NUMERICAL SIMULATION OF THE NEW SOUTH WALES FIRE BRIGADE COMPARTMENT FIRE BEHAVIOUR TRAINING TEST CELL

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ABSTRACT

The New South Wales Fire Brigade currently gives practical flashover and backdraft training to fire fighters using a Compartment Fire Behaviour Training test cell. The test cell is a converted shipping container, where chipboard is set alight and the fire is allowed to develop into flashover. In this paper, computational models are described that are being developed with the New South Wales Fire Brigades 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 are also compared, with particular consideration of the effect on time to flashover and temperature trends. The inclusion of a baffle and vent was found to have a significant effect on maximum temperatures.

1. INTRODUCTION

Flashover is a transition from a slow growth period to a fully developed fire in a compartment. Fig. 1 shows the expected fire development for a compartment fire as presented by Graham et al. [1]. 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, and there is 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 [2] conducted a series of experiments to determine the criteria for the onset of flashover and these experiments led to the two common definitions which are when the heat flux at the floor reaches 20 kWm^{-2} or when the temperature of the hot layer at the ceiling reaches 600^oC [3].

Flashover and other rapid fire phenomena have potentially disastrous consequences for the fire brigade and those they try to protect. Grimwood [4] 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.

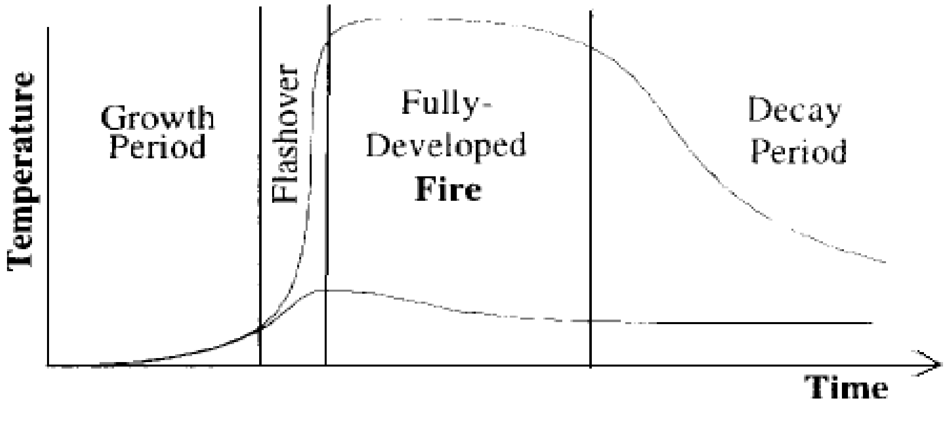


Fig. 1: Stages in a compartment fire temperature history [1]

The objective of this study is to determine the ability of the Computational Fluid Dynamics (CFD) program Fire Dynamics Simulator (FDS) [5,6] to accurately simulate compartment fire behaviour by examining the flashover event in the CFBT demonstration cell. Successful validation will also allow different set-ups of the demonstration cell to be tested computationally first before live fire testing, ensuring safety concerns are met.

Computational results obtained using the field model FDS are examined with qualitative thermocouple data with comparisons made for temperature and time to flashover. Variations of the CFBT demonstration cell set-up, including modifying ventilation conditions are analysed, investigating their influence on temperature and time to flashover. The visualisation program Smokeview [7] is used to view results.

2. DEMONSTRATION CELL

The CFBT cell is adapted from a shipping container, with dimensions 2.4 m by 12 m by 2.6 m. A doorway exists at 2.5 m from the entry and the floor toward the back of the cell is made from brick. Backing board lines the back corner including the roof as shown in Fig. 2. A small crib made from chipboard is used as the ignition source, lit with a blowtorch at the base, for approximately one minute. The crib consists of 16 particle board sticks with dimensions 295 mm $\times$ 38 mm $\times$ 15 mm stacked two at a time. A 0.6 m baffle exists 6.5 m from the cell entry and a vent 1.76 m by 0.59 m exists on one wall of the cell opposite to the crib (not shown in Fig. 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.

During CFBT training sessions, temperature data is routinely recorded. This data will be used for comparison with the CFD model, however as it is taken during real time live fire training no two data sets are identical.

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. Fig. 3 shows typical temperature plots for the CFBT cell during a training session, where thermocouple 1 (TC1) is located on the roof of the cell approximately one metre from the crib, thermocouples 2, 3 and 4 (TC2, TC3 and TC4 respectively) are attached to a wall on the same side of the cell as the crib and 300 mm closer to entry than the baffle, at 150 mm from ceiling, kneeling height and 150 mm from floor respectively. The different peaks and troughs are due to the spray of water into the air to cool the environment, making it safe for the fire fighters inside. Also the two data sets are taken when two different fire fighters were controlling the cell.

The temperature in the back portion of the room which contains TC1 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^{o}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 (TC3) do not exceed 150^{o}C.

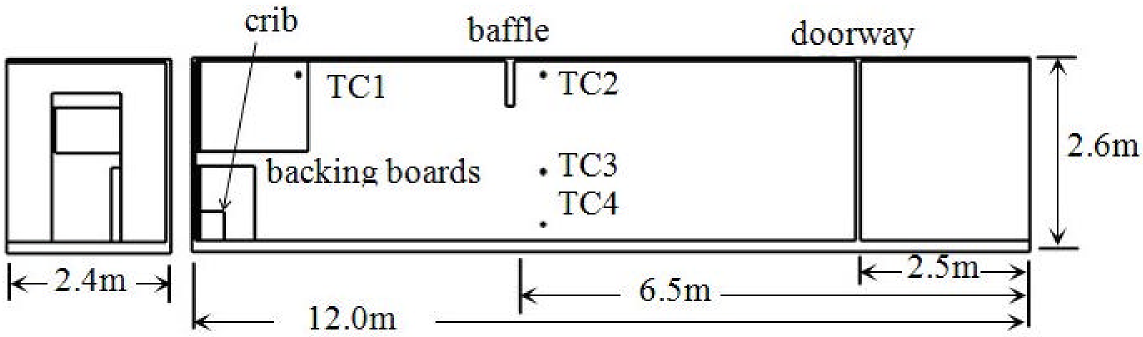
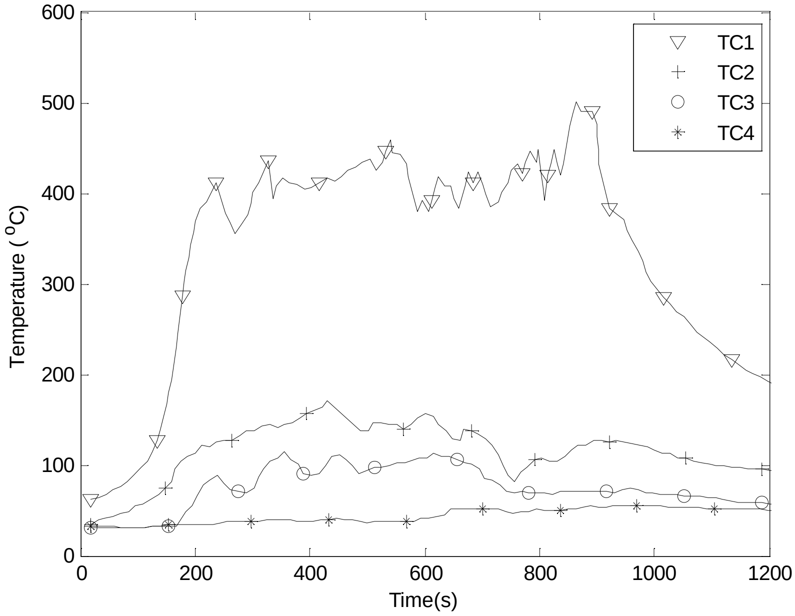


Fig. 2: CFBT demonstration cell



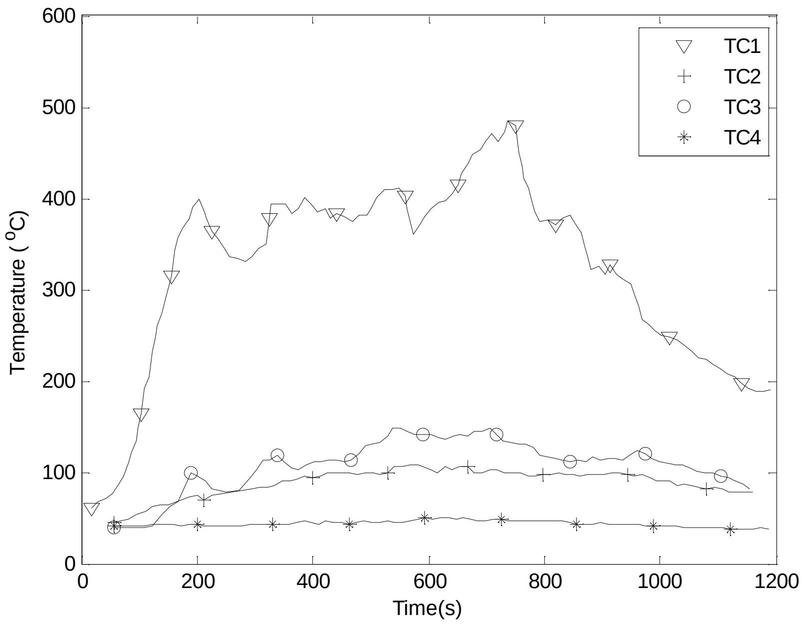


Fig. 3: NSWFB thermocouple graphs for the demonstration cell

3. THE NUMERICAL MODEL

Recently flashover has been modelled using CFD with some success [8-10]. Zou and Chow [11] 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. Merci and van Maele [12] also had good correlation between FDS and full scale tests in a small compartment with natural roof ventilation. They found the influence of the roof opening to only have a small influence on temperatures in the smoke layer. It is expected the current work will have a greater error than these studies because of the unpredictable nature of the crib as opposed to the pool fires.

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. The Smagorinsky model models the turbulent viscosity μ_{LES} as :

$$m_{LES} = r\left(C_s\Delta\right)^2\left|\bar{S}\right|$$

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

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

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 [5].

In this study, the crib was modeled as a solid block with boundary condition set as a heat release rate per unit area of 1200 kWm^{-2}, which ramps to full value in 700 s. As shown in Fig. 2, the back portion of the floor was modeled as brick which is the same as the demonstration cell. The backing board was modeled with similar material properties 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 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 result. Originally the boundaries were set to the confines of the demonstration cell and the computational domain was then extended 1 m 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 Fig. 2 was removed to determine the effect it had on temperature and time to flashover.

4. RESULTS AND DISCUSSION

4.1 Model Optimization

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. Fig. 4 shows a comparison of the temperature plots for the three grids for thermocouple 2. Significant differences can be seen in the 0.15 m and 0.1 m grids, however the 0.1 m and 0.075 grid are within 5% of each other which is considered to be in good agreement. Thermocouple 1 produced the highest difference between the 0.1 m and 0.075 m grids varying from 8 to 13%, however this is still considered to be adequate for determining fire behaviour.

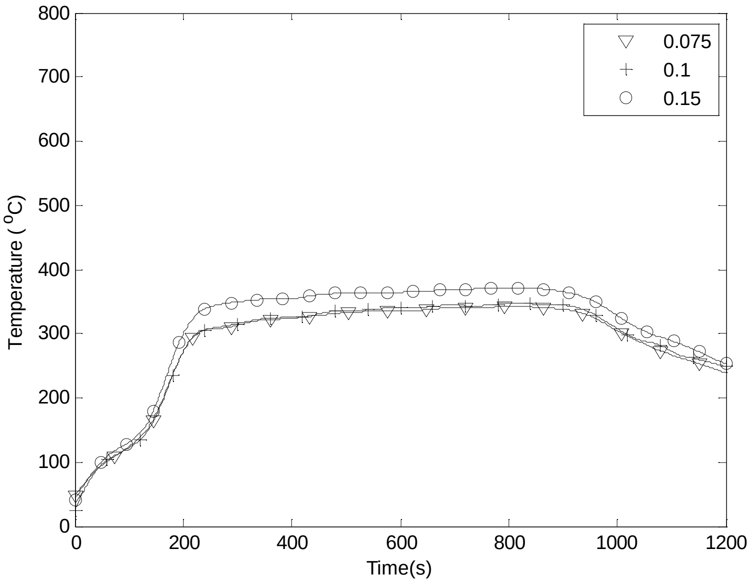


Fig. 4: Temperature profiles at thermocouple 2 for varying grid sizes

The placement of the computational boundaries was examined at three locations. In Fig. 5, Domain1, Domain2 and Domain3 refer to an extension of 2.5 m, 0.8 m and 0 m respectively of all domain boundaries. As can be clearly seen in Fig. 5, reducing the domain to only include the test 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 Domain1 and Domain2 and hence the domain was extended to 0.8 m for all subsequent cases.

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

4.2 Comparison with Expected Results

It is stressed that only general comparisons with the experimental data, shown in Fig. 3, can be made as fire suppression is taking place and this will result in lower temperatures particularly close to the floor. All CFD cases were solved with a 0.075 m grid and extended computational domain. If we take the ceiling temperature value of 600^{o}C to be representative of the occurrence of 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 s could be seen as a prelude to flashover which may have occurred at approximately 200 s.

Fig. 6 compares results from the computational simulation with the first of the NSWFB thermocouple readings. The FDS results shown in Fig. 6 increase steadily over the first 200 s and flashover (as taken to be when the temperature reaches 600^{o}C) occurs at 210 s. Peak temperatures of close to 650^{o}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 TC3 and TC4 are deliberately kept low for the safety of fire fighters. Fire suppression occurs in front of the baffle which is why the temperature for TC2 is significantly different between the experimental values shown in Fig. 3 and those in Fig. 6, however the general shape of the temperature curve is consistent with expected results. Since it is shielded by the baffle, the temperature in TC2 is expected to be considerably smaller than TC1. TC3 and TC4 do not reach temperatures greater than 100^{o}C, indicating that flaming combustion did not reach all the way to the floor.

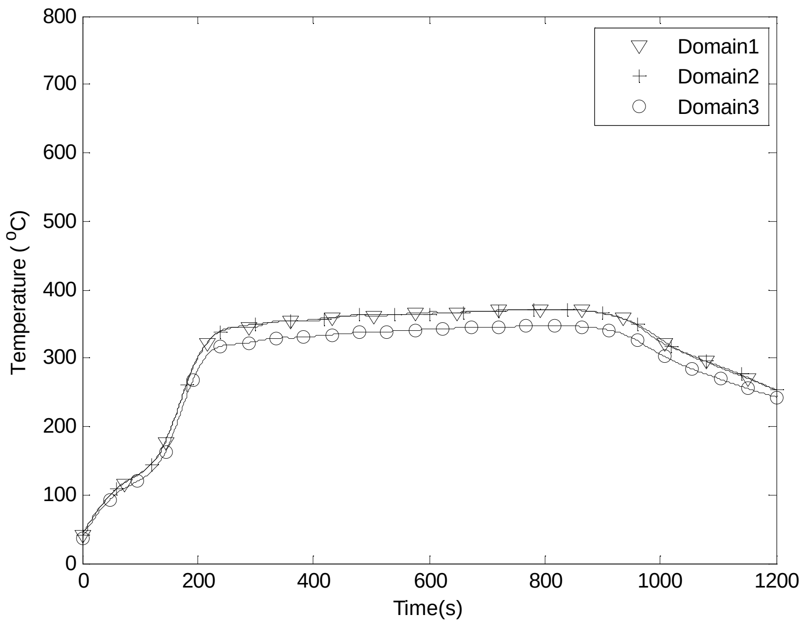


Fig. 5: Temperature profiles at thermocouple 2 for varying domain sizes

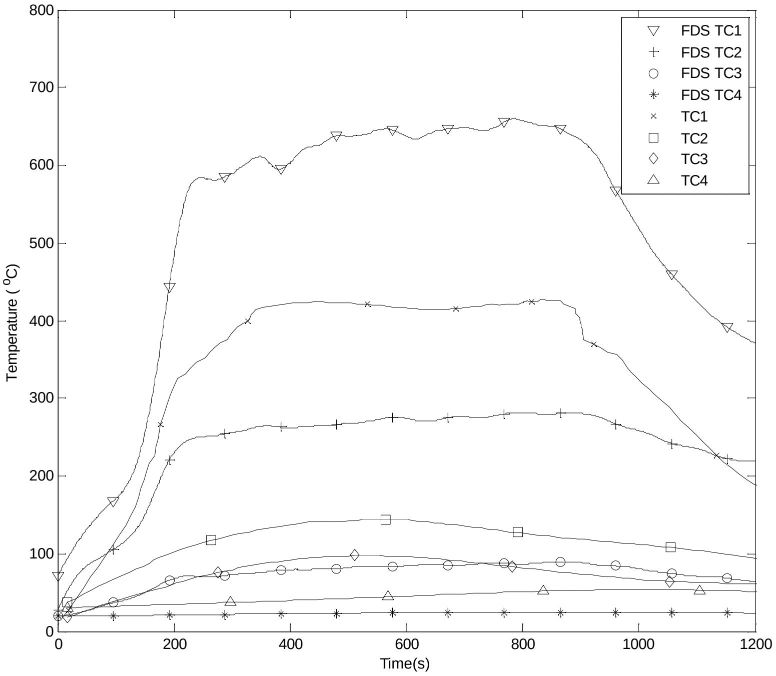


Fig. 6: FDS temperature profiles at four thermocouple locations

4.3 Effect of Ventilation

The model was solved under identical conditions as in the previous section, 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 1.76 m by 0.59 m and is located 1.7 m above the floor. Fig. 7 shows the temperature profiles for the same thermocouple locations.

Fig. 7 shows that with the vent in place, the required flashover temperature is not achieved. Maximum temperatures were maintained close to 500^{o}C Similar profiles are seen for thermocouples 1, 2 and 4 compared with those in Fig. 6, 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, as since no baffle exists to shield the thermocouple, it would be expected that the temperature would increase beyond 300^{o}C, however a maximum temperature of 290^{o}C is found after 550 s. 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. Due to the high aspect ratio of the compartment and the placement of the vent, a larger influence is observed by increasing ventilation than is shown in Merci and Maele [12].

4.4 Effect of Baffle

The baffle contains the smoke in the front portion of the cell until sufficient build up has occurred, and as with the vent the baffle can be removed. With the baffle removed a higher temperature were recorded by thermocouple 2 which reached 350^{o}C after 850 s, this is expected as it is no longer shielded. Fig. 8 shows a graphical representation of the temperature field one metre on the fire side of the baffle and one metre on the open side of the baffle. On the open side temperatures are far cooler and there is a gradual decrease in temperature until the lower cool layer is reached. However on the fire side of the baffle, the entire upper layer is close to uniform temperature with a severe drop in temperature at the bottom of the baffle. Comparison of thermocouple 2 in Figs. 7 and 9 highlight the reduction in temperature brought about by the introduction of the vent into the demonstration cell.

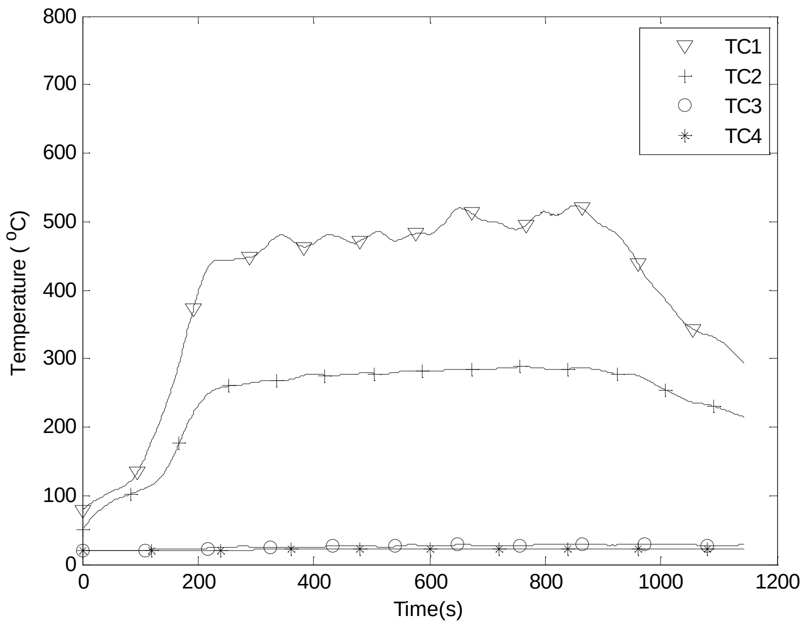
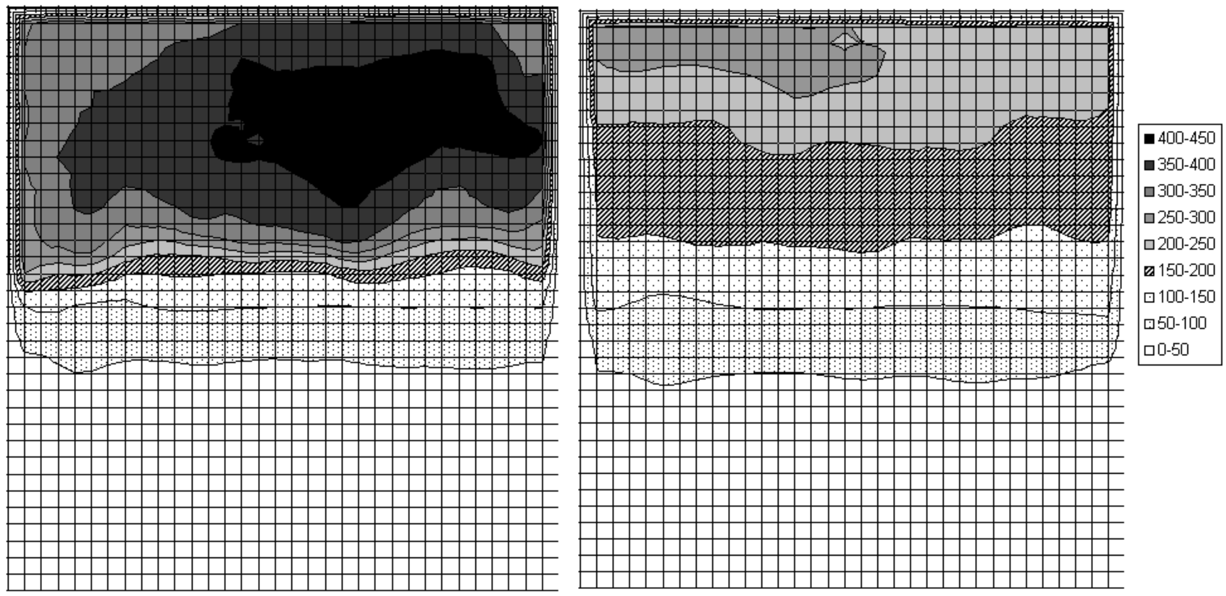


Fig. 7: FDS temperature profiles of the demonstration cell with vent open at four thermocouple locations



(a) On fire side of the baffle

(b) On open side of the baffle

Fig. 8: Graphical representation of the temperature field

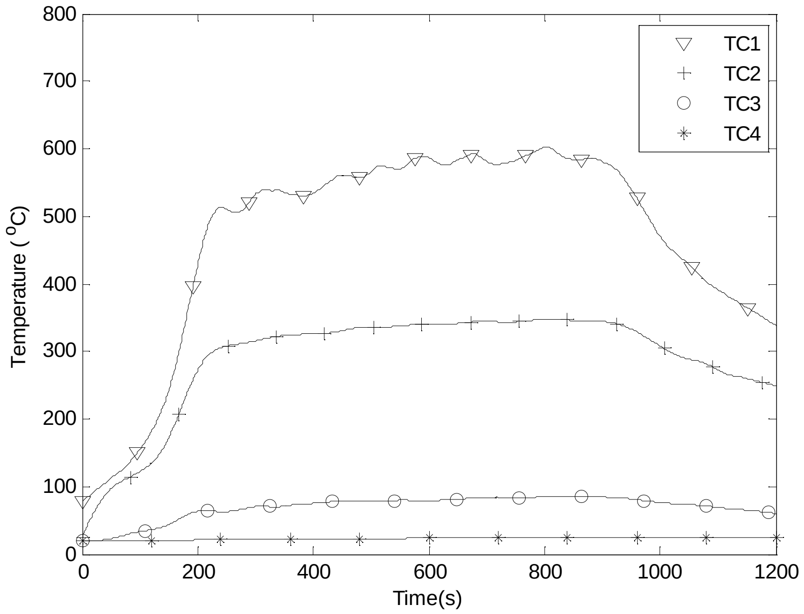


Fig. 9: FDS temperature profiles of the demonstration cell without the baffle at four thermocouple locations

5. CONCLUSIONS

Multiple simulations of the NSWFB demonstration cell were generated in order to optimise the grid used in the final cases. Grid independence is important in gaining confidence in a numerical simulation and it was found that a grid size of 0.075m with domain boundaries extended beyond the sides of the cell produced acceptable results.

It has been shown there was good agreement for the fire behaviour between qualitative experimental data and computational results. The FDS model produced temperatures up to 100^{o}C higher than the experimental data. However this was anticipated as small amounts of fire suppression were slightly cooling the upper smoke layer in the experimental results. Temperature profiles produced were in good agreement with experimental results and expected compartment fire profiles for fire development.

The baffle and vent had a measurable influence on the temperatures in the hot gas layer. The introduction of a vent was found to remove a significant amount of heat from the front portion of the room as expected. Removal of the baffle showed increased temperatures in the mid region of the demonstration cell which would have been otherwise shielded by the baffle. This demonstrates the effectiveness of using these modifications to the demonstration cell as well as qualifying their use for live fire training purposes.

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REFERENCES

1. T.L. Graham, G.M. Makhviladze and J.P. Roberts, “On the theory of flashover development”, Fire Safety Journal, Vol. 25, pp. 229-259 (1996).

2. T.E. Waterman, “Room flashover – criteria and synthesis”, Fire Technology, Vol. 4, pp. 25-31 (1968).

3. F.M. Liang, W.K. Chow and S.D. Liu, “Preliminary studies on flashover mechanism in compartment fires”, Journal of Fire Sciences, Vol. 20, pp. 87-112 (2002).

4. P. Grimwood, Firetactics.com. Website accessed July 2007. http://www.firetactics.com/

5. K. McGrattan, B. Klein, S. Hostikka and. J. Floyd, Fire Dynamics Simulator (version 5) user’s guide, National Institute of Standards and Technology, USA (2006).

6. K. McGrattan, S. Hostikka, J. Floyd, H. Baum and R. Rehm, Fire Dynamics Simulator (version 5) technical reference guide, National Institute of Standards and Technology, USA (2006).

7. G.P. Forney and K. McGrattan, User’s guide for Smokeview version 4 – A tool for visualizing Fire

Dynamics Simulator Data, National Institute of Standards and Technology, USA (2006).

8. M. Luo, Y. He and V. Beck, "Application of field model and two-zone model to flashover fires in a full-scale multi-room single level building", Fire Safety Journal, Vol. 29, pp. 1-25 (1997).

9. A.Z. Moghaddam, K. Moinuddin, I.R. Thomas, I.D. Bennetts and M. Culton, "Fire behaviour studies of combustible wall linings applying Fire Dynamics Simulator", 15th Australasian Fluid Mechanics Conference, Sydney, Australia (2004).

10. A. Hamins, E. Johnsson, M. Donnelly and A. Maranghides, "Energy balance in a large compartment fire", Fire Safety Journal, Vol. 43, pp. 180-188 (2008).

11. G.W. Zou and W.K. Chow, "Evaluation of the field model, Fire Dynamics Simulator, for a specific experimental scenario", Journal of Fire Protection Engineering, Vol. 15, pp. 77-92 (2005).

12. B. Merci and K. van Maele, "Numerical simulations of full-scale enclosure fires in a small compartment with natural roof ventilation", Fire Safety Journal, Vol. 43, pp. 495-511 (2008).