Evaluation of Initial Fire Extinguishing System for Marine ESS

Seung-Yul Lee 1, In-Chul Park 2, Jeong-Hoon Park 2 and Hyo-Seok Jung 1, *

1 The Korea Ship and Offshore Research Institute, Pusan National University, Busan 46241, Republic of Korea; sylee7@pusan.ac.kr
2 Korea Marine Equipment Research Institute, Busan 49111, Republic of Korea; icpark@komeri.re.kr (I.-C.P.); park2604@komeri.re.kr (J.-H.P.)
* Correspondence: hyoseokjung@pusan.ac.kr; Tel.: +82-55-880-3552

Abstract: A fire in a marine energy storage system (ESS) has a high risk because of the special situation of the sea compared with land systems. To mitigate serious damage in the event of a fire in marine ESSs, initial suppression of the fire is extremely important. In this study, a unit module-based fire extinguishing system was constructed for the initial suppression of an ESS fire, and a unit module fire suppression test was conducted. In addition, multiple modules were constructed to evaluate the impact of unit module fire suppression on adjacent modules. Novac 1230 and F-500, which are adaptable to ESS fire control, were used as extinguishing agents. The fire suppression test results showed that both extinguishing agents could effectively suppress the ESS fire in the initial stage using the proposed fire extinguishing system. The results of this study will contribute to the development of maritime safety protocols and practical measures for reinforcing preparation for ESS-related fire accidents.

Keywords: marine ESS; ESS extinguishing system; lithium-ion battery; thermal runaway

1. Introduction

Marine energy storage systems (ESSs), which primarily serve as propulsion power sources or auxiliary energy sources for ships, have attracted considerable attention as a way of increasing the energy efficiency of ships owing to their high spatial efficiency and energy density [1,2]. Typically, ESSs are comprised of essential components including a battery for energy storage, a battery management system responsible for battery control and monitoring, a power conditioning system (PCS) for converting battery energy into both direct current (DC) and alternating current (AC), and a power management system facilitating their integration with power grids and generation facilities through PCS control. Notably, lithium-ion batteries serve as the cornerstone of these systems [3]. The increasing focus on eco-friendly ship technologies, driven by stringent greenhouse gas emission regulations set forth by the International Maritime Organization, has propelled ESSs and fuel cells into the spotlight as promising next-generation energy sources for ships [4]. In response to these regulatory measures, the optimization of ESSs’ operation has become imperative, with emphasis placed on charging and discharging control mechanisms to maximize efficiency. Specifically, ESS load calculations are meticulously conducted to ensure that the generator load aligns with the maximum efficiency load point, thereby facilitating the optimal power supply from the generator to the ESS. This strategic control over generator and power loads enables significant reductions in pollutant emissions during ship operations while simultaneously promoting fuel consumption savings. Despite the undeniable advantages offered by lithium-ion batteries, their utilization in ESSs necessitates stringent safety considerations. Due to the volatile nature of lithium-ion battery electrolytes, primarily composed of organic solvents, the risk of fire or explosion is inherent, particularly in scenarios involving exposure to high temperatures or external impacts [5].
A lot of researchers have actively investigated lithium-ion battery fires in order to find an effective extinguishing agent. A halon-based extinguishing agent has been reported by the National Technology Information Service, but it cannot control temperature rises and stop re-ignition after the extinguishment of a fire [6,7]. Heptafluoropropane-based extinguishing agents such as HFC-227ea and Novec 1230 were investigated and they showed outstanding performance in suppressing lithium-ion battery fires [8,9]. Water has been reported to have a cooling effect on the extinguishing of lithium-ion battery fires undergoing thermal runaway. Water is an excellent cooling agent due to its high heat capacity and latent vaporization, and it is able to mitigate the propagation of thermal runaway to surrounding batteries [10]. Water-based extinguishing agents such as F-500 and FireIce (water surfactants) have been studied for their effectiveness as extinguishants [11]. These water-based extinguishants show a better continued cooling ability compared to non-aqueous extinguishing agents [12]. However, water can react with lithium salt such as LiPF_6 and form toxic and harmful hydrogen fluoride [13]. Various types of extinguishing agents have been studied as fire suppressants for lithium-ion battery fires, but each has its own advantages and disadvantages. Furthermore, empirical evidence regarding whether these extinguishing agents effectively operate under all conditions is still lacking.

In the field of ESS fire suppression, the development of mathematical and numerical models to predict thermal runaway of lithium-ion batteries for battery packs with thermal runaway safety features has been reviewed as ESSs with multiple interconnected batteries can pose a significant safety issue because thermal runaway can cause a fire to spread [14]. Another study approached the development of dedicated fire extinguishing agents for ESS fires to minimize secondary damage resulting from extinguishing agent discharge due to malfunctions, by employing a localized discharge method at the rack level rather than a system-wide discharge system [15]. Consequently, ensuring the safety of ESS deployment on ships is paramount, with rigorous safety protocols and standards mandated to mitigate potential risks. The unique operational environment of ships at sea necessitates stringent safety standards to safeguard against the potential hazards posed by fires or explosions [16]. Unlike land-based systems, the remote and isolated nature of maritime operations amplifies the severity of any onboard incidents. In the event of an ESS fire onboard a ship, the situation can escalate rapidly if not promptly suppressed. Typically, ESS fires initiate with the thermal runaway of unit cells within a module, with the potential for fire propagation stemming from the transfer of thermal energy to adjacent cells, thereby triggering thermal runaway throughout the module [17]. Failure to suppress the module fire in its initial stages may result in the propagation of thermal runaway to neighboring modules and ultimately the entire ESS rack, rendering containment efforts futile. Thus, early-stage fire suppression within the ESS module, initiated at the onset of thermal runaway in a single cell, represents the most effective strategy to mitigate severe damage. It is more important to cool the cells in an ESS module, to prevent heat propagation, than to extinguish fires from a single cell. The best fire extinguishing medium for a lithium-ion battery is yet to be established [18].

In this study, a fire extinguishing system for the initial control of marine ESS fires was developed, and the extinguishing performance for single and multiple modules was evaluated using water-based extinguishing agents known to be suitable for lithium-ion battery fires as well as non-aqueous extinguishing agents.

2. Marine ESS Fire Extinguishing System

2.1. ESS Extinguishing Agents

Novec 1230 (3M Co., Berkshire, UK) [19] and F-500 (Hazard Control Technologies, Georgia, USA) [20], which are adaptable to lithium-ion battery fires, were selected as extinguishing agents, and their initial suppression performances for ESS fires were compared. Novec 1230 is a unique formulation that enables it to be stored and transported in a liquid state at standard room temperature and atmospheric pressure, ensuring
convenience and ease of handling. Its high electrical insulation properties make it particularly well-suited for fire control within ESS environments, as it can effectively suppress fires without compromising the integrity of electronic equipment. Novec 1230 is used as an effective fire extinguishing agent through the mechanism of action of the combination of heat absorption, free radical chain reaction interruption, cooling effect, and rapid evaporation. However, it is essential to exercise caution when handling Novec 1230 due to its relatively higher cost compared to other extinguishing agents. Additionally, its reaction with heat can produce hydrogen fluoride, a toxic byproduct that poses health risks to humans. Despite these considerations, Novec 1230 remains a preferred choice for fire suppression applications where electrical insulation and compatibility with sensitive equipment are paramount.

F-500 was developed by “HCT” in the United States. This extinguishing agent rapidly suppresses fires by encapsulating and cooling combustible liquids or vapors, effectively inhibiting oxidation reactions and preventing the spread of fire. F-500 is typically combined with water to form a foam agent, with a recommended concentration of 3% for combating Class D fires, including lithium-ion battery fires. This versatile formulation enhances its effectiveness in extinguishing a wide range of fire types, making it a valuable asset in fire suppression scenarios.

While Novec 1230 exhibits a good performance in rapid evaporation, F-500 provides effective cooling and penetrating properties. The selection between these extinguishing agents should consider factors such as the specific requirement of the ESS installation.

This study evaluates a marine ESS fire extinguishing system. However, it is worth noting that the fire extinguishing agents used for marine ESS systems are typically the same as those used on land. Table 1 presents the specifications of the ESS extinguishing agents used in this study.

<table>
<thead>
<tr>
<th>Properties</th>
<th>Novec 1230</th>
<th>F-500</th>
</tr>
</thead>
<tbody>
<tr>
<td>Color</td>
<td>colorless</td>
<td>dark brown</td>
</tr>
<tr>
<td>pH</td>
<td>-</td>
<td>7.0</td>
</tr>
<tr>
<td>Solubility in water</td>
<td>insoluble</td>
<td>soluble</td>
</tr>
<tr>
<td>Boiling point (°C)</td>
<td>49.2</td>
<td>121.1</td>
</tr>
<tr>
<td>Density (g/mL)</td>
<td>1.6</td>
<td>0.9</td>
</tr>
</tbody>
</table>

2.2. Fire Extinguishing System

A fire extinguishing system to spray water-based extinguishing agents for marine ESS fire suppression was constructed as shown in Figure 1a. This comprehensive system comprises essential equipment for the effective distribution of water-based extinguishing agents, including a high-capacity pump, an extinguishing agent tank constructed from corrosion-resistant stainless steel with a substantial volume of 125 L, a network of flexible pressure hoses utilized as pipelines to transport the extinguishing agents, and specialized full-cone nozzles manufactured from durable stainless steel 304. Notably, the pump is equipped with a pump-up head of 52 m or higher, ensuring sufficient pressure to facilitate the effective dispersion of the extinguishing agents across the targeted area. The stainless steel composition of the extinguishing agent tank serves as a protective measure against corrosion, safeguarding the integrity and longevity of the tank. The flexible pressure hoses employed as pipelines offer versatility and ease of installation, enabling seamless transport of the extinguishing agents to the desired locations within the ESS environment. Moreover, the full-cone nozzles are meticulously designed with a flow rate of 3.2 LPM, an operating pressure of 5 bars, and an injection angle of 60°, facilitating optimal coverage and dispersion of the extinguishing agents. Figure 1b shows the components of the fire extinguishing system.
Figure 1. Fire extinguishing system for ESS; (a) Schematic; (b) Components.

3. Experiment

The investigation into the efficacy of a fire extinguishing system in mitigating thermal runaway events within an ESS was conducted within the confines of a fire test building measuring 20 m × 25 m × 13 m, outfitted with dust collector fans and fire insulation, thereby simulating realistic fire scenarios. Thermal runaway incidents were deliberately induced in both a unit module and multiple modules, following the standardized procedures delineated in UL 9540A [21]. The primary objective of this study was to evaluate the suppression performance of the fire extinguishing system under these controlled yet representative conditions. Upon positioning the ESS rack centrally within the fire test building, meticulous precautions were taken to ensure the safety and integrity of the experimental setup. The fire extinguishing system, comprising essential components such as the extinguishing agent tank, pump, pipelines, and extinguishing nozzles, was seamlessly integrated with the ESS rack via interconnected pipelines. To mitigate any potential risks associated with the operation of the extinguishing system, strategic placement of the extinguishing agent tank and pump at a safe distance from the rack was implemented, complemented by the installation of protective panels to fortify their structural resilience against potential fire-related hazards.

The induction of thermal runaway events within the ESS modules constituted a critical phase of the experimental protocol, necessitating precise control and monitoring to ensure accurate data collection. Leveraging a DC power supply, voltage was meticulously applied to heating pads strategically positioned within the ESS modules, thereby initiating the thermal runaway phenomenon and elevating temperatures within the individual cells to critical levels of over 80 °C. This controlled approach enabled the replication of...
realistic fire conditions within the experimental setup, facilitating a comprehensive evaluation of the fire extinguishing system’s efficacy in suppressing thermal runaway events.

To capture and analyze temperature variations within the ESS modules ensuing from thermal runaway, K-type thermocouples were used to measure the temperature change inside the module caused by thermal runaway. These thermocouples served as instrumental probes, facilitating real-time temperature monitoring and data acquisition, thereby enabling researchers to capture nuanced insights into the thermal dynamics associated with the thermal runaway phenomenon. Concurrently, a sophisticated data logger boasting a capacity of 20 channels was employed to meticulously record and store the acquired temperature data, ensuring comprehensive coverage and accuracy throughout the experimental duration. Imaging was performed using a camera to observe the fire caused by the thermal runaway of the ESS module and the suppression effect of the fire extinguishing system. See Figure 2.

Figure 2. Fire test room.

3.1. ESS Module

Figure 3a shows the internal structure of the ESS module, consisting of 160 18650 type cylindrical lithium-ion batteries connected in series, serving as unit cells. Each unit cell possessed a voltage rating of 3.7 V and a current capacity of 2500 mAh, resulting in a module capacity of approximately 1.48 kW. Additionally, Figure 3b shows the casing of the ESS unit module, featuring three apertures in the front section of the rack to accommodate the installation of fire extinguishing system nozzles.

Figure 3. Photograph of ESS module; (a) Lithium-ion battery cells; (b) ESS unit module.
Prior to the experimental phase, preprocessing of the ESS module was conducted, involving two cycles of charging and discharging to ensure uniformity and stability. The module’s state of charge was maintained at 100% and stabilized for one hour preceding the experiment to establish baseline conditions. Thermal runaway was initiated within the ESS module by affixing a heating film measuring 20 cm × 5 cm to five individual cells at the module’s center; activation of the heating film was performed with 12 volts and 10 watts power output. Temperature changes resulting from thermal runaway were monitored using K-type thermocouples installed on both the single cells and adjacent cells within the module as illustrated in Figure 3a.

3.2. Unit Module Fire Suppression Test

This study addresses the critical issue of fire propagation in ESS installations, particularly focusing on the role of thermal runaway in initiating and propagating fires within ESS modules. The research aims to investigate methods for controlling heat transfer to adjacent cells within the module to prevent the spread of fires throughout the ESS. Experimental analysis was conducted using a single unit module installed in an ESS rack, with a focus on evaluating the effectiveness of fire extinguishing systems in suppressing thermal runaway-induced fires. To simulate heat transfer to adjacent cells resulting from thermal runaway, a single unit module was installed in the ESS rack as shown in Figure 4. Extinguishing nozzles, integral components of the fire extinguishing system, were strategically positioned in three holes in the front section of the module and on top of the rack. Thermal runaway of unit cells was induced by heating five cells at the module’s center using a heating film. To monitor temperature variations and assess the efficacy of fire suppression measures, four K-type thermocouples were installed at the cells undergoing thermal runaway and adjacent cells within the module. Real-time temperature measurements were recorded throughout the fire suppression process. Thermal runaway was initiated by activating the heating film within the cells, and the fire extinguishing system was activated upon detection of off-gas eruption and flames from the cells. The operation of the heating film ceased upon the onset of off-gas eruption and flames, triggering the release of the extinguishing agent for approximately 10 s. Temperature monitoring continued for over 300 s to verify re-ignition after the extinguishing agent was dispensed. Two types of extinguishing agents for ESS fires (Novec 1230 and F-500) were used, and their fire suppression effects were examined.

![Figure 4. Configuration of ESS unit module fire suppression test.](image)

3.3. Multi-Module Fire Suppression Test

The multi-module fire suppression test was conducted to assess the impact of the process of suppressing the fire generated in the unit module on adjacent modules by
installing dummy modules above and below a unit module. The dummy modules were installed to assess the impact on adjacent modules during the suppression process of a fire originating in the unit module (target module). For the test, one unit module and dummy modules were installed in the ESS rack as shown in Figure 5. Extinguishing nozzles, which are the components of the fire extinguishing system, were installed in the three holes in the front part of the unit module and on top of the rack. The thermal runaway of unit cells was caused by heating the five cells at the center of the unit module using a heating film. Four K-type thermocouples were installed at the cells that caused thermal runaway and adjacent cells to measure the thermal runaway of the unit cells and the temperature change inside the module during the fire suppression process. The temperature was measured in real time. Thermal runaway was induced by heating the internal cells of the unit module using the heating film installed inside the cells. The operation of the heating film was stopped at the time of the off-gas eruption and flames from the cells inside the module, and the extinguishing agent was released for approximately 10 s by operating the fire extinguishing system. The temperature was monitored for more than 300 s to verify re-ignition after spraying the extinguishing agent. Two types of extinguishing agents for ESS fires (Novec 1230 and F-500) were used, and their fire suppression effects were examined.

Figure 5. Configuration of ESS multi-module fire suppression test.

4. Test Results
4.1. Unit Module Fire Suppression Test Results

Figure 6 shows the results of the unit module fire suppression tests, depicting key events and procedures involved in the experimental setup and fire suppression process. In Figure 6a, a unit module is installed in the ESS rack, followed by the induction of thermal runaway by heating unit cells within the module using a heating film. During thermal runaway, flammable gas is generated through internal electrolyte decomposition, leading to a discharge pressure exceeding the battery’s design threshold. Consequently, off-gas is released through the vent, accompanied by flames resulting from combustion, as shown in Figure 6b. As the primary objective of this study is to achieve rapid suppression of ESS fires, the fire extinguishing system is activated almost simultaneously with the onset of thermal runaway within the unit module. The onset of thermal runaway in a lithium-ion battery is defined as the point at which the exothermic reactions within the battery become self-sustaining, leading to a rapid increase in temperature. Figure 6c shows the operation of the fire extinguishing system, wherein the extinguishing agent is sprayed through the extinguishing nozzles to suppress the fire and cool the module. Subsequently, temperature monitoring is conducted for a predetermined duration to observe any signs of re-
ignition within the module. The test concludes when no further temperature rise is observed, indicating successful fire suppression, as shown in Figure 6d.

Figure 6. Progress in testing fire suppression performance of ESS unit module; (a) test setup, (b) thermal runaway of cells inside of unit module, (c) extinguishing agent (Novec 1230) release, and (d) after unit module fire is extinguished.

Figure 7 shows the results of the unit module fire suppression test using the Novec 1230 and F-500 extinguishing agents, detailing the temperature changes within the module cells over time. K-type thermocouples were strategically installed on the surface of cells heated with a heating film, as well as on adjacent cells, to monitor temperature variations during the tests. As shown in Figure 7a, depicting the results of the unit module fire suppression test with Novec 1230, thermal runaway induced by cell heating occurred 318 s after the test initiation, with a peak temperature of 386.5 °C recorded at TC 2. Subsequent to the onset of thermal runaway, the extinguishing agent was promptly sprayed, leading to a significant decrease in temperature within the module. Although a temperature rise of 47.1 °C was observed at TC 2 approximately 20 s after the temperature drop, the temperature gradually decreased thereafter, with no instances of re-ignition or special events observed.
Figure 7. Time–temperature variation of the unit module as a result of fire suppression test; (a) Novec 1230; (b) F-500.

Figure 7b shows the results of the unit module fire suppression test with the F-500 extinguishing agent. Thermal runaway occurred 332 s after the test initiation, with a peak temperature of 388.1 °C recorded at TC 2. Following the initiation of thermal runaway, the extinguishing agent was immediately sprayed, resulting in a substantial reduction in temperature within the module. Despite a negative peak observed at TC 2 between 336 s and 353 s after the temperature drop, likely due to thermocouple error, temperature measurements remained within the normal range thereafter, gradually decreasing without any indication of re-ignition.

The comparative analysis of fire suppression effectiveness using the Novec 1230 and F-500 extinguishing agents provides valuable insights into the performance and suitability of each agent for suppressing thermal runaway-induced fires in ESS modules. By evaluating the ability of each agent to rapidly contain and extinguish fires, this research informs the selection of optimal fire suppression strategies tailored to specific ESS configurations and operational requirements. Figure 8 shows a comparison of the temperature drop effect of the Novec 1230 and F-500 extinguishing agents on TC 2 of the single module. The surface temperature of the battery cell of TC 2 attached to the cell with heating film was set to 100 when the peak temperature was reached by thermal runaway, and the ratio of the temperature drop after the extinguishing agent was released was calculated. In the case of Novec 1230, the initial temperature decrease was higher than F-500, and the rate
of temperature drop was almost the same at 240 s after the extinguishing agent was released. Both of the extinguishing agents used in the fire extinguishing system for the ESS unit module were effective for the initial fire suppression of the module. Novec 1230 exhibited a slightly higher cooling effect for the cells that caused thermal runaway than F-500.

![Comparison of the temperature decrease effect of Novec 1230 and F-500 on fire extinguishing agents on the cell (TC 2) of the unit module.](image)

**Figure 8.** Comparison of the temperature decrease effect of Novec 1230 and F-500 on fire extinguishing agents on the cell (TC 2) of the unit module.

4.2. Multi-Module Fire Suppression Test Results

The multi-module fire suppression test results provide a detailed chronological account of the experimental procedure and outcomes, as shown in Figure 9. Figure 9a shows the setup, wherein multiple modules are strategically positioned within the ESS rack, with dummy modules installed both above and below the target module responsible for inducing thermal runaway. This arrangement ensures comprehensive coverage and facilitates the assessment of the fire suppression system’s efficacy across multiple modules. Thermal runaway is intentionally induced within the target module by applying heat to the unit cells, as shown in Figure 9b. This process involves the utilization of a specialized heating film, meticulously positioned to initiate thermal runaway in a controlled manner. Upon detection of thermal runaway within the target module, the fire extinguishing system is promptly activated to mitigate the fire hazard. Figure 9c shows this pivotal moment, depicting the rapid deployment of the fire extinguishing agent through the nozzles. The simultaneous activation of the system ensures swift intervention, effectively containing the fire and preventing its escalation to neighboring modules. This prompt response is crucial for minimizing potential damage to the ESS and mitigating the risk of fire spreading throughout the rack.
Following the application of the extinguishing agent, continuous monitoring of temperature dynamics within the modules is conducted to assess the effectiveness of fire suppression and detect any signs of re-ignition. This post-suppression monitoring phase is essential for verifying the system’s ability to maintain fire control over an extended period. The test was completed when no temperature rise was observed. Figure 9d shows the completion of the test.

Figure 10a shows the multi-module fire suppression test results when Novec 1230 is used as the extinguishing agent. The temperature change of the cells inside the modules over time can be seen. A total of 12 K-type thermocouples were installed inside the modules, including four in the target module (TC 1 to 4), four in the dummy module above the target module (TC 5 to 8), and four in the dummy module below the target module (TC 9 to 12). The thermocouples installed in the target module were the same as those installed in the unit module. As shown in Figure 10a, the thermal runaway caused by cell heating occurred 344 s after the start of the test, at a temperature of 247.8 °C at TC 2. Following the occurrence of thermal runaway, the extinguishing agent was sprayed immediately and the temperature inside the module rapidly decreased. For TC 2, a temperature
rise of 6.9 °C was observed for approximately 12 s at 508 s after the temperature drop. However, the temperature slowly decreased subsequently with no special event. For TC 1, a temperature rise of 21.7 °C was observed for approximately 49 s at 398 s. However, the temperature slowly decreased, subsequently, with no special event or re-ignition. The heat transfer to the adjacent dummy modules caused by the thermal runaway of the target module was not observed as indicated by the temperature change in TC 5 to 12 as shown in Figure 10a.

Figure 10. Time–temperature variation of the multi-module as a result of fire suppression test; (a) Novec 1230; (b) F-500.

Figure 10b shows the multi-module fire suppression test results when F-500 is used as the extinguishing agent. The temperature change in the cells inside the modules over time can be observed. K-type thermocouples inside the modules were installed similarly to the aforementioned fire suppression test that used Novec 1230. As shown in Figure 10b, the thermal runaway caused by cell heating occurred at 334 s after the start of the test at a temperature of 342.7 °C at TC 3. Following the occurrence of thermal runaway, the extinguishing agent was sprayed immediately and the temperature inside the module rapidly decreased. For TC 2, a temperature rise of 17.3 °C was observed for approximately 3 s at 377 s after the temperature drop. However, the temperature gradually decreased, subsequently, with no special event or re-ignition as in the case of Novec 1230. The heat transfer to the adjacent dummy modules caused by the thermal runaway of the target module was
not observed as indicated by the temperature change in TC 5 to 12 in Figure 10b. The fire suppression results for the ESS multiple modules by the fire extinguishing system showed that fire propagation to the adjacent modules could be prevented because the system enabled the initial suppression of the target module in which thermal runaway occurred.

Figure 11 shows a comparison of the temperature drop effect of the Novec 1230 and F-500 extinguishing agents on TC 2 of the multi-module system. As in the case of the single module, the rate of temperature drop in TC 2 was calculated. The initial temperature drop for Novec 1230 was slightly higher than for F-500, and the ratio of the temperature drop was almost the same 150 s after the extinguishing agent was released. In both the single and multi-module cases, the temperature drop of the initial temperature was higher for Novec 1230.

5. Conclusions

In this study, the performance of the fire extinguishing system was evaluated for the unique characteristics of ESS fires that may occur on ships. Fire control in the initial stage of a fire was possible owing to rapid intervention through the ESS unit module-based approach. In addition, the possibility of minimizing the expansion of fire to the entire ESS via initial fire suppression was presented using the ESS multi-module-based approach.

In particular, we evaluated the performance of the system for suppressing ESS fires in the initial stage. In the results of the tests that used Novec 1230 and F-500 as extinguishing agents, excellent ESS fire suppression effects were confirmed in the unit module-based and multi-module-based fire suppression systems. Both the Novec 1230 and F-500 extinguishing agents demonstrated effectiveness in the initial suppression of fires within the ESS unit module. However, the study revealed some distinctions in their performance. Notably, Novec 1230 exhibited a slightly higher cooling effect for the battery cells experiencing thermal runaway compared to F-500.

This study emphasizes the necessity of specialized fire suppression systems for maritime energy storage systems (ESSs), considering the unique conditions of the marine environment. With the potential risks of ESS fires that could lead to major disasters at sea, the research results on systems capable of preventing the escalation of fires through early suppression are expected to contribute to the development of maritime safety protocols and practical measures to enhance preparedness for ESS-related fire incidents.
The suppression effect of the fire extinguishing agent was evaluated solely based on the temperature changes of the ESS modules in this study. Therefore, future research should adopt an approach that focus on the suppression mechanism of the fire extinguishing agents.

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