Fire Development in a Deep Enclosure

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ABSTRACT

The behaviour of fire within a deep (high depth to height ratio) enclosure with various openings in one end has been studied experimentally and by simulation (using FDS4). Sixteen fuel-trays were placed within an 8.0 m long x 2.0 m wide x 0.6 m high steel enclosure. The experiments confirmed previous smaller scale experiments, showed that the fires in deep enclosures are strongly influenced by the ventilation and are not at all uniform through the depth of the enclosure. The severity of exposure of structural members is much more severe near the ceiling near the front of the enclosure compared with the back of the enclosure. Depending on the criterion used the severity at the front may be from twice to five times as severe as at the back of the enclosure. The movement of the flame-front in the FDS4 simulation is similar to that found experimentally, but the predicted timing of flame-front movement and predicted HRR varies considerably from the experimental values.

KEYWORDS: burning rate, mass loss rate, deep enclosure, ventilation factor

NOMENCLATURE

A	opening area	*h*	opening height
H	enclosure height	*HRR*	heat release rate (kW)
L	enclosure length	*W*	enclosure width

INTRODUCTION

Enclosures in buildings occur in a wide range of sizes and shapes. Many rooms in residential accommodation and some commercial accommodation (offices, etc.) are roughly cube shaped (*L*, *W*, *H* all similar magnitude). However, in many buildings the spaces can be very wide, deep or both in comparison with their height. For example many open plan office storeys can have a floor to ceiling height of about 2.4 m, and floor to floor height of about 3.0 m, but may be up to 40 m or even 60 m square in plan. If, in a fire situation, they are ventilated only from one side the depth to height ratio can be of the order of 10 to 25. Ceiling spaces can be even more extreme.

This means that the behaviour of fires in wide and deep enclosures needs to be understood and be accurately modeled by fire models such as the Fire Dynamics Simulator (FDS) [1], FAST [2], etc. The research program reported in this paper extended experimental research reported previously [3] and compared the experimental data with the results of simulations using FDS4 (version 4 of FDS). The previously reported experiments were conducted in an enclosure 1.5 m by 0.6 m by 0.3 m high and it was considered important to conduct similar tests at a larger scale. The experimental program and corresponding numerical simulation was designed to investigate the influence variation in the opening size and shape has on fire in a deep enclosure (*L/H*~ 13), to investigate whether the simulation of such fires by FDS4 is accurate, and to assess the fire severity (in relation to damage to structural members, etc.) at various locations in the enclosure.

The simulation of many of the fires using FDS was initially undertaken prior to conducting the experiments using FDS3 on the basis that a designer using FDS to predict fires in these enclosures would not have the benefit of specific experimental data to inform or calibrate the simulations. Thus standard properties and FDS default settings were initially used in the simulations. The simulations were rerun when FDS4 was released and some modification of default settings was undertaken as specified below.

EXPERIMENTAL PROGRAM

The enclosure was 8.0 m long, 2.0 m wide and 0.6 m high and was constructed of 1.6 mm thick sheet steel except as follows. One 2.0 m side of the enclosure (Fig. 1) was used as the opening (for ventilation) by varying the construction of this wall. The other sides were completely closed, but three windows (of fire-resistant glass) in the walls allowed details of the shape and behaviour of the fire to be viewed.

The opening size was varied with eight different test configurations as shown in Table 1. With the "half centre open" configuration a further test was conducted during which all of the enclosure sides were insulated with 25 mm 'Kaowool' blanket. The specified opening existed throughout a test allowing free passage of entering air and the outgoing products of combustion, which were then collected in the hood of an oxygen calorimeter [4] for heat release rate (HRR) estimation. Four type K thermocouples were placed above the centre of each tray as shown in Fig. 1. The thermocouples on the enclosure roof were spot-welded to the steel and were intended to measure the steel temperature while the other thermocouples were used to record gas temperatures. The tests were also videoed.

The fuel used was commercial grade methylated spirits, a liquid consisting of 97% ethanol and 3% water. During the test, 16 fuel trays were placed within the enclosure as shown in Fig. 1. The fuel trays were 0.90 m by 0.90 m by 0.05 m deep and were constructed of steel. Each tray rested on a weigh scale so that the mass of the fuel could be measured throughout each test. Ignition was at the rear of the enclosure using a gas flame inserted via a small hole that was quickly sealed following ignition.

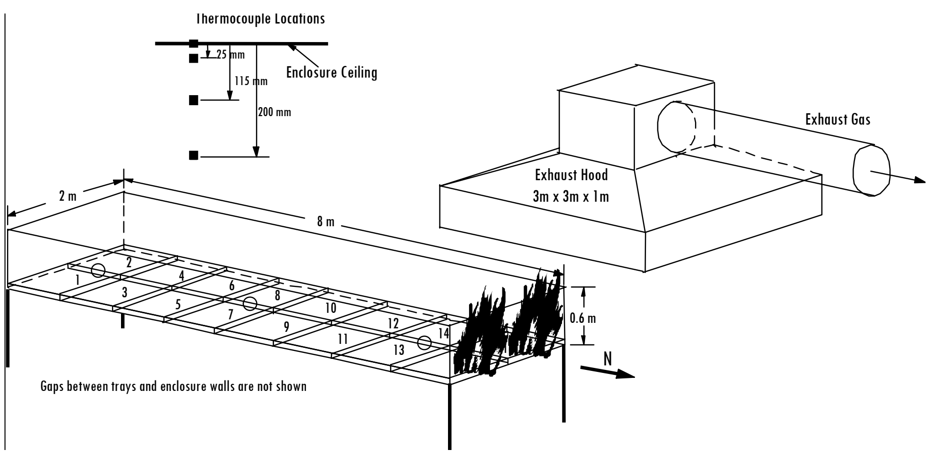
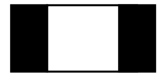


Fig. 1. Schematic diagram of experimental test configuration.

Table 1. Schematic of deep enclosure test openings.

Test Name	**Opening Configuration**	**Test Name**	**Opening Configuration**
Fully Open End		Half Open Centre	
Half Open Top		Half Closed Centre	
Half Open Bottom		Quarter Open Centre	
Half Open Side		Quarter Open Side	

OVERVIEW OF FDS SIMULATION

FDS is the only fire modeling program known to the authors to model accurately the movement of the fire in these tests and in the previously reported tests [3]. The form (shape, dimensions and location) and movement of the flames predicted by previous FDS simulations was remarkably similar to that observed during the previous [3] tests.

The FDS Large Eddy Simulation (LES) methodology was used and combustion was modeled using the mixture fraction approach incorporated in FDS4 [1]. FDS4 data files were created to model the enclosure and fuel arrangements. The computational domain was extended beyond the enclosure (as shown in Fig. 2) as it was expected that much of the combustion in some tests would take place outside the enclosure. Each fuel-tray was modeled as an obstruction with the dimensions of the actual trays and placed appropriately in the enclosure. The top face of the obstruction was used to simulate the fuel surface using adjusted properties for ethanol to simulate the methylated spirits. As a liquid fuel in FDS the methylated spirits burns without requiring an ignition source. However in FDS it does not flow like a real liquid and burns back from the front of each ‘tray’ as would a solid, whereas in the tests while the bottom of a tray was covered in fuel the flames remained at the front of the tray. The internal surfaces of the enclosure were modeled as steel sheet using properties similar to the default properties in the FDS4 database but appropriately altered for the actual steel thickness. For the simulations of the test in which the enclosure was insulated the backing of the steel sheet was specified as ‘INSULATED,’ for all other simulations it was specified as ‘EXPOSED.’

For all cases a cubic cell 0.050 m x 0.050 m x 0.050 m was used having been found by trial and error to be an appropriate cell size for these simulations. The combustion parameters and material properties of the default FDS4 database were used for the fuel except as follows: firstly the burning rate limitation of 15 $g/m^2/s$ was removed, secondly the RADIATIVE_FRACTION was set to 0.0 (this causes the calculation of source term in the radiation transport equation to be based on T^4 rather than the heat released in each cell [1]), and finally the thermal properties of ethanol were modified to accommodate the effect of 3% water in commercial grade methylated spirits.

The burning rate limitation was removed because initial simulations showed that it always governed and usually resulted in HRRs substantially under those obtained experimentally. The radiative fraction was set to zero because it was found that once the burning rate limitation was removed the HRRs were usually substantially overestimated, and that then lowering the radiative fraction did little to reduce the calculated HRRs.

The FDS simulations were run to burnout for each opening configuration, in some cases taking over three weeks on new, fast and large memory PCs.

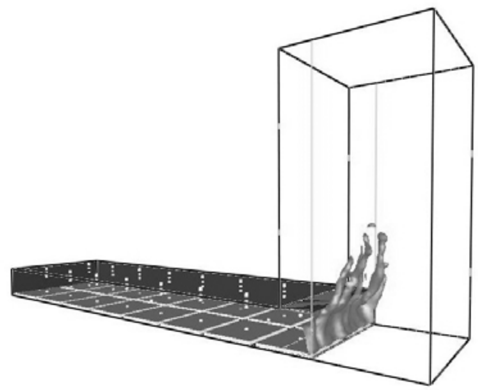


Fig. 2. Deep enclosure model for numerical simulation (Smokeview graphics).

EXPERIMENTAL RESULTS

The burning behaviour in these deep enclosures was found to be identical to that reported in [3]. In general when the fuel in a rear tray was ignited the flame front moved quickly to the front of the enclosure. This behaviour varied slightly depending on the ambient temperature at the commencement of the test. In tests conducted with the ambient temperature below about 15°C it was possible to ignite the fuel in an individual tray, and the flame could be observed moving across that tray, then to other nearby trays, and once trays across the width of the enclosure were ignited the flames moved rapidly towards the opening (the front of the enclosure). In tests with the ambient temperature above about 20°C the introduction of a flame into the rear of the enclosure caused very rapid propagation of flames through the enclosure and these very rapidly subsided except at the opening where burning continued. This second mode is similar to the commencement of burning that occurs in FDS simulations.

In both cases the flame front rapidly established itself at the front edge of the front two trays with little of the fuel having been burned in the process. When the fuel in the front trays was exhausted the flame front usually jumped to the front of the second row of trays where it burned until the fuel in these trays was exhausted. It then jumped to the front of the next rearward row and so on until finally the fuel in the rear most row of trays was exhausted. In some cases the flames stayed at the opening even after the front trays were empty, and in fewer cases even after several rows were empty.

During the previous tests [3] three phases of burning were identified. They were also observed in these experiments as follows:

Phase I: Rapid transition of burning up to the front of the front two rows. When the opening was not across the full width of the enclosure, burning in the front two rows took place across the width of the opening(s), not across the width of the trays or the enclosure. In these cases, as the fuel in the front trays burned out and the flame-front moved to the second row and the flame-front extended across the full width of the enclosure. Full width burning was then maintained as the fire moved back over the other rows of trays. As noted above in some cases (but this was the exception rather than the usual situation) the flame front remained at the opening for much of the test even though the fuel in the front rows was exhausted.

Phase II: Relatively stable burning from the end of Phase I up to the burning of fuel trays in the sixth row. During this phase the flames and smoke flows in the enclosure were essentially two-dimensional (i.e., when viewed from the side, the shape of the flames was the same across the width of the enclosure). There were two sub-phases as reflected by the HRR curves: initially the HRR was fairly constant, but often then decreased fairly linearly while burning in the rearward trays.

Phase III: A period of more vigorous burning then took place, generally when the flame front reached the back two trays. In some cases the fuel was expended in the back row before the flame front reached these trays (see mass loss discussion below), and the final phase of burning was actually in the second back row.

These phases can be readily identified in the HRR versus time profiles shown in Fig. 3. A summary of test results is presented in Table 2.

The HRR versus time profiles from all of the experiments mentioned are plotted in Fig. 3. In Fig. 3 the HRR - time profile for the fully open end test is plotted as well as the HRR - time profile from other tests as follows:

Group 1: Half open top and half open bottom
Group 2: Half open side, half open centre and half closed centre
Group 3: Quarter open side and quarter open centre

In the fully open end case when the flame-front reached the front of the enclosure the burning quickly became stable. In this case, as in all of these experiments, the measured HRR varied considerably as the test proceeded. In this case after an initial very sharp peak the burning (and HRR) was reasonably stable with the HRR gradually falling as the flame front moved from row to row. Then as the flame front reached the last row the HRR rose steeply and then fell sharply when the fuel was exhausted (Fig.3).

In the Group 1 tests it was noticeable that when the flame-front reached the front of the enclosure the burning was rather unstable but eventually became stable as the flame front moved back through the enclosure. This was particularly so for the half open top case – the first fire self-extinguished shortly after reaching the front of the enclosure. The second attempt continued to burn as shown in Fig. 3 but for period was very unstable as reflected in the HRR. Based on the HRRs shown in Fig. 3 reducing the opening height by half (with width unchanged) reduced the average burning rate to 49% (top open) and 44% (bottom open) of that for the fully open case rather more than expected using the $A\sqrt{h}$ ventilation factor which predicts 35% of the fully open case for both.

Reducing the opening width by half (Group 2 cases) reduced the average burning rate but only to 74% of the fully open case for the half open side case, and 68% (half open centre and half closed centre) much greater than the 50% figure expected based on $A\sqrt{h}$. Burning at the opening was more stable in these cases than in the Group 1 cases but some fluctuation occurred while the flame front was in the opening.

In the Group 3 cases (quarter width, full height) $A\sqrt{h}$ comparison leads to an expected HRR of 25% of the fully open case, much lower than 47-48% obtained experimentally.

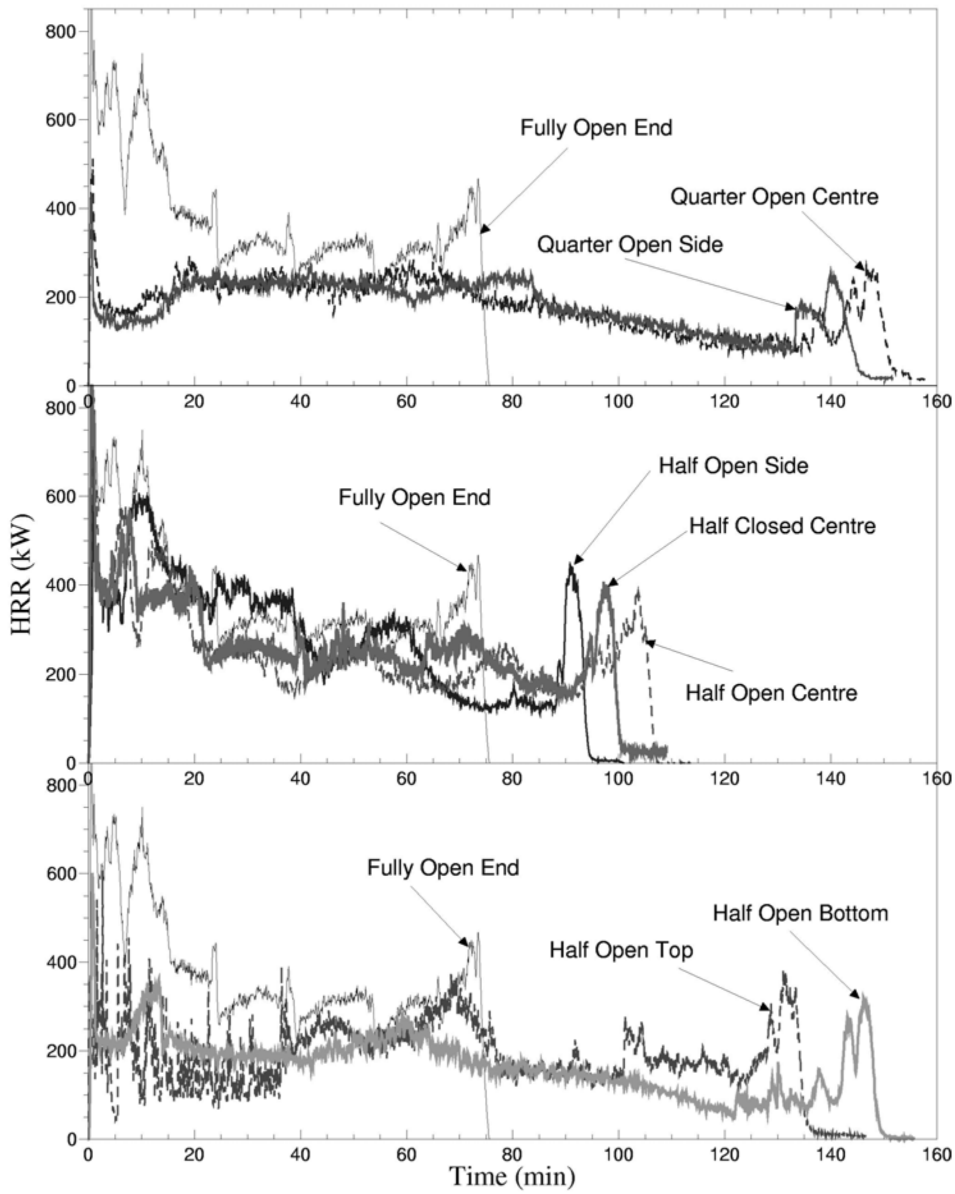


Fig. 3. HRR from deep enclosure tests.

Table 2. Summary of experimental results.

Test Name	Average HRR (kW)			Maximum Temperature (^oC)		Duration of Burning (min)
	Over-all	Phase I-II	Phase II-III	Gas	Steel	
Fully Open End	372	543 [a]	311	862	450	70
Half Open Top	183	212 [b]	153	735	395	134
Half Open Bottom	164	215 [b]	116	738	425	147
Half Open Side	276	373 [b]	181	900	450	93
Half Open Centre	253	306 [c]	207	836	450	106
Half Closed Centre	254	317 [c]	200	760	412	100
Quarter Open Centre	175	222 [d]	126	806	410	150
Quarter Open Side	177	215 [e]	124	812	405	144

[a]first 24 minutes [b]first 50 minutes [c]first 75 minutes [d]first 80 minutes [e]first 88 minutes

It is clear that the ventilation factor $A\sqrt{h}$ does not provide a particularly good prediction of the average burning rate based on these experiments.

In view of the complexity of the HRR-time curves in Fig. 3 the average burning rate may not a good measure of HRR. The HRR generally fell significantly as burning progressed except for the final peak that occurred in all cases. In the fully open case the average burning rate during the first 24 minutes was 543 kW compared with 311kW during the remaining 51 minutes. Similarly there was a decrease in all cases as shown in Table 2.

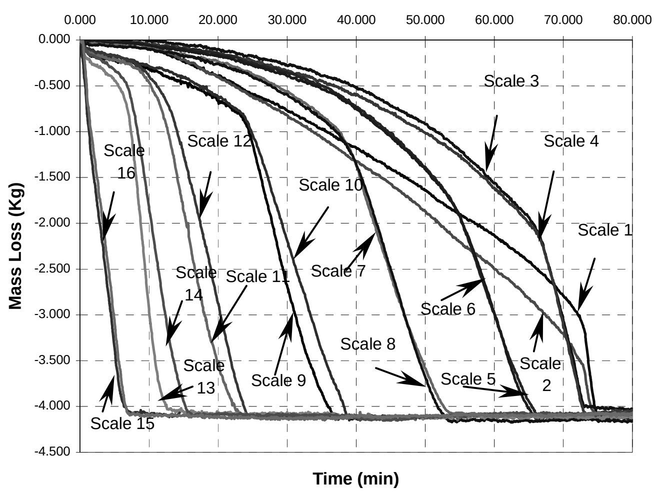


Fig. 4. Fuel mass-time relationship for each tray of fuel (fully open end test).

The mass loss from each tray is presented in Fig. 4 for the fully open end case. The trends in the mass loss during the other tests were similar. Note that scales 1 and 2 are trays at the rear of the enclosure, through to scales 15 and 16 for front row trays. In Fig. 4 it can be seen that fuel is being lost from all trays (with fuel remaining) throughout the test. However the rate of mass loss is greatest for the trays adjacent to the flame front and for them is fairly constant once burning in the tray is established. It can also be seen that the mass loss rate for the trays in the back row is greater through much of the test than for trays towards the rear of the enclosure but between the back row and the burning row. In this case (but not in every case) this results in the back row of trays being depleted of fuel before the second-back row. For the remaining (intermediate) rows the mass loss rate (the slope of the mass loss – time curves shown) decreases with distance from the opening and the flame front. Close correspondence between the measured HRR and the total mass loss rate was obtained in all tests.

Figure 5 shows the gas temperatures above the front two rows and back two rows during the fully open end test. Similar trends were seen during the other tests. It is clear from Fig. 5 that the temperature near the ceiling above the front row of trays was much higher for most of the test than the temperature above the rear trays. This indicates that the severity of the exposure of structural members is much more severe near the ceiling near the front of the enclosure than near the back of the enclosure. If the area under the temperature-time curve is taken as indicative of severity of exposure then the severity at the second front row is over twice as severe as the back row. Alternatively, if the duration of time above a temperature high enough to cause structural weakening, etc. is used as the criterion the difference is far greater. For example, if the duration above 600°C is taken as the criterion, then the second front row location is more than five times as severe as the back row.

Table 2 shows that the peak gas temperature attained during the tests varied from 735°C to 900°C, the highest being for the half open side case apparently due to strongly channelled flames through the unsymmetrical opening. However, considering averaged temperatures, the highest average was recorded for the fully open end case and the lowest was for the quarter open side case (710°C). The peak gas temperatures are generally recorded above the second row of trays from the opening. However for the last two tests it was recorded (very briefly) above trays in the second or third last row. A different trend was observed for the steel temperatures. All peak temperatures were recorded above the second row of the trays from the opening. The peak steel temperatures varied between 395°C to 450°C.

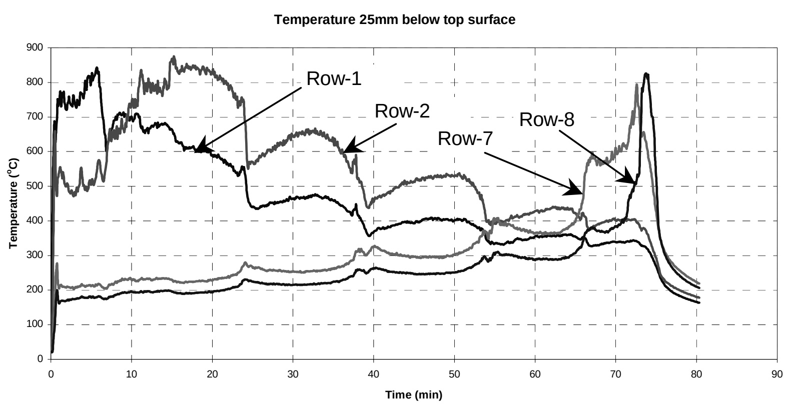


Fig. 5. Gas temperature-time relationship above front and back rows (fully open end).

SIMULATION RESULTS

The burning behaviour as simulated by FDS4 was somewhat different from that observed during the physical tests. In the simulations the fuel in all trays started burning simultaneously but the flame front (as represented by the ideal mixture fraction or heat release rate per unit volume) very rapidly moved towards the opening. This was followed by a quick flash of flames outside the opening but the flame front quickly settled at the opening (see Fig. 2). Unlike the experiments, the flame front did not move back to the front of the next row of trays when the fuel in trays adjacent to the opening was exhausted. Rather vapourised fuel was continuously transported to the opening and steady burning took place at the opening for much longer than in the experiments. A summary of the results of each simulation is presented in Table 3.

In the FDS4 simulations, as in the actual enclosure fires, the gas mixture behind the flame front is fuel rich but with a low oxygen concentration, while the inflow area in front of the flame front is oxygen rich. The initial movement of the flame front towards the opening occurs as the oxygen in the rear of the enclosure is depleted and cannot be replaced. Once the flame front moves to the opening it appears that it stays in the opening while the rate of vaporization of fuel is greater than the rate at which the vaporized fuel can burn inside the enclosure. Thus the flame front remaining at the opening for longer in the simulations than in the experiments is likely to be because the fuel is being vaporized too rapidly in the simulation. This is despite the calculated temperatures in the enclosure being less than the measured temperatures.

Table 3. Summary of FDS4 results.

Test Name	Average HRR (kW)	Maximum Temperature (°C)		Duration of Burning (minutes)
		Gas	Steel	
Fully Open End	636[a]	650	455	41
Half Open Top	334[b]	560	380	94
Half Open Bottom	622[c]	680	465	45
Half Open Side	346	670	460	81
Half Open Centre	431	520	360	74
Half Closed Centre	388	495	335	71
Quarter Open Centre	274	440	305	111
Quarter Open Side	201[d]	530	360	156

[a]691 kW/580 kW [b]364 kW/287 kW [c]748 kW/496 kW [d]217 kW/172 kW

As most of the burning in the FDS4 simulations was taking place at the opening it is useful to understand the proportion of the combustion (heat release) that was taking place inside the enclosures. The HRR inside the enclosure (cf. the total HRR in the computational domain) was recorded by FDS and for most cases apart from the very brief period at the start when the fire was moving towards the opening and a short period at the end when the fire retreated into the enclosure there was virtually no heat released inside the enclosure. Overall, for most cases, the heat released inside the enclosure was less than 5% of the total heat released. The HRR inside the enclosure was not measured experimentally but from observation the proportion would have been much higher than this in all cases.

Consequently it is not surprising that comparison of Tables 2 and 3 reveals that there is little correspondence between the average HRR in the physical tests and that in the FDS4 simulations. There is also very little correspondence between the HRRs from the simulations and the ventilation factor $A\sqrt{h}$.

Comparison of Tables 2 and 3 also shows that the gas temperatures in the enclosure calculated by FDS are significantly lower than the experimentally measured temperatures. Strangely the steel temperatures predicted by FDS4 are closer to the experimental values and in some cases the calculated steel temperature was actually greater than the measured maximum temperature.

COMPARISON OF DATA FOR TEST/SIMULATIONS WITH AND WITHOUT WALL INSULATION

The half centre open case was used to compare test and simulation results for the enclosure with and without insulation. The insulation used as 25 mm 'Kaowool' blanket outside the steel enclosure. The HRR versus time profile of the insulated and non-insulated physical test is compared in Fig. 6. The profiles are identical up to 8 minutes but from then on the HRR for the insulated test is greater than for the non-insulated test and the duration of burning was correspondingly less.

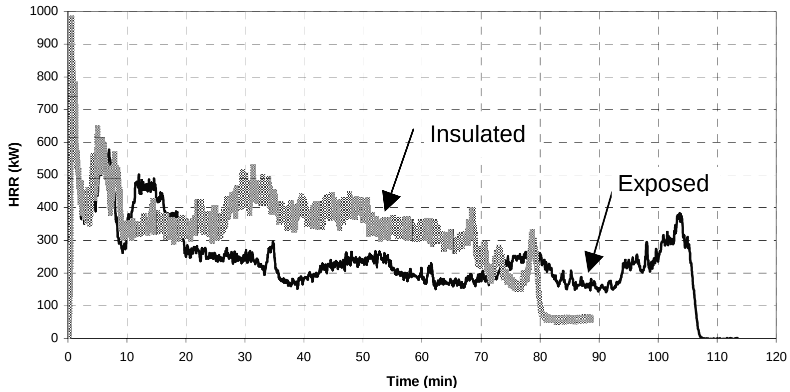


Fig. 6. Comparison of HRR for half centre open tests with exposed and insulated enclosure walls.

Table 4 presents a summary of data from both tests and the corresponding numerical data. For both cases FDS4 predicts a higher HRR than the corresponding experimental value. It is notable that despite lower measured HRRs than in the simulation higher gas and steel temperatures were obtained in the enclosure experimentally than in the simulation, obviously because the heat was released in the enclosure rather than outside it in the simulation.

CONCLUSIONS

The experimental program and numerical simulations using FDS were designed to investigate the influence variation of opening size and shape has on a fire in a deep enclosure (L/H~ 13) and to investigate whether the simulation of such fires by FDS4 is accurate. In relation to potential damage to structural members the variation in fire severity at different locations in the deep enclosure was also investigated.

The experiments confirmed previous smaller scale experiments and showed that the fires in deep enclosures are strongly influenced by the ventilation but are not at all uniform through the depth of the enclosure. The severity of the exposure of structural members is much more severe near the ceiling, particularly near the front of the enclosure compared with the back of the enclosure. If the area under the temperature-time curve is taken as indicative of severity of exposure then the severity at the front is over twice that at the back, but if the duration of time above a temperature high enough to cause structural weakening is used (for example 600^{o}C) the difference is far greater, about five times as severe in some cases.

Table 4. Comparison of results with and without insulated wall.

Investi -gation	**Ventilation**	**Average HRR** (kW)			**Maximum Temperature (^{o}C)**		**Duration of Burning (min)**
		Over-all	**Phase 1-II**	**Phase II-III**	**Gas**	**Steel**	
Expt.	Half Open Centre (insulated)	349	396	228	815	670	80
	Half Open Centre	253	306	207	836	450	106
FDS	Half Open Centre (insulated)	653	585	721	500	360	48
	Half Open Centre	431	432	430	515	350	74

The initial movement of the flame-front through the enclosure in FDS4 is similar to that found experimentally. However the predicted timing of movement of the flame-front later in the fire, and predicted HRR and gas and steel wall temperatures vary greatly from the experimental values for many ventilation conditions, largely because the heat is largely released outside the enclosure in the simulation rather than inside it for much of the time in the experiments.

These results indicate that further development of the combustion modeling in FDS is required to ensure users can be confident of the predictions obtained from FDS even for relatively simple simulations.

REFERENCES

[1] McGrattan, K.B. and Forney, G.P., Fire Dynamics Simulator Users Guide NIST Special Publication 1019, National Institute of Standards and technology, U.S. Department of Commerce, Gaithersburg, MD, July 2004.

[2] Peacock, R.D., Reneke, P.A., Jones, W.W., Bukowski, R.W., and Forney, G.P., A User's Guide for FAST: Engineering Tools for Estimating Fire Growth and Smoke Transport, Special Publication 921, National Institute of Standards and technology, U.S. Department of Commerce, Gaithersburg, MD, January 2000.

[3] Thomas, I.R. and Bennetts, I.D., "Fires in Enclosures with Single Ventilation Openings-Comparison of Long and Wide Enclosures," *Proceedings of Sixth IAFSS Symposium*, 1999, pp. 941-952.

[4] Huggett, C., "Estimation of Rate of Heat Release by Means of Oxygen Consumption Measurements," *Fire and Materials,* 4, 1980, pp. 61-65.