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CFD Model of a Specific Fire Scenario

D. Mackay, T. Barber and E. Leonardi

School of Mechanical and Manufacturing Engineering
University of New South Wales, New South Wales, 2052 AUSTRALIA

Abstract

Flashover is a complex and potentially very dangerous phenomenon. The NSW Fire Brigade currently conducts training courses in flashover and backdraft using a test cell made from a shipping container where chipboard is set alight in the test cell and the fire is allowed to develop into flashover. As part of a collaborative project with the NSWFB, computational models are being developed to aid in the training procedure. CFD models of the test cell in advancing flashover scenarios, using the code FDS are compared with qualitative experimental data, with good agreement shown for the fire behaviour. Models with different configurations of the test cell were also compared, with particular consideration on the effect on time to flashover and temperature trends.

Introduction

Flashover is a transition from a slow growth period to a fully developed fire in a compartment. Figure 1 shows the expected fire development for a compartment fire as presented by Graham *et al* [2]. In the initial growth period the fire develops as the fuel burns provided enough oxygen is present, allowing hot gases with unburnt fuel to build-up on the ceiling of the compartment. Fire progression occurs as the compartment transitions into high temperatures, ignition of the unburnt fuel particles and flames spread throughout the compartment with all combustible material involved. Although flashover is rapid, it cannot be easily defined as a discrete event and hence quantifying the 'flashover event' is difficult. Waterman [9] conducted a series of experiments to determine the criteria for the onset of flashover and Liang [4] notes that these experiments lead to the two common definitions used in literature which are when the heat flux at the floor reaches 20kW/m^2 or when the temperature of the hot layer at the ceiling reaches 600^{o}C.

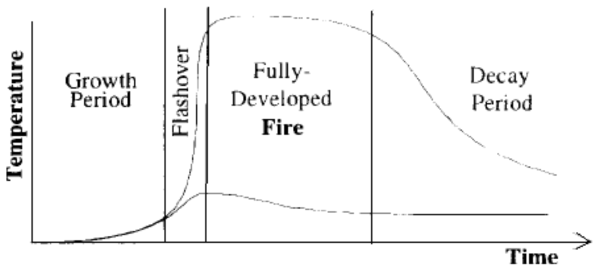


Figure 1. Stages in a compartment fire temperature history. Graham *et al* [2].

Flashover and other rapid fire phenomena have potentially disastrous consequences for the fire brigade and those they try to protect. Grimwood [3] notes that "during a tragic five week period between June and July 2007, twenty-two US Firefighters have been killed or badly burned through events associated with rapid fire phenomena". The NSW Fire Brigade has commenced compartment fire behaviour training (CFBT), to train fire fighters in rapid fire phenomena, the practical component of which involves using a large demonstration cell which is internally set alight and allowed under controlled conditions to reach flashover.

This study examines the flashover event in the CFBT demonstration cell using the computational fluid dynamics (CFD) program Fire Dynamics Simulator (FDS) [6, 7], and the visualisation program Smokeview [1]. Results of the field model FDS will be compared to qualitative thermocouple data with comparisons made for temperature and time to flashover. Variations of the CFBT demonstration cell set-up, including modifying ventilation conditions will be compared and the influence on temperature and time to flashover examined.

Demonstration Cell

An outline of the CFBT demonstration cell modelled in FDS is shown in figure 2.

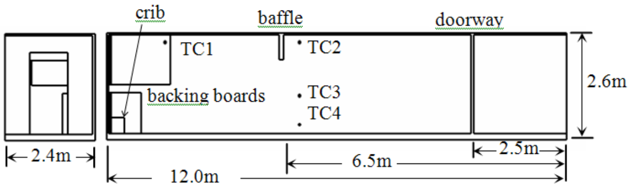
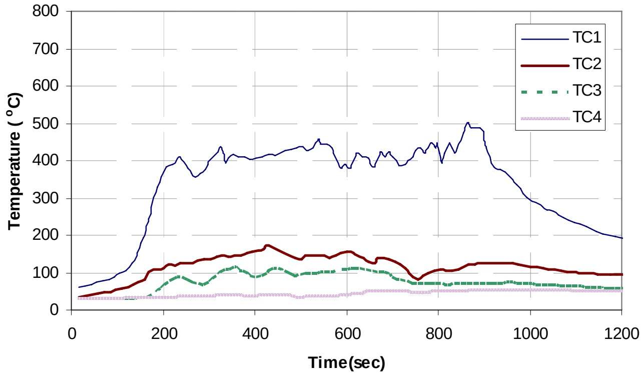


Figure 2. CFBT demonstration cell.

The cell is adapted from a shipping container with dimensions 2.4m by 12m by 2.6m. A doorway exists at 2.5m from the entry and the floor toward the back of the cell is made from brick and backing board lines the back corner including the roof as snown in figure 2. A small crib made from chipboard is used as the ignition source. A 0.6m baffle exists 6.5m from the cell entry and a vent 1.76m by 0.59m exists on one wall of the cell opposite to the crib but is not shown in figure 2. The vent is controlled by the instructor who may open it during a burn if desired. The baffle is used to contain smoke in the front portion of the room until sufficient build-up has occurred, however it is not always utilised.

Four thermocouples are attached to the side and ceiling of the cell, allowing CFBT inspectors to examine the temperature profiles at these locations after a training session has been completed. Since these measurements are taken during a training session, which includes having the inspector and fire fighters in the cell (near door), fire suppression takes place as the fire develops. It includes short pulses which are used to cool the smoke on the inside of the door, however no water is applied directly to the flames. The aim of this study is to model the demonstration cell without fire suppression taking place as the main focus is flashover development. Only qualitative comparisons will therefore be made with the CFBT thermocouple data. Figure 3 shows typical temperature plots for the CFBT cell during a training session, thermocouple 1 is located on the roof of the cell approximately one metre from the crib, thermocouples 2, 3 and 4 are attached to a wall on the same side of the cell as the crib 300mm closer to entry than the baffle at 150mm from ceiling, kneeling height and 150mm from floor respectively.

The temperature in the back portion of the room which contains thermocouple 1 is allowed to reach much higher temperatures as fire fighters will not enter this area. As the backing boards begin to burn and flames begin to spread in this region a rapid increase in temperature is found, limited initially to approximately 400°C by fire suppression. The fire is allowed to burn steadily for approximately 10 minutes while fire fighters observe the fire behaviour. Appropriate cooling techniques are used in the front portion of the room to ensure conditions at kneeling height (T3) do not exceed 150°C.



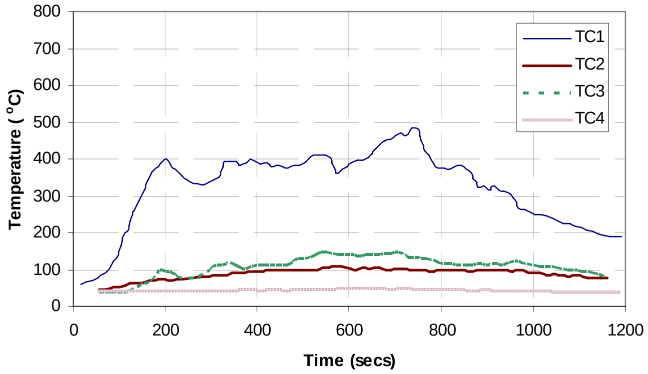


Figure 3. NSWFB thermocouple graphs for the demonstration cell.

The Model

Recently flashover has been modelled using CFD with some success [5, 8, 10]. Zou and Chow [10] successfully used FDS to model a compartment fire with gasoline pool fires as an ignition source and found good agreement between full scale experiments and FDS output. FDS is a field model which numerically solves the Navier-Stokes equations. It assumes low-speed, thermally driven flow and utilizes the Smagorinsky form of Large Eddy Simulation (LES) to solve the flow. Direct Numerical Simulation (DNS) is also available as an alternate solution option. The Smagorinsky model models the turbulent viscosity μ_{LES} as :

$$\mu_{LES} = \rho (C_s \Delta)^2 |\bar{S}|$$

where $\bar{S} = \sqrt{2\bar{S}_{ij} \cdot \bar{S}_{ij} - \frac{2}{3}(\nabla \cdot \bar{u})^2}$

And Δ is typically given by $(control\_volume\_element)^{\frac{1}{3}}$.

The default value for the Smagorinsky constant C_s of 0.2 was used in this study.

FDS includes a combustion model where gas species are described by its mixture fraction. At each point in time in each volume the mixture fraction is given for the gas species. The mixture fraction is the ratio of mass for the species compared to the total mass.

Finite volume methods are applied to thermal radiation transport and Lagrangian particles are used to simulate the smoke movement. A rectilinear grid is applied which all geometry must conform to [7].

In this study the FDS model was matched as closely as possible to the demonstration cell. The crib was modeled as a solid block with boundary condition set as a heat release rate per unit area of 1200kW/m^2, which ramps to full value in 700 seconds. As shown in figure 2 the back portion of the floor was modeled as brick which is the same as the demonstration cell. The backing board was modeled as a similar material to the chipboard used during burns.

A grid sensitivity study was undertaken on all models tested. Grid sizes of 0.15, 0.1 and 0.075 were compared. The FDS Technical Reference Guide [7] states "The grid size is the most important numerical parameter in the model, as it dictates the spatial and temporal accuracy of the discretized partial differential equations". Information within a cell is constant and it is expected that a finer grid will produce more accurate results as it should increase the resolution, aiding in the accurate representation particularly of flame spread and fire growth.

The effect of time step was also investigated and initial time steps were varied for the cell from 0.05 to 0.1 to determine the effect on the solution. The default time step for FDS is set by dividing the size of a grid cell by the characteristic velocity of the flow [6].

The placement of computational boundaries or domain size can have a significant effect on the flow. Originally the boundaries were set to the confines of the demonstration cell. The computational domain was then extended 1m in each direction.

The model was solved both with and without the vent which can be opened and closed by an instructor during a demonstration cell burn. The baffle as shown in figure 2 was removed to determine what effect it had on temperature and time to flashover.

Results and Discussion

Model Optimisation

A grid sensitivity study was performed with default time steps and the computational domain was bound by the shipping container. The baffle was not included in these cases. Figure 4 shows a comparison of the temperature plots for the three grids for thermocouple 2. Significant differences can be seen in the 0.15m and 0.1m grids however the 0.1m and 0.075 grid are within 5% of each other which is considered to be in good agreement. Figure 5 shows the percentage difference between the 0.1m and 0.075m grid for thermocouple 1 which had the worst agreement of all the thermocouples but is still considered to be adequate for determining fire behaviour.

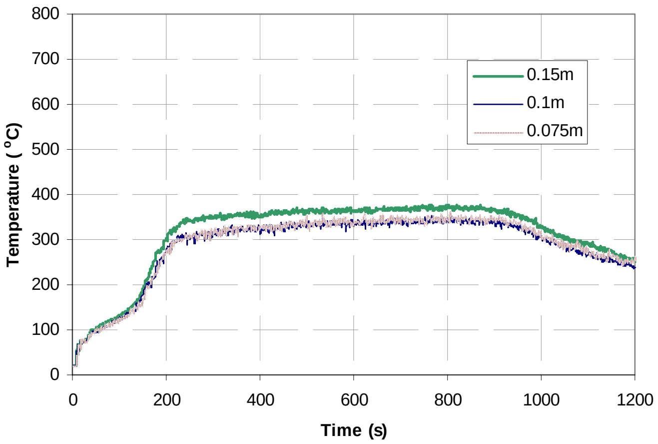


Figure 4. Temperature profiles at thermocouple 2 for varying grid sizes

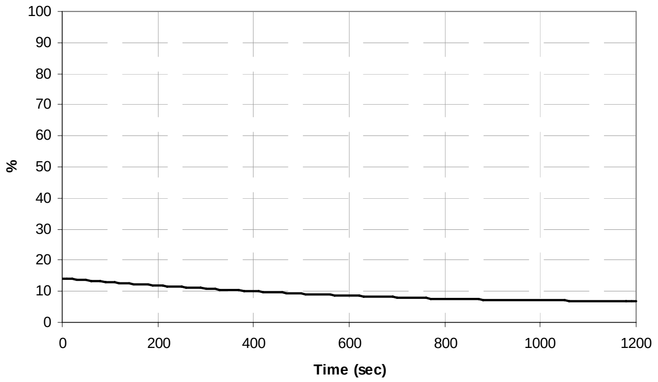


Figure 5. Temperature profiles at thermocouple 2 for varying grid sizes

The placement of the computational boundaries was examined at three locations. In figure 6 Domain1, Domain2 and Domain3 refer to an extension of 2.5m, 0.8m and 0m respectively of all domain boundaries. As can be clearly seen in figure 6 reducing the domain to only include the cell itself reduced the temperature by up to 12%. In this case vents are placed at any exit to the cell but any flow dynamics occurring at or near the boundary may not be fully captured. Minimal difference was found between Domain 1 and Domain 2 and hence the domain was extended to 0.8m for all subsequent cases.

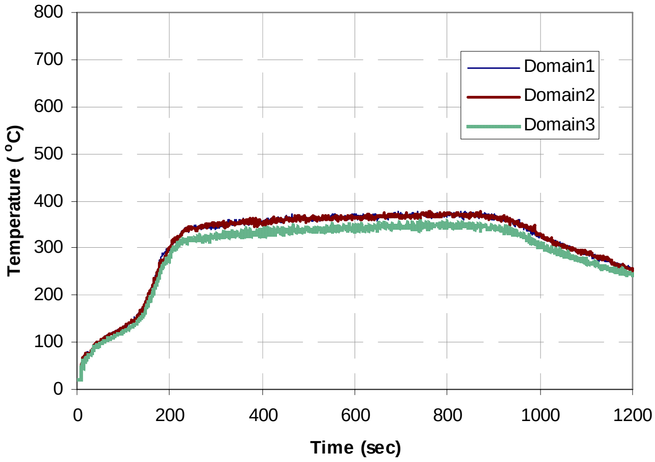


Figure 6. Temperature profiles at thermocouple 2 for varying domain sizes.

Variation of the time steps had no measurable impact on results. The default setting was therefore used for all FDS cases.

Comparison with Expected Results

It is stressed that only general comparisons with the experimental data, shown in figure 3, can be made as fire suppression is taking place, this differs for each burn run as shown by the differences in the temperature graphs in figure 3. All CFD cases were solved with a 0.075m grid and extended computational domain. If we take the ceiling temperature value of 600°C to be the flashover then the experimental results do not reach flashover, this is due to fire suppression taking place at critical times to ensure safety for fire fighters. However the sharp temperature rise which occurs between 100 and 200 seconds could be seen as a prelude to flashover which may have occurred at approximately 200 seconds. The FDS results shown in figure 7 increase steadily over the first 200 seconds and flashover, as taken to be when the temperature reaches 600°C, occurs at 210 seconds. Peak temperatures of close to 650°C persist as the backing boards burn. The time to flashover as well as the general temperature profile is found to be consistent with the experimental results and expected temperature curve for compartment fires.

The experimental results for thermocouples 2, 3 and 4 are deliberately kept low for the safety of fire fighters. Fire suppression occurs in front of the baffle which is why the temperature for thermocouple 2 is significantly different between the experimental values and those in figure 7, however the general shape of the temperature curve is consistent with expected results. Since it is shielded by the baffle the temperature in thermocouple 2 is expected to be considerably smaller than thermocouple 1. Thermocouples3 and 4 do not reach temperature greater than 100°C indicating that flaming combustion did not reach all the way to the floor.

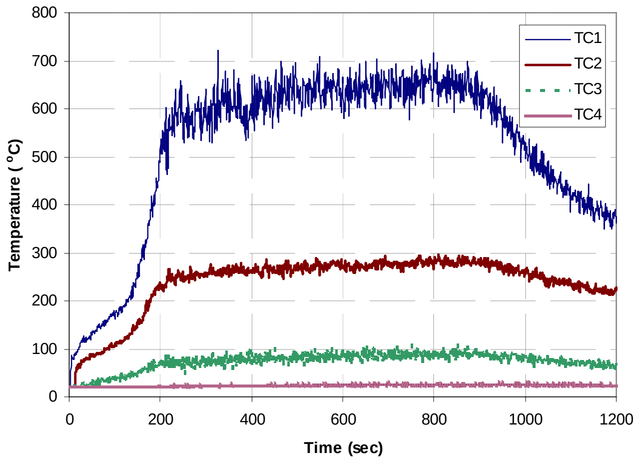


Figure 7. FDS temperature profiles at four thermocouple locations.

Effect of Ventilation

The model was solved under identical conditions except a vent was added and the baffle was removed. The vent is part of the demonstration cell and gives instructors control over ventilation in the back portion of the room. The vent is 1.76m by 0.59m and is located 1.7m above the floor. Figure 8 shows the temperature profiles for the same thermocouple locations.

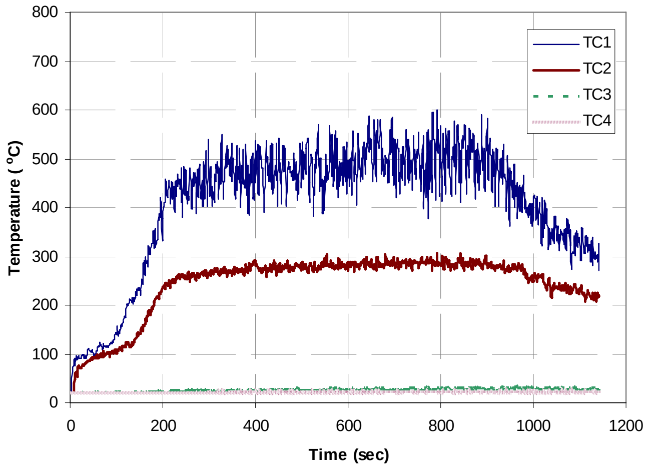


Figure 8. FDS temperature profiles of the demonstration cell with vent open at four thermocouple locations.

Figure 8 shows that with the vent in place the required flashover temperature is not achieved. Maximum temperatures were maintained close to 500°C Similar profiles are seen for thermocouples 1, 2 and 4 compared with those in figure 7, however thermocouple 3 does not increase far beyond standard conditions showing that the increase in temperature did not reach to that portion of the room. This can also be seen in thermocouple 2, since no baffle exists to shield the thermocouple it would be expected that the temperature would increase beyond 300°C however a maximum temperature of 290°C is found after 550 seconds.

With the open vent close to the fire source smoke and heat are able to leave the compartment before reaching the front portion of the room where the three measurements are being taken. The heat leaving the compartment reduces the temperature around the fire source and backing boards such that flashover is no longer achieved. Figure 9 shows fire and smoke leaving the compartment via the vent displayed in Smokeview.

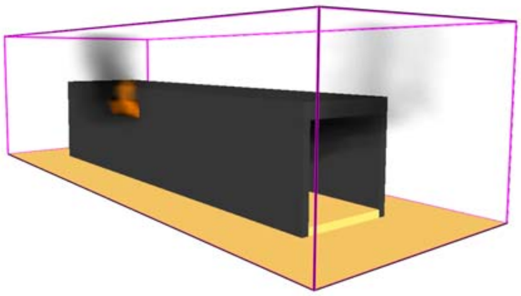


Figure 9. A Smokeview representation of the cell with vent open.

Effect of Baffle

The baffle contains the smoke in the front portion of the cell until sufficient build up has occurred, as with the vent the baffle can be removed which was modelled in FDS. With the baffle removed a higher temperature were recorded by thermocouple 2 which reached 350°C after 850 seconds, this is expected as it is no longer shielded. Comparison of thermocouple 2 in figures 8 and 10 highlight the reduction in temperature brought about by the introduction of the vent into the demonstration cell.

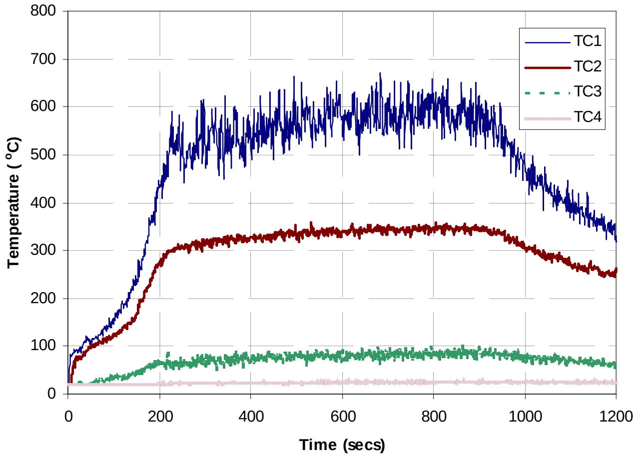


Figure 10. FDS temperature profiles of the demonstration cell without the baffle at four thermocouple locations.

Conclusions

Grid optimisation of the FDS simulation for the NSWFB demonstration cell showed that a 0.075m grid with domain boundaries extended beyond the sides of the cell produced the most accurate results.

Good agreement was shown for fire behaviour in comparison with qualitative experimental data. The FDS model produced higher temperatures of up to 100°C however since fire suppression is included in the experimental results this was expected. Temperature profiles produced were in good agreement with experimental results and expected compartment fire profiles for fire development.

The introduction of a vent was found to remove a significant amount of heat from the front part of the room. Removal of the baffle showed increased temperatures in the front region which would have been otherwise shielded by the baffle.

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