Numerical Simulation of Natural Ventilation Effectiveness in Removing Fire Smoke at Multi-Storey Car Park

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ABSTRACT

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A simulation study using Fire Dynamic Simulation (FDS) has been conducted on a simplified car park model. As this work aims to analyse the effectiveness of natural ventilation in the dissipation of smoke, all models' dimensions and opening size corresponded to the Uniform Building by Law (UBBL) 1984 requirements, which allowed the models to be without any mechanical ventilation system or alarm. The fire source is produced by a modelled car located at the centre of the building at the rate of 4MW. This is to represent a possible case within a car park area. Focuses were placed on the heat and hazardous gases produced by the car. The result shows that designs with different parameters exhibited different natural ventilation results for temperature and visibility at a preset height of 2.5m. Another critical observation was made on the smoke concentration and temperature outputs, which concentrated on the opening and tight corners. This is due to the inability of the heat flow to be removed from the building via natural ventilation. Therefore, this study reasonably concludes the importance of opening size and fire position with this simulation results and data.

Keywords: *fire dynamic; FDS simulation; natural ventilation; fire safety design*

INTRODUCTION

Modern buildings are becoming more complex to keep up with the latest changes in the industry. Nowadays, car parks are designed as a part of buildings. Design goals such as material optimisation, energy efficiency, sustainability, or architectural expression are constrained by fire safety regulations (Maluk et al., 2017). It is stated in the Uniform Building By-Laws (UBBL) Malaysia that there is no need for mechanical ventilation and sensors for buildings with a floor area less than $750m^2$ (International Law Book Service, 1984). Based on the "rule of thumb" for all designs under $750m^2$, the external wall's opening area must be greater than 40% of the total wall area. Designing smoke ventilation in a car park has the primary goal of allowing firefighters to approach the fire within a specific distance (Horváth et al., 2013). The concern for human survival during this situation is also vital. The smoke's visibility and temperature will prevent the occupant from fleeing the building effectively. The effects of CO and CO_2 must also be considered during evacuation and fire rescue. (Zhao et al., 2017).

Computational Fluid Dynamics (CFD) analytical tools are a great alternative to experimental setups. A reasonable simulation result is within 20% of the actual cases (Wang & Quintiere, 2009). CFD simulation allows complex designs to be analysed in depth. While some experiments, especially destructive tests like fire, cost much money, CFD has proven to be more cost-effective with acceptable results (Yau et al., 2003).

This study analyses the different percentages of a car park wall opening to smoke removal effectiveness. A 20 – 50% opening range was tested to identify which setting could fulfil the design requirement. Natural smoke ventilation inside a building can help to extend the Available Safe Egress

Time (ASET), which determines a person can escape a fire situation (Ghani & Aripin, 2018). For this case, a source of fire from the burning of a car with a heat release rate of 4MW was simulated inside the car park. The usage of Fire Dynamic Simulator as the tool for the analysis was considered the best option. It provides an excellent low-speed (Ma < 0.3) thermally driven flow suitable for smoke analysis and heat transfer. The simulated outcomes of temperature and visibility will be the focus of this paper. However, for this study, the research will be focusing on the already developed fire from the car as its primary fire source.

Based on the results obtained, a better understanding of the relationship between opening size percentage and smoke evacuation can be established.

METHODOLOGY

Building Design Modelling

This study has four case designs - Case I, Case II, Case III, and Case IV. The dimensions of the modelled structure are 18m x 18m x 4m, and the floor area is 324m^2. The surrounding and initial temperature of the car park is 27^{0}C, which is the same as Malaysia's average air temperature. Considering the worst-case scenario, no external airflow is simulated in this case study. The 4MW fire is in the model's centre. Because the simulation is in a parking lot, the heat release rate value is acceptable. No mechanical or forced ventilation was simulated, and only the natural ventilation system of the car park was considered. A car park's horizontal plane ceiling is modelled. Table 1 shows the Scenario 1 parameter settings. The opening walls were adjacent to one another. Each opening is reduced from 50% to 20% to test the effectiveness of natural ventilation.

Table 1: The parameter setting for all cases in Scenario

Case	Total Wall Opening Side	Wall Opening Percentage	Total Wall Opening (m^2)
I	2	50%	72
II	2	40%	57.6
III	2	30%	43.2
IV	2	20%	28.8

Prediction of the smoke behaviour

As the simulation was conducted, the sensor's location must be determined. Based on the result of the simulation, at the height of 2.5 m, the concentrations of all the measured parameters such as temperature, carbon dioxide, carbon monoxide, and the smoke area were observed to be accumulated highest at the corner in which the no opening was available (SCDF, 2018). This is due to the heat and buoyancy of the smoke produced. Figure 1 shows the general design of the structure. The location of car burning will be at the centre of the car park. All other simulations in Scenario 1 will follow the same design with differences only to the opening sizes. From the initial observation, the worst condition is predicted to be at the closed corner of the wall.

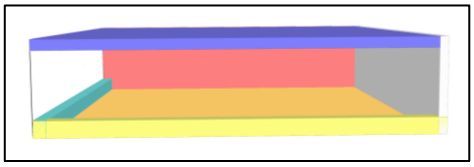
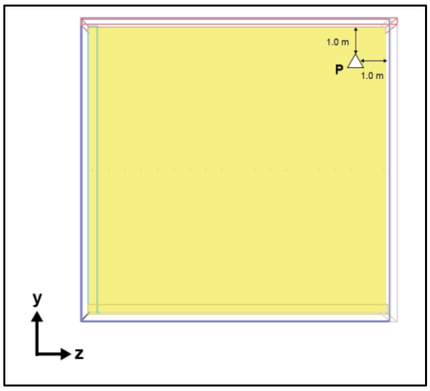


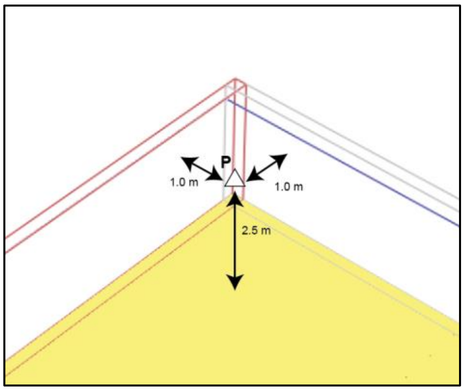
Figure 1: General 3D view of the design

Location of P

P is the sensor location where the temperature and visibility information were recorded. Figure 2(a) shows the location of P from the top view. The distance from the closed corner wall of the car park is 1.0 meters. P is at the closed corner of the parking area, which is 1.0m from both walls with a height of 2.5 m. Based on the study conducted in Malaysia, the mean height for Malaysian aged between 20-40 years old is around 165 cm (Lim et al., 2000). By referring to the UBBL, it does not state the minimum height of the design smoke layer. However, according to the SCDF in the Code of Practice for Fire Precautions in Buildings, the design of the smoke layer base must be above the heads of people escaping under it, which is 2.5m (SCDF, 2018). In this study, the readings of all parameters were taken according to this guideline.



(a) Top view of the location of P



(b) Isometric view of the position of P from the corner

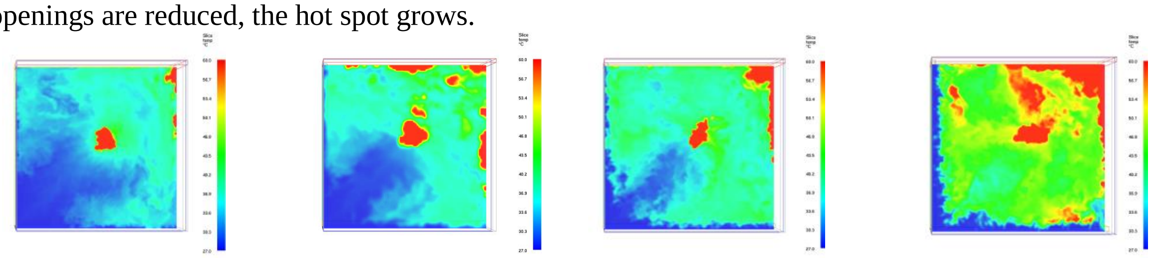
Figure 2: Location of P (a) Top View of the location of P (b) Isometric view of the position of P from the corner

RESULTS AND DISCUSSION

The result is presented in visualising the parameters measured at 600 seconds of continuous combustion and tabulated the time average for the relevant parameters.

Temperature Results Inside Car Park

Figure 3 shows the cross-sectional temperature results at 2.5m above the floor at 600s. The time taken at 600s is because the simulation is steady. As seen, the P is in the closed corner of the car park. The temperature rises as the opening size decrease from 50% to 20%. The high temperature is negligible at the car park corner in Case I. This indicates that the car park heat is adequately vented. However, as openings are reduced, the hot spot grows.



Case I: 50% Opening Case II: 40% opening Case III: 30% Opening Case IV: 20% Opening

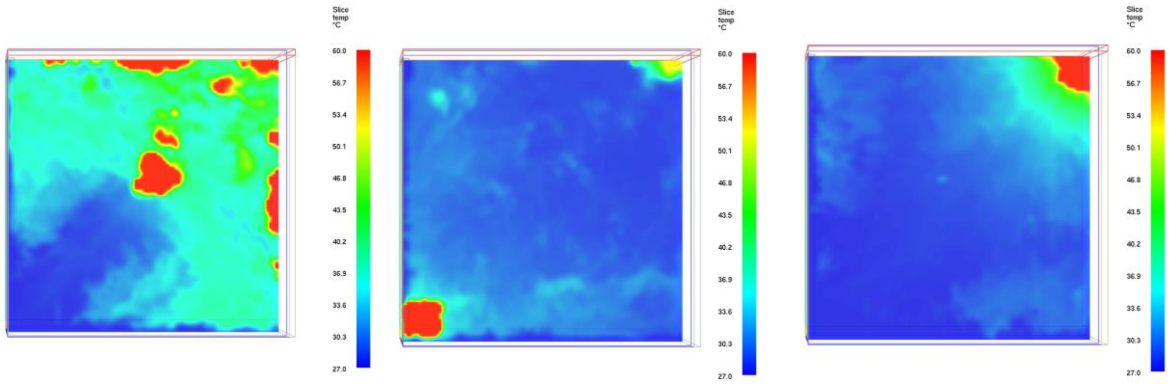
Figure 3: Scenario 1 - Temperature of the Car Park at 600s viewed at height 2.5m

If the temperature rises above 60^{0}C, it will lower the chances of human survival. Therefore, it is essential to ensure that the temperature is controlled below the limit. Table 2 shows the time average result for the above simulation on temperature. From the results shown in Table 2, only Case I has complied within the limit. As for Case II, which followed the recommended opening percentage by the UBBL is also failing. This has proposed that the natural ventilation strategy is unsuitable for cases II, III, and IV. An excellent natural ventilation system will probably remove the heat from the car park at reasonable rates. This shows that the openings are insufficient for heat to flow out and cold air to enter the car park.

Table 2: Result based on temperature limit of 60^{0}C

Time Average	Temperature (^{0}C)	Judgment
Case I	52.43	Pass
Case II	73.32	Fail
Case III	80.93	Fail
Case IV	93.17	Fail

To further investigate this result in Case II, another simulation was done. The position of fire is placed at different parts of the design. In Case V, the fire is put at the open corner of the car park, and for Case VI, the fire is placed at the closed corner of the wall. The results are shown in Figure 4. For Case V, the heat is removed from the car park model. However, small heat spots are generated at the location flows near the closed corner of the car park, which suggested that the dissipation of heat was not effective. In Case VI, the heat can be adequately removed as the heat flows outward towards the open corner of the car park. Since there is no obstruction, the temperature at the car park was found to be acceptable between 30^{0}C to 35^{0}C. This shows that in Case II, with the same opening as Case V and VI, placing the fire source at the centre causes the heat flow to be improper. This makes Case II fails, whereas Case V and VI pass.



Case II: Fire in the middle of the car park

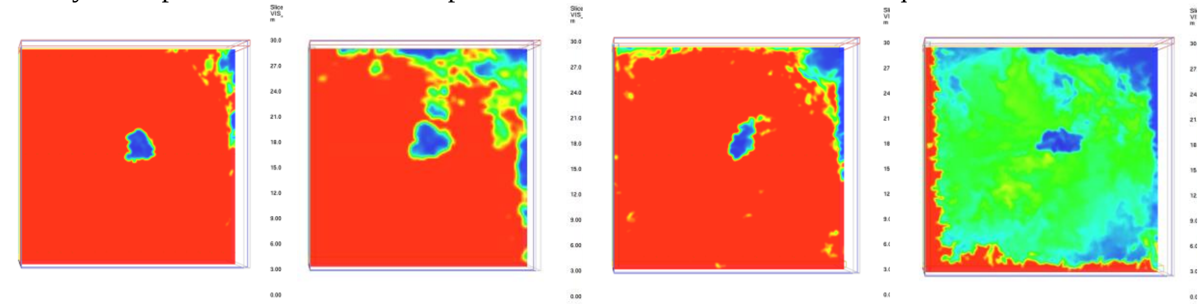
Case V: Fire at an opened wall corner of the car park

Case VI: Fire at a closed corner of the car park

Figure 4: Scenario 2 - Temperature of the Car Park at 600s viewed at height 2.5m

Smoke Behavior and Visibility Inside Car Park

By referring to Figure 5, the visibility also shows the same pattern as the temperature profile. The fire plume provides a hot space for the gases to float to the higher region of the car park and prevent it from dropping below and effect the person (Yau et al., 2003). So, keep burning fire sources to keep the smoke rising. However, as the temperature drops, the smoke dissipates, affecting visibility. The blue spot indicates poor visibility as the wall opening shrinks. Case I shows a good result because the area inside the car park is clear with a 30m visibility. Case II's blue spot, on the other hand, grew and merged into a more prominent place. This impaired one's ability to see clearly and locate the exit. Case III has the same result as Case II, with low visibility at the car park's close corner wall. Finally, Case IV shows significant observation due to poor visibility of 15m to 30m throughout the car park. This shows a poor opening that prevents smoke from exiting and clean air from entering. A 40 per cent opening was used to analyse the position of fire in both open and closed corners. The UBBL requires this.



Case I: 50% Opening Case II: 40% opening Case III: 30% Opening Case IV: 20% Opening

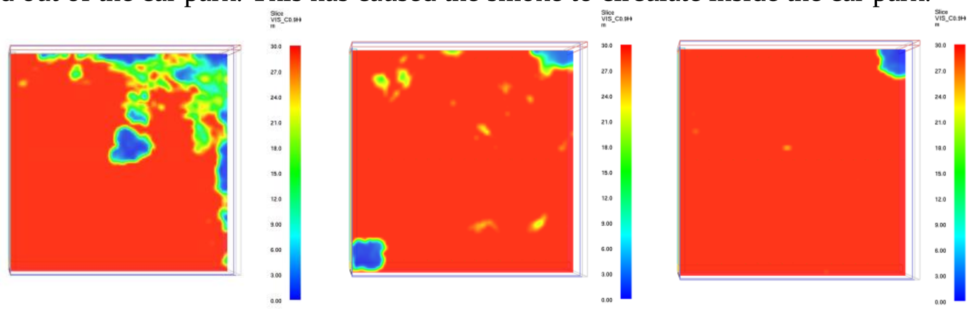
Figure 5: Scenario 1 - Visibility of the Car Park at 600s viewed at height 2.5m

Table 3 shows the average visibility at Point P. The result indicates that as the opening decreases, the visibility also decreases, with the worst being at 20%. At that state, the ability for a person to identify the signage and indicator toward the exit is affected as their vision is limited by the smoke. Therefore, it is vital to improving the condition by either creating more openings to allow the smoke to be ventilated out or introducing a mechanical ventilation system to help remove trapped smoke at Point P.

Table 3: Result of the average visibility at Point P

Time Average	Visibility (m)
Case I: 50% Opening	13.06
Case II: 40% Opening	5.99
Case III: 30% Opening	4.61
Case IV: 20% Opening	2.88

In Cases V and VI (Figure 6), the smoke can be removed effectively. In both cases, the red spot is significant. There is no visible blue spot of trapped smoke in the car park. Case II shows low natural ventilation capability with the exact opening size at 40%. The position of the fire restricts the flow of air into and out of the car park. This has caused the smoke to circulate inside the car park.



Case II: Fire in the middle of the car park Case V: Fire at an opened wall corner of the car park Case VI: Fire at a closed corner of the car park

Figure 6: Scenario 2 - Visibility of the Car Park at 600s viewed at height 2.5m

Figure 7(i) shows the temperature slice in the middle of the car park (y=0m). It shows that the smoke is concentrated near the car park's impenetrable wall. The smoke is thin on the open side of the wall. On the other hand, fresh air enters the car park from the opening area, as shown in Figure 7(ii). In contrast, in Figure 7(iii), the smoke accumulates at the close wall, increasing thickness and temperature.

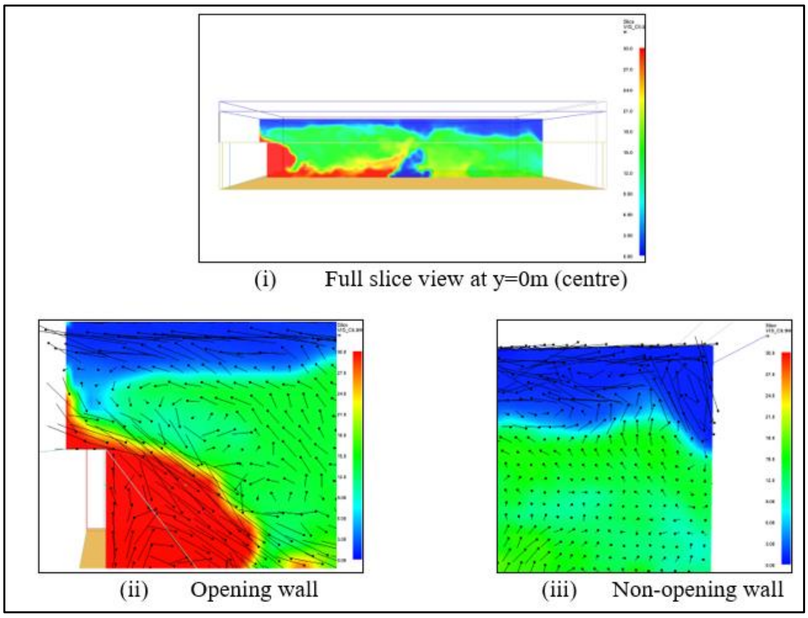


Figure 7: Close up temperature flow at (i) y = 0m (ii) Opening wall (iii) non-opening wall

The effectiveness of natural ventilation is determined by interpolating the results from Scenario 1 and 2. Figures 8 and 9 show temperature and visibility vs opening size. The result for temperature is linear, while visibility is exponential. However, the simulation did not account for the smoke's buoyancy and the fire release rate (Zhao et al., 2017). Based on the findings of this study, the UBBL parking guidelines must be more specific to address various Scenarios because the flow direction of smoke varies depending on the fire location.

CONCLUSION

This study examined the impact of wall opening size and fire position on the UBBL-recommended natural ventilation design. In Scenario 1, only Case I, where the opening is 50% at two walls, met the simulation's constraints. Case I has a maximum temperature of 52.43^{0}C and a visibility of 13.06 meters. Both parameters were limited to the UBBL requirements of 60^{0}C and 10 meters. So, the temperature and visibility results are over the limit.

In Scenario 2, the output was compared to the fire position. Cases II and V have the same results, with the same fire position and 40% opening two walls. In Scenario 1, Case II's result is unsatisfactory because it exceeds the limit. However, in Scenario 2, moving the fire results in a different outcome. In Scenario 1, the measured point is at P, which is at coordinates x = 8.0m, y = 8.0m, z = 2.5m. Since the measured point in Case VII is at X, the measured point in Scenario 2 must be changed. These three cases had significant differences in the slice view at 2.5 meters. Temperature and visibility are significantly lower in Case VI and VII than in Case V. This shows that the UBBL's 40 per cent opening design can also meet the limitation depending on the fire position. As a result, the results of this study have shown that increasing the opening size of the wall allows for better natural air circulation, removing heat and other pollutants. However, this also depends on the fire size that influence the rate of temperature rise (Li et al., 2013). The position of fire can also result in the effectiveness of natural ventilation. Heat and harmful substances cannot be effectively removed from the car park if the fire hinders the airflow.

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