# CFD modelling of energy storage room fire with low-pressure water mist extinguishing

## Modelowanie CFD pożarów magazynów energii z systemami gaszenia mgłą wodną

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The increasing use of lithium-ion batteries has made their fire prevention and protection a critical aspect for users. This article presents the application of computational fluid dynamics (CFD) modelling of energy storage room fire and its low-pressure water mist extinguishing. Real-scale experiments and CFD simulations indicated that without fire extinguishing, battery fires can lead to uncontrolled temperature rises, jet flames, or explosions. While the installation of water mist systems can prevent the fire propagation, lower the temperature, and control fire propagation on adjacent modules, even in complex battery systems. The CFD simulations proved the effectiveness of this approach in the design of water mist systems in energy storage rooms. The article presents a structured research procedure in which the computer model allows for the analysis of fire development from a single cell to a full-scale energy storage facility.

*Keywords: battery fire; energy storage room; CFD;*

Wraz z dynamicznym rozwojem technologii magazynowania energii, opartych na bateriach litowo-jonowych, problem ich bezpieczeństwa pożarowego nabiera coraz większego znaczenia. Baterie te, zawierające palne elektrolity organiczne, w warunkach przegrzania, przeciążenia lub uszkodzeń mechanicznych mogą ulec zjawisku ucieczki termicznej, prowadzącej do emisji gazów, zapłonów wtórnych, a nawet eksplozji. Artykuł prezentuje wyniki badań numerycznych (CFD) dotyczących skuteczności systemów gaszenia z użyciem niskociśnieniowej mgły wodnej w pomieszczeniach magazynów energii. Badania wykazały, że choć mgła wodna nie zatrzymuje samego procesu ucieczki termicznej w pojedynczym ogniwie, znacząco ogranicza propagację ognia, obniża temperaturę oraz redukuje ryzyko zapalenia sąsiednich modułów. Modelowanie CFD w programie Fire Dynamics Simulator pozwoliło na odwzorowanie warunków pożarowych od poziomu pojedynczego ogniwa, aż po skalę pełnego pomieszczenia magazynowego, potwierdzając wysoką skuteczność mgły wodnej w kontrolowaniu rozwoju pożaru. Wyniki badań podkreślają konieczność stosowania systemów gaszenia jako uzupełnienia zabezpieczeń wewnętrznych baterii oraz wskazują na możliwości dalszej optymalizacji rozkładu dysz i wielkości kropel w projektowaniu instalacji ochrony przeciwpożarowej dla magazynów energii za pomocą symulacji komputerowych CFD.

*Słowa Kluczowe: baterie, pożar, magazyn energii, CFD*

## Introduction

Lithium-ion batteries (LiBs) are widely used in various energy systems. They contain flammable organic electrolytes, which pose a significant risk of ignition in cases of uncontrolled temperature increases, overcharging, or mechanical damage to the battery [1], [2]. As confirmed by numerous studies, with the rapid increase in battery applications, thermal propagation becomes a serious concern for fire risk [3]. Unfortunately, the actual fire protection measures remain unsatisfactory. Beyond improving battery fire prevention methods, their fire protection continuously presents a significant challenge. Thermal runaway (TR) occurs mostly when the internal separator between the cathode and anode becomes damaged, leading to a violent exothermic reaction and the vaporisation of the electrolyte. Although various common agents could potentially extinguish these fires, in practice, the effects of TR cause far more problems than other types of fire, requiring prolonged cooling to control cells and prevent re-ignition [4]. The TR phenomenon is typically accompanied by one or more of the following events: the release of smoke and gas, the rupture or explosion of the cell casing, gas explosions, and the spread of heat to adjacent LiB cells [5], [6].

Recent investigations have shown that gases such as HF, $POF_3$, and CO are frequently released during thermal runaway, representing both acute toxicity hazards and early detection opportunities [7]. These findings underscore the importance

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of detection systems that can identify emissions before ignition occurs [8].

Fires in LiB batteries can start due to several conditions that lead to TR, presented in Fig. 1. They include electrical abuse, such as overcharging or overdischarging, which can cause lithium plating or dendrite formation, resulting in internal short circuits. Thermal abuse, where temperatures reach critical points, can cause the decomposition of battery components, releasing heat and exacerbating the situation. Mechanical abuse, such as impact or bending, can compromise the battery's structure, leading to short circuits. Internal short circuits can also occur due to manufacturing defects or separator damage, allowing for anode-cathode contact. These conditions increase cell temperature, trigger exothermic reactions, and create a feedback loop of heat and pressure build-up, ultimately leading to cell rupture and potentially resulting in fire [9].

Although lithium iron phosphate batteries (LFP) are often marketed as safer alternatives, recent large-scale incidents have demonstrated that they remain susceptible to thermal runaway, fire, and explosions under certain abuse conditions [10].

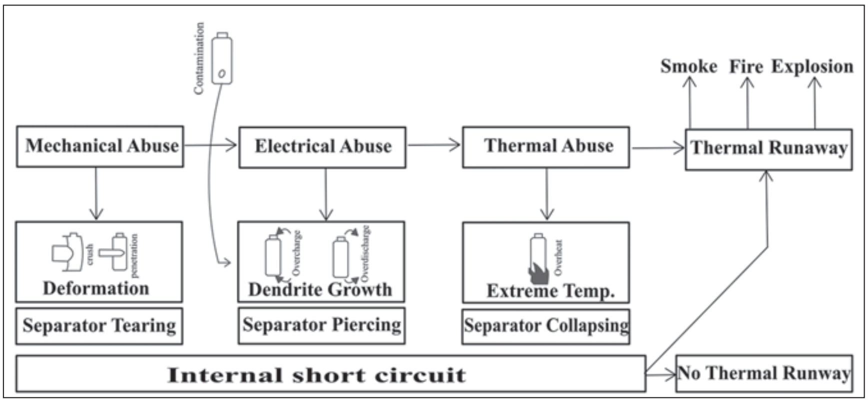

**Figure 1.**
**Battery fire reasons**
***Rysunek 1. Przyczyny pożarów baterii***

Even with numerous internal battery protection mechanisms in place, their fires cannot always be prevented. For this reason, guidelines for battery energy storage systems increasingly emphasise risk assessment. Increasing separation distances, gas monitoring, and integration of fire suppression systems, such as water mist or sprinklers are applied [11]. Research has shown that while some cell chemistries, such as LFP, are less reactive, no chemistry can be considered completely safe, and large-scale energy storage fires have demonstrated severe propagation even in LFP-based systems [11]. Therefore, external fire extinguishing systems are necessary for various applications of LiBs. Chemical aerosols and water are often recommended as the most effective agents, although $CO_2$ and foam systems are sometimes also proposed [12]. However, $CO_2$ and chemical aerosols have been found to be insufficiently effective due to their low cooling effect [13], [14]. In conclusion, although water cannot break the iniciated thermal runaway process, it can cool the surrounding environment and prevent adjacent cells from heating and igniting [14], [15]. Therefore, this study examined the effectiveness of extinguishing LiB fires using water mist. The aim was to analyse the effectiveness of suppression and control of the fire by preventing spread to neighbouring modules [16], [17].

In addition to real fire experiments, computer simulations are widely used. The Fire Dynamics Simulator (FDS) is a computational fluid dynamics (CFD) model developed by NIST to simulate the movement of fire and smoke. FDS is used in fire safety engineering to predict fire behaviour and its impact on buildings or environments. FDS provides insight into smoke development, heat transfer, and the spread of toxic gases during a fire. It also allows visualisation to demonstrate how a fire progresses over time in complex environments. In the FDS, thermodynamics is modelled using the Navier-Stokes equations for low-speed, thermally driven flows, incorporating the ideal gas law to relate temperature, pressure, and density. Heat transfer is facilitated by convection, conduction, and radiation, while combustion processes contribute heat and influence the gas temperature. The mass transfer model uses advection-diffusion equations to simulate the movement of gases, such as oxygen, $CO_2$, and smoke, and tracks the fuel-oxygen mixture during combustion. FDS can also model evaporation and condensation processes, and simulate mass transfer between phases, such as the evaporation of liquid fuels into vapour. The software uses rectilinear computational meshes to divide the simulation space into a grid of rectangular cells, thereby simplifying the numerical solution of fluid dynamics equations. Considering all the capabilities of the FDS programme, it can be considered an appropriate tool to model the conditions of battery fire development and its extinguishment using water mist. Recent fire safety research confirms that CFD tools, such as FDS, are increasingly being applied to evaluate water mist systems in battery storage facilities, demonstrating how numerical modelling supports the design of ventilation, suppression, and explosion protection [10]. However, it is necessary to be aware that the simulation's accuracy is highly dependent on mesh resolution; finer meshes provide more detailed results, but require more computational resources. Therefore, designing an effective mesh involves balancing detail and computational efficiency, often requiring iterative adjustments to optimise simulation performance and accuracy [18].

The subject of the research presented in this article was to present the simulations of defined fire scenarios in energy storage rooms, starting from a small scale – a single cell fire – and reaching a large scale – a storage room fire with a demonstration of water mist effectiveness [19]. The simulations assumptions based on the experimental results, presented in [20], [21].

## Materials and Methods of the Fire Simulations

This chapter describes the research methods and tools used to carry out battery fire experimental tests, which were then used to develop a CFD computer model – Fire Dynamics Simulator (FDS). The program FDS is the most often chosen by users, and currently has several thousand users, and in this field is the best-verified around of all simulation programs [21], [22], [23]. Due to the above, the FDS was chosen for the simulations presented below.

The project was divided into two stages:
- Small scale – the single cell fire test;
- Large-scale – storage room with water mist extinguishing fire tests.

Details of the work that was carried out are described below.

### *Single cell fire simulation*

The single cell model was performed based on the assumption of the literature, the total HRR of this cell was taken as 30-

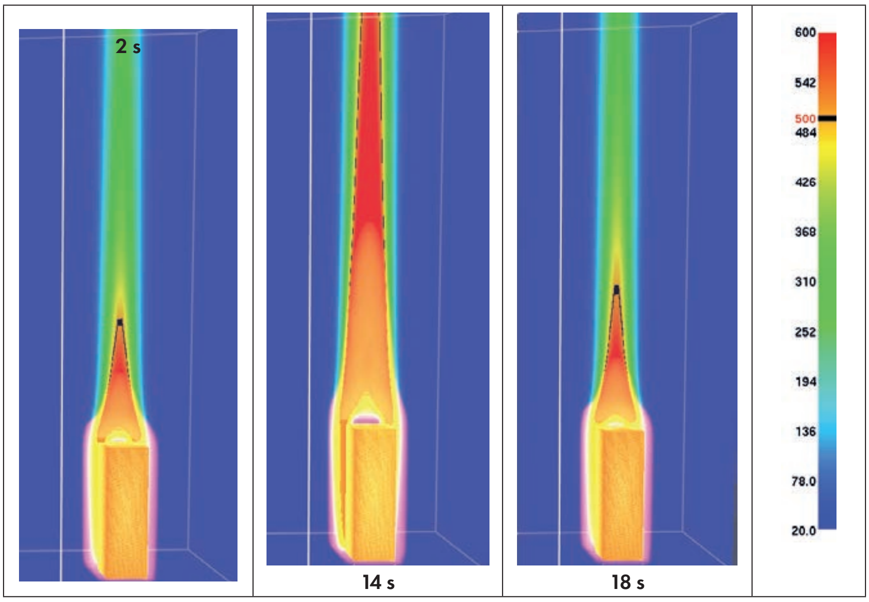

**Figure 2.**
**CFD simulation of the single cell fire**
***Rysunek 2. Symulacja CFD pożaru pojedynczego ogniwa***

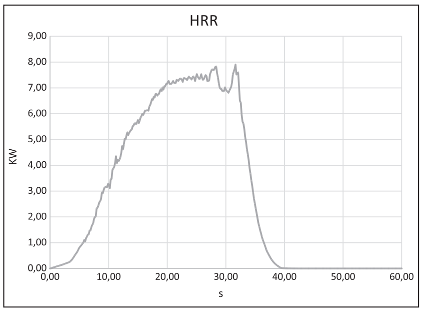

**Figure 7.**
**HRR curve from CDF simulation of a single module with central ignition**
***Rysunek 7. Krzywa pożaru modułu na podstawie symulacji CFD przy zapłonie centralnym***

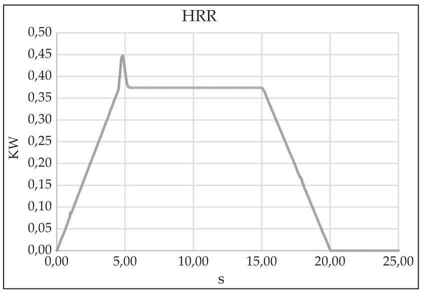

**Figure 3.**
**HRR curve achieved in the single-cell CFD simulation**
***Rysunek 3. Krzywa pożaru pojedynczego ogniwa na podstawie symulacji CFD***

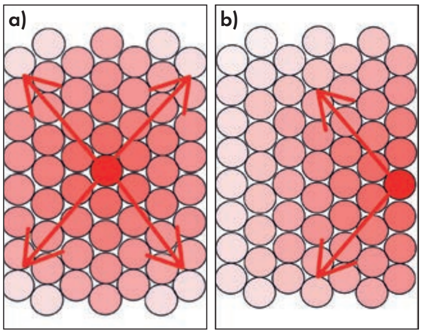

**Figure 4.**
**Fire spread in the module: a) central ignition, b) edge ignition**
***Rysunek 4. Rozprzestrzenianie się pożaru w module: a) zapłon centralny, b) zapłon skrajny***

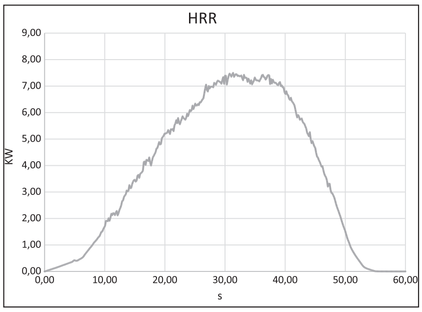

**Figure 8.**
**HRR curve from the CDF simulation of a single module with edge ignition**
***Rysunek 8. Krzywa pożaru modułu na podstawie symulacji CFD przy zapłonie skrajnym***

40 kW [1], and the single cell fire 9 Fig 2) and its curve was modelled (Fig. 3).

## *Single module fire simulation*

To achieve reliable results of fire development in a single battery element, the heat release rate (HRR) curve was prescribed using a single cell fire test modelled by FDS. Using that estimated curve, the authors ran two CFD simulations of entire modules built of 59 cells, represented an exemplar battery module. Their goal was to predict fire curves for one module fire in two scenarios: central and edge ignition (Fig. 4). In both scenarios, the ignition of the first cell was predefined, while the fire in the next cells started automatically when their internal thermocouples (THCP) reached 500°C. Each cell had 4 THCPs in each corner. The spread of the fire of the individual cell was based on the HRR curve previously defined for the single cell. The fires of modules in both scenarios are presented in Figs. 5 and 6, and their fire curves can be seen in Figs. 7, 8.

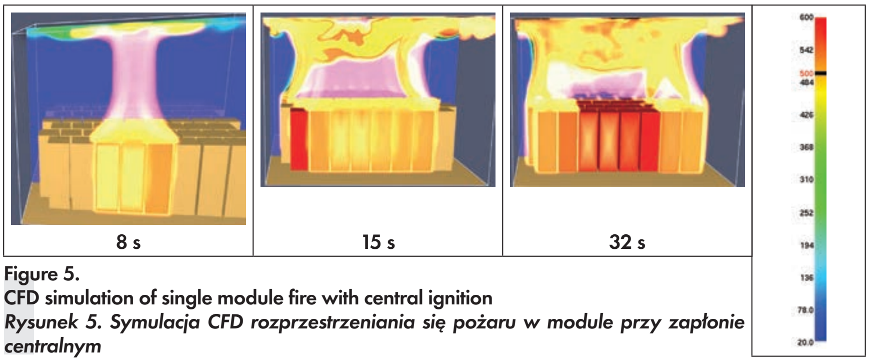

**Figure 5.**
**CFD simulation of single module fire with central ignition**
***Rysunek 5. Symulacja CFD rozprzestrzeniania się pożaru w module przy zapłonie centralnym***

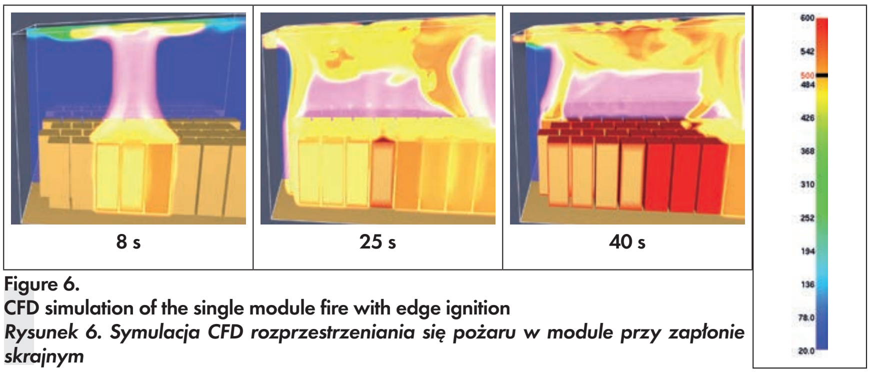

**Figure 6.**
**CFD simulation of the single module fire with edge ignition**
***Rysunek 6. Symulacja CFD rozprzestrzeniania się pożaru w module przy zapłonie skrajnym***

## *Large-scale storage room fire CFD simulations*

Based on the preliminary simulation results, the large scale research stage was realised. It simulated a full energy storage room fire and compared its propagation in dependence on water mist extinguishing. Fig. 9 presents the modelled storage room

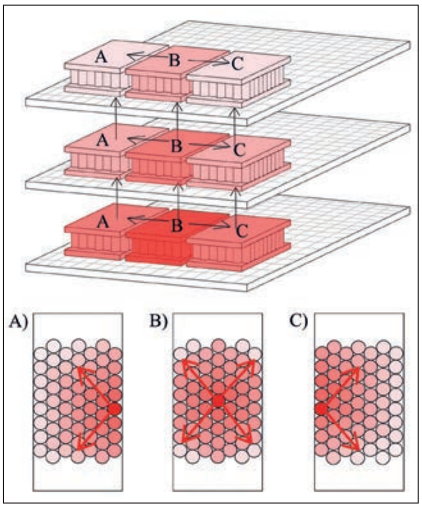

**Figure 9.**
**The theoretical spread of fire in large-scale tests**
***Rysunek 9. Rozprzestrzenianie się pożaru w magazynie energii w pełnej skali***

and the fire distribution inside and between the modules. Similarly to the previous stage, the simulations assumed predefined ignition of the first module, while the next module fire started automatically when its internal thermocouples (THCP) reached 500°C. Each module had 32 thermocouples in the corners and walls. The spread of the fire is based on the HRR curve previously defined for the single module.

The main purpose of building the model to perform computer simulations was to reproduce the action of water mist in extinguishing battery fires. The simulation results are presented in Fig. 10, and the fire curve obtained in this case is visible in Fig. 11. Then, the same parameters were simulated again, but without the use of water mist. It confirmed that without the use of the extinguishing system, the fire spreads rapidly to all modules in the energy storage. The simulation results are presented in Fig. 12, and the fire curve received in this case is visible in Fig. 13.

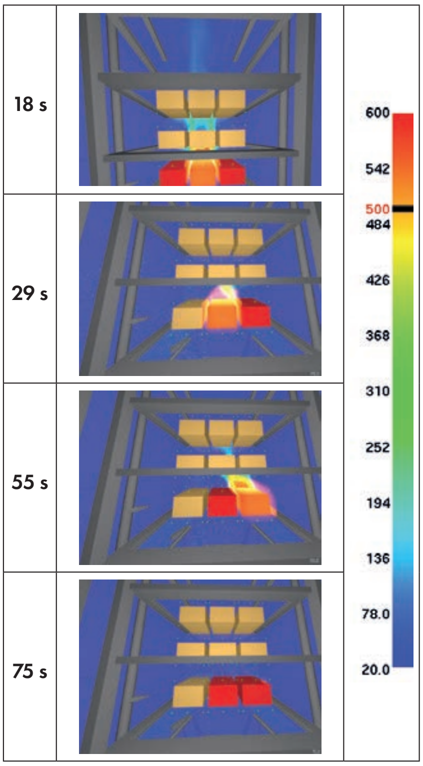

**Figure 10.**
**CFD simulation of the fire in energy storage with water mist extinguishment**
***Rysunek 10. Symulacja CFD rozprzestrzeniania się pożaru w magazynie energii z mgłą wodną***

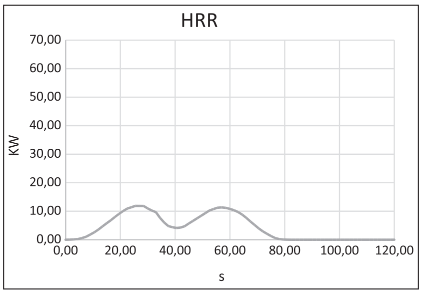

**Figure 11.**
**HRR curve from the CDF simulation of fire in energy storage with water mist extinguishment**
***Rysunek 11. Krzywa pożaru modułu na podstawie symulacji CFD w magazynie energii z mgłą wodną***

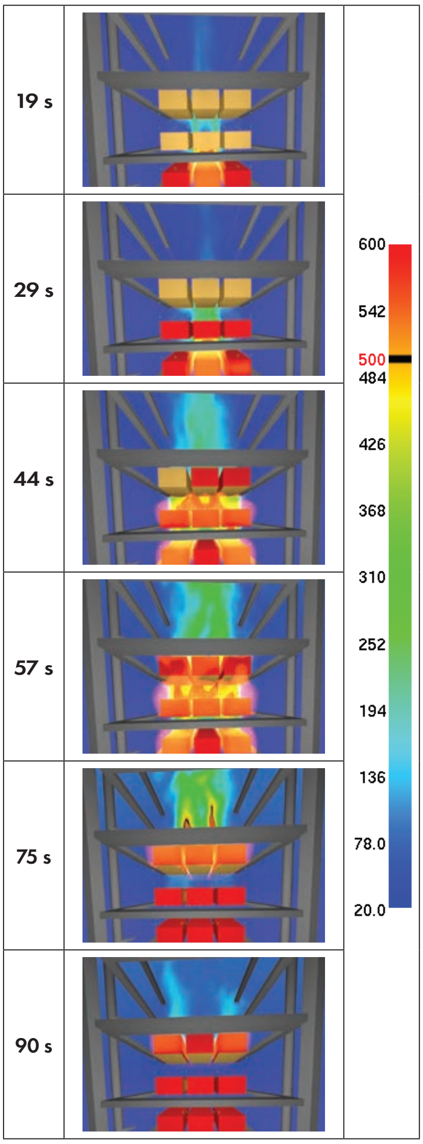

**Figure 12.**
**CFD simulation of fire in energy storage without water mist nozzles**
***Rysunek 12. Symulacja CFD rozprzestrzeniania się pożaru w magazynie energii bez mgły wodnej***

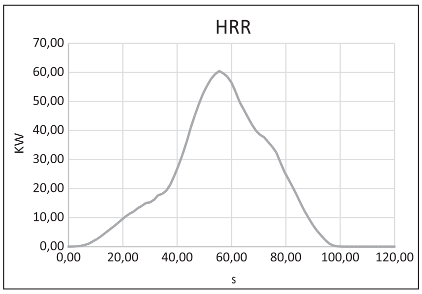

**Figure 13.**
**HRR curve from the CDF simulation of fire in energy storage without extinguishment**
***Rysunek 13. Krzywa pożaru modułu na podstawie symulacji CFD w magazynie energii bez mgły wodnej***

## Discussion and Conclusions

Although internal battery protection mechanisms are important and helpful, they may not always be sufficient to prevent fires, highlighting the need for external extinguishing solutions. This study emphasises the crucial role of low-pressure water mist systems in controlling LiB fires, especially under thermal runaway conditions. Although water mist systems do not directly stop the single cell thermal runaway, they provide significant cooling to prevent further ignition of neighbouring cells and their reignition, proving their effectiveness as a safety measure in battery storage room applications.

The article presents a structured research procedure in which the computer model was adapted and the first stage small scale of research was expanded using the pre-verified CFD model. The main purpose of this article was to build a model for performing computer simulations and to reproduce the action of water mist in extinguishing a battery storage room fire. It was confirmed that the extinguishing system could effectively control the fire in the energy storage room and prevent it from spreading to subsequent battery modules. Through the advanced computational fluid dynamics (CFD) modelling, the research demonstrates that the water mist effectively reduces temperatures and inhibits the spread of fire to adjacent modules. The CFD simulations provided detailed insights into the interaction between water mist and the thermal characteristics of LiB fires, revealing potential possibilities for optimising mist distribution and droplet size to achieve maximum cooling efficiency and effective support for CFD modelling in designing fire protection systems for energy storage rooms.

Future research should further focus on the use of CFD techniques to optimize water mist applications and explore other extinguishing agents. Enhancing fire suppression capabilities through simulation and modelling will be vital for various LiB configurations and operating conditions, contributing to safer battery technologies.

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