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Fire Characteristics of Motorcycles in Open Areas at UNJ Campus Using PyroSim

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ABSTRACT

The motorcycle open parking space provided by UNJ (State University of Jakarta) has limited capacity, but the number of the academic community is increasing. The arrangements are sometimes done in a scrambled mode with very limited spacing, and these motorcycles are parked in a hot condition due to the engine and environment. As a result, an uncontrolled two-wheeled vehicle layout can pose a danger in the event of a fire. This study uses PyroSim 2025 software as a pre-processor for the FDS (Fire Dynamic Simulator) that will analyze the flame spread, the increase in HRR (Heat Release Rate), and the heat transfer graphs (conduction, convection, and radiation). The object that is burned is in the form of a motorcycle, with a material consisting of foam (as a motorcycle seat) and polypropylene (as a motorcycle body). Furthermore, the chemical reaction to be used is propylene. The particle ignitor model is designated as the ignition source in the foam material. In this simulation, the influence of wind is ignored to see the magnitude of the influence of radiation and natural convection on heat transfer on the spread of fire. The simulation results presented are in the form of a graph of a significant increase in HRR (Heat Release Rate) when the fire starts to ignite and grows to spread to the surrounding motors, visualization shows that the fire spreads in the direction of the model's material geometry, and heats the surrounding material with the principles of conduction, radiation and natural convection. The heat release rate spikes immediately as soon as most of the material had decomposed and turned into flashover. The radiation also increases as the fire spreads and the flame size becomes enormous. The heat release rate, flame spread, flame size (height and diameter), and radiation increased almost linearly. This study contributes to fire safety engineering by providing quantitative characterization of the heat release rate, flame spread behavior, and radiative/convective heat transfer of motorcycle fires in open parking configurations, which can serve as a scientific basis for improving parking layout design, fire protection strategy, and evacuation planning in open motorcycle parking areas such as university campuses.

Keywords: HRR, convection, conduction, radiation, fire spread, evacuation

INTRODUCTION

The characteristics of the parking area greatly affect the dynamics of fire development and smoke dispersion when a fire occurs [1]. In open parking areas, freer natural air circulation plays a role in cooling the area around the fire source and diluting the concentration of smoke, so that heat accumulation takes place more slowly [2, 3]. Fire spread in parking areas is caused by radiation, as demonstrated by the fact that the closer a vehicle is to the fire source, the more likely it is to be heated and to catch fire [4]. Some of the main factors that can cause a vehicle to catch fire are vehicle engines that overheat, fuel leaks, faulty electrical installations or short circuits, leaving electronic devices such as powerbanks in the vehicle, and poor vehicle maintenance [5]. In addition, changes in vehicle design and the increased use of plastics and other combustible materials have been shown to raise the fire hazard posed by modern vehicles in parking facilities compared with older vehicles [6], motivating the compilation of updated statistical design-fire databases from full-scale vehicle fire experiments for car-park safety design [7], as well as stricter fire-protection regulations governing the construction and control of hazards in parking structures [8].

When a fire occurs, the distance between vehicles greatly affects the rate of fire spread; for example, the shortest effective distance of 2.2 m results in the highest probability of fire spread, which is 0.90, and the longest effective distance of 3.2 m results in the lowest probability, which is 0.63 [4]. The maximum fire load of a 50 cc scooter-type motorcycle is 1.4 MW and the average flame height is 2.6 m, and the fire load of a 250 cc scooter-type motorcycle reaches 5 MW and the height exceeds 3 m [9]. Smoke caused by fires in open areas can cause panic and unclear evacuation routes and can be a major problem [10]. The fire hazard of two-wheeled vehicles is further compounded by the growing adoption of battery-powered motorcycles and e-scooters, whose lithium-ion batteries can enter thermal runaway and produce rapid, high-intensity fires that are more difficult to control than fires involving conventional fuel-powered vehicles [11].

Therefore, this study aims to investigate the fire characteristics of motorcycles in an open parking area, including heat release rate (HRR), flame spread, and heat transfer through conduction, convection, and radiation, using PyroSim/FDS simulation, in order to provide a scientific basis for improving parking layout design and fire safety management in open motorcycle parking areas such as the UNJ campus parking area.

METHOD

Simulation Software and Environment

This study utilized PyroSim 2025 (Thunderhead Engineering) as a pre-processor for the Fire Dynamics Simulator (FDS), a computational fluid dynamics (CFD) model developed by the National Institute of Standards and Technology (NIST). PyroSim was employed to construct the geometric model, define material properties, specify the ignition source, and analyze the fire dynamics outputs, including flame spread, Heat Release Rate (HRR), and heat transfer mechanisms (conduction, convection, and radiation) [12]. FDS numerically solves a large-eddy-simulation form of the Navier–Stokes equations for low-speed, thermally driven flow, and its governing equations, numerical methods, and validation basis are extensively documented by its developers at NIST [13]. The FDS simulation has good compatibility with experimental results, so it is effectively used to analyze fire behavior [14].

Model Geometry and Object Specification

The simulated object was a standard motorcycle, modeled with two primary material components based on typical motorcycle construction:

Motorcycle seat*:* Assigned a foam material.

Motorcycle body (fairings/fenders): Assigned a polypropylene material.

The thermal and physical properties for these materials are summarized in TABLE 1.

The chemical reaction used in the simulation was defined as propylene (C_3H_6), which served as the combustion reaction mechanism for the pyrolysis and burning of the assigned materials. The simulation assumed an open-space parking environment (consistent with the State University of Jakarta conditions) with no obstructions to airflow. The influence of wind was explicitly ignored to isolate and quantify the effects of radiative and natural convective heat transfer on fire propagation.

Ignition Source

A particle ignitor model was designated as the ignition source [12]. The ignitor was placed directly on the foam material of the motorcycle seat to simulate a localized ignition event (e.g., an electrical short or hot engine component contacting the seat).

TABLE 1. *Material Properties (Source: Thunderhead Engineering)*

Properties	Foam	Polypropylene
Density (kg/m^3)	40	900
Conductivity (W/m·K)	0.1	0.15
Absorption Coefficient (/m)	50,000	5,000
Specific Heat Capacity (kJ/kg·K)	1	2
Emissivity	0.9	0.9
Reference Temperature (°C)	280	550

Fire Simulation Parameters and Data Collection

The FDS simulation was executed with the following outputs recorded over the simulation timeframe:

- ***Heat Release Rate (HRR):*** A time-history graph of HRR (kW) was generated to capture the rate of energy release from ignition through to fire growth and spread to adjacent motorcycles.
- ***Flame Spread Visualization:*** A 3D visual output from PyroSim was used to observe the spatial and temporal propagation of flames relative to the modeled material geometry.
- ***Heat Transfer Analysis:*** Surface and gas-phase sensors recorded data on conductive heat flux (through solid materials), convective heat flux (from hot gases to surfaces), and radiative heat flux (between flames and surrounding objects).

Assumptions and Boundary Conditions

The fire was assumed to occur on open land, providing a continuous and unlimited oxygen supply. Wind effects were neglected to emphasize the role of natural convection and radiation. The initial ambient temperature was assumed to be consistent with typical conditions in Jakarta (30 °C to 32 °C). Fire spread to surrounding motorcycles was modeled when the incident heat flux from the source motorcycle exceeded the critical ignition threshold of adjacent materials.

Mesh Generation

In this study, a mesh size of 0.15 m was used because it was considered to be able to represent the development of fire and smoke spread in the motor vehicle parking area quite well. In addition, the mesh size was chosen so that the simulation process remains stable and the computation time can still be run on the specifications of the device used. The use of a mesh that is too small can significantly increase the number of cells, extending the simulation time and increasing the risk of numerical instability in the FDS [12].

We used an Intel Core i7-12700 (2.1 GHz) processor with 16 GB of RAM, PyroSim software for numerical calculation, and Pathfinder software for evacuation simulation. Pathfinder is an agent-based egress simulator that combines steering behaviors with physical constraints to model occupant movement and evacuation time based on the motion of individual agents [15]. This simulation ignores wind speed due to its non-constant nature. The scenario is that a fire occurs in the entrance, middle, and exit areas of the parking lot. We designed the size of the layout according to the original size of the open parking area. The fuel that burned was a motorcycle modeled as a beam measuring 1.7 m long, 0.8 m wide, and 1.2 m high. The combustible material was represented by two materials, namely foam and polypropylene. The simulated room size is 2,080 m^2 and 3 m high, and the distance between motorcycles is 0.1 m. All simulations were carried out over 17 minutes of combustion. The following is a picture of the position where the fire started to burn.

Fire Scenario

In the first scenario (FIGURE 1), the starting point of the fire was on a motorcycle located at the entrance to the parking area. This scenario is used to analyze how a fire develops if a fire occurs in an area close to the entrance.

In the second scenario (FIGURE 2), the starting point of the fire is on a motorcycle located in the middle of the parking area. This scenario is considered important because the center position is usually surrounded by other vehicles, so the potential for heat transfer and the spread of fire to surrounding vehicles can occur quickly.

In the third scenario (FIGURE 3), the starting point for the fire is on a motorcycle located on the side of the exit of the parking area. This scenario is used to analyze how a fire develops if a fire occurs in an area close to the exit.

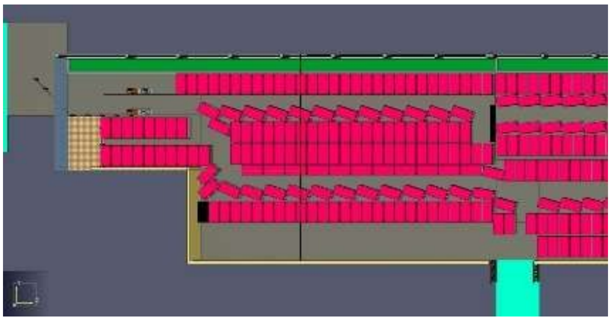


FIGURE 1. Scenario 1, where the starting point of the fire is in the entrance area.

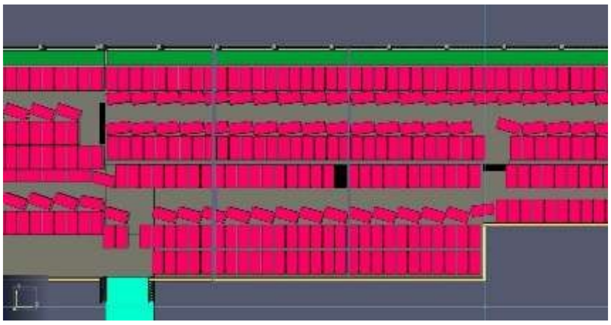


FIGURE 2. Scenario 2, where the starting point of the fire is in the middle of the parking area.

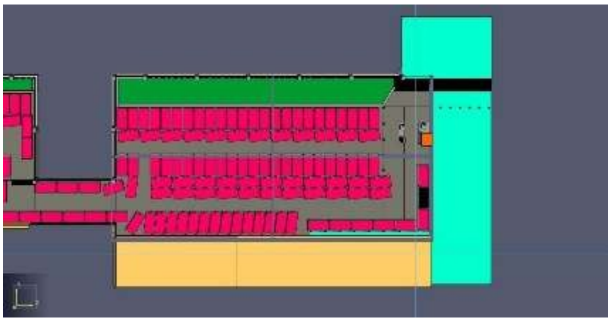


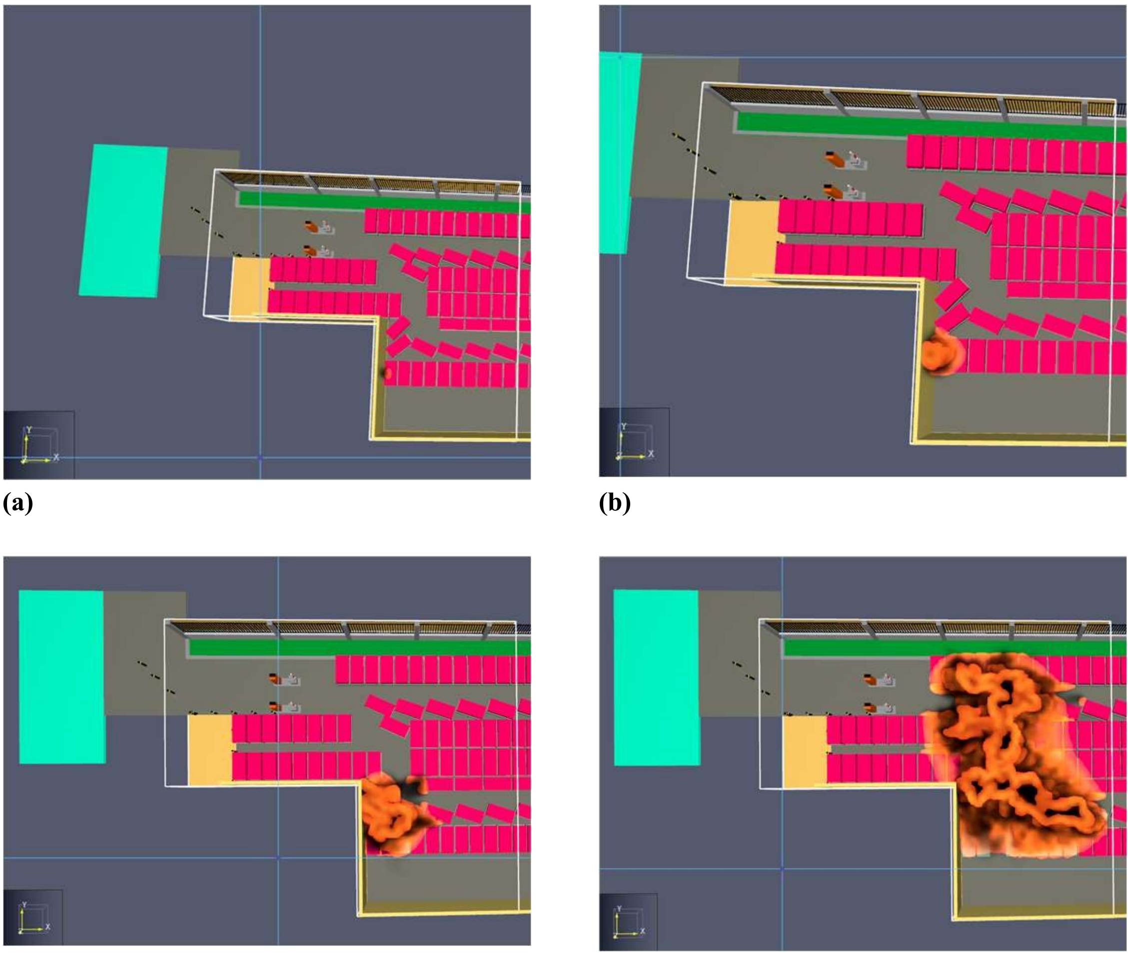
FIGURE 3. Scenario 3, where the starting point of the fire is in the exit area.

RESULT AND DISCUSSION

Fire Scenario 1

As seen in FIGURE 4(a), the fire started at 41.5 s after the simulation began, meaning that the ignitor started to heat the polyurethane foam, causing it to decompose and burn. This process acts as the initial combustion that spreads across the surface of the polyurethane foam, which acts as the motorcycle seat, as it is heated and accumulates heat. The foam decomposed into flammable aerosols indicated by black smoke that emerged from the surface. The smoke then ignited upon reaching 280 °C. The flame size gradually increased as the reaction gradually grew across the surface.

As time passed, the fire grew toward the lower part of the block, which represents the other material of the motorcycle. The polypropylene started to burn at 550 °C. This added extra flame height and diameter, and the radiation accelerated thermal decomposition of neighboring motorcycles. The increasing HRR caused conduction between the polyurethane



(a) **(b)** **(c)** **(d)**

FIGURE 4. Fire development sequence for Scenario 1 (ignition at the entrance): **(a)** ignition at t = 41.5 s; **(b)** fire developed and beginning to spread at t = 228.5 s; **(c)** fire spreading to multiple motorcycles at t = 532 s; **(d)** fire fully engulfing the entrance area at t = 1000 s.

and polypropylene, contributing to the flame height through convection of the decomposing vapor fuel. FIGURE 4(b) shows that at this stage, the fire started spreading to neighboring motorcycles on the east and north sides. This was caused by the radiation that built up, which ignited the neighboring surfaces and led to flashover. This behavior is consistent with the point-source radiation model, which has been shown to be the most robust and accurate method for estimating the radiative heat flux received by a target object from a nearby fire source [16]. As can be seen, the fire developed rapidly within the last 300 s (5 minutes), spreading from 1 motorcycle to 2, and then to 6 motorcycles within 500 s.

After 15 minutes, the fire had engulfed most of the entrance area, with a high flame height and a large radiation diameter (FIGURE 4(c) and (d)). This flashover occurred because most of the motorcycles had thermally decomposed, and the reaction zone developed above the decomposed material, resulting in a blazing fire followed by high heat release. At this moment, more than 10 motorcycles were burning, showing no sign of stopping.

FIGURE 5(a) and (b) explain the phenomenon of the incipient stage in the first 50 seconds, marked by the increase in HRR. The growth stage is shown from that point to the next 1000 s, proven by the significant rise in HRR, radiation, and convection to the environment. The rise in HRR, whether through radiation or convection, will continue until the fuel is depleted.

(a)

(b)

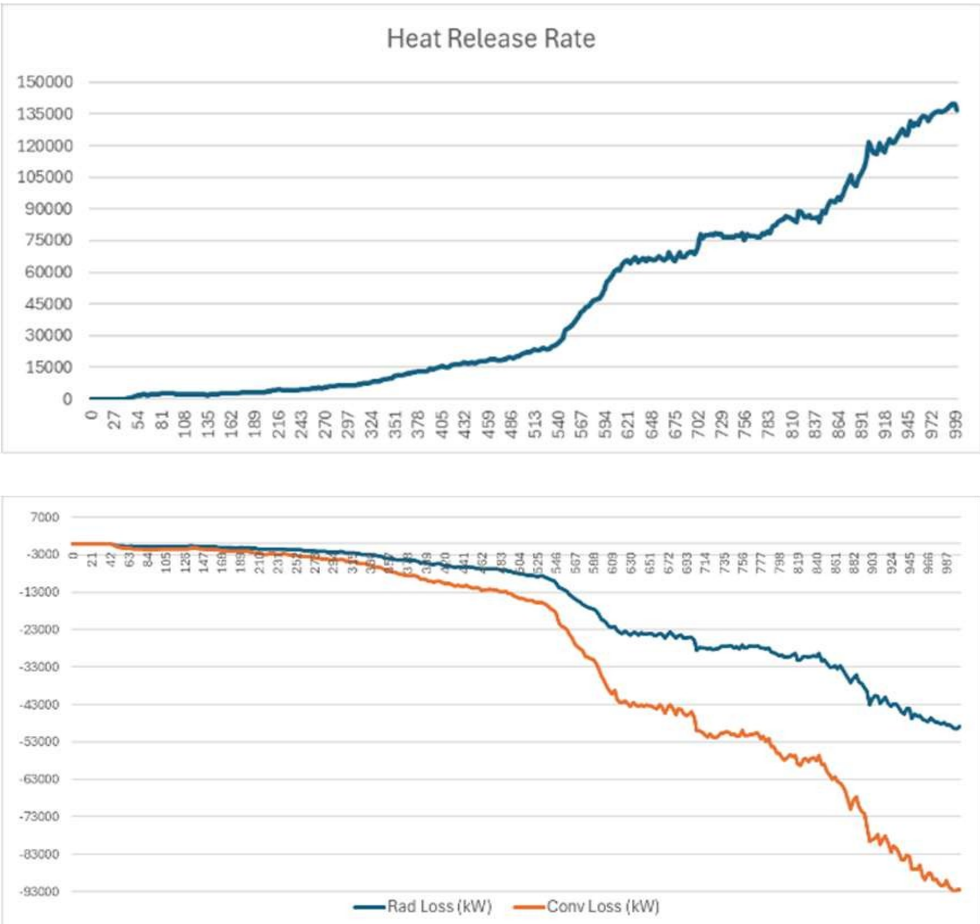


FIGURE 5. (a) Heat Release Rate (HRR) and **(b)** Radiation and Convection graphs for Scenario 1.

Fire Scenario 2

From FIGURE 6(a), it can be seen that the incipient stage of the fire started later compared to the motorcycle located near the wall at the entrance of the parking area. The location right in the middle created a cylindrical radiation surface, meaning that more heat was reflected than when a wall was present nearby. The fire started to grow about 3 minutes after the incipient stage, engulfing the motorcycle. This is the crucial time for fire suppression, since the flame height is still a manageable size, less than 1 meter. FIGURE 6(b) explains the effect of radiation on the surroundings; motorcycles on the north side started to burn. The motorcycle on the south side had not yet ignited because of the floor-level difference compared to the position of the ignition source. Since the fire grew bigger, as shown in FIGURE 6(c), where the HRR rose significantly, the radiation from the north side started to burn the south side. The flame size managed to overcome the floor-level difference and started to heat the south part.

The HRR and radiation/convection behavior for Scenario 2 are summarized in FIGURE 7. The incipient stage for scenario 2 started at 140 s after heating was initiated, and the growth rose significantly from 315 s onward. From this point, the HRR developed into a massive flame that increased radiation and convection, and when the flame size covered more than 10 motorcycles, the HRR reached a large value of around 5.5 MW. This value matches the results of research conducted by Kakae et al. [9]. This finding is also consistent with FDS-based studies of confined-space vehicle fires, in which increased ventilation and closer vehicle spacing were similarly found to intensify flame radiation and heat release rate [17].

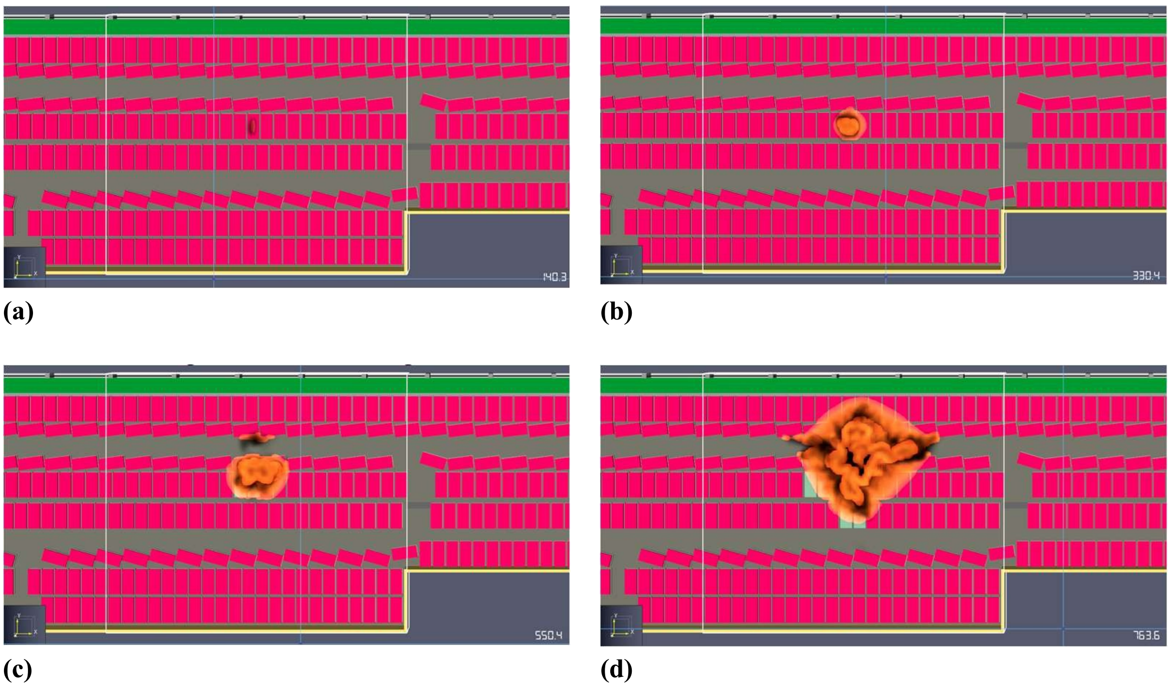


FIGURE 6. Fire development sequence for Scenario 2 (ignition in the middle of the parking area): **(a)** incipient stage at t = 140 s; **(b)** fire growth affecting the north side at t = 330 s; **(c)** fire spreading toward the south side at t = 550 s; **(d)** established fire at t = 763 s.

(a)

(b)

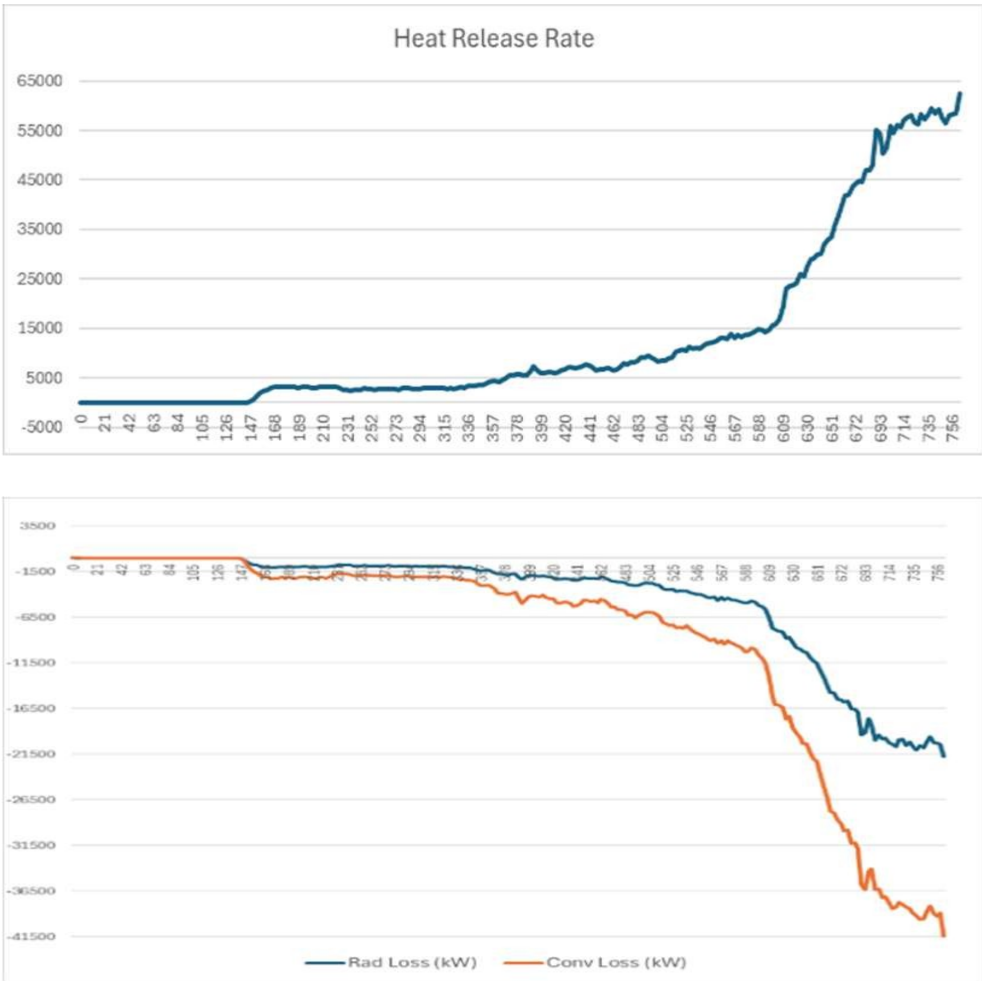


FIGURE 7. (a) HRR graph and **(b)** Radiation and Convection graph for Scenario 2.

Fire Scenario 3

Based on the results of the combustion simulation using the PyroSim application, the fire development process began from the predetermined ignition point in the rear parking area of the UNJ Campus. In the early stages, fires began to appear on motor objects in the corner near the exit, which became the source of the fire. In this phase, heat energy begins to be released from the burning material. The flame ignited at the top layer of material, marked as an orange block, and the ignition point and flame first became visible at 130 seconds. This is shown by the black clouds representing smoke development (FIGURE 8(a)). As the simulation time increased, fire began to develop due to the process of heat transfer through conduction, convection, and radiation. The heat generated from combustion causes the material around the fire point to also heat up. When the temperature of the material reaches a certain condition, the combustion process can extend to the surrounding area. So, at 405 seconds, the flames began to spread to motorcycles farther away as a result of the radiant heat produced (FIGURE 8(b)). The time between 350 s and 405 s is the critical period to extinguish the fire, since the HRR is still at a manageable level using a small fire extinguisher weighing less than 6 kg.

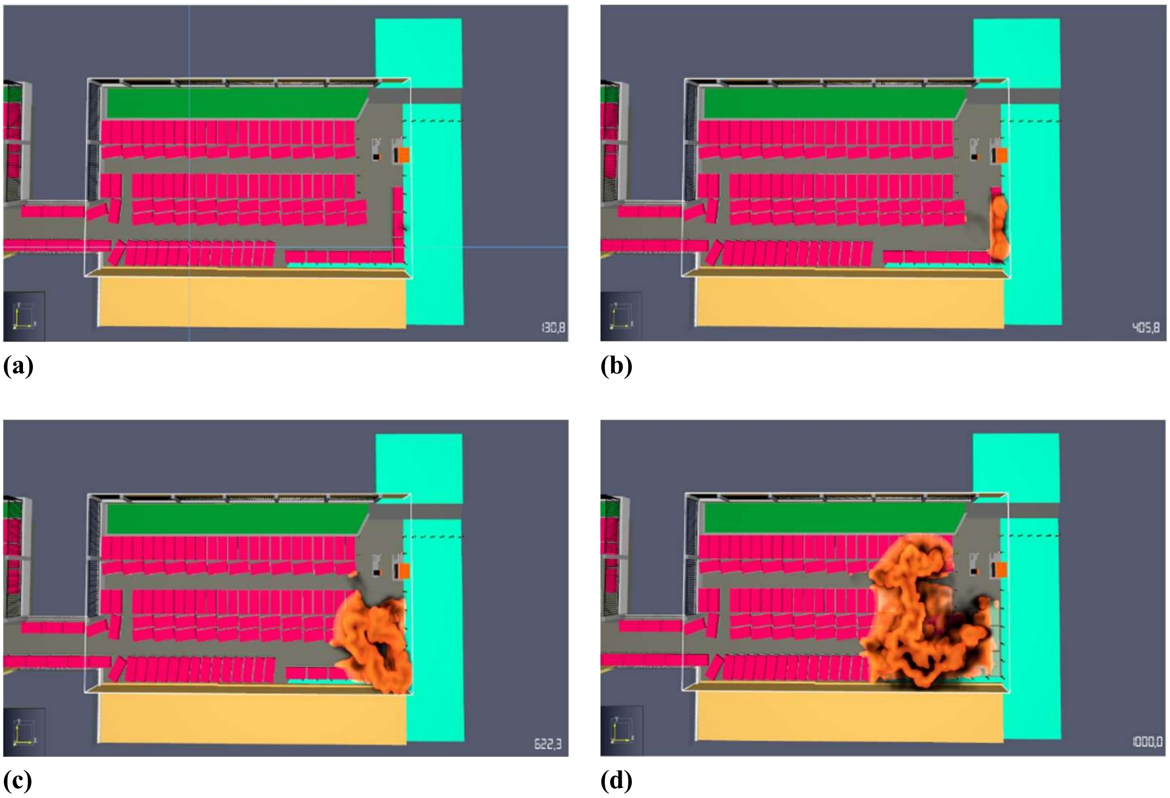


FIGURE 8. Fire development sequence for Scenario 3 (ignition at the exit): **(a)** ignition visible at t = 130 s; **(b)** fire spreading to farther motorcycles at t = 405 s; **(c)** fire engulfing about 10 motorcycles at t = 622 s; **(d)** fire spread to the central parking area at t = 1000 s.

At about 622.3 seconds the fire had developed from the starting point of ignition on the right side of the parking area (FIGURE 8(c)). The flames were seen getting bigger and began to burn about 10 motorcycles around the source of the fire. At this moment, a large amount of water and foam would be needed to fight the flame. At about 1000 seconds, the fire had grown significantly from the ignition point and spread to the central area of the parking lot (FIGURE 8(d)). The flames were seen to grow and began to burn more motorcycles around the source of the fire. This phase indicates that the flame is raging and difficult to suppress without sufficient cooling capacity. Also, at this phase, it becomes very difficult to localize the flame, and the radiation has already reached a dangerous level.

The HRR and radiation/convection behavior for Scenario 3 are summarized in FIGURE 9. Based on the HRR graph over time, the heat release rate at the beginning of the simulation was still very low because the fire was only in the ignition stage. As time goes on, the HRR value begins to slowly increase which indicates that the fire is starting to burn the material around the starting point of the fire. A fairly sharp increase in HRR occurred in a time span of about 450–650 seconds, indicating that the fire began to spread to the surrounding motor vehicles. After that, the HRR continued to increase until near the end of the simulation, which showed more and more vehicles and flammable materials involved in the combustion process. The highest HRR value occurs near the time of 950–970 seconds, then decreases slightly at the end of the simulation. This shows that the intensity of combustion begins to decrease

(a)

(b)

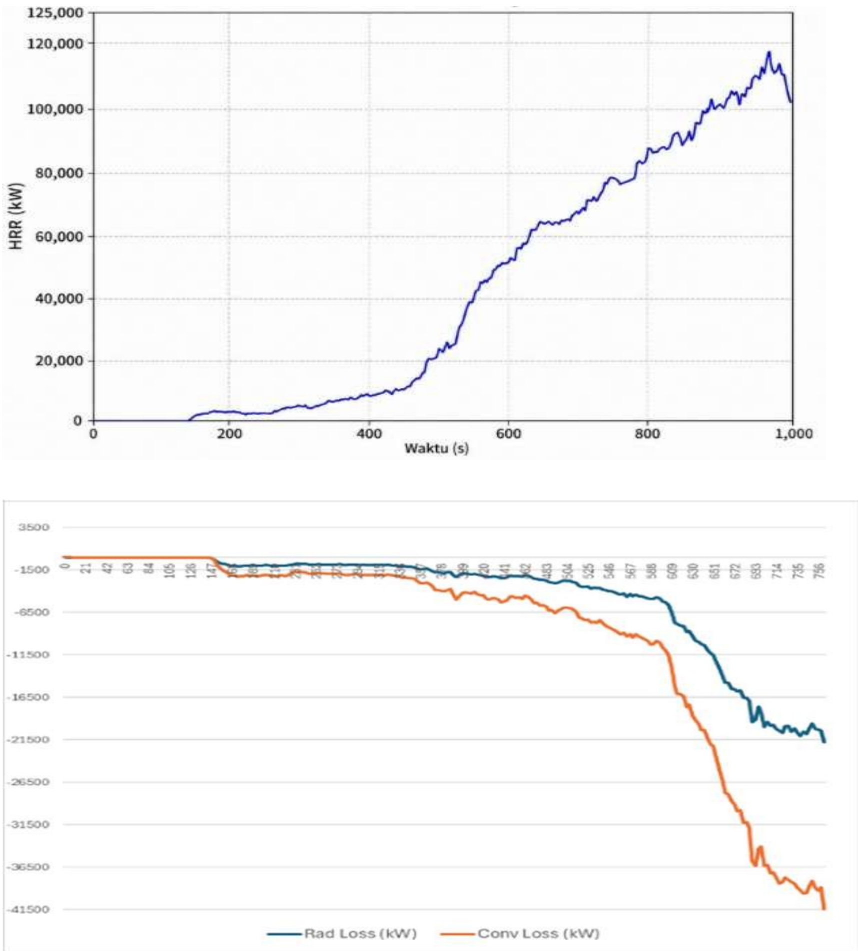


FIGURE 9. **(a)** HRR graph and **(b)** Radiation and Convection graph for Scenario 3.

because some of the burned materials have decreased the amount of fuel. On the Q_RADI graph against time, the calorific value of the radiation at the beginning of the simulation is still close to zero because the fire has not developed significantly. Once the fire begins to burn the material around the ignition point, the Q_RADI value begins to decline in a negative direction. This decrease in value indicates that radiant heat energy is beginning to be released from the combustion process. At a time span of about 500–650 seconds, there is a sharper decrease in Q_RADI, which indicates that the fire is starting to develop and spread to the surrounding motor vehicles. Until the end of the simulation, the value of the Q_RADI continued to move more and more negatively, indicating that the radiant heat generated was increasing as the intensity of combustion increased and the amount of vehicle material burned increased.

CONCLUSION

The flame start ranged from 41 seconds to 140 seconds; this stage is called the incipient stage. This terminology follows the classical description of enclosure fire development, which comprises the incipient, growth, flashover, fully developed, and decay stages [18]. The growth stage spanned from 228 seconds to 405 seconds; this is the threshold within which the fire can be suppressed, since the HRR is manageable with a light fire extinguisher of less than 6 kg made of dry chemical powder (a Class A/B/C-rated portable extinguisher as classified under NFPA 10 [19]). The fully developed stage lasted from 532 seconds to 622 seconds, during which the blaze is hard to control with dry powder. Greater efforts are needed, combining cooling and smothering methods, to fight the HRR at this level. At the fully developed stage, the HRR can reach 5.5 MW, releasing heat through radiation in a dangerous manner. A safe distance needs to be established to keep people away from burns; this means localization is required. Localization of the material will be difficult, since the gaps between motorcycles are narrow compared to the radiation power. From the simulated scenarios, close gaps, high HRR, and high radiation energy cause rapid thermal decomposition and large flame size.

From this situation, a safety dividing wall can be considered to prevent radiation from heating the surroundings. Separation between parking floor levels also helps delay heat transfer from radiation to the level below. The thickness and height of the divider wall must be taken into consideration, since the flame height determines the energy transfer. A higher wall provides better blockage of radiation, while a thicker wall provides better blockage of conduction and convection. Separation will give better geometry to direct the movement of smoke, consistent with numerical studies showing that the sequencing and placement of mechanical smoke-management systems significantly affect smoke distribution and visibility in enclosed parking areas [20].

In terms of scientific contribution, this study provides a quantitative, scenario-based characterization (ignition point at the entrance, middle, and exit of an open parking area) of the fire stages, heat release rate, flame spread, and conduction/convection/radiation behavior of motorcycle fires in an open parking environment. These findings offer a scientific basis for open motorcycle parking layout design (minimum inter-vehicle spacing and dividing-wall specifications), fire suppression equipment sizing, and evacuation time planning for campus and similar open-air parking facilities.

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