Journal of Applied Engineering and Technological Science
Vol 4(2) 2023: 644-654

ANALYSIS OF FIRE SIMULATION ON POLYURETHANE FOAM USING FDS IN A UNIVERSITY MEETING ROOM

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Received : 11 January 2023, Revised: 19 February 2023, Accepted : 05 March 2023
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ABSTRACT
The polyurethane foam material is commonly used and marketed in two forms, namely flexible and rigid. Flexible foam is used as a cushion, with various applications for commercial products such as chair support. Therefore, this study aims to describe the occurrence of a fire situation in a university room filled with many polyurethane foam chairs. It also aims to provide awareness regarding potential flame hazards, by using a fire modelling method with FDS. The results showed that fires on PU foam materials produced a high HRR and a wide spread of flame and smoke. From this context, the harmful effects of the fire on the room occupants were emphasized. The results obtained are expected to support the theory of compartment fire, flame distribution in solid materials, PU Foam inferno behaviour, etc. It is also expected to provide additional fire protection and evacuation training for room occupants.
Keywords : *FDS, Fire, Smoke, HRR, Foam*

1. Introduction

The occurrence of fire is very possible in all buildings and often causes death, injury, property loss, and environmental damage (Buchanan & Abu, 2017; Novanandini et al., 2021; Nyankuru et al., 2017). According to the National Fire Protection Association (NFPA), a total of 1,353,500 fires occurred within the U.S. in 2021, causing an estimated $15,957 million in direct property loss (Hall & Evarts, 2022). This show that direct property loss is one of the main signs used to measure the severity of a fire (N. Wang et al., 2022). A university comprises numerous buildings primarily designated for educational purposes, with others serving as offices. Based on SNI 03-3989-2000, these buildings were classified as light fire hazard dwellings, due to their low thermal quantity and ease of burning. In this case, minimum heat is often produced during a fire outbreak, leading to slow flame distribution (BSN, 2000). Although the structures are classified as light fire hazard residences, lecture buildings still need to be highly considered for active and passive fire safety. As with other disasters, everyone should also importantly increase their knowledge of fire hazards from various media (Wijaya et al., 2022). Moreover, the influence of the building environment workers' on risk management has been identified, including the uncertainty of fire hazards (Pramudya & Andesta, 2022). From these descriptions, buildings are required to maintain prescriptive or performance-based safety specifications, to protect human life and property according to fire protection regulations (Himoto & Suzuki, 2021). In the NFPA, educational buildings need to have the necessary installation of extinguishers, due to the involvement of many people in the class activities (National Fire Protection Association., 2015).

Based on the understanding of light fire hazard housing, heat release and the distribution rate of flame are highly emphasized through simulations, by using the FDS (Fire Dynamics Simulator) software. This software commonly simulates a fire scenario through a pre-designed technical approach, within a predetermined time. It is also used to simulate fire in highly populated areas with various construction structures, such as in a theatre (M. Y. Wang et al., 2008; Wu et al., 2008), supermarket (Ling & Kan, 2011), compartment (Matheislová et al., 2010; Thomas et al., 2007; Zhang et al., 2010; Zou & Chang, 2005) or building (Date & Material, 2004; Horová et al., 2013; Hwang et al., 2010). In a previous study, the speed of fire spread was influenced by wind direction and the location of the initial source (Nanda, 2016; Setyadi et al., 2021). Ria Sari also stated that the number of fuel sources, the motor distances, and the compartment system affected the speed of fire distribution during an outbreak (Hidayah, 2016).

To extinguish fires in buildings, active protection is found to be very useful and necessary. This protection form includes standardized sprinklers, which greatly assist in the inferno suppression process. These descriptions are in line with the analysis of Fajar Septian (Septian, 2017), with subsequent observation aiming to determine the influential levels of various factors on different conditions. Therefore, this study aims to describe the occurrence of a fire situation in a university room filled with many polyurethane foam chairs. It also aims to provide awareness regarding potential flame hazards, by using a fire modelling method with FDS

This study was conducted by modelling a fire in the meeting room, namely the L2 building of the Faculty of Engineering, due to its very large capacity. From this context, the fire was modelled for 30 mins in a room of 40 people. The HRR obtained from each simulation was also emphasized, accompanied by the visualization of the fire and smoke distribution. Although various materials were in the room, limitations were considered for the performance of this analysis. In this case, concrete, wood, and polyurethane foam were the materials used in the fire modelling data. Polyurethane foam is used as a fuel due to its high flammability, compared to other materials. This foam was the most abundant material in the room, leading to the possibility of continuous fire distribution. Data related to material properties were also obtained from the FDS documents. For the ignition source, the emergence of fire from the chair seat was assumed by inputting the HRRPUA data with the SURF_ID parameter. Therefore, a 0.1 m mesh with good resolution was used to enhance FDS processing, as shown through Smokeview.

This study is grouped into several categories, with Sections 1 and 2 emphasizing the introduction and various related literature reviews, respectively. Sections 3 and 4 also presented the experimental methods, as well as described the results and discussion of the analyzed fire modelling, respectively. Meanwhile, Section 5 focused on the conclusions obtained for the outputs of the experiment.

2. Literature Review

Compartment Fire

Compartment fire is used to describe a flame situation confined within a building (Drysdale, 2011). This is because most fires often originated in closed building spaces, with some previous reports showing that more combustible room materials led to higher construction load during flame outbreaks (Laszlo et al., 2022). The following are the stages of flame development during a compartment fire hazard.

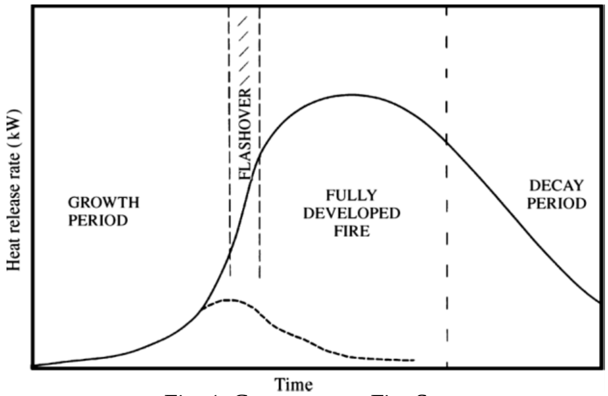


Fig. 1. Compartment Fire Stage

Based on Figure 1, the course of fire in a well-ventilated compartment was the rate of heat release with time. The dotted lines also represented fuel depletion under various conditions, such as pre-flashover occurrence, limited ventilation situations, and reduced burn rate due to oxygen drop level (Drysdale, 2011). During the development stage, the fire increased from a small to a large level involving the entire room. At the fully developed stage, the entire room and its contents were then engulfed in flames. This was accompanied by the decay phase after the consumption of the available oxygen (Davie County, 2018).

Spread of Fire in Solid Materials

Several factors were found to affect the rate of flame spread over combustible solids (Friedman, 1977). For the chemical material factors, fuel composition and the presence of retardants were observed, while the physical variables contained the initial temperature, surface orientation, propagation direction, thickness, thermal capacity and conductivity, density, geometry, and continuity. Various environmental factors also included the atmospheric composition and pressure, temperature, imposed heat flux, and air velocity (Friedman, 1977) .

Heat Release Rate

Heat Release Rate (HRR) is used to quantitatively describe the size of a fire during an inferno (Drysdale, 2011). This indicates that the HRR of the burning material is measured in kilowatts (kW) when the combustion reaction produces heat (Babrauskas, 2016a). From this context, four small-scale calorimeters are generally used, namely the Ohio State University, the cone, the fire propagation, and the microscale combustion (Janssens, 2016). The cone calorimeter is the commonly used small-scale instrument, due to being able to determine other parameters such as effective combustion heat, mass loss rate, ignitability, smoke and soot, and toxic gases (Babrauskas, 2016b). The following is one of the HRRPUA (Heat Release Rate Per Unit Area) measurement performed through a cone calorimeter complying with ISO 5560 standards on polyurethane foam material (Park & Kwark, 2021).

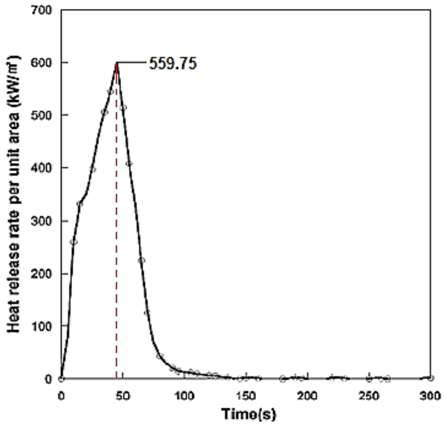


Fig. 2. HRRPUA for Polyurethane Foam

Based on the Figure 2, the HRRPUA of the PU foam material was 559.75 kW/m^2. These data are subsequently in this present study as a source of ignition applied to the surface of objects.

Polyurethane Foam Material

Polyurethane (PU) foam material is commonly used and marketed in two forms, namely flexible and rigid. The flexible PU foam is characterized by interconnected pores of small size and irregular shape (Huang et al., 2015). According to Federico and Alberto, flammability was evaluated through a horizontal flame spread test, by comparing three types of PU foam materials. This indicated that two of the materials were coated with three elements, namely PAA/MMT, PDAC/BOH, and APP/MMT. Meanwhile, the uncoated PU foam was easily ignited by methane fires (Carosio & Fina, 2019). The combustion of polyurethane often decompose and produce several hazardous materials, such as CO and HCN (McKenna & Hull, 2016). The following is the general mechanism of the polyurethane decomposition process (T et al., 2011).

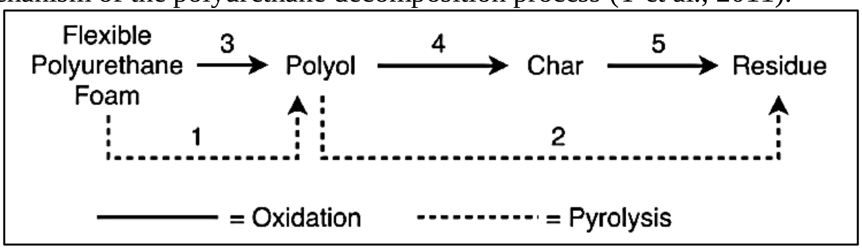


Fig. 3. Polyurethane Decomposition Mechanism

Fire Dynamics Simulator

Fire Dynamics Simulator (FDS), is a CFD (computational fluid dynamics) of fire-driven fluid flow. This simulator numerically solves a specific Navier-Stokes equation suitable for low velocity (Ma < 0.3), thermally-driven smoke flows, and heat transfer from fires (K. McGrattan et al., 2020). Furthermore, turbulence is treated through Large Eddy Simulation (LES), with possibility observed for the performance of DNS (Direct Numerical Simulation) when the underlying numerical mesh is appropriate. In LES technique, the large eddies are also resolved, with only the effect of the small forms being modelled (Merci, 2016). For most of its applications, FDS subsequently employs a combustion model based on limited mixing and infinitely fast reactions of the incorporated species (K. B. McGrattan et al., 2020). In addition, Smokeview is a separate visualization program used to display FDS simulation outputs. This shows that FDS and Smokeview are mainly used to model and visualize fire phenomena at varying periods (Forney, 2020).

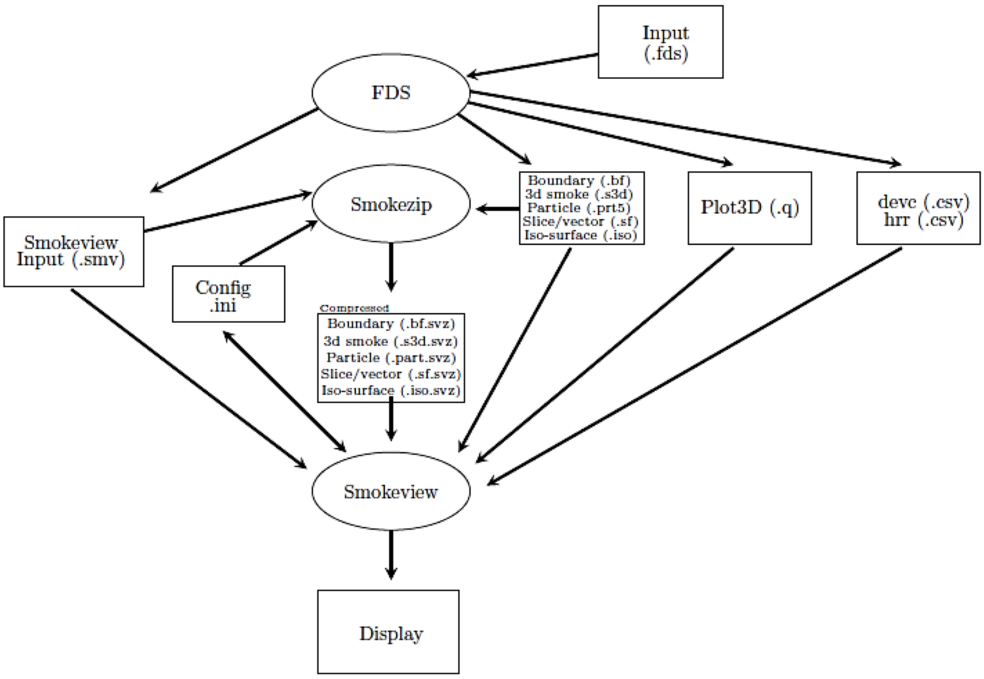


Fig. 4. FDS workflow

3. Research Methods

This qualitative study modelled fire scenarios on PU foam materials by using FDS (Figure 4). At the beginning of the experimental process, a preliminary analysis was conducted to select the sample room. This was accompanied by the identification of the experimental location problems. Literature study was also carried out to support the determination of appropriate methods, regarding the solution of the identified problems. In addition, data were obtained from various observations, such as the room size, the materials and their values, etc.

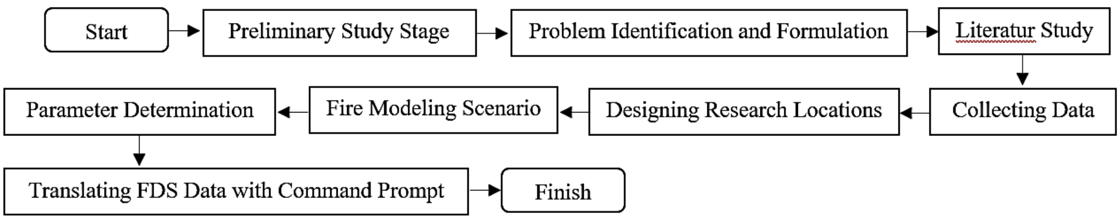


Fig. 5. Study method flowchart

The design of the experimental location was carried out after the data collection stage, with the analysis focusing on modelling the meeting room, L2 building, Faculty of Engineering, Jakarta State University. In this case, the room was modelled with a size, area, and height of 7.2 x 12.4 m, 89.28 m^2, and 3 m, respectively. This was accompanied by the determination of the initial fire location source, which is important due to being a determinant of the subsequent inferno development. From this context, the material used as fire modelling fuel was the polyurethane foam employed for meeting room chairs. This showed that a large amount of fuel material in one room was considered to potentially be the main cause of the fire distribution. In this model, the selected chair had a seat size and height of 40 x 50cm and 70cm, respectively. Its shape also emphasized the two cushion chair in a book written by Vytenis Babrauskas and John Krasny (Krasny & Babrauskas, 1985). Based on these various factors, two fire models were carried out with different starting points. The following is a summary of the fire analyzed modelling process.

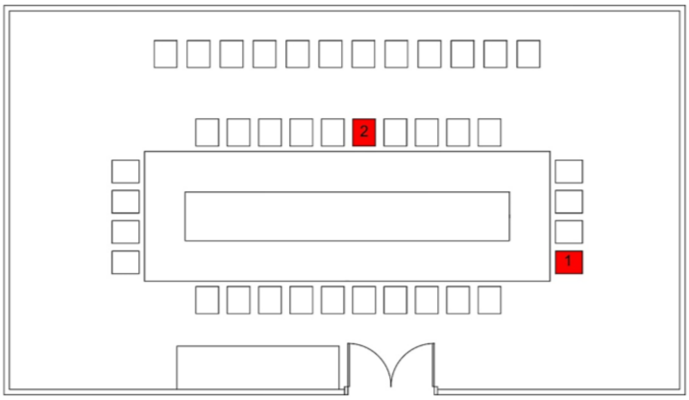


Fig. 6. Location of Starting Point of Fire

From various surveys, the most common sources of residential fires were cooking, incendiary, open flame, smoking, electrical equipment, or the heating system (Ocran, 2012). Based on assumption, the fire originated from excessive current in the power cable near the fuel material, triggering a spark after the wire sheath was released. When the fire modelling began at 0 s, the burning of the material was observed. This proved that air entered and exited the process through doors and ventilation openings, respectively. In this case, 8 ventilations were observed, with 4 of them each leading to the front and back of the building. Based on assumptions, the front and rear openings were 0.6 m x 1.2 m and 0.9 x 1.2 m when the vents were completely opened, respectively. However, the air flow through the window was not velocity determined, leading to a natural atmospheric condition. Air was also assumed to have passed through the door at a speed of -1 m/s, with the entrance size being 1.6 x 2 m. From this study, a fire was subsequently simulated for 1800 s or 30 mins, through a 0.1m mesh. The following is the material data used in this experiment (Babrauskas, 2016a; Drysdale, 2011).

Table 1 - Material Data

Parameters	PU Foam	Concrete	Wood
Specific Heat	1	0.88	2.38
Conductivity	0.1	1.4	0.17
Density	40	2300	800
Reference Temperature	280		
Heat of Reaction	800		
Heat of Combustion	22700		12400

After all data were written to Notepad, the next step focused on the command prompt on the desktop when installing FDS.

4. Results and Discussions

In this section, the fire simulation outputs in two scenarios was presented. Based on the first scenario, the heat release rate was emphasized.

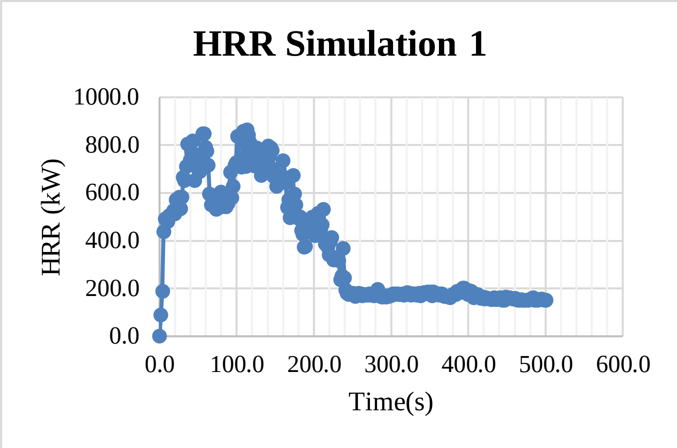


Fig. 7. Chart HRR simulation 1

From Figure 7, an enlarged graph of Simulation 1 was observed1, regarding the heat release rate. This proved that the HRR value increased rapidly, reaching 437.7 kW within 5.4 s from the commencement of the simulation. At 55.8 s, the HRR value increased until the first peak of 848.6 kW, before drastically experiencing a drop to 531.6kW at 73.8 s. Furthermore, the value increased until the highest estimation of 864.1 kW was achieved at 113.4 s. The existence of these two HRR peaks emphasized their association with the foam combustion on the horizontal chair seat. This was cited from the analysis of Mowrer and Williamson, where composite products and materials exhibited complex combustion behaviour, which produced more than one HRR peak (Hopkin et al., 2019; Mowrer & Williamson, 1990). After the peak point at 113.4 s, the HRR value slowly decreased until the end of the simulation, indicating the adjustment of the fire from the fully developed period to the decay time.

In the decay period, the HRR value did not reach 0 kW, proving that the fire had been completely extinguished. This was caused by the burning material producing char, with the existence of heat still observed. At 244.8 s, this value was at the transition point to the decay period due to being constant. From 500 to 1800 s at the end of the simulation, the HRR value still fluctuated between 150.5 and 157.2 kW. Besides the HRR data display, FDS visually showed the spread of fire and smoke through smokeview. Figures 8 and 9 indicates the spread of fully developed fire and smoke, where the entire room and its contents were engulfed by the inferno. When no attempt is made to extinguish the fire, combustion continues until the consumption of the fuel and/or available oxygen in the room or area (Davie County, 2018).

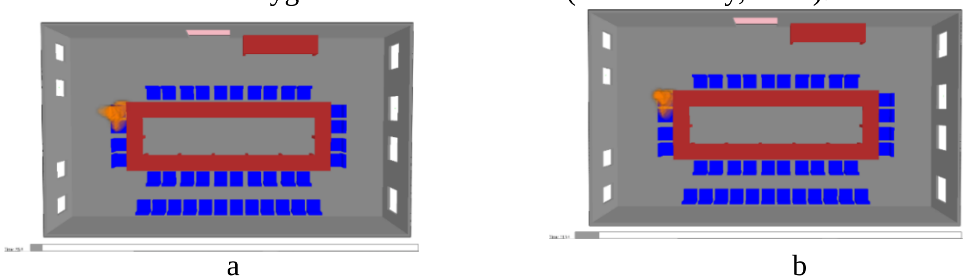
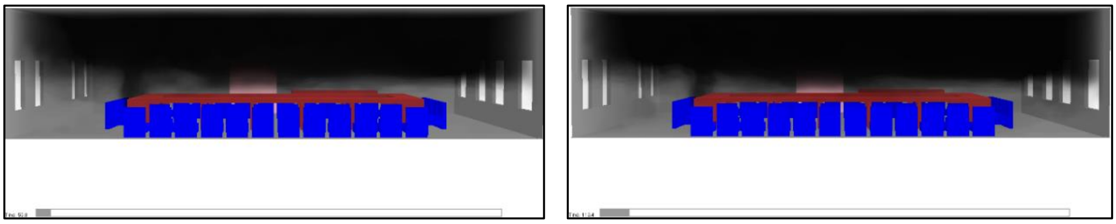


Fig. 8. Fire spread at seconds a. 55.8 and b. 113.4

Based on Figure 8, the fire distribution expanded at 55.8 s. This indicated the spread of the fire to a close chair and the ceiling in Simulation 1. Meanwhile, the fully developed period was reached in 113.4 s, where the flame spread to a chair next to the starting point of the combustion. Regarding these results, the fire activities in this simulation had twice the fully developed period, although some differences were observed between both inferno times, considering the HRR value and the temperature. From 244.8 to 1800 s, no fire spread was observed in the two simulations, as the flame only smoldered the starting point of the combustion. These conditions confirmed that the fire had reached a cooling or decay period. In line with the spread of fire, the following is a visualization of the smoke distribution.



a b

Fig. 9. Smoke spread at seconds a. 55.8 and b. 113.4

A small rise in the temperature or dispersion of smoke is capable of causing damage to specific building components, such as non-structural members, equipment systems, and stored items with relatively low fire resistivity (Himoto & Suzuki, 2021). During Simulation 1, the smoke in the corner of the room ascended to the ceiling before colliding with the left wall and descending downwards. This proved that the smoke moved very fast until 55.8 s, where it covered the entire ceiling of the room. Meanwhile, the thick smoke filled almost half of the room at 113.4 s. At the end of the simulation, the smoke gradually dissipated and thinned out from its previous thickness. This phenomenon was found at 244.8 to 1800 s, where the smoke gradually dissipated and accumulated close to origin of the fire. After completing the first simulation, the next step was to display the data and visualization outputs of the second fire model, as shown in Figure 10.

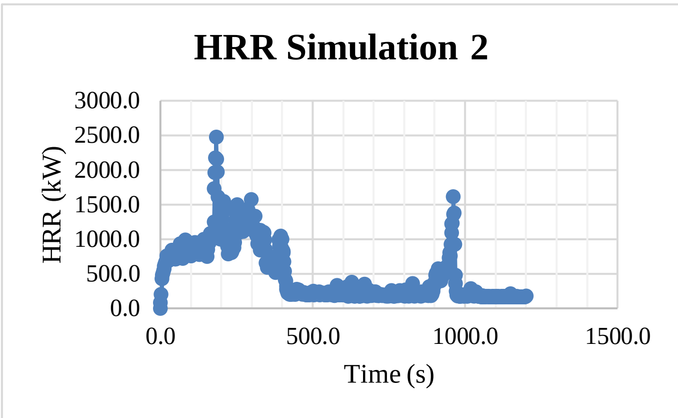
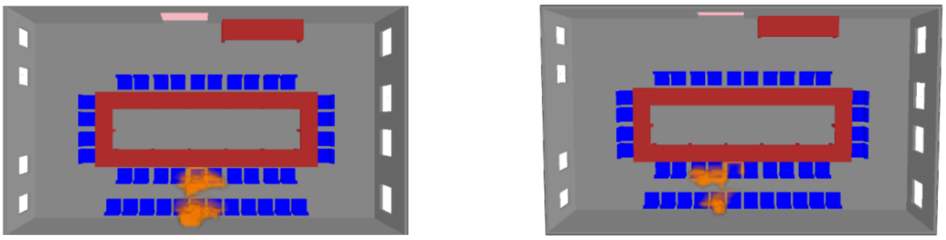


Fig. 10. Chart of HRR simulation 2

Figure 10 showed an enlarged graph of Simulation 2 output, where the heat release rate indicated a very large HRR value. Similar to Simulation 1, this value increased rapidly in the first few seconds, with 431.5 kW achieved at 5.4 s. The HRR value also increased until 2471.04 kW at 183.6 s, accompanied by a gradual decrease ranging from 205-210 kW at 423 to 891 s, respectively. After this drop, a short-term surge of 1609.3 kW was found at 961.2 s. Besides the influence of the material, as explained by Mowrer and Williamson, the second peak of HRR was also obtained from the combustion of unburned chairs. This indicated that the HRR value increased rapidly due to a new ignition or fire propagation in a different direction. At 975.6 s, this value entered the final stage of the fire after gradually decreasing from the second HRR peak. In this case, the HRR value slowly decreased and did not possess a large difference. Meanwhile, the values of 182.7, 173.6, and 160.5 kW were observed at 1200.6 to 1800 s.

From Figure 10, the fully developed period at 183.6 s was observed. This confirmed that the spread of fire in Simulation 2 was wider than Model 1. Figure 11 shows the inferno distribution in Simulation 2, where the 3 parallel and 3 rear seats close the starting point of the fire were burned due to the direction of the wind. Based on these results, the spread of fire was wider in Simulation 2 than Model 1.

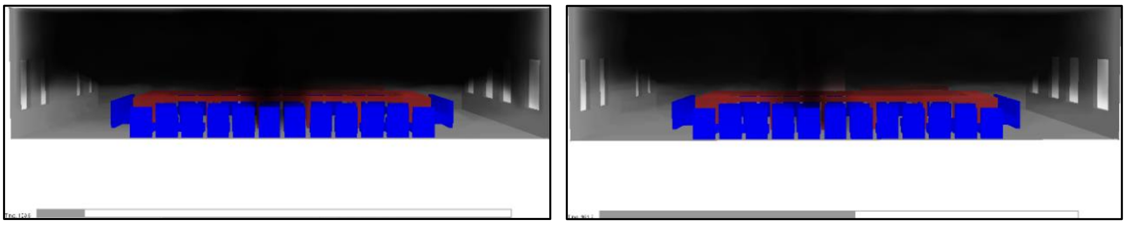


a b

Fig. 11. Fire spread at seconds a. 183.6 and b. 961.2

In Figure 11b, the fire distributed in a different direction from the previous distribution, indicating the spread to the left of the initial combustion point. In this case, the fire burned the 2 parallel and 2 rear seats to the left part of the initial flame source. This led to the observation of two fire ignition peaks, which were not higher than the previous HRR peak at 183.6 s.

From 183.6 s to 1800 s, no fire propagation was observed, as the conflagration was confined to the seat of origin, which had become charred. Under these conditions, the fire had reached a cooling or decay period.



a b

Fig. 12. Smoke spread at seconds a. 183.6 and b. 961.2

Based on Figure 12, the thickness of the smoke was in line with the spread of the fire. This indicated that the smoke was thicker and widely distributed in Simulation 2 than Model 1. This was because the fire spread wider and burned more chair material, leading to the emission of more smoke.

Discussion

From this result, the highest heat release rate was achieved in about 3 mins. This was in line with a similar study with a larger scale, where a school building fire modelling and HRR peak production was achieved in 3 mins (Antonov & Borisov, 2018). Despite having similar time, the HRR value in the previous simulation was almost five times higher than the estimation of this present study. This was because the experiment was conducted at a 4-storey school, which had more flammable materials for the fire to emit greater heat. In another previous study, a compartment fire analysis was carried out in a small cinema hall (Valasek & Glasa, 2017). This employed three simulation materials, namely wall concrete, chair upholstery, and the inert material for other surfaces such as the door, stage, etc. The results confirmed that FDS provided reliable smoke dispersion simulations, as well as obtained and visualized the specific phenomena emerging during cinema building fires. From the simulation, a safety threat was provided to the audiences sitting or standing in different locations within the cinema (Valasek & Glasa, 2017).

Based on the meeting room outputs, the highest total HRR reached 852.1 kW in the second scenario within the first minute of the fire analysis. This was not in line with the cinema hall analysis, where the maximum total HRR value achieved in the first minute was 416.23 kW. In addition, the arched ceilings and sloping doorways significantly contributed to increased safety risks for seated or escaping individuals, even during the first minutes of a fire (Valasek & Glasa, 2017). From these various previous results, the Fire Dynamics Simulator (FDS) realistically visualized infernos. Despite the various outputs, reports are yet to be found with 100% similarities regarding fire scenarios, due to specific difference. This suggests that regardless of the similarities in the input data, the large amount of information influencing each of the developed fire scenarios led to the acquisition of distinct outputs.

5. Conclusion

Based on the results, FDS visually presented the occurrence of flames through fire or smoke dispersion. This indicated that the starting point influenced the spread of fire and smoke. The location of the flame origin surrounded by flammable materials and sufficient air supply also led to a high HRR value. Moreover, the achievement of outputs when the HRR value had two peaks was triggered by the burning of different chairs. This was in line with Mowrer and Williamson, where the occurrence of fire was related to the burning of foam on horizontal chair seats, as well as composite products and materials exhibiting complex combustion behaviour capable of producing more than one HRR peak.

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