The Effect of Fuel Quantity and Location on Small Enclosure Fires

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ABSTRACT: Results from an experimental program undertaken to study the effect of fuel quantity and location on ethanol pool fires in the open and in a small enclosure (an ISO 9705 room) are compared with simulations using the Fire Dynamics Simulator version 4.03 (FDS4). The fuel in trays is placed at three locations (front, back, and center) within the room enclosure as well as directly under the calorimeter hood. The measured heat release rate (HRR) is found to vary substantially when a fuel package consisting of different quantities of ethanol is placed at different locations within the room. Instead of prescribing this HRR into the FDS simulation, these experimental results are compared with HRR predictions obtained using the FDS4 combustion model. The comparison reveals that there are significant and variable differences between the experimental results and the FDS4 predictions in contrast to simulations where the HRR is prescribed.

KEY WORDS: burning rate, heat release rate, pool fire, ISO 9705 room, fuel location, grid size.

INTRODUCTION

KNOWLEDGE OF THE behavior of fires in enclosures (rooms and other spaces in buildings) is an essential element in predicting the level of fire safety in buildings and in designing building fire safety systems. This research was undertaken to investigate the behavior of relatively simple fuel packages in the open and when placed at different locations within a small

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room. In addition, a commonly used computational fluid dynamics (CFD) program, FDS4 [1–3] was used to simulate each of the tests and the predictions of FDS4 were compared with the experimental results. The purpose of this research was to obtain an improved understanding of the effect of fuel quantity and location on the behavior of fire in enclosures; the relevance of burning behavior under the hood of a calorimeter (effectively, burning in the open) to burning of the same fuel package at various locations in a small room; the resulting heat release rates (HRRs); gas, wall, and ceiling temperatures and radiation fluxes in the room; and to determine the ability of FDS4 to predict these quantities.

Flammable liquids in trays are relatively simple fuel 'packages' that burn as 'pools' with horizontal fuel surfaces [4]. A pool fire consists of turbulent diffusion flames burning above vaporizing fuel, with the fuel vapor having zero or low initial momentum [5]. In the open, these fires are well ventilated but within enclosures they may be ventilation controlled and otherwise influenced by the enclosure. It is reasonable to assume that, in general, prediction of the burning rate of such fuel packages is easier than similar predictions for the more complex, generally solid and often composite, fuel packages that make up the majority of the combustible items in buildings. Thus it is easier to compare predictions of burning rate and the resulting temperature changes in the room with the experimental results.

The burning rate of a flammable liquid in a tray is reported to be constant when the liquid surface of the pool is maintained at a constant elevation with respect to the rim of the tray. This is not a usual situation when flammable liquids are burned. In practice, as the burning progresses the rim above the liquid is more and more exposed. As described in [6] pool fires are sensitive to the geometric and thermal details of the container (tray) rim surrounding the fuel. It has been found that the burning rate could increase by 60% as the bounding rim increases from 0 (i.e., flush) to 13 mm above the fuel level [6].

EXPERIMENTAL PROGRAM

The experimental program was conducted in the ISO room facility at Centre for Environmental Safety and Risk Engineering (CESARE), Victoria University. The room fires were conducted in a standard ISO 9705 room [7], except as noted here. The room walls and the ceiling were constructed of 25 mm thick fire-resistant gypsum plasterboard placed within steel studs on the outer face and two layers of 12 mm thick fire-resistant gypsum plasterboard mounted inside on the same steel studs. Preliminary measurements showed that this combination acts as a near perfect insulation.

The walls and ceiling were then lined with 1.6 mm steel sheet to help protect the plasterboard due to the large number of tests being conducted. Thus the walls and ceiling were approximately 52 mm thick. The floor was constructed of a layer of 12 mm thick millboard covered by two layers of 6 mm thick cement sheeting. When these tests were conducted the room had been subjected to a large number of similar tests.

The room was ventilated solely by a doorway 2.0 m high by 0.8 m wide (as specified in ISO 9705) located at the center of one 2.4 m wall. The doorway was fully open during all the tests. The outflowing products of combustion were collected by an exhaust hood and directed to an oxygen consumption calorimeter [8].

The locations of thermocouples within the ISO room are shown in Figure 1(a). Three type K thermocouples were spot-welded to the steel lining (equally spaced horizontally) on each 3.6 m wall 1.8 m above the floor (TC 15, 16, and 17 on the west wall and TC 21, 22, and 23 on the east wall). Three similar thermocouples were spot-welded to the ceiling on the centerline (TC 18, 19, and 20). Two thermocouple trees consisting of seven type K thermocouples were located on the centerline: one at the center of the room and the other 300 mm inside the door. Thermocouples were placed at 0.67, 0.97, 1.27, 1.42, 1.57, 1.72, and 2.1 m above the floor.

Two water-cooled Gardon-type infrared radiometers were placed on the centerline of the floor 1.0 m away from the door and the rear wall, respectively. Each radiometer was equipped with a sapphire window for elimination of convective heat flux. The total view angle of the radiometers, with the sapphire window installed, was 150°.

The fuel trays used were of $0.81 \times 0.70 \times 0.05\,\mathrm{m}^3$ size and were constructed from steel. The trays were spaced 0.05 m apart in all tests. Standard commercial grade methylated spirit, consisting of 97% ethanol and 3% water, was used as the fuel with 5, 10, or 20 L of fuel in each tray.

The HRR of the trays when arranged as in the room but burning in the 'open' was obtained by placing the trays directly under the hood of the calorimeter as shown in Figure 1(b). The room tests were conducted with two trays and with three trays, the trays being placed across the room just inside the door, in the center of the room, or adjacent to the back wall. A summary of the hood and room tests is given in Tables 1 and 2.

OVERVIEW OF FDS SIMULATION

The simulations were conducted using the mixture fraction combustion model and the large eddy simulation (LES) mode of FDS4 [3]. In this method, since the reactants are not premixed, it is assumed that the reaction

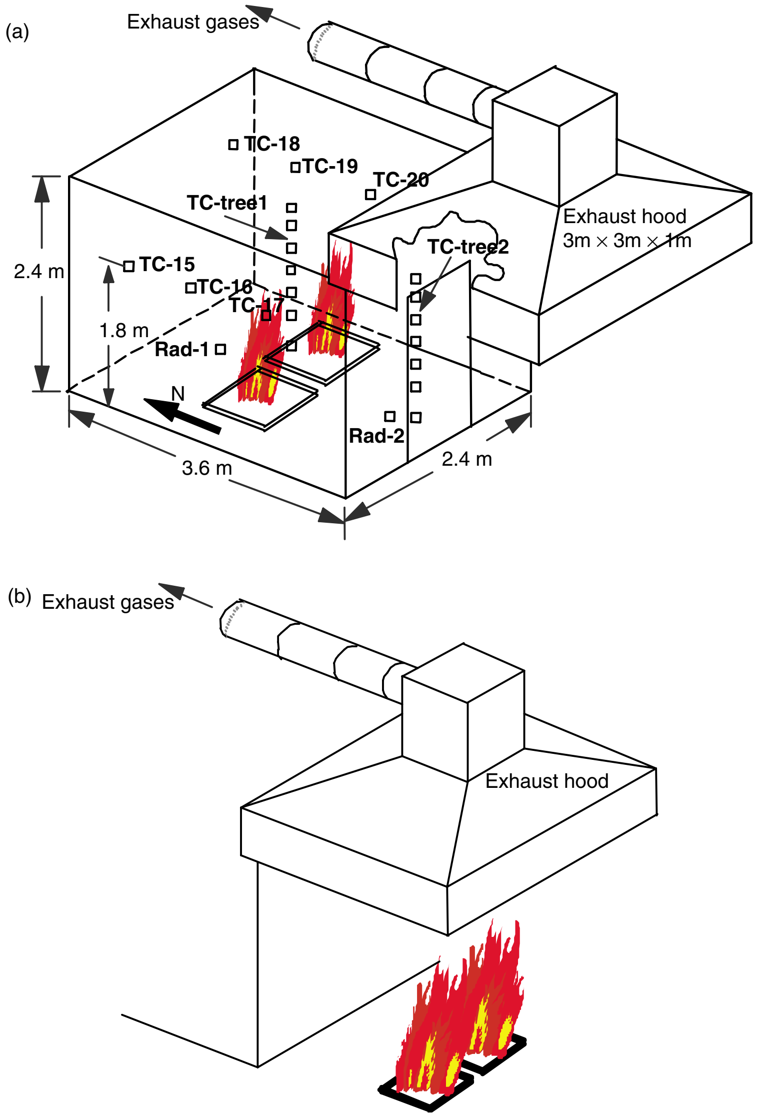


Figure 1. *Schematic diagram of the experimental setup: (a) room tests and (b) hood tests. (The color version of this figure is available online.)*

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. An infinite rate of reaction between fuel vapor and oxygen is assumed when the mixture fraction is at the stoichiometric value.

Table 1. Hood tests.

Test name	Number of fuel trays	Amount of fuel in each tray (L)	Pool thickness (mm)
Hood-2-10	2	5	8.82
Hood-2-20	2	10	17.64
Hood-2-40	2	20	35.27
Hood-3-30	3	10	17.64

Table 2. Room tests.

Tray location within enclosure	Test name	Number of fuel trays	Amount of fuel in each tray (L)
Back (100 mm clear of the back wall)	Back-2-10	2	5
	Back-2-20	2	10
	Back-2-40	2	20
	Back-3-30	3	10
Center	Center-2-10	2	5
	Center-2-20	2	10
	Center-2-40	2	20
	Center-3-30	3	10
Front (150 mm inside of the door)	Front-2-10	2	5
	Front-2-20	2	10
	Front-2-40	2	20
	Front-3-30	3	10

Creation of FDS Data File

An FDS data file was constructed to model the experimental setup for the ISO room. The computational domain extended beyond the enclosure to capture all of the combustion activity (Figure 2(a)). The fuel trays were modeled as an obstruction with dimensions similar to the actual size, placed appropriately in the room. The top face of the obstruction was used to simulate the fuel surface and the other faces were modeled as steel sheet. The limitation of this modeling is that it cannot take into account the container rim effect as well as heat transfer to the steel container; however, no alternative modeling is available for FDS. The internal surfaces of the ISO room were modeled as a steel sheet with properties as specified in the FDS4 database except that the backing was specified as insulated. The floor was specified as concrete.

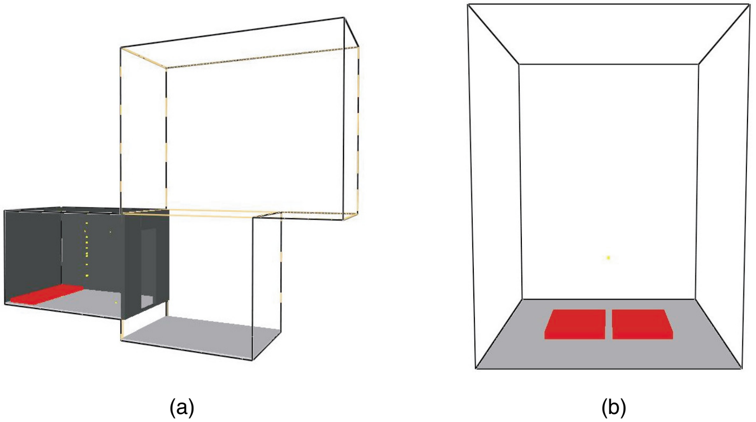


Figure 2. Computational domain: (a) room fire and (b) hood fire. (The color version of this figure is available online.)

The simulations of the hood tests used a 4.0 m high computational domain with lateral extension of 1.0 m beyond the fuel trays in both directions (Figure 2(b)). The floor was specified as concrete and the remaining five sides were open. The fuel trays were modeled similarly to the room simulations and were placed at the center of the floor.

Grid Resolution

In conducting CFD analysis it is good practice [9,10] to undertake a process of grid refinement in which the grid spacing used in the analysis is gradually reduced and the effects of the reduced grid spacing on the predicted outcomes are examined. It is usual to find that as the grid spacing is reduced the results converge to a unique solution. Thus further reducing the grid spacing has virtually no effect on the results produced (but may greatly increase the time taken to complete the simulation). It is usual to adopt a grid spacing that produces results close to the converged results but that does not require excessive computation. As stated in [3], by modifying the stoichiometric ratio it is possible to get a reasonable approximation of the HRR of the fire even when the fire is not well resolved. Such an automatic modification routine is included in FDS4. However, this routine obviously may fail if the grid resolution is too coarse. Therefore, it was imperative to conduct a grid independence test for large pool fires.

To obtain an appropriate grid size, a hood test with a single tray containing 5 L of fuel was simulated adopting 100, 50, and 25 mm cells.

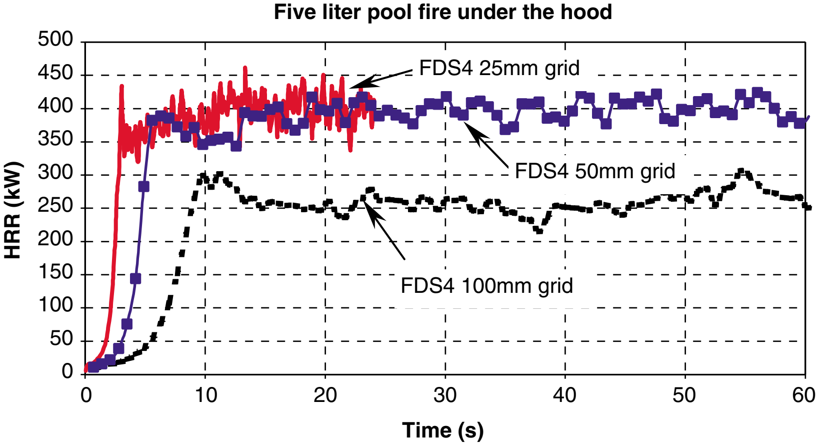


Figure 3. *Grid independence tests in terms of HRR. (The color version of this figure is available online.)*

Table 3. Comparison between simulations with 50 and 25 mm grids using FDS4.

	50 mm grid	25 mm grid	Difference (%)
Quasi-steady state HRR (kW)	≈410	≈410	<1
CPU time for 20 s simulation	1 h	3.8 h	380

For all cases, cubic cells were generated. It was found that results did not change appreciably between cell sizes of 50 and 25 mm as shown in Figure 3. Therefore, for all the cases of hood and ISO tests, the grid was specified to create a cubic cell of $50 \times 50 \times 50\,\mathrm{mm}^3$ size. Table 3 compares the value of quasi-steady state HRR and CPU time for 20 s simulations for 50 and 25 mm grids.

Combustion Parameters and Material Properties

The combustion parameters and material properties of the FDS4 database were used for the ethanol fuel and reaction except as follows. Firstly, the thermal properties of ethanol in the database were modified to allow for the effect of 3% water in the fuel. Secondly, the burning rate limitation of $15\,\mathrm{g/m^2\,s}$ was removed based on a previous study [2] that showed that retaining the burning rate limitation produced very unsatisfactory results, particularly when simulating fires in the ISO room.

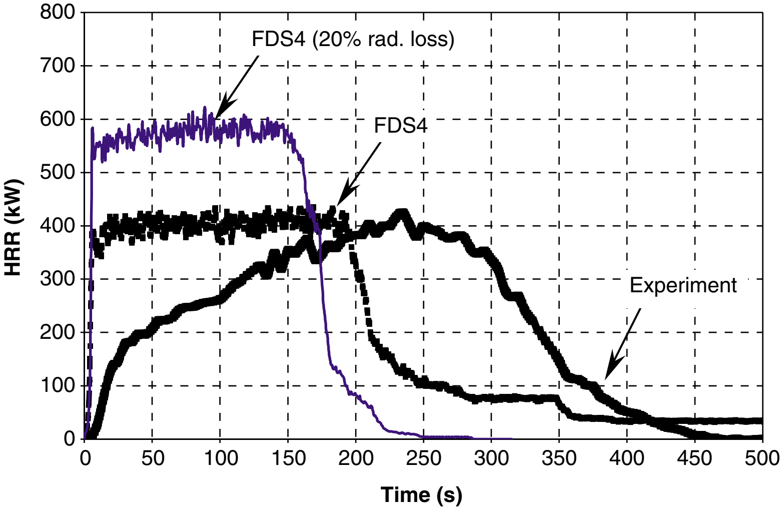


Figure 4. *Comparison of HRR predicted by FDS4 with the experimental data during 5 L pool fire under the hood. (The color version of this figure is available online.)*

Finally, based on the following analysis, RADIATIVE–FRACTION = 0.0 was set, which means that the calculation of the source term in the radiation transport equation is based on the cell temperature rather than the heat released in the cell [3].

Figure 4 shows a comparison of the HRR from the experimental study and FDS4 simulations for the single tray pool fire outside the ISO room. Two FDS4 simulations with the 50 mm grid were conducted. In the first simulation, default radiation heat loss (20%) was assumed keeping RADIATIVE–FRACTION = 0.2 in the reaction database for ethanol. In the second one, the simulation was carried out by setting RADIATIVE–FRACTION = 0.0, which enabled the calculation of the source term in the radiation transport equation based on T^4 criteria instead of considering radiation as a percentage of heat released in the cell. Note that the latter simulation is the same simulation whose result is presented in Figure 3. The experimental curve shows slower growth of fire compared to the numerical curves and unlike the simulations no significant plateau is observed. After a rapid rise up to 35 s, an approximately linear growth of measured HRR continues until reaching the peak value of 420 kW at 235 s, followed by a decay to near zero HRR at 450 s. The first simulation calculated a 44% higher peak HRR value than that of the experimental study. On the other hand, the second FDS4 simulation calculated approximately the same peak HRR value as the experimental data.

EXPERIMENTAL RESULTS

Heat Release Rate

The HRR versus time profiles from all the physical tests mentioned in Tables 1 and 2 are plotted in Figure 5. Figure 5(a) presents data from the four tests with two fuel trays each containing 5 L of fuel placed at three locations within the enclosure and at one location outside the enclosure (under the exhaust hood). Similarly, data from tests with two fuel trays each containing 10 and 20 L are shown in Figure 5(b) and (c), respectively and with three fuel trays each containing 10 L in Figure 5 (d).

Inspection of Figure 5 reveals that in no case was the HRR in the enclosure identical to that obtained when the fuel was burned under the hood and that there is substantial variation in the HRR with changes in the location of the fuel trays within the room. The maximum HRR always occurred when the fuel was located close to the front of the enclosure. This is attributed to the combined effect of the radiation feedback from the enclosure and enhanced exposure to oxygen compared to the other enclosure locations. In these cases, the peak HRR was from about 1.4 to 2.7 times the peak HRR that occurred under the hood. In the two-tray tests, the ratio increased with increased amounts of fuel in each tray: from about

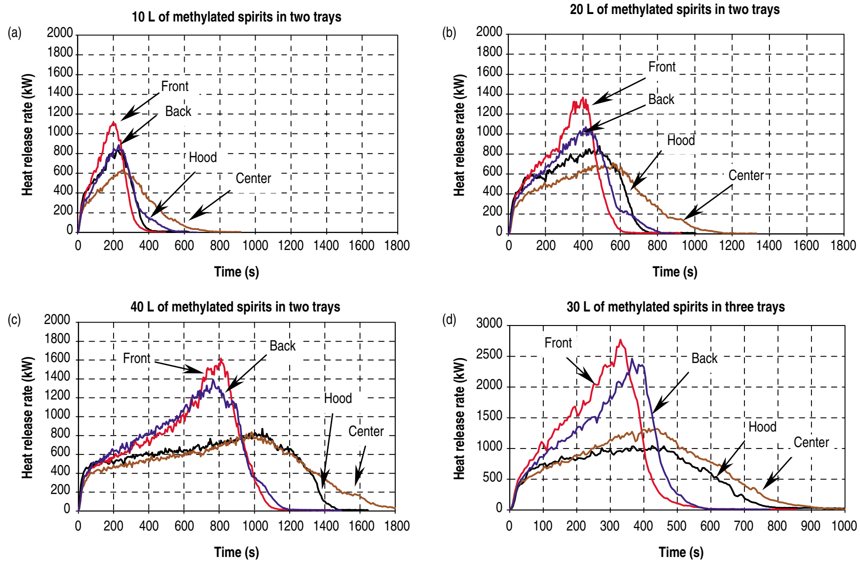


Figure 5. *Comparison of the HRR–time profiles for various locations of fuel trays–experimental results. (The color version of this figure is available online.)*

1.4 with 5 L/tray to about 2.0 with 20 L/tray. The ratio was the highest i.e., 2.7 in the three-tray case. The longer burning duration contributes to the increased evaporation through additional radiation feedback.

The lowest HRR in the enclosure consistently occurred in the tests with the trays in the middle of the enclosure. In some of these cases, the HRR was substantially less and in others it was slightly greater than that occurred under the hood. At that location the fuel package, due to its distance from the enclosure walls, received reduced radiation feedback and the oxygen supply was comparatively less than that in the hood test scenario. The HRR with the trays near the back wall of the enclosure was consistently less than that with the trays near the front but, particularly in the higher fuel quantity cases, was generally greater than the HRR under the hood. As the fuel package location is close to the enclosure boundary, the flame temperature will decrease less rapidly with height as the rate of mixing with inflowing cold air will be significantly less than that for other cases. Flame extension at a noncombustible wall will occur for the same reason, as the flame has to increase in size to give a large enough area through which to entrain air to burn the fuel volatiles. Furthermore, the flame will be deflected toward the restricting wall as a result of the net directional flow of air into the fire plume (see Section 4.3.3 of [4]). This will lead to high back wall temperature and eventually additional radiation feedback.

Gas and Steel Temperature

The differences in HRR due to fuel amount and fuel location resulted in substantial differences in the maximum gas and steel lining temperatures measured in the room tests, as shown in Figures 6 and 7. When the fuel packages were placed at the center and at the back of the enclosure, the maximum gas temperature was recorded by the thermocouple located at the top of thermocouple-tree 1. In contrast, when the fuel packages were placed at the front, the thermocouple located at the top of thermocouple-tree 2 recorded the maximum gas temperature. It can be seen in Figure 6 that the maximum measured gas temperatures were very similar when the fuel was located near the front and back of the room, even though the locations at which they were measured were quite different. Both of these maximum gas temperatures were substantially higher than those measured when the fuel was located at the center of the enclosure.

Figure 7 shows that the measured maximum steel temperatures differed substantially, depending on the fuel location, with the maximum temperature being higher when the fuel was near the back of the room due to the close proximity of the wall and with the center location again resulting in the lowest measured maximum steel temperatures. The differences varied

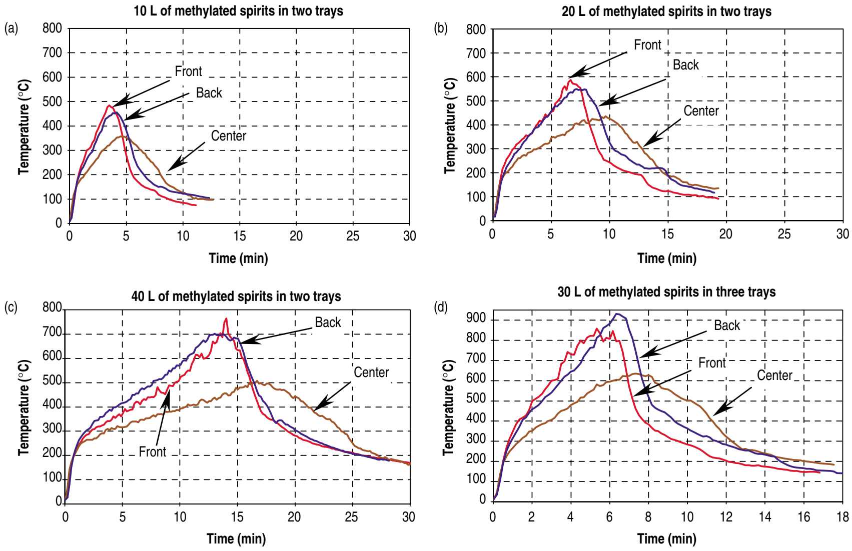


Figure 6. *Comparison of the maximum gas temperature vs time profiles for various locations of fuel trays–experimental results (recording thermocouples for back and center tray cases top T/C of TC-tree 1 and for front tray cases top T/C of TC-tree2). (The color version of this figure is available online.)*

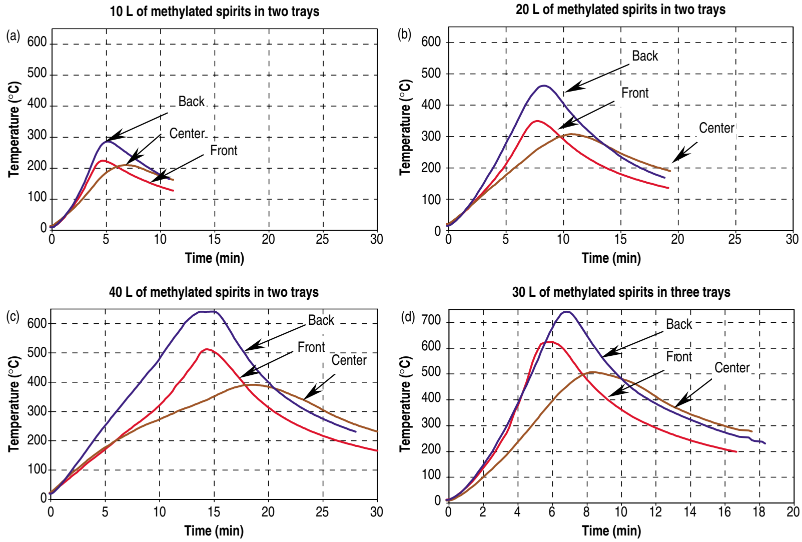


Figure 7. *Comparison of the maximum steel temperature vs time profiles for various locations of fuel trays–experimental results (for recording thermocouples see Table 4). (The color version of this figure is available online.)*

Table 4. Thermocouples that recorded maximum steel temperature.

Fuel tray location	All two-tray tests	Three-tray tests
Back	TC 21[a]	TC 18
Center	TC 19[a]	TC 18
Front	TC 20	TC 20

[a]TC 18 was not active during these tests.

depending on the quantity and arrangement of fuel, with the highest temperatures and greatest differences occurring for the three-tray cases followed by the two-tray case with the largest quantity of fuel.

Radiation Flux

The measured radiation flux at two locations shown in Figure 1(a) is plotted in Figure 8. In the two-tray cases, the maximum radiation flux at both locations is usually recorded when the total quantity of fuel is 40 L. The exception to this is when two trays with 40 L of fuel are placed at the front of the enclosure. The front radiometer then recorded values substantially lower than for cases with the same tray locations but with a lower quantity of fuel. This phenomenon is not understood. In the two-tray cases, a radiation flux of nearly 12 and 30 kW/m^2 was recorded at the front and rear locations, respectively.

A substantially higher radiation flux was recorded at both locations when three trays of fuel were placed at the back of the ISO room, reaching up to nearly 50 kW/m^2 at the rear location. When these trays are placed near the door, a radiation flux of nearly 30 kW/m^2 was recorded at the front location.

SIMULATION RESULTS

The HRR simulation results are presented in Figure 9 which may be compared directly with Figure 5. Temperature and radiation flux results are not shown because discrepancies between the experimental HRR results and the simulation HRR results make the predictions meaningless.

It is notable in Figure 9 that the HRR predicted by the FDS4 simulations rose very rapidly, and in the case of the hood simulations also very rapidly stabilized and remained relatively constant until most of the fuel was burned, at which time it fell very rapidly. The simulations inside the room were similar, but after the initial very rapid increase the HRR continued to rise at a much-reduced rate until most of the fuel was consumed, when it

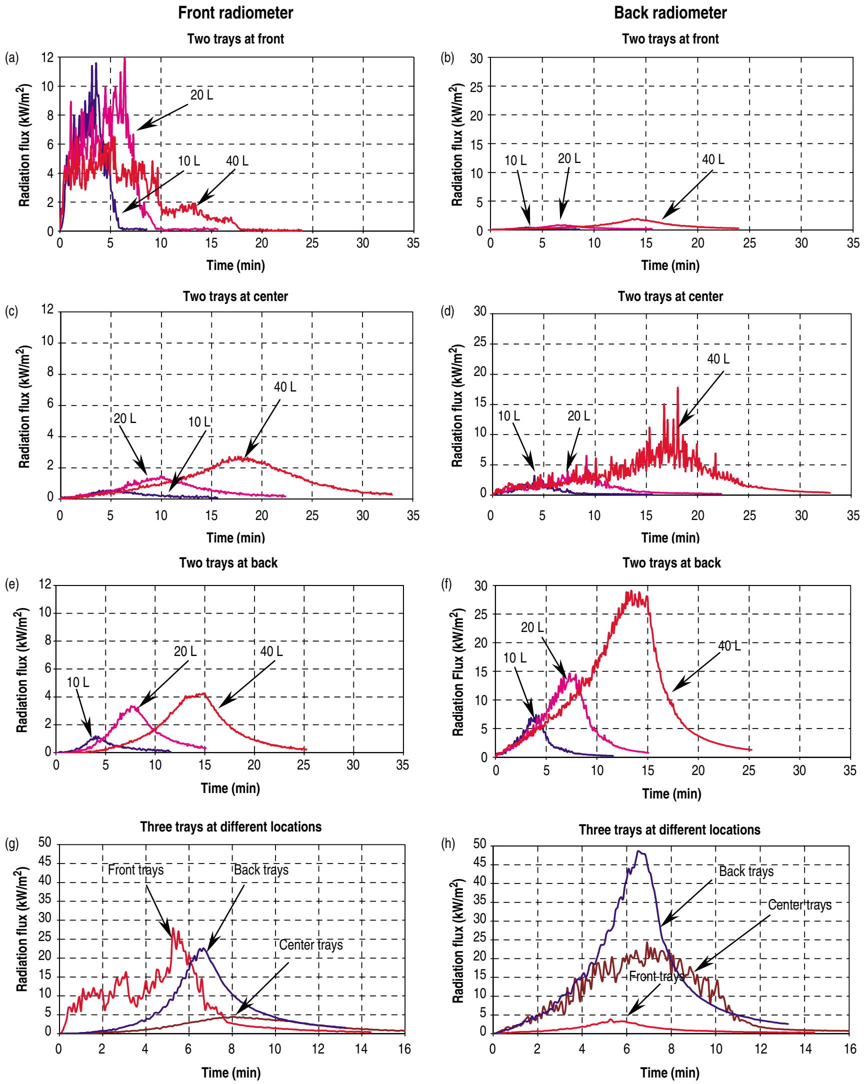
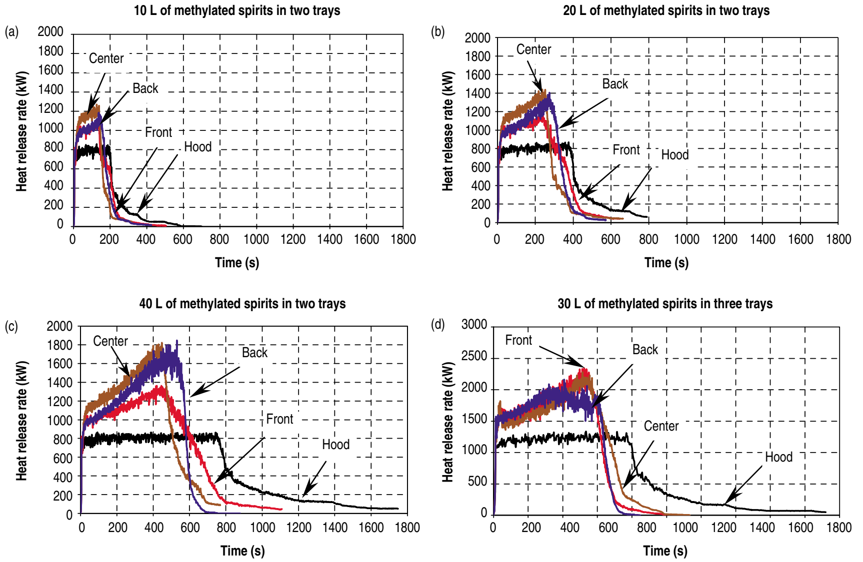


Figure 8. *Comparison of the radiation flux–time profiles for various locations of fuel trays – experimental results. (The color version of this figure is available online.)*

decreased very rapidly. The initial rapid rise of the HRR may partially be attributed to the inability of FDS to handle the heat transfer to the steel tray. In all cases, the HRR in the room simulations substantially exceeded the HRR in the hood simulations. There is some variability as to the location in the room that resulted in the highest HRR, but generally the


(a) 10 L of methylated spirits in two trays

(b) 20 L of methylated spirits in two trays

(c) 40 L of methylated spirits in two trays

(d) 30 L of methylated spirits in three trays

Figure 9. Comparison of the HRR–time profiles for various locations of fuel trays – FDS4 simulation results. (The color version of this figure is available online.)

HRR was lower when the fuel was located at the front of the room and highest when it was at the center of the room. These variations are quite different from those that occurred in the experiments.

COMPARISON OF EXPERIMENTAL AND SIMULATION RESULTS

The HRR obtained from the hood simulations may be compared with the experimental results by comparing Figure 9 with Figure 5. It is clear from this comparison that the HRR versus time curves from the simulations differ markedly from those obtained experimentally. In the simulations, for a given number of trays, the HRR rose very rapidly to a level that was virtually independent of the quantity of fuel, was virtually constant (plateaued) for a period that depended heavily on the quantity of fuel and then fell very rapidly. By contrast, in the experiments, the HRR rose rapidly but to a level substantially below that obtained in the simulations, then rose steadily but at a much lower rate until it reached a maximum that was generally similar to the level of the plateau in the simulations, and then decreased at a somewhat similar rate to the previous steady increase. As a consequence, the HRR was sustained for a substantially longer time in the experiments than in the simulations. In summary, the HRR curves obtained experimentally and from the simulations were quite different, although they generally reached similar maximum HRRs.

Turning now to the room experiments and simulations, a similar comparison reveals wide discrepancies in the HRR versus time curves obtained experimentally and by the simulation. In the case of the fuel near the front of the room, the initial increase in HRR in the simulations was much more rapid and reached a much higher initial level than in the experiments. In the simulations, the subsequent slower increase in HRR was generally less than the rate of increase obtained experimentally and eventually the experimental HRR exceeded the value for the same time in the simulation. In addition, the duration of burning in the simulations was substantially less than in the experiments. The comparison is similar for the fuel at the back of the room, except that in all cases, the maximum HRR from the simulation substantially exceeded that obtained experimentally. In the case of the fuel at the center of the room, the discrepancy between the simulation and the experimental results is much greater. In all cases, the initial rise in HRR of the simulations was much more rapid and much greater than in the experiments and the maximum HRR obtained numerically grossly exceeded that obtained experimentally. As a consequence, the duration of burning in the experiments was much longer than predicted by the simulations.

In summary, the HRR predictions obtained from the room fire simulations differ from those obtained experimentally in substantially different ways depending on the placement of the fuel in the room. In some cases the maximum HRR was overpredicted by >100% and in others underpredicted by up to about 20%. The ranking of the maximum HRR with location within the enclosure is changed by the simulation from front → back→ center (descending order for the experimental data) to center → back → front and front → center → back for the two-tray and three-tray simulation cases, respectively. The initial rise in HRR was in all cases too rapid, and as a consequence of excessive predictions of the early HRR, the duration of burning was in all cases underestimated, in many cases substantially. As mentioned before, the inability of FDS to handle the heat transfer to the steel tray may partially contribute to the initial rapid rise of the HRR.

A further comparison of the experimentally obtained HRR results and those obtained from the simulations is instructive. Figure 10 shows the experimental and simulation HRR versus time curves as a function of the different quantities of fuel. It is notable that the shape of the experimental curves is quite different for each fuel quantity from very early in the burning process whereas each increment in fuel quantity simply extends the duration of a given simulation curve while preserving the same shape. This may be attributed to the container rim effect in the experimental study.

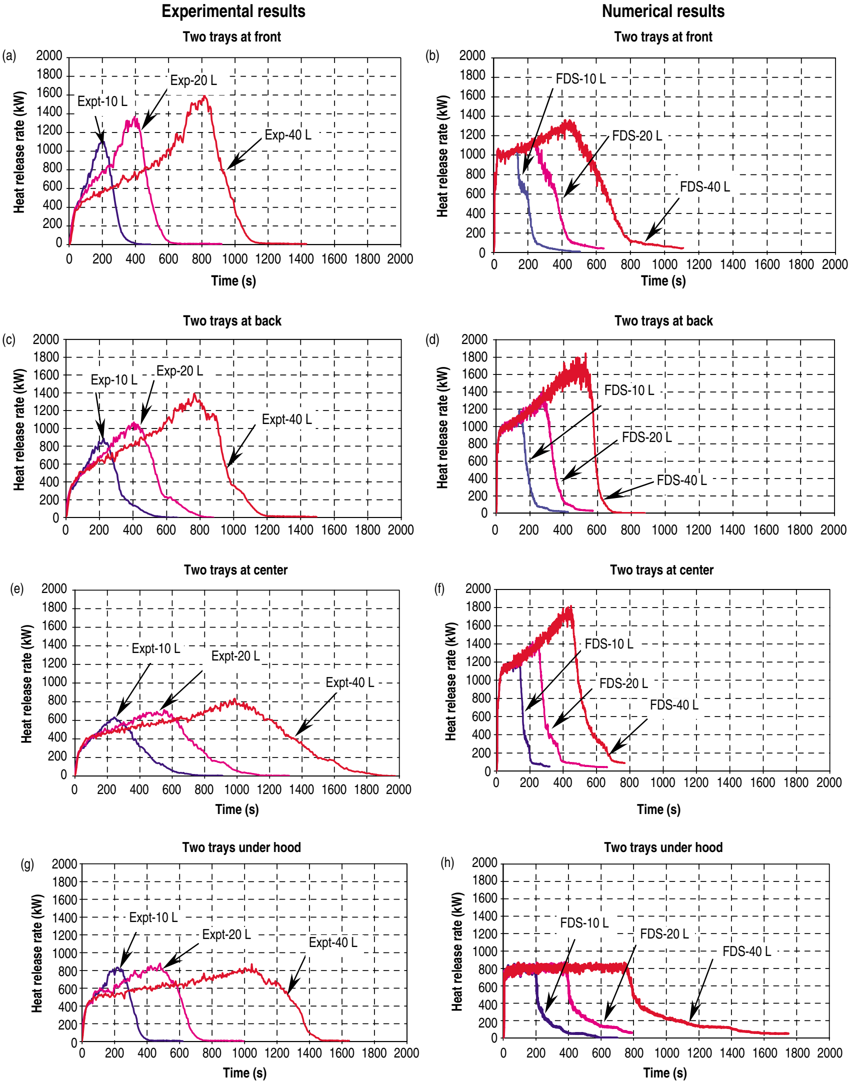


Figure 10. *Comparison of the experimental data, with trays at various locations but fuel amount varied. (The color version of this figure is available online.)*

Overall, it appears from the experimental results that there are significant differences in the burning process depending on the location of the fuel that are not being correctly predicted in the simulation. These differences are currently under further investigation.

CONCLUSIONS

Prediction of the size and effects of fires in enclosures is important in predicting the level of fire safety in buildings and in designing building fire safety systems. This research was undertaken to investigate fires due to relatively simple fuel packages in the open (equivalent to furniture calorimeter results) and when placed at different locations within a small room. The experimental results have been compared with FDS4 predictions of the HRR.

It is concluded that the HRR obtained experimentally using calorimetry data should be used extremely carefully when being used to estimate the likely HRR of fires in room and other enclosures as the HRR of the enclosure fires may vary substantially with the position of the fuel in the room. From the room fire tests, the ranking of the maximum HRR with fuel location within the enclosure is observed to be front → back→ center in a descending order.

FDS4 is able to predict reasonably accurately the maximum HRR obtained from calorimeter measurements in an open situation. However, when fires were simulated within a small room, the HRR predictions obtained from the FDS4 simulations differ markedly from those obtained experimentally and did so in substantially different ways depending on the placement of the fuel in the room. In some cases, the maximum HRR was significantly overpredicted and in other cases underpredicted. The ranking of the maximum HRR with location within the enclosure is changed by the simulation to center → back → front and front → center → back for two-tray and three-tray cases, respectively.

It is recommended that further research be undertaken to improve the combustion and the radiation modeling in FDS4 and that further experimental investigations be undertaken to understand whether the degree of dependency of fuel position in a room is similar for realistic solid fuel packages to that obtained for the liquid fuel packages used in this study.

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