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Abstract

This paper considers the predictive capabilities of FDS for sprinkler actuation time when benchmarked against data from a series of 22 enclosure experiments. Sensitivity analyses have been undertaken for grid size, conductivity factor, radiative fraction and enclosure leakage areas. ‘Goodness of fit’ calculations indicate that FDS is able to provide an average prediction of sprinkler actuation time within a Euclidean Relative Difference of 0.18.

Comparisons to results determined in previous studies, using different modelling methods and FDS versions, have also been made. The sensitivity analyses and comparisons indicate the importance of the decisions made by the modeller in representing fire scenarios, even when modelling ‘simple’ experiments where data for inputs such as the heat release rate, geometry and sprinkler characteristics are available. The comparisons therefore indicate that with the reduced degrees of freedom compared to other modelling studies, there is still potential for a range of assumptions and simulation results.

Keywords

Fire modelling, benchmarking, sprinkler actuation, FDS.

Introduction

Computational models are regularly used by fire engineers to assess the expected sprinkler actuation time in an enclosure. This time may be used, for example, to determine anticipated fire growth characteristics to be used for other analyses, such as the application of the heat release rate (HRR) curves following sprinkler actuation described in the guidance document PD 7974-1 [1]. It is therefore important to know whether the computational tools used are able to predict sprinkler actuation times to an appropriate level of accuracy.

One of the most commonly applied methods to determine whether a model can encapsulate behaviours observed in real life is to benchmark against experimental data. The Fire Dynamics Simulator (FDS) validation and verification guides [2] [3] include benchmarking of experiments by UL/NFPRF and Vettori for sprinkler actuation times. The former measured sprinkler actuation times for a series of heptane spray burner incorporating water flow [4], while the latter considered sprinkler actuation times in flat and sloped ceiling experiments, where sprinklers did not include water flow and 'first' actuation times could be considered for multiple sprinkler heads [5]. In certain cases, simulations modelled in FDS have been shown to match experiments within the bounds of experimental uncertainty, while in others there is more variation in values. This provides an indication of the FDS model accuracy based on a limited number experiments such that the consideration of more data for benchmarking is always beneficial to further determining the accuracy of a tool. The analyses described in this paper have since been incorporated into the FDS Validation Guide [3], with input files and experimental results available in the FDS online repository [6].

Previous work by Bittern [7] and Wade et al. [8] involved the undertaking of experiments on sprinkler actuation in a room-sized enclosure and comparing the experiment results against simulated results using FDS 3 and BRANZFIRE (now known as B-RISK [9]) computational modelling tools. For this paper, these works have been revisited in the context of the latest publicly available version of FDS (version 6.6.0 [10] [11]) to consider the accuracy of the tool's capability to predict sprinkler actuation time for a specific set of fire scenarios. For reference, FDS estimates sprinkler actuation and the temperature of the sensing 'link' based on the differential equation of Heskestad and Bill [12], with an additional term to account for the cooling of the element by water droplets [11] not applicable to the contents of this paper. The differential equation, excluding cooling by water droplets is given by

$$\frac{\mathrm{d}T_l}{\mathrm{d}t} = \frac{\sqrt{|\mathbf{u}|}}{\mathrm{RTI}}\left(T_g - T_l\right) - \frac{C}{\mathrm{RTI}}\left(T_l - T_m\right)$$

where **u** is the gas velocity, RTI is the response time index, T_l is the link temperature, T_g is the gas temperature in the neighbourhood of the link, T_m is the temperature of the sprinkler mount (assumed ambient) and C is the conductivity-factor, discussed later.

In addition, the decisions made by different modellers and the effect it can have on the outcome of a modelling exercise has been examined. Blind modelling studies, such as the work by Rein et al. [13] on the Dalmarnock Fire Tests, have highlighted the difficulty in predicting dynamics when there are increasing degrees of freedom. More recently Baker et al. [14] have presented a blind modelling study of furniture fires in a ISO 9705 [15] room using B-RISK, concluding that the results provided an illustration of the subjectivity that can occur in everyday performance-based fire safety engineering [14]. In this paper, the impact of modelling decisions in the context of analyses with fewer degrees of freedom have been considered, where the experiments have provided an opportunity to simulate a 'simple' enclosure and compare to past simulations, with data available for inputs including HRR, geometry, sprinkler characteristics and construction materials.

Experiments

In 2004 a set of 22 fire experiments were undertaken where a single upholstered chair was burned within an enclosure [7]. Two sprinkler heads were installed within the enclosure and for each experiment the sprinkler actuation time was measured.

The enclosure had internal dimensions of 8 m by 4 m by 2.4 m high, based on the room specifications contained in UL 1626 [16]. The enclosure was built from timber-framed walls and ceiling and was lined with 10 mm thick gypsum plasterboard [7]. A single door was located in one of the short walls of the enclosure. This door consisted of a wooden frame with a plywood door leaf, and was 0.8 m wide by 2.1 high and during the experiments it was either fully open or closed. The enclosure layout, dimensions and experimental arrangement are shown in Figure 1.

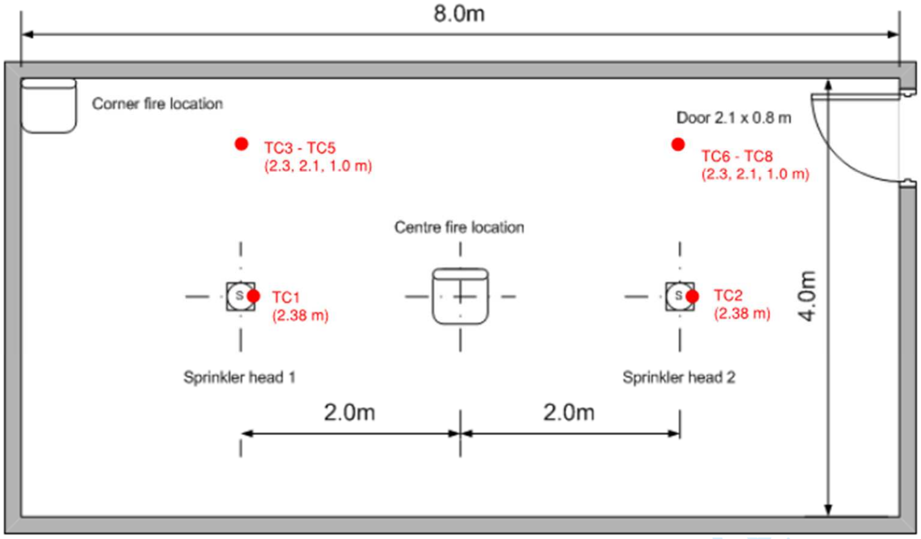


Figure 1: Compartment layout (plan view) [8]

The upholstered chair was constructed of a seat on a metal frame where the seat was made of two non-fire retardant flexible polyurethane foam slabs of density 28 kg/m^3, covered with a 10 g/m^2 acrylic fabric. Each slab measured approximately 0.5 m by 0.4 m by 0.1 m thick with one forming the horizontal ‘base’ of the seat and the other the vertical ‘back’. Plasterboard was used to form a backing board for the seat and the chair was placed on a load cell to record mass loss (measured in increments of 5 g), with the base of the seat approximately 0.65 m from floor level (FFL). The seat was ignited using a solid petroleum firelighter. The HRR was estimated from the recorded values of mass loss rate and heat of combustion of the foam where the average heat of combustion was measured in a cone calorimeter to be 21.0 MJ/kg (Experiment 1 to 10) and 20.4 MJ/kg (Experiment 11 to 22) [7] [8]. The seat was located in one of two locations in the enclosure: either in the centre or the corner opposite the door as shown in Figure 1.

While gas velocities were not recorded, gas temperature profiles were measured using bare-wire Type K thermocouples located within the enclosure, adjacent to each sprinkler head and away from the sprinklers at heights of 1.0 m, 2.1 m and 2.3 m FFL (Figure 1).

Sprinkler Characteristics

Experiments incorporated different residential and standard response sprinkler heads installed flush beneath the ceiling. The sprinkler heads were not charged with flowing water during the experiments, but pipe sections connected to the head contained a small volume of water under pressure. Pressure gauges were installed immediately upstream of each sprinkler head before the closing valve to indicate sprinkler actuation [8].

The assumed parameters of the sprinkler types used in the experiments are shown in Table 1. These characteristics are based on the manufacturer's specification where available or otherwise estimated based on literature. The sprinkler offset below the ceiling has been selected based on an approximate 20 mm glass bulb length and a C-factor of 0.4 $(\mathrm{m/s})^{1/2}$ selected based on sensitivity analyses undertaken in the original studies and the subsequent work of Tsui [17] [18]. Additional sensitivity analyses for the C-factor have been undertaken using FDS and are discussed later.

Table 1: Sprinkler head characteristics

Ref.	Sprinkler type	Parameters	Value
Res A	Residential (3 mm glass bulb)	C-factor	0.4 $(\mathrm{m/s})^{1/2}$
		RTI	36 $\mathrm{m}^{1/2}\mathrm{s}^{1/2}$
		Rated temperature	68 °C
Res B	Residential (3 mm glass bulb)	C-factor	0.4 $(\mathrm{m/s})^{1/2}$
		RTI	36 $\mathrm{m}^{1/2}\mathrm{s}^{1/2}$
		Rated temperature	68 °C
SS68	Standard Response (5 mm glass bulb)	C-factor	0.4 $(\mathrm{m/s})^{1/2}$
		RTI	95 $\mathrm{m}^{1/2}\mathrm{s}^{1/2}$
		Rated temperature	68 °C
SS93	Standard Response (5 mm glass bulb)	C-factor	0.4 $(\mathrm{m/s})^{1/2}$
		RTI	95 $\mathrm{m}^{1/2}\mathrm{s}^{1/2}$
		Rated temperature	93 °C

Results

Table 2 shows a summary of the results of the experiments, indicating the fire location, experiment number, sprinkler head type for each sprinkler, as well as the recorded sprinkler actuation time. The sprinkler actuation times were dependent on the type of sprinkler head as well as the position of the fire relative to the sprinkler head. Also shown is the average ambient temperature recorded from the thermocouples in the enclosure prior to ignition, which has been incorporated into the modelling using an initial ambient temperature applied across the domain.

Table 2: Summary of experiment results

Fire location / door configuration	Experiment	Head 1	Time (s)	Head 2	Time (s)	$T_{ambient}$ (°C)
Fire in centre of room / door open	1	Res A	210	Res A	250	23.7
	2	Res A	225	Res A	211	25.5
	3	Res B	192	Res B	192	25.5
	4	SS68	226	SS68	226	25.7
	5	SS68	266	SS68	272	27.5
	6	SS68	216	SS68	211	27.7
	7	Res A	182	Res A	186	28.2
	8	Res B	182	Res B	187	27.9
	9	Res B	233	Res B	230	28.9
	10	Res A	183	Res B	184	29.4
Fire in centre of room / door shut	11*	SS68	199	Res B	175	N/A
	12	SS68	246	Res B	228	24.0
	13	SS68	204	Res B	194	24.5
	14	SS68	203	Res B	187	24.2
	15	SS68	270	Res B	253	23.7
Fire in corner of room / door shut	16	Res B	178	Res A	224	20.6
	17	Res B	181	Res A	228	23.8
	18	SS68	187	Res A	221	25.0
	19	SS68	189	Res A	223	26.4
	20	SS68	205	Res A	None	25.3
	21	SS93	216	SS93	330	25.2
	22	SS93	205	SS93	263	25.2

** As ambient temperature and mass loss rate were not successfully recorded for Experiment 11, it has been excluded from all subsequent analyses*

The HRR for experiments with the door open (Experiment 1 to 10) are shown in Figure 2 and door closed experiments (Experiment 12 to 22) in Figure 3. Since the mass loss data was measured in 5 g increments and the combustible mass of the two flexible polyurethane foam slabs was approximately 1120 g [7], the HRR was able to be recorded in a maximum of 224 increments.

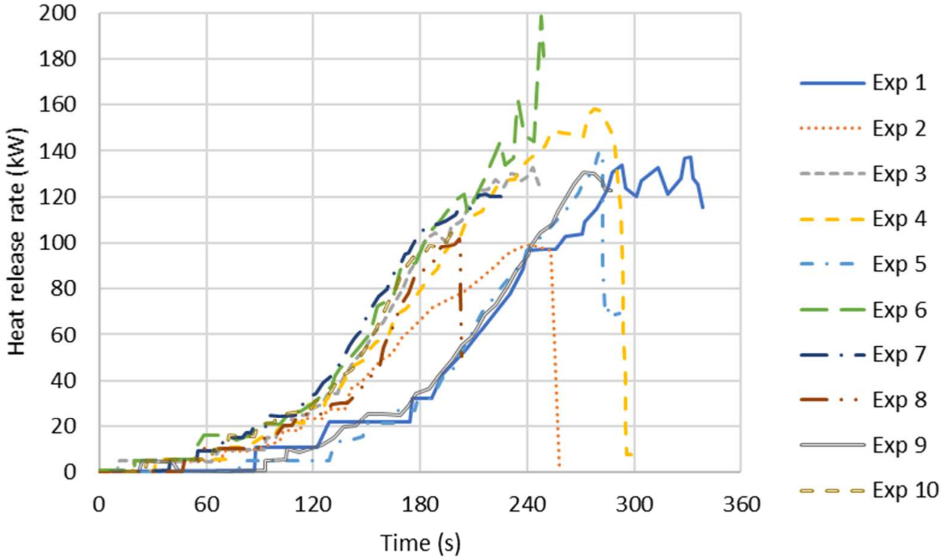


Figure 2: HRR curves for Experiment 1 to 10

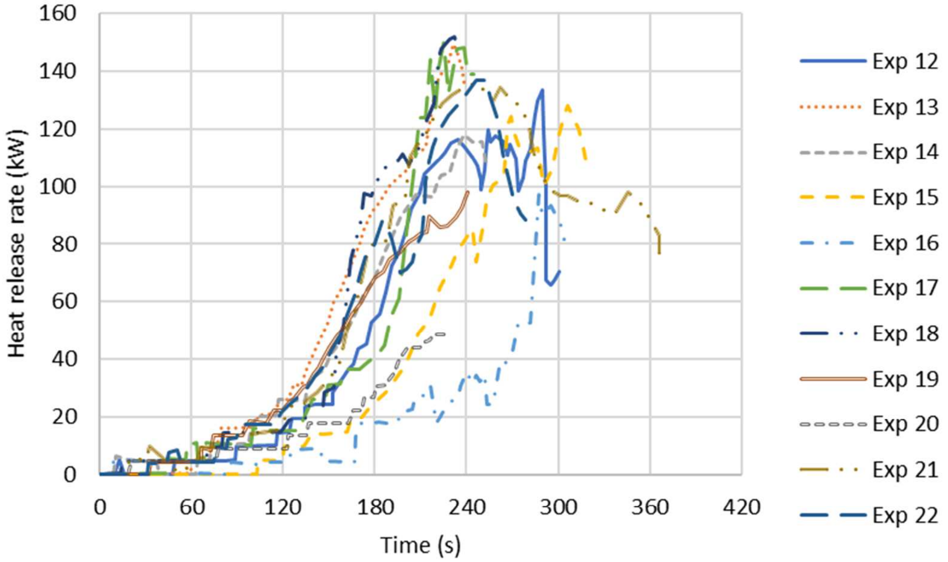


Figure 3: HRR curves for Experiment 12 to 22

In the original experiments, the mass loss rate was only recorded for a brief period following sprinkler actuation. For certain analyses presented here the simulations are not able to determine the time of sprinkler actuation prior to the end of the timeline of available HRR data. This is applicable in cases where the model overestimates sprinkler actuation time compared to the experiments. Therefore, in the absence of data, additional simulations have been run assuming that the fire is capped once it has reached peak HRR and that it continues to burn at this rate for an indefinite period. This has been subsequently referred to as a 'capped fire' for all following discussion in this paper. An example of an assumed 'capped fire' is shown in Figure 4.

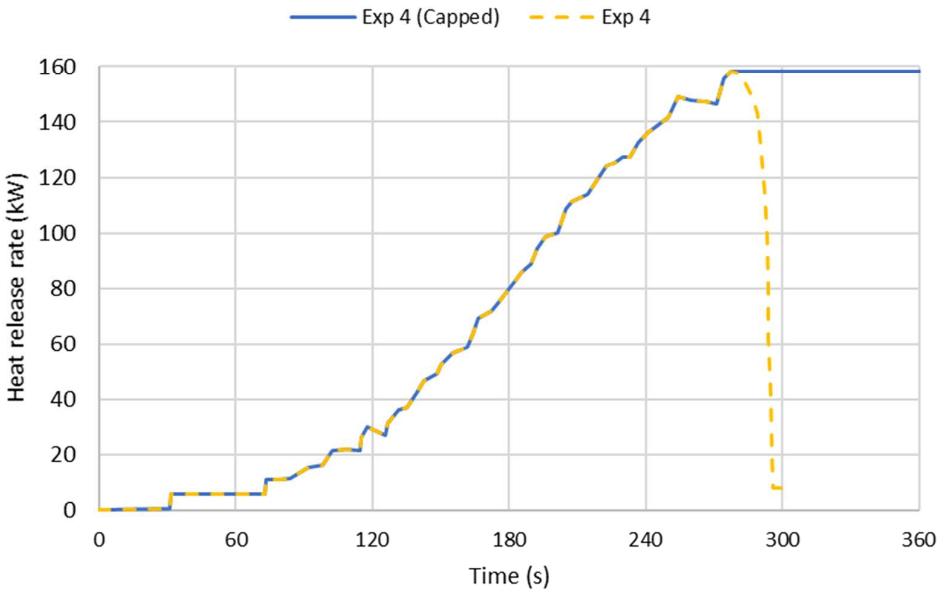


Figure 4: Example of capped HRR curve (Experiment 4)

Simulation Descriptions and Methodology

The material and thermal properties of the modelling have been selected in line with those assumed in the previous studies [7] [8], and have been summarised in Table 3.

Table 3: Material properties assumed for modelling

Lining	Material	Selected input
Walls and ceiling	Gypsum plasterboard	Thickness = 0.01 m Density (ρ) = 731 kg/m^3 Specific heat (c) = 900 J/kg·K Conductivity (κ) = 0.17 W/m·K Emissivity (ε) = 0.88
Floor	Concrete	Thickness = 0.1 m Density (ρ) = 2300 kg/m^3 Specific heat (c) = 880 J/kg·K Conductivity (κ) = 1.2 W/m·K Emissivity (ε) = 0.50

Since the primary fuel used in the experiments was flexible polyurethane foam, the radiative fraction assumed in the fire model was 0.46 based on the radiation of the radiative to chemical heat of combustion for GM23 foam [8]. Other combustion parameters were as for polyurethane foam, and all parameters selected are consistent with those used in the original BRANZFIRE study [8].

The simulations apply the FDS burner capability using the HRR obtained from the experiments. The burner area of 0.4 m by 0.5 m has been assumed for the 'base' of the seat, positioned 0.65 m FFL. This is consistent with the assumptions of the BRANZFIRE study [8] but differs from the modelling assumptions of the original study [7], which adopted a smaller burner area intended to represent the 'back' of the seat as discussed later.

Table 4: Fire parameters assumed for modelling

Parameter	Selected input
Radiative fraction	0.46
Heat of combustion	21.9 MJ/kg (Experiment 1-10) 20.4 MJ/kg (Experiment 12-22)
Soot yield	0.227 kg/kg [19]
Burner area	0.4 m by 0.5 m (0.2 m^2)
Height of burner above floor	0.65 m

As part of its 'simple chemistry' combustion model, FDS includes inputs for stoichiometric yields for the fuel reaction. Values have been selected from literature based on GM23 foam, with a formula of $CH_{1.8}O_{0.35}N_{0.06}$ [20].

Sensitivity Analyses

Prior to performing simulations for the full series of experiments, sensitivity analyses were also undertaken to determine the appropriate grid sensitivity, C-factor, leakage area and radiative fraction.

Grid Sensitivity

To determine an appropriate grid size for the modelling which is able to best reflect the results of the experiments, a grid sensitivity analysis has been undertaken in line with the recommendations of the FDS User's Guide [10]. This recommends that "in general, you should build an FDS input file using a relatively coarse mesh, and then gradually refine the mesh until you do not see appreciable differences in your results" [10]. While this method does not guarantee convergence as the grid is refined, it is a common and practical method adopted by fire engineers to consider grid sensitivity.

In the original study [7], a grid sensitivity study was undertaken for the modelling of the experiments in FDS 3, considering grid sizes between 0.15 m and 0.05 m. While a 0.05 m grid size was shown to provide the closest match to the experiments, it was concluded that a grid of 0.1 m was sufficiently refined for the modelling while also reducing the computational time compared to the 0.05 m grid.

For the grid sensitivity analysis of this study, a single scenario has been selected (Experiment 10) and considered for four different uniform grid sizes from 0.2 m to 0.025 m, as summarised in Table 5. Experiment 10 has been selected as it does not require a capped fire to determine sprinkler actuation time as well as providing a shorter computational time for the simulations.

Table 5: Grid sensitivity analysis

Grid size	No. of cells
0.025 m	6,182,400
0.050 m	772,800
0.100 m	96,600
0.200 m	12,592

The results of the grid sensitivity analysis indicate that the differences between a 0.025 m and 0.05 m grid size are small (0% difference for sprinkler head 1 and 1% for head 2). For grid sizes of 0.1 m and 0.2 m, the model is not able to predict sprinkler actuation time for both sprinklers prior to the end of the simulation. The grid sensitivity analysis therefore indicates that, for this specific set of experiments, a 0.05 m grid size should be able to appropriately capture sprinkler actuation times and this grid has been selected for the FDS 6.6.0 modelling.

For each of its test series, the FDS Validation Guide [3] provides parameters for numerical resolution, which is partly intended to outline the range of applicability of the validation studies. These parameters include the characteristic fire diameter (D^*) using peak HRR, the plume resolution index ($D^*/\delta x$) and the enclosure ceiling height relative to the fire diameter (H/D^*). The plume resolution index in particular is dependent upon the selected grid size (δx). For the series of simulations described in this paper, the range of values for these numerical parameters are shown in Table 6 for a selected grid size of 0.05 m. Experiment 10 has also been specifically highlighted due to its use in the grid sensitivity analysis. This provides relevant numerical values which modellers can compare against when simulating similar applications.

Table 6: Summary of numerical parameters

Parameter	Experiment 10	Experiment 1 to 22
D^*	0.4	0.3 – 0.5
$D^*/\delta x$	7.9	5.8 – 10.0
H/D^*	6.1	4.8 – 8.3

C-Factor

One important input used for determining sprinkler actuation time is the C-factor, or conductivity factor, with Heskestad [21] reporting that it has a critical role to play and the effects become increasingly important as both RTI and fire growth decreases. The C-factor characterises the heat loss to the sprinkler housing due to conduction [22].

In the original study [7], it was found that C-factors significantly affected the predicted sprinkler actuation times. C-factors of 0.0 $(m/s)^{1/2}$ and 0.3 $(m/s)^{1/2}$ provided the closest prediction of the experimental results for the residential heads. A C-factor of 0.65 $(m/s)^{1/2}$ gave the closest comparison to the standard response heads, although C-factors below 0.65 $(m/s)^{1/2}$ were only modelled for the residential heads. Tsui [18] measured the C-factor for residential sprinkler heads similar to those used in the study with values in the range of 0.33-0.45 $(m/s)^{1/2}$ and an estimated uncertainty of up to 20%. On this basis, a C-factor of 0.4 $(m/s)^{1/2}$ was selected in the BRANZFIRE study [8].

While a C-factor of 0.4 $(m/s)^{1/2}$ has been determined as appropriate from the work of Tsui, a sensitivity analysis has been undertaken for a single scenario (Experiment 10), where the C-factor is varied between 0.0 $(m/s)^{1/2}$ and 0.8 $(m/s)^{1/2}$. The results of this analysis are shown in Figure 5 indicates that a C-factor between 0.2 $(m/s)^{1/2}$ and 0.4 $(m/s)^{1/2}$ provides the most consistent match with Experiment 10, depending on the sprinkler head location, in line with Tsui's 0.33-0.45 $(m/s)^{1/2}$ range. Although only a single example, this provides an indication that the 0.4 $(m/s)^{1/2}$ value assumed from literature is appropriate for use in further analyses.

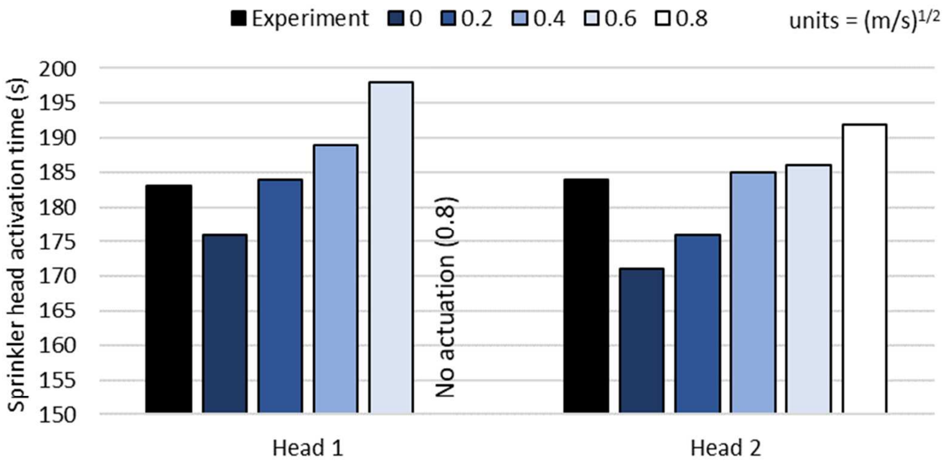


Figure 5: C-factor sensitivity analysis, comparison of sprinkler head actuation time (Experiment 10)

Leakage Area

For Experiment 11 to 22 of the original study, the door to the enclosure was closed. While this would have limited the supply of air to the enclosure, the construction would have incorporated a certain amount of leakage area for the wall, floor and ceiling materials, connections between walls, the door construction etc. Since the degree of leakage was not measured in the experiments, BS EN 12101-6 [23] has been used to approximate leakage areas of the space (for combined wall, ceiling and floor area plus door leakage). For this, air leakage data for walls and construction elements, assuming loose-fitting internal walls, and leakage from a single leaf door, has been applied, resulting in an estimated total leakage area of 0.053 m^2.

To simplify the modelling, the enclosure leakage has been represented using the localised leak vent function in FDS at the location of the door, with the total leakage area evenly distributed across the door area. To confirm that the leakage area is sufficient in maintaining the HRR recorded in the experiments, a sensitivity analysis has been undertaken the for a single experiment (Experiment 12) with varying leakage areas, shown in Figure 6. Experiment 12 has been selected as it is a scenario which incorporates the door being closed, does not require the modelling of a capped fire to determine sprinkler actuation and also provides a comparatively large HRR.

In the simulation where no ventilation has been included, the HRR does not adhere to the data recorded in the experiment and results in large fluctuations in HRR. However, the estimated leakage area of 0.053 m^2 provides an HRR consistent with a larger leakage area of 0.5 m^2, indicating that the calculated area does not throttle the development of the fire. In addition, the predicted sprinkler actuation times do not change when the leakage area is taken to be 0.053 m^2 or 0.5 m^2.

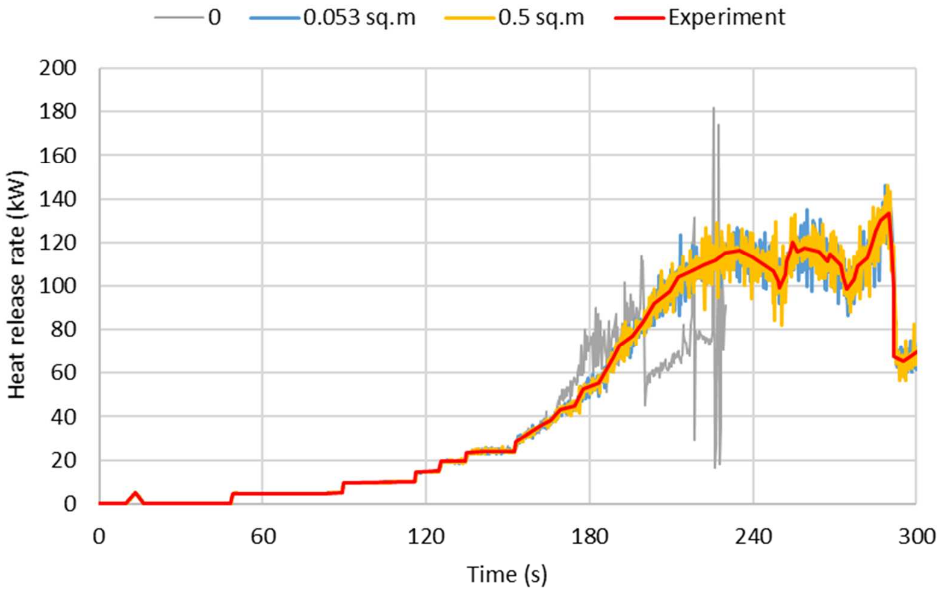


Figure 6: Leakage sensitivity analysis, HRR (Experiment 12)

Radiative Fraction

By default, FDS incorporates a radiative fraction based on species, where the default for ‘all other species’ is 0.35 which is representative of a typical design value. For the simulations, a radiative fraction of 0.46 has been adopted based on GM23 foam from the original BRANZFIRE study [8]. The selected radiative fraction will impact upon the results of the simulations in terms of convective heat flow, which in turn affects sprinkler actuation. A sensitivity analysis has been undertaken for Experiment 10 to determine the impact of the selected 0.46 radiative fraction compared to the 0.35 FDS default. The results of this analysis indicate that the selected radiative fraction of 0.46 provides a more consistent match for Experiment 10 compared to the default, with the variation of sprinkler actuation times between the two simulated radiative fractions is 6% and 7% for head 1 and head 2 respectively. The assumed 0.46 fraction therefore appears reasonable.

Experimental and Model Uncertainty

The FDS Validation Guide [3] and Vettori [5] suggests a range of experimental uncertainty, with a relative standard deviation in sprinkler actuation time of approximately 6%. Also described in the FDS Validation Guide is the concept of model uncertainty and model bias, with the guide determining a model relative standard deviation of 0.19 and a model bias factor of 1.02. For this paper, these uncertainty values have been highlighted in figures shown later, although they apply for the entire sprinkler actuation data set in the Validation Guide and are not specific to the experiments discussed here.

Modelling Results

Figure 7 provides a comparison of the sprinkler actuation times recorded in the experiments against the sprinkler actuation times determined from the FDS simulations for the ‘uncapped fire’. Also shown is the range of experimental (shown as a black small-dashed line) and model uncertainty (shown as a red long-dashed line).

The graph has 35 data points in total, with 6 missing data points compared to the experiments. For the missing data points, as discussed previously, the simulations were not able to determine the sprinkler actuation time prior to the end of the HRR data determined in the experiments. With a few exceptions, the simulation results are within the bounds of model uncertainty.

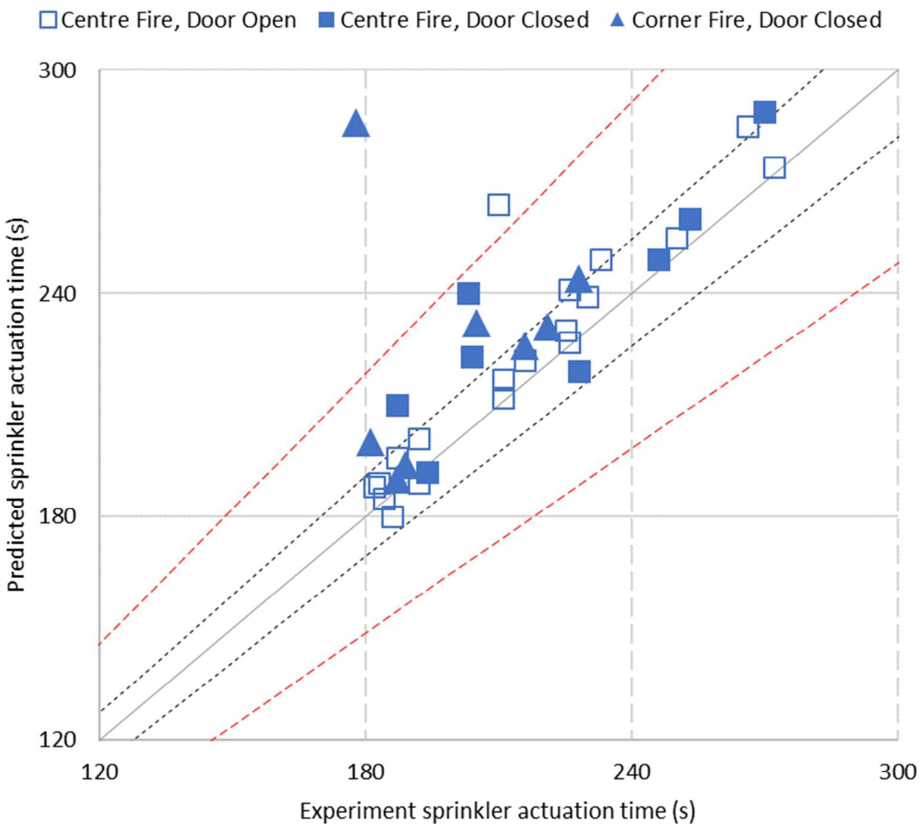


Figure 7: FDS predicted against experiment sprinkler actuation time

For a capped fire, shown in Figure 8, all sprinkler heads are actuated in the simulations and therefore includes the missing actuations not determined in the uncapped simulations. However, it can be seen that in cases of a corner fire with the door closed (Experiment 16 to 22), the model is less accurate in its prediction, where in some cases it over-predicts the actuation time by as much as 108 s.

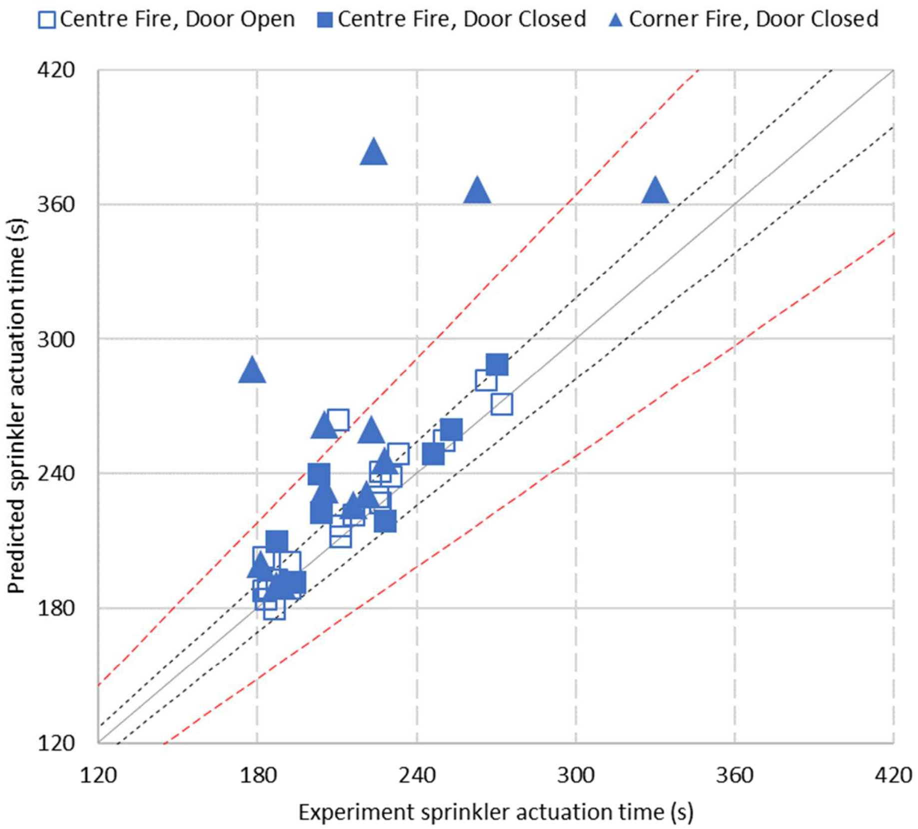


Figure 8: FDS predicted against experimental sprinkler actuation time for a capped fire

The Euclidean Relative Difference (ERD) has been used to assess the average difference between the experimental data and the model data to provide an indication of the 'goodness of fit' beyond the visual inspection of graphs. The equation for the ERD is given as:

$$\frac{\|E - m\|}{\|E\|} = \frac{\sqrt{\sum_{i=1}^{n}(E_i - m_i)^2}}{\sqrt{\sum_{i=1}^{n} {E_i}^2}}$$

where E is the experimental data and m is the equivalent data point estimated by the model. For this measure, the closer the model data to the experimental data, the closer the ERD is to 0 [24]. For example, an ERD of 0.2 taken for all the data points indicates that the average absolute difference between the model and experimental data points is 20% [25].

The ERD has been calculated for all simulations relative to the experimental data. The ERD for the prediction of all sprinkler heads is shown in Table 7. The average percentage difference (relative to experimental data) not considering absolute values and the number of missing data points, i.e. non-actuated sprinkler heads within the model compared to the experimental data, have also been shown.

Table 7: Euclidean Relative Difference (ERD) calculations

Scenario	Fire	ERD	Average difference	Missing data points
All experiments	Uncapped	0.11	+6.4%	6/41
	Capped	0.18	+9.7%	0/41
Excluding corner fire experiments	Uncapped	0.12	+6.4%	1/29
	Capped	0.12	+6.5%	0/29

Overall, the ERD indicates that FDS is able to closely predict the experimental results. As shown by the average percentage difference, FDS typically overpredicts the experiment sprinkler actuation times for these experiments to within less than 10%.

In all cases it was observed visually that corner fire scenarios appeared to be less accurate for the capped fire modelling. Therefore, the ERD has been calculated excluding these experiments, also shown in Table 7. From this it can be observed that the accuracy of capped fire scenarios improves when excluding corner fires, as well as reducing the number of missing data points. This may indicate that, for this set of experiments, FDS is better at predicting sprinkler actuation for fires positioned in the centre of the enclosure. However, this is shown only for a limited quantity of data.

Comparison with the 2004 Study

Revisiting the results from the original experiments and modelling study gives a rarely investigated opportunity to consider not only whether the development of model has affected its predictive capability but also the impact of decisions made by the modeller.

In the previous study [7], multiple C-factors were considered for different experiments, with C-factors of 0.0, 0.3, 0.65 and 1.0 $(m/s)^{1/2}$ modelled in some capacity. A C-factor of 0.65 $(m/s)^{1/2}$ was the most consistently modelled throughout the study, with full results for sprinkler actuation time determined for Experiment 1 to 10 (centre fire, door closed). Therefore these 10 experiments have been considered for comparison.

To determine the variation in results between FDS 3 and FDS 6.6.0, the previous approach has been remodelled for Experiment 1 to 10, with C-factor of 0.65 $(m/s)^{1/2}$ and a uniform grid size of 0.1 m consistent with the original modelling. A C-factor of 0.65 $(m/s)^{1/2}$ has been modelled as it provides the most available data for comparison between the studies.

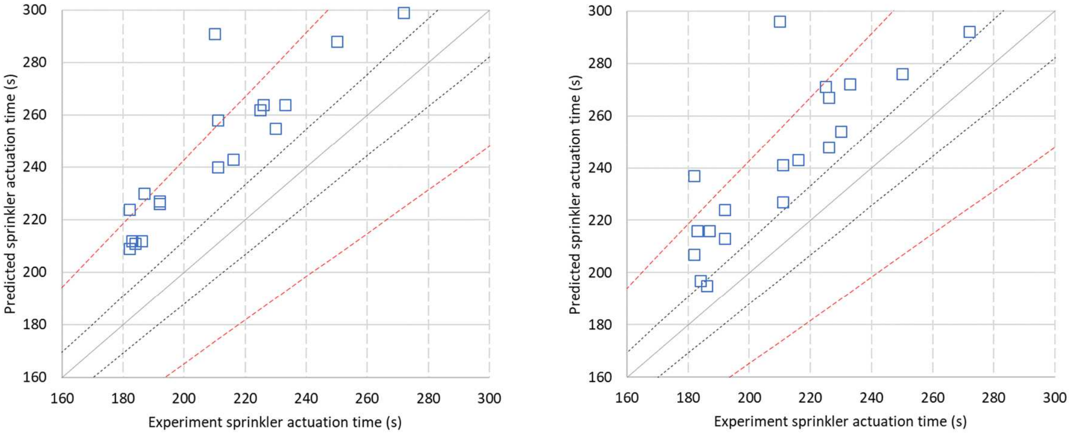
In the previous work the fire was modelled with an area of 0.04 m^2 (0.1 m by 0.4 m) based on observation from the experiments, where it was noted that “fire spread from the ignition point favoured the direction of the vertical lying foam slab” [7]. This differs from the approach adopted by Wade et al. [8] and the approach subsequently applied in this study, which assumes an area of 0.2 m^2 (0.4 m by 0.5 m) for the seat or ‘base’ of the chair. Therefore, also considered in this work is a comparison between the different methods of modelling the fire area.

A summary of the methods which have been compared is shown in Table 8. For each method, the HRR has been selected based on the ‘capped fire’ discussed previously.

Table 8: Summary of compared methods

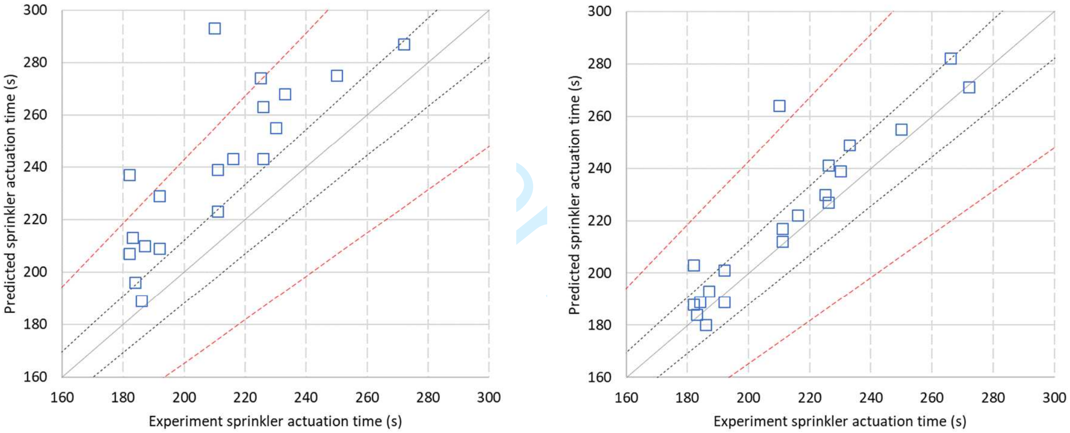
Methods	FDS version	C-factor	Fire area	Grid size	Comment
Original	3	0.65 $(m/s)^{1/2}$	0.1 m by 0.4 m	0.1 m	Original FDS 3 study
Remodelled	6.6.0	0.65 $(m/s)^{1/2}$	0.1 m by 0.4 m	0.1 m	Original study method remodelled in FDS 6.6.0 but with the same fire area, sprinkler C-factor and grid size
Amended	6.6.0	0.65 $(m/s)^{1/2}$	0.4 m by 0.5 m	0.1 m	Amended approach for fire burner area using FDS 6.6.0
Final	6.6.0	0.4 $(m/s)^{1/2}$	0.4 m by 0.5 m	0.05 m	Final approach assumed in this study

Figure 9 provides plots for the experiment sprinkler actuation time against the predicted actuation time, based on the above methods. Figure 10 shows a comparison of sprinkler actuation times for the first sprinkler head actuation while Table 9 provides the ERD for all sprinkler head actuations.



a) Original

b) Remodelled



c) Amended

d) Final

Figure 9: Experiment vs. predicted plots for the comparison of methods, Experiment 1 to 10 (all sprinkler heads)

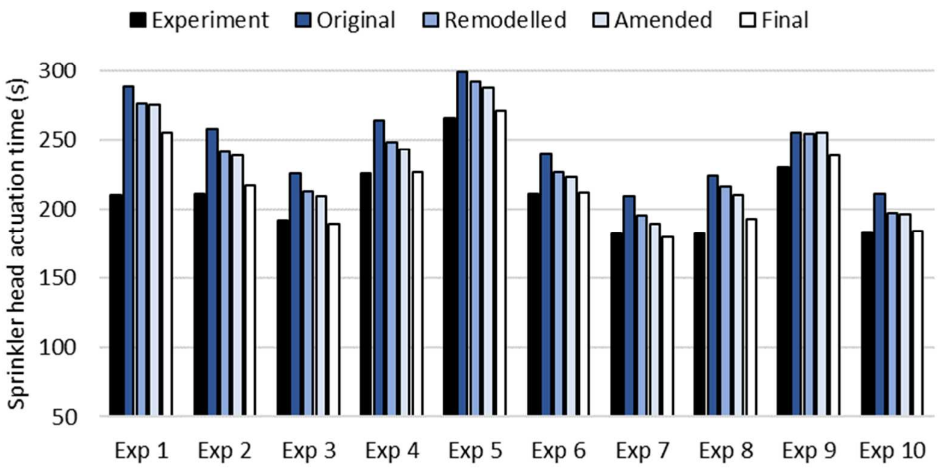


Figure 10: Comparison of methods, first sprinkler head actuation time

Table 9: ERD for all sprinkler head actuations, for different methods

Method	ERD	Average % difference
Original	0.18	+17.1%
Remodelled	0.17	+15.0%
Amended	0.16	+14.1%
Final	0.07	+4.0%

The comparisons indicate that the remodelled method using FDS 6.6.0 provides a better prediction than when it was originally modelled in FDS 3 in 2004 – changes to the software between 2004 to present appear to have improved its sprinkler actuation predictive capability. The only difference between the original and remodelled methods is the use of the different versions of FDS and it is unlikely this improvement is directly as a result of the sprinkler actuation capability in FDS but instead a result of changes to other parts of the model. However, it is not possible to directly identify the specific reasons for the improvement from these analyses. It is also worth noting that for the original and remodelled methods, the average percentage difference of 15-17% is marginally lower to the 21% difference determined by Wade et al. [8] when using the BRANZFIRE model where this improvement comes at a computational cost to the modeller.

Differences in how the burner area is modelled improves the prediction further, with a greater burner area (and therefore lower HRR per unit area) resulting in a marginal reduction in predicted sprinkler actuation time. When modelling a burner to represent a fire, the modeller must make decisions on how the burner is configured, where there is often no single correct method and the choice is dependent on subjective input and estimation. Therefore, approaches can vary and have an influence on the modelling results, as shown by the difference in the approach of the original study [7] and the approach taken by Wade et al. [8] which has been applied in this paper. Furthermore, in this study the base of the fire has been restricted to a single height above the floor. Varying the base location would affect the plume entrainment height, thus the convective flow into the ceiling jet and consequently the actuation of the sprinkler heads. It could be argued that, in the experiments assessed here, flames travelling across the seat and up the back would change the effective height of the base of the fire. However, this effective base would likely not only vary dynamically during a particular experiment but also not be consistent between experiments. Assessment of this complex issue would challenge the capabilities of FDS and, even when choosing a single effective height, would require additional simulations and analyses not considered in this paper.

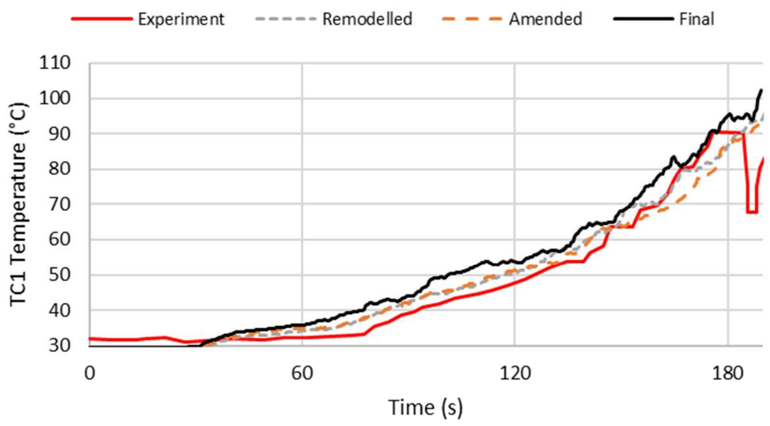
The refined grid and reduction in C-factor applied for the study described in this paper results in the greatest level of improvement between methods, with ERD reducing by as much as 0.11 compared to other methods. This is consistent with the results shown in the sensitivity analyses for both grid size and C-factor. For FDS, the determination of grid size has a particularly important influence, and the methods for determining an appropriate grid size are to some extent specific to the FDS tool. Decisions relating to grid sensitivity are dependent on the modeller's understanding of the tool, as well as the availability of computational resources, time constraints, the intent of the modelling and the required level of accuracy. There is therefore no fixed or 'correct' grid size / arrangement. In the original study [7] a 0.1 m uniform grid was applied instead of a 0.05 m grid to reduce computational time. This is a decision which would have differed, for example, with the availability of better computational resources or if more time was available to run the simulations.

In the context of designers, fire engineering of buildings often requires consideration of multiple facets of design. A fire engineer may therefore not undertake sensitivity analyses with the specific intent of determining an accurate sprinkler actuation time but choose a coarser grid which is able to appropriately encapsulate phenomena relevant to other aspects of design. These choices may also take into account time constraints and computational resources that are present within the practicalities of a commercial design environment.

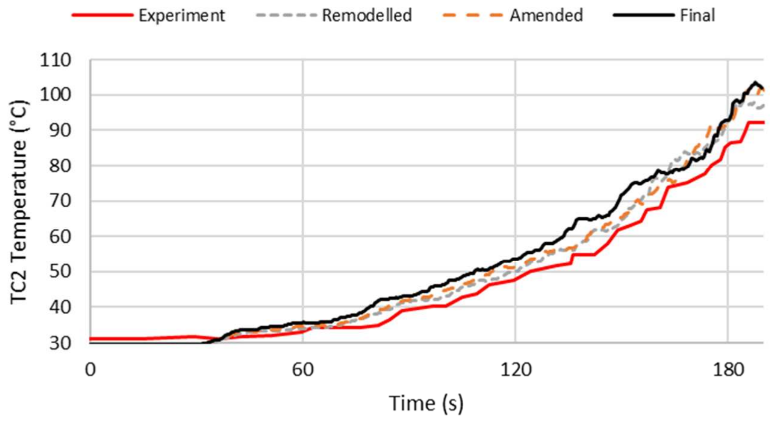
Ceiling Jet Characteristics

Determination of sprinkler actuation time in FDS is dependent on the gas temperature and gas velocities local to the sprinkler head, as well as the properties of the sprinkler head, as expressed through the differential equation of Heskestad and Bill [12] discussed previously.

To investigate the differences between the methods further, the temperatures and gas velocities in proximity to the sprinkler heads have been considered, where in the case of the temperatures, experimental data from thermocouples is available for comparison. Figure 11 provides the temperatures measured for the experiment as well as the remodelled, amended and final methods, in the location of sprinkler head 1 and head 2. The original method has not been included due to a lack of readily available data, and only Experiment 10 is presented here, although observations for this experiment are consistent with others. The average percentage difference in temperature for the amended method compared to the remodelled method is -1% and +1% for head 1 and head 2 respectively, indicating only a marginal difference in predicted temperatures at the sprinkler heads due to a change in the burner arrangement. However, the final method provides an average percentage difference of +7% for head 1 and +3% for head 2 from the amended method. Therefore, with the refining of the mesh, the predicted temperatures have increased at the sprinkler head locations. However, compared to the experimental data, all methods on average over-predict the temperatures, with the final method predicting temperatures furthest from the experimental data.



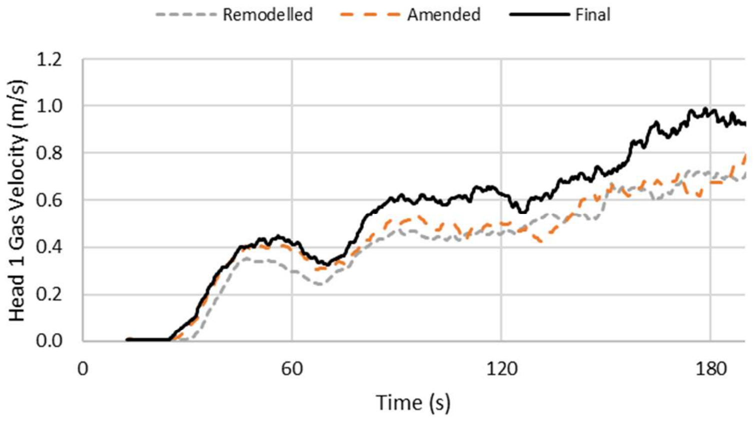
a) Head 1 (TC1)



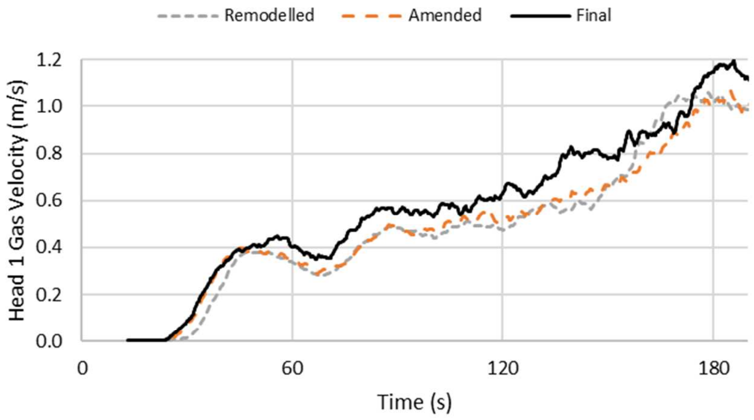
b) Head 2 (TC2)

Figure 11: Thermocouple temperatures adjacent to sprinkler heads (Experiment 10)

Figure 12 provides the simulated gas velocities recorded in the location of the sprinkler heads for Experiment 10, using a 30-point moving average to reduce fluctuations in the data. The original FDS 3 simulations have not been included as velocities were not documented. The average percentage difference of the amended method to the remodelled method is +7% for head 1 and +1% for head 2, indicating that the burner arrangement has had a greater influence on gas velocity when compared to the temperature. The final method provides an average percentage difference of +30% for head 1 and +22% for head 2 and the refined mesh has therefore further increased the simulated velocities local to the sprinkler heads. This variation is noticeably greater than when compared to the simulated temperatures.



a) Head 1



b) Head 2

Figure 12: Gas velocities at sprinkler heads (Experiment 10)

For the final method overall, the increase in both gas temperatures and velocities at the sprinkler heads, combined with the change in the C-factor from 0.65 $(m/s)^{½}$ to 0.4 $(m/s)^{½}$, has reduced the predicted sprinkler actuation time and hence provides results closer to those observed in the experiments. If it can be assumed that the Heskestad and Bill differential equation is applicable to sprinkler actuation without error, it may be expected that velocities observed in the experiments would be greater than those observed in the FDS models, as higher temperatures are predicted in the models but sprinkler actuation time is still overestimated. However, the assumed sprinkler characteristics such as the C-factor and RTI may also be a factor.

Conclusions

For the experiments, CFD-based fire modelling in FDS provides an ERD of 0.13 to 0.15 (depending on whether the fire is simulated as capped or not) and an average percentage difference of +6.4% to +9.7%. In all cases it was found that the modelling over-predicted the sprinkler actuation time.

When comparing to results determined in previous studies and applying different modelling methods and assumptions, there is a difference in the predicted sprinkler actuation times, also shown by the sensitivity analyses. Each variation in the modelling methods resulted in an incremental change to the predicted sprinkler actuation times, indicating that no single change solely influenced the outcomes. By observing the characteristics of the ceiling jet, it can be seen that the variation in methods and assumptions influence the simulated temperatures and gas velocities at the ceiling, impacting upon the sprinkler actuation predictive capabilities of the model. The comparison stresses the importance of the decisions made by the modeller in representing fire scenarios using FDS, where even in cases of modelling 'simple' experiments with few degrees of freedom for inputs including HRR, geometry, sprinkler characteristics, construction materials etc., there is shown to be variation in both methodology and results.

The paper also points towards the influence of wider design decisions. These decisions are multi-faceted and often need to consider level of accuracy desired within the context of an entire project, the computational tools available at the time both in terms of the types of models available and what version of a model to use, the availability of computing resources and imposed time constraints.

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