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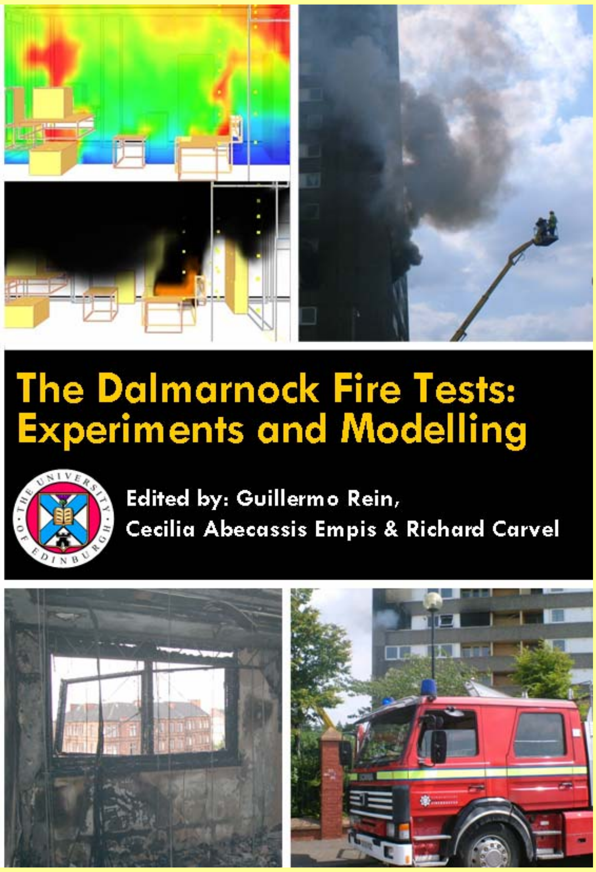
The Dalmarnock Fire Tests: Experiments and Modelling
Edited by G. Rein, C. Abecassis Empis and R. Carvel



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11. *A Posteriori* Modelling of Fire Test One

By Wolfram Jahn, Guillermo Rein and José L. Torero

Introduction

Reconstruction of fire disasters in order to understand what happened is a very important component of fire safety engineering. It has gained even further interest after the events of 9/11 and the collapse of the WTC. *A posteriori* investigation of a past fire event has to be conducted combining fire sciences with the witnesses' accounts and physical evidence. The larger the amount of information on the initial conditions and actual fire development, the more robust the conclusions will be. When fire modelling is involved, data gathering and scenario definition focuses on the creation of the input file or files that the model will use to produce simulations of the fire development. These simulations are then compared with the evidence and conclusions could be drawn.

The best possible information during the investigation of a fire emergency is that related to the actual or real-time development of the blaze. Unfortunately, in most real fire scenarios, live data acquisition is very difficult given that modern buildings rarely have any more sophisticated sensors than smoke detectors and a few CCTV cameras. Without more information of this type, it is difficult to validate the process of fire reconstruction of real fires.

For the simulation of fires in real building enclosures, the selection of the input parameters is complicated by the fact that the layout of the rooms and fuel loads is generally not available with the level of detail that is required. This can potentially lead to erroneous conclusions, since different fire scenarios could produce similar visual outcomes. Thus, it is required that modellers use other means to select the correct input parameters.

For example, in the initial attempts to model the fires in WTC (Rehm *et al.* 2002, Prasad and Baum 2005), the geometry, fuel load, ventilation and fire spread patterns were largely unknown, forcing the modelers to create the input data to the simulations based on visual recordings of the external events, like the evolution of post-impact fireballs, and smoke and flames appearance. Rather than being able to conclude on the actual fire development and the governing mechanisms, this approach proved to be useful to rule out some scenarios and to give a general idea of what might have happened. Nevertheless some special cases such as some hospitals, the fire load is much better known or large-scale tests can be conducted in order to reproduce the major events in a fire and the input data for the simulations can be created with higher fidelity. Hertzberg *et al.* (2007) reconstructed the fire in the 2003 Växjö hospital (Sweden) experimentally and was able

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to identify the floor PVC carpet and its burning behaviour as the principal reason for the very fast intoxication-induced deaths.

In the last few years computational fluid dynamics (CFD) modelling seems to have displaced zone models for compartment fire simulations. Only field models are capable of simulating transient 3D behaviour using the full geometry and fire spread to other items or compartments. Also, ventilation flows could be modelled satisfactorily using CFD (Kerber and Mielke 2007). Comparisons between CFD and zone models and validations of the latter show that they are generally in good agreement regarding the average transport processes taking place in the hot and cold layers, but the modelling in the regions near the flames provides rather poor agreements, especially in later stages of the fire (Rein *et al.* 2006, Rehm *et al.* 2002, Floyd *et al.* 2003).

CFD modelling of compartment fires has been a challenge for scientists since the introduction of the technique. Only recently the available computational power has become sufficiently high to produce simulations of fire development in full size enclosures with fine enough grids to reproduce fire-driven flows reasonably well. However, still there is no CFD code which can combine in detail all the complex phenomena involved in fire and a series of approximations have to be applied in the treatment of the turbulence, buoyancy, radiation and combustion mechanisms (Novozhilov 2001, Floyd *et al.* 2003).

Many studies have been conducted applying CFD codes to fire dynamics (Ma and Quintiere 2003, Hasib *et al.* 2007, Lattimer *et al.* 2003, Sally *et al.* 2007, Yeoh *et al.* 2003, Wen *et al.* 2007). Generally, these studies find the simulations in good agreement with the measured data, although the more complicated mechanisms such as flame spread and window breakage are not analyzed in any detail. Simple pool fires or single source fires in different locations and under different conditions are generally used, and very little research has been done comparing simulations with real scale fire tests.

There are mainly two large-scale tests of realistic fires with the required level of instrumentation that can be used for model comparison: the BRE large compartment test series (Welch *et al.* 2007) and the Dalmarnock Tests presented in this book (Chapters 2, 3 and 4). Related to the former, for example, Pope *et al.* (2006) compared FDS simulation and analytical calculations to the measured temperatures and obtained reasonable agreement within the context of structural fire safety, although FDS temperatures were slightly underpredicted. Related to Dalmarnock, the current article is the first one to make the comparison of *a posteriori* simulations to the measured data.

A key difference between previous modelling studies of large-scale tests and the present work is that the Dalmarnock Fire Tests provided measurements at sufficient spatial resolution to be compared with field models, not on an averaged level, but on a scale comparable to the grid size (Chapter 2).

The state-of-the-art of fire modelling shows several limitations. Before the Dalmarnock Tests were carried out, a round-robin study of blind predictions (Chapter 10) was conducted in order to explore the *a priori* predictive capabilities of fire modelling in

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realistic scenarios. Several independent teams provided simulations of the fire using a common set of information from the experimental set-up. The results showed large discrepancies between each other and with the measurements, especially at small spatial scales and long time scales. The general conclusion is that the modelling of realistic enclosure fires must be conducted with the aid of experimental measurements of fire tests directly related to the event under study.

The dynamics of enclosure fires can show a complex behaviour driven by critical events, such as the ignition of a secondary items, window breakage, flashover, sprinkler activation, fire intervention, etc. These events can change the course of the fire drastically due to the non-linear component of fire dynamics and from the mathematical point of view this could lead to bifurcations of the solution and large sensitivity to the initial and boundary conditions and to model parameters. Furthermore, the incomplete understanding in simple terms of some of the underlying physical and chemical mechanisms involved in fire dynamics and the large computational resources required to run simulations make even more difficult, if not impossible, to predict fire phenomena at large time scales. The aim of the present work is to show that it is possible however to reproduce fire behaviour quite satisfactorily if sufficient measured data is available to properly set up the input file for the model, and that *a posteriori* modelling leads to a better understanding of the experiments.

The ultimate aim of this work is to provide a basis for realistic scenario fire modelling in super-real-time the context of the FireGrid project (Chapter 1). In this context not only the consequences the fire has on the integrity of the structure are of interest, but also the course of the fire, starting at a localized point in a certain compartment, spreading within the room and later on to other rooms. The predictions of the course of the fire must be obtained in super-real-time, *i.e.* faster than the fire actually occurs, in order to assist the emergency response mechanism. This work is only the first step in that direction, but it throws some light on many interesting issues to be considered.

Dalmarnock Test One

Detailed information about experimental set-up and the chain of events that occurred during the Test One can be found in Chapters 2 and 3. The HRR curves of the sofa and one bookshelf were measured in the furniture calorimeter (using exact replicas of those in the test) and are shown and analyzed in Chapter 6. The HRR in the fire tests was calculated by oxygen depletion calorimetry, using the measurements from the Bi-directional Air Velocity Probes at the ventilation openings (Chapter 3). An estimation for the post-flashover fire results in a 3 MW before the first window breakage, and about 5 MW after the second breakage. At 800 s and 1100 s the two panes of the main compartment window broke as recorded during the experiments. Window breakage was not predicted in this study but the times were introduced into the simulations to model the ventilation conditions.

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A posteriori simulations

The Fire Dynamics Simulator (McGrattan 2006, McGrattan and Forney 2006) is one of the most commonly used fire CFD codes, and version 4.07, is used in this work.

The geometry of the real compartment and adjacent rooms and the detail fuel load is described in Chapter 2. In order to make the modelling more efficient in terms of computational time, the domain concentrated on the main compartment room and its vent openings (Figure 1). For eventual fluid dynamic effects on the ventilation flows, the kitchen and an artificial hallway are included. The other rooms of the apartment were not considered, since they did not contribute to the fuel load nor significantly affected the ventilation flows.

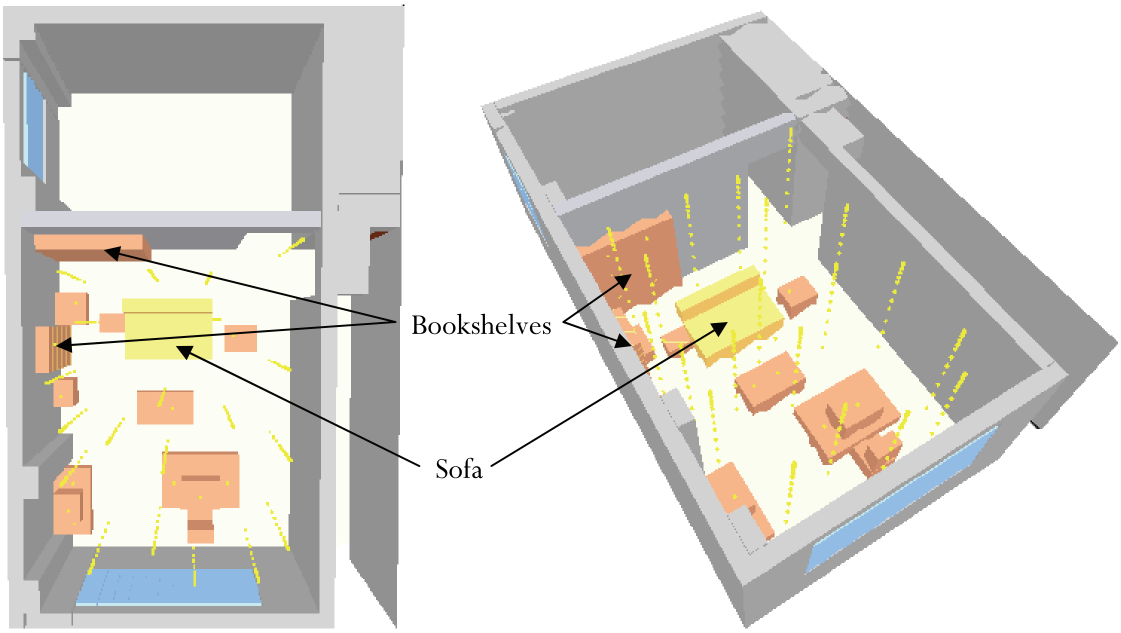

Figure 1: Computational domain and fuel items used in the simulations.

The following subsections describe how the different parameters of the input file describing the grid, the ignition source, fuel load and the HRR were determined using all the measurements and evidence available after the tests.

Grid size

Many simulations had to be run in to reach a good agreement with the measured data. In the one hand, it is necessary to use a relatively coarse grid allowing for an efficient use of the computational resources. On the other hand, too coarse a grid would induce a lack of accuracy in the solution, Therefore, a compromise solution between a coarse and a fine grid is required.

FDS results tend to depend rather strongly on the size of the numerical grid since not only the LES approximation but other mechanisms within FDS depend on the grid size (radiation, flame location, boundary layers). In order to decide which grid size to use, the simulation was run for 500 s with different grid sizes (5 cm, 10 cm and 15 cm edge

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cubes). For this preliminary runs, the ignition and fuel load parameters in the input file were large based on the *a priori* simulations (Chapter 10). In order to compare the results from the different grids, two outputs were used as criteria: the HRR and the temperature profiles vs. height at all 20 thermocouple trees.

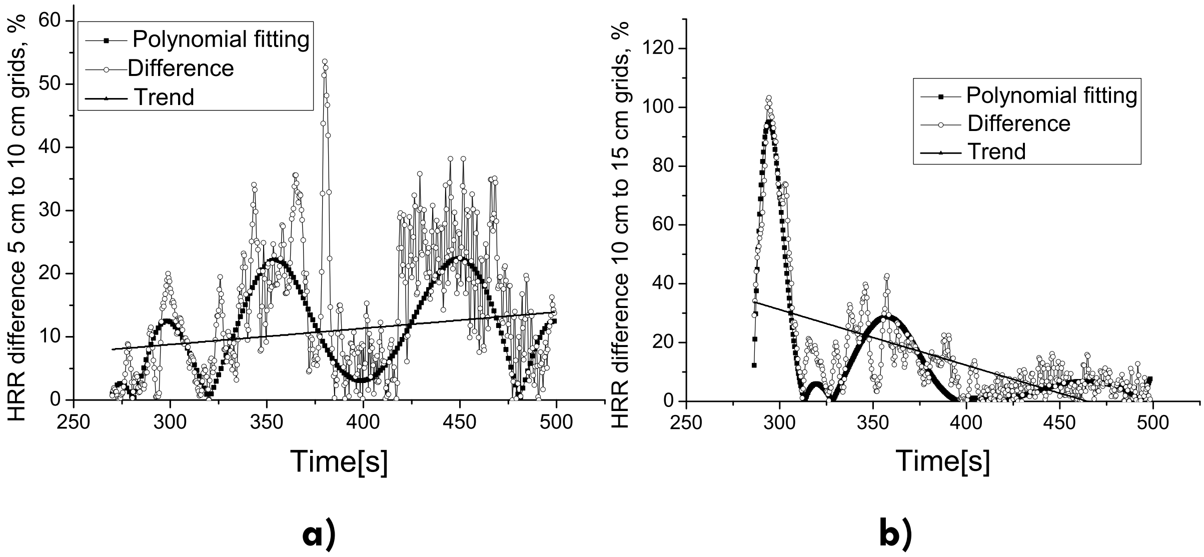

Figure 2: Comparison of differences in the HRR for different grid sizes. a) Differences between 5 cm and 10 cm grids; b) Differences between 15 cm and 10 cm grids. Before 300 s no difference in the HRR was detectable.

The differences in the HRR between grids show a significantly higher difference than in temperatures, mainly due to important localized fluctuations. In order to get rid of the fluctuations, a polynomial was fitted to each of the simulated HRR and those were compared. The percentage of difference between 10 cm and 5 cm is within 20% as Figure 2a shows. The differences between 15 cm and 10 cm are much bigger at the beginning, but show an obvious decreasing trend. Figure 3 shows that the HRR for the 5 cm grid presents a slight delay in time compared to the 10 cm grid. Between 270 s and 300 s both shapes still agree, whereas at 370 s an obvious delay in the 5 cm grid simulation can be noted. The sudden increase in the HRR at 370 s for the 10 cm grid occurs at around 390 s, *i.e.* about 20 s later in the 5 cm grid simulation. Generally the resulting HRR is very similar in shape and magnitude for 10 cm and 5 cm. The graph in Figure 3 was produced comparing similar events; therefore the 5 cm grid results were compared to 10 cm grid results with a 20 s delay.

Comparison of the temperature distributions for different grid size can be seen in Figure 4. The profiles proved a very good agreement in shape for the 5 cm and 10 cm grid. For regions near highest fuel load (Figure 4a), the 15 cm grid showed important differences. The average values differed by about 10-13% on average.

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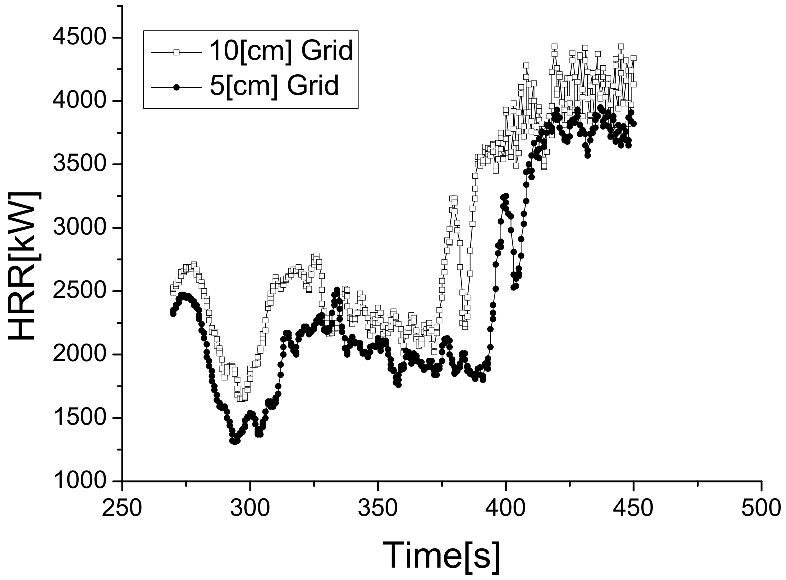

Figure 3: Resulting HRR curves for 10 cm and the 5 cm grids. The 5 cm curve seems stretched with a delay of about 20 s.

Based on these results, it is shown that a grid of 10 cm is a good compromise between fire resolution and an efficient use of computational resources.

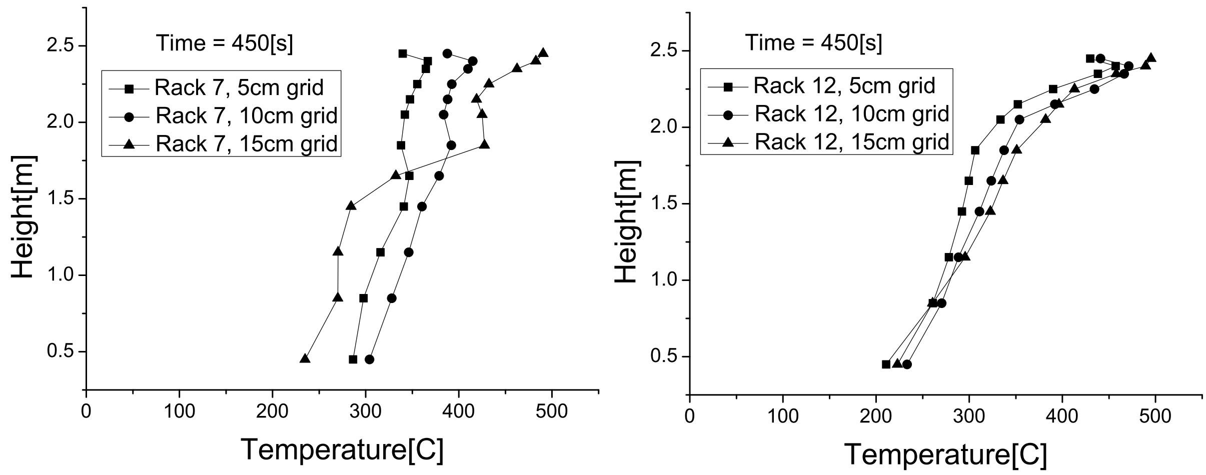

Figure 4: Comparison of height vs. temperature distributions for grid size at 450 s (right after flashover). a) Distribution at the north wall next to the bookshelf (Tree 7); b) Distribution at the south of the centre table (Tree 12).

Ignition Source

The burning of the wastepaper basket, the blanket and the cushions, and the sofa control the initial fire development. The sofa's HRR curve measured in the laboratory (Chapter 6) proved to give a slower HRR than that observed in the large-scale fire. The flashover in Dalmarnock occurred at about 300 s, only 100 s after the period where the basket fire

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dominated the HRR in the laboratory experiment. Comparison of the fire development using the video available from both fires confirms the difference between the HRR of the sofa measured at the laboratory and the one in the Dalmarnock Test. This is presumably due to the fact that in the calorimeter the smoke layer is extracted continuously by the hood and therefore the radiative heat flux to the sofa is lower than it had been in the real fire (this effect is larger as the enclosure smoke layer grows). Another factor would be the ignition source. The initial HRR from a sofa fire shows a strong dependence on the ignition protocol. The exact amount of fuel load and accelerant in the bin and blanket (which acted as ignition source) was not characterized well and leaves space for some uncertainty. In order to estimate a more realistic heat release rate, another sofa experiment conducted by NIST was consulted (Lawson *et al.* 1983). The heat release rate reported by NIST is considerably higher (peaks at 3 MW) than the Dalmarnock-sofa replica measured in our furniture laboratory. The flame heights observed in real time in the Dalmarnock Test were more similar to the flame heights seen in the NIST test. Assuming the following correlation for pool fire plumes (Drysdale 2002):

$$\dot{Q} = \left(\frac{l + 1.02D}{0.23} \right)^{5/2} \tag{1}$$

where l is flame length and D is diameter, holds for sofa fires, an estimate of the HRR based on flame height measured from images of the laboratory test may be proposed. The Dalmarnock initial fire shows that at 150 s, the flame height is of the order of 1 m, which corresponds to a HRR of roughly 0.7 MW. This indicates that the heat release rate in the test was in the beginning phase more similar to the NIST sofa test results (a medium growth t^2 curve). In order to make use of the original laboratory measurement in which exactly the same sofa as in Dalmarnock was used, the general shape of the measured curve was used, simply displacing the curve on the time axis to the left in order to obtain a bigger HRR, more similar to that estimated roughly from photographs.

Criteria for fire spread

There are several approaches to modelling the ignition of secondary items that drive the growth of an enclosure fire. Theoretically, the most realistic approach would be to use a pyrolysis model, like the one built within FDS. This allows calculating the production rate of pyrolysis gases based on the heat feedback from the fire. However, because of the complex mechanisms of flame spread and the multiple fuel items in the Dalmarnock scenario, the FDS simulation proved to be very sensitive to the many different parameters describing the process, such as the kinetics parameters and other material properties (Kwon *et al.* 2007).

An alternative simpler approach is to fully prescribe the HRR of each item in the room and determine their respective ignition times based on the ignition temperature and/or the critical heat flux. The values for these variables governing ignition were obtained from the literature (Drysdale 2002). This approach has proven to be generally valid. For the critical heat flux approach in this particular case, it proved not be precise enough, since the transient change of heat fluxes on the items in the vicinity of the fire source turned out to be too small, which meant that little uncertainties in the critical heat flux would produce large ignition-time intervals of more than 100 s.

Fully Prescribed HRR approach

The first approach was to fully prescribe the HRR. The focus is on the fire growth leading to flashover, since afterwards the fire size is limited by the ventilation conditions rather than the prescribed value of the HRR.

The HRR of the ignition source (the basket and the sofa) was prescribed following the measurements and extrapolations in Chapter 6. The individual HRR curves for each furniture item in the room were also prescribed, and the total imposed HRR was the sum of the individual contributions (Figure 5). The time of ignition of each item was not decided solely upon incoming heat-flux, but also upon the time required so that combining all items the flashover would occur around 300 s. Nonetheless the incoming heat-flux was used to decide the order in which the items would ignite. In order to assure flashover after 300 s, items in the compartment were ignited sequentially after 275 s. First to ignite at 275 s was the closest bookshelf (the one with the highest incoming heat flux) as it was also observed in the Dalmarnock Test. After ensuring that the simulated heat flux was above the critical and that the surface temperature of the bookshelf is above 350 °C, which is the approximate ignition temperature for many different solid fuels (Drysdale 2002). This ignition was prescribed in the HRR of the input file and the model run again. The next item to receive the highest incoming heat flux was the second bookshelf which was determined to ignite at 280 s, and so on. After two iterations the incoming heat flux of the remaining furniture was so high that simultaneous ignition could be assumed, indicating flashover is reached close to 300 s. It is important to notice that the heat flux was not used as an ignition criterion, since that depends also on the thermal inertia of the item, but it was used only to confirm that the incoming heat flux is within the correct range.

The heat release from each piece of furniture was imposed in the model as the corresponding heat release per unit area multiplied by the total exposed surface. Other than the sofa, three different fuel types were identified as the most important elements within the compartment: the three bookshelves, several wood elements and some plastic elements. All items in the main compartment were modeled using one of these surfaces. Greater detail for paper sheets or other low mass material lying on the table was considered as not necessary since their released energy would be negligible. Generally, tables are considered to be wooden items, whereas bookshelves had to be simulated separately following the measured HRR in the furniture calorimeter (Chapter 6), since they were composed of a heterogeneous load of plastic boxes, video tapes, CDs, books, magazines and other typical shelve items. The bookshelf used in the laboratory experiment provided approximately the same fire load as the one in the Dalmarnock Test. For wooden items such as the computer desk, the general shape seen in the bookshelf's HRR was used with a lower peak value.

The overall imposed heat release rate curve is the sum of the individual HRR of each flammable item. These are shown in Figure 5.

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The ventilation conditions were modelled prescribing a wind speed of 1.5 m/s perpendicular to the kitchen window. Additionally, a few small leakages were modelled in the window panes.

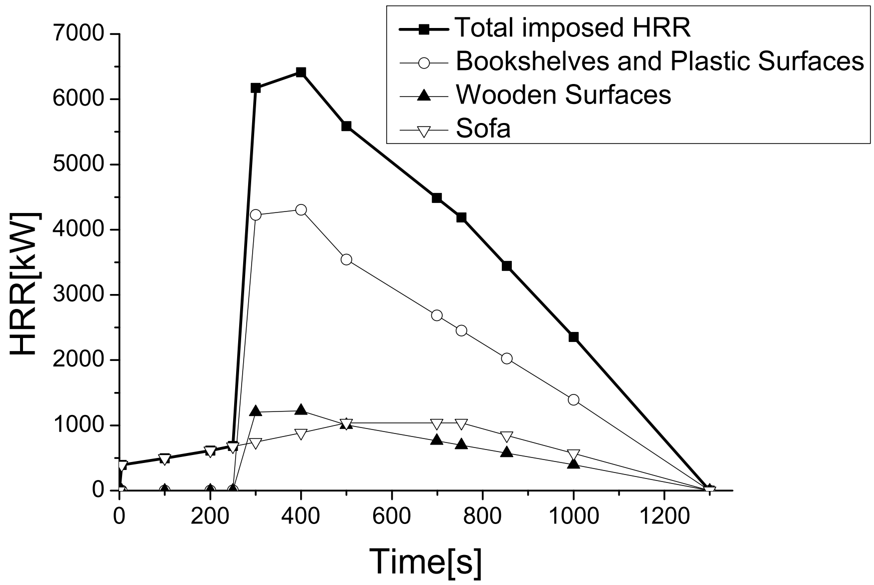

Figure 5: The individual HRR prescribed in the simulations and the total one for the fully prescribed HRR approach.

Partially prescribed HRR approach

The second approach to simulate the fire was to prescribe the HRR only for the two controlling items leading from ignition to flashover; the sofa and the bookshelf right next to it. The burning of the other items was characterized according to their heat of combustion and heat of vaporization (Tewarson 2002). This approach allows linking the heat feedback from the fire to the fuel production during the post-flashover. However it is important to notice that this approach applies only to steady-state burning and in the context of this work it is used as an approximation.

Ventilation conditions of this model were the same as for the fully prescribed HRR, *i.e.* the comparment window was removed at 800 s partially and at 1100 s completely, and a wind speed of 1.5 m/s was considered.

Radiative heat transfer from the smoke layer plays a very important role in fire growth inside enclosures. This radiation depends on the concentration of soot and other combustion products. But soot production is very difficult to predict, since it depends among others features on the combustion conditions at the flame. FDS4 does not predict the actual soot yield; rather this is prescribed by the user. A full sensitivity analysis regarding radiation is beyond the scope of this article, nonetheless the influence of different soot yields was studied and no significant differences were detected in the output, indicating a relative insensitivity of the results to this parameter.

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Results

Many criteria can be used to conclude on the goodness of the output of the simulations when compared to the experiment data. The first and most natural criteria would be to match the heat release rates. The HRR is the single most important variable in a fire (Babrauskas and Peacock 1992). It is has been argued many times that if the HRR is reproduced properly, the simulated temperatures, heat flux and species concentrations in the compartment should be in good agreement with the reality. However, the total HRR of a fire is a global measurement of development in the integral compartment and can mask and compensate local processes. This effect is expected to be larger as the size of the enclosure grows. Thus, it is interesting to take advantage of the high density of measurement points in the Dalmarnock Test to compare simulation and experiments at both the global and a more detailed local level.

Heat Release Rate

The entirely prescribed heat release rate for all the items in the room as fire growth criterion did not work well. As shown in Figure 5, the total imposed HRR reaches over 6 MW between 300 s and 400 s. Due to lack of oxygen in the ventilation-controlled fire the actual simulated HRR is much lower (between 2 and 3 MW). It was noticed that for higher imposed HRR the simulated HRR also rises, although in less degree. FDS treats an imposed heat release rate as an injection of combustible gases which, if entirely burnt, would produce the prescribed HRR. If not enough oxygen is available to burn the fuel, the combustible gases accumulate and eventually begin to flow through openings to the surrounding rooms, where combustion finally takes place.

In the simulations using the entirely prescribed HRR approach (Figure 6), after flashover is reached the compartment begins to fill with unburnt gas fuel as the oxygen is being consumed. At a certain point (at 300 s in Figure 6a) no more oxygen is available in the room for the combustion reaction, and the fuel leaves through doors and windows to the kitchen and to the outside. When it meets fresh air with enough oxygen to produce a stoichiometric mixture, combustion takes place. Therefore flames appear outside the main compartment. Inside the compartment, where all the fuel sources are, no combustion takes place and the room begins to cool down. Since the rate of fuel injection is prescribed and does not depend on physical conditions like temperature or heat flux, more and more fuel is being injected into the compartment and prevents fresh air from entering the room. For the rest of the simulation no further combustion takes place in the main compartment and this leads to unrealistically low temperatures, especially far from the kitchen and hallway door, as shown in Figure 6b.

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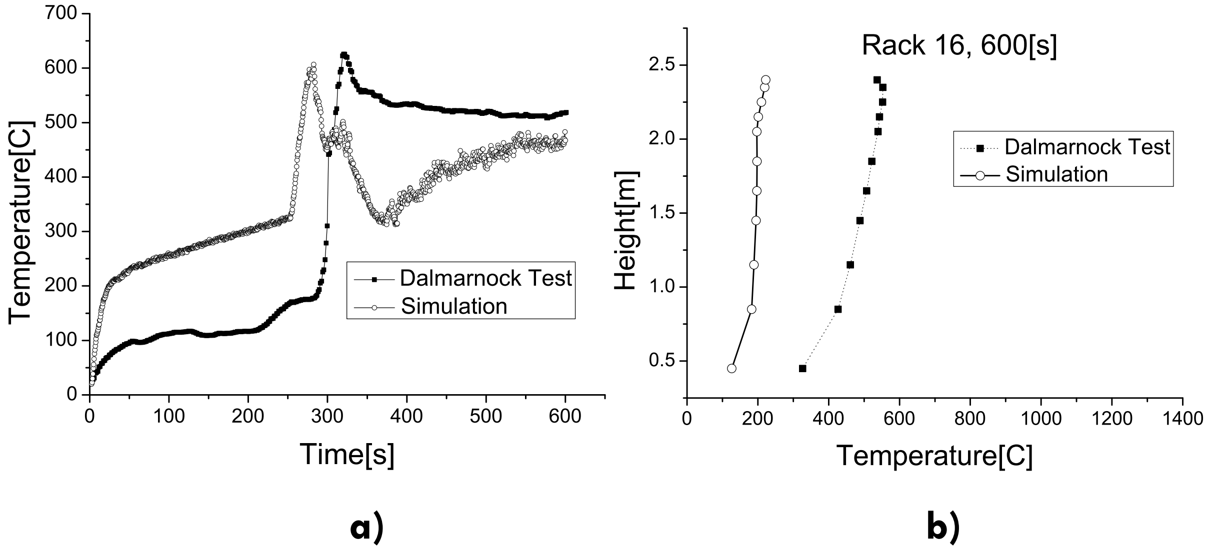

Figure 6: Comparison of temperature for the entirely prescribed HRR approach. Graph a) shows that the simulated average hot layer temperature in the compartment is overpredicted by 30 % during growth and underpredicted 20 % during post-flashover. Graph b) shows that the temperature near the window (Tree 16) is underpredicted by more than 50%.

The partially prescribed HRR criterion was tried next. The predicted HRR and average hot layer temperatures can be seen in Figure 7. The agreement with the measurements is reasonable up to 800 s. Before flashover no comparison can be made, since the method to estimate HRR in Dalmarnock does not apply until flashover. The predicted HRR in the first post-flashover stage is quite constant at around 2.3 MW (25% lower than the measurements), as shown in Figure 7a. During the preparation process of the input file, it was noticed that the ventilation conditions in the main compartment were extremely important, as expected. From visual material it is possible to infer that in Dalmarnock the main window had small leaks of smoke before the window broke. These small leakages may influence the ventilation condition but are much smaller than the grid size and therefore it is not straightforward to model them without introducing numerical errors. It is assumed that the error due to leakages is in the order of magnitude of the error introduced by the HRR calculation method.

After the window breakages the simulated HRR is overpredicted by 60%. Investigation of where the simulated HRR is coming from indicates that 60% of the overprediction is due to external flaming at the vents. External flaming was seen out of the compartment window in the Dalmarnock Test starting at 1080 s, but its contribution to the measured HRR is not taken into account, since it applies only to the burning within the compartment. However, the hot layer temperatures measured in the room are significantly lower than those simulated as seen in Figure 7b, which indicates that in the simulation there is still a significantly higher heat release rate inside the compartment than in the actual experiment, regardless of effect of the external flaming.

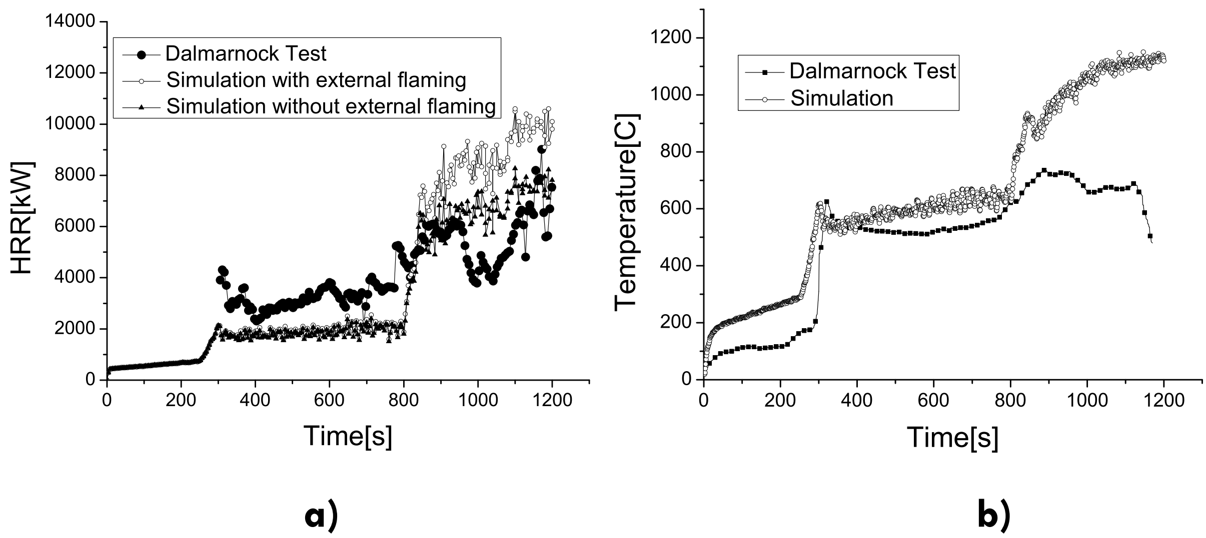

Figure 7: Comparison of results for the partially prescribed HRR approach. a) The simulated HRR shows good agreement with the measurements between 300 s and 800 s. After 800 s, external flaming causes to overpredict the HRR; b) Comparison of the average hot layer temperatures show good agreement expect for the second flashover stage (t>800 s) where temperatures are overpredicted

Temperatures

Temperatures inside the compartment were compared at two different levels. First the average temperature of the hot layer was analysed, which gave an idea of how well the field simulation is capable of capturing general fire behaviour. Afterwards, taking advantage of the density of data collected during the Dalmarnock Fire Tests, the temperature distribution as a function of the height was compared at each thermocouple tree. This comparison allows for conclusions regarding the capability of the field model to reproduce the local fire environment when the global HRR is predicted well (between ignition and 800 s) and poorly (for times larger than 800 s).

Average Temperatures

The simulated average temperatures using the partially prescribed HRR of the hot layer is in good agreement with the measured data for the period before window breakage. This is in agreement with previous FDS validations (Sally *et al.* 2007) that use the average temperature as the basis of comparison. In the growing phase the average temperature rises from about 150 °C shortly after ignition to around 200 °C just before flashover in a steady manner. During flashover at 300 s, the average temperatures of the hot layer, both simulated and measured, experience a sudden increment of about 400 °C. In the interval between flashover and window breakage at 800 s, the temperature stays more or less constant, with the measured data reproduced closely by the simulation. The measured data indicate that the breakage of the window at 800 s had a small impact on the average thermal field. While measured temperatures rise by just about 100 °C up to 700 °C,

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simulations present a very steep change producing hot layer temperatures of over 1100 °C. Moreover, the simulation shows a continuous increase in average temperature after the windows fall, whereas this is not seen in the measured data and even a slight decrease in temperature is recorded.

Local spatial temperature distribution

Figure 8 shows plots of temperature distribution at different locations and times. In general, the temperatures of the top hot layer are in better agreement than those at the bottom of the cold layer. At 600 s, a time between flashover and the first window breakage, good general agreement is achieved. The temperatures in the hot layer are predicted within 10% and those in the cold layer within 80%. At 900 s, after the first pane of the window broke, temperatures show an error of 40% in locations near the window (Tree 19) where flaming occurs in the simulation, which is reduced down to 10% away from it (Tree 4). In the middle of the room (Tree 10) the upper part is reproduced closely, but near the floor the temperature is underpredicted. After 1100 s the comparison shows that the simulation predicts much higher temperatures (above 100% difference) and a sharper boundary between hot and cold layer. Indeed, the boundary between the two layers in the experiment disappeared as seen in the test data, indicating that the smoke layer fills completely the room.

Analysis of the spatially distribution of temperatures in the compartment reveals that the best agreement is achieved generally away from the flames. Before the first window breakage, the best agreement was found in Tree 19, *i.e.* away from the region with larger fuel load. After the window breakages, when flames move towards the vents, the best agreement is in locations near the large fuel load (Tree 4).

The simulation overpredicts flame temperatures, since the maximum recorded in the Dalmarnock Test was less than 1000 °C, and the predicted temperatures near flaming zones reach up to 1300 °C. This is somehow expected since the flame temperature that can be easily over- or underestimated by CFD models, that require many approximations and sub-models to simulate the zone near the flame, the most challenging region. However, it is the temperature of the smoke layer away from the flame that can vary greatly from flame temperatures to ambient, and CFD models do a much better job calculating it (as can be seen in the results here).

These results show that it is possible to get good agreement with experimental data for growing and fully developed fires when sufficient data is provided to guide the modelling. However, a sudden change in ventilation conditions due to the critical event of the main compartment window breaking induces large divergences which in the HRR and the temperature fields are not easily captured and need further investigation.

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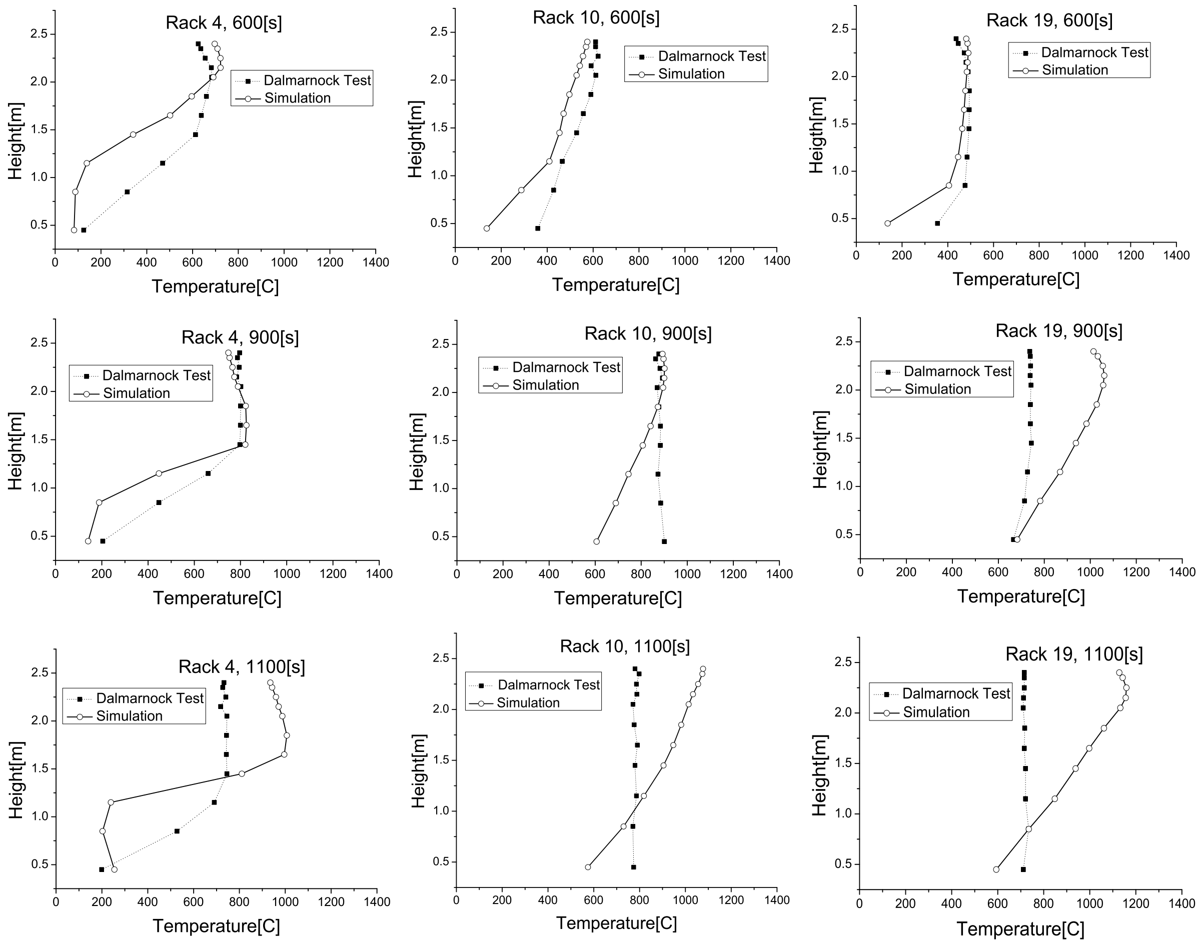

Figure 8: Comparison of height distribution of temperature at different locations and times. The left column shows temperature distribution in the southeast corner (Tree 4) at 600 s, 900 s and 1100 s respectively, the middle column shows temperatures in the central part (Tree 10) near the northern wall, and the right column shows temperatures near the window (Tree 19). For 600 s and 900 s good general agreement is achieved.

Comparison of other variables

Wall temperatures were recorded at the east wall of the main compartment. Figure 9 shows that a good agreement between measurements and simulations can be achieved, although the simulations tend to underpredict the temperature on the lower part of the wall, especially after the window breakage, which is consistent with the observations made in the gas phase temperature comparison.

Good agreement is achieved even after 800 s, which leads to the conclusion that window breakage had no sensitive effect, neither on the measured data, nor on the simulated results. Gas phase temperature analysis shows that the new ventilation condition affected the agreement between simulation and measurements more on the trees near to the window, and had only a slight effect in the part of the flat away from the window. The comparison of wall temperatures confirms this tendency.

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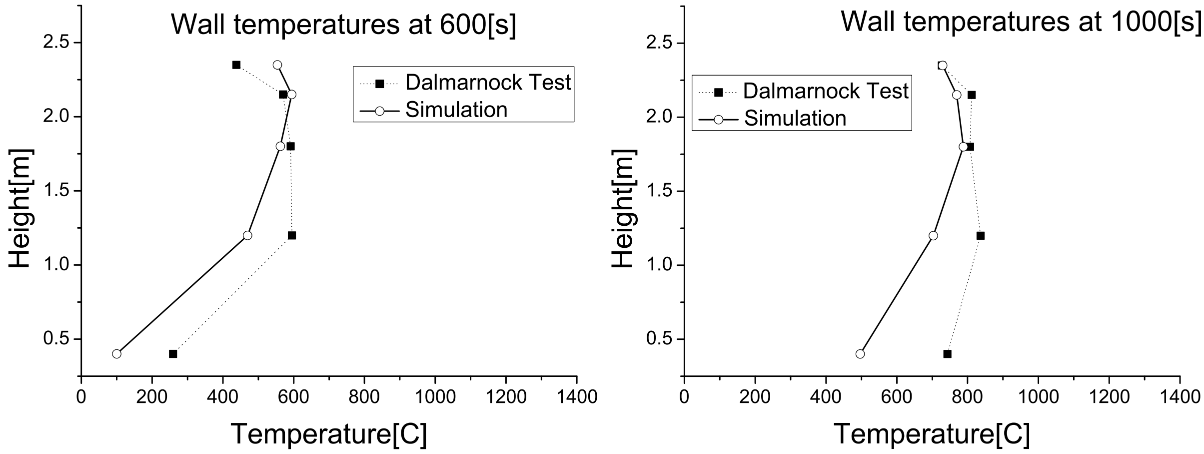

Figure 9: Height distribution of wall surface temperature at the kitchen wall on the east side of the flat.

Figure 10 shows that the simulated incident heat flux at the kitchen wall (east wall of the experimental compartment) is slightly overpredicted, but in very good qualitative agreement for the upper part of the wall. The test results show an increase of incoming heat flux with decreasing height on the lower part of the wall, which is contrary to the simulations predicting decreasing heat flux with decreasing height.

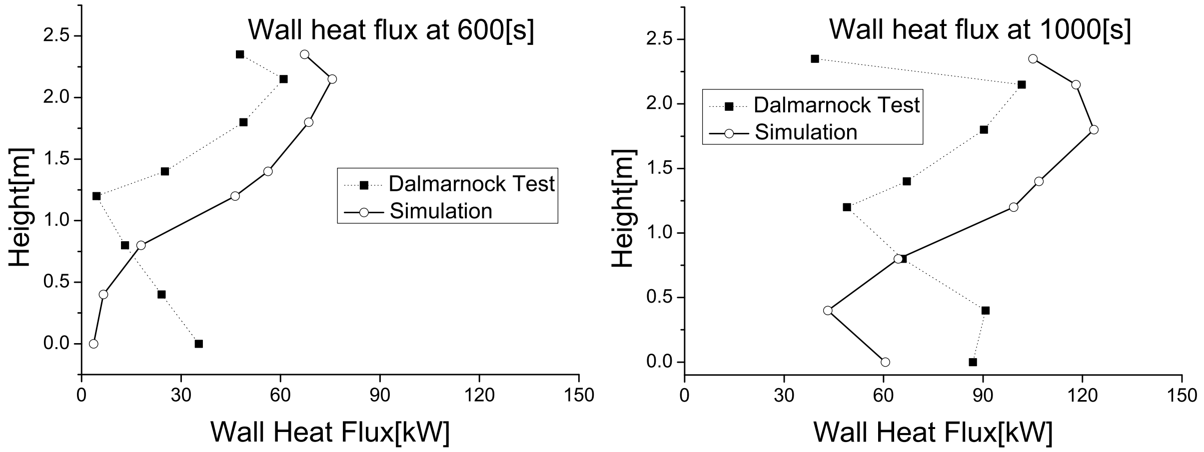

Figure 10: Height distribution of total wall heat flux at the kitchen wall on the east side of the flat.

The extinction coefficient is greatly overpredicted by the simulations as shown in Figure 11. It is not surprising to obtain big differences between measurements and simulations, since the extinction coefficient depends strongly upon soot production in the fire, which has not been analyzed in this work. Also the measurements of the extinction coefficient did present some difficulties and important experimental errors are involved.

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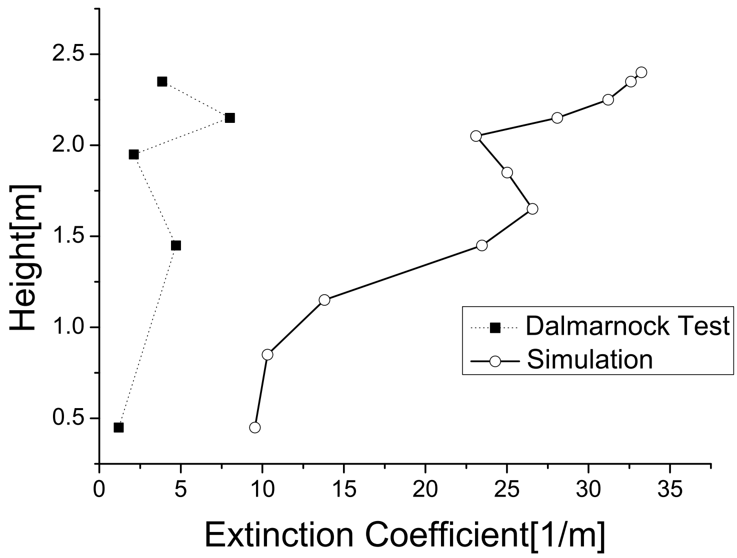

Figure 11: Extinction coefficient in the southeast corner of the compartment (Tree 4) at 600 s.

Conclusions

A priori predictions of the fire development in Dalmarnock (Chapter 10) show that the state-of-the-art only allows qualitative blind predictions of fire development in realistic scenarios. However, this Chapter shows that *a posteriori* simulations aided by measurements of the event allows for reconstructing realistic fire scenarios, both qualitatively and quantitatively. The modelling process was difficult, and it was by no means straightforward to build the input file. The fuel layout, geometry and ventilation conditions do not provide enough information to the fire modelling and direct access to the measurements was required. As expected, the fire development depends on many different parameters which have to be analyzed and adjusted separately. It is not surprising then that intrinsic fire dynamics make so difficult to reach good blind fire predictions in complex scenarios.

The reconstruction of the event provides an understanding and quantification of the mechanisms in the fire as well as a good analysis of the characteristics that were not directly measured.

It is important to notice that this work provided a calibration only for the input parameters to the model and not the model used. For a different enclosure, the work would have to be repeated in order to adjust the input parameters to the corresponding measurements. This fact highlights the importance of sensor data being assimilated into simulations in order to be able to produce predictions of fire dynamics.

The most important variable to simulate in a fire is the HRR. Most of the effort was put into getting the input right so the HRR was in agreement with measurements. The average hot layer temperatures show generally good agreement, although they are largely overpredicted in the later stages of the post-flashover. The local spatial distribution of temperatures seems to follow the measurements qualitatively. It is seen that focusing on

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the global HRR inside the compartment masks local behaviour. The global HRR is more important for zone models and analytical calculations than for CFD models that require more details of where the flames are and where the fire spreads to.

The different fire phases required different modelling approaches. In the growth phase, the fire is better simulated as a prescribed HRR. But during ventilation-control phases, it is more convenient to predict the HRR, at least partially, because an imposed HRR tends to err the flame locus. Imposing the HRR decouples the production of pyrolyzates from the flame heat feedback. The decoupling together with the use of a mixture fraction model tends to locate flames at the vents during ventilation-control conditions. In turn, this leads to temperature and heat flux underpredictions away from the vents and overpredictions near them. The flame-locus defect leads to erroneous fire predictions during post-flashover in large compartments, increases with the volume of the enclosure and decreases with the vent size.

Further work

As stated before the present work is a first step towards the predictions of the realistic fires of the Dalmarnock Tests. It proves the importance of using sensor data to properly create the input parameters for the particular scenario. However, not all data are equally useful. A sensitivity analysis will be carried out in order to determine the most important input parameters.

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References

Babrauskas, V., Peacock, R., Heat Release Rate: The Single Most Important Variable in Fire Hazard, *Fire Safety Journal*, **18**, No. 3, 1992, pp.255-272.

Dreisbach, J., McGrattan, K., Verification and Validation of Selected Fire Models for Nuclear Power Plant Applications, Volume 6: FDS, NUREG-1824 Report, U.S. Nuclear Regulatory Commission, Office of Nuclear Regulatory Research, 2006.

Drysdale, D., An Introduction to Fire Dynamics, 2nd edition, John Wiley and Sons, Chichester, UK, 2002.

Floyd, J., McGrattan, K., Hostikka, S., Baum, H., CFD Fire Simulation Using Mixture Fraction Combustion and Finite Volume Radiative Heat Transfer, *Journal of Fire Protection Engineering*, **13**, No. 1, 2003, pp. 11-36.

Hasib, R., Kumar, R., Shashi, Kumar, S., Simulation of an experimental compartment fire by CFD, *Building and Environment*, **42**, No. 9, 2007, pp. 3149-3160.

Hertzberg, T., Blomqvist, P., Tuovinen, H., Reconstruction of an arson hospital fire, *Fire and Materials*, **31**, No. 4, 2007, pp. 225-240.

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Kerber, S., Mielke, J., Using FDS to Simulate Smoke Layer Interface Height in a Simple Atrium, *Fire Technology*, **43**, No. 1, 2007, pp. 45-75.

Kwon, J., Dembsey, N., Lautenberger, C., Evaluation of FDS v4: Upward Flame Spread, Fire Technology 2007, in press.

Lattimer, B., Hunt, S., Wright, M., Sorathia, U., Modeling fire growth in a combustible corner, *Fire Safety Journal*, **38**, No. 8, 2003, pp. 771-796.

Lawson, R., Walton, D., Twilley, W.,Fire Performance of Furnishings As Measured in the NBS Furniture Calorimeter Part 1, U.S. Department of Commerce, National Bureau of Standards, NBSIR 83-2787, August 1983, www.nist.gov.

Ma, T., Quintiere, J., Numerical simulation of axi-symmetric fire plumes: accuracy and limitations, *Fire Safety Journal*, **38**, No. 5, 2003, pp. 467-492.

McGrattan, K., Fire Dynamics Simulator (Version 4) Technical Reference Guide, NIST Special Publication 1018, 2006.

McGrattan, KB. & Forney, G. Fire Dynamics Simulator (Version 4) User's Guide, NIST Special Publication 1019, National Institute of Standards and Technology, Gaithersburg, MD, USA, 2006.

Novozhilov, V., Computational fluid dynamics modelling of compartment fires, *Progress in Energy and Combustion Science*, **27**, No. 6, 2001, pp. 611-666.

Pope, N., Bailey, C., Quantitative comparison of FDS and parametric fire curves with post-flashover compartment fire test data, *Fire Safety Journal*, **41**, No. 2, 2006, pp. 99-110.

Prasad, K., Baum, H., Coupled fire dynamics and thermal response of complex building structures, *Proceedings of the Combustion Institute,* **30**, 2005, pp.2255-2262.

Rehm, R., Pitts, W., Baum, H., Evans, D., Prasad, K., McGrattan, K., Forney, G., Initial Model for Fires in the World Trade Center Towers, NISTIR 6879, 2002.

Rein, G., Bar-Ilan, A., Fernandez-Pello, C., A Comparison of Three Models for the Simulation of Accidental Fires, *Journal of Fire Protection Engineering*, **16**, No. 3, 2006, pp. 138-209.

Sally, M., Dreisbach, J., Hill, K., Kassawara, R., Najafi, B., Joglar, F., Hammins, A., McGrattan, K., Peacock, R., Gautier, B,. Verification and Validation – How to Determine the Accuracy of Fire Models, *Fire Protection Engineering*, **34**, Spring 2007.

Tewarson, A., Generation of Heat and Chemical Compounds in Fires, The SFPE Handbook of Fire Protection Engineering, 3rd Edition, pp.3.82 – 3.162, 2002.

Welch, S., Jowsey, A., Deeny, S., Torero, J., BRE large compartment fire tests – characterising post-flashover fires for model validation, to appear *Fire Safety Journal*, 2007.

Wen, J., Kang, K., Donchev, T., Karwatzki, J., Validation of FDS for the prediction of medium-scale pool fires, *Fire Safety Journal*, **42**, No. 2, 2007, pp. 127-138.

Yeoh, G., Yuen, R., Lo, S., Chen, D., On numerical comparison of enclosure fire in a multi-compartment building, *Fire Safety Journal*, **38**, No. 1, 2003, pp. 85-94.

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