Comparison of Large-Scale Façade Fire Test Benches: Methodological Approach

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ABSTRACT

The development of external thermal insulation in buildings has given rise to a risk of fire spread by the façade of buildings, as was demonstrated by the recent Grenfell Tower fire. In order to assess this risk, several countries have enforced mandatory real-scale tests, but these test methods are very different from one country to the next. In these tests, the fire performance assessment is based on different criteria, such as temperature thresholds or propagation. Considering all these differences, comparing the results obtained between different façade fire tests is difficult. The aim of this study is to develop an alternative approach based on a numerical tool (FDS), in order to compare façade fire tests. The analysis focuses on the dynamic evolution of the incident heat flux and its surface distribution. Results indicate that this new approach is able to discriminate between the test benches, and a correlation was exposed between surface impact and heat flux.

KEYWORDS: façade fire, modeling, CFD, thermal stress, comparison methodology, test bench.

INTRODUCTION

Fire is one of the main hazards in high-rise buildings, especially the risk of fire propagation from one floor to the next. For this reason, most building regulations impose fire-protection systems to be implemented in these buildings, especially to prevent the fire to reach the staircases (containment). Another way of fire propagation is via the outside [1], where the fire can make contact with additional fuel, namely the External Thermal Insulation Component Systems (ETICS). These systems are made of a thermal insulation layer (like mineral wool, Polyurethane or Polyisocyanurate), assembled with a wooden or metal structure, sometimes associated with an external cladding (which can be burnable or inert) and an air gap. If the insulation system is not correctly designed, the flame propagation on the façade can be dramatically increased, as it was the case in the Grenfell Tower fire.

These insulation systems often require a specific fire test to be performed to assess their effect on fire spread. Test methods varies considerably from one country to the next, but are often based on full scale test benches, which consider both reaction and resistance to fire. In these tests, a post-flashover room fire scenario is assumed, where the fire destroyed the room's window and is venting through the opening. The ETICS to be tested is fitted on the bench's wall, exposed to the flame.

As these benches are very different from one another (on both geometry and fire source), it is difficult to compare their results and requirements [2,3]. The only common point between these test benches is that they have a compartment fire venting through an opening, with the test wall above the opening. In the literature, experimental data can sometimes be found on reference tests

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performed without an ETICS fitted on the benches. Based on geometrical features, two groups of benches can be identified:

- Corner tests, fitted with a side wall to add a corner effect to the plume. ISO [4], DIN (Germany) [5] and BS (UK) [6] are part of this group.
- Flat wall tests that can include windows (which can be a parameter of the test procedure). LEPIR (France) [7] and SP (Sweden) [8] are example of that group.

A review of the tests' criteria was recently published by Smolka [3], pointing at the diversity of parameters considered during the tests. Most common parameters are visual flame spread and temperature levels at specific height above the fire source. Smolka also pointed the absence of heat exposure measurement in these tests, and named it a crucial parameter in the development of a harmonized test methodology.

A possible way to evaluate the heat exposure is the incident heat flux on the ETICS, and its repartition over the tested surface. This parameter is of utmost importance, as the same amount of fuel can give very different heat exposure given the effect of the geometry, ventilation and wind, as was also pointed out by Smolka [3].

From an experimental standpoint, as the heat flux is distributed on the surface, it would require a prohibitively large amount of heat flux gauges to measure it accurately over the entire exposed surface of a full scale test bench (test surface area is often around 25 square meters). Experimental data exists but was mostly aimed at obtaining a vertical distribution of heat flux above the opening [9, 10].

On the numerical side, simulation studies of different test benches were conducted [11, 12, 13]. However, these studies were mostly concentrating on the gas phase parameters like temperature and velocity profiles inside the plume.

Thus, an alternative approach was developed, using numerical simulations and data treatment to gain insight on the surface distribution of the incident heat flux. Each test bench was simulated, and the data were used to build correlations representing the distribution of the thermal stress imposed by each bench on the ETICS' surface.

NUMERICAL SIMULATIONS

Numerical tool

The modeling tool used in the present work is FDS, v6.5.2 [14]. FDS solves an approximation of the Navier–Stokes equations appropriate for low-Mach number, thermally driven flows. The numerical algorithm employed is an explicit predictor/corrector scheme, second order accurate both in space and time, using a direct Poisson solver. Turbulence is treated using Large Eddy Simulation (LES), via the Deardorff subgrid scale model. A lumped species combustion model assuming a unique, Arrhenius piloted global chemical reaction is used to estimate the heat release and smoke distributions in the computational domain. The radiation transport is treated using a finite volume solver in which grey gas absorption coefficient for soot and gas species is linked to the products fraction.

Modelling of testing facilities

Three dimensional models of the façade fire tests were created by using a Cartesian mesh. The quality of the computational mesh and the resolution of flow field can usually be assessed by non-dimensional ratio $D^*/\Delta d$. Lin et al. [15] recommend $D^*/\Delta d \geq 10$ or more to predict with precision the radiative heat flux. The recent MaCFP workshop report [16] gave more insight on the importance of taking into account other length scales to select the mesh size. According to this requirement, the cells dimensions should be order of 10 cm. Therefore, a uniform numerical grid Δd of 5 cm was chosen, as a result of a compromise between flow resolution and computational time. The computational domain is defined in order to contain the flame as a whole. The domain boundaries are located at a sufficient distance from the building (and the flame) so that they do not incorrectly affect the flame dynamics. Minimal distance between the solid walls and the domain boundaries is 0.5 meters.

The test apparatus was dimensioned according to the experimental test facility. The dimensions of the test benches are adapted to fit within the chosen spatial discretization. The errors induced on the dimension are in the range of 5%.

As initial conditions, the gas in the computation domains was set still with ambient temperature (T_∞ = 23°C). At the domain borders, a zero normal gradient static (Neumann type) was employed. The atmospheric pressure is fixed at 101325 Pa and the humidity is defined at 50%. Thermal properties of the materials were unified between the different benches to focus the analysis on the effects of bench design and fire source. Table 1 details the material properties used in the simulations. Table 2 lists the features of the tests benches, as defined by their respective standards, as well as the dimensions of the computational domain considered.

Table 1. Material properties

Property	Combustion chamber	Test wall
Specific heat, kJ/(kg·K)	0.88	0.88
Thermal conductivity, W/(m·K)	0.92	0.76
Density, kg/m^3	2500	1500

DATA PROCESSING

In order to compare the benches, data from the simulations should be extracted; this is usually done with localized sensors in FDS, measuring the values of a quantity through time at a pre-determined position in space. However, one would need a (very) large amount of sensors to obtain the complete heat flux mapping on the tested wall. In this paper, a new approach is presented, using the boundary files data. Boundary files are often used for qualitative observations, but are scarcely used for quantitative measurements, in no small part due to the fact that these files are encoded for Smokeview and not readily understandable for the user.

The fds2ascii program is a small utility software used to extract data from the boundary files (.bf extension) in a human-understandable format. Using a MATLAB script to perform repeated calls of this software through a loop, the time-resolved incident heat flux data were obtained, using a 10 s time averaging. This 10 s averaging was deemed a good compromise between time resolution and data volume. These data are then converted in stacks of matrix format, whose dimensions are equivalent to the size of the considered wall (3rd dimension is the time). For test benches outfitted with a side wall, main wall and side wall are treated separately then the side wall piece matrix is appended to the main wall matrix.

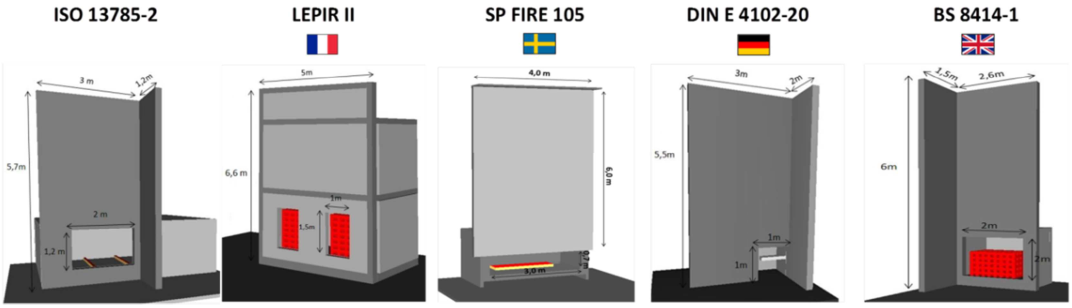
The matrix dimensions are limited by the mesh size used during the FDS simulations. In order to ensure a better behavior of subsequent image treatment algorithms, a bicubic interpolation scaling [17] was used to increase each dimension by a factor 5.

By considering the heat flux matrices as images, a thresholding algorithm was then applied, converting the values in each cell to a zero or a one whether their values are below or above the considered threshold. Threshold values were chosen from 10 to 70 kW/m^2, with 5 kW/m^2 steps. An example of the original Smokeview visualization and corresponding binary image is presented in Fig. 1.

Table 2. Test benches features

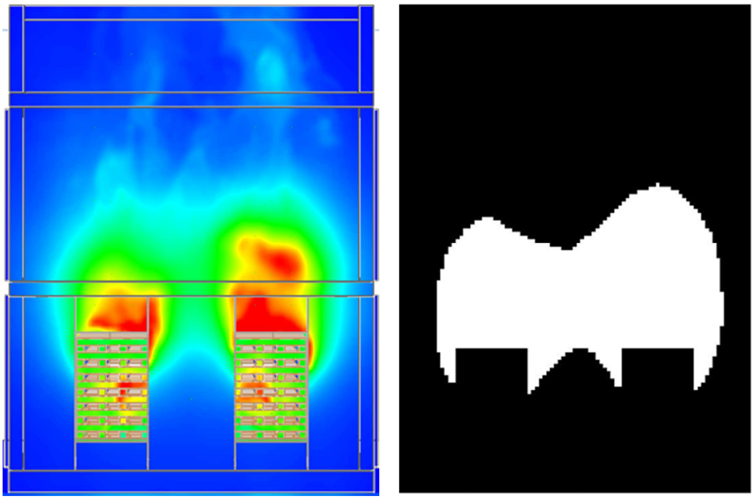
Standard	ISO 13785-2	LEPIR II	SP FIRE 105	DIN E 4102-20	BS 8414-1
Ref.	[4]	[7]	[8]	[5]	[6]
Country	International	France	Sweden	Germany	UK
Configuration	Corner	Flat wall	Flat wall	Corner	Corner
Vertical main test wall	w ≥ 3.0 m h ≥ 4.0 m	w = 5.0 m h = 6.5 m	w = 4.0 m h = 6.0 m	w ≥ 2.5 m h ≥ 5.5 m	w ≥2.6 m h ≥6.0 m
Vertical return wall (wing at 90°)	w ≥ 1.2 m	-	-	w ≥ 1.5 m	w ≥1.5 m
Volume of Combustion chamber	$20 \leq V \leq 100$ m^3	30.3 m^3	6.74 m^3	0.7 m^3	≥ 4.275 m^3
Main opening	2.4 m²	2 x 1.5 m²	2.13 m²	0.7 m²	4 m²
Secondary opening Natural ventilation	-	0.99 m² on rear face by a variable opening	0.94 m²	-	-
Heat source	a/ Propane b/ Liquids c/ Wooden cribs	Wooden cribs (x2)	Heptane fuel	a/ Wooden crib b/ Liquids	a/ Timber crib b/ Liquids
Fuel quantity	a/ Calibration b/ ~ 60 liter (ex: Heptane) c/ ~400 kg	300 kg each	60 liter	a/ 30 kg b/ propane	a/ Nominal total heat output of 4500 MJ (30 min) at a peak rate of 3 ±0.5 MW
Test duration	23 - 27 min	60 min	15-20 min	a/ 20 min b/ 30 min	30 - 60 min
Computational domain dimensions	8.1 x 7.2 x 7.2 m^3	7 x 8 x 7.2 m^3	6 x 6 x 8 m^3	4.5 x 3.2 x 6 m^3	5.4 x 5 x 9 m^3

(h: height above the window opening)



At each time step, each binary matrix is summed, and the result is then divided by the total number of cells in the matrix (minus the cells representing the openings). Thus, the time-resolved fraction of the surface area that received a heat flux superior to the threshold value is obtained. This parameter S/S_0 will be called surface impact (S_0 being the total surface area of the bench, minus the openings).

Using the same binary image, the maximum height reached by the threshold heat flux can also be measured (measurement axis being the centerline of the opening). Normalizing by the height above the opening give the second parameter H/H_0, called height impact. Figure 2 resumes the quantities measured, using the ISO bench as an example.



(a) (b)

Fig. 1. LEPIR Bench. (a) Incident heat flux as seen in Smokeview; (b) associated binary image (Threshold 20 kW/m^2).

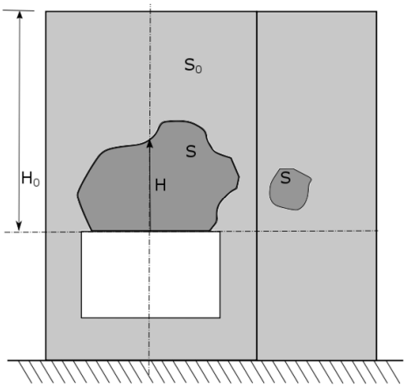


Fig. 2. Measured quantities on the ISO bench.

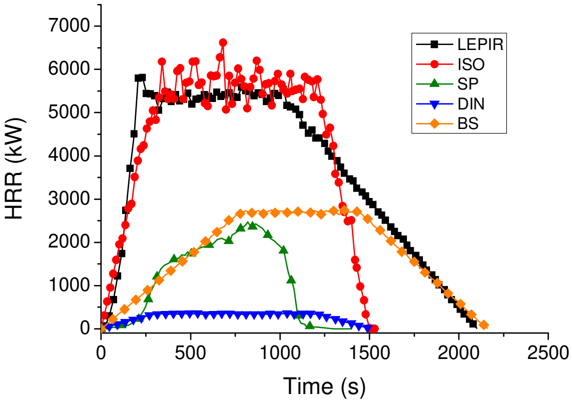


Fig. 3. Heat Release Rate (HRR) used for each simulation.

The use of the opening centerline as an axis for the measurement of H warrants a discussion. One could argue that, due to the corner effect, maximum height will be reached at (or toward) the corner and not on the centerline. However, the available experimental data mostly give centerline measurements [9,10]. Furthermore, in order to maintain comparability between flat and corner benches, a compromise had to be made. In the future, the possibility to consider the tilt angle and length of the plume (instead of raw height) will be investigated.

All the heat release rates (HRR) used in the simulations present a stationary stage (except SP), as described in Fig. 3. Hence, the surface fraction and maximum height associated to each threshold value were averaged on the time window corresponding to this stationary stage. For the SP bench, as an experimental HRR curve was used [18], the averaging window was centered on the maximum HRR and spanned 2 min before and 2 min after the maximum. Table 3 gives the parameter used for the determination of the stationary state.

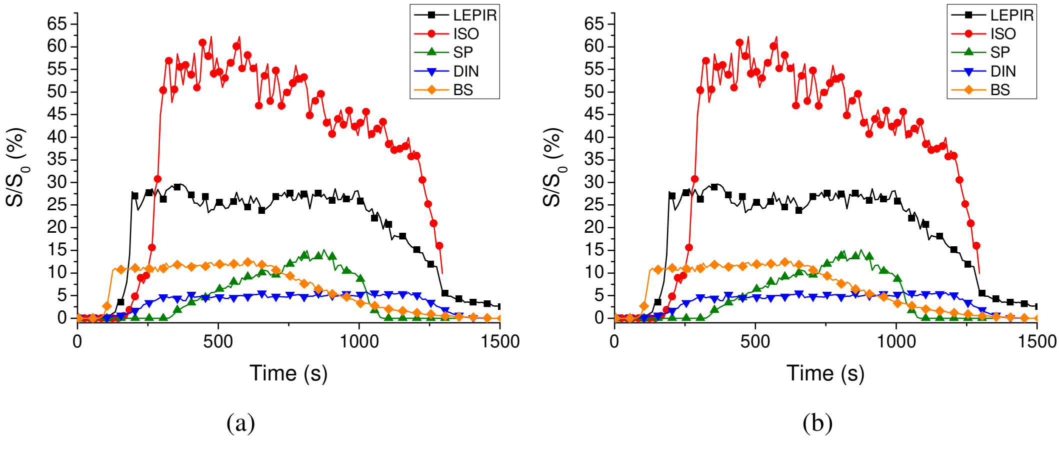
Table 3. Stationnary state parameters used for each test bench

Test bench	Start time (s)	End time (s)	HRR (kW)
ISO	330	1200	5687
LEPIR	200	1000	5403
SP	710	950	2500
DIN	300	1200	340
BS	135	620	2507

RESULTS AND DISCUSSION

Time-dependent measurement of surface area

Figure 4 represents the obtained results of surface impact associated to thresholds of 20 and 40 kW/m^2, as a function of time. The behavior of the surface impact variable is following the HRR curves, with the exception of the ISO bench showing a general decreasing tendency after the initial increase. This figure also shows that the choice of the incident heat flux threshold value can change the relative position of each bench. For a 20 kW/m^2 threshold, SP and BS are equivalent (considering maximum values), while SP reaches higher than BS for 40 kW/m^2.



(a) (b)

Fig. 4. Surface impact as a function of time. (a) Threshold value 20 kW/m^2; (b) Threshold value 40 kW/m^2.

Time-averaged values of surface area

As explained previously, the obtained data were time-averaged on the duration of the stationary stage. This step was necessary to filter out the fluctuation associated with the turbulent fire plume. The results are shown on Fig. 5 as a function of heat flux values, where error bars are the standard deviation on the interval considered for the time-average.

From these results, several conclusions can be drawn. It appears first that the ISO bench is generating the most thermal stress on the wall, being systematically above the other benches, surface-wise, on the entire heat flux range considered. The LEPIR bench, while using a slightly less powerful heat source (5.4 MW vs 5.7 MW for ISO), has less of an impact on the test wall. It is clear that this difference is caused by the geometric features of the benches, especially opening dimensions and side wall.

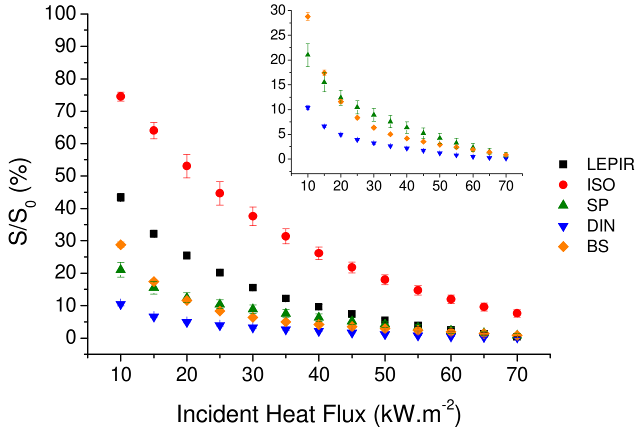


Fig. 5. Surface impact as a function of incident heat flux (in picture: zoom on the SP, BS and DIN values).

Comparing the SP and BS benches (both 2.5 MW) shows a different behavior. Except for 10 kW/m^2, where the BS surface impact is higher, both benches give similar results in terms of surface impact, despite their geometric differences. On the other hand, BS and DIN have very different surface impact, despite having very similar geometric features. This can be explained by the relatively low heat release rate used for the DIN test (340 kW).

Surface impact data correlates extremely well with the incident heat flux q_i'', following a decreasing exponential law: $s/s_0 = \alpha \exp(-q_i''/\beta)$. Table 4 lists the exponential laws parameters α and β, as well as the correlation coefficients R² for each bench. So far, there is no physical interpretation of this correlation, as it is probably a combination of several parameters of the tests. More than likely, heat release and geometry both contribute to this correlation.

Table 4. Exponential regression parameters for surface impact

Test bench	α	β	R²
ISO	108.4	27.9	0.999
LEPIR	72.4	19.2	0.997
SP	30.6	23.9	0.990
DIN	17.2	17.5	0.983
BS	55.8	13.9	0.977

Time-dependent measurement of height

Figure 6 represents the maximum height obtained for the same thresholds. It is difficult to draws a conclusion when considering the height parameter, as this parameter is very sensitive to the geometrical features of the bench (corner effect, number of openings) as well as the effect of turbulence. It must be noticed that for a 20 kW/m^2 threshold, the maximum height for the ISO bench equals the height of the bench (e.g. the flame reaches higher than the wall). This behavior is a potential source for uncertainties.

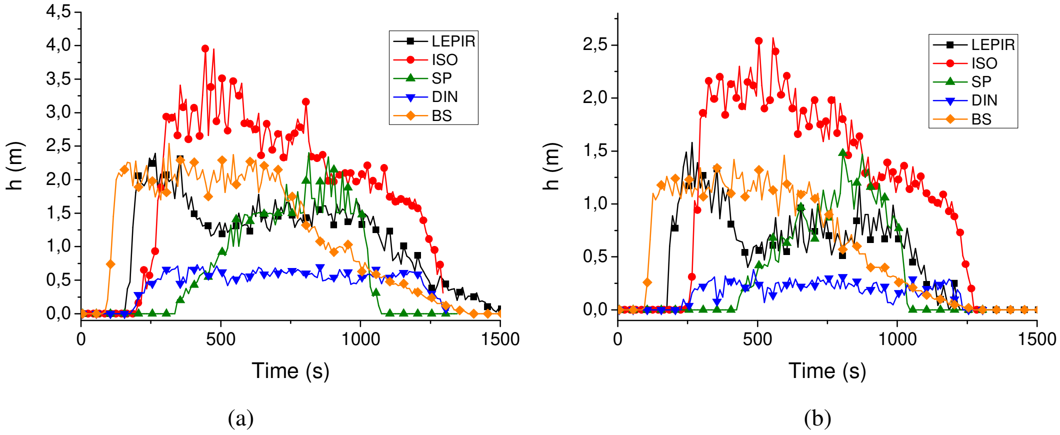


Fig. 6. Height impact as a function of time. (a) Threshold value 20 kW/m^2; (b) Threshold value 40 kW/m^2.

Time-averaged values of height impact

The treatment used for surface impact was also applied for height data, and presented on Fig. 7. The transition from flaming region to plume region is difficult to identify on these data. Previous experimental work by Lee et al. [10] produced correlations between the external heat release (fuel burning outside of the combustion chamber) and the vertical variation of heat flux received on the wall. These correlations were relying on measurements of the flame height but such a parameter is difficult to access in a numerical simulation, as there are several possible parameters to consider (HRRPUV, temperature, etc.).

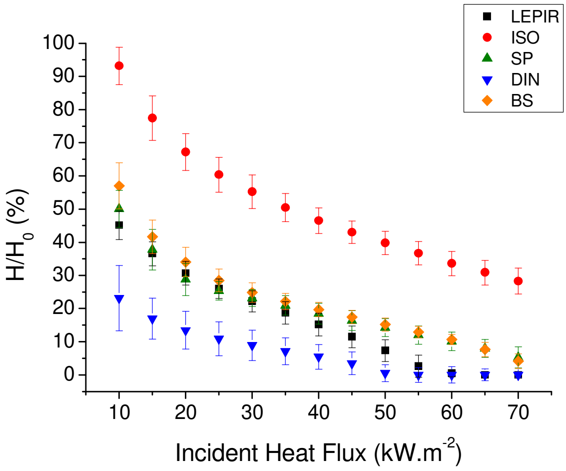


Fig. 7. Normalized height impact as a function of incident heat flux.

Uncertainties and sensibility

The existing literature on numerical simulation of this type of test benches [12, 13] yields uncertainties on numerical values of heat flux in the range of 15%. This means that uncertainties in the present results are to be expected on the higher heat flux values considered, as a constant 5 kW.m^{-2} interval was used in this work. Height impact values appear to be more prone to variations that surface values. This is coherent with the fact that the flame oscillates more on the vertical axis than on the horizontal axis; it is a reasonable assumption to consider that most of the variation in the surface impact values are generated by vertical variations.

CONCLUSION AND FUTURE WORK

In this work, numerical simulations of different façade fire test benches were conducted, and a numerical methodology was proposed for the heat flux data. This methodology is designed for data distributed over a planar surface, so it could also be used for wall temperature, or even accumulated thermal energy (using time integration of net heat flux). The proposed methodology gave access to the time-resolved surface distribution of incident heat flux for the test benches. From this distribution, two time-averaged parameters can be derived, namely surface impact and height impact. These values, being based on the incident heat flux, are representative of the thermal stress imposed by the test procedure on the surface.

The most evident added value of these parameters is that they can be defined independently of the bench geometry (flat wall or corner). It can even be used for smaller test benches like ISO 13785-1 or EN 13823 (Single Burning Item). As these parameters are based on the surface distribution of heat flux, they are less sensitive to local effects and completely independent of sensor positioning as the entire surface is the sensor. Height impact could be associated to flame height measurements, in order to check the available correlation of the literature. This would require a reliable numerical measurement of flame height.

The presence of wind during outside tests (namely LEPIR) can tilt and/or stretch the flame, generating an oblique thermal imprint on the surface. This would likely have no influence on the surface impact values, but the height impact values can be severely affected by this phenomenon, as only the vertical direction was considered in the present work, and the measurement were made on the centerline. Future development will include numerical simulations with variable wind speed and orientation, as well as data treatment modifications to deal with oblique thermal plume. This development will also be used to investigate oblique plume generated by corner effects.

If the façade material could be considered as a single, homogeneous material, a critical heat flux measurement could be used to evaluate immediately the minimal surface that is going to be burned during the test. However, most external insulation systems are assemblies of several different materials (insulation, cladding etc.) with different properties. The way the system is assembled is also a critical parameter, especially for ventilated air gap systems, like the one used on the Grenfell Tower.

Given the scale of the test benches and the costs to run them, it is difficult to obtain validation data to compare the simulations with experiments. Furthermore, in the considered test benches, it is sometimes difficult to obtain an accurate measurement of the actual HRR, especially when using solid (wood cribs) or liquid (hydrocarbon) fuel. Analytical approach currently used to estimate the HRR/MLR of such type of fire source is designed for an open space fire and is not suitable for a semi-confined room fire. It is also difficult to determine the amount of fuel that burns outside of the combustion chamber. This fraction is of critical importance as it is responsible for the most part of the thermal stress imposed on the surface. Hence, it may be difficult to compare the present results with the existing correlations built on intermediate scale tests [1].

In order for the proposed methodology to be relevant, more experimental data will be required, especially on the true heat release rate to be considered. This might be a challenge given the size of the experimental facilities involved, but there is a need for reliable heat release data in order to consolidate this comparison methodology.

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