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Fire Behaviour Studies of Combustible Wall Linings Applying Fire Dynamics Simulator

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Abstract

In this paper the results of a large eddy simulation of an ISO 9705 room corner fire are presented. The field model, Fire Dynamics Simulator (FDS) was used to study the corner fire with and without combustible wall linings. Comparison of the results from simulations with prescribed heating and published experiments showed that with 50 mm grid spacing it is possible to quite accurately reproduce the experimental temperature data locations inside the room. When a combustible wall lining is included a T-shaped flame pattern similar to that observed in the experimental study was obtained but only with a particular grid size and reaction model. Inconsistent results were obtained with varying grid sizes and reaction models when combustible wall lining tests were modelled.

Introduction

Fire modelling is a highly desirable tool for fire safety design engineers. Since the introduction of the early version of FDS in 2000 with its relatively accurate pool-fire simulation results and free accessibility via the NIST website it has found widespread applications in fire engineering design and research. FDS is a computational fluid dynamics (CFD) model of fire driven flow, and a detailed description of the model is provided in the FDS manual and also by others [1-3]. FDS applications reported in the literature are almost exclusively aimed at verification of FDS results with experimental data using a single fuel, usually comprising the burning of a liquid fuel in pool form or gas from a burner. For ISO 9705 room corner fire scenarios, FDS has only been applied to a sand burner with propane [4], not to a liquid pool fire. Moreover, to the best of our knowledge no report on the application of FDS for multiple fuel scenarios has been published.

In this work two separate FDS simulations of the ISO room with a liquid fuel fire were conducted. The first simulation involves a tray of methylated spirit (consisting of 93% of ethanol and 7% of methanol) as a corner fire source in order to develop base line data for the later ISO room simulations with combustible wall linings. It is referred to herein as the pool fire. It is necessary to successfully reproduce the pool fire experimental results to then be able to carry out successful FDS calculations of the same room with combustible wall linings.

In the second simulation methylated spirit was the source-fire fuel and plywood as wall linings was the main fuel. The outputs of both simulations are compared with the experimental results [5]. In FDS, when two types of fuel are involved, the specification of the governing combustion reaction needs to be considered very carefully.

The FDS package includes Smokeview, a graphical program that allows visual observation of the FDS results. In room lining fire simulations, due to the availability of the large combustible surface area it is possible to observe from Smokeview animations the important stages of fire development including the flame spread pattern, the approach of flashover and the post flashover stage. These observations provide valuable information on the prediction ability of FDS.

Experimental work

The experimental data used here are from previous work carried out at the Fire SERT Centre, University of Ulster [5]. Here only a brief summary of the test method is provided.

The experiments were conducted in an ISO 9705 room the west wall of which was modified to include three windows which enabled a direct view of the north and east wall. Double-glazing was employed to ensure the integrity of the enclosure boundary was maintained up to and beyond flashover, thus facilitating observation and video recording. The remaining enclosure walls and the ceiling consisted of masonry construction and were lined internally with 15 mm thick ceramic fibre insulating board. The floor surface was covered with concrete blocks. The primary fuel source used was a 0.55 m × 0.55 m × 0.1 m deep pool of methylated spirit located in the northeast corner of the room and placed 0.4 m above the floor and 0.05 m away from both walls. For each test 8 kg of methylated spirit was used.

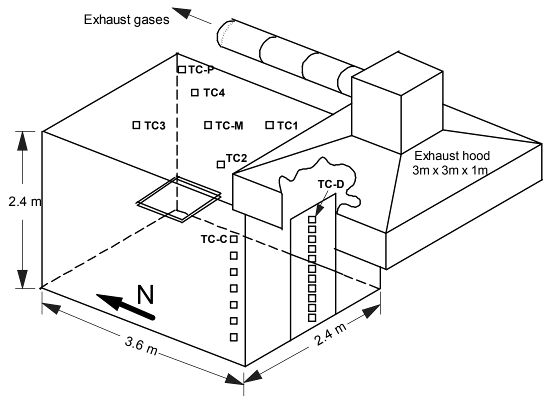

Figure 1. Schematic diagram of ISO 9705 fire test room

A doorway 2 m high × 0.8 m wide was located at the centre of the south wall. The doorway was fully open in all tests providing free passage of entering air and the outgoing products of combustion which were then collected by an exhaust hood and directed to an oxygen analysing system.

Gas temperatures were measured using type K thermocouples. Six thermocouples were placed on the ceiling, one directly above the burner to record plume temperature, another in the centre of the ceiling with the remaining four were located symmetrically around this central thermocouple as shown in figure 1. A thermocouple tree consisting of ten thermocouples was located in the middle of the doorway. Another thermocouple tree was placed inside the room in the southwest corner in accordance with the ISO standard to measure the variation of temperature with height off-the-floor [6]. To allow visual observation of surface flame and char development, lines were drawn horizontally and vertically on the east and north wall combustible lining surface at 0.2 m spacing. Prior to the main lining test a series of pool-fire tests were conducted to determine the HRR from the pool fire.

Overview of FDS Simulation

For the current FDS simulation the LES method of calculation is used. This uses a mixture fraction combustion model. In this method since the reactants are not premixed it is assumed that the reaction is diffusion controlled. Consequently the progress of the reaction depends on the degree of mixing. This is represented by a parameter defined as the mixture fraction (Z). An infinite rate of reaction between the fuel and oxygen is assumed when the mixture fraction is at the stoichiometric value. This assumption together with the Hoggets relationship [7] for the heat release rate as a function of oxygen consumption leads to the correlation

$$\dot{q}''_c = \Delta H_O \left.\frac{dY_O}{dZ}\right|_{z<z_f} (\rho D)\nabla Z \cdot n \quad (1)$$

Where $\dot{q}''_c$ is the heat release rate per unit area of the flame sheet, Y_o is the oxygen mass fraction, ρ is density of the air, D is diffusivity, n is the unit normal facing outward from the fuel [1].

Burning takes place (at a distance from the fuel surface) only where the mixture fraction is at the stoichiometric value. Just above the fuel surface the mixture is mostly fuel and the mixture fraction Z is close to the maximum value of 1. Moving away from fuel surface Z begins to reduce and at some point its value will equal the stoichiometric value. This is where it is assumed that burning takes place and where the flame sheet is located

In FDS mixture fraction combustion calculations, the reaction of only one fuel is considered. In the ISO room-lining test, even though two fuels are actually involved only one of them can be modelled. In this work two reactions were considered: 'Ethanol' and 'Wood'. The results of both are presented below.

The objective of lining tests is to determine the contribution that combustible lining materials make to the growth of a room fire. Similarly with the FDS simulation, in order to calculate the fire behaviour and contribution of lining materials to the heat release rate (HRR) an FDS simulation of the pool (source) fire is required.

An FDS model was constructed to resemble the experimental set-up for the ISO room, initially for the pool fire test. The computational domain was 2.4 m high by 2.4 m wide and 5.0 m long. Since calculations up to the flashover stage were intended the overall domain size was selected as minimum possible to avoid prolonged calculation times at small grid sizes. The burner was modelled as an obstruction with the dimensions similar to the actual size, placed at the north-east corner of the room, 0.05 m off the north and east walls. The top section of the obstruction was used to simulate the source fire, this was done in two ways: firstly simulating as methylated spirit fuel which was allowed to burn by itself and secondly by assigning a ramped heat release rate per unit area (HRRPUA) closely modelled on the experimental findings.

The internal surfaces were modelled as a thermally thick solid. Wall surfaces and the ceiling were covered with 12 mm thick layer of Kaowool and the floor was assumed to be of concrete. The thermal diffusivity and the thermal conductivity of Kaowool used were 1.80 x 10^{-6} °Km^2/s and 0.135 w/m°K respectively [5,8].

Results and Discussions

Pool fire test

Figure 2 shows a comparison of the experimental heat release rate (HRR) and the FDS simulations. The experimental heat release rate shows an initial rapid raise changing to a lower slope about 100 s after ignition. The maximum HRR was about 190 kW about 800 s after ignition.

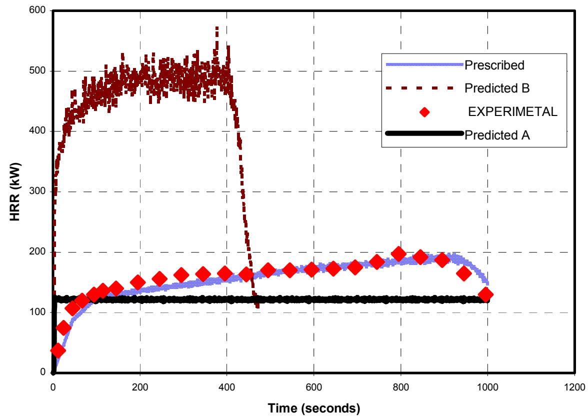

Figure 2. HRR profiles from FDS and experimental results

The HRR calculated in the FDS simulations was affected by input variables such as grid spacing and maximum burning rate. The initial estimate of HRR (Prediction A in figure 2) attained a maximum value of 120kW, well below the experimental value, and remained constant on this value. This unvarying result was unexpected, but after checking it was realised that it was the consequence of a maximum burning rate (15 g/m^2/s) incorporated in the data for ethanol in FDS3 database. A similar limitation is also incorporated for other fuels. This limitation was incorporated based on a study by McGrattan *et al.* [2], which showed that the FDS predicted burning rate of methanol was much higher than the experimental values. Setting such a limitation they could reasonably reproduce temperatures found experimentally.

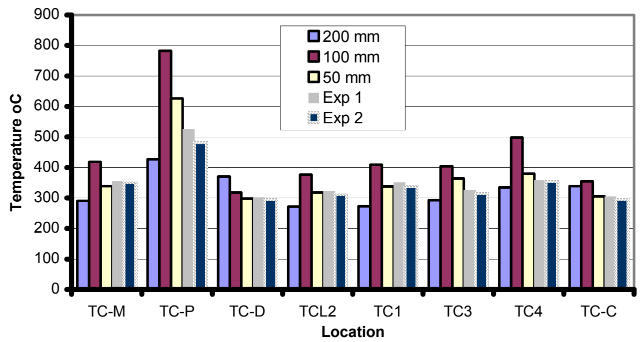

Figure 3. Comparison of temperatures predicted by FDS with the prescribed HRR and measured temperatures

However in enclosure fires the burning rate may be strongly influenced by radiative and convective heat feedback. When the burning rate limitation was removed the resulting HRR estimate (Prediction B in figure 2) was much higher with a maximum value of 500 kW and the fuel was consumed in a much shorter period than found experimentally. Rather than persist with attempting to model the experimental HRR with a pool fire simulation it was simulated using a prescribed ramped heating rate (figure 2).

This pool fire case was then checked for grid convergence. In figure 3 the experimental maximum gas temperature at each labelled point shown in figure 1 is compared with the corresponding temperatures calculated using FDS with three grid spacings. It is notable that at nearly all locations the best agreement with the experimental results is provided by the smallest grid size 50 mm. Due to the long computational time taken for the simulation the run with 25 mm grid spacing was stopped at 200 seconds. With the larger grid spacings the maximum temperature is found at about 950 seconds. Calculated time-temperature curves for the thermocouple near the centre of the ceiling are presented in figure 4. It shows that altering the grid size from 50 mm to 25 mm resulted in little change in the temperature profile, inferring convergence at the 50 mm grid spacing.

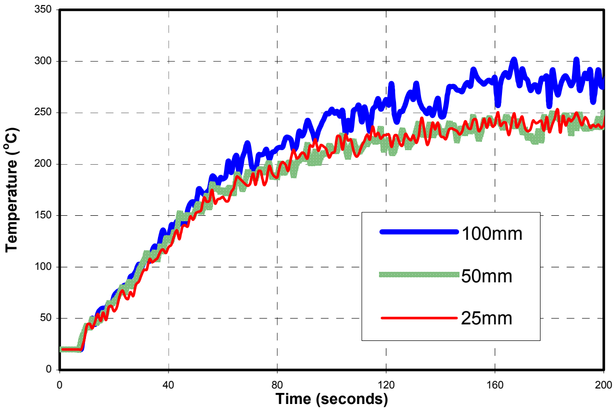

Figure 4. Calculated temperature profiles at the ceiling midpoint (TC-M) for different grid sizes

Fire Spread on Wall linings

Following the pool fire simulations, FDS simulations were conducted with the same enclosure but with plywood used as wall lining over part of the wall. In these FDS simulations the upper part of the north and east walls were partially lined with plywood whilst the reminder of the walls were lined with 12 mm thick gypsum plasterboard as shown in figure 5. Initially the reaction used was specified as 'Ethanol', as in the previous simulations, this was then changed to "Wood" from the FDS database. Similar temperature predictions as described for the pool fire simulations were made.

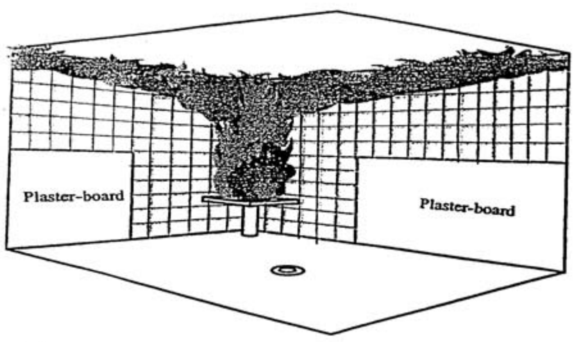

Figure 5. Typical flame spread patterns observed experimentally (schematic view is drawn based on video recording and the figure is reproduced from [5]).

In order to use the FDS calculations effectively, the combustion parameters of plywood as input data were selected carefully. From the available sources three main parameters; ignition temperature, heat of gasification and heat of combustion were found to be 270 ^{o}C, 1800 and 18000 KJ/Kg respectively [9-11]. These values were adopted in all of the FDS calculations.

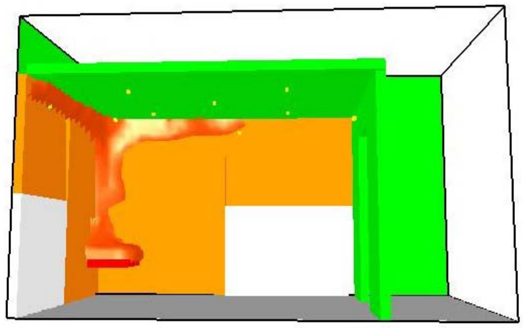

Figure 6. Smokeview flame spread on lining surface at 100 Sec.

Observations made of the experimental tests using video recordings suggest that the ignition of the plywood lining material began at the area adjacent to the source flame about 200-300 mm above the base of the pool fire. After ignition the flame spread vertically towards the ceiling, then horizontally at the intersection of the ceiling and walls (where the gas temperatures are highest, figure 5). Horizontal flame spread continued until the flame front approached the corners of the enclosure at which time the flames started to descend. This heralded the onset of flashover. The Smokeview animations of both mixture fraction and HRR outputs from ignition until the time at which the HRR reaches 1 MW (taken as an indication of flashover) were analysed. The observations showed that the spread of flame after reaching the ceiling follows a similar T-shaped pattern as observed experimentally. At the stage when HRR reached 1 MW flames descended down the wall to approximately the midpoint and flames emerged from top of the doorway. In figure 6 a snapshot from Smokeview shows the shape of the T-shaped propagation of the flame front.

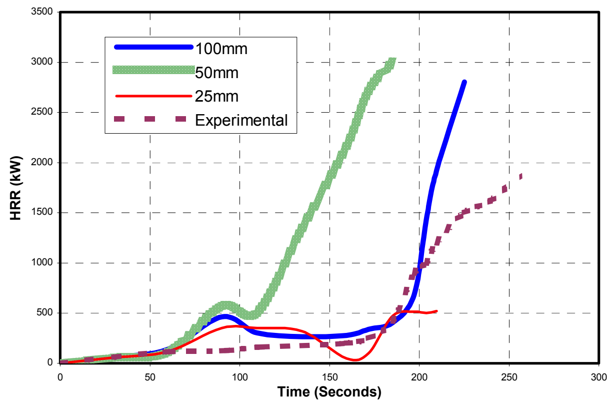

Figure 7. Experimental and FDS, HRR profiles when stoichiometry of reaction is 'Ethanol'.

In figure 7, the HRR profiles resulting from FDS calculations using the "Ethanol" reaction at different grid sizes are presented. It should be noted that as the grid size is reduced the main events relating to HRR occur more rapidly after ignition.

In table 1 the time to flashover is presented utilizing three different flashover criteria [12,13]. With 100 mm grid size the predicted time to flashover was found to approximately be in agreement with the experimental data. However, when a finer grid size (50 mm) was used the predicted time became more inaccurate, and when the 25 mm grid spacing was used the inaccuracy increased too the extent that the HRR remained below 500 kW (figure 7) and never approached any of the flashover criteria.

Table 1 FDS and experimental time to flashover parameters

Test	Time to flashover Seconds		
	1 MW HRR	600°C	HF20 kW/m^2
Experimental	200	200	207
FDS 50mm	127	103	128
FDS 100mm	201	199	203

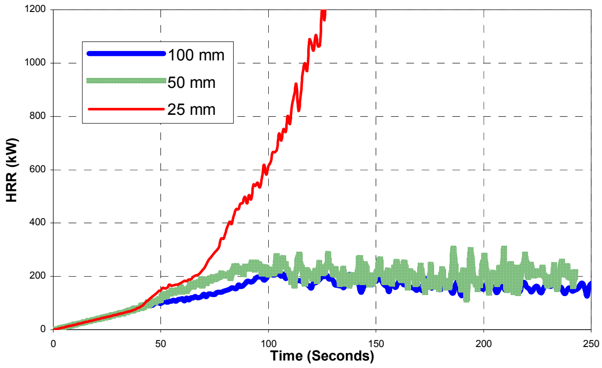

Figure 8. Experimental and FDS, HRR profiles when stoichiometry of reaction is ‘Wood’.

When the reaction was set to “Wood” in the FDS calculations, the Smokeview animation showed a similar surface flame spread pattern as explained previously. However the HRR profiles with wood reaction were found to be quite different from those obtained when the ‘Ethanol’ reaction was used. As shown in figure 8 flashover is reached only with the finest grid spacing (25 mm) is used. With 50 mm and 100 mm grid spacings the fire did not grow sufficiently to reach flashover. Adjustment of the plywood combustion parameters did not change the overall results.

Conclusions

FDS simulations of the ISO room pool fire test showed that with the prescribed heating rate and fine grid spacing the temperature at different locations could be reproduced in close agreement with the experimental data. Comparison of time-temperature curves obtained at different grid sizes show that convergence is approached at 50 mm grid spacing.

Reproduction of the experimental ISO room pool-fire test by prescribing the HRR made it possible to simulate the ISO room lining test with two fuel: methylated spirit as the source fire and plywood wall lining as the main fuel. With plywood as the wall lining, when the reaction was taken as that of “Wood” an increase in the HRR sufficient for flashover was predicted only with the finest grid spacing (25mm). By contrast when the “Ethanol” reaction was used, FDS simulated flashover with grid spacings of 50 mm and above, but not with the 25 mm grid spacing.

In conclusion the FDS surface flame spread modelling results show significant inconsistency, with grid size variation and choice of the fuel reaction.

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