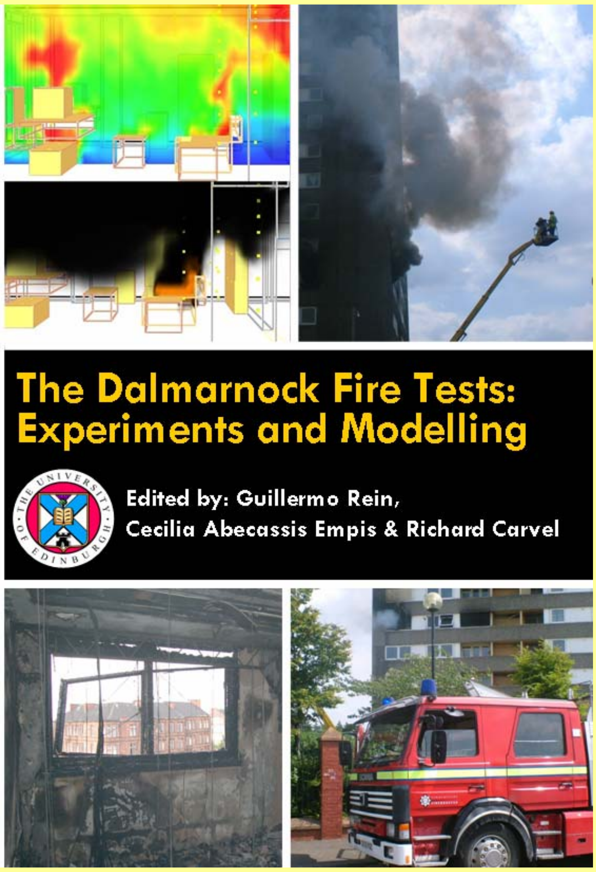
The Dalmarnock Fire Tests: Experiments and Modelling
Edited by G. Rein, C. Abecassis Empis and R. Carvel



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7. Heat Transfer to the Structure during the Fire

By Allan Jowsey, José L. Torero & Barbara Lane

Introduction

The post-flashover Fire Test One of a furnished room in Dalmarnock provides a wealth of information including measurements in both the gas phase and on compartment boundaries (Chapter 3). Total heat fluxes at a number of locations in the room were obtained together with gas flow velocities at all major openings. Materials involved comprised thermally-thick and thermally-thin elements including ceilings, internal and external walls and small length-scale members. This chapter presents the spatial distribution of heat fluxes within the compartment and uses the data to validate an analytical model developed to act as an interface between the gas-phase fire environment and the solid-phase structural elements using a computational fluid dynamics (CFD) based approach. It is anticipated that the output of such a model can be used on a larger stage to conduct a structural analysis.

It is shown that the model defines convective, radiative and total heat fluxes within the Dalmarnock post-flashover Fire Test, based on localised properties of the fire environment and takes advantage of the characteristic heating timescales of the surface material to define the thermal boundary condition. The outcome of such an analysis demonstrates good agreement between model predictions and the measured test data, yet shows significant discrepancies in the heat flux spatial distributions. This observation points towards an important limitation in current heat transfer calculations for structural analysis that assume homogeneous temperature distributions within compartments.

The current field of structural fire engineering can incorporate many sophisticated tools to evaluate the performance of buildings at elevated temperatures. One of the prime issues of debate though is the definition of the heat input to structural elements as a result of the fire (Welch *et al.* 2007). Current methods treat the fire as a simplified boundary condition, however, it is becoming increasingly recognised that a more proper thermal input to structural elements is required to accurately evaluate the mechanical response for a given fire. Furthermore, an accurate thermal load distribution on structural members allows for a safer and more economical structural protection arrangement to be specified.

Typically in structural fire engineering design, the definition of a fire environment is specified in terms of a single temperature-time curve to represent the entire fire

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compartment in a post-flashover, fully-developed scenario. This implies that all structural members within the compartment are subject to the same thermal severity regardless of their location.

For the case of a fully developed fire, the Eurocodes describe the action of the fire in terms of temperature-time curves. Nominal curves are given in Eurocode 1 (BS EN 1991-1-2:2002). The most common method for representing a post-flashover compartment fire is that of the standard curve, also referred to as the standard ISO-834 curve, given by,

$$T_g = 20 + 345\log_{10}(8t + 1) \tag{1}$$

where T_g is the average gas temperature and t is the time in minutes. If, following the growth of a fire, a decay phase is to be considered, then Annex A of Eurocode 1 provides a method for determining an appropriate temperature-time curve by,

$$T_g = 20 + 1325\left(1 - 0.324e^{-0.2t^*} - 0.204e^{-1.7t^*} - 0.472e^{-19t^*}\right) \tag{2}$$

where $t^* = t\Gamma$ and $\Gamma = (O/b)^2(0.04/1160)^2$. The opening factor is given by $O = A_v\sqrt{H_{eq}}/A_t$, while b incorporates the thermal properties of the compartment linings $(k\rho c)^{1/2}$. The duration of the heating phase can be defined in relation to the fire growth rate and fuel load densities. Parametric temperature-time curves of this kind are however limited to certain size compartments, for example Eurocode 1 limits the use of its parametric fire curve to floor areas of up to 500 m^2 and a maximum compartment height of 4 m.

A reliable, robust and accurate methodology to allow the use of computational fluid dynamics for the definition of the thermal boundary condition for structural design purposes is not available due to the lack of proper validation against full-scale fire tests. Work is ongoing to address this area (Pope and Bailey 2006, Welch *et al.* 2007, Chapter 11). In addition to the lack of testing, deficiencies in terms of the grid size to represent structural members and issues regarding flame spread and conjugate heat transfer adds to the resistance against widespread use of CFD (Torero *et al.* 2008).

Guidance for the evaluation of the thermal analysis for structures including the heat transfer phenomena which defines the thermal boundary condition is given in many sources including industry-orientated publications (Milke 2002) and in the standard design guides (BS EN 1993-1-2:2005). Solutions can be obtained at several levels; from tabular or graphical data, through simple numerical calculations to detailed numerical methods performed by computer. When a single temperature-time curve is used to define the fire regime, a simple lumped mass capacity (uniform heating) approach is commonly adopted to evaluate the temperature rise of a steel member as described in the Eurocode (BS EN 1993-1-2:2005). This methodology allows for unprotected and protected elements to be considered although this method still relies on the simplified thermal boundary condition represented by a single temperature-time curve, such as those prescribed by Eurocode 1.

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Heat Flux Model

The heat flux model used in this chapter is based on local gas conditions (Jowsey 2006). In essence this means that for the structural component of interest, surface heat fluxes can be evaluated providing it is completely engulfed in smoke and products of combustion or flames. The typical condition for the model is the post-flashover regime whereby the generation of smoke is at its greatest and heat fluxes are at a maximum.

To attempt the characterization of the temperature rise of structural elements, a post-processing model for CFD tools was developed to establish the heat fluxes imposed on all surfaces by a fire. Such a model can only work on the basis of well resolved local gas conditions. Analysis of the smoke layer and products of combustion allow for heat fluxes to be defined based on smoke absorption coefficients and temperatures. Heat fluxes can be defined at all points on the structure by consideration of the full spatial and temporal distributions. Furthermore, heat fluxes are defined by considering length and time scales in fires. Length scales are evaluated for different structural member geometries, while time scales are evaluated for different structural materials including applied fire protection. It is the output given by this model that would provide the input for the thermal analysis of the structural members and is a necessary step prior to a structural analysis being undertaken. In comparison to heat flux output provided directly by CFD models, this heat flux model is specifically designed for structural elements by taking into consideration their length scale geometry that cannot be accounted for due to the necessary CFD grid scales, a direct calculation of the convective heat transfer coefficient is provided for structural members and the model can be quickly re-run without the need for potentially lengthy additional CFD calculations to be performed.

Radiation can become the dominant mode of heat transfer to a surface when the element is engulfed in smoke or flames, nonetheless, convective heating can still play an important role in some cases. The evaluation of radiant intensity is achieved by consideration of the optical depth through either products of combustion or the flame itself. From the gas-phase of a CFD analysis it is possible to extract an extinction coefficient κ which when paired with a given path length L through products of combustion, allow the following limits to be defined,

$$\kappa L >> 1 \quad \text{Optically thick}$$
$$\kappa L << 1 \quad \text{Optically thin}$$

When a region is optically thick surrounding a structural member then the heat flux to its surface can be calculated based on local gas conditions. It is within this limit that the heat flux model described here can be applied. If however a region is optically thin, then the penetration distance is much larger than the path length and radiation can pass entirely through without appreciable extinction. When this is the case, local conditions cannot be applied and potential radiation from a further distance must be taken into account.

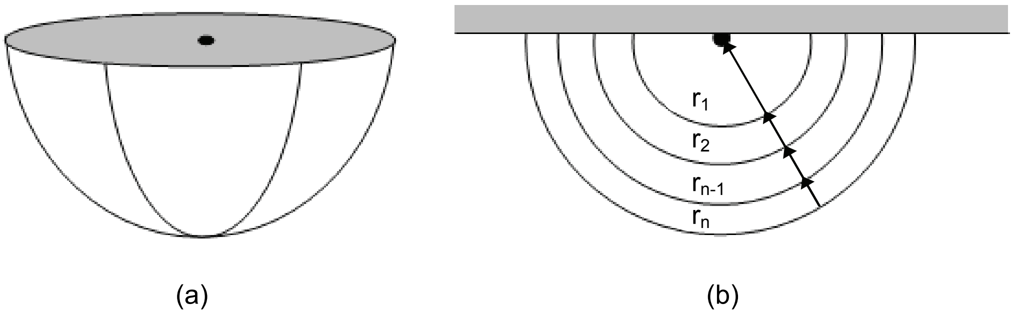

Figure 1: (a) Hemispherical control volume and (b) multiple shells through which radiative flux calculations are made

Figure 1 shows the hemispherical control volume used in the calculation of the total radiative intensity at a point in space. A number of hemispheres or shells comprise the control volume. Gas parameters including extinction coefficient and temperature are recorded at various points on the surface of each to allow an average to be assigned to each shell. Using these values and knowledge of the hemispherical geometry it is possible to evaluate the radiative intensity (Siegel and Howell 1992). In the case of multiple n shells, the transmissivity τ through the smoke to the surface point source can be written as,

$$\tau = \tau_1 \cdot \tau_2 \cdot \cdots \cdot \tau_n \qquad (3)$$

where the transmissivity is calculated by,

$$\tau_g = \exp(-\kappa L_g) \qquad (4)$$

Local gas emissivities ε are calculated by;

$$\varepsilon_g = 1 - \exp\left(-\kappa L_g\right) \qquad (5)$$

allowing total radiative fluxes q_r'' to be calculated for n shells using,

$$q_r'' = \sum_{shell=1}^{n} \phi\left(\varepsilon_{g,shell}\sigma\left(T_{g,shell} + 273\right)^4 \tau A_{shell}\right) \qquad (6)$$

where A_{shell} is the surface area of the shell, σ is the Stefan-Boltzmann constant and $\phi = 1/2$ is the configuration factor required to evaluate the radiative intensity that the point source on the surface receives from the surface area of the hemisphere. The above equations briefly outline the theory behind the radiative heat transfer employed by the model, full details including sensitivity studies can be found in (Jowsey 2006).

The calculation of the convective heat flux q_c'' is based on local temperature and can be expressed to a cold surface by,

$$q_c'' = h\left(T_g - T_s\right) \qquad (7)$$

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where T_g is the gas temperature, T_s is the temperature of the structural surface or compartment boundary and h is the convective heat transfer coefficient which can be established from the simplified relationship to the convective length scale and velocity as shown in Figure 2. This plot is a summary of a study of the convective heat transfer coefficient magnitude for structural elements of varying size and geometry placed within gases of different temperature and velocities. Further discussion on the background to this plot is not presented in this paper, however full details can be found in (Jowsey 2006).

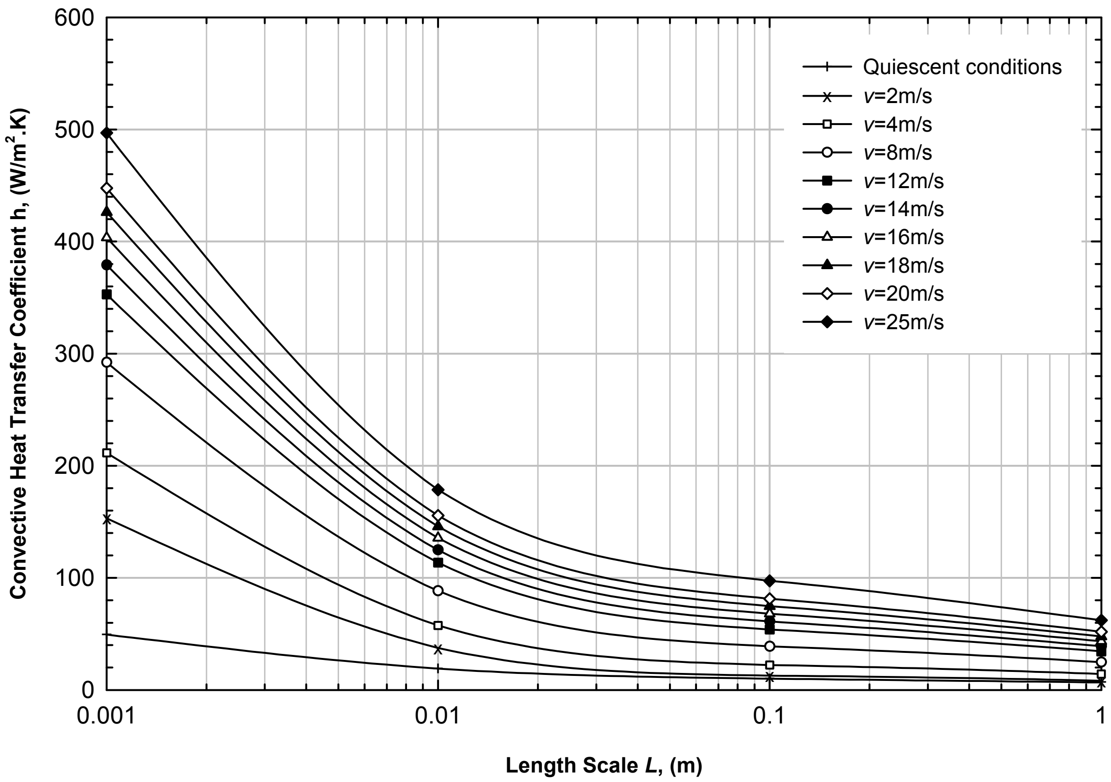

Figure 2: Variation of the convective heat transfer coefficient for various gas velocities over structural elements of different lengths

Consideration of the Biot number (Incropera and DeWitt 2002) allows characteristic heating times for different materials to be defined. Between these time periods, heat fluxes can be averaged without loss of accuracy. This conduction analysis in terms of thermal thickness, allow transient environments to be transformed into quasi-steady-state conditions to simplify the analysis into a summation of a series of steady-state solutions.

CFD Modelling

The fire evolution of the uncontrolled Dalmarnock Fire Test One (Chapter 3) has been recreated in a blind attempt to capture the order of magnitude of the fire intensity and its severity on the structure during the post-flashover fire period. The CFD tool for this exercise was chosen as the Fire Dynamics Simulator (FDS) (McGrattan 2004) as studies have shown (Olenick and Carpenter 2003) that for buoyancy driven flows, a large eddy simulation (LES) solution of a turbulent-closure is more representative of reality than the various k-ε models. A simplified flame spread model based on ignition temperature and a fixed heat release rate was defined for the items in the room. This method assumed all items have an associated ignition heat flux of 20 kW/m^2 together with a simplified heat release rate to determine the duration for which it would contribute as a fuel load. The heat release rates were obtained from experimental data (Mitler 1997) for fuel items that corresponded in size and material content to those in the Dalmarnock compartment (Chapter 2). An initial model was run using the sofa as the ignition source. Surface heat fluxes on items around the compartment were monitored during the simulation and the time they reached 20 kW/^{2} was noted. A subsequent model was then run, introducing at the noted time a prescribed heat release rate for the item that had met the heat flux ignition criteria. This process was repeated until all items in the room had been ignited and were involved in the fire. By adopting this approach, an estimation of the fire environment can be obtained despite limited data on the actual fuel load within the compartment.

Ventilation conditions included a partial opening of the kitchen window, doors to the compartment open and a forced removal of the entire main fire compartment window 800 seconds after ignition in accordance with the manual breakage during the test itself.

Results and Discussion

The intention here is to investigate the thermal severity following flashover and during the fully developed fire period. For this reason, the growth period of the fire is ignored and comparisons are only made following flashover in both the CFD and the experimental cases. Figure 3 shows a comparison between the average temperatures recorded in the test and by using a CFD approach. In addition, the single temperature-time curve for the standard fire is shown together with a parametric fire curve accounting for the geometry and ventilation of the compartment and for an office design fire load as specified in the Eurocodes (BS EN 1991-1-2:2002). The pattern of the CFD averaged temperature agrees well with the experiment in the post-flashover period, but the fire growth is under-estimated by approximately 16 min. Hence in accordance with the aims of this work and for the sake of better comparison, the CFD temperatures have been manually offset to match better those recorded in the test – it is again important to state that this chapter focuses on the magnitude of the compartment boundary heat flux during the post-flashover period, it is not the intention to investigate the transient growth and decay behaviour of the fire environment. Readers are referred to Chapters 10 and 11 for a detailed discussion on CFD prediction of the transient fire periods in the Dalmarnock Fire Test One.

For convenience, both Eurocode fire curves are assumed to start at the same time as the test. The grey box on the plot represents the time period during which comparisons to test data can be made. This box marks the test events of ignition and fire-fighter's intervention to extinguish the fire.

The temperatures plotted in Figure 3 suggest that following flashover, the CFD prediction is able to capture the behaviour of the fire in terms of peak values as a result of dynamics due to window breakages and fuel heat release rates. The magnitude of the

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temperatures predicted are slightly higher than those recorded in the test (about 50 to 80 °C). In comparison the standard fire is seen to initially over-predict the growth rate of the fire while temperatures are always over-predicted during the fully developed fire period. The parametric fire again, over-predicts the fire growth rate, yet temperatures following flashover are reasonably well predicted. While the comparison shown in the plot suggests that the Eurocode design fires may predict the temperature evolution of the fire with a certain amount of confidence, these results must be considered with caution. These are average temperatures within the entire compartment and as such spatial errors are always going to be eliminated in that some areas temperatures will be under-predicted while others are over-predicted. By adopting an average temperature as implied by the Eurocode, the thermal severity to structural elements within the compartment will likewise be under and over-predicted depending on the member's spatial location. It is further interesting to note that despite the test fire being extinguished, the CFD prediction can still be compared to the Eurocode design fires for a long period of time. Both the Eurocode fires predict a very high temperature, 850 °C and 750 °C for the standard and parametric fires respectively, while the CFD model predicts a steady-state temperature of approximately 600 °C for the fully-developed fire environment.

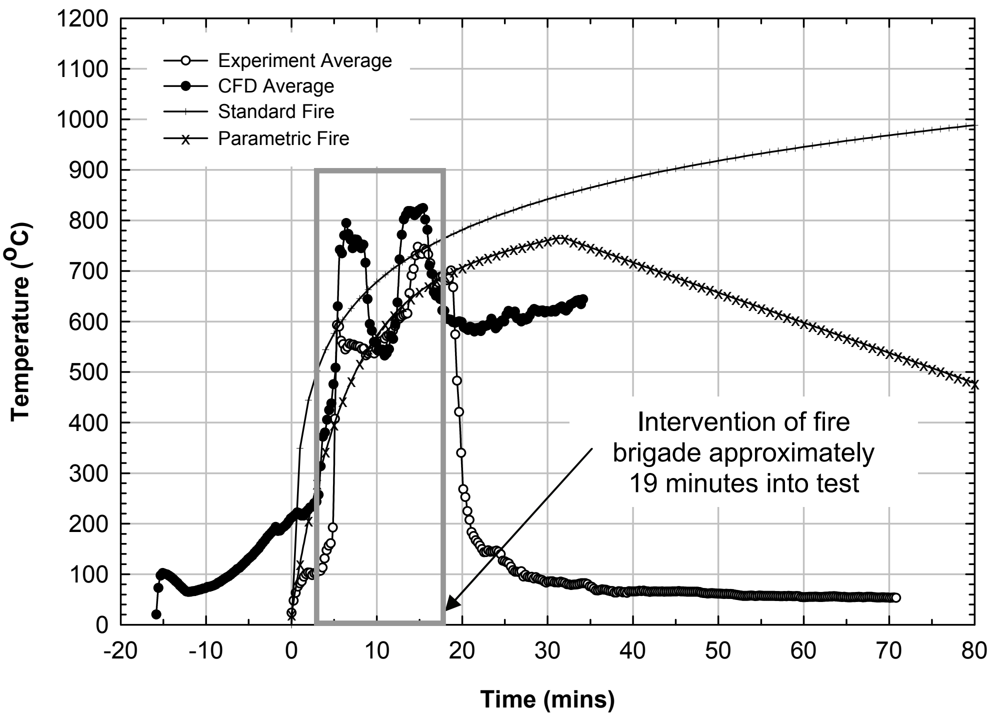

Figure 3: Average compartment temperature for experiment, CFD simulation and Eurocode design fires. CFD results are offset in time to match post-flashover conditions in the test. Frame marks the fully-developed fire period for which comparisons are made to the experimental data

Average temperatures really only provide a limited insight into the behaviour of a compartment fire. In order to fully appreciate the spatial variations that may exist,

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temperature maps or for structural members, total heat flux maps can be created. These are discussed below for the current test.

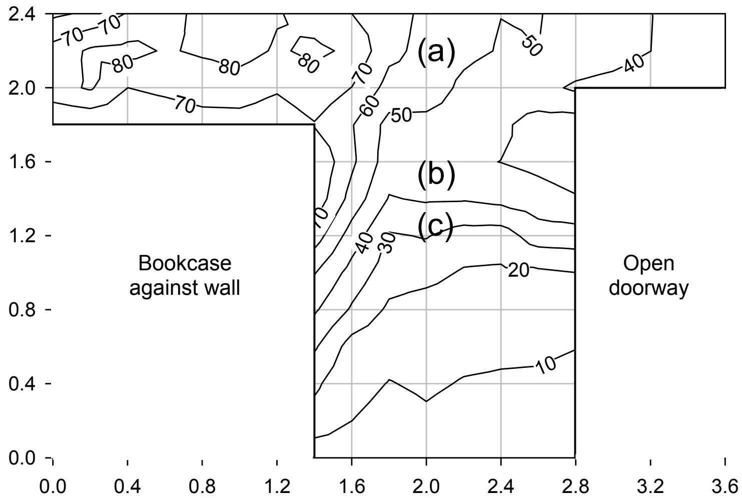

Figure 4: Contour plot of total heat flux on the rear wall of the compartment at *t*=15 mins. Axis labels are dimensions in m, while contour labels are kW/m².

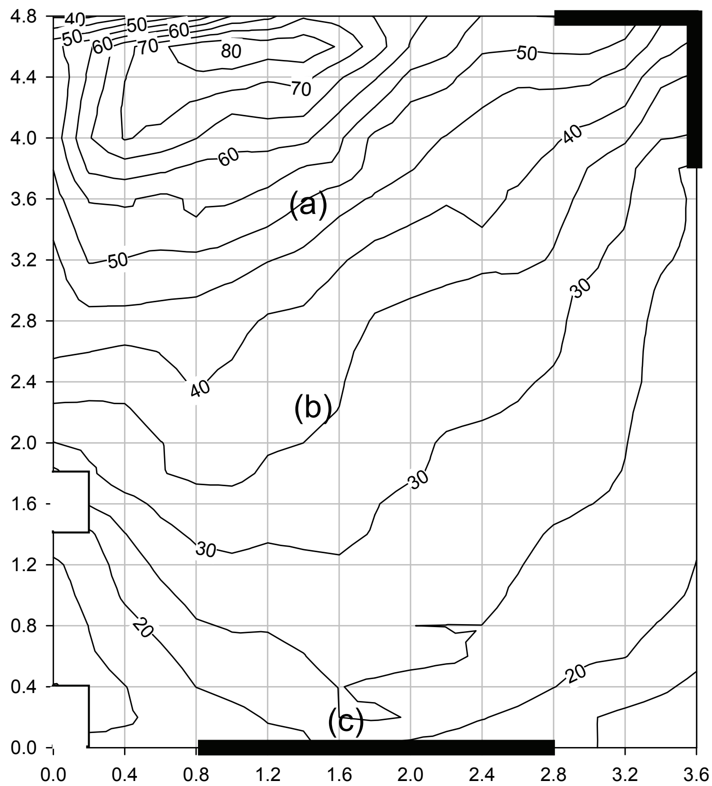

Figure 5: Contour plot of total heat flux over the ceiling of the compartment at *t*=15 mins. Axis labels are dimensions in m, while contour labels are kW/m². The black rectangles represent the location of ventilation openings.

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Figures 4 and 5[†] show the total heat flux maps predicted by the heat flux model at *t*=15 mins for the rear wall and the ceiling respectively (see Figure 3). At this time, the conditions are well into the fully-developed fire regime and therefore thermal severities can be expected to be at their most intense. It is clear from both contour plots that an extreme variation in total heat flux is created over the areas considered. The rear wall experiences high fluxes towards the ceiling due to the creation of the smoke layer, while lower parts that are outside the smoke experience a lower heat flux. The highest values are found directly above the bookcase against the wall as a result of its direct involvement in the fire and the resulting flames it creates, in agreement with experimental measurements (Amundarain *et al.* 2007). Furthermore, the influence of the window and doorway ventilation openings in Figure 6 result in the fire being forced into that same corner, creating the most intense severities. On the ceiling, the lowest heat fluxes are found nearest to the window with a strong gradient created towards the rear of the compartment – further highlighting that the premise of a single heat flux to represent an entire compartment is fundamentally incorrect.

Figures 6 and 7 show the evolution of heat fluxes for three locations on the rear wall and ceiling respectively. The experimental results are for the incident heat flux using calibrated skin calorimeters and the details are reported in (Amundarain *et al.* 2007). Again, as in Figure 3, only the post-flashover results can be compared effectively. Due to all locations being immersed within the smoke layer to represent the location of typical structural members, the heat flux model captures both the magnitude of total heat fluxes and behaviour to a reasonable extent. The reduction in heat flux on the ceiling from the rear of the compartment to the window in Figure 7 is most notable. In comparison, the Eurocode design fires typically over estimate and under-estimate thermal severities, although as stated above, this is best highlighted using the contour maps.

Summary

This chapter has presented the distribution of the post-flashover heat fluxes within the Dalmarnock fire compartment and places them within a context of the validation of a model that allows for surface convective, radiative and total heat fluxes to be evaluated on a structural member based on a CFD fire environment.

The heat flux model has been used to predict and compare the spatial distribution of heat fluxes within a full-scale fire test. The predicted heat fluxes agree well with those measured during the test. In addition these values have allowed a comparison to the current method of adopting a single uniform temperature-time relationship throughout the entire compartment. Indeed it is shown that there is a strong likelihood that using this simplified approach may induce significant errors. Quantification of the errors is scenario specific thus no attempt is made here to establish the general accuracy of this methodology. It is understood however that the ability to predict the spatially resolved heat fluxes may highlight areas where local heating may be more detrimental to structural

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[†] Note that the coordinate systems used in Figures 4 and 5 are defined relative to the wall and ceiling, respectively, and are not the same as the coordinate system used in Chapter 2.

behaviour than uniform heating. Furthermore, the ability to recreate the spatial distribution of heat flux as seen in the Dalmarnock fire test provides a method for the definition of the thermal boundary condition that allows a more precise evaluation of the structural response by incorporating a realistic fire scenario.

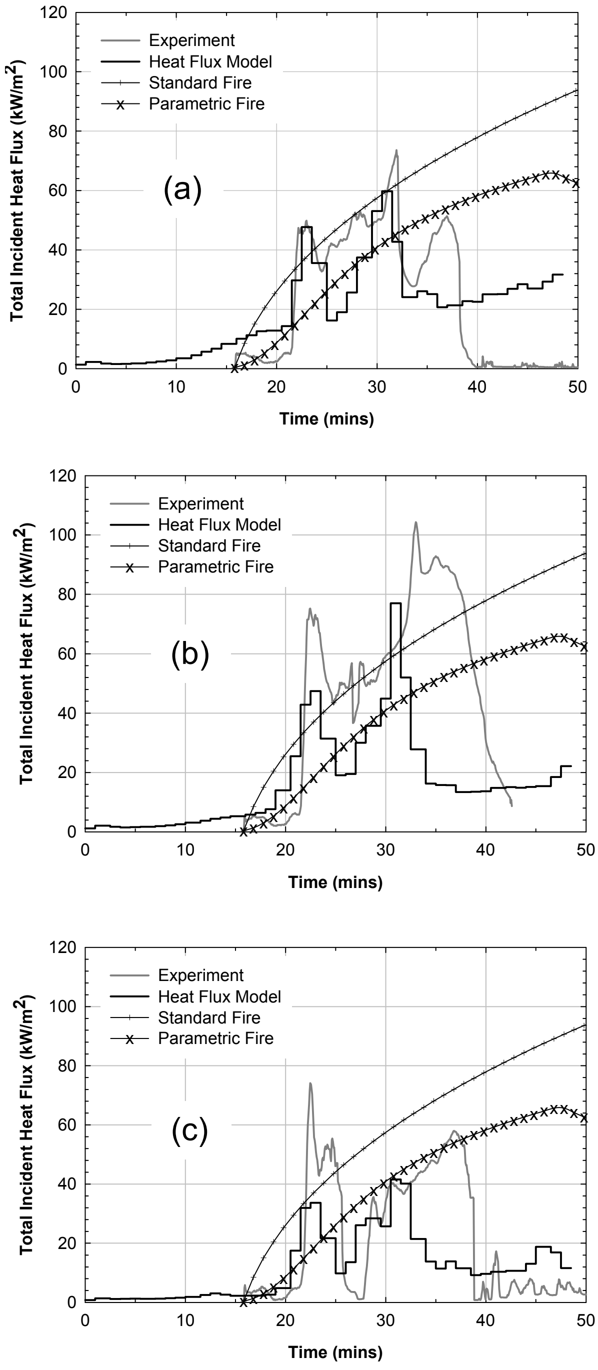

Figure 6: Comparison of total incident heat flux at locations on the rear wall. The location of (a), (b) and (c) is given in Figure 4.

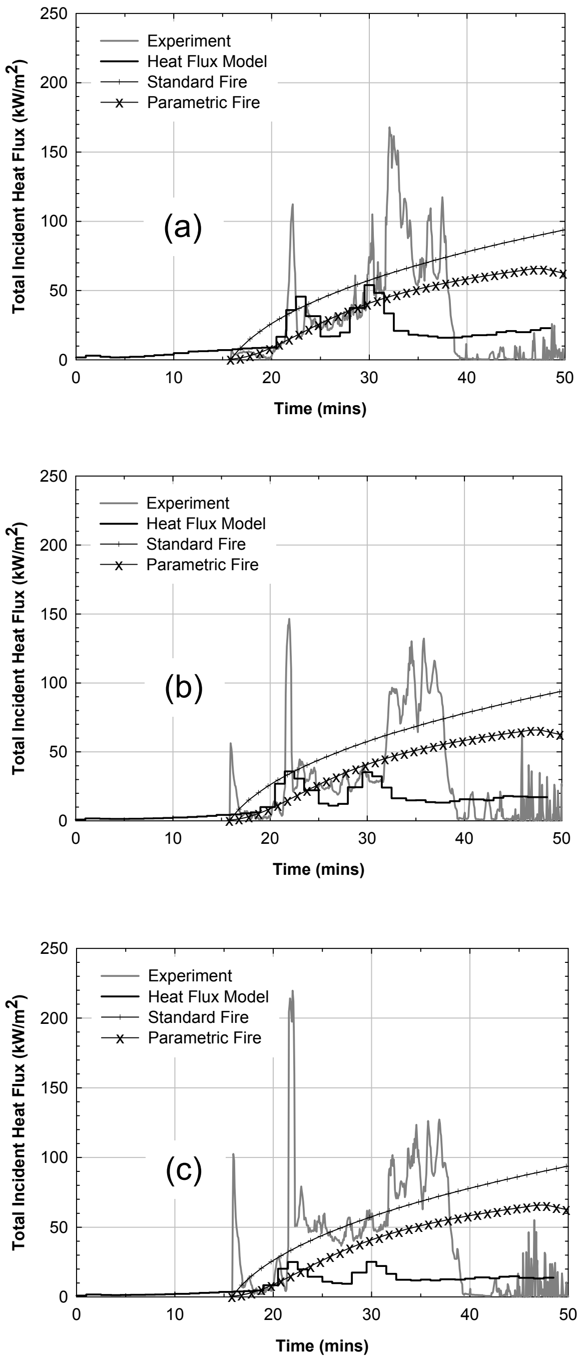

Figure 7: Comparison of total incident heat flux m at locations on the ceiling. The location of (a), (b) and (c) is given in Figure 5.

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