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MODELLING OF THE GROWTH PHASE OF DALMARNOCK FIRE TEST ONE

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ABSTRACT

The challenge of modelling a well characterized full-scale fire test using computational fluid dynamics is illustrated in this work comparing *a priori* and *a posteriori* simulations. In 2006, The Dalmarnock Fire Tests were conducted in two identical 3.5 m 4.75 m 2.5 m concrete enclosures with a real residential fuel load. This data set provides measured data at the highest spatial resolution available from a fire experiment to date. Prior to the tests, an international study of fire modelling was conducted in order to assess the state-of-the-art of fire simulations using a round-robin approach. Each of the seven round-robin teams independently simulated the test scenario a priori using a common detailed description of the compartment geometry, fuel packages, ignition source and ventilation conditions. Most teams decide to use the numerical code Fire Dynamics Simulator (FDSv4). Comparison to the experimental measurements showed a large scatter and considerable disparity (much larger than the error and variability associated to the experiments). The study showed that the accuracy predicting fire growth is poor. *A posteriori* simulations of the growth phase were conducted afterwards while having full access to all the measurements. No previous fire simulation had this large amount of data available for comparison. Simulations were compared against average and local measurements. The heat release rate is reconstructed from additional laboratory tests and upper and lower bounds for the fire growth are found. Within these bounds and after adjusting uncertain parameters, the level of agreement reached with the measurements was of 10 to 50% for the evolution of the average hot layer temperatures and between 20% and 200% for local temperatures.

INTRODUCTION

Modelling of compartment fires using computational fluid dynamics (CFD) has been a research topic since the introduction of computational techniques in fire science in the 1980's[1]. Only in the last decade the available computational power and knowledge of fire dynamics have grown sufficiently to carry out simulations in real-size building enclosures, using grids that are fine enough to reproduce fire-driven flows reasonably well[2]. Since then, CFD has been used extensively to model enclosure fire dynamics[3, 4, 5] both in research and in industrial applications. There are two common industrial uses of CFD. One is for design of the fire safety strategies in the built environment (life safety and structural integrity, and which results are rarely made available for public scrutiny) and the reconstruction of accidental fires as part of forensic investigations (recent examples are the 2001 WTC[6], the 2003 Station Nightclub[7] and the 2005 German five-storey apartment[8]).

The state of the art of fire modelling is such that given a fire of known size and power (evolution of the heat release rate (HRR)), CFD calculates the resulting temperature and smoke concentration fields. The fire source is therefore treated as an input into the model by means of a prescribed HRR as a function of time. This poses a problem in the study of accidental fires where the HRR is unknown. Predicting the evolution of the HRR (i.e., spread rate and growth pattern) instead of measuring it is among the most challenging pending issues in fire research[9, 10].

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Most modelling work in the literature corresponds to scenarios with simple fire sources, like pool fires or a single burning item of constant or near constant HRR. This type of scenario avoids the more complex processes of flame spread and fire growth observed in real fires. Little research has been done comparing simulations with real-scale fire tests that use realistic fuel loads. Some important examples using pool and crib fires are presented here. Reneke et al.[11] conducted a posteriori simulations of fire tests involving crib fires in a full scale single compartment with a zone model obtaining reasonable agreement with the measured average temperatures when the measured HRR is used as an input. Miles et al.[12] obtain good results in average temperatures when performing a posteriori simulations of a series of fire tests involving wood cribs. Although local measurements where available, none of these two simulation papers compared results at the field or local level. Rinne et al.[13] found temperature profiles, smoke layer heights and gas species concentrations in a 10 by 10 by 5 m compartment predicted by FDSv4 to be in good agreement with experimental data for the burning of pool fires (heptane or toluene) and single cribs (PMMA or wood). The measured mass loss rate of the fuel was used to calculate the HRR, which was then input into the model.

The evaluation of the entire process of fire modelling, in which the mathematical model is only a component, is an important task for the advancement of fire safety engineering. The state-of-the-art of fire modelling is reflected not only in the mathematical model's capabilities, but also on how it is implemented throughout the different stages of fire modelling[9]. The assumptions made by the user, the collection of data for input and the selection of the parameter values are crucial components leading to the creation of the input file. This is particularly important when advanced and complex computational tools are used (eg CFD and evacuation modelling). Under the current state of the art, there are many ill-defined and uncertain parameters within the models which cannot be rigorously and uniquely determined. Thus, there is plenty of space for uncertainty and doubt to unravel, and for curve fitting and arbitrary parameter value selection to take place. This is summarised best in the words attributed to the German scientist Carl Friedrich Gauss (1777 – 1855): "*Give me four parameters, and I will draw an elephant for you; with five I will have him raise and lower his trunk and his tail*".

This paper reports a series of CFD simulations (with FDSv4) conducted a posteriori to reproduce the large-scale Dalmarnock Fire Test One that involved several real burning items leading to a complex fire spread process. The interested reader is referred for more details to Jahn et al.[14] on which this work is largely based.

DALMARNOCK FIRE TEST ONE

Detailed information about the experimental set-up and the chain of events that occurred during the Test One can be found elsewhere[15, 16], but a short summary is given here. Test One was held in a two-bedroom single family flat, with the living room set up as the main experimental compartment. This compartment was 3.50 m by 4.75 m wide and 2.45 m high and made of concrete walls. It had two-pane window as shown in Fig. 1.

While the main source of fuel was a two-seat sofa stuffed with flexible polyurethane foam, the compartments also contained two office work desks with computers, each with its own foam-padded chair, three tall wooden bookcases, a short plastic cabinet, three small wooden coffee tables, a range of paper items and two tall plastic lamps. A plastic wastepaper basket filled with crumpled newspaper and 300-500 ml of heptane was the ignition source. The fire spread to a blanket on the sofa hanging into the basket, igniting the seating area of the sofa. After about 275 s the bookshelf next to the sofa ignited and was rapidly engulfed in fire. Within 25 s after ignition of the bookshelf the compartment reached flashover conditions (see Table 1 for a time line of the events). An estimation for the post-flashover fire results in about 3 MW before the first window breakage, and about 5 MW after the second breakage[16]. But the evolution of the HRR during fire growth is unknown. Figure 2 shows the average temperature of the hot layer d in Test One and Test Two. A detailed presentation of the data can be found in[15, 16].

Prior to Test One, laboratory experiments were conducted in order to determine the HRR curves for the sofa and the bookshelves inside the furniture calorimeter (using an exact replica of those used in Test One)[15]. A second series of laboratory experiments was conducted after Test One in order to analyze variations to the ignition protocol[17]. These two sets of experiments were the only direct source of information on the HRR in Test One.

Figure 1. Room layout with location of furniture and sensors[15, 16].

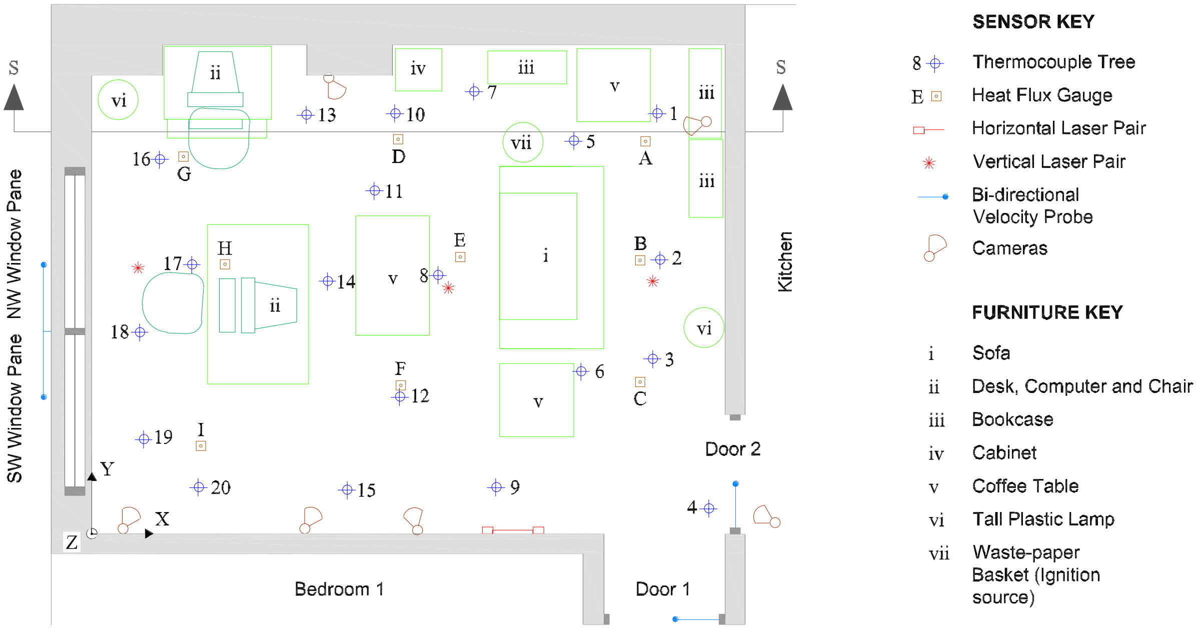


Figure 2: Top:Average of the measured temperatures in the hot layer (corrected for radiation) in the Dalmarnock Test One and Test Two. The shaded areas indicate standard deviation. Test One was allowed to continue burning during the post-flashover stages whereas Test Two was extinguished immediately after flashover. Bottom) View of the ignition source, the sofa and nearby items in the main compartment: a) before the fire and b) after the fire.

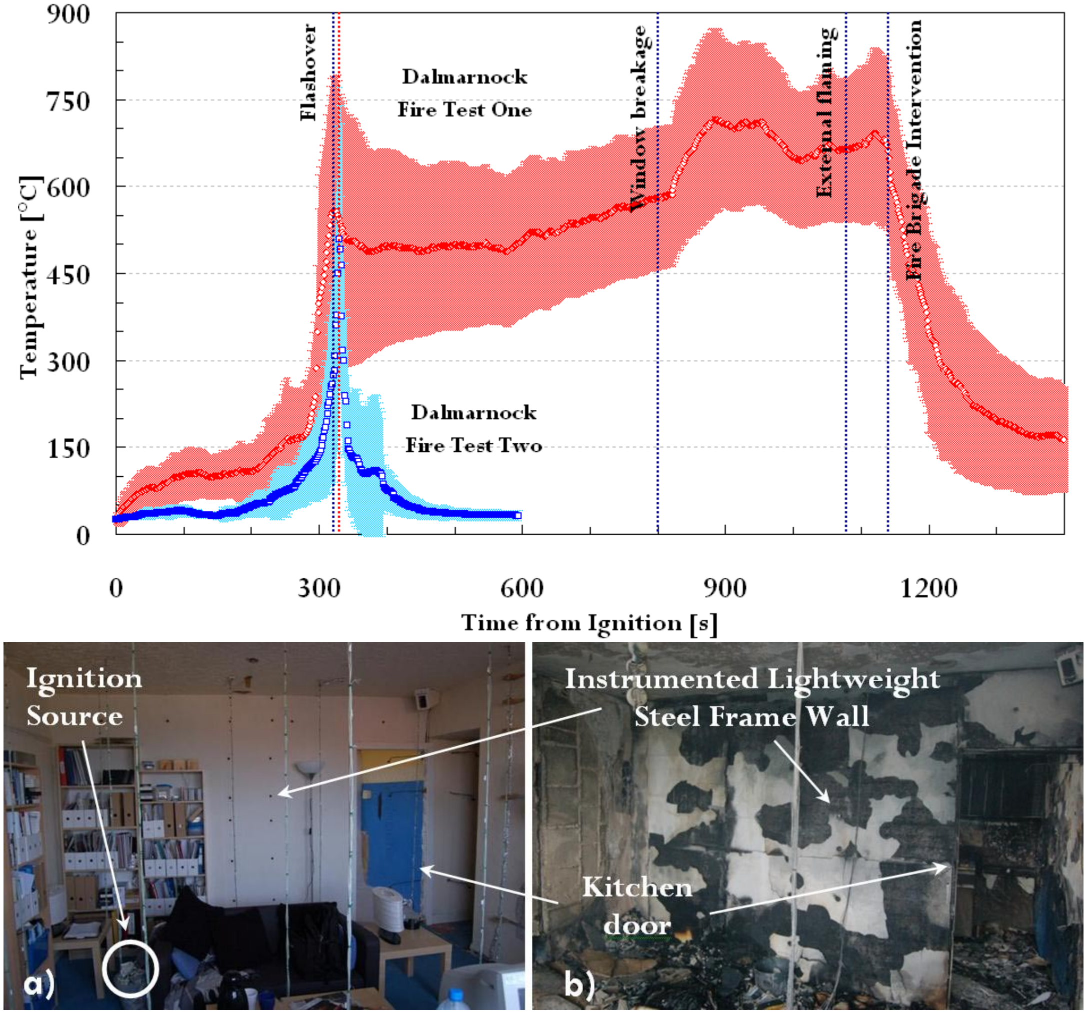
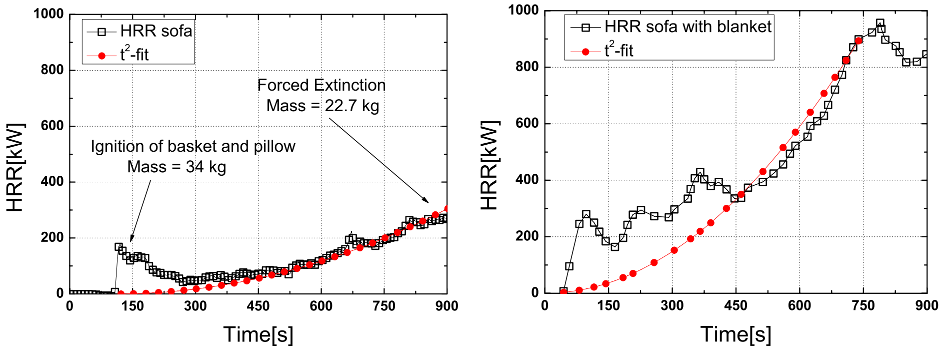


Figure 3 shows the evolution of the HRR of the sofa and the effect of variations to the ignition source. The experiment conducted prior to Test One (referred to as Set 1) consisted of a sofa with two cushions, and a waste paper basket located next to the sofa. Accelerant was poured into the paper basket and the basket was ignited. The fire then spread over the armrest to the sofa and was stopped about 800 s after ignition when approximately one third of the sofa had been burnt. In the experiments conducted after Test One (referred to as Set 2), the exact ignition protocol of Dalmarnock Test One was replicated, which was like Set 1 but including a blanket that had been placed over the armrest of the sofa, and the accelerant distributed between basket and blanket. The presence of the blanket in Set 2 allowed the fire to bypass the armrest fire barrier and led to a faster growth rate involving the cushions. The fire growth rate for Set 2 is equivalent to a t-squared fire with growth constant 1.6 W/s (a medium fire [18]). The constant in Set 1 is 0.5 W/s (corresponding to a slow fire [18]). The two tests show that the uncertainty in the growth rate of the sofa fire during the early stages is significant and varies between a slow and a medium fire.

Figure 3 suggests two patterns in the burning behaviour; an initial peak that rapidly decreases is followed by a growing fire that resembles a t-squared curve. A similar behaviour can be seen for Set 2. It is conjectured that the initial peak corresponds to the waste paper basket, accelerant and the blanket (in the case of Set 2), while the t-squared fire corresponds to the sofa itself.

Figure 3: Measured HRR for variations to the ignition source and equivalent t-squared fires: a) measured in the laboratory prior to Test One including sofa and waste basket (Set 1); and b) after Test One including the sofa, waste basket and blanket (Set 2).



[Set 1: Sofa without blanket] **[Set 2: Sofa with blanket]**

A PRIORI VS. *A POSTERIORI* MODELLING

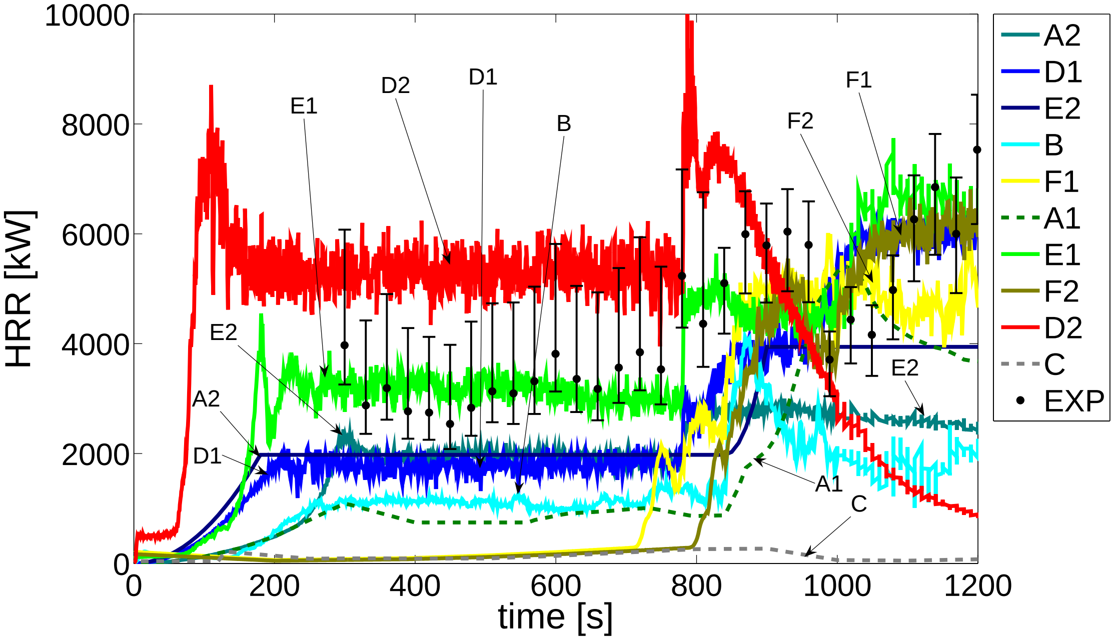
Before the Dalmarnock Tests were carried out, a round-robin study of blind predictions[9] was conducted in order to explore the a priori predictive capabilities of fire modelling in realistic scenarios. The aim of the exercise was to forecast the fire development as accurately as possible and compare the results. Comparison of the modelling results showed a large scatter and considerable disparity among the predictions, and between predictions and experimental measurements. The scatter of the simulations was much larger than the error and variability expected in the experiments. The study emphasized on the inherent difficulty of modelling fire dynamics in complex fire scenarios like Dalmarnock, and showed that the accuracy of blind prediction of fire growth (i.e. evolution of the heat release rate) is poor.

During the growth phase, most simulations over-predicted the hot layer temperature I the range of 20% to 500%. During the post flashover, most simulations under-predicted the hot layer temperature between 20 % to 80 %.

The present work revisits the modelling of the Dalmarnock Fire Test One, this time using the large set of measurements available. That is, the work is conducted a posteriori. Many different simulations are conducted and many parameters are adjusted and readjusted until acceptable agreement is reached. Work is focused only on the growth phase of the Dalmarnock fire Test One. The interested reader is referred for more details to Jahn et al.[14] on which this work is based.

As mentioned before, during the growth phase of Test One the evolution of the HRR is unknown. Moreover, the laboratory experiments of the sofa and similar ignition sources show significant uncertainty. Indeed, this is one of the most important issues addressed in this article. The challenge is to be able to reproduce the HRR such that the fire environment (temperature and smoke) is simulated correctly. The work solves a large and complex inverse problem by trial and error.

Figure 4: Evolution of the global heat release rate within the compartment. Legend for the different curves: continuous line for CFD simulations; dashed line for zone model simulations; and dotted for the experimental data with error bars. From ignition to growth phase up to flashover and suppression.



COMPUTATIONAL MODEL

The code Fire Dynamics Simulator v4.07[19, 20], one of the most commonly used fire CFD codes, is used here. FDS solves a form of the Navier-Stokes equations adequate for low-speed thermally driven flows. While large eddies are solved directly, turbulences at subgrid scale are modelled using Smagorinsky's approach[21].

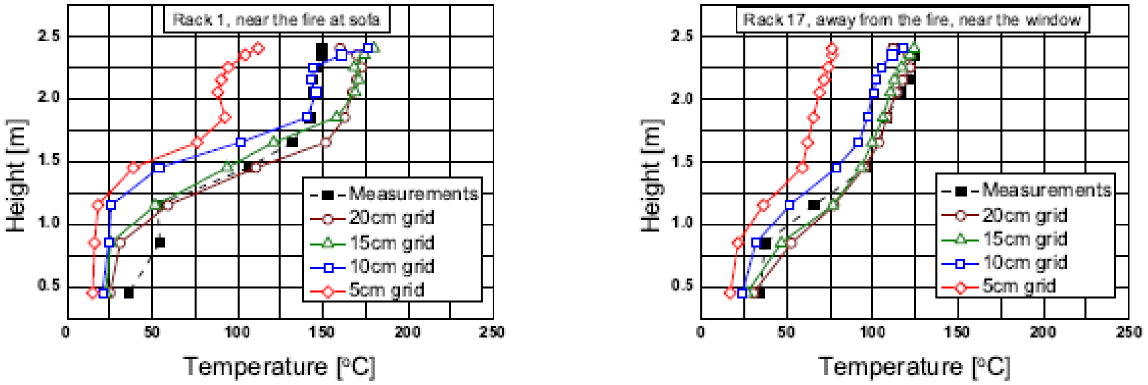
FDS is a tool still under active development, and improved versions are released with some frequency. At the time this paper goes to press, FDS v5 had been released and FDSv6 is expected soon. But research has a characteristic time that seems to be longer that the time between version releases of FDS. This means that by the time a research project has been completed and conclusions have been reached, newest versions might be available. While not all of the fine results of this paper might apply directly to FDSv5 or FDSv6, the merit of the study is that the bulk of the conclusions relate to the significant amount of papers in the technical literature where FDSv4 was used, and to current fire safety engineering. This last is particularly important for infrastructure designed, approved and built, and to forensic findings agreed on with the aid of FDSv4.

The computational domain used reproduces in detail the main Dalmarnock compartment and includes the vent openings (two pane windows to the exterior), the nearby kitchen (with another window to the exterior) and the hallway connecting to the apartment entry. The fuel load in the main compartment was reduced to the fuel elements involved in the growth phase; the sofa, the ignition source and two bookshelves in the corner behind the sofa.

The grid size is one of the most critical parameters in numerical simulations. In the scope of this work a large number of simulations had to be run in order to converge toward good agreement with the measured data and it was therefore necessary to use a sufficiently coarse grid allowing for an efficient use of computational resources. However, too coarse a grid could induce significant numerical errors in the solution. It has been proposed[23, 24] that to resolve the fire plume properly, the ratio between the characteristic fire diameter and the grid size should be at least 5 to 10.

During the growth phase, the peak of the HRR is ~300 kW, and the characteristic diameter of the sofa is around 0.6 m. Hence the grid size should be smaller than 11 cm for an adequate plume resolution. In order to select an adequate grid size, simulation were run with a wide range of different grid sizes: 5 cm, 10 cm, 15 cm and 20 cm edge cubes. The HRR was prescribed according to the laboratory experiment Set 1. Figure 5 shows the temperature vs. height distribution at two different locations in the experimental compartment, one near the burning sofa, and one near the window away from the fire (see Figure 1 for rack locations). The time of comparison is 140 s with data are averaged in time (10 s). The simulations using coarser grids (15 and 20 cm) actually showed better agreement when compared to the measured data, both qualitatively and quantitatively than the finer grids (5 and 10 cm).

Figure 5: Comparison of results with different grid sizes at 140 s: a) distribution at the north wall next to the bookshelf (rack 1); and b) distribution near the window (rack 17). Data are averaged over 10 s.



(a) (b)

Based on this grid dependency study, the 10 cm grid was chosen because it showed good comparison to the experiments, allowed for fast computations and complied with the recommendation associated to the characteristic fire diameter[23, 24].

HOT LAYER AVERAGE TEMPERATURES

Two distinct levels of detail are analysed. This section predicts the average hot layer temperature while the next section looks at the distribution of local field temperature and wall heat fluxes. Comparison at detailed level requires a good agreement at averaged level first.

As seen in the Set 1 and Set 2 experiments, the blanket significantly modifies the HRR. A possible HRR of the blanket alone can be estimated assuming quadratic growth and decay phases. The blanket, made of cotton, weighed 1 kg, hence the total combustible energy stored in the blanket including 100 ml of accelerant can be estimated to be around 21 MJ[22], assuming a heat of combustion of 16.5 MJ/kg for the cotton. The resulting peak HRR would be 150 kW. This is not negligible compared to the measured HRR of the sofa in the early stages, and should therefore be included in the input HRR for the model. Figure 6 shows the reconstructed HRR of the blanket alone and its addition to the HRR of Set 1. The resulting HRR is referred to as Set 1b. Note that here the data is shifted by 150 s compared to Fig. 3, so that the ignition occurs at 0 s.

The predicted hot layer average temperature using different HRR and comparison to measurements are shown in Figure 7. For the Set 1 (Fig. 7a), the simulated hot layer temperature rise agrees with the measurements during the first 100 s. Results are in lower (up to 50% error) for the simulated average temperatures after t=100 s. For Set 1b (Fig. 7b), the simulated hot layer temperatures are in good agreement with the measured temperatures (within the instrumental uncertainty) until 200 s into the fire. After that, the simulated temperature decreases in contrast to the measured temperature which rises continually until flashover. For Set 2 (Fig. 7c), the average hot layer temperature is overpredicted by about 50% between 25 s and 100 s, and by about 35% between 150 s and 250 s.

Overall, it is seen that Set 1 results in unrealistically low average temperatures for the hot layer, but Set 1b and Set 2 provide predictions closer to the measurements. Thus, it is concluded that Set 1b provides a lower bound to the HRR curve during the growth phase, while Set 2 is an upper bound. This range captures the intrinsic uncertainty of fire growth in real complex scenarios and also includes experimental variability. The uncertainty in the average temperature predictions using these HRR bounds is between 0 and 50%. It confirms that to predict temperatures with reasonable agreement, the HRR must be well characterized.

Figure 6: Addition of the blanket to the HRR measured in Set 1 (Measured sofa fire) to obtain Set 1b (combined fire).

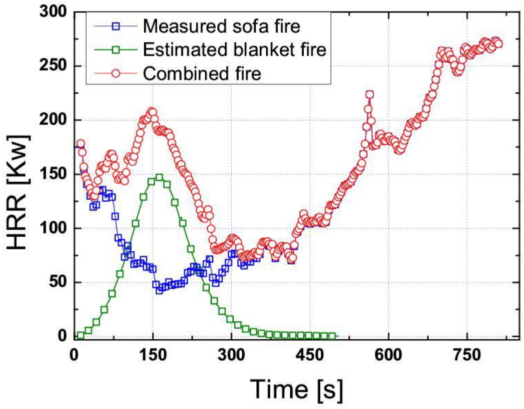
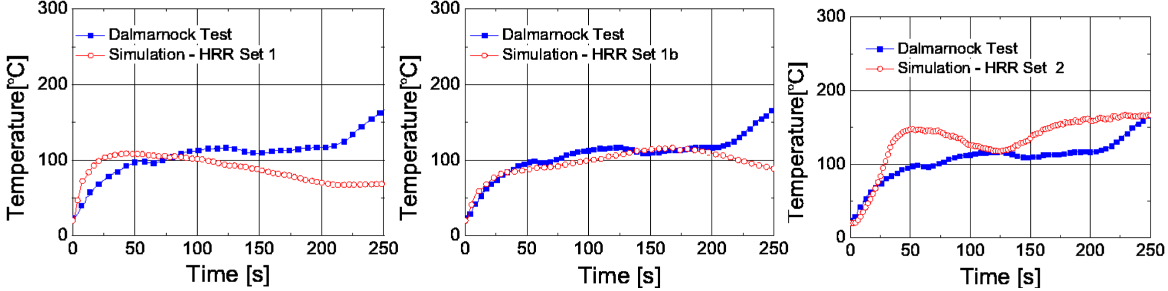


Figure 7: Predicted average hot layer temperatures; a) Set 1; b) Set 1b and c) Set 2.



(a) Set 1 (b) Set 1b (c) Set 2

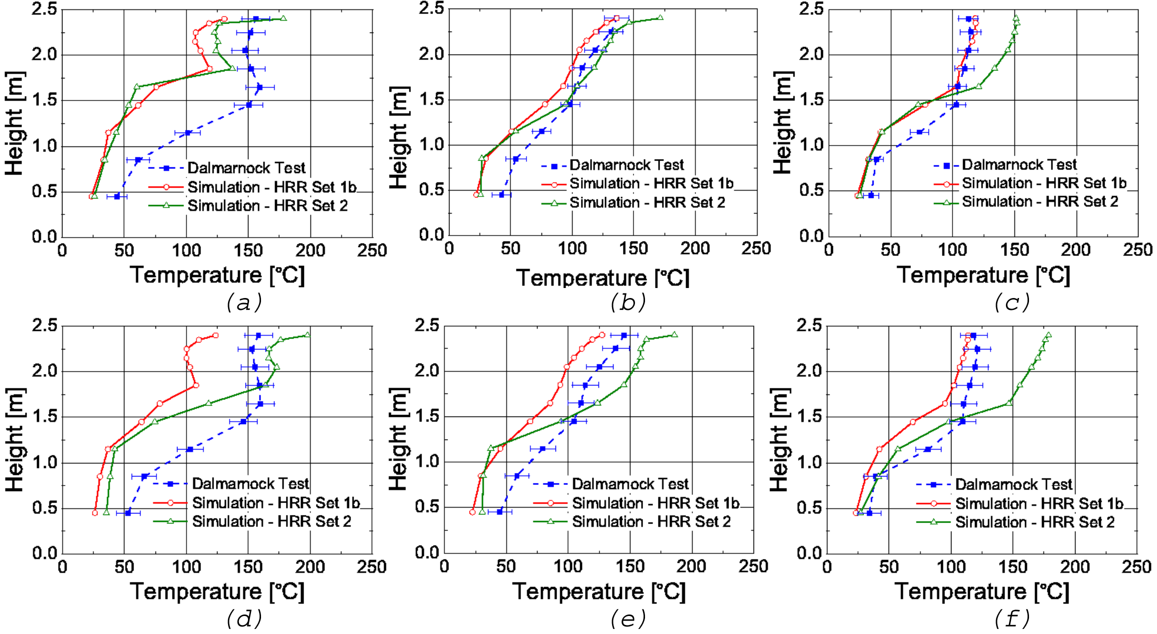
COMPARISON OF LOCAL MEASUREMENTS

The density of measurements in Test One presents an opportunity to assess field level simulations. Figure 8 shows the temperature vs. height distributions at different locations (three vertical thermocouple racks) in the experimental compartment using the two bounding HRR curves Set 1b and Set 2. Two different times, 150 s (HRR plateau) and 200 s (rapid HRR rise), are chosen arbitrarily for illustration purposes. In general the simulations are in reasonable agreement with the measurements, although it can be seen that the further away from the burning sofa the better the agreement between measurements and simulations.

As expected the lower and upper HHR bounds result in upper and lower bounds for the smoke temperatures. It is observed that the thickness of the hot layer is not significantly affected by the HRR within the bounds, but the upper HHR leads to higher temperatures in smoke. Within the cold layer, the simulations underpredict the temperature even for the upper HHR bound. This indicates that the Dalmarnock Fire Test had a less well defined hot layer than predicted.

At thermocouple rack 7, roughly 1.5 m from the fire, the temperatures are underpredicted by 20-200% at 150 s (Figure 8a) for both lower HRR bound (Set 1b) and the upper HRR bound (Set 2). At rack 11, near the centre of the compartment, and 150 s into the fire (Figs. 8b) the simulations with both input HRR curves are in good agreement with the measured data lying within the experimental error in the hot layer, and underpredicting the temperatures in the cold layer by about 40%. At rack 19, near the window, and 150 s (Fig. 8c), the lower HRR bound produces temperatures that lie within the experimental error in the hot layer, while the upper HRR bound results in overprediction by about 30%.

Figure 8: Temperature vs. height distribution at different locations in the compartment at 150 s (a,b and c) and 200 s (d, e and f). Thermocouple rack 7 (a,d) is located near the fire, rack 11 (b,e) is located near the centre of the compartment, and rack 19 (c,f) is located near the window. See Fig. 1 for rack location. Data are averaged over 10 s.



(a) (b) (c)

(d) (e) (f)

At 200 s the hot layer temperatures at rack 7 are slightly overestimated (although close to the experimental error, Fig. 8d) when using the upper HRR bound, and underestimated by around 35% when using the lower HRR bound. The cold layer temperatures are underestimated by 50-100% for both input HRR curves. At rack 11 temperatures simulated with the lower HRR bound are underpredicted by less than 20% in the hot layer (Figs. 8e), having similar shape to the measured distribution. With the upper HRR bound as input, the temperatures at rack 11 are overpredicted by about 25% in the hot layer, but underpredicted by about 35% in the cold layer, thus indicating higher temperature differences between hot and cold layer. Near the window, at rack 19 (Figs. 8f), the temperatures are in good agreement with the lower HRR bound as input, although the predicted hot layer height is around 0.5 m higher than that observed. But the upper HRR bound overpredicts the hot layer temperature by 40%, which is in accordance to the overprediction by around 40% of the hot layer average temperature resulting from the upper HRR bound at 200 s (Fig 7c).

CONCLUSIONS

This work presents a detailed account of the modelling of Dalmarnock Test One. *A priori* and *a posteriori* simulations of the growth phase were compared against detailed measurements.

A priori simulations overpredicted the hot layer temperature by 20-500%, whereas *a posteriori* simulations were able to reduce the error to 10-50%. For the field values, a *priori* simulations overpredicted the local temperatures by 20-800%, and *a posteriori* simulation reduced it to 20-200%.

Comparison of the field temperatures in the experimental compartment show that far away from the fire, the simulations are capable of capturing the temperature vs. height distribution of the gas phase (provided an acceptable HRR is input), while close to the fire important differences between simulations and measurements were consistently observed, both qualitatively and quantitatively.

Three main conclusions are reached

- Even in *a posteriori* simulations (with full access to the measurements), it is not easy to satisfactorily reproduce the fire.
- The incapability of predicting fire growth is shown to be a fundamental constraint to fire modelling.
- When the HRR is unknown as it is in most practical cases, the use of lower and upper HRR bounds should be included as to reflect in the predictions the effect of uncertainty in the HRR. This is an important issue for the application of fire modelling to real scenarios when the HRR is unknown (ie, forensic investigations and assumed design scenarios).

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