [25] for cubic enclosures are also included for comparison. The results indicate that all cases follow the trend as that shown in Figure 1.

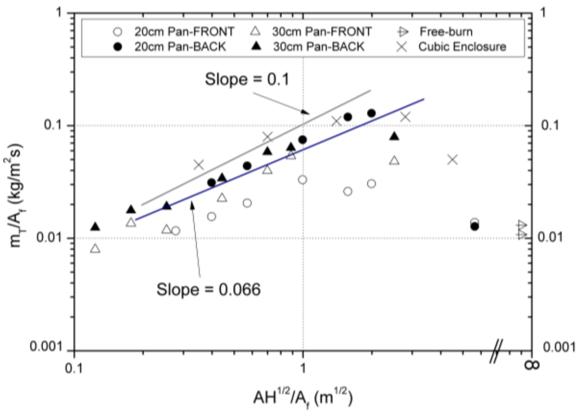

Figure 7. Mass pyrolysis rate against ventilation factor, both normalised by the fuel area for corridor-like enclosures of the present work compared with data [25] for cubic-like enclosures using ethanol as fuel.

As the ventilation factor increases, the mass pyrolysis rate also increases until a maximum value corresponding to the transition from ventilation- to fuel-controlled conditions, after which it starts decreasing. For the largest openings, the mass pyrolysis rate approaches the free-burn burning rate. It is noted that in all cases with the 10 x 10 cm opening, the air flowing inside the corridor was not sufficient for the fires to sustain and they were self-extinguished after 3-4 min. Thus, data from experiments having the 10 cm x 10 cm opening are not included in the plot. MLR for two self-extinction cases are shown in Figure 8.
As discussed in [3], using data from [2], [3] and [25] for different fuels, the slope of the ventilation-controlled regime for cubic-like enclosures is found to be 0.1.
A linear fit of the data in the ventilation-controlled regime in Figure 7 gives:

$$\frac{\dot{m}_T}{A_F} = 0.066\frac{AH^{1/2}}{A_F} \tag{4}$$

Comparing Equation (4) with Equation (2), it follows that ventilation-controlled fires in corridors burn at a rate of about 2/3 the mass loss rate of cubic-like enclosures for the same ventilation factors.

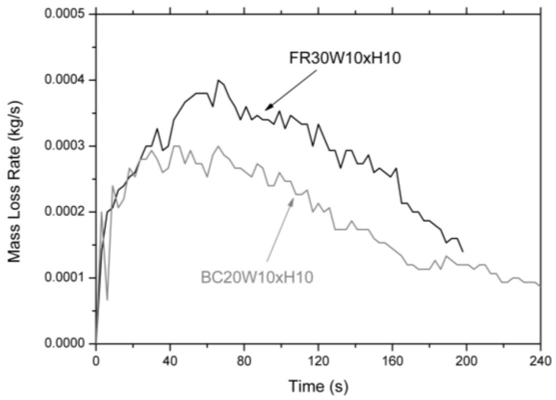

Figure 8. MLR for self-extinction cases FR20H10xW10 and FR30W10xH10

3.3. Pan Location and Size Effect on Burning Behaviour

Figure 9 shows the MLR for all cases with an opening size of 30 cm x 30 cm which according to Figure 7 is in the ventilation-controlled regime. In case FR20W30xH30, the initial mass loss rate for this case is similar to that in open conditions. The mass loss rate for the burner located at the front box did not reach the steady state even after 40 mins of burning because the enclosure was not heated fast enough. This is also shown in Figure 10 (Left), where temperature evolution of the highest and lowest locations inside the Box A, where the pan was located, are plotted. Temperatures of the upper and the lower layer increase with increasing mass loss rate, but did not reach the steady state after 40mins. For the BC20W30xH30 case, the initial mass loss rate is almost the same as that when the same burner is located at the front indicating that there is no hot smoke layer providing extra heat feedback to the fuel surface. After the initial stage, the mass loss rate for the burner at the back increases up to about five to six times of that for the burner at the front, indicating the formation of the hot gas layer. The increase of the mass loss rate corresponds with the time when the temperature of the upper and lower layer inside the Box F became steady, as shown in Figure 10 (Left), indicating that steady state conditions are established. Figure 10 (right) shows the average temperature of steady-state period along the corridor for the top and lower position. Temperatures close to the ceiling of the corridor reach about 1000 ^{o}C inside the back box and decreases to about 800 ^{o}C towards the opening. Similar results are observed for the cases with the 30 cm pan, but all cases reach the steady state and the burner location has less effect on the burning rate than that observed for the smaller pan.

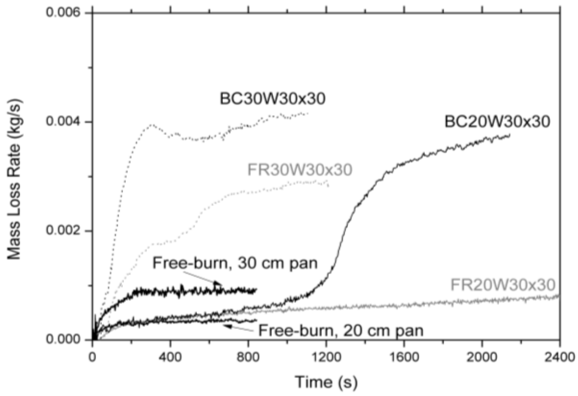

Figure 9. MLR histories for FR20H30xW30, FR30W30xH30, BC20W30xH30 and BC30W30xH30 cases.

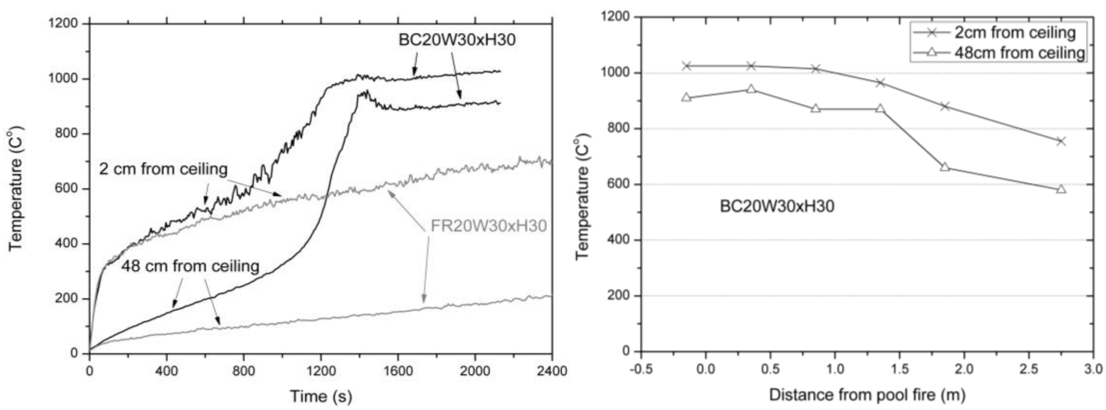

Figure 10. Temperature profiles inside Box A for FR20W30xH30 and Box F for BC20W30xH30 at the top and lower location (Left) and steady-state average temperature at the top and lower location for BC20W30xH30 versus distance from pool fire (Right).

Using the 30 cm pan, in cases FR30W20xH20 and FR30W25xH25, flames came out after 7 mins, instead only 2 mins for larger openings. FR30W15xH15 was the only case without flames emerging from the opening.

When the pan was located in Box F, higher MLR was observed in every single case with the same opening comparing with the cases when the pan was placed in Box A, showing major enhancement to the fire due to radiation feedback from corridor's walls, especially the back end. Although placing the 20 cm pan at the back of the corridor resulted in larger MLR, thus theoretical HRR, flames only came out through the opening for few cases. Only in cases BC20W30xH30 and BC20W50xH25 flames were noticed emerging consistently.

Figure 11 shows the HRR histories measured in the hood for the cases BC20W25xH25, BC20W50xH25 and BC20W50xH50. Free-burn case of the 20 cm pan is also plotted. In the BC20W50xH25 case the HRR firstly follows that in open conditions and then there is a sudden increase reaching about 75 kW. According to visual observations (also supported by video observation) this increase coincides with the time when the flames started moving towards the opening due to lack of oxygen for combustion. After a few minutes, flames came out burning steadily out of the corridor. For the ventilation-controlled regime having smaller openings, no flames came out, but an increase of HRR is noted as a result of formation of gas layer inside the corridor. An example for that is case BC20W25xH25 with its steady-state average temperature profiles versus height shown in Figure 12. Temperatures are homogeneous in over 0.15 m height forming a thick hot gas layer with temperatures being over 600^{o}C close to the opening and increasing towards Box F. It is noted that the HRR of BC20W50xH50 case, approaches the HRR of the free-burn case validating the expected burning behaviour of large ventilation factors as was shown in Figure 1.

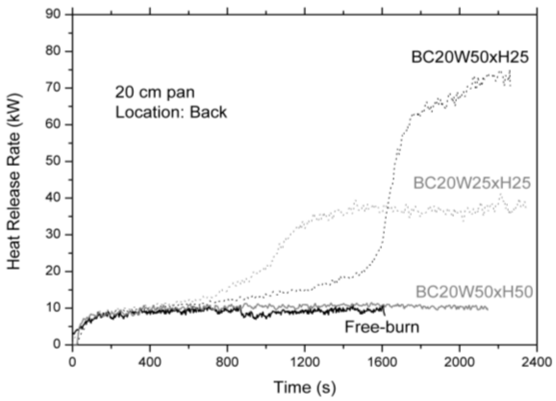

Figure 11. HRR profiles measured on the hood for BC20W25xH25, BC20W50xH25 and BC20W50xW50 case.

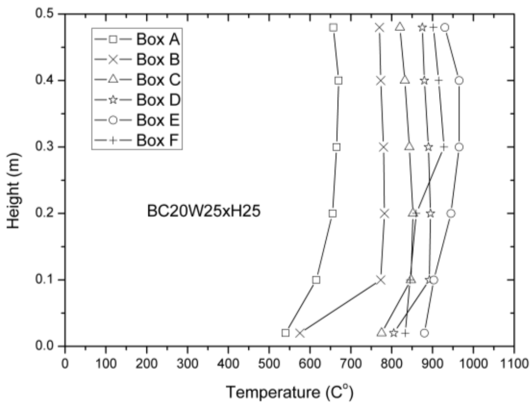

Figure 12. Average steady-state temperature versus height for BC20W25xH25 case.

Significant differences are observed for the 30 cm pan cases compared to the 20 cm pan as shown in Figure 13. Figure 13 shows the cases BC30W25xH25, BC30W50xH25, BCW50xH50 and free-burn of 30 cm pan. With a large pan, the HRR increases much faster than the cases using the small pan and the flames were observed to detach from the pan after a short period of time. This behaviour is clearly depicted in Figure 13, for the BC30W50xH25 case, where the HRR increases rapidly after a very short period becoming steady at 70 kW and then further increases to 80 kW, coinciding with the time when the flame came out. This rapid HRR increase was observed in all cases using the 30 cm pan inside the Box F. Case BC30W25xH25 is also shown in Figure 13, behaving in a similar way. It is noted that the case of the fully-open opening with the 30cm pan –case BC30W50xH50- was not similar to the free-burn case of the same pan due to ceiling effect, as flames reached the ceiling from the beginning. Formation of upper hot gas layer was also observed having 0.15 m depth as depicted in Figure 14 plotting the average steady-state temperatures over height in each box for the BC30W50xH50 case.

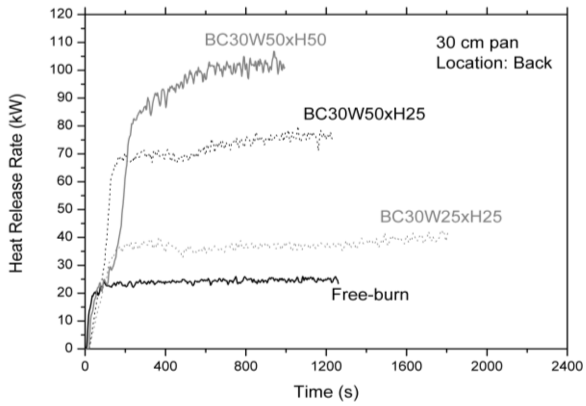

Figure 13. HRR profiles measured on the hood for BC30W25xH25, BC30W50xH25, BC30W50xH50 case.

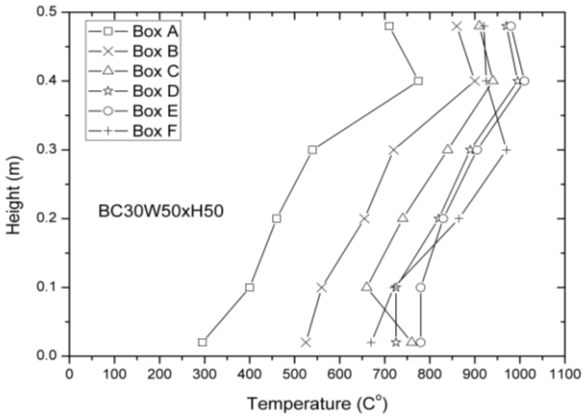

Figure 14. Average steady-state temperature versus height for BC30W50xH50 case.

3.4. Efficiency of Combustion

In Figure 15, combustion efficiency is plotted versus the ventilation factor for four cases: namely both pans placed at the Box A or Box F. It can be observed that combustion efficiency decreases as the ventilation factor decreases. This is related to the availability of oxygen which is needed for combustion. Using smaller openings less air is entrained through the opening so less oxygen reaches the pool surface for mixing with fuel. As the opening dimensions increase more air is circulated inside the corridor formatting a cold layer close to the floor with more oxygen reaching the fuel surface. This was validated by observing the combustion efficiency of the fully-open opening cases which has the largest values of combustion efficiency as expected. When the pans were positioned at the rear of the corridor the combustion efficiency was decreased compared the experiments where the pans were placed at the front box. The combustion efficiency for both pans at the front box was more than 0.7 for all the ventilation factors, while for the small openings when pan was located at the rear of the corridor the combustion efficiency was slightly larger than 0.5. The pans at the front were very close to the opening and fresh air was reaching the fuel surface easily, resulting in more oxygen available for combustion, but the air could not easily reach at the rear of the enclosure. This phenomena can be validated by observing the way that the combustion efficiency increases in the experiments having decreased openings. In contradiction with this observation, as discussed before, the flames moved from the rear of the corridor, where the pans were placed, towards the opening detaching from the pan. In conclusion, there is more unburnt fuel inside the corridor when pans are at the back.

Figure 16 presents the combustion efficiency history for the case BC20W20xH20 along with the theoretical and actual (calorimetry) HRR profiles. For the first 650 s, the two HRR profiles are similar with the combustion efficiency value approaches unity. Initially, combustion efficiency is high because burning is similar to free-burn burning, as there is sufficient oxygen for complete combustion. After this period combustion efficiency starts decreasing while radiation feedback from the corridor walls influences the burning rate of the pool fire. After 2200 s steady conditions are established inside the corridor and combustion efficiency reaches its lowest value, retaining steady value following HRR profiles.

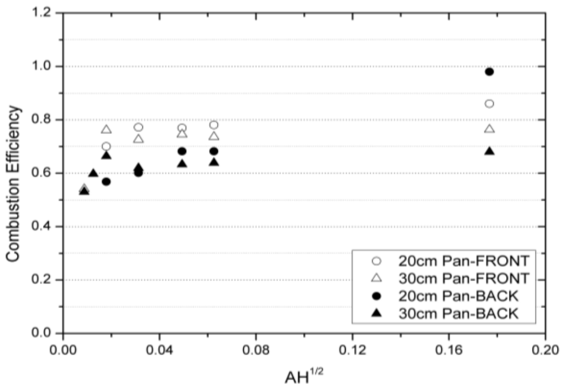

Figure 15. Combustion efficiency over ventilation factor.

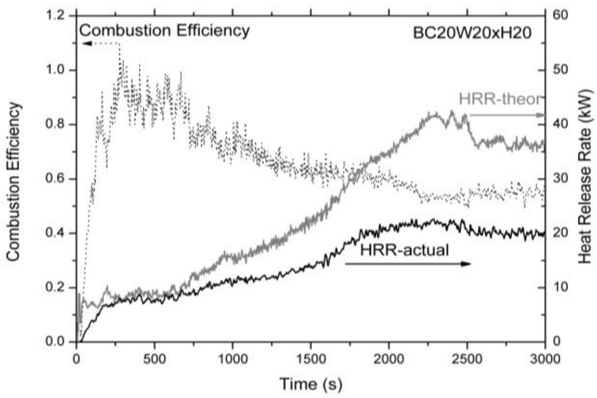

Figure 16. HRR and combustion efficiency over time for BC20W20xH20 case.

4. CONCLUSIONS

The objective of this study was to present an extensive experimental work of constant fuel surface liquid pool fires in a reduced-scale corridor-like enclosure, aiming to examine the influence of the pool size and location and ventilation openings in the burning behaviour of ethanol pool fires. The results of this work show that an increase of the ventilation factor, thus incoming air, affects the mass loss rate (MLR) by increasing it up to a point when transition from under- to over-ventilated conditions is established. In large openings MLR is similar to free-burning conditions. In under-ventilated conditions, MLR in corridor-like enclosure was found to be decreased by a factor of 1/3 of the MLR in rectangular enclosures. The location of the pan can have a strong impact to HRR, as moving the pan towards the closed end of the corridor the HRR was found higher due to heat feedback back to the pool surface by the closed-end wall and the formation of the hot gas layer along the corridor. Regarding the pan size, an initial period of burning like in free-burn case was observed using the small pan, but this was not the case using the large pan, as a rapid increase of HRR was occurred.

Future experimental work should focus on using additional fuels and pan sizes to further quantify the MLR and HRR versus ventilation factors in corridor-like enclosures with or without a closed-end. In addition, the obtained set of experimental data can be used to validate CFD models.

5. ACKNOWLEDGEMENTS

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