IJoCED

Indonesian Journal of Computing, Engineering, and Design

Journal homepage: http://ojs.sampoernauniversity.ac.id/index.php/IJOCED

Fire Safety Assessment of a Typical Sports Hall Building Based on Fire Dynamics and Crowd Movement Models

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ABSTRACT

Fire risk analysis is one of the essential components of building design to ensure the safety of occupants and properties in case of fires. Currently, the Ministry of Public Works and Housing Regulation No. 20/PRT/M/2009 provides guidelines for conducting a fire risk analysis, however, without a clear consideration of fire dynamics in the estimation of the fire risk level. In this work, we investigate the fire safety aspects of a typical sports hall buildings by a fire dynamics deterministic model (Fire Dynamics Simulator (FDS) of the National Institute of Science and Technology, USA) and crowd movement model for occupant evacuation (Pathfinder of Thunderhead Engineering). Systematic investigations were made on the effects of the fire growth category and smoke extraction system on the Available Safe Egress Time (ASET). The results of ASET were then compared to the Required Safe Egress Time (RSET) which is obtained from the evacuation model. Our results suggest that ASET decreases exponentially with fire growth rate, especially from slow to medium growth rate. The fire growth rate significantly affects the acceptable fire risk of ASET longer than RSET. Occupant capacity, fire management systems, and smoke extraction system play important roles in reducing fire risk. However, as the fire growth rate increases, the effects of smoke extraction in maintaining safe conditions diminish. This study provides recommendations to reduce risks to the occupants in case of fire, contributing to the considerations of the design and management of a typical sports hall building.

ARTICLE INFO

Article History:
Received 06 Aug 2024
Revised 01 Oct 2024
Accepted 02 Oct 2024
Available online 15 Oct 2024

Keywords:
ASET,
Fire dynamic evaluation,
Fire evacuation,
Fire growth category,
Fire safety,
RSET.

1. INTRODUCTION

Fire incidents can have devastating impacts, claiming lives and causing significant property losses. Worldwide, the number of deaths caused by fires was 15,416 in 2020, with 82.7% were deaths due to residential fires (Brushlinsky et al., 2022), though residential fires only account for 24.2% of fire occurrences. The higher rate of fatality due to residential fires compared to other fires signifies the urgent need for proper fire safety consideration during the design stage of a building, especially a building that will have a large number of occupants.

In Indonesia alone, the number of fatalities caused by fire, heat, and hot substances was around 1,500 every year from 2017 to 2021 (IHME, 2024). Through the Ministry of Public Works and Housing, Indonesia formalized regulation No. 20/PRT/M/2009 providing guidelines for conducting fire risk analysis for buildings. However, this regulation lacks the consideration of proper fire dynamics as the basis to estimate fire risk, resulting in an unclear baseline on the determination of fire safety design, such as fire protection system, fire load design, and occupancy capacity.

The protection of life and property is the objective of fire protection system design. Many literature reports fire safety studies on residential area (Buchanan & Abu, 2017; Gerges et al., 2017; Hamida & Hassanain, 2019; Jennings, 2013; Korman, 2013; Liu & Chow, 2014; Salminen & Hietaniemi, 2018; Warda & Ballesteros, 2007; Young & Fleischmann, 2007), industrial facilities (Benichou et al., 2002; Cosgrove & Buchanan, 1996; Davletshina, 1998; Ljubinković et al., 2023), school (Hassanain, 2006; Hassanain et al., 2022), and health-care facilities (Agus Salim et al., 2023; Ebekozien et al., 2021; Muhamad Salleh et al., 2020). However, few investigated fire safety considerations of public facilities that would involve a large number of occupants such as indoor facilities that are often utilized for bazar, concerts, and exhibitions.

Yemelyanenko et al. (2020) reported a study on the fire risk estimation of the office and auditorium area of the Lviv State Palace of Aesthetic Education of Youth by using Consolidated Model of Fire and Smoke Transport (CFAST) of the National Institute of Standards and Technology (NIST) (Peacock et al., 2015a). Recommendations on the addition of fire curtain and fire alarm system were made based on the assessment of individual fire risk.

However, the assumption of two zone model in CFAST limits the capability to predict fire dynamics of complex building geometry (Peacock et al., 2015b). Thus, In this study we utilize Fire Dynamics Simulator (FDS), a computational fluid dynamics (CFD) model of fire-driven fluid flow (McGrattan et al., 2023) to estimate the the fire dynamics in a typical sports hall building. The results of fire simulation then compared to evacuation simulation conducted by using Pathfinder.

2. RESEARCH METHODOLOGY

The typical sports hall building chosen in this study is Istora Senayan Indoor Sports Hall (**Figure 1**). This building is chosen mainly due to its indoor feature and the history of utilization as exhibition, bazar, and concert events. Different purposes of a building equal to different fire risks. Thus, the fire protection system should be designed accordingly. The overall dimension of the hall are 92.23 m long, 73.77 m wide, and 18.45 m high. The maximum capacity of the hall is 7,627 persons. The entrances to or exit from the hall are through 15 openings which can be seen in **Figure 2**. The width of the openings are 1.7 to 2.7 m.

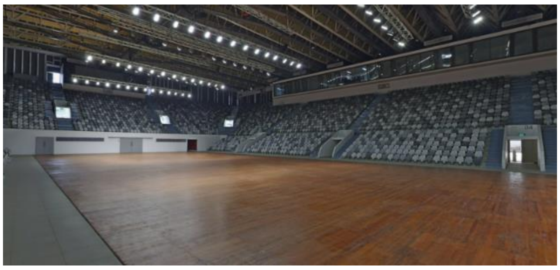

Figure 1. Istora Senayan Indoor Sports Hall

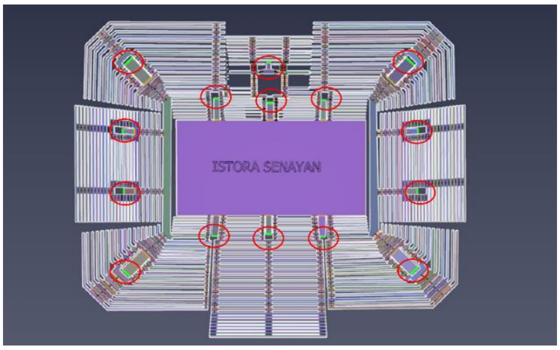

Figure 2. Top view of the designed geometry for the Crowd Movement Model, with exit openings marked by red ovals.

The available safe egress time (ASET) is defined as the time from the start of the fire to the moment when the environmental condition is hazardous for continued human occupancy (Cooper, 1982, 1983). The hazardous conditions were based on temperature, CO concentration, and visibility with thresholds of 60°C (CIBSE Guide E-Fire Safety Engineering, UK), 420 ppm (NFPA 130), and 10 m (British Standards 7947), respectively.

In this study, ASET was estimated by using Fire Dynamics Simulator (FDS) (McGrattan et al., 2021). FDS solves numerically a form of the Navier-Stokes equations appropriate for low-speed (Ma < 0.3), thermally driven flow with an emphasis on smoke and heat transport from fires. Mathematical formulations and numerical solutions methodology of FDS are covered in (McGrattan et al., 2023).

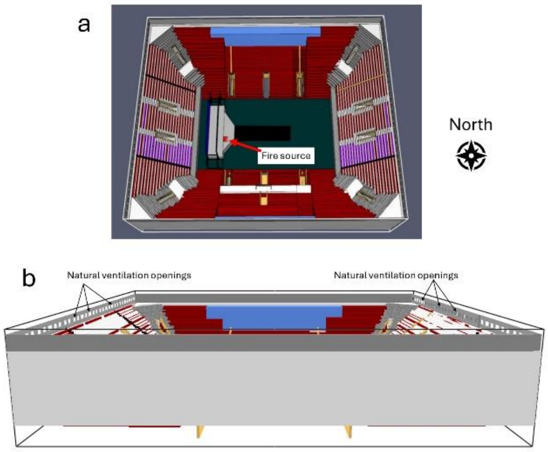

Figure 3. Geometry model for fire dynamics simulator. (a) The fire source location was indicated by a red arrow. (b) Natural ventilation openings at the upper section of west and east sides.

Figure 3a shows the FDS geometry model in this study, with the location of the fire was assumed to be on an event stage. Natural ventilation was provided by openings at the upper level of the west and east sides of the hall (**Figure 3b**). The design fire in this study was set to be 5 MW, according to ministerial regulation PU no. 26: 2008 for an atria-like compartment. The fire was modeled as t^2 fires as shown by Equation 1 below.

$$\dot{Q} = \alpha t^2 \quad (1)$$

With $\dot{Q}$, α, and t^2 are heat release rate (kW), fire growth coefficient (kW/s^2), and time (s), respectively. In this study, the growth rate coefficient varied from 0.00293 kW/s^2 (slow), 0.01172 kW/s^2 (medium), 0.0469 kW/s^2 (fast), to 0.1876 kW/s^2 (ultrafast) (Hadjisophocleous & Mehaffey, 2016) (**Figure 4**). The variation of growth rate coefficient represents the reactivity and amount of the burning material.

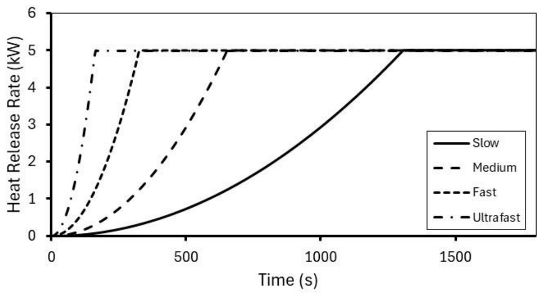

Figure 4. Heat release rate according to fire growth coefficient

The characteristic diameter of the fire was calculated according to Equation 2 (McGrattan et al., 2023).

$$D^* = \left(\frac{\dot{Q}}{\rho_\infty c_p T_\infty \sqrt{g}}\right)^{2/5} \quad (2)$$

with D^*, ρ_∞, c_p, T_∞, and g are characteristic diameter of the fire (m), air density (kg/m^3), air specific heat (kJ/kg-K), and gravity acceleration (m/s^2). With heat release rate of 5 MW, the characteristic diameter in this study is 2.1 m. The mesh resolution for FDS simulation was set based on $5 \leq {D^*}/{\delta x} \leq 6$, according to the FDS validation of VTT large hall experiments (McGrattan et al., 2023).

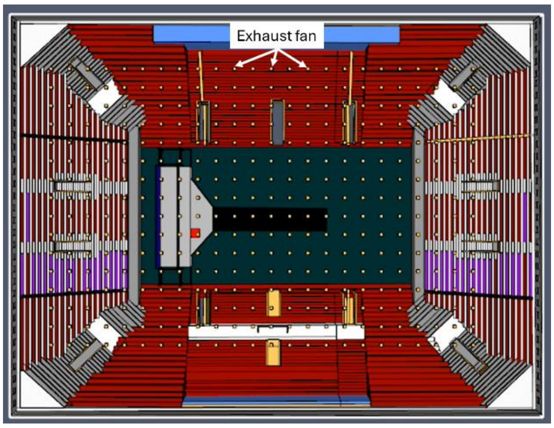

Figure 5. Top-view of the hall with exhaust fans at the ceiling height

The dominant combustion reaction of the fire was assumed to be of rigid polyurethane foam GM37 (SFPE Handbook of Fire Protection Engineering, 2016), which is a thermosetting material often used in decoration and residential settings such as for thermal insulation, cushion, and seating material. The chemical formula is $CH_{1.2}O_{0.2}N_{0.08}$, with heat of combustion (ΔH_c) of 17.9 MJ/kg, CO yield of 0.024, and soot yield of 0.113.

The effects of exhaust fans on ASET were investigated in this study by conducting FDS simulation with 384 fans positioned at the ceiling height of the hall (**Figure 5**). The volumetric flow of each fan is 1.6 m^3/s. The total volumetric flow is 614.4 m^3/s, which equals ~18 air change rate per hour (ACH).

The crowd movement simulation was conducted by using Pathfinder. Pathfinder is an agent-based egress simulator that uses steering behaviors to model occupant motion (Thunderhead Engineering, 2021). The result of the crowd movement simulation was then used to estimate the Required Safe Egress Time (RSET). RSET is defined as the time from when the fire started until all the occupants arrived at a safe location (Baek et al., 2016; Danzi et al., 2021).

As can be seen in **Figure 6**, RSET is the sum of detection time, alarm time, pre-movement time, and travel time. The detection time is the duration from the fire to the detection of the fire. The alarm time is the duration from the detection time to the moment the evacuation alarm or announcement was given. The pre-movement time is the duration from which the evacuation alarm was given to the moment the occupants start to move to evacuate the building. The travel time is the duration of the occupants moving to a safe location or outside the building. The travel time was obtained from the crowd movement simulation.

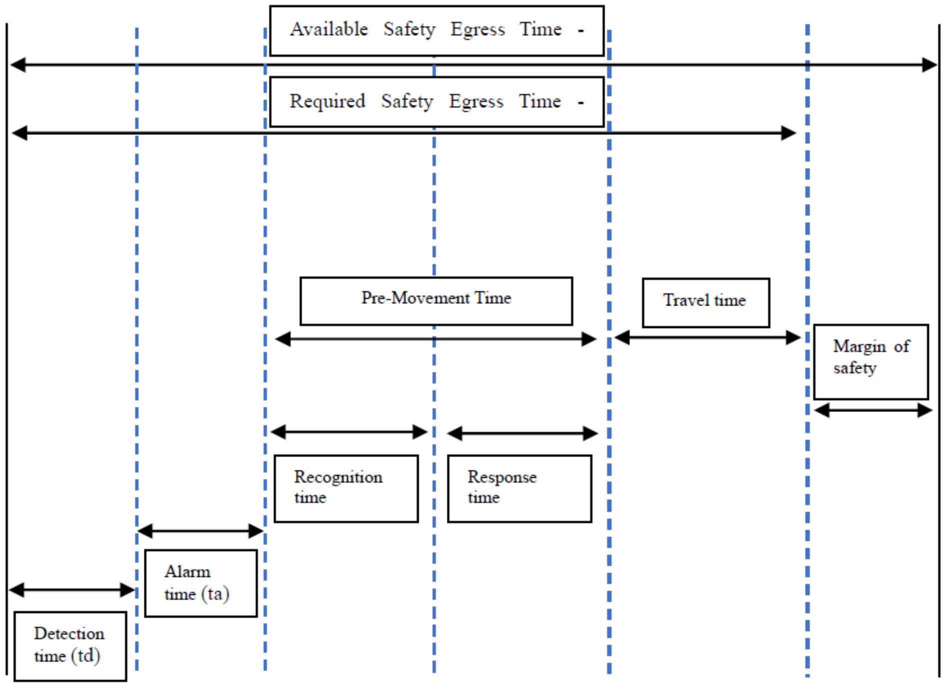

Figure 6. Schematic illustration of Available Safe Egress Time (ASET) and Required Safe Egress Time (RSET) (modified from Danzi et al. (2021))

The detection and alarm time were assumed to be 0 s as the fire occurrence inside a hall during an active event will likely to be identified immediately. The pre-movement time was estimated according to FLAME methodology by Danzi et al. (2021), considering the characteristics of the occupants in terms of alertness, mobility, social affiliation, role, position, commitment, focal point, and familiarity. Here, we estimate the characteristics of occupants of the hall as listed below:

- Alertness: having an average degree of attention
- Mobility: normal ambulation
- Social affiliation: among many people who do not recognize each other (tourists, occasional guests)
- Role: low level of responsibility
- Position: sitting
- Commitment: generic guest
- Focal point: strongly focused (audience, spectator)
- Familiarity: having good orientation capacity

The pre-movement time was then calculated based on the estimation of the alarm base time (Danzi et al., 2021). The alarm base time represents the effectiveness of the alarm system in motivating the occupants to start the evacuation. In best, medium, and worst scenarios of alarm base time, the pre-movement time was estimated to be 4.5, 7.5, and 10.5 min, respectively.

For traveling time, the crowd movement simulations were conducted at 25% (1,906 occupants), 50% (3,813 occupants), 75% (5,720 occupants), and 100% (7,627 occupants) capacities. The occupants were 30 to 50 years old with walking speed of 0.97 m/s as minimum, 1.30 m/s as average, and 1.62 m/s as maximum, varied according to crowd density and elevation change (walking on stairs) (Thunderhead Engineering, 2021). The traveling time was then noted when the last occupant exited the hall.

3. RESULTS AND DISCUSSION

Figure 7 shows the results of FDS simulation in terms of CO concentration, temperature, and visibility. Both CO concentration (**Figure 7a**) and temperature (**Figure 7b**) of the hall did not increase to the ASET thresholds, i.e. 420 ppm (0.34 mole fraction) for CO concentration and 60°C for hall temperature, even at steady state condition ($t = 1800\ s$). Relatively safe conditions according to CO concentration and hall temperature were due to the large dilution and cooling effects of the large hall, and the concentrated location of the fire, i.e. only on the makeshift stage (see **Figure 3)** where the fire was not modeled to spread spatially.

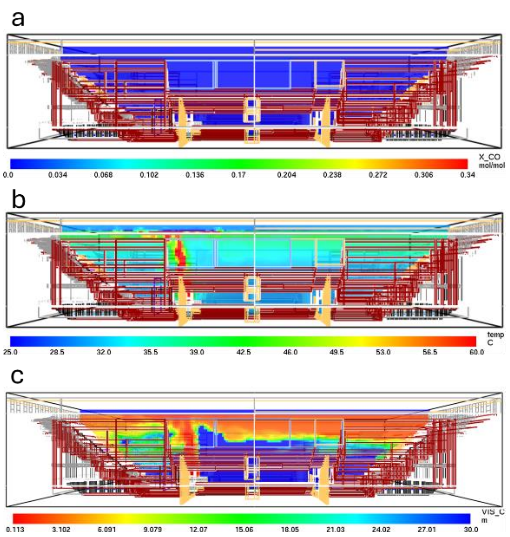

Figure 7. FDS simulation results at steady state with slow fire growth coefficient, (a) Results of CO concentration and ASET threshold is 0.34 of mole fraction with air (420 ppm). (b) Result of temperature and ASET threshold is 60°C. (c) Result of visibility and ASET threshold is 10 m.

Unsafe condition was obtained according to the visibility condition (**Figure 7c**). At steady state ($t = 1800\ s$), the visibility decreased below 10 m around the middle to the upper tribune seat. Thus, the visibility condition can be dangerous for the occupants in those tribune seat levels. The smoke from fire, having higher temperature and lower density than the surrounding air, will move upwards to the ceiling (**Figure 8a** and **8b**). Afterwards, the smoke spread horizontally under the ceiling, forming ceiling jet (**Figure 8c**), and filling the upper region of the hall, forming smoke upper layer (**Figure 8d**).

In indoor hall such as the one used in this study, the fire risk for the occupants seated in the upper level are likely to be higher than the occupants in the lower level due to the possible fire smoke exposure. The natural ventilation openings (**Figure 3b**) had minimal effects on maintaining safe condition at these upper levels. For the following discussions, ASET will be determined according to the visibility level.

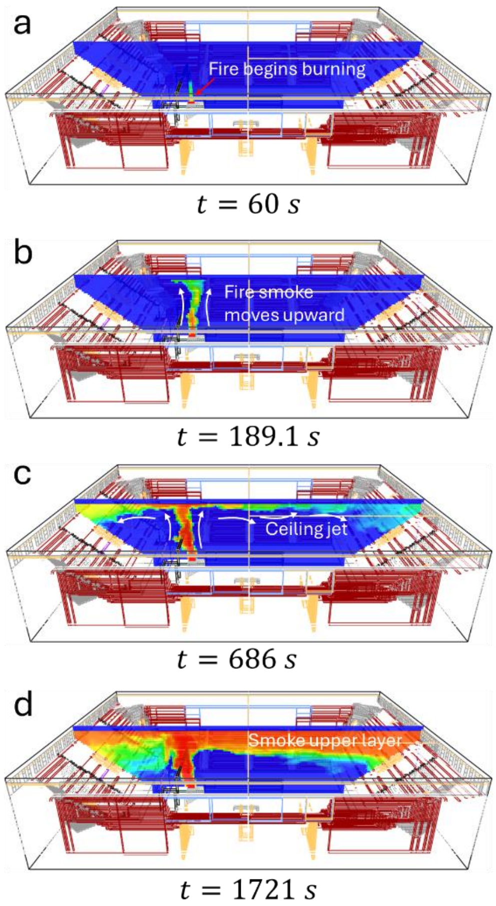

Figure 8. Fire smoke dynamics: (a) first 60 seconds of the simulation, (b) at 189.1 seconds, smoke rises to ceiling level, (c) at 686 seconds, smoke moves horizontally, forming a ceiling jet, and (d) at 1721 seconds, smoke fills the upper region of the hall, creating an upper smoke layer.

Figure 9 shows that ASET decreases exponentially as fire growth rate increases, especially from slow to medium growth rate. The middle level tribune seating area can be seen to be relatively safer than the upper level as its ASET is generally longer by around 5 minutes. At slow, medium, fast, and ultrafast fire growth rate, ASETs at the middle level tribune seat are longer by 7.6 minutes, 5.4 minutes, 4.5 minutes, and 2.6 minutes than the upper level, respectively. As the difference between ASET at the middle and upper layer decreases with fire growth level, the fire risk at the middle level are increasingly similar to the upper level.

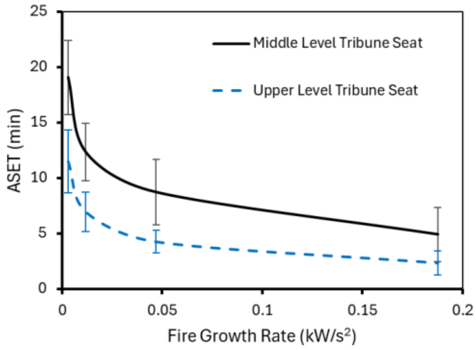

Figure 9. Plot of ASET vs. Fire Growth Rate at the middle and upper-level tribune seats. The lines plot the average of ASET from the north, south, west, and east sides of the hall.

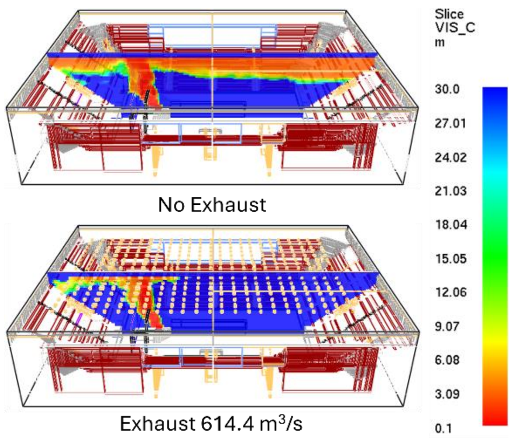

Figure 10. Visibility contours at 600 seconds from fire simulations with and without an exhaust rate of 614.4 m^3/s, under an ultrafast fire growth rate (α = 0.1876 kW/s^2).

The effects of 614.4 m^3/s exhaust on the smoke dynamics can be seen in **Figure 10**. The exhaust effectively extracts the smoke outside the hall. Only the west upper side of the tribune area was exposed to the smoke, while all the middle to lower tribune areas were completely safe from the smoke exposure.

Figure 11 shows the upper-level tribune ASETs for all fire growth categories with and without exhaust fans. It can be seen that the exhaust fans had significant effects on prolonging ASET at slow and medium fire growth rates, longer by 2.7 and 1.8 min, respectively. As the fire growth rate increased to fast and ultrafast, the effect of exhaust fans diminished, i.e. had a minuscule effect with fast fire growth rate, and prolonged ASET only 0.5 min with ultrafast fire growth rate.

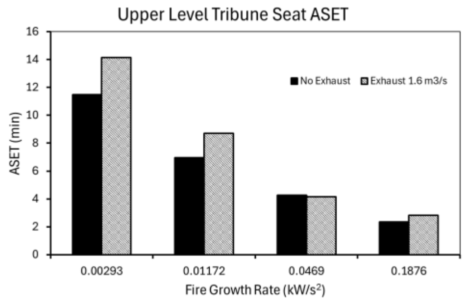

Figure 11. ASETs of the upper-level tribune seats according to various fire growth rates and exhaust conditions

Figure 12 shows the visualization of crowd movement simulation with 100% hall capacity, containing 7,627 people. All occupants immediately started queuing to exit the hall through all 15 openings. As the agent movement was not modeled to jump through the seating line, a long queue was made from the upper to the lower tribune level for a significant amount of time. Up to 180 s (3 minutes), occupants at the upper tribune level were still queuing waiting to move downward to the exit at the middle level. The upper-level occupants were successfully moved downward at 296 s (around 5 minutes). All occupants finished evacuating the hall with a travel time of 381 s (6.34 minutes). Compared to **Figure 9**, the ASET at the upper-level tribune with ultrafast fire was 2.4 minutes, already shorter than the travel time alone, i.e. not even considering the pre-movement time yet.

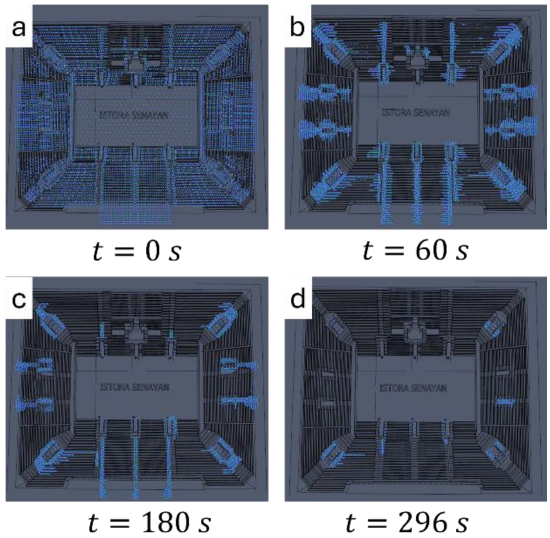

Figure 12. Crowd movement simulation result showing the evacuation at (a) $t = 0\ s$, (b) $t = 60\ s$, (c) $t = 180\ s$, and (d) $t = 296\ s$.

Table 1 summarizes the travel time for various occupant capacities. The RSET then the summation of the pre-movement time and travel time. As discussed before in the methodology section, the detection and alarm time were assumed to be 0 s. The fires were likely to be immediately identified by occupants during an active event. The RSET is then just composed of the duration for the occupants to decide to start the evacuation (the pre-movement time) and the travel time.

Table 1. Pre-movement and travel time results using the FLAME methodology and crowd movement simulation with Pathfinder, respectively

Capacity	Pre-Movement Time (min)			Travel Time (min)
	Worst	Medium	Best	
100 % (7,627 people)	10.5	7.5	4.5	6.34
75 % (5,720 people)				4.63
50 % (3,813 people)				3.33
25 % (1,906 people)				1.95

The comparison between ASET (**Figure 11**) and RSET (**Table 1**) is shown in **Table 2**. NA stands for Not Acceptable. An acceptable fire risk is determined if the ASET is longer than the RSET. **Table 2** shows that an acceptable fire risk was generally obtained for all occupant capacities if the fire growth rate was slow, with and without exhaust, and if the base alarm system was in the base scenario. The best scenario could be achieved, for example, if there is a good standard operating procedure for emergency evacuation and a trained emergency safety officer available to direct the occupants to immediately start the evacuation. Exhaust rate can also be seen to have a significant effect in reducing the fire risk. The fire risk becomes acceptable with the installation of 614.4 m^3/s exhaust for 75 and 100% hall capacities in the medium scenario of alarm base time, and for 25 and 50% capacities in the worst scenario of alarm base time.

Table 2. Mapping of fire risk condition based on comparison of ASET and RSET

Fire Growth Rate	Exhaust	Capacity (%)	Acceptable fire risk (ASET > RSET)		
			Worst	Medium	Best
Slow	No exhaust	25	NA	Acceptable	Acceptable
		50	NA	Acceptable	Acceptable
		75	NA	NA	Acceptable
		100	NA	NA	Acceptable
	614.4 m^3/s	25	Acceptable	Acceptable	Acceptable
		50	Acceptable	Acceptable	Acceptable
		75	NA	Acceptable	Acceptable
		100	NA	Acceptable	Acceptable
Medium	No exhaust	25	NA	NA	Acceptable
		50	NA	NA	NA
		75	NA	NA	NA
		100	NA	NA	NA
	614.4 m^3/s	25	NA	NA	Acceptable
		50	NA	NA	Acceptable
		75	NA	NA	NA
		100	NA	NA	NA
Fast	No exhaust	25	NA	NA	NA
		50	NA	NA	NA
		75	NA	NA	NA
		100	NA	NA	NA
	614.4 m^3/s	25	NA	NA	NA
		50	NA	NA	NA
		75	NA	NA	NA
		100	NA	NA	NA
Ultrafast	No exhaust	25	NA	NA	NA
		50	NA	NA	NA
		75	NA	NA	NA
		100	NA	NA	NA
	614.4 m^3/s	25	NA	NA	NA
		50	NA	NA	NA
		75	NA	NA	NA
		100	NA	NA	NA

As the fire growth rate increased to medium, only 25% hall capacity has resulted in acceptable fire risk, if the alarm base time was in best scenario. The installation of 614.4 m^3/s exhaust can also be seen to allow an acceptable fire risk with 50% hall capacity and an alarm base time, also, in the best scenario. With increased fire growth rate to fast and ultrafast, no acceptable can be found in this study among all scenarios of alarm base time and with or without the 614.4 m^3/s exhaust (around 18 ACH).

The fire growth rate strongly affects the acceptable fire risk according to ASET and RSET. Being related to the reactivity and amount of the combustible materials, comprehensive consideration should be made in organizing an event and managing the fire load in a typical sports hall building so that a fire will unlikely to grow with a rapid rate. As formalized by Hadjisophocleous & Mehaffey (2016), slow, medium, fast, and ultrafast fires are ones that grow to 1 MW in 600 s, 300 s, 150 s, and 75 s, respectively. The typical combustible materials for each of the fire growth rate designation can be seen in (Hadjisophocleous & Mehaffey, 2016).

After the fire growth rate, alarm base time scenarios, occupant capacity, and smoke exhaust system play an important role in reducing the fire risk. Smoke exhaust system, particularly the 614.4 m^3/s (around 18 ACH) investigated in this study, has allowed an aceptable fire risk condition for an increased occupant capacity and worse alarm base time scenarios, with slow fire growth rate.

4. CONCLUSION

Computational study to investigate the fire risk of a typical sports hall building has been conducted by estimating the available and required safe egress times. The available safe egress time (ASET) was estimated based on computational fluid dynamics model for fire (McGrattan et al., 2023), while the required safe egress time (RSET) was estimated based on pre-movement time and travel time. The pre-movement time was calculated according to FLAME methodology (Danzi et al., 2021), while the travel time was calculated by using a crowd movement model (Thunderhead Engineering, 2021).

Our results suggest that the ASET decreases exponentially with fire growth rate, especially from slow to medium growth rate. As the fire smoke moves upward and forming ceiling jet, the fire risk for occupants at the upper-level tribune seat are higher than the occupants at the medium and lower level. With increasing fire growth rate, however, the difference of ASET between the upper and middle-level tribune seat decreases.

We found that the fire growth rate significantly affects the acceptable fire risk of ASET longer than RSET, indicating the importance of the management of combustible materials in the hall, thus stressing the urgency of comprehensive consideration in allowing an event to be held in the hall. Such event should goes along with combustible materials with such reactivity and amount that if burning will resulted in a slow growing fire. Occupant capacity, fire management system, and smoke exhaust system play important roles in reducing fire risk. Fire risk decreases with decreased occupancy, better fire management system, and the installation of smoke exhaust system. Smoke exhaust system significantly reduces fire risk with a slow growing fire. As the fire growth rate increases, the effects of smoke exhaust system in maintaining safe condition diminishes.

ACKNOWLEDGEMENTS

The authors thanks all our colleagues for the insightful discussions and technical support throughout the study.

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