Analysis of Fire and Smoke Spread in Ki Hajar Dewantara Auditorium, State University of Jakarta, Using Fire Dynamics Simulator

Pratomo Setyadi, Ariq Harits Arrizq*

Department of Fire Safety Engineering, Faculty of Engineering, Universitas Negeri Jakarta
Jl. Rawamangun Muka RT.11/RW.14, Jakarta Timur, 13220, Indonesia
**Corresponding author: ariqharits27@gmail.com*

Article history:
Received: 3 March 2023 / Received in revised form: 4 May 2023 / Accepted: 7 June 2023
Available online 22 June 2023

ABSTRACT

Fire behavior and smoke spread are influenced by various factors, including the amount and condition of combustible material, ventilation openings, and ceiling height. A high amount of combustible material in the auditorium poses a significant fire hazard, hence, efforts need to be made to minimize the risk. One approach is to use Computational Fluid Dynamic software, such as Fire Dynamics Simulator (FDS), to model fire combustion. In this research, it provides an overview of the heat release rate (HRR) of fires that occur as well as the effect of differences in ceiling height and the effect of ventilation on fire spread. This research employed Polyurethane foam, commonly used for auditorium seats, as the sample material. Furthermore, it modeled two fire points, one on the 9th floor and the other on the 10th floor, in the middle of seat rows. The development of fire in the modeling was described by the results of visualization, HRR, burning rate, and temperature rise. These results provided insight into the speed at which fire and smoke spread. The starting point on the 9th floor had the highest flame spread rate due to the ceiling jet phenomenon, where a high amount of combustible material caused the ceiling temperature to increase, producing a heat flux that could burn surrounding seats. In both scenarios, the smoke spread rapidly toward the ventilation openings. However, it was denser on the 9th floor as the starting point was farther from the ventilation openings, and the smoke on the 10th floor was less dense.

Keywords: *Auditorium, ceiling, FDS, HRR, polyurethane foam, temperature, ventilation*

I. Introduction

According to the Decree of the State Minister of Public Works with Number 11/KPTS/2000 concerning Technical Provisions for Fire Management in Urban Areas, the auditorium falls under fire hazard risk classification 4. This classification signifies a high fire hazard risk due to the presence of a large quantity and content of combustible materials [1]. Based on data from the DKI Jakarta Provincial Statistics Agency, 429 buildings caught fire in 2020. A significant number of these fire incidents were caused by electrical disturbances or cigarette butts [2]. Unfortunately, fire has recently occurred in Indonesia, particularly in auditorium, including the RRI Auditorium Building in Jember in 2022 due to an electrical short circuit [3], the Nusa Cendana University Auditorium in Kupang in 2021 due to an electrical short circuit [4], and the PPOP Ragunan Auditorium Building in Jakarta in 2019 caused by cigarette [5]. Based on the magnitude of activities and losses resulting from fire, it is imperative to take measures to prevent its outbreaks by understanding the characteristics of fire and smoke spread. Some of the factors influencing the characteristics of fire and smoke spread include combustible material, structure, air openings, etc.

DOI: 10.17977/um016v7i12023p076

With the development of technology, a device called the Fire Dynamics Simulator (FDS) can be used to determine the characteristics of fire and smoke spread during its occurrence in a particular location. This device provides information on the rate of heat release, smoke spread, and temperature, which enables the prediction of the potential fire phenomenon and can also help in conducting a review of the fire safety aspects of the auditorium. Previous research supported the use of this technology, for example, Valasek and Glasa (2017) modeled a fire in a cinema or auditorium with an area of 12 m x 16 m for 60 seconds. It was found that the temperature continued to increase beyond 370°C within 20 seconds, and the reat release rate (HRR) reached 400 kW, while smoke filled the ceiling of the room [6]. Huang et al. (2018) discovered that the HRR in a cinema can reach 10.000 kW within 900 seconds, and the polyurethane foam material poses a significant danger [7]. Research on this phenomenon, flame spread in motorcycle parking areas compiled by Nanda Yola, concluded that the wind and the starting point of the fire can affect the speed of its spread [8]. The research conducted by Ria Sari, difference in fuel location, indicated that the number of combustible material sources, the distance between them, and the compartment system influenced fire spread [9]. This practical engineering approach allows the modeling of fire, which provides valuable insights into the level of danger posed and an additional review of the safety aspects of Ki Hajar Dewantara Building Auditorium.

This research was conducted by modeling a fire in the Auditorium of Ki Hajar Dewantara building, due to its very large capacity and various activities. In this research, it will provide an overview of the HRR of fires that occur as well as the effect of differences in ceiling height and the effect of ventilation on fire spread. 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, gypsum, polypropylene, acoustic panel 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. In addition, this research will describe the level of fire hazard and fire spread caused by differences in ceiling height. and will present the difference in full development time due to differences in fire location with ventilation.

This research is grouped into several categories, Section 1 described the introduction and objectives of the research. Section 2 presents the experimental method, and section 3 describes the results and discussion of the analyzed fire modeling. Meanwhile, Section 4 focuses on the conclusions obtained from the experimental results.

II. Material and Methods

1. Research Method

This qualitative research modeled a fire scenario involving Polyurethane Foam chairs in Ki Hajar Dewantara Auditorium, State University of Jakarta, using FDS software is shown in Figure 1. At the beginning of the process, a preliminary analysis was conducted to select the room to be modeled. This was supported by identifying the problem with the experimental location. To support the determination of appropriate methods for solving the identified problems, a literature review was also conducted. Additionally, various observations, such as room size, materials, and their respective values, were obtained.

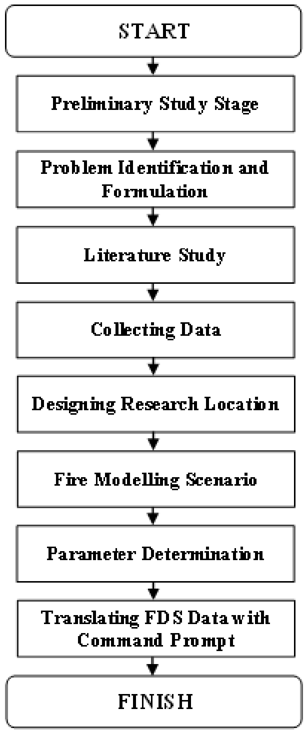


Fig. 1. Research Method Flowchart

FDS is a Computational Fluid Dynamics (CFD) model that utilizes numerical modeling to solve the Navier-Stokes equations applicable to low-velocity fluid (Ma<0.3), smoke, and heat movement flow caused by fire [10]. On the other hand, Smokeview is FDS companion program that can generate images and animations from FDS literacy results. In recent years, this program has advanced to be able to realistically visualize fire and smoke [11].

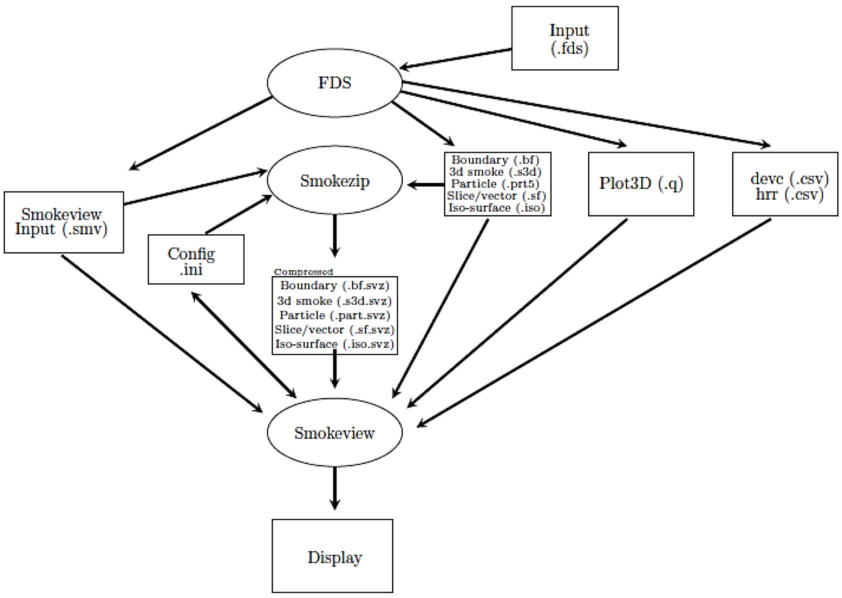


Fig. 2. FDS workflow

Figure 2 gives an overview of how data files used by the NIST Fire Dynamics Simulator and Smokeview are related. A typical procedure for using FDS and Smokeview is to : (1) Set up an FDS input file, a file with a .fds extension (e.g., a file named "casename.fds"). (2) Run FDS. (e.g. by typing fds < casename.data at a command line). The fire model FDS then creates one or more output files with extensions .smv, .part, .sf, .q, .bf, .iso . These files are the Smokeview file, particle file, slice file, Plot3D file, boundary file and isosurface file, respectively. (3) Run Smokeview to analyze the output files

2. Mesh

Meshing is the process of dividing the fluid component to be analyzed into small and discrete elements [12]. In FDS, the mesh was calculated based on several parameters, namely the total HRR (Q), air density (p∞), gravity (g), ambient temperature (T∞), and the specific heat of the air. Due to the large diameter of the fire and the HRR that could vary over time, the mesh produced was relatively coarse. However, the mesh could be refined by considering the size of the combustible material or obstruction in the modeling, leading to a smaller mesh size without reducing the resolution of the object [10].

$$D *= \left(\frac{\dot{Q}}{\rho\infty \; C\infty \; T\infty \; \sqrt{g}}\right)^{\frac{2}{5}} \quad \ldots\ldots(1)$$

In this scenario, data with a domain of 24 m x 14 m x 11 m were used for mesh modeling, and it consisted of a Total HRR (Q) of 559 kW for Polyurethane Foam material, measured using a cone calorimeter that met the ISO 5560 standards [13]. The air density (p∞) at normal temperature and not exceeding 50 km above the surface was 1,293 kg/m³ [14], and gravity (g) was 9.81 m/s². The initial temperature in the room, or ambient temperature (T∞), was 301 K. The calculation showed that the maximum mesh that could be used with a relatively coarse resolution was 0.19 m. Due to the size of the room modeled, the rendering process took a long time, implying that a mesh with a relatively coarse resolution of 0.15 m was used to determine the possibility of fire phenomena occurring. It is crucial to note that the rendering process for this model took up to 2 months.

3. Modeling

The State University of Jakarta auditorium had an area of 432 m² and a height of 11 m. The walls were 0.2 m thick, and there was only one inlet air ventilation opening measuring 2 x 0.7m, as well as three outlet air ventilation openings measuring 0.5x0.5 m. Fire in the modeling was assumed to occur during the day when the doors were closed, and there were no people inside. According to the ignition handbook, the fire could be caused by several sources, including cooking equipment, heating equipment, electrical, smoking materials (cigarettes), or other factors such as negligence and arson [15]. In addition, previous fire incidents in the auditorium were caused by electrical and cigarette sources [3] - [5].

The chair geometry was assumed to be 0.5x0.5 m in size with a depth of 1.5 m, and the straight rows of chairs did not follow the original slope because FDS software could only model objects with straight or rectilinear geometry. The chair material was made of polyurethane foam and followed the modeling geometry standard specified, with a two-cushion chair shape [16].

The determination of the starting point of fire was crucial and was based on certain criteria that posed the highest level of risk in the event of fire outbreak. According to the fire triangle theory, the presence of oxygen and combustible materials were the primary factors that contributed to the growth of fire. Furthermore, Drysdale and Macmillan reported that fire spread could be significantly exacerbated by blocked airflow caused by walls [17]. Since this building housed numerous people, the accessibility of the exit route was a critical consideration when determining the fire modeling scenario for the starting point of the fire. Consequently, the fire modeling scenario for this origin is described in Table 1.

Table 1. Fire Modeling Scenario

Scenario	Starting Point of Fire	Model Name
1	Close to the exit and in the middle of a row of seats on the 9th floor	Modeling 1
2	Close to ventilation and access doors and in the middle of a row of seats on the 10th floor	Modeling 2

4. Data Collecting

Polyurethane foam was the recommended choice for combustible material due to its highly flammable nature compared to other materials and also because of the limitations of FDS, which could only simulate one combustion reaction at a time. Additionally, polyurethane foam fell under the category of fast-spreading materials [18]. HRR experimental calculations discovered that a polyurethane foam chair could burn completely in less than two minutes [13], [19]. The material data used are highlighted in Table 2.

Table 2. Material Data

Material	Specific Heat	Conductivity	Density	Reference Temperature	Heat of Reaction	Heat of Combustion
Concrete	0.880	1.40	2300			
Polypropylene	1.9	0.24	940			43300
Wood	2.38	0.17	800			19500
Acoustic Panel	1.0	0.06	200			18965
Foam	2.0	0.04	100	295	847	27000
Gypsum Plaster	1.0	0.50	500			

Source: [17],[19],[20]

After all, data had been recorded in Notepad, the command prompt that appeared on the desktop during FDS installation was used.

III. Results and Discussions

1. Data Analysis of Fire Modeling I

Heat Release Rate

The Figure 3 is the HRR in Fire Modeling 1. Modeling 1 showed the stages of fire, which included growth, flashover, full development, and decay. The figure also supported the discovery of Drysdale that in a compartment of fire with limited ventilation, the full development period was shorter than the ones with sufficient ventilation [17]. This was due to the depletion of combustible material or oxygen, which reduced the combustion rate. The

HRR in Figure 5, the growth period occurred from 5 to 574 seconds, with a range of 45-700 kW. The pre-flashover period in this modeling took longer because the smoke layer temperature, concentration, and HRR reached a quasi-steady state [21],[22]. When the conditions were sufficient, a flashover occurred, leading to a significant increase in heat due to the concentration of monoxide, which reached a peak of up to 70,000 kW. During the post-flashover or decay period, the HRR returned to a quasi-steady-state phase but did not reach 0 kW. This was because the burning combustible material was still generating heat, and the combustion continued until the combustible material and oxygen available in the room were exhausted [22].

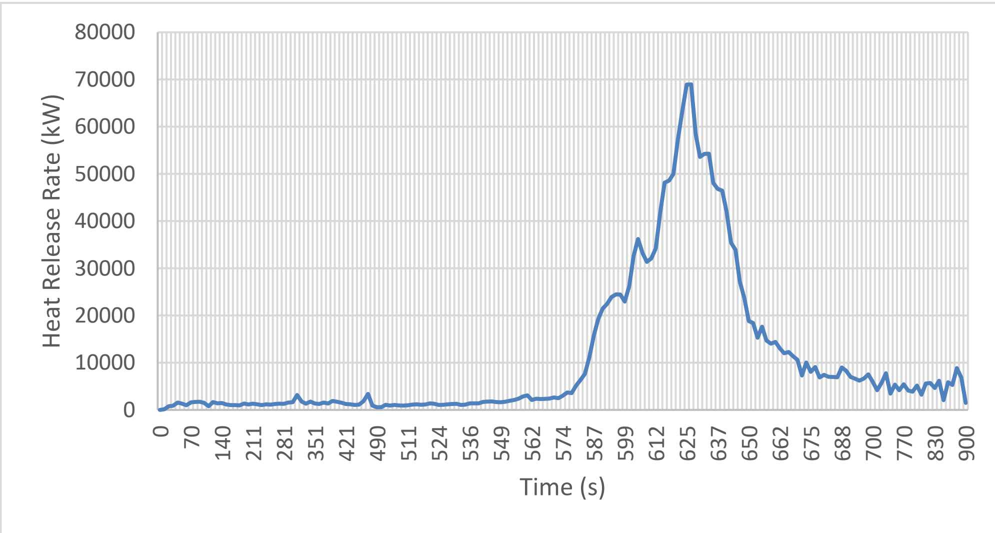


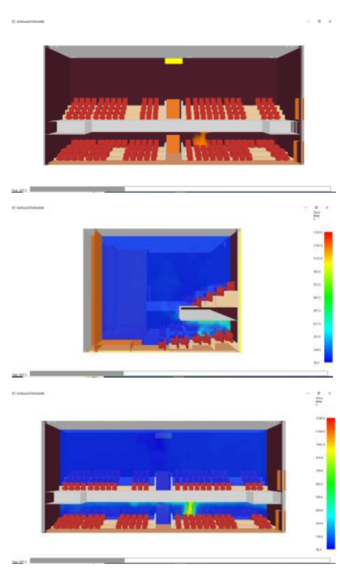
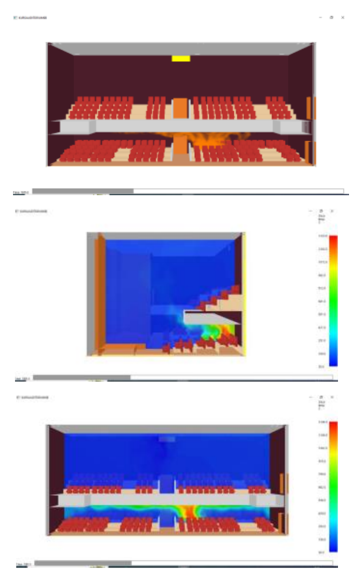
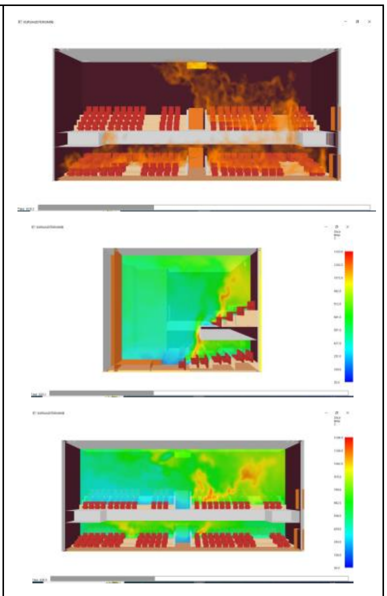
Fig. 3. HRR Graph of Modeling 1

Fire and Smoke Spread

In Table 3, it was observed that the fire spread followed the shape of the ceiling. The fire occurred on the 9th floor, with a ceiling height of 2.7 m. In a multi-story building with a low ceiling height, the fire could rapidly spread from the floor to other open rooms [21].

Table 3 shows the final phases of the ceiling jet, namely the Pre-Flashover and Post-Flashover Vented periods. During the Pre-Flashover period, the smoke layer had descended to fire source and suppressed it due to oxygen depletion in the smoke layer. Conceptually, smoke is the residual combustion product of pyrolysis or a hot plume. At 585 seconds, as the smoke continued to accumulate, the temperature significantly increased because the smoke layer temperature around the ceiling had reached a critical value of around 600°C [22]. This temperature increase caused a heat flux of 20 kW/m, igniting objects with surfaces directly facing the smoke in a short time in the room [20]. At 630 seconds, the fire reached the Fully- Developed HRR period at its peak, where unburned gas had accumulated on the ceiling, causing flames and heat in the compartment ranging from 700°C-1200°C. In the absence of any extinguishing efforts, fire tended to burn continually until the available combustible material and oxygen had been exhausted [23]. When the vent opening had not contained sufficient oxygen, fire entered the Decay period. The HRR decreased proportionally to the decrease in oxygen concentration, but the temperature continued to increase for some time because the compartment contained smoke from the combustion pyrolysis, which had a high concentration and heat and could become a new combustible material [24].

Table 3. Fire Spread in Modeling 1

Spread			
Sec.	565	585	630

The visualization of the smoke spread in line with the fire is presented in Table 4.

Table 4. Smoke Spread in Modeling 1

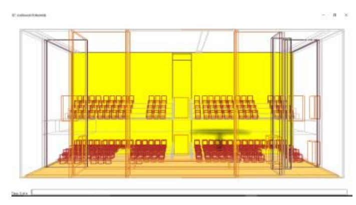
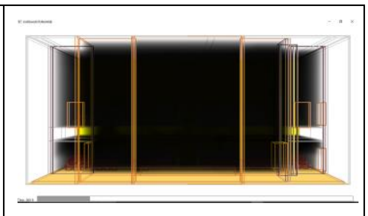
Spread			
Sec.	5	100	630

Table 4 shows how quickly the smoke spread, contributing significantly to the destruction of specific building components, such as structures, equipment, and stored goods with low fire resistance [25]. Within the first five seconds of fire plume/ceiling jet, the smoke moved horizontally along the shape of the ceiling, and the buoyant gases spread radially beneath the ceiling in a relatively thin layer. After hitting the wall at 100 seconds, the smoke began to turn downward, accumulating under the ceiling until it pressed towards the fire source, with some of the smoke moving towards the 10th floor. At 630 seconds, the smoke had filled the entire room, and its temperature had risen to 600°C, causing the post-flashover phase and igniting surrounding objects on fire [20].

2. Data Analysis of Fire Modeling 2

Heat Release Rate

The HRR in Fire Modeling 2 (Figure 4) shows the HRR value rose from 50 kW to 5000 kW between 5 to 238 seconds, and also increased rapidly to 1300 kW at 259 seconds. The HRR peak point in this modeling occurred at 410 seconds, with HRR exceeding 30,000 kW.

This was followed by a decrease to 10,000 kW at 432 to 900 seconds. Notably, during this decrease, there was a brief spike due to the complex combustion behavior of the polyurethane foam composite material [26], [27].

Figure 4 also validated the discovery of Drysdale (2011) that compartment fire with sufficient ventilation or close to its source had a longer fully-developed phase. In Modeling 2, the fully-developed phase occurred between 260 to 432 seconds, with an HRR range of 12000-3000 kW. This was in contrast to Modeling 1, which had a relatively short fully-developed period of 60 seconds. The time from the growth period to flashover was shorter, taking only 250 seconds compared to Modeling 1, which took up to 560 seconds. Although the HRR in Modeling 2 was not higher than in Modeling 1, the fire did not spread through the ceiling because its height on the 10th floor was higher than on the 9th floor [21].

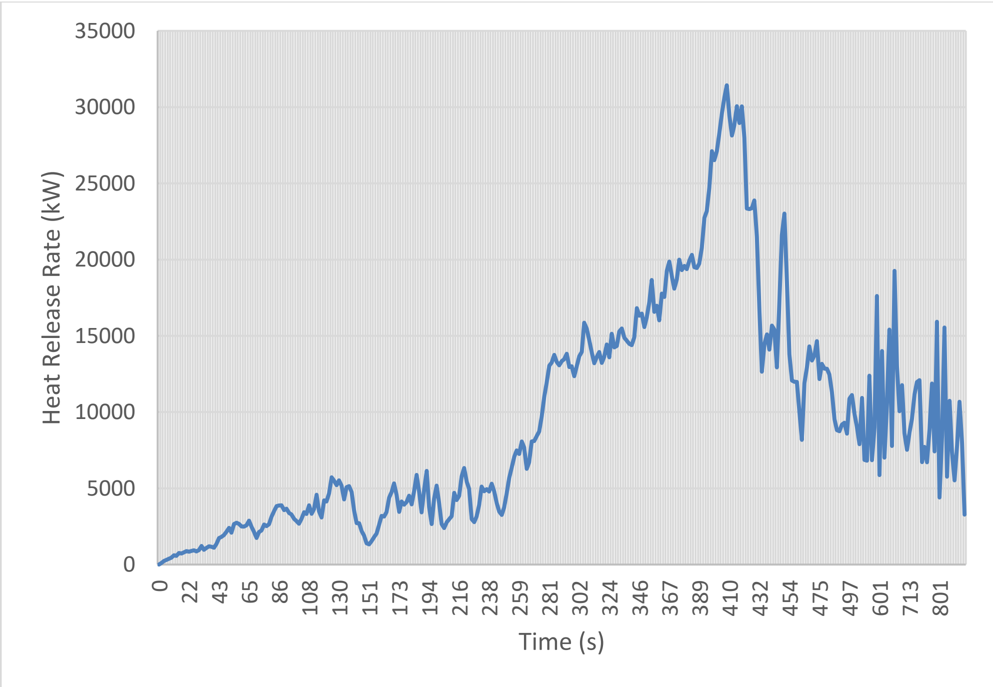


Fig. 4. HRR Graph of Modeling 2

Spread of Fire and Smoke

In Table 5, the distance between fire source and the ventilation was relatively small, and the ceiling height was 5.5 m. In the event of fire, the spread was not extensive and could be contained within the room or only spread to the area adjacent to its source [21]. In this scenario, fire tended to move towards the chair that was higher than the burning chair, then spread towards the wall and reached the ceiling. Although the temperature of fire reached 700°C, it did not spread to burn all the seats on the 10th floor due to the ceiling height being high enough to prevent heat propagation.

In Table 6, the speed and density of smoke accumulation were only observed on the 10th floor, which was different from Modeling 1 where smoke rapidly filled the entire auditorium with high density due to the proximity of ventilation to fire source. The smoke was emitted through the roof opening, and at 5 seconds, the thin smoke reached the ceiling, continuously growing until it covered the ceiling on the 10th floor along with the number of burning seats. The smoke continued to build up and filled the 10th floor until 500 seconds.

Table 5. Fire Spread in Modeling 2

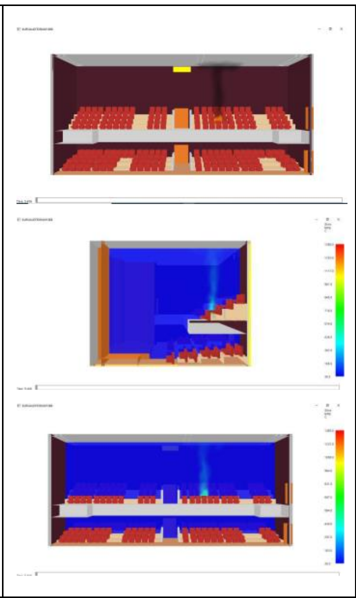
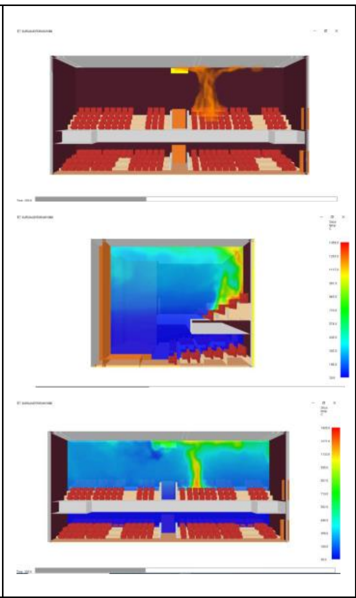
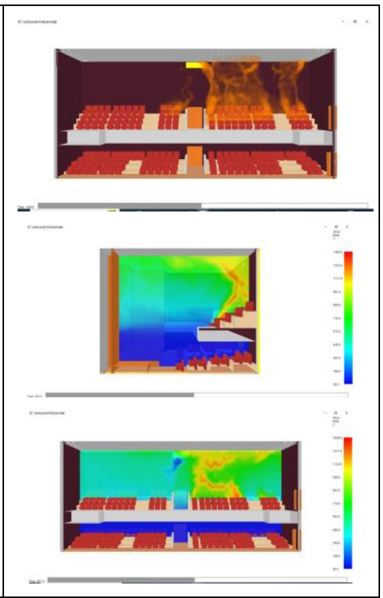
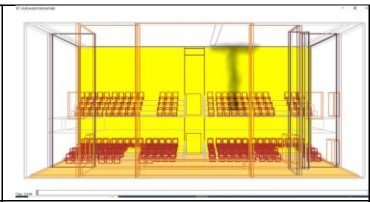
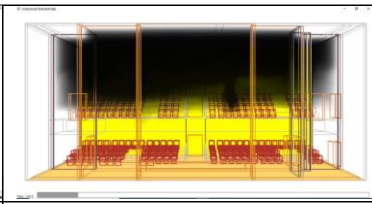
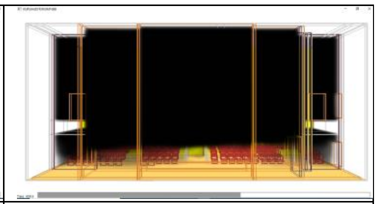
Spread			
Sec.	5	300	400

Table 6. Smoke Spread in Modeling 2

Spread			
Sec.	5	100	500

IV. Conclusions

Flame spread is influenced by factors such as the location and amount of combustible material, ceiling height, etc. Specifically, the ceiling jet phenomenon causes fire spread, and a room with a low ceiling height experience faster and more extensive fire spread following the shape of the obstacle. Meanwhile, in a room with a high ceiling height, the fire only spreads in the room and is easier to extinguish. In case a room has poor ventilation or a large distance between fire source and ventilation, fire tends to take longer before reaching the flashover period, but the fully-developed period is shorter. This leads to denser smoke spread and increased room temperature as the smoke fills the room faster and traps the burning room. In an area with good ventilation or ventilation close to the fire source, fire can quickly reach the flashover period, but the fully-developed period is prolonged. The room temperature is not too high due to the influence of outside air, and the smoke can escape through ventilation, reducing the smoke density.

Acknowledgment

The authors are grateful to the State University of Jakarta for providing the facilities to conduct this research.

References

[1] Kementerian PU, "*Kepmen PU No. 11/KPTS/2000 tentang ketentuan teknis manajemen penanggulangan kebakaran di perkotaan"*. Kementerian PU RI, 2000.

[2] C. M. Annur, "Ragam objek kebakaran di DKI Jakarta 2020," *DataBoks.com*, 2022. https://databoks.katadata.co.id/datapublish/2022/02/07/perumahan-objek-kebakaran-paling-sering-terjadi-di-dki-jakarta-selama-2020 (accessed Dec. 17, 2022).

[3] Y. Mulyono, "Kebakaran gedung RRI Jember berasal dari ruang auditorium," *DetikJatim.com*, 2022. https://www.detik.com/jatim/berita/d-5980921/kebakaran-gedung-rri-jember-berasal-dari-ruang-auditorium (accessed Dec. 17, 2022).

[4] A. K. Ose, "Auditorium Undana Kupang terbakar," *KupangTerkini.com*, 2021. https://kupangterkini.com/2021/10/04/auditorium-undana-kupang-terbakar/ (accessed Dec. 17, 2022).

[5] Kompas, "Auditorium PPOP Ragunan terbakar, diduga gara-gara putung rokok," *Kompas.com*, 2019. https://megapolitan.kompas.com/read/2019/05/21/11393931/auditorium-ppop-ragunan-terbakar-diduga-gara-gara-puntung-rokok (accessed Dec. 17, 2022).

[6] L. Valasek and J. Glasa, "On realization of cinema hall fire simulation using fire dynamics simulator," *Computing and Informatics*, vol. 36, pp. 971–1000, 2017, doi: 10.4149/cai.

[7] Z. Huang, Y. Meng, R. Yang, Y. Gao, Z. Yinghua, and S. Wang, "Numerical simulation of a cinema fire based on FDS," *International Journal of Simulation and Process Modelling*, vol. 13, no. 3, p. 200, 2018, doi: 10.1504/IJSPM.2018.093093.

[8] P. Setyadi and Y. F. Nanda, "Karakteristik penyebaran api ketika terjadi kebakaran berbasis metode FDS (Fire Dynamics Simulator) pada parkiran sepeda motor kampus A Universitas Negeri Jakarta," *Konversi Energi dan Manufaktur UNJ*, vol. 2, pp. 89–98, 2017.

[9] R. S. Hidayah, "*Pengaruh tata letak terhadap perambatan nyala api berbasis metode FDS (Fire Dynamics Simulator) pada parkiran sepeda motor kampus A Universitas Negeri Jakarta*," B.Ed. thesis, Universitas Negeri Jakarta, Jakarta, 2016.

[10] K. B. McGrattan and G. P. Forney, "*Fire dynamics simulator (version 4)*," Gaithersburg, MD, 2004. doi: 10.6028/NIST.SP.1019.

[11] G. P. Forney, *Smokeview, a tool for visualizing fire dynamics simulation data volume I: User's Guide*. USA: National Institute of Standards and Technology, 2016.

[12] A. Yusra, I. Haryanto, and Jamari, "Analisa kontak elastis antar hemispheres menggunakan metode elemen hingga," *ROTASI*, vol. 10, no. 1, pp. 1–5, 2008.

[13] J. Park and J. Kwark, "Experimental study on fire sources for full-scale fire testing of simple sprinkler systems installed in multiplexes," *Fire*, vol. 4, no. 1, pp. 1–16, Mar. 2021, doi: 10.3390/fire4010008.

[14] C. Albers, "Air mass/density," *Nasa Official (EarthData)*, 2022.

[15] V. Babrauskas, *Ignition Handbook*. USA: Fire Science Publishers, 2003.

[16] John. Krasny, W. J. (William J. Parker, and Vytenis. Babrauskas, *Fire behavior of upholstered furniture and mattresses*. New York: Noyes Publications, 2001.

[17] D. Drysdale, *An Introduction to Fire Dynamics*. Chichester: John Wiley & Sons, Ltd, 2011.

[18] *ISO/TS 16733:2006 - Fire Safety Engineering — Selection of Design Fire Scenarios and Design Fires*. ISO/TS 16733:2006, 2006.

[19] P. McKeen and Z. Liao, "A three-layer macro-scale model for simulating the combustion of PPUF in CFD," *Build Simul*, vol. 9, no. 5, pp. 583–596, Oct. 2016, doi: 10.1007/s12273-016-0287-2.

[20] M. J. Hurley, *SFPE Handbook of Fire Protection Engineering*, Fifth Edition. USA: Springer, 2015.

[21] M. Tanubrata and H. Wiryopranoto, "Penjalaran kebakaran pada suatu konstruksi bangunan gedung akibat sumber panas," *Jurnal Teknik Sipil*, vol. 12, no. 1, pp. 14–43, 2016.

[22] W. Zhao, R. Zong, B. Yao, J. Gao, and G. Liao, "Analysis of influencing factors on flashover in the long-narrow confined space," *Procedia Eng*, vol. 62, pp. 250–257, 2013.

[23] N. F. M. O. Davie County, "Stages of fire growth," 2018, Accessed: Apr. 17, 2023. [Online]. Available: https://www.daviecountync.gov/883/Davie-County-Fire-Marshals-Office-SOGs

[24] B. Karlsson and J. G. Quintiere, *Enclosure fire dynamics*. CRC Press, 2000.

[25] K. Himoto and K. Suzuki, "Computational framework for assessing the fire resilience of buildings using the multi-layer zone model," *Reliab Eng Syst Saf*, vol. 216, p. 108023, Dec. 2021, doi: 10.1016/j.ress.2021.108023.

[26] C. Hopkin and M. Spearpoint, "A Review of design values adopted for heat release rate per unit area," *Fire Technol*, vol. 55, no. 5, pp. 1599–1618, Sep. 2019.

[27] A. F. Baguian, S. K. Ouiminga, C. Longuet, A.S. C. Bretelle *et al.*, "Influence of density on foam collapse under burning," *Polymers (Basel)*, vol. 13, no. 1, p. 13, Dec. 2020, doi: 10.3390/polym13010013.