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## EXPERIMENTAL INVESTIGATION OF LIQUID POOL FIRES AND EXTERNALLY VENTING FLAMES IN CORRIDOR-LIKE ENCLOSURES

Kostantinos Chotzoglou<sup>1</sup>, Eleni Asimakopoulou<sup>2</sup>, Jianping Zhang<sup>3</sup>, Michael Delichatsios<sup>4</sup>

### ABSTRACT

Understanding of the physics and mechanisms of fire development and externally venting flames (EVF) in corridor-like enclosures is fundamental to studying fire spread to adjacent floors in high-rise buildings. This work aims to investigate the burning behaviour of a liquid fuel pool fire in a corridor-like enclosure and to identify the key factors influencing EVF characteristics and its impact on façades. A series of experiments is conducted in a medium-scale corridor-façade 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 and the façade. Three distinct burning regions are observed and their characteristics as well as the ones of the subsequent EVF depend on the pan size and ventilation factor. A power dependence of EVF height in relation to excess heat release rate has been found. The impact of EVF on the façade has been investigated by means of heat flux at the façade using thin steel plate probes measurements. EVF characteristics strongly depend on opening characteristics; for large opening widths EVF tend to emerge from the opening as two separate fire plumes.

**Keywords:** liquid pool fire, corridor-like enclosure, façade fire, flame height, heat flux

### 1 INTRODUCTION

Understanding of the physics and mechanisms of fire development in enclosures and flames emerging through openings is fundamental to studying fire spread to adjacent floors and subsequent evaluation of the integrity of structural elements. Recent high-rise building fires around the world highlight the importance of understanding the mechanisms of fire spread not only at the interior of buildings but also due to Externally Venting Flames (EVF) [1,2]. Consequences of these EVF induced fire events include loss of life and injuries, health impact through smoke exposure, property and infrastructure loss, business interruption, ecosystem degradation, soil erosion and huge firefighting costs [1,3]. Though substantial research has been conducted on fire characteristics of EVF in typical cubic-like compartments [4,5,6], there is still limited data in other geometries (e.g. long corridors, tunnels etc). For the few studies in corridor-like enclosures [7], gaseous fuels were used. As the mass flow rate (thus heat release rate) of gaseous fuels must be pre-defined, it does not consider the interaction

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<sup>1</sup> PhD Candidate. Belfast School of Architecture and the Built Environment, Ulster University, Belfast, UK and Effectis, UK/Ireland.  
e-mail: [chotzoglou-k@ulster.ac.uk](mailto:chotzoglou-k@ulster.ac.uk)

<sup>2</sup> Research Associate. Belfast School of Architecture and the Built Environment, Ulster University, Belfast, UK  
e-mail: [e.asimakopoulou@ulster.ac.uk](mailto:e.asimakopoulou@ulster.ac.uk)

<sup>3</sup> Reader. Belfast School of Architecture and the Built Environment, Ulster University, Belfast, UK  
e-mail: [j.zhang@ulster.ac.uk](mailto:j.zhang@ulster.ac.uk)

<sup>4</sup> Northeastern University, Boston, USA and University of Science and Technology of China (USTC), Hefei, China  
e-mail: [madelicha@aol.com](mailto:madelicha@aol.com)

between the flame, hot gas layer and the pyrolysis rate of the fuel, which is of fundamental importance in growth and development of real fires. This work investigates the burning behaviour of a liquid fuel pool fire in a corridor-like enclosure and the heat impact of the subsequent EVF on the façade. The effects of the size and location of the pool fire and the dimensions of the opening on the burning characteristics of the EVF are examined. Experimental measurements consist of gas temperature inside the enclosure, mass burning rate, heat release rate, heat fluxes on the enclosure floor and on the façade and production of CO and smoke. The experiments were video recorded, based on which the flame height of the EVF is deduced using an in-house image processing software. The deduced flame height is correlated with the external heat release rate and compared to previous studies using gaseous fuels.

## 2 EXPERIMENTAL DETAILS

### 2.1 Corridor-like enclosure and façade configuration

The experiments were conducted in a medium-scale corridor-façade configuration having internal dimensions 3 m x 0.5 m x 0.5 m and a 1.8 m x 1 m façade was attached to the front box. A schematic of the experimental facility, illustrating the locations of the employed measuring devices, is given in Fig. 1.

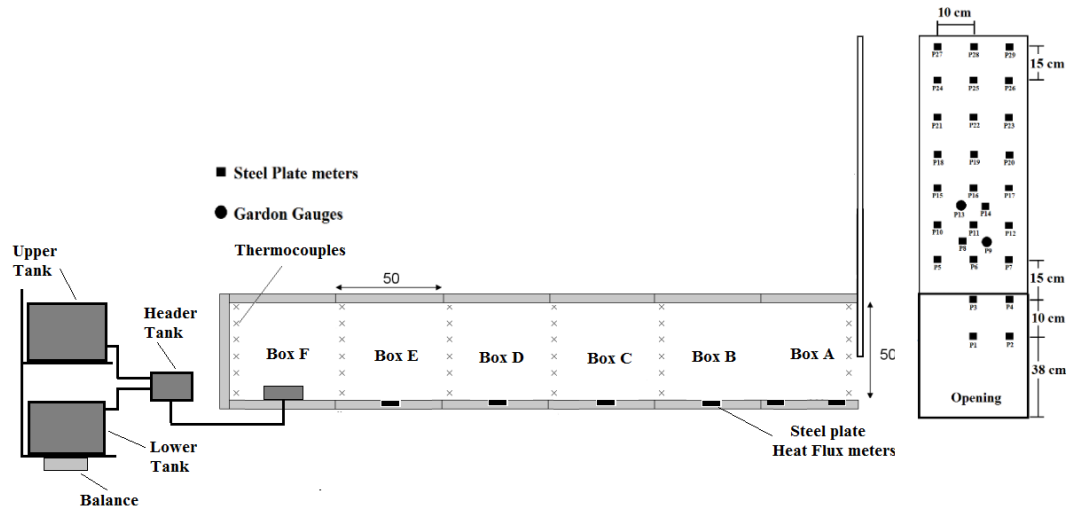


Fig. 1. Fire test configuration and experimental setup.

A new liquid fuel supply system was developed to keep the fuel level constant to minimize lip effects; ethanol was used in a circular sandbox burner positioned either in the geometrical centre of Box A or F. The fuel surface area and ventilation factor (opening size) were varied to examine their effects on the fire development. In total, more than 60 experiments were conducted, and the effect of ventilation is investigated by altering the dimensions of the door-like opening. A summary of the main operational parameters, i.e., burner position, opening size (opening width  $W_o$  and opening height  $H_o$ ), ventilation factor ( $A_o H_o^{1/2}$  where  $A_o$  corresponds to the opening area), Global Equivalence Ratio (GER), ventilation regime (i.e., under-ventilated or over-ventilated), and the characteristic length scale ( $l_l = (A_o H_o^{1/2})^{2/5}$ ) [6] is shown in Table 1 for the test cases where EVF was observed.

### 2.2 Sensors and data acquisition system

A total of thirty-six K-type 1.5 mm diameter thermocouples were used to monitor gas temperatures inside the enclosure every 6 s [7,8], with six thermocouple trees located in each of the boxes and 5 cm from the side wall. The six thermocouples are located at 2, 10, 20, 30, 40 and 48 cm height from the floor. Both steel plates (square shape) and Gardon gauges (round shape) have been used to monitor

the heat flux at the façade as shown in *Fig. 1*. The experimental set-up was placed under a 3 x 3 m<sup>2</sup> 1 MW hood to measure the experimental heat release rate,  $\dot{Q}_{exp}$ , production of CO, CO<sub>2</sub> and smoke. Videos were recorded by a CCD camera facing the façade, based on which an in-house developed image processing tool is used to evaluate the geometric characteristics of the façade fires by calculating the average flame probability (intermittency) [9]. Each frame was converted into a binary image using a set of rules, employing appropriate threshold limits for Red, Green and Blue colour levels and luminosity, based on the prevailing lighting conditions in each test case. The threshold limits were acquired through an extended statistical analysis of the flame at *Region III*.

*Table 1.* Summary of main operational parameters for all the test cases with EVF.

a/a	Test	Burner position	Pan diam.	Opening size	$A_o H_o^{1/2}$	Ventilation regime	GER	$l_f$
		Box	m	m x m	m <sup>5/2</sup>		-	-
1	FR20W20xH20	A	0.2	0.20x0.20	0.0179	O	0.64	0.20
2	FR20W25xH25	A	0.2	0.25x0.25	0.0313	O	0.59	0.25
3	FR30W10xH25	A	0.3	0.10x0.25	0.0125	U	1.37	0.17
4	FR30W20xH20	A	0.3	0.20x0.20	0.0179	O	0.83	0.20
5	FR30W25xH25	A	0.3	0.25x0.25	0.0313	O	0.91	0.25
6	FR30W30xH30	A	0.3	0.30x0.30	0.0493	U	1.02	0.30
7	FR30W50xH25	A	0.3	0.50x0.25	0.0625	U	1.09	0.33
8	FR30W50xH50	A	0.3	0.50x0.50	0.1768	O	0.34	0.50
9	BC20W25xH25	F	0.2	0.25x0.25	0.0313	U	1.35	0.25
10	BC20W30xH30	F	0.2	0.30x0.30	0.0493	U	1.36	0.30
11	BC20W50xH25	F	0.2	0.50x0.25	0.0625	U	1.16	0.33
12	BC30W25xH25	F	0.3	0.25x0.25	0.0313	U	1.38	0.25
13	BC30W30xH30	F	0.3	0.30x0.30	0.0493	U	1.50	0.30
14	BC30W50xH25	F	0.3	0.50x0.25	0.0625	U	1.29	0.33
15	BC30W50xH50	F	0.3	0.50x0.50	0.1768	O	0.57	0.50

### 3 RESULTS AND DISCUSSION

#### 3.1 Heat release rate inside the enclosure

A parametric analysis was performed to identify the main parameters influencing the burning behaviour and subsequent EVF namely pan size, pan location and ventilation factor. To demonstrate the main characteristic stages regarding the fire growth, the temporal evolution of measured HRR,  $\dot{Q}_{exp}$ , and theoretical HRR,  $\dot{Q}_{th}$ , are plotted in *Fig. 2* for two characteristic under-ventilated test cases, namely for BC20W30H30 and BC30W30H30. The theoretical HRR,  $\dot{Q}_{th}$ , is calculated by multiplying the fuel mass loss rate by the heat of combustion of ethanol, 26.78 MJ/kg. The maximum HRR in stoichiometric conditions inside an enclosure,  $\dot{Q}_{st,in}$ , can be calculated by multiplying the air inflow rate by the heat released by complete combustion of 1 kg oxygen, which for most fuels is found to be approximately equal to 3000 kJ/kg [3].

A general description of the fire temporal evolution is presented based on visual observations and *HRR*. For all under-ventilated fires with the pan located in Box F, as indicatively shown in *Fig. 2*, the fire behaviour is characterized by three distinct phases namely *Regions I, II* and *III* 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. During *Region II*, fire gradually

becomes ventilation-controlled;  $\dot{Q}_{exp}$  reaches a plateau until flames ejects through the opening and  $\dot{Q}_{exp}$  does not reach the maximum heat released inside the enclosure approaching  $1500A_oH_o^{1/2}$  value according to relevant research concerning compartment fires [5]. This value is decreased, calculated at approximately  $1100A_oH_o^{1/2}$ , as the amount of air inflow in long corridors is less than in rectangular enclosures with the same opening geometry [10]. GER is used to describe the fire in during *Region II* as fuel- or ventilation-controlled [11] by calculating the ratio of the fuel mass flux,  $\dot{m}_T$ , to the oxygen mass flux entering the enclosure,  $\dot{m}_{O_2}$ , divided by the fuel-to-oxygen stoichiometric ratio of the fuel,  $S$  [3]. Relevant results of GER for each test case are presented in Table 1.

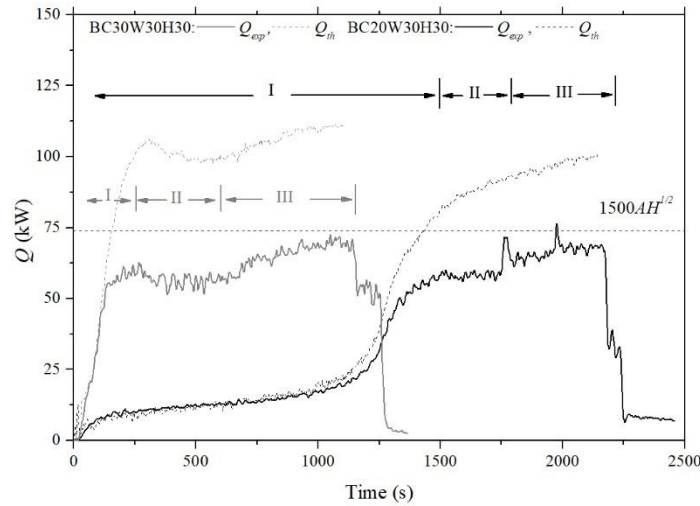


Fig. 2. Temporal evolution of  $\dot{Q}_{exp}$  and  $\dot{Q}_{th}$  for test cases BC30W30H30 and BC20W30H30.

Flames ejection, often associated with a sudden increase in the  $\dot{Q}_{exp}$  indicates the beginning of *Region III*, where sustained external burning is observed until a plateau is formed indicating that steady state conditions are established. As depicted in Fig. 2, not all the excess fuel burns at the exterior of the corridor as the combustion is incomplete and the combustion efficiency in *Region III* is calculated at approximately 0.74 for both cases. As demonstrated in Fig. 3, pan size has a significant effect on the time to reaching steady burning, as in test cases using smaller pans it takes longer for the walls to be heated. For under-ventilated cases with the fuel pan located at the rear of the corridor and larger pan sizes, EVF appeared shortly after ignition and the duration of *Regions I* and *II* becomes considerably reduced as the increasing rate of the mass loss rate/heat release rate is significantly increased. The start of *Region II* corresponds to a transition from fuel controlled to ventilation- controlled conditions where combustion efficiency is decreased due to insufficient  $O_2$  availability thus resulting in an increase production of intermediate products, e.g.  $CO$ . During *Region III*, the concentration of intermediate combustion products, e.g.  $CO$ , exiting through the opening is decreased due to external burning. In order to determine the external heat release,  $\dot{Q}_{ex}$ , it is assumed that the burning inside the corridor remains the same and thus  $\dot{Q}_{ex}$  can be found from the difference between the steady heat release rate in *Region III* and that at the end of *Region II* and the relevant values are shown in Table 2, along with the flame height, which will be further discussed in Section 3.3.

Table 2. Summary of main operational parameters for the examined test cases.

a/a	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15
$\dot{Q}_{exp}$ (kW)	12.1	21.5	22.2	17.0	31.0	56.1	75.1	69.5	39.0	68.5	74.0	39.5	70.0	77.0	105.0
$\dot{Q}_{ex}$ (kW)	-	-	-	-	-	-	-	-	2.5	11.1	9.0	2.9	14.0	9.0	-
$Z_f$ (m)	0.11	0.21	0.22	0.13	0.34	0.49	0.48	0.33	0.22	0.51	0.37	0.19	0.58	0.64	0.30

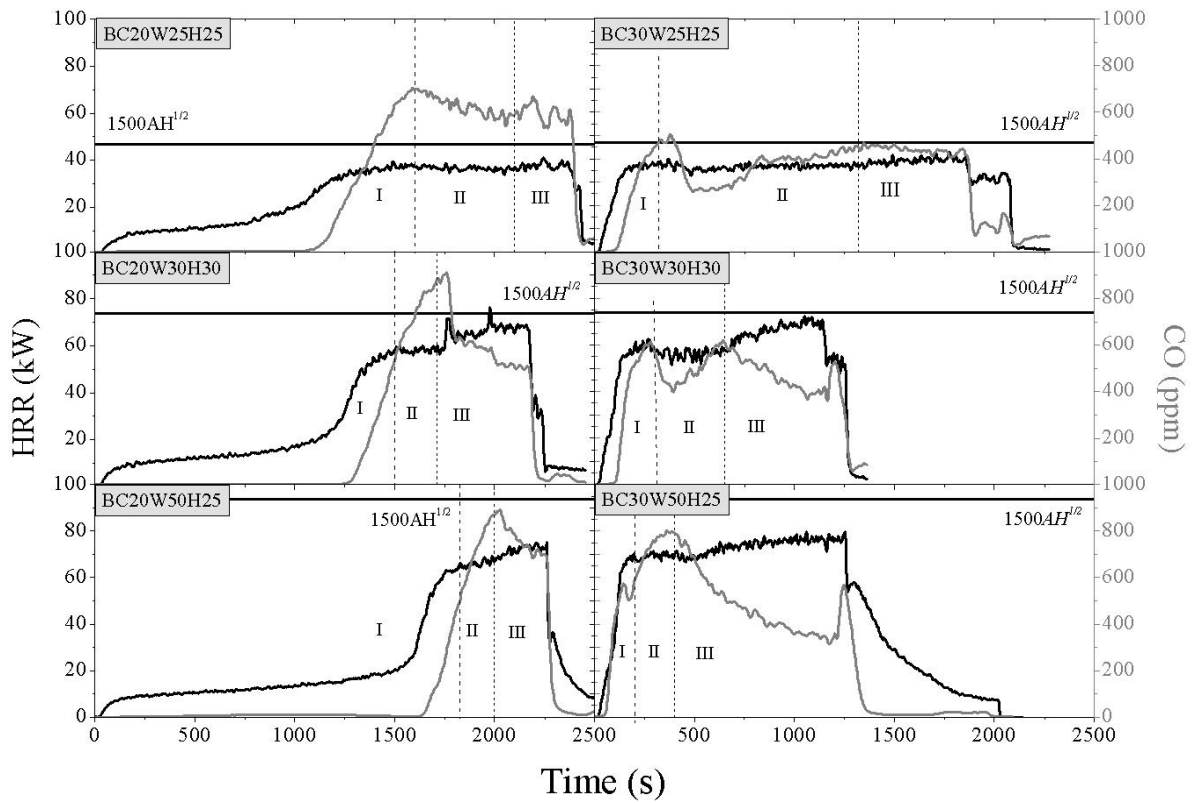


Fig. 3. Temporal evolution of  $Q_{exp}'$  and CO volume concentrations measured at the hood for test cases B20W25H25, B20W30H30, B20W50H25 (left) and B30W25H25, B30W30H30, B30W50H25 (right).

### 3.2 Gas temperature inside the enclosure

The present analysis focuses on under-ventilated cases in which EVF occur. The gaseous temperature inside the corridor at three characteristic time frames representing the three Regions discussed in previous section for test cases BC30W30H30 and FR30W30H30 is depicted in Fig. 4.

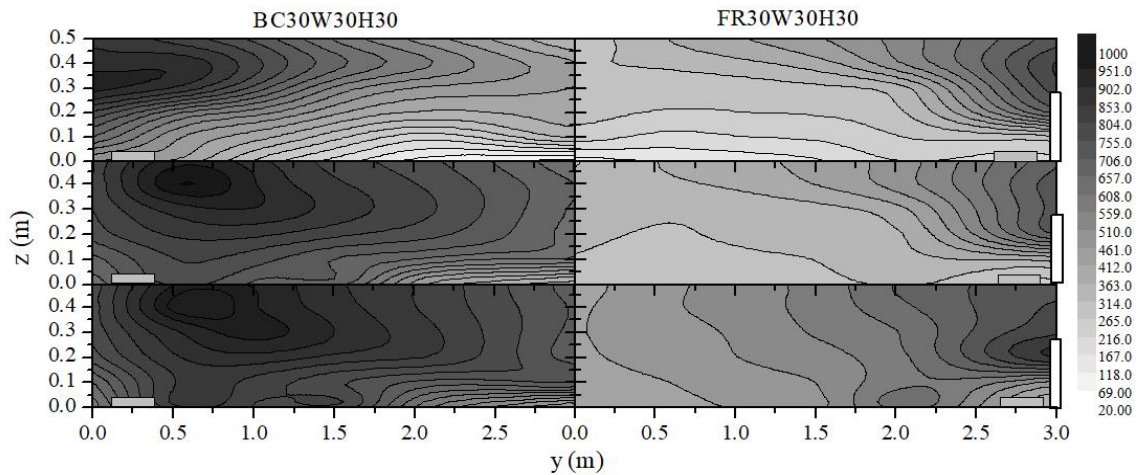


Fig. 4. Spatial visualization of gaseous temperature at the interior of the corridor for test cases F30W30H30 (left) and B30W30H30 (right) for 120, 400 and 900s

During *Region I*, low gas temperatures are observed in the lower layer as fresh air enters the enclosure through the opening that is located at the right side of the corridor. In BC30W30H30 test case, during *Region II*, highest temperatures are observed at the vicinity of Boxes E and D indicating that combustion mainly takes place in those regions and flames gradually propagate towards the opening seeking for available oxygen [7, 8]. During *Region III*, the difference of gas temperatures between the upper and the lower layer decreases towards the closed end of the corridor, but still, they cannot be assumed uniform inside the corridor. In *Region III*, flames fill the upper layer of the corridor extending towards the opening and eventually emerges from the opening when the HRR becomes sufficiently large. In test case FR30W30H30, temperature stratification in the interior of the corridor is less evident as EVF emerge more quickly from the opening resulting in lower temperature profiles at Boxes C to F.

### 3.3 EVF height

Figure 5 plots dimensional flame height,  $Z_f/l_1$ , against dimensionless external heat release rate,  $\dot{Q}_{ex}^*$ , using experimental data from gas burner experiments in rectangular geometries [8], corridors [7] and liquid pool fires in corridors (current study). It is demonstrated that for small flame heights and larger openings the power dependence on the  $\dot{Q}_{ex}^*$ , calculated in accordance to established methodology [7], is 2/3 in accordance the physical mechanism corresponding to “wall fire”, flame attached to the façade wall and “half axisymmetric fire”, flame detached from the façade wall, regimes [8, 11, 12]. For  $\dot{Q}_{ex}^* > 1$  and subsequent larger flame heights, gas burner experimental results from both rectangular and corridor geometries corroborate a 2/5 dependence on the  $\dot{Q}_{ex}^*$  [8,11,13].

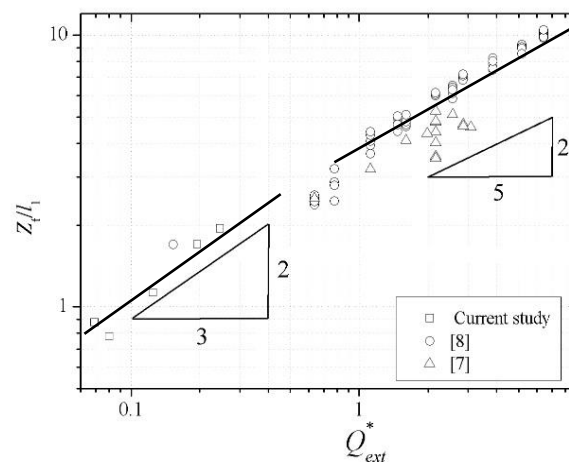


Fig. 5. Flame height correlation for gas burner experiments in rectangular geometries [8] corridors [7] and liquid pool fires in corridors (current study).

### 3.4 Heat fluxes

Heat fluxes on the façade were measured using thin steel plate probes [8,14], the results of which have been verified by comparison with the Gardon gauge results [15]. Fig. 6 depicts the vertical distribution of the heat flux measurements at the centreline of the façade for all test cases. Measured heat fluxes decrease with increasing height as expected. The highest heat flux is always found along the centreline above the opening except for test cases with the widest opening, i.e., BC30H50W50 and FR30H50W50. As it can be seen from their intermittency contours in Fig. 7, the resulted EVF for these two cases tend to emerge as two separate fire plumes from the opening and as a result the maximum heat flux values are off the centreline in contrast to other cases. This finding highlights the importance of the width of the opening in addition to the ventilation factor. For the same opening and pan size, higher heat flux values are found when the fuel pan is positioned in Box A, near the opening.

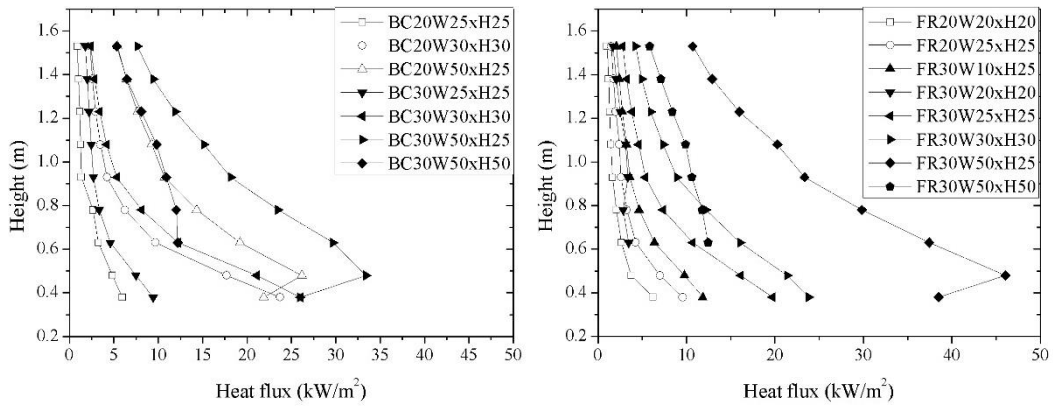


Fig. 6. Vertical distribution of heat flux at the centreline of the façade for the BC (left) and FR (right) cases.

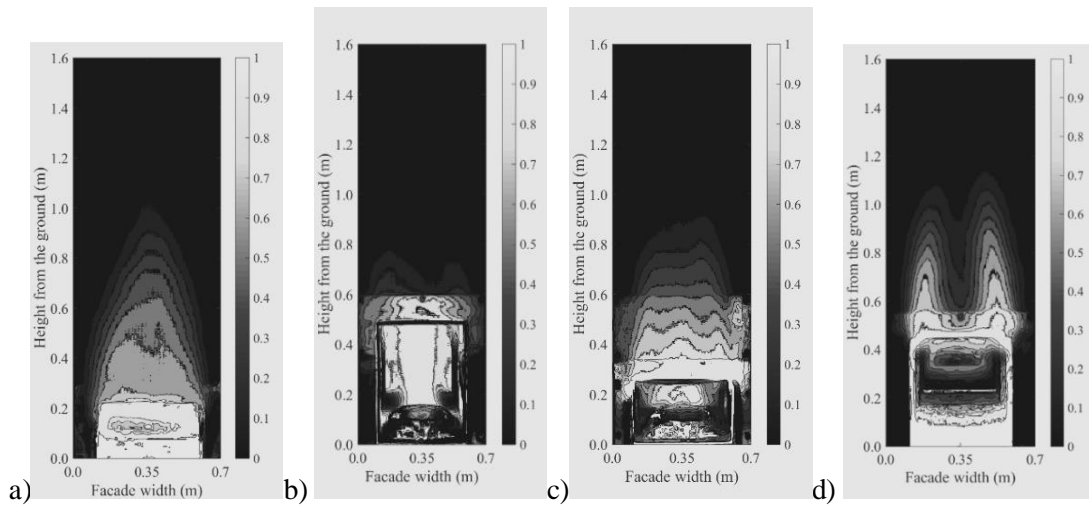


Fig. 7. Intermittency contours for (a)BC30H25W50, (b)BC30H50W50, (c)FR30H25W50, (d)FR30H50W50.

#### 4 CONCLUSIONS

We presented an experimental study on burning characteristics of a liquid pool fire in a reduced-scale corridor-like enclosure and the resulting externally venting flames (EVF) and their impact on the façade. The size and location of the pool fire and opening size were systematically varied. The main conclusions of this work are:

1. Three distinct burning regions (*Region I, II* and *III*) were observed based on  $\dot{Q}_{exp}$  corresponding respectively to fuel-controlled, ventilation-controlled and steady-state burning.
2. The location and size of the fuel pan has a strong impact on HRR and subsequent EVF characteristics.
3. For the cases with small flame heights and larger openings, the power dependence of the flame height of the EVF on the dimensionless external heat release rate  $\dot{Q}_{ex}^*$  is 2/3, compared to 2/5 for larger  $\dot{Q}_{ex}^*$  values found for gaseous fuels in previous studies [7,8].
4. The heat flux measurements using thin steel plate probes are consistent with those measured using Gardon gauges. Centreline heat fluxes are nearly constant just above the opening where the consistent flame region is and subsequently decreases with height. The heat fluxes measurements are consistent with those of heat release rate and flame height.
5. EVF for openings with the largest width (same as that of the enclosure) exhibit different characteristics and tend to emerge from the opening as two separate fire plumes resulting in lower heat flux values at the façade centreline.



- The obtained extensive set of experimental data derived for the interior and exterior of the corridor-like enclosure, can be used to validate CFD models or to evaluate the accuracy of available fire design correlations.

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