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SIMULATION OF AN ELECTRIC VEHICLE FIRE ON A RO-RO FERRY

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With the increasing demand for electric vehicles (EVs), the maritime transportation of these vehicles has become commonplace. Nevertheless, transporting EVs via car carriers presents a potential fire hazard. Data from the National Transportation Safety Board (NTSB) indicates that in 2020, 52 recorded fires involving EVs in the United States. These fires may be attributed to various factors, including battery malfunctions, overcharging, and damage sustained during transit. Once ignited, these fires can spread rapidly due to the proximity of the vehicles and the limited firefighting resources available on board. Numerous fire incidents involving car carriers transporting EVs have prompted safety concerns and underscored the necessity for enhanced regulations and safety protocols in recent years. According to the National Transportation Safety Committee (NTSC), Indonesia has reported 34 fires on vessels from vehicle incidents since 2007. Consequently, this research aims to mitigate damage and ascertain whether existing extinguishing systems effectively extinguish EV fires or if new recommendations are warranted. This study employs the Fire Dynamic Simulator (FDS) program to simulate fire behaviour, smoke propagation, and extinguishing. The findings highlight the importance of reducing fire temperatures to below 70°C within 400 to 500 s, particularly in the recommended scenario 2, which involves utilizing dedicated EV confined spaces. Ultimately, this approach minimizes smoke dispersal and emphasizes the necessity of lower temperatures for effective firefighting measures and reducing damage severity.

Keywords: electric vehicle (EV), fire dynamics simulator, Ro-Ro Ferry, reducing mortality

1 INTRODUCTION

The trend of using environmentally friendly vehicles is increasing, related to the evolution of sustainable transportation, especially in replacing conventional vehicles with non-fossil fuel vehicles. Several countries, including China and the United States, have committed to replacing their entire fleet of conventional vehicles with environmentally friendly fuel vehicles [1]. According to the Ministry of Energy and Mineral Resources (MEMR), Indonesia already has 94,000 units of EVs [3]. Based on the Planned Energy Scenario (PES) developed under cooperation between the MEMR and IRENA (International Renewable Energy Agency), Indonesia is projected to have 7 million units of EVs in 2030. In addition, based on the Transforming Energy Scenario (TES) research, Indonesia is projected to have 3 million units of EVs in 2030 and 51 million units of EVs in 2050, respectively, as shown in Fig. 1 [2,3]. Following Indonesia's net zero emissions target by 2060 [4], the number of EVs is projected to be 42 million units. EVs are a potential solution to achieving this goal, although the risk of fire, especially in the case of lithium-ion batteries, is a significant concern [5].

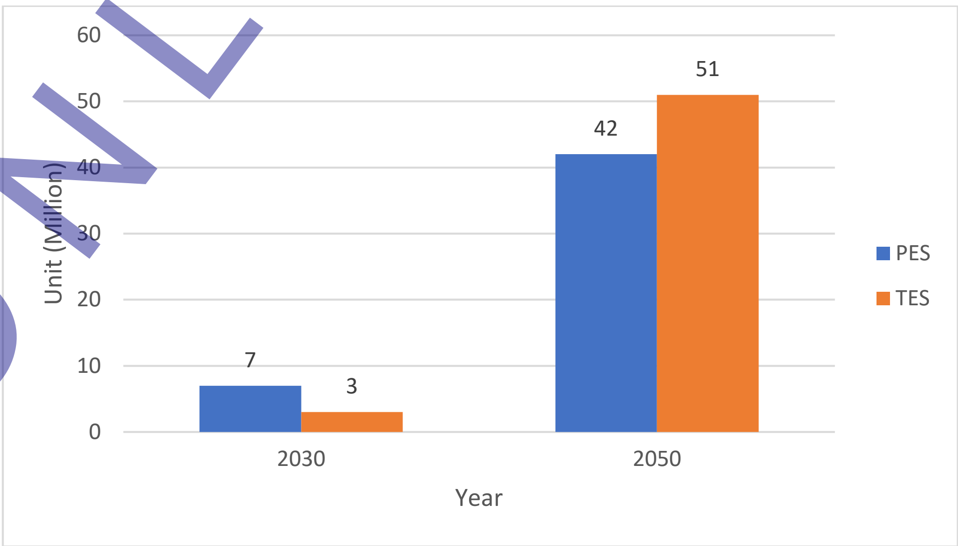

Fig. 1. Indonesia's projection regarding EV numbers based on PES (Planned Energy Scenario) and TES (Transforming Energy Scenario)

Several studies have also highlighted the safety challenges associated with fires in EVs. As the primary power source in EVs, lithium-ion batteries have the potential to catch fire, especially when experiencing thermal runaway [14,15]. Although fires can be extinguished using various methods, the risk of re-ignition and difficulty sustaining the battery are significant concerns. The accident data in 2018 showed several EV fire incidents at various locations, emphasizing the need for more effective preventive measures and careful handling [6].

In response to the risks associated with EVs, this study discusses fire-extinguishing methods for lithium-ion battery-based EVs. Water-based methods, such as water mist, have proven effective for extinguishing fires and cooling batteries [7]. However, additional challenges arise in the maritime environment, especially concerning Ro-Ro Ferries. Research on EVs' safety and firefighting ability on ferries is important, considering the risk of maritime accidents, especially fires, which continue to occur in Indonesian waters. This study also discusses the need for further research into extinguishing agent methods and improving Indonesia's maritime transportation safety and security regulatory system regarding the transportation of lithium-ion battery-based EVs.

This research is urgent because the world, including Indonesia, has agreed to change conventional vehicle fuel to alternative sources, such as lithium-ion batteries [1]. However, the extinguishing system for lithium-ion battery fires does not yet have a definite solution. Moreover, the nature of lithium-ion battery fires is very different from fuel oil vehicle fires. Apart from that, the transportation of EVs by ship will increase along with the increasing frequency of EVs in Indonesia; therefore, it is important to research how to extinguish lithium-ion battery-based EV fires on ships. In this research, Ro-Ro Ferries are used.

This paper consists of 5 parts. The first part explains the importance of evaluating fires caused by EVs on ships. The second part explains the originality of the research, described through a literature review of several researchers who have researched EV fires. The third section explains the use of the FDS to model fires in EVs by considering the location of the EV on the ship's vehicle deck. Meanwhile, the fourth section describes the simulation results with the FDS, which shows that the heat release rate value cannot be decreased due to the extinguishing coefficient, which has not been researched. The final section concludes the results of the fire evaluation and provides recommendations for mitigating EV fires.

2 LITERATURE STUDY

Numerous Fire Dynamic Simulator (FDS) models have been conducted, encompassing fire modeling in various environments such as buildings, ferries, and other structures [8,9]. This indicates that FDS is instrumental in modeling fire spread and estimating an object's heat release rate (HRR).

The safety plan for Ro-Ro ships was assessed through FDS, which facilitates risk assessment during a ship fire. The results from this simulation reveal four primary scenarios in which a fire may occur, one of which transpires on the car deck [10].

Ghiji et al. have indicated that the use of halon as a fire extinguishing agent is prohibited due to its adverse environmental effects, particularly its impact on the ozone layer [7]. Water has been identified as the most effective means of continuously extinguishing and cooling batteries. Water mist is recognized as highly effective for fire suppression; however, limited information exists regarding its application specifically for lithium-ion battery (LiB) fires. Combining water mist with additives and surfactants, or gas extinguishing media, is deemed the most promising method for extinguishing and cooling LiB fires. Nevertheless, further investigation is warranted concerning the fire properties of lithium-ion batteries when extinguished using water and other media [7].

Research on the types of electric vehicles (EVs) that have gained public acceptance is categorized into Battery Electric Vehicles (BEV) and Plug-in Hybrid Electric Vehicles (PHEV) [1]. Investigations into the components of lithium-ion batteries—such as the cathode, anode, electrolyte, and separator—alongside the design of the battery structure have been thoroughly conducted [7,11,12,13].

A full-scale experiment was performed on an EV powered by lithium-ion batteries [26,27]. The full-scale experiments involved incineration of several EVs equipped with heat sensors and thermocouples. In one instance, a vehicle fitted with sensors and thermocouples was ignited during a comprehensive fire test of EVs. All vehicles were incinerated entirely in an open environment for up to 70 minutes. Kang et al. determined that in the event of a BEV fire, the predominant contributor to the total heat release rate stemmed from the conventional material combustion of the BEV body (Peak Heat Release Rate (pHRR): 7.81 MW, Total Heat Release (THR): 7.53 GJ), rather than from the lithium-ion battery package (pHRR: 1.54 MW, THR: 1.30 GJ) [27]. However, the intensely ejected flame jet from the lithium-ion battery package aggravated the fire's spread to adjacent combustible materials, rapidly escalating the overall vehicle fire [5,16,27].

The heat release rate is critical for characterizing the flammability and fire hazards associated with materials [17,18]. Several investigations have been conducted to explore methods for extinguishing burning lithium-ion batteries. Researchers have concluded that, at present, the preeminent method for suppressing lithium-ion battery fires is water mist, albeit with further research required [7,19,20,21,22,23,24,25]. Additionally, studies concerning fire suppression agents for lithium-ion batteries have been undertaken, with F-500 combined with water mist being one effective agent. The findings indicate that fires attributed to lithium-ion batteries can be extinguished within 15 seconds, with no risk of reignition [24].

Based on the existing literature, the study of fire modeling related to electric vehicles represents the most recent and significant research aimed at elucidating the consequences of an EV fire on maritime vessels, particularly in light of the increasing prevalence of such incidents EVs.

3 METHODOLOGY

This research starts with data collection, problem identification, ship modeling, and determining the location of the fire. The explanation of each step in the methodology is as follows:

3.1 Data Collection

Data collection entails the acquisition of information or facts pertinent to addressing previously identified problems. The initial data set comprises the general arrangement of the Ro-Ro Ferry, as illustrated in Fig. 2, and is used to model the PyroSim application. Furthermore, a fire safety plan is required to ascertain the location of fire extinguishers to extinguish electric vehicle (EV) fires. This fire safety plan is procured through a direct survey of the Ro-Ro Ferry. Fig. 2 also delineates the decks' names, which convey information regarding the location of vehicles. The study concentrates explicitly on fires occurring on the car deck, situated on decks C, D, E, F, and G. Decks C and D are designated for use by lorries or large vehicles. In contrast, the remaining decks (E, F, and G) are allocated for private car parking.

Subsequent data on EV fires is systematically collected to support the objectives of this research and elucidate the causes of such fires. The data sought principally pertains to the combustion of lithium-ion batteries. A predominant cause of these battery ignitions is identified as thermal runaway. This information is processed and further analyzed to yield the study's results.

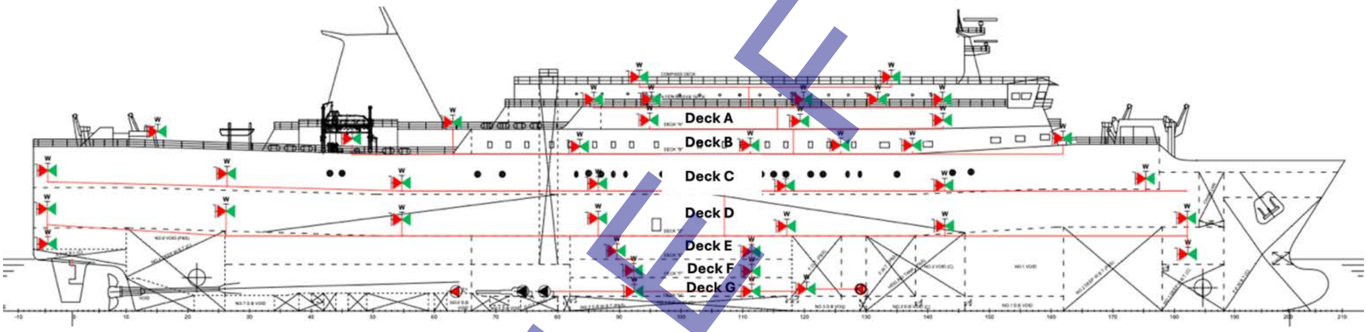

Fig. 2. General arrangement of the Ro-Ro ferry as the subject of study.

3.2 Problem Identification

The methodology commences with the identification of issues presented in the literature review. There is a singular concern: the fire extinguishing system of the Ro-Ro Ferry remains untested due to an electric vehicle (EV) fire that originated onboard and involved lithium-ion batteries. Moreover, there is a global inclination towards acquiring EVs, including those powered by lithium-ion batteries. Many Ro-Ro ferries in Indonesia cannot still manage fire incidents effectively. Comprehensive research and experimentation are imperative regarding the lithium-ion battery extinguishing system, particularly in thermal runaway situations and the appropriate water usage for extinguishment mist.

3.3 Ship Modeling

The ship modeling used the Fire Dynamics Simulator (FDS) with Pyrosim version 2023.1.0426. The vessel utilized for this simulation was a Roll-on/Roll-off (Ro-Ro) ferry, measuring a total length of 170 m, a perpendicular length of 158 m, a width of 2 m, a height of 17.20 m, and a maximum draft of 5.90 m, with a gross tonnage of 11,931 GT. This ferry can accommodate 690 passengers, 93 small vehicles, and 130 large lorries operated by a crew of thirty-three members. The complete deck of the vessel was modelled in Pyrosim to assess the repercussions of an electric vehicle (EV) fire scenario, albeit with a limited set of materials. The ship model was simulated with a mesh size of 1.5 m and compared with findings from prior research conducted by Kang et al. [27]. The simulation outcome, utilizing a mesh size of 1.5 m, is closely aligned with the heat release rate (HRR) and time curve documented in the previous study [27].

3.4 Scenario development

The positioning of Electric Vehicles (EVs) on the Roll-on/Roll-off (Ro-Ro) Ferry was initially formulated before the simulation. Consequently, the simulation scenario encompasses various factors, including the incidence of EV fires and their respective locations. Due to the absence of precise data from prior studies regarding the number of EVs aboard, a rough estimation is rendered by juxtaposing the existing number of EVs in Indonesia with the total vehicle count reported by the Ministry of Industry. As of September 2022, the number of car-type EVs in Indonesia reached 3,317 units. In contrast, based on Central Bureau of Statistics, Indonesia 2024, the total frequency of passenger vehicles in Indonesia after 2022 was recorded at 17.2 million. Therefore, this data allows for a comparative value of 0.0001928, which, when rounded, results in a value of 1. While this comparative figure may appear minimal, projections by the International Renewable Energy Agency (IRENA) suggest that Indonesia will boast over 30 million EVs by 2030 [2].

The placement of EVs on the Ro-Ro Ferry is informed by historical operational data, in which smaller vehicles typically occupy designated parking spaces. These vehicles are predominantly situated on decks E, F, or G, as depicted in Figure 2. Identifying the fire origin point is directly correlated with the positioning of EVs within the Ro-Ro Ferry. This determination is primarily based on documented incidents of Ro-Ro Ferry fires in Indonesia that were attributed to vehicles in the car decks, leading to the conclusion that the initial fire location is in the car deck of the Ro-Ro Ferry, specifically on decks E and G.

In light of the aforementioned considerations, the analysis is concentrated on two distinct scenarios: Scenario 1 proposes the placement of an EV on deck E, which is designated for small and private vehicles, and scenario 2 posits the placement of an EV on deck G, a specifically designed to incorporate additional containment space. Ghiji et al. have indicated that the most effective fire suppression method evaluated is a water mist system augmented with specific additives and surfactants [7]. By this assertion, the simulation employs the PyroSim feature to integrate sprinkler systems and nozzles designed to extinguish fires while emitting water and carbon dioxide.

3.5 Simulation of Fire and Extinguishing

The Pyrosim software facilitates a numerical fire simulation on the Ro-Ro Ferry. The primary objective of this analysis is to ascertain whether the existing fire suppression system is adequate to extinguish an electric vehicle (EV) fire. The parameters to be established include the simulation duration, which pertains to the fire curve, the specific moment the sprinkler system activates, and the duration required for fire suppression. Additionally, the spread of smoke from the fire and the efficacy of the ship's existing ventilation in mitigating smoke accumulation have been considered. Table 1 delineates the material components commonly utilized in electric vehicles, with the accompanying numbers representing the mass fraction of each material used as input for the numerical analysis.

Moreover, the numerical fire simulation analysis seeks to assess the efficacy of the fire safety plan for a Ro-Ro Ferry in managing incidents involving EV fires. The simulation results will indicate whether the current fire safety measures are sufficient for effectively extinguishing such fires. Should the analysis reveal inadequacies, a comprehensive review of the fire safety plan will be undertaken. The findings from the simulation will yield a thorough evaluation of the fire extinguishing system on the Ro-Ro Ferry. Recommendations have been developed to enhance the fire extinguishing system, ensuring that the vessel is better prepared for the transportation of battery-based electric vehicles in the future, thereby minimizing the impacts associated with potential fire risks.

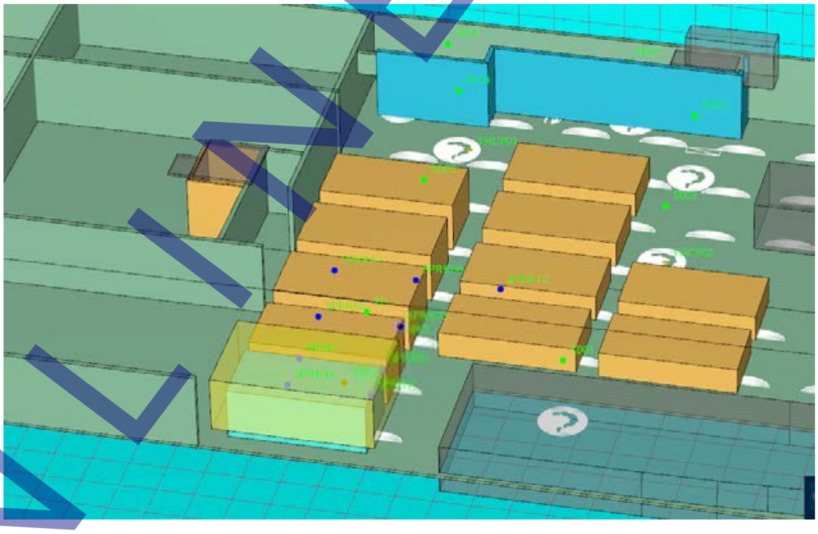

Fig. 3. An EV model of scenario 1 at deck E.

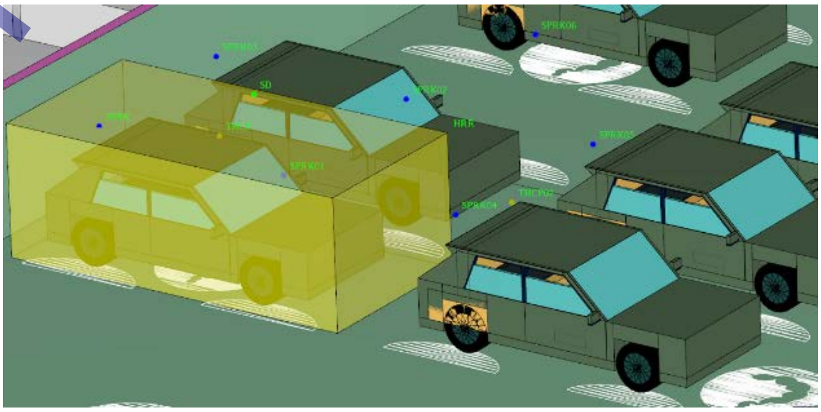

Fig. 4. An EV model of scenario 2 at deck G.

The evaluation has been further enhanced by employing a variety of electric vehicle (EV) material compositions relevant to the simulation's focus. Scenario 1 incorporates an EV model, simplified into a geometric configuration approximating the dimensions of an actual vehicle (5 m x 2 m x 2 m), as depicted in Fig. 3. This scenario features customized EV materials, as outlined in Table 1. Conversely, scenario 2 utilizes a model that closely resembles an EV, as illustrated in Fig. 4. This model was meticulously engineered to determine whether a more precise representation would produce heat release rate (HRR) measurements, temperature variations, and fire HRR graphs that accurately reflect the full-scale experimental HRR graphs presented by Kang et al. in 2023, as indicated in Fig. 4 [27]. However, a recognized limitation of this model is its lengthy simulation time.

Table 1. Material components of EVs in scenarios 1 and 2 [8]

No.	Mass Fraction	Material	Component Name
1	0.0064	Lithium	Battery
2	0.57912	Steel	Body
3	0.14	Aluminum	Body
4	0.08	Plastics	Interior
5	0.05	Glass	Windshield
6	0.02	Rubber	Tyre

4 RESULTS

Kang et al. undertook a comprehensive experiment regarding electric vehicle (EV) fires [27]. The findings of the research indicated that, in the case of battery electric vehicle (BEV) fires, the primary factor influencing the overall heat release rate is the combustion of the conventional materials constituting the BEV body (peak heat release rate: 7.81 MW, total heat release: 7.53 GJ). Consequently, the heat release rate parameter targeted in this simulation experiment closely approximated the heat release rate of 7.81 MW [27].

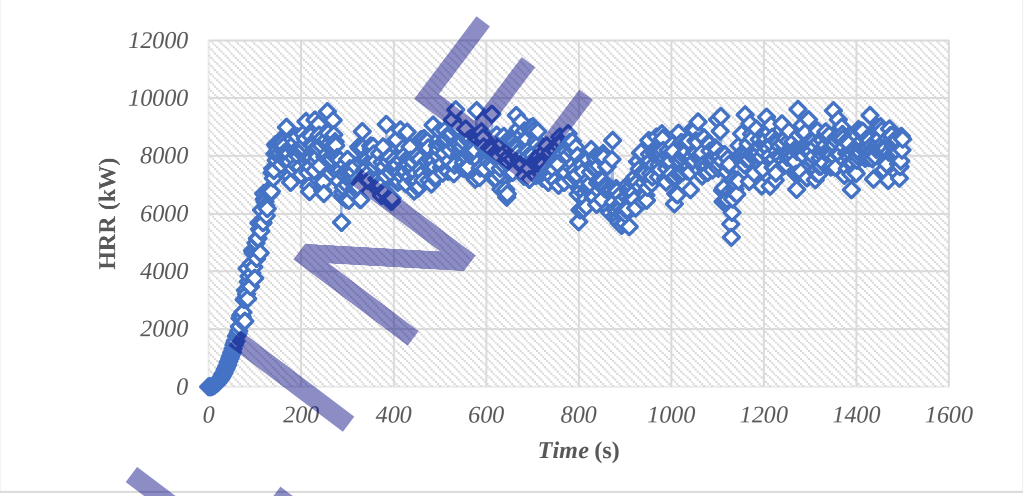

Fig. 5. HRR curve for scenario 1

In scenario 1, the model was simulated over 1500 s, employing a mesh size of 1.5 m, which was determined based on various experiments and the computational capabilities of the system. The ignited electric vehicle (EV) was positioned on deck E of the vessel, where smaller vehicles were also located. The heat release rate (HRR) curve illustrates that the peak HRR value reaches 10000 kW, commencing at 200 s, and subsequently fluctuates between 6000 kW and 9500 kW from 250 to 1500 s, as represented in Fig. 5. This value exceeds the findings of the experiments conducted by Kang et al. and Hynynen et al. [16,27]. The observed plateau in the HRR curve is attributed to the lithium battery (LiB) displaying reduced efficacy when extinguished by sprinkler systems. The smoke generated at 63.6 s nearly filled deck E and propagated to deck D, as illustrated in Fig. 6. Despite installing nine sprinklers, the temperature did not decrease over 1500 s. As depicted in Fig. 7, the maximum temperature reached 148°C at 200 s and fluctuated between 80°C and 140°C from 200 to 1500 s. However, the highest temperature recorded by the temperature sensor (thermocouple) on the floor reached 800°C, likely due to the fire not being exposed to water.

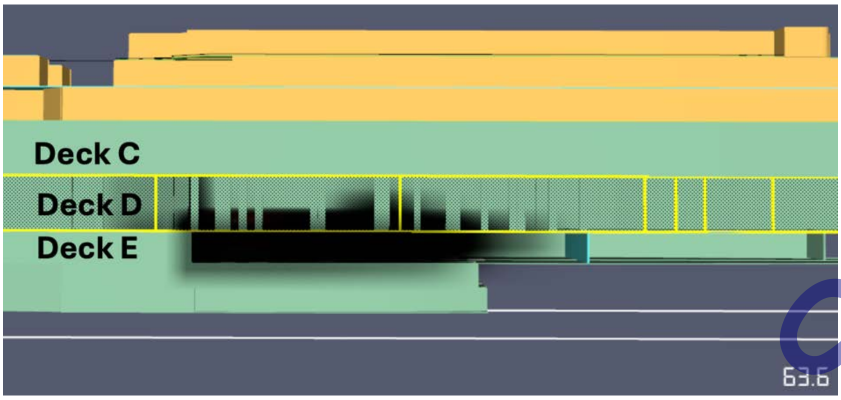

Fig. 6. Smoke spreading in scenario 1.

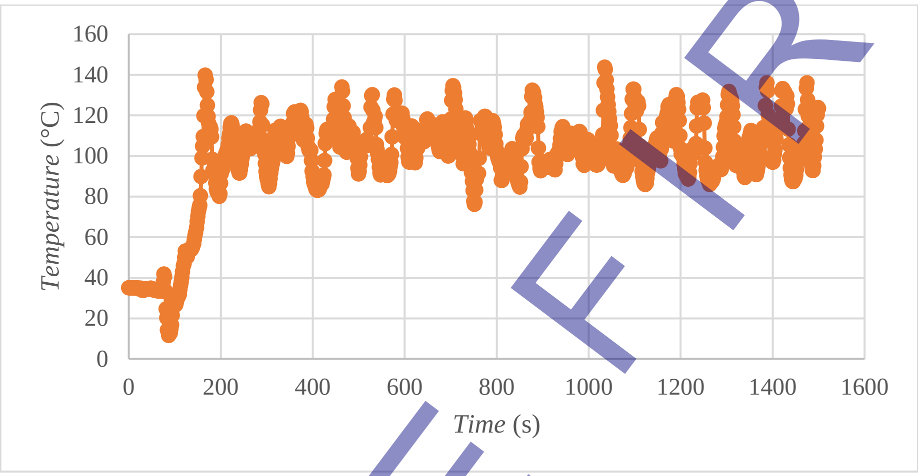

Fig. 7. Temperature curve of scenario 1.

In scenario 2, the model was simulated for 576 s, utilizing a mesh size of 1.5 m based on empirical data and computational efficiency. The ignited electric vehicle was strategically positioned on deck G of the vessel, where it was contained within a designated containment area. As depicted in the Heat Release Rate (HRR) curve presented in Fig. 8, the HRR escalates to a peak value of 2500 kW until 380 s, followed by a transient decline to approximately 250 kW before reverting to 2000 kW. This decrease may be attributed to the operational status of the sprinklers. Furthermore, the containment of the electric vehicle serves to mitigate the dispersion of smoke and fire, as evidenced in Fig. 9, indicating that the specified containment area effectively suppresses the fire. It is important to note that, similarly to Scenario 1, the fire was not entirely extinguished despite the activation of eight sprinklers; however, it did not propagate to other vehicles. This limited effectiveness of the sprinklers can be ascribed to their constrained efficiency in combating fires involving lithium-ion batteries.

In Fig. 10, the THCP sensor at the top of the vehicle recorded the highest temperature of 280°C at 550 s, previously dipping to around 70°C at 400 s. This indicates the significant role of the sprinkler in cooling the temperature, although the temperature ultimately rises again. Meanwhile, at the bottom of the vehicle, from 500 to 576 s, the temperature was approximately 130°C, differing from scenario 1, where the temperature from the sensor beneath the vehicle is higher than that from the sensor above it.

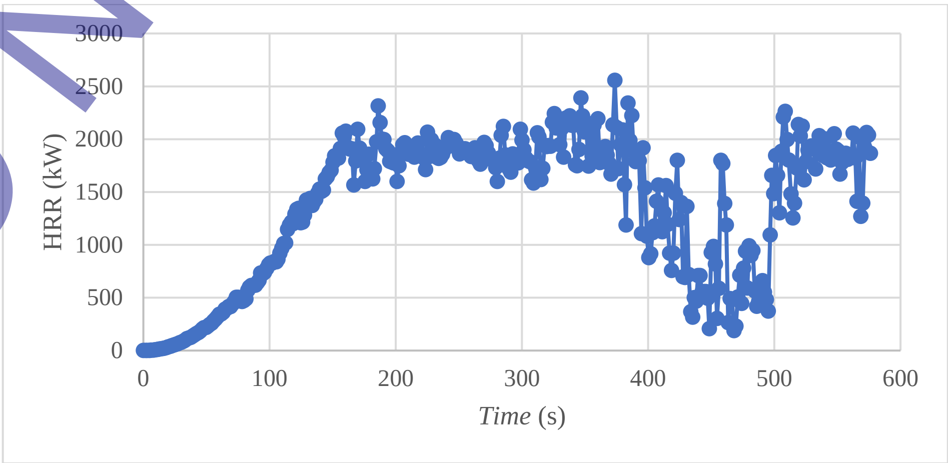

Fig. 8. HRR Curve for scenario 2.

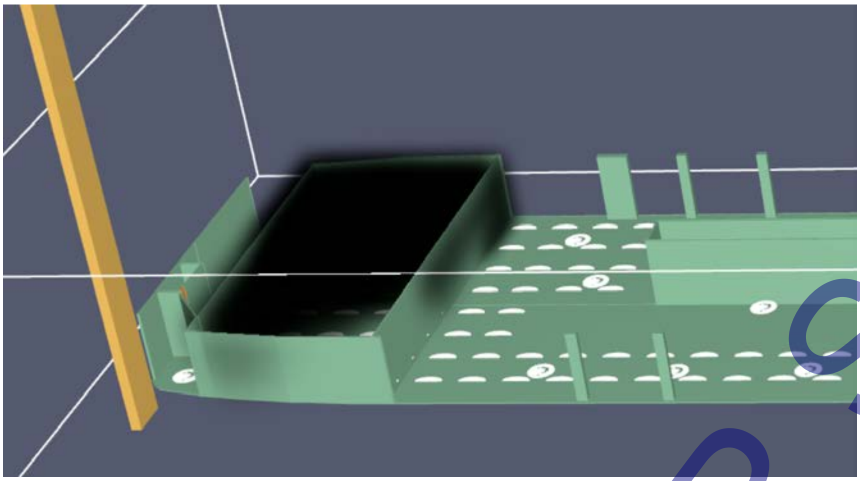

Fig. 9. Smoke spread in scenario 2.

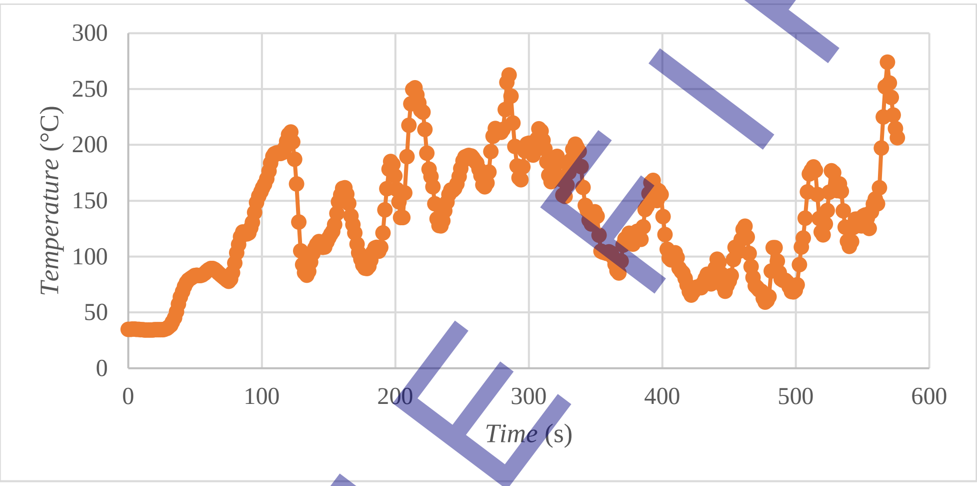

Fig. 10. Temperature curves of scenario 2.

5 DISCUSSION

In scenario 1, the fire on deck E persisted throughout the 1500 s simulation despite the activation of nine sprinklers. The highest recorded temperature reached 148°C, fluctuating between 80°C and 140°C, while the floor sensor indicated a significantly higher temperature of 800°C. This notable disparity suggests that the water from the sprinklers did not sufficiently douse the fire. The ineffectiveness of the sprinklers in penetrating and suppressing the intense heat generated by the lithium-ion battery fire highlights the limitations of conventional water-based systems in addressing such incidents. Conversely, in scenario 2, the fire on deck G was better controlled due to its position within a unique containment space. With eight sprinklers activated, the highest temperature recorded above the vehicle was 280°C, and the temperature beneath the vehicle stabilized around 130°C during the latter part of the 576 s simulation. Although the sprinklers managed to temporarily reduce the temperature, as evidenced by a drop to 70°C at 400 seconds, they ultimately failed to extinguish the fire completely. The containment space was crucial in moderating the fire’s intensity and maintaining the temperature within manageable limits. This comparison underscores the necessity of integrating containment designs with existing suppression systems for enhanced effectiveness.

Smoke dispersion in scenario 1 was rapid and extensive, filling deck E within 63.6 seconds and spreading to deck D. The uncontrolled spread of smoke created severe visibility challenges for firefighting crews, complicating their ability to locate and suppress the fire. Furthermore, the pervasive smoke posed significant risks during evacuation by obstructing escape routes, heightening panic, and increasing the likelihood of smoke inhalation, especially for passengers and crew on affected decks.

In contrast, scenario 2 significantly improved smoke management outcomes due to the unique containment space. The containment structure effectively restricted smoke dispersion, confining it within deck G and preventing it from reaching adjacent decks. This localized smoke control greatly enhanced the efficiency of firefighting efforts by maintaining clearer visibility and enabling firefighters to concentrate on the contained area. Additionally, evacuation risks were minimized as smoke was prevented from spreading, ensuring that escape routes on other decks remained unobstructed and safe for use.

Comprehensive mitigation measures must be implemented to enhance fire safety and response capabilities on Ro-Ro ships carrying EVs and address the challenges identified in both scenarios.

1. Crew Training Enhancements

Advanced firefighting training specifically designed to address the distinct hazards posed by lithium-ion battery fires is of paramount importance. Crew members ought to be proficiently trained in managing thermal runaway incidents and utilizing alternative suppression techniques, such as dry chemical agents or gaseous extinguishing systems. Realistic fire simulations incorporating electric vehicle fires may offer valuable hands-on experience and enhance overall preparedness. Furthermore, it is essential to conduct regular smoke management and evacuation drills to ensure that the crew can effectively navigate low-visibility scenarios and execute safe evacuation procedures for passengers.

2. Enhancements in Firefighting Equipment

Upgrading firefighting systems is essential to address the limitations of sprinklers. Supplementary suppression methods, such as F-500 with water mist, should be incorporated to combat lithium-ion battery fires effectively [24]. Firefighters should also have enhanced personal protective equipment (PPE), including high-temperature-resistant suits and advanced breathing apparatus. Tools like thermal imaging cameras can assist in locating fire sources, even in dense smoke conditions.

3. Design and Structural Improvements

Dedicated containment areas for electric vehicles (EVs) are essential in mitigating the propagation of fire and smoke. These areas should be constructed utilizing fire-resistant materials and integrated with thermal sensors and automated extinguishing systems. Furthermore, comprehensive ventilation and smoke extraction systems should be implemented to effectively clear smoke and prevent infiltration into adjacent spaces' decks.

4. Operational and Procedural Updates

Fire safety protocols must be regularly reviewed and updated to address the evolving risks associated with EV transportation. Stricter monitoring and segregation of EVs during loading operations should be enforced to ensure proper placement within containment spaces. Emergency communication systems should also be enhanced to provide clear instructions and guidance during fire incidents, ensuring that passengers and crew are well-informed and can respond effectively.

6 CONCLUSIONS

Simulation in scenario 1 did not successfully reduce the temperature of the fire. Nevertheless, simulation in scenario 2 successfully prevented high temperatures and significantly reduced to 70°C using sprinklers, which were activated from 400 to 500 s. To enhance safety measures, the implementation of a dedicated EV compartment is advised to restrict smoke from reaching other decks. A ventilation system can also be employed to help reduce smoke. The floor was the hottest area, with temperatures measured on decks containing burning vehicles reaching 800°C. Based on American Elements steel manufacturing, steel has a melting point of 1425°C-1540°C. Therefore, damage to the ship's structure is unlikely. The comparison of scenario 1 and scenario 2 highlights the critical role of containment spaces in managing the risks associated with EV fires. While sprinklers alone were insufficient in extinguishing the fires, their effectiveness was significantly enhanced when combined with containment structures, as observed in scenario 2. However, additional measures are required to address the challenges posed by lithium-ion battery fires entirely. Enhanced crew training, upgraded firefighting equipment, advanced containment and smoke management systems, and updated operational protocols are essential for enhancing fire safety on Roll-On/Roll-Off vessels. Implementing these strategies will ensure better preparedness, minimize risks during emergencies, and safeguard both passengers and crew. Some recommendations include establishing a dedicated parking area for EVs and using F-500 agents in combination with water mist to extinguish fires. Video monitoring has been introduced to the parking area to facilitate immediate fire response. Charging is prohibited on board except from outlets specifically designed and approved for battery charging. Such outlets should be able to be disconnected from the vessel's electrical system in an accessible location if the vehicle being charged ignites. Training should be provided to crew members who may respond to fires involving EVs. Crews engaged in firefighting should recognize EVs, understand the risks posed by high-powered equipment, and be aware of potential toxic gas releases. In subsequent research endeavors, the extinguishing coefficient (EC) must be determined through empirical experimentation to enhance the functionality of the Pyrosim application. The EC serves as a critical input variable that significantly influences the duration of fire extinguishment. Presently, the most reliable methodology for establishing the EC involves conducting comprehensive full-scale test experiments and systematically comparing the empirical results with those generated by the Pyrosim application. Further research and validation of the EC must be pursued. Moreover, additional investigations are warranted to design optimal spaces for electric vehicle (EV) parking areas.

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