

**IMPROVING THE COOLING PERFORMANCE OF
CYLINDRICAL LITHIUM-ION BATTERY USING
PASSIVE METHODS IN A BATTERY THERMAL
MANAGEMENT SYSTEM**

BY

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Dedication

I dedicated this thesis to my beloved wife, whose unwavering support, patience, and encouragement have been my greatest source of strength throughout this journey. To my wonderful children, Huda and Mohammed, you are my inspiration and my greatest joy.

Your love has given me the motivation to persevere and achieve this milestone.

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LIST OF ABBREVIATIONS

BTMS	:	battery thermal management system
EV	:	Electrical Vehicles
PCM	:	phase change material
<i>P</i>	:	pressure, Pa
<i>g</i>	:	gravitational acceleration, m/s ²
<i>H_{PCM}</i>	:	enthalpy, J/kg
<i>ΔH_{PCM}</i>	:	enthalpy difference, J/kg
<i>H</i>	:	characteristic length, m
<i>h_{PCM}</i>	:	sensible heat, J/kg
<i>h</i>	:	heat transfer coefficient, W/(m ² .K)
<i>h_a</i>	:	reference enthalpy, J/kg
<i>k</i>	:	thermal conductivity, W/(m.K)
<i>q</i>	:	heat generation rate, W/m ³
<i>T_a</i>	:	ambient temperature, K
<i>T_{house}</i>	:	housing temperature, K
<i>T_s</i>	:	solidus temperature, K

T_l	:	liquidus temperature, K
C_p	:	specific heat capacity at constant pressure, J/(kg.K)
t	:	time, s
u	:	velocity, m/s
n	:	normal direction
ξ	:	thermal expansion coefficient, 1/K
τ	:	stress tensor
L_{PCM}	:	latent heat, J/kg
A_{mush}	:	mushy zone constant
ρ_a	:	density at ambient temperature, kg/m ³
β	:	liquid fraction
A_t	:	total heat transfer area, m ²
Fo	:	Fourier number
Nu	:	surface Nusselt number
Ste^*	:	modified Stefan number
Q_{abs}	:	absorbed heat, W
α	:	thermal diffusivity, m ² /s

ABSTRACT

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The growing demand for advanced lithium-ion batteries (LIBs) in renewable energy systems and electric vehicles underscores the importance of effective thermal management to ensure safety, longevity, and efficiency. This research aims to develop a novel passive Battery Thermal Management System (BTMS) for cylindrical 26650-type LIBs, integrating Phase Change Material (PCM) and fin structures to enhance heat dissipation and maintain optimal operating temperatures. Experiments were first designed to test the thermal performance of different BTMS configurations. Numerical simulations were performed using ANSYS Fluent to model the thermal behavior, and the model was validated against experimental and previously published results for reliability. The study systematically evaluated the effects of varying fin numbers (4, 8, 12, and 16) and thicknesses (1, 2, and 3 mm) on heat dissipation capability. It was found that 8 fins provided the best configuration, balancing cost and weight, and is practical for real applications, with a working improvement of 86.52% compared to no fins. While increased fin thickness slightly improved BTMS performance. Additionally, configurations with higher fin numbers (12 and 16) showed reduced performance due to decreased PCM volume. A novel S-shape fin design was proposed, demonstrating a 12.7% improvement in battery working time. Numerous heat transfer regimes were recognized throughout the phase change

material melting progression. These findings contribute to advancements in low-carbon energy systems and sustainable transportation by supporting the development of compact, cost-effective, and high-performance thermal management solutions for next-generation battery technologies.

ملخص الرسالة

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تزايد الطلب على بطاريات الليثيوم أيون المتقدمة في أنظمة الطاقة المتجددة والمركبات الكهربائية يبرز أهمية الإدارة الحرارية الفعالة لضمان السلامة وطول العمر والكفاءة. يهدف هذا البحث إلى تطوير نظام إدارة حرارية مبتكر للبطاريات الأسطوانية من نوع 26650، يدمج بين مادة التغير الطوري وهياكل الزعانف لتحسين تبديد الحرارة والحفاظ على درجات حرارة تشغيل مثلى. تم تصميم تجارب لاختبار الأداء الحراري لتكوينات مختلفة من نظام الإدارة الحرارية. وتم إجراء محاكاة عددية باستخدام برنامج أنيسيس فلونت لنمذجة السلوك الحراري، وتم التحقق من صحة النموذج بمقارنته مع النتائج التجريبية والمنشورة مسبقاً لضمان الموثوقية.

قامت الدراسة بتقييم منهجي لتأثير تغيير عدد الزعانف (4، 8، 12، و16) وسمكها (1، 2، و3 ملم) على قدرة تبديد الحرارة. وتبين أن استخدام 8 زعانف هو التكوين الأفضل، حيث يوازن بين التكلفة والوزن ويعتبر عملياً للتطبيقات الواقعية، مع تحسين بنسبة 26.8% مقارنة بـ 4 زعانف. وعلى الرغم من أن زيادة سمك الزعانف حسّنت أداء النظام الحراري، إلا أن التحسين كان طفيفاً وغير كافٍ للنظر فيه عملياً. بالإضافة إلى ذلك، أظهرت التكوينات التي تحتوي على عدد زعانف أكبر (12 و16) أداءً أقل بسبب انخفاض حجم مادة التغير الطوري.

تم اقتراح تصميم مبتكر لزعانف بشكل حرف S، وأظهر تحسناً بنسبة 12.7% في وقت عمل البطارية. كما تم التعرف على أنظمة نقل حراري مختلفة خلال عملية انصهار مادة التغير الطوري، مما وفر رؤى لتحسين الأداء الحراري. تسهم هذه النتائج في تعزيز أنظمة الطاقة منخفضة الكربون والنقل المستدام من خلال دعم تطوير حلول إدارة حرارية مدمجة وفعالة من حيث التكلفة وعالية الأداء لتقنيات البطاريات المستقبلية.

CHAPTER 1

INTRODUCTION

1.1 Background

Global warming, driven by greenhouse gas emissions, is an urgent concern that necessitates a shift toward cleaner energy alternatives like renewable sources such as solar, wind, and hydropower [1]. These renewable sources produce minimal greenhouse gas emissions and offer long-term sustainability, making them effective solutions to issues such as oil depletion, carbon emissions, and rising energy demand [2]. However, the inherent variability and intermittency of solar and wind power present significant challenges. To address this, energy storage systems play a crucial role by catching surplus energy in times of tremendous output and discharging it during times of demanding request or short supply [3]. This capability is essential for meeting renewable energy targets and increasing the infiltration of renewable sources. In response, numerous solar and wind energy projects have been developed, with many more under construction, supported by government policies and incentives designed to promote renewable energy growth.

Energy storage systems are classified based on the form of energy they store, such as chemical, electrochemical, thermal energy, electrical, and mechanical [4]. Electrochemical storage involves loading electrical energy in the shape of chemical energy, which can later be converted back into electricity when needed. Examples of electrochemical storage

systems include fuel cells [5], electrochemical capacitors [6], and rechargeable batteries [7]. Between these, Li-ion batteries have become widespread in current computer electronics and EVs, attributable to their superior energy density, comparatively low weight, and outstanding rechargeability [8]. Li-ion batteries function by transferring lithium ions between electrodes to generate an electric current, with various cell designs such as cylindrical [9], prismatic [10], and pouch cells [11] suiting different applications. The three designs are shown in Figure 1.1.

Lithium-ion batteries have established themselves as indispensable power sources for portable devices like smartphones, laptops, and tablets, thanks to their energy density and long cycle life [12, 13]. Beyond these traditional uses, lithium-ion batteries have become critical in energy storage systems, especially in renewable energy solutions and electric vehicles (EVs). Their ability to efficiently store high amounts of energy makes them ideal for capturing and utilizing energy from intermittent sources like wind and solar power. Lithium-ion batteries are increasingly being integrated into residential off-grid energy storage systems, particularly in photovoltaic (PV) setups within buildings, contributing to energy independence and enhancing the resilience and sustainability of modern energy infrastructures [14]. One notable type of lithium-ion battery is the cylindrical battery, which is recognized for its tubular design and versatility for uses varying from personal electronics to EVs. These cells, which feature a rolled jelly roll assembly consisting of a cathode, anode, separator, and current collectors, have become industry standards in sizes such as 18650 [15] and 26650 [16]. The relationship between energy sustainability and lithium-ion batteries is essential, as they enable the storage and use of clean energy, reduce reliance on fossil fuels, and facilitate the transition to a more sustainable energy future.

Consequently, exploring the thermal management of these essential components is crucial for improving their efficiency and safety in high-demand applications.

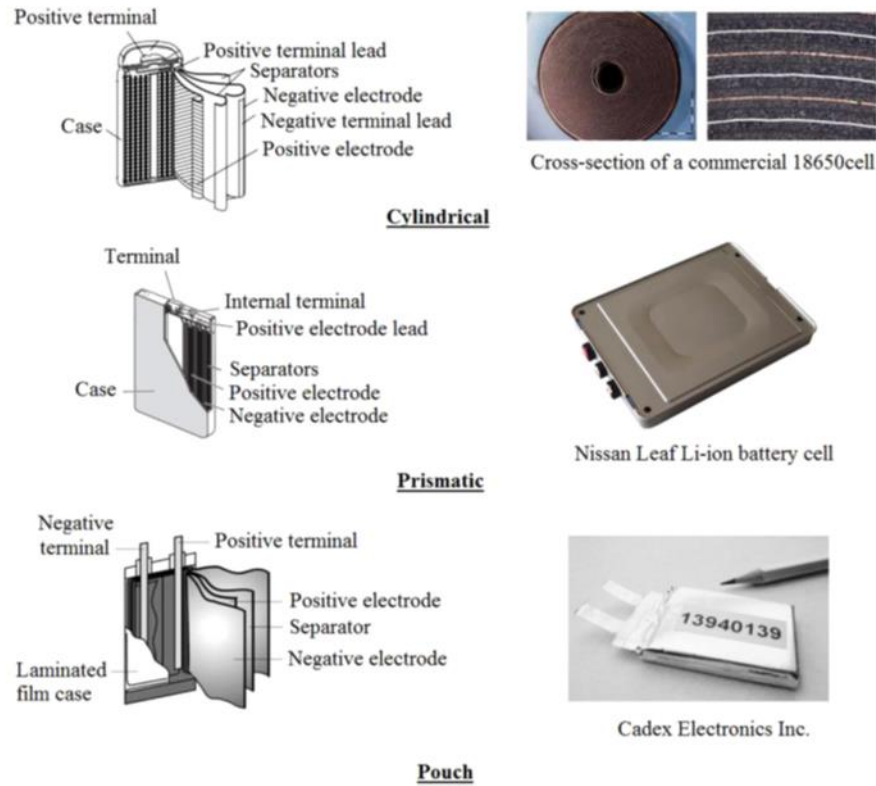


Figure 1.1 Battery cell configurations [17].

The thermal management of lithium-ion batteries is a critical aspect of their design and operation, primarily due to the multiple heat sources generated within the cells. The main sources of heat include heat from reversible reactions, by-reaction heat, Joule heat, and the heat of polarization [18]. The heat from reversible reactions is associated with the electrochemical processes that occur during charging and discharging. By-reaction heat arises from side reactions within the battery, such as electrolyte decomposition or the formation of solid-electrolyte interphase (SEI) layers. Joule heat, also known as resistive heating, is generated because of the interior resistance of the battery components as current

flows through them. Lastly, the heat of polarization refers to the thermal energy produced due to the overpotential required to drive the electrochemical reactions at a practical rate.

The design of cylindrical BTMS packs must prioritize temperature regulation to keep the battery within its operating range of 15-40°C [19, 20], thus preventing excessive heat buildup that can lead to safety hazards like thermal degradation. Effective heat dissipation is also vital, requiring resources with great thermal conductivity or cooling methods to efficiently dissipate the generated heat coming from the batteries. Temperature uniformity across all cells is necessary to evade differences in performance and degradation [21]. High charging currents and speeds further aggravate heat generation by increasing internal resistance and side reactions, making thermal management even more critical [22]. Additionally, preventing thermal runaway, where the heat generated exceeds the battery's ability to dissipate it, plays a key role in safety, as runaway events can result in harmful gas emissions, combustion, or even explosions [23-25]. Addressing these challenges cost-effectively, considering factors such as energy consumption, material choice, and space constraints, is crucial for the extensive implementation of lithium-ion batteries in numerous applications. Therefore, a finely designed thermal management system must comprehensively report temperature control, heat dissipation, and safety to improve the performance and durability of cylindrical lithium-ion batteries.

1.2 Problem Statement

Heat generation in a battery pack plays a significant role in its degradation, ultimately shortening its lifespan and negatively affecting performance. Since a battery pack consists of numerous cells, even a small temperature rise can have considerable consequences [26].

For example, a 1 °C increase within the typical operating range of 30°C to 40°C can reduce the battery's lifespan by up to two months [27]. As the temperature continues to rise, the degradation of power and capacity becomes more noticeable, increasing the risk of thermal runaway [28]. This degradation manifests as a loss of available energy and power, driven by heat generated during chemical reactions and current flow within the battery. The rise in temperature directly influences the battery's kinetics, and when batteries are charged or discharged at high rates, the small thermal conductivity of the electrodes aggravates heat buildup in the core [29]. This heat buildup accelerates the degradation of the electrode microstructure, potentially triggering side reactions, internal short circuits, and ultimately leading to thermal runaway and battery failure.

While the cylindrical shape of battery cells is often selected for its structural benefits, it poses challenges for heat dissipation due to the relatively small surface area compared to its volume. This limited surface area restricts the cell's ability to efficiently release heat, resulting in elevated core temperatures, which can be problematic in applications requiring precise temperature control, such as in electrical components. To address this, cylindrical batteries are frequently equipped with fins or other extended surfaces structures designed to increase the active surface area for cooling. Fins, which are thin, extended surfaces, enhance heat dissipation by increasing airflow and heat exchange [30]. Their design requires careful consideration of factors such as material properties, length, spacing, and thickness to optimize performance. By promoting better airflow and increasing the surface area, optimized fin structures improve the system's overall cooling efficiency, making them critical for maintaining optimal battery performance [31].

Thermal runaway (TR) in lithium-ion batteries occurs when mechanical, electrical, or thermal failures, such as overcharging, internal short circuits, crushing, or overheating, cause an uncontrollable rise in temperature [32]. Initially, this temperature increase is gradual. However, as the cell components decompose exothermically, the self-heating rate surpasses the heat dissipation rate, resulting in a rapid and exponential temperature rise that destabilizes the battery [33]. At higher temperatures, several chemical transformations occur, including electrolyte decomposition, reactions between the electrolyte and electrode materials, and the breakdown of the solid electrolyte interface (SEI) layer [34]. These reactions further elevate the internal temperature, ultimately triggering thermal runaway. In extreme cases, this can result in fire, smoke, gas emissions, and the decomposition of electrolyte and electrode materials [35]. The process of thermal runaway mirrors that of an internal combustion engine, where a slow temperature increase is followed by a sudden and dramatic escalation, potentially leading to catastrophic events like fires.

Effective heat management is essential for ensuring cylindrical lithium-ion batteries' longevity, safety, and performance, particularly in high-power applications like electric vehicles as well as industrial energy storage technologies. As the demand for high-power, high-energy-density, and fast-charging batteries grows, there will be an increasing need for more efficient, stable, economical, and compact battery thermal management systems (BTMS). These advanced BTMS solutions will be critical for ensuring that the next generation of batteries can meet the performance and safety requirements of future technologies while maintaining long-term reliability and efficiency.

Given the critical challenges posed by heat generation within battery packs, it is clear that effective thermal management is vital for extending the lifespan and ensuring the safe

operation of lithium-ion batteries. The combination of cylindrical cell design limitations and the hazards linked with thermal runaway highlights the need for innovative solutions that enhance heat dissipation and mitigate temperature-induced degradation. Addressing these thermal challenges is not only crucial for improving battery performance but also for preventing catastrophic failures like fires or explosions. The development of high-performance thermal management technologies, including the integration of fins and other heat-dissipating structures, will play a vital role in the evolution of safer and more reliable battery technologies. These solutions will be especially important as the interest in high-performance, energy-efficient batteries continues to grow across many industries, from electric vehicles to renewable energy storage systems.

1.3 Objectives

1. **Design and develop an innovative thermal management system** for cylindrical 26650-type Li-ion cell by integrating PCM with fin structures to enhance heat dissipation and maintain optimal operating temperatures.
2. **Perform comprehensive three-dimensional numerical simulations** using ANSYS software to model the thermal behavior of the proposed PCM-fin structure, ensuring accuracy through validation against previous numerical and experimental studies.
3. **Investigate the impact of varying fin configurations**, including different numbers (4, 8, 12, and 16) and thicknesses (1, 2, and 3 mm), to determine the optimal design for maximizing heat transfer within the battery module.

4. **Propose and evaluate a novel fin structure** consisting of a cylindrical ring and S-shaped fins, with simulations assessing its performance.
5. **Provide practical insights and recommendations** for researchers and engineers to guide the development of efficient battery thermal management systems, contributing to advancements in low-carbon and sustainable transportation solutions.

1.4 Scope of the Study

This research will investigate the thermal management of cylindrical 26650 type lithium-ion battery using phase change materials (PCM) and fin structures. The focus will be on enhancing heat dissipation and preventing thermal runaway during high discharge rates. The study will employ numerical simulation to evaluate the performance of different fin configurations, including variations in the number and thickness of fins. All simulations will be conducted using ANSYS Fluent 24/R1. This study will be limited to passive cooling techniques, excluding external techniques such as air or liquid cooling. The research will not only aim to optimize battery temperature control but also to propose a novel fin design for improved heat transfer performance.

1.5 Thesis Structure

This thesis is organized into the following chapters:

Chapter 1: Introduction

This chapter establishes the importance of lithium-ion batteries in renewable energy storage and high-demand needs. It outlines the challenges associated with heat generation

in cylindrical cells and the need for advanced thermal management systems. The problem statement, research objectives, and scope of the study are presented, providing the foundation for the research.

Chapter 2: Literature Review

The literature review provides a comprehensive overview of BTMSs, with a focus on PCMs, fin structures, and combined PCM-fin approaches. The review identifies key research gaps and justifies the need for the proposed study.

Chapter 3: Methodology

This chapter describes the numerical methods employed to investigate the thermal performance of the PCM-fin battery thermal management system. It includes details on the simulation setup, governing equations, validation processes, and parametric studies conducted to evaluate various configurations.

Chapter 4: Results and Discussion

This chapter presents the findings of the study, including the impact of different fin numbers, fin design, and configurations on the heat management efficiency of the battery. The results are analyzed and discussed in the context of existing literature, with a focus on the novel fin structure.

Chapter 5: Conclusions and Recommendations

The concluding chapter summarizes the key findings of the research and their implications for battery thermal management. Suggestions for further study are provided to guide the development of more efficient and sustainable BTMS solutions.

CHAPTER 2

LITERATURE REVIEW

2.1 Overview of Battery Thermal Management

The performance of lithium-ion batteries is highly sensitive to thermal behavior, which directly impacts their energy density, life cycle, and overall efficiency. Despite the critical role of thermal management, it has historically received less attention compared to manufacturing and material innovations [36]. At elevated operating temperatures, the rate of capacity fade in lithium-ion cells accelerates [37]. If the accumulated heat is not adequately controlled, the battery risks overheating, potentially leading to thermal runaway, a condition that poses severe safety concerns, particularly for high-capacity batteries favored by electric vehicle (EV) manufacturers. This sensitivity to temperature is a notable limitation for lithium-ion batteries, hindering their widespread adoption. The heat generated during charging and discharging can degrade battery performance and, in extreme cases, jeopardize passenger safety. On the other hand, operating at low temperatures can result in capacity loss and material degradation, as slower electrochemical reactions take place [38].

To address these challenges, an effective thermal management system (TMS) is vital for ensuring the efficient and safe working of cylindrical Li-ion battery packs. The design of such systems must focus on maintaining the battery in its ideal temperature range to prevent overheating and its associated safety risks. Heat dissipation plays a critical role, requiring

the use of good thermal conductivity materials or alternative cooling methods to efficiently dissipate heat from the cells. Ensuring temperature uniformity across all cells is equally important, as uneven temperatures can lead to performance imbalances and accelerated degradation. In addition, thermal insulation must be incorporated to protect against the adverse effects of low temperatures, and safety measures should be implemented to prevent thermal runaway.

The primary objectives of a battery thermal management system (BTMS) are to maintain the battery within its optimal temperature range and minimize thermal gradients between cells in a pack or within individual cells, where temperature variations often occur between or within layers. The BTMS must achieve these goals while minimizing mass, volume, energy consumption, and both initial and operational costs, ensuring continuous, long-term, and safe battery operation [39]. This is especially important for the extensive implementation of lithium-ion battery cells across several applications, where price considerations related to materials, energy and space are critical. In the context of electric vehicles (EVs), an effective and economical BTMS is essential to support their adoption across different environmental conditions while ensuring longevity, mileage, and performance. The BTMS must not only cool the battery pack when temperatures exceed the allowed range but also warm it up in low-temperature environments. Additionally, it ensures uniform temperature distribution among battery cells to prevent uneven voltage levels. Over the past few decades, numerous studies have emphasized the importance of BTMSs in electric vehicle powertrains, highlighting their critical role in ensuring the safety, efficiency, and reliability of EV battery systems.

When designing a BTMS, in addition to the general considerations, two factors specific to cylindrical batteries must be taken into account. First, cylindrical cells exhibit anisotropic thermal conductivity, with axial thermal conductivity being significantly higher than radial conductivity. This property facilitates more efficient heat dissipation along the axial direction. Second, the cylindrical shape of the cells introduces challenges in battery pack design, as the arrangement of these cells inevitably creates gaps between them. These interstitial spaces reduce the overall volumetric energy density and pose additional challenges for thermal management system design and heat removal process.

There are two approaches to reducing the heat generated by lithium-ion batteries: (i) Internal BTMS, which involves modifying the battery's internal structure to diminish heat production, and (ii) External BTMS, which focuses on implementing an outer thermal management system to improve the removal of heat from the battery cells. A comprehensive classification of BTMS methods is provided in Figure 2.1.

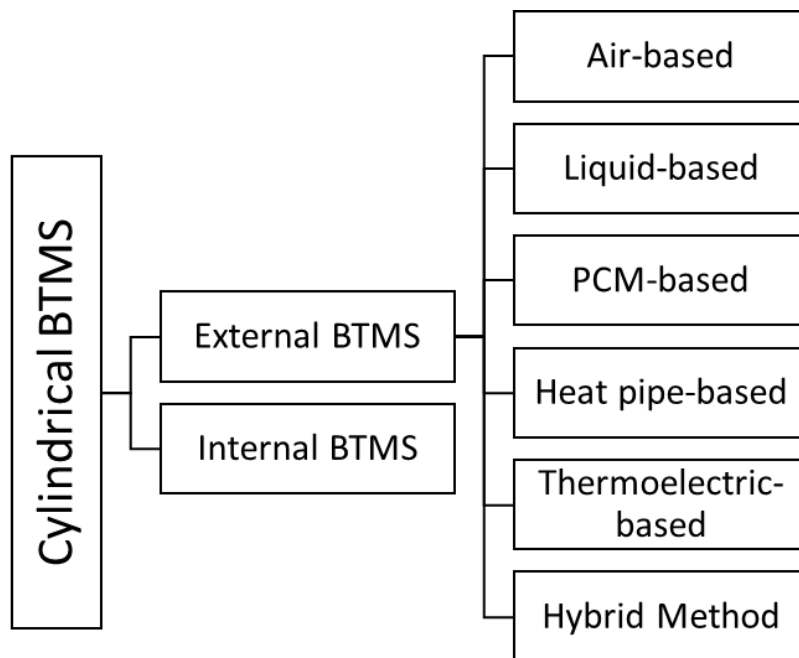


Figure 2.1 Classification of BTMS.

2.1.1 Internal BTMS

Internal battery thermal management system enhances heat dissipation capability by reducing internal resistance, a goal often achieved by modifying the anode and cathode materials as well as adjusting electrode thickness. Electrode thickness plays a direct role in heat generation; thicker electrodes increase the distance electrons and ions must travel, resulting in higher internal resistance and more heat production [40]. It is recommended that electrodes be designed to be as thin as feasible while retaining sufficient strength and flexibility to manage the stress caused by lithium-ion diffusion [41]. Nevertheless, thinner electrodes contain less active material, which can reduce energy density, making it crucial to find the optimal electrode size that balances performance and durability. Considerable research has focused on using novel materials for the anode and applying surface coatings to better manage heat generation while improving the chemical, electrical, and temperature control of lithium-ion cells. Materials such as carbon, oxides, or graphene are commonly applied to the cathode to enhance electrochemical reaction rates and conductivity [42-45]. While these modifications can indeed lower internal resistance, they often lead to a reduction in energy storage capacity, making them less ideal for applications where high energy density is critical.

2.1.2 External BTMS

In an external battery thermal management system, battery cell temperature is controlled by an outside medium, such as liquid or air, without altering the battery's internal components. These systems are categorized as active, passive, or hybrid, depending on the cooling method and power consumption. Active BTMS, including air or liquid-based and thermoelectric systems, require electrical power to actively remove heat from the battery.

This is achieved through mechanisms like liquid cooling, which uses coolants liquid to take and transfer heat from the cells, or forced air convection, where fans or similar devices facilitate heat exchange.

In contrast, passive BTMS rely on natural heat dissipation and do not require electrical power. These systems use materials with high thermal conductivity, such as phase change materials (PCM) and heat pipes, to manage heat passively. Components like heat sinks or PCMs are often integrated to dissipate heat effectively without the need for active cooling elements or external power.

The selection between passive and active structures is determined by aspects such as the specific application, available space, and the thermal management necessities of the system. This highlights the need for a customized approach to BTMS design, ensuring optimal performance, efficiency, and safety in cylindrical Li-ion battery packs.

2.2 Air-based BTMS

In air-based battery thermal management systems, cooling is primarily accomplished through forced convection, which has gained popularity due to its simple design, low cost, and lightweight structure. Air cooling is favored for dissipating battery heat because of several advantages, including comfort of maintenance, long lifetime, easiness in changing individual cells, and low power consumption at lower discharge rates. While natural convection methods are limited, particularly under challenging environmental conditions caused by air's low heat transfer efficiency, forced-air systems offer a more effective solution by reducing maximum temperatures at the cost of additional power consumption.

In these forced-air systems, cooling fins or other thermal dissipation components are often incorporated to expand the contact area exposed to airflow, allowing for more efficient heat removal. As air passes over these surfaces, it absorbs heat and carries it away, preventing the battery from overheating. To further boost cooling efficiency, active gears such as fans are typically used to improve air flow, ensuring that heat is effectively dissipated from the battery cells.

Researchers have investigated air-cooling systems for varying configurations of lithium-ion batteries (LIBs), ranging from single cells to full battery packs. These studies considered important aspects such as battery kind, quantity of batteries, requirement conditions, pack prearrangement, and airflow inlet design, all aimed at improving the overall thermal performance and effectiveness of the cooling system.

Yang et al. [46] proposed an air-cooling battery thermal management system with a bionic external surface radiator for cylindrical Li-ion cell modules, aiming to improve cooling efficiency while minimizing energy usage, as shown in Figure 2.2. The battery module includes cylindrical cells, radiators, a fan, insulated frames, and walls, with radiators made from aluminum and featuring a novel bionic surface. The batteries are set in parallel, with three rows aligned on the axis, separated by protected frames. In the experimental setup, an 18650 Li-ion battery was discharged at a 3C rate, with thermocouples placed at different points on the cell to measure temperature. The experiment involved measuring temperature changes during discharge while varying the inlet air velocity and the radiator's structural parameters. The findings revealed that increasing inlet velocity improved cooling performance, with an optimized radiator design reducing temperature difference by 8.1% and power consumption by 15.54%, compared to the original system.

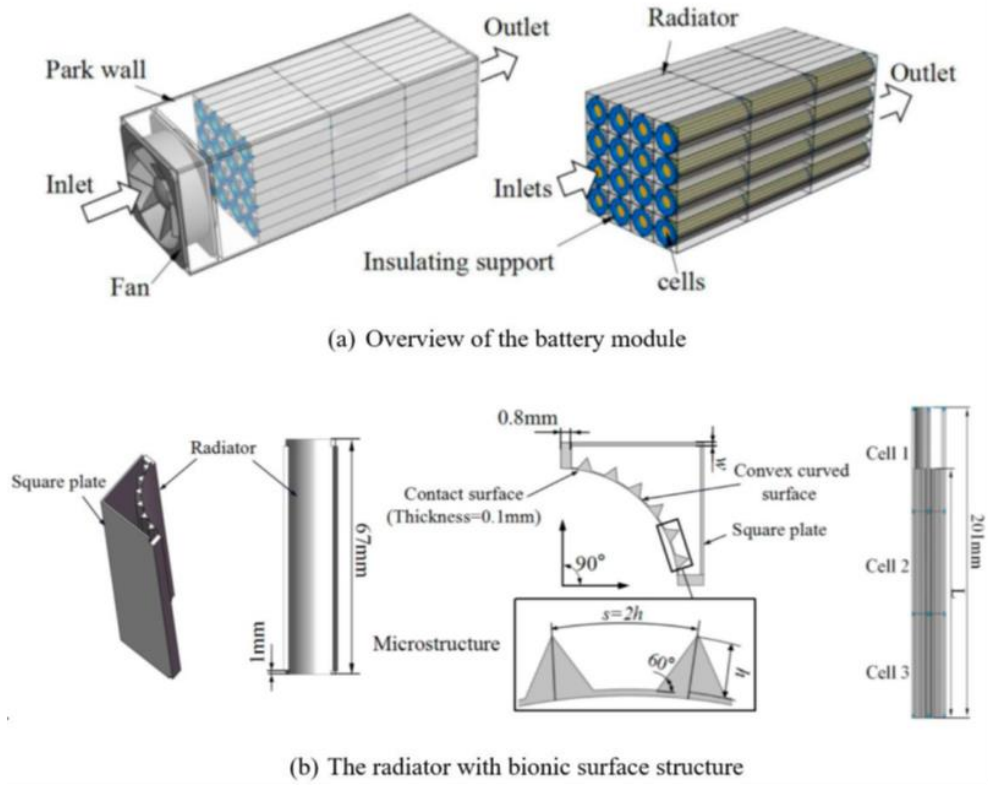


Figure 2.2 A schematic of the air-cooled unit featuring a bionic assembly [46].

Incorporating great thermal conductivity materials in gears such as thermal interface materials enhance heat transmission and facilitate more efficient heat dissipation. Kausthubharam et al. [47] examined a novel air-cooled BTMS aimed at enhancing the cooling efficiency of cylindrical Li-ion battery modules through forced convection as shown in Figure 2.3. The primary objectives are to lower the peak temperature and achieve a uniform temperature distribution across the battery pack, particularly under high discharge rate conditions. The module consists of 36 cylindrical 18650 cells, arranged in a 6s6p configuration, housed in an aluminum casing with thermal interface material to improve heat dissipation. In the experimental setup, forced air cooling is applied at varying airflow velocities, with air inlets and outlets positioned either centrally or at the top-left and bottom-right corners of the module. A coupled CFD and lumped thermal model is used

to simulate airflow and temperature distribution, with experiments conducted at different air velocities (0.1, 0.5, and 1 m/s) and C-rates (1C and 4C). The outcomes show that forced air cooling reduces the maximum temperature by up to 4.5°C compared to natural convection, although it leads to a higher temperature gradient across the pack. Central air inlet and outlet placement enhance temperature uniformity, while increased airflow velocity lowers peak temperatures but also raises power consumption.

One of the key challenges in air-cooling systems is creating a structural design for optimal air circulation for improved cooling performance. Yang et al. [48] introduced an air-cooled BTMS for a honeycomb-structured cylindrical Li-ion battery pack designed to enhance cooling efficiency and temperature uniformity using bionic heat sinks and an air distribution plate (ADP), as illustrated in Figure 2.4. The battery module contains 24 hexagonal modules, each containing 37 cylindrical 18650 cells arranged in a hexagonal layout. Support blocks and bionic heat sinks are positioned between the cells to strengthen the structure and improve heat dissipation. The honeycomb arrangement optimizes airflow and cooling. A computational fluid dynamics (CFD) model was created to simulate airflow and assess cooling performance, focusing on the effects of varying air inlet velocities (8 to 14 m/s) and structural parameters of the ADP and heat sinks on temperature distribution and efficiency. The study measured the $T_{\max}$, ΔT , and pressure drop, with simulations evaluating the influence of air velocity and structural configurations. The results indicated that the ADP enhanced airflow distribution, lowering the maximum temperature by 1.7 K and ΔT by 7 K at an inlet velocity of 12 m/s compared to a module without the ADP. Additionally, the incorporation of bionic heat sinks further improved cooling, with the

optimal configuration reducing the maximum temperature to 311.0 K and ΔT to 1.7 K, indicating better temperature uniformity and cooling efficiency.

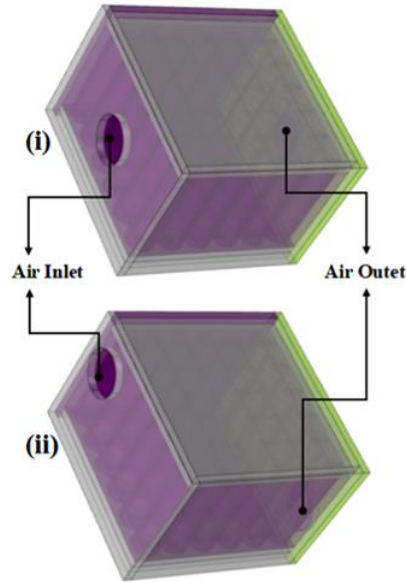


Figure 2.3 Diagrams of the novel BTMS incorporating forced air cooling, with: (i) air inlet and outlet boundaries positioned centrally and (ii) air outlet and inlet boundaries positioned at the bottom right and top left [47].

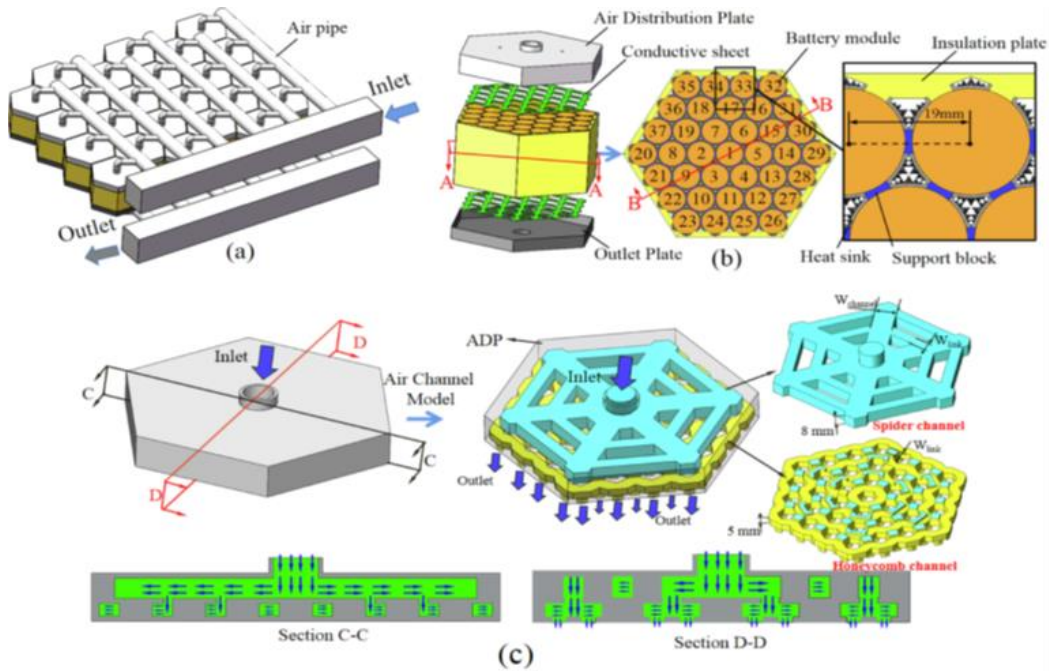


Figure 2.4 Components of the air-based BTMS include: the battery pack (a), the battery module (b), and the air distribution plate (c) [48].

Studies have been carried out to explore geometric modifications aimed at enhancing air circulation. In a related work, Zhou et al. [49] presented a novel air cooling method for cylindrical lithium-ion battery modules utilizing air distribution pipes with orifices, aimed at lowering the $T_{\max}$ and enhancing temperature consistency during discharge. The module contains a 3×3 array of 18650 cylindrical cells, with cooling achieved through air distributed via pipes that feature rows of orifices designed to evenly direct airflow across the battery surfaces as shown in Figure 2.5. The air distribution pipes are optimized to improve heat dissipation. A three-dimensional CFD model simulates the module's thermal behavior under various conditions, such as different orifice diameters (1 mm, 1.5 mm, and 2 mm), varying numbers of orifice rows (3, 4, and 5 rows), and differing inlet pressures. The study measures maximum temperature ($T_{\max}$), temperature difference ($\Delta T_{\max}$), and power consumption (P_w) during battery discharge at 3C, 4C, and 5C rates. Results show that increasing the orifice dia. and the amount of rows reduces $T_{\max}$, with the optimal configuration being a 1.5mm orifice diameter and five rows. At a 3C discharge rate, the maximum temperature decreased from 325.9 K to 305.7 K, maintaining temperature uniformity within 3 K. However, at a 5C rate, ΔT slightly exceeded the ideal range, suggesting that higher heat dissipation is necessary at elevated discharge rates.

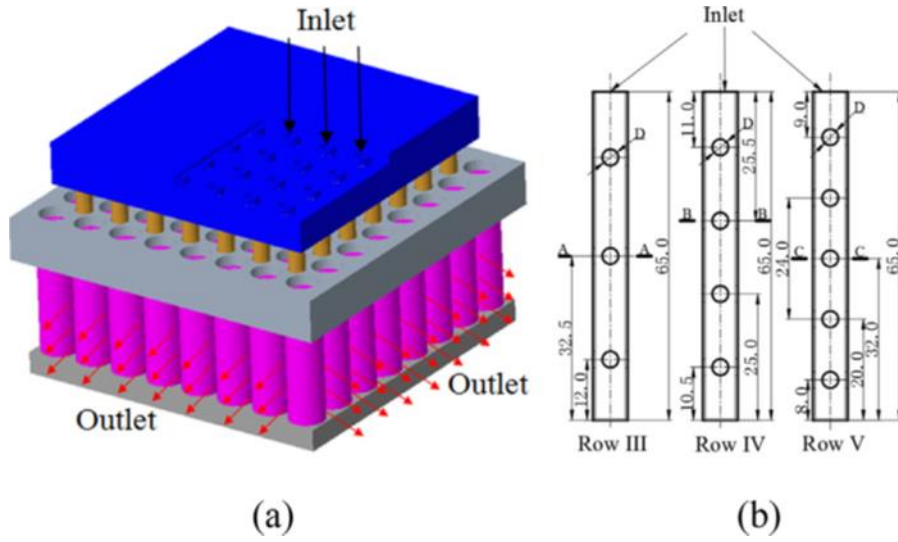


Figure 2.5 Diagram of the battery module utilizing an air distribution pipe system [49].

Optimizing airflow patterns has demonstrated significant improvements in temperature control and overall system performance. Zhang et al. [50] presented an optimized air-cooling system for lithium-ion BTMS by changing airflow patterns to enhance cooling efficiency and minimize temperature variations as shown in Figure 2.6. The BTMS features a 4×9 array of 21700 cylindrical battery cells, with airflow directed through multiple exit zones near the inlet to improve heat dissipation. The cells are arranged linearly in this 4×9 configuration within the cooling module to facilitate efficient airflow. The experimental framework employs computational fluid dynamics (CFD) simulations to assess different flow patterns, such as U-type, Hook-type, and Z-type, at various air velocities. The study investigates the impact of different wind speeds (ranging from 2 m/s to 8 m/s) on cooling performance, with a focus on optimizing the distance of the exit area from the module's centerline. Results indicate that the Hook-type BTMS IV design delivered the best cooling performance, exhibiting the lowest maximum temperature and temperature difference, and showed that increased wind speeds further improved temperature regulation. Additionally, a polynomial fitting model was developed to predict the relationship between wind speed,

exit area positioning, and cooling efficiency, providing a basis for optimizing air-cooled BTMS designs. On the same aspect, Liu et al. [51] introduce an innovative J-type air-based BTMS, which combines U and Z-type structures to enhance thermal performance and temperature control in Li-ion battery modules. The J-type system features two outlets equipped with control valves, enabling it to switch between U and Z-type modes for optimized air distribution and heat dissipation. The battery cells are organized in grouped channels with varying sizes, allowing for adaptive airflow and uniform cooling throughout the module. A CFD model is employed to simulate the thermal performance under various operating conditions, examining key design factors such as channel size, manifold design, and airflow rate, with the simulations validated against experimental data. Surrogate-based optimization is used to reduce temperature rise and enhance temperature uniformity, focusing on optimizing the design of the grouped channels and manifolds. The findings reveal that the J-type system surpasses the performance of U and Z-type configurations, reducing temperature rise by 31.18% and improving temperature uniformity by 67.8%, with its adaptive control system enabling real-time optimization of cooling strategies based on battery conditions.

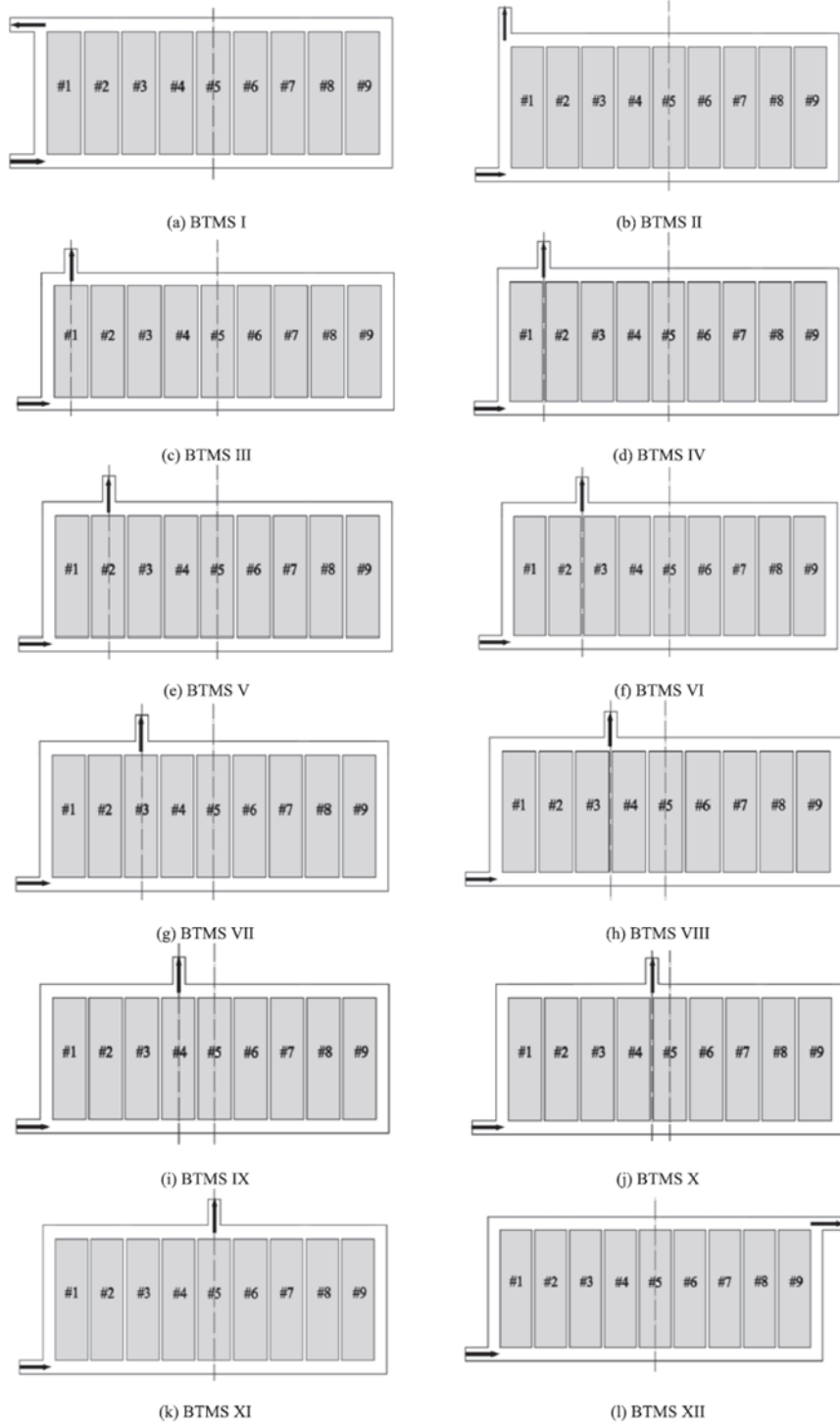


Figure 2.6 Schematics of various BTMSs considered in the study [50].

Many researches highlight the importance of optimizing battery cell spacing to improve the thermal management of air-cooled battery packs. Verma et al. [52] presented an

optimized air-cooled BTMS for a 4P7S configuration of 18650 lithium-ion cells, aimed at enhancing cooling performance by adjusting the spacing between cells to reduce maximum temperature ($T_{\max}$) and temperature differences ($\Delta T_{\max}$) as shown in Figure 2.7. The battery module contains 28 cylindrical cells arranged in a 4P7S aligned configuration, with cooling channels incorporated to manage airflow. The investigation examines the effects of varying longitudinal pitch (D_x), transverse pitch (D_y), and the distance from the side walls (D_w) on temperature distribution and cooling efficiency. Using CFD simulations and experimental testing, air is forced through the battery pack at an inlet velocity of 1.5 m/s, and key parameters such as $T_{\max}$, $\Delta T_{\max}$, and power consumption (P) are recorded to assess system performance. The experimental setup employs the Taguchi Design of Experiments (DOE) method to determine optimal cell spacing, focusing on minimizing $T_{\max}$, $\Delta T_{\max}$, and improving the space utilization factor (α). Results indicate that increasing D_x enhances cooling by promoting stronger airflow vortices, with an optimal D_y of 24 mm and D_x of 36 mm minimizing $T_{\max}$ and $\Delta T_{\max}$. The D_w also impacts performance, with 12 mm being identified as the optimal value. The numerical simulation results closely aligned with experimental data, showing a maximum relative error of 1.48%. On the same focus, Yang et al. [53] introduced an optimized air-cooled battery pack with a staggered arrangement and reverse-layered airflow, designed to enhance cooling performance, specifically for IFR-38120 LiFePO₄ cylindrical cells as shown in Figure 2.8. The staggered arrangement creates alternating airflow paths that boost turbulence and heat transfer, while the reverse-layered airflow improves cooling for the rear cells. The study examines how varying the cell-to-cell intervals (d), cell-to-wall intervals (s), and two-roll intervals (r) affect cooling efficiency. A three-dimensional CFD model is employed to simulate airflow and

temperature distribution, and the Design of Experiment (DOE) method is used to optimize the structural parameters for optimal cooling. Numerical simulations assess $T_{\max}$, $\Delta T_{\max}$, pressure drop (Δp), and space utilization factor (α) across different configurations. The results show that the optimized configuration reduced $T_{\max}$ to 310.46 K and $\Delta T_{\max}$ to 6.6 K. Moreover, the inclusion of spoilers further improved temperature uniformity by reducing $\Delta T_{\max}$ by 1.85 K, though this came with a minor increase in pressure drop.

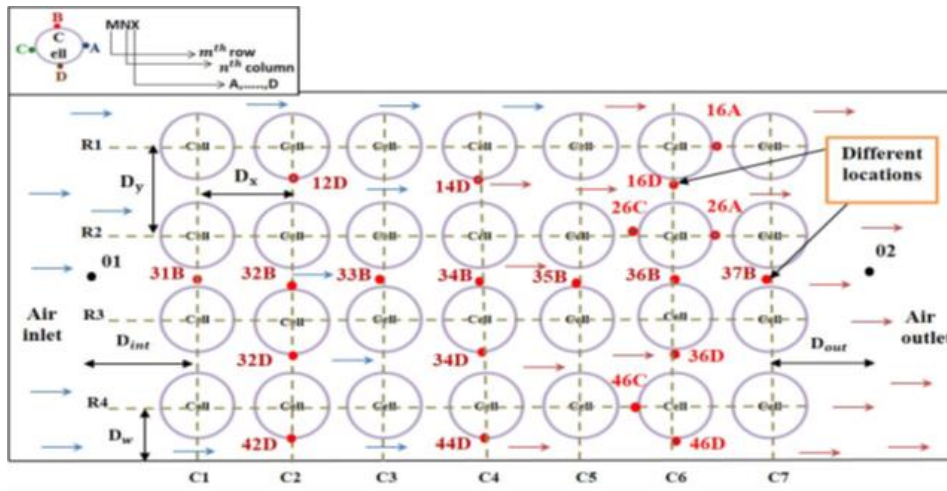


Figure 2.7 Battery cell configuration [52].

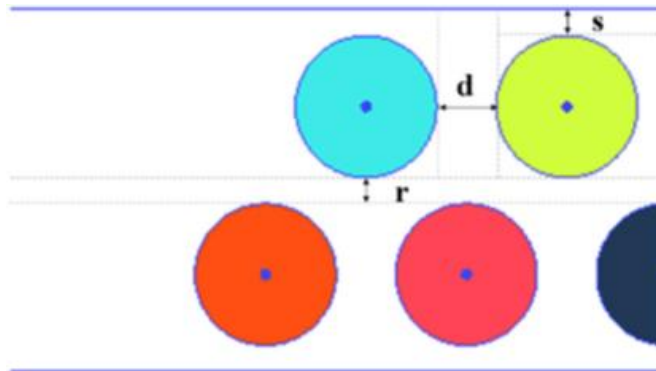


Figure 2.8 The illustration of the d , s , and r in the stagger-arranged battery pack [53].

Researchers emphasize the importance of optimizing cooling channel dimensions, air supply methods, and channel length to improve thermal management in systems utilizing forced air cooling. Lu et al. [54] introduced an enforced air-cooling approach for a

staggered Li-ion battery pack, aiming to improve cooling efficiency and temperature regulation by examining the impact of cooling channel size, air supply mode, and channel length. The battery pack, composed of 18650 cylindrical cells in a staggered arrangement, increases the cooling channel cross-sectional area, thereby improving airflow distribution. A three-dimensional CFD model is used to simulate airflow and temperature distribution under various conditions, including cooling channel sizes (from 0.1 mm to 2 mm), different air supply modes (inlet/outlet positions), and varying channel lengths in the direction of airflow. Key parameters such as maximum temperature ($T_{\max}$), temperature difference ($\Delta T_{\max}$), cooling efficiency (β), and space utilization (α) are measured. Results indicate that larger cooling channels decrease $T_{\max}$ but reduce space utilization, with 1 mm identified as the optimal channel size. Cooling efficiency is highest when the inlet and outlet are positioned at the top of the battery pack. While increasing channel length diminishes cooling efficiency, arranging 10 rows of cylindrical cells along the airflow direction strikes the best balance between power density and cooling performance. In another study, Ji et al. [55] proposed a battery module design with varying cell intervals to improve temperature and discharge uniformity, with the goal of minimizing temperature and voltage discrepancies among lithium-ion cells for enhanced performance. The battery module contains 49 series-connected 18650 NCM lithium-ion cells, using two different spacing strategies, arithmetic ratio and geometric ratio, to adjust the intervals between cells. In the arithmetic ratio arrangement, the intervals between cells increase linearly, while in the geometric ratio, they decrease proportionally. A finite element model is employed to simulate thermal behavior during discharge at 25°C and a 0.6C discharge rate. The experiment evaluates the temperature and voltage differences in cells using both spacing

strategies, with varying intervals, to assess their effects on temperature uniformity, maximum temperature difference, and final voltage difference. Results demonstrate that the arithmetic ratio prearrangement significantly enhances thermal uniformity, lowering the temperature difference by 13% and lowering the last voltage to 2.5 mV when the early spacing goes to 5.5 mm. The study concludes that the arithmetic ratio arrangement is more effective than the geometric ratio in improving temperature consistency and discharge uniformity.

Including baffles in the battery module effectively improves cooling performance, reduces temperature gradients, and ensures uniform temperature distribution. Kummitha et al. [56] proposed a thermal management system for cylindrical lithium-ion battery modules that uses baffles as fins to improve airflow cooling. The system contains 207 IFR32700 Li-ion cells, organized into 23 modules, each containing 9 cells in a 3×3 arrangement, with baffles placed between the cells to improve thermal control and achieve even temperature distribution. A 3D CFD model was created to simulate the system's thermal performance at different discharge rates (1C, 2C, and 3C), comparing a base model (without baffles) to the new design (with baffles). The experiment focused on analyzing temperature contours and profiles to evaluate the effect of baffles on cooling efficiency. The findings demonstrate that the new model with baffles significantly lowered maximum temperatures and temperature gradients in comparison to the base model. At a 1C discharge rate, the temperature difference between cells dropped from 0.26°C in the base model to 0.04°C in the new model. The new design also displayed better cooling efficiency at higher discharge rates, maintaining a more consistent temperature distribution due to the improved airflow provided by the baffles.

Battery configuration and optimized air-cooling techniques significantly improve the thermal management of lithium-ion battery modules. Wang et al. [57] examined the thermal performance of lithium-ion battery modules with dissimilar cell prearrangement assemblies and forced air-cooling approaches, aiming to improve cooling efficiency and ensure uniform temperature distribution. The battery modules consist of cylindrical cells arranged in various configurations, including 1×24 , 3×8 , and 5×5 rectangular layouts, as well as 19-cell hexagonal and 28-cell circular formations. These configurations are tested to evaluate their impact on heat dissipation. A three-dimensional CFD model is used to simulate airflow and heat transfer within the modules, and experiments are conducted at a 3 C discharge rate with varying fan positions and air outlet locations. Key parameters measured include the maximum temperature ($T_{\max}$), temperature difference (ΔT), and average temperature (T_{avg}) across different setups. The results show that forced air cooling substantially enhances thermal performance, with the 5×5 cubic arrangement and a top-mounted fan achieving the most effective cooling, reducing both $T_{\max}$ and ΔT . The hexagonal arrangement offers optimal space utilization while maintaining efficient cooling, and an inter-cell spacing of 1 mm is identified as the ideal balance between space conservation and cooling effectiveness.

The studies on air-cooling systems for lithium-ion battery modules focused on optimizing several key aspects to improve performance. Efforts were made to optimize cell arrangements, including rectangular, hexagonal, and staggered configurations, to enhance airflow and heat dissipation. Various cooling strategies were developed, such as adjusting fan placement and designing inlet/outlet configurations to improve airflow distribution and reduce hot spots. Inter-cell spacing and cooling channel design were optimized to balance

effective cooling and space utilization, with recommended minimum distances around 1 mm. Airflow patterns and direction control were enhanced using components like baffles, air distribution pipes, and spoilers, ensuring efficient cooling across the battery module. The systems were also tested under different discharge rates (e.g., 1C, 3C, 5C) to maintain temperature uniformity during various operating conditions. Additionally, thermal management components like heat sinks and air pipes were introduced or modified to further direct airflow and improve heat dissipation, collectively enhancing cooling efficiency, temperature uniformity, and space utilization within the modules.

The reviewed studies identified several drawbacks and limitations of air-cooling systems for lithium-ion battery modules. One major limitation is the reduced cooling capacity at high discharge rates (e.g., 3C, 5C), where air cooling struggles to maintain temperature uniformity and prevent overheating. Temperature gradients and hot spots are also common, especially in larger modules with long airflow paths, leading to uneven cooling and potential performance degradation. Optimizing inter-cell spacing for better cooling often increases the size of the battery pack, reducing space efficiency. Airflow control limitations were observed, with certain fan placements resulting in poor cooling efficiency across the entire module. Additionally, achieving higher cooling performance typically requires increased power consumption, reducing the overall energy efficiency. Finally, air-cooled systems are dependent on ambient environmental conditions, with performance declining in hotter external environments. The limitations and drawbacks highlighted in these studies emphasize the necessity to explore substitute cooling solutions, particularly for requirements with challenging temperature situations.

2.3 Liquid-based BTMS

A liquid-cooled battery thermal management systems employ a liquid, typically as a liquid coolant, to maintain optimal battery temperature in operation. In this arrangement, the liquid flow between the battery pack, capturing heat produced throughout the working cycles, and then carries it away to a cooling mechanism where the heat is dissipated. Because of its superior thermal conductivity and heat storage capacity relative to air, liquid provides a more efficient solution for managing battery temperatures. Liquid-based BTMS are categorized as either active or passive, depending on the system design, and can utilize various transfer media such as refrigerants, water, glycol, oil, or acetone, offering flexibility and enhanced cooling capabilities for different applications.

One of the key priorities for researchers is designing new arrangements tailored to the configuration of cylindrical batteries. Rao et al. [58] introduced a liquid cooling system for cylindrical lithium-ion battery modules, utilizing aluminum blocks with variable contact surfaces to improve thermal dissipation and uniform temperature distribution. The system contains six cylindrical cells aligned along a cooling channel, with aluminum blocks positioned between the cells to transfer heat to the water flowing through the channels, as shown in Figure 2.9. The cells are arranged linearly, with gaps of 2 mm in the x-direction and 5 mm along the z-axis. The contact surfaces between the cells and the aluminum blocks are designed to either remain constant or vary in size. A three-dimensional CFD simulation is employed to assess the impact of aluminum block length and inlet speed on cooling performance, testing various configurations with inlet velocities ranging from 0.05 m/s to 0.3 m/s. The experiment evaluates the maximum temperature and temperature differences

within the module, comparing constant and variable contact surface designs (with slopes of 1 mm, 2 mm, and 3 mm). Results indicate that the variable contact surface design significantly improved temperature uniformity, reducing temperature differences by up to 28% and system weight by 47%, while maintaining a maximum temperature below 40°C at an inlet velocity of 0.05 m/s. Gao et al. [59] proposed a liquid-cooled BTMS featuring a gradient channel design (GCD) to improve thermal uniformity and cooling efficiency for cylindrical 18650 lithium-ion batteries as shown in Figure 2.10. In this system, the batteries are equally placed on both sides of an aluminum cooling tube, which is divided into large and small flow channels to improve fluid-solid contact and boost heat dissipation. Numerical simulations using ANSYS Fluent were performed to compare the GCD with a uniform small and large channel design. Additionally, experiments were conducted using 18650 batteries, with water as the coolant and flow rates ranging from 180 to 900 ml/min. Key parameters measured in the experiments included maximum temperature ($T_{\max}$) and temperature difference (ΔT) across the different designs. The results showed that the GCD significantly improved thermal uniformity, with the 2-segment GCD reducing ΔT by 69.4% and 41.3% compared to the uniform large small channel design, respectively, at a flow rate of 360 ml/min. Furthermore, the GCD reduced $T_{\max}$ and ΔT by 79.2% and 60.2%, respectively, particularly at lower flow rates, making it more energy-efficient than the uniform channel designs.

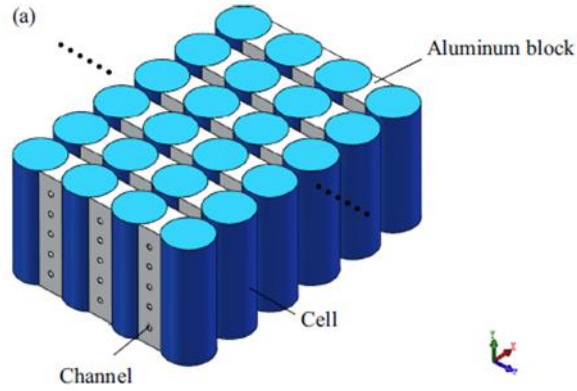


Figure 2.9 Liquid cooling system for the battery module [58].

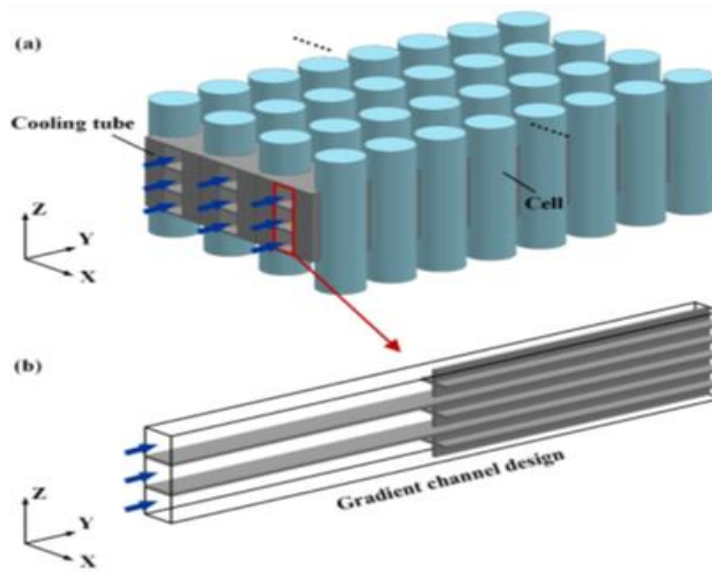


Figure 2.10 Liquid-cooled BTMS layout featuring a GCD [59].

Mini-channel cooling plates have gained widespread application in cylindrical batteries' liquid-based battery thermal management systems. Li et al. [60] investigated a mini-channel cold plate-based BTMS designed to improve adaptability across various ambient temperatures, especially under extreme conditions. The system contains a cylindrical battery array with 24 cells arranged in a 4×6 configuration, where each row of six batteries is cooled by cold plates containing mini-channels for coolant flow. The 18650 batteries are tightly arranged in rows, with cold plates positioned on both sides to ensure efficient cooling. Numerical simulations using COMSOL Multiphysics were performed to evaluate

the system's thermal performance at ambient temperatures between 25°C and 45°C, analyzing factors such as coolant inlet temperature, flow rate, and convection coefficients. The experiment measured $T_{\max}$ and $\Delta T_{\max}$ under numerous conditions, including coolant inlet temperatures (varying between 20°C to 35°C) and flow rates (from 0.2 to 0.6 m/s). Results showed that higher ambient temperatures (35°C and 45°C) caused significant temperature differences, badly impacting battery longevity, while increasing coolant temperature reduced peak intensity but raised $T_{\max}$. The study proposed a strategy of gradually reducing coolant inlet temperatures and lowering flow rates to enhance thermal uniformity in high ambient temperature environments.

The energy-efficient cooling capabilities of liquid immersion cooling make it an effective strategy for resolving thermal problems associated with high-rate charging. Li et al. [61] introduced a liquid immersion cooling (LIC) system using FS49, a dielectric fluid with high thermal stability, to cool 18650 lithium-ion cell modules during fast charging, with the objective of comparing LIC's performance to forced air cooling (FAC), as shown in Figure 2.11. The system consists of 21 cylindrical cells (Sony VTC6) arranged in three parallel branches, with seven cells per branch, fully immersed in FS49. The experimental setup tests LIC and FAC under fast charging conditions (2C and 3C rates), measuring parameters like $T_{\max}$, ΔT , and power consumption. The outcomes show that LIC significantly reduces peak temperatures during fast charging, lowering $T_{\max}$ by 7.7°C and 19.6°C under 2C and 3C rates, respectively, compared to FAC. LIC also enhances temperature uniformity, with peak temperature differences of only 1.1°C and 1.2°C, much lower than FAC's 6.3°C and 10.2°C. Furthermore, LIC consumes considerably less energy, using only 14.4% and 40.4% of the energy required by FAC at 2C and 3C charging rates.

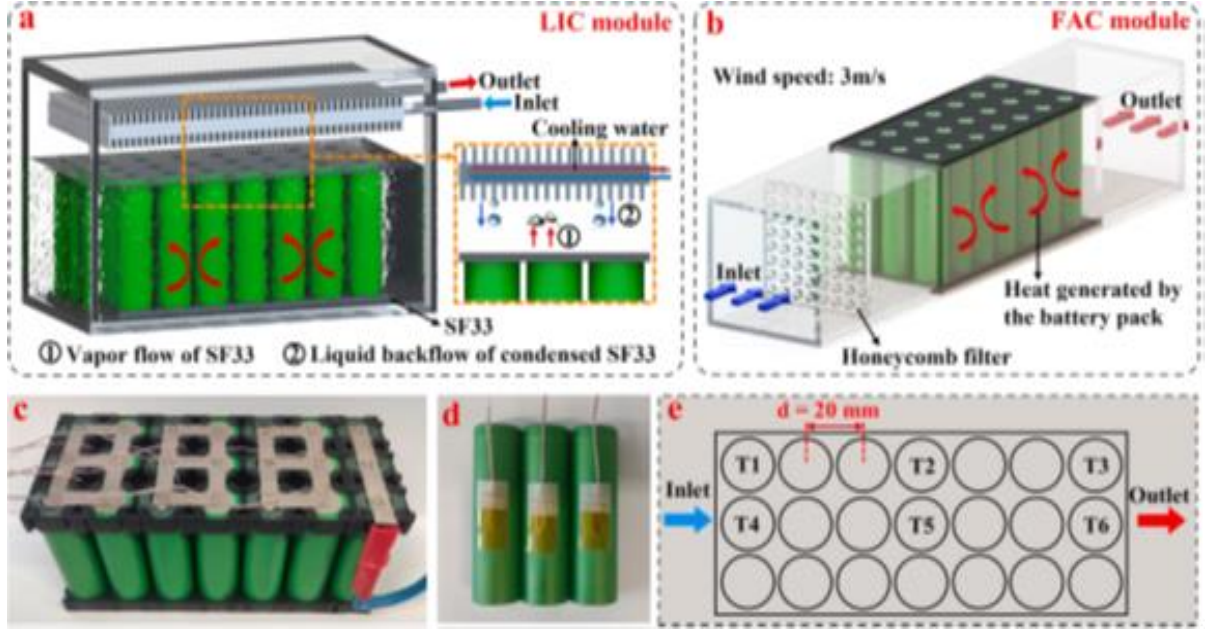


Figure 2.11 Diagram illustrating (a) the LIC module and (b) the FAC module; (c) the structure of the cell pack; (d) the thermocouple placement on the cell wall surface; and (e) the thermocouple positions within the cell module [61].

An essential characteristic of a BTMS is its ability to be lightweight and compact by efficiently utilizing the spaces between cylindrical cells. Shan et al. [62] proposed a liquid cooling battery thermal management system including axially mounted cooling tubes to provide a compact and lightweight solution for Li-ion cells, as illustrated in Figure 2.12. The system is composed of 50 tightly arranged 18650 batteries in a 5×10 array, with cooling tubes positioned between the cells. Two cell arrangement configurations, staggered and aligned, are evaluated. The staggered arrangement includes tubes with three curved contact surfaces, while the aligned arrangement has four. Numerical simulations are conducted to assess the cooling performance at various coolant speeds (0.01 m/s to 0.04 m/s) and discharge rates (1C to 3C), focusing on maximum temperature ($T_{\max}$), temperature difference ($\Delta T_{\max}$), and temperature uniformity. The aligned arrangement (Design B) exhibited superior cooling performance, with a lower $T_{\max}$ and better temperature uniformity, while the staggered arrangement (Design A) was more compact and

lightweight, resulting in a BTMS weight ratio of 5.4%, compared to 24.1% in Design B. Despite Design B's enhanced heat dissipation, Design A was considered more suitable for applications prioritizing compactness and reduced weight. In another study, Liange et al. [63] proposed a unitization-based battery thermal management system that employs an advanced distributed water-cooling component (WCC) to enhance temperature distribution and stop the thermal runaway in cylindrical batteries, as shown in Figure 2.13. The system contains six WCCs arranged along the axial way of the battery to create a basic BTMS unit, with four units combined into a module, separated by isolating pillars to ensure thermal isolation. The system utilizes commercial 18650-type batteries, with each unit having an independent water-cooling system. Numerical simulations using COMSOL were performed to evaluate key factors, such as volume flow rate (V_{ef}), the number of WCCs (N_{cc}), and inlet water temperature (T_{in}), under elevated surrounding temperature (35°C) and high discharge rate (3C). The simulations examined T_{max} , ΔT_{max} , and power consumption to optimize cooling efficiency while minimizing energy usage and weight. The optimal setup, with a V_{ef} of $9 \times 10^{-7} \text{ m}^3/\text{s}$, 4 WCCs, and T_{in} of 34°C, maintained T_{max} below 38.95°C with a ΔT_{max} of 4.36°C. Reducing T_{in} below 32°C led to higher power consumption without a notable improvement in cooling performance.

The integration of the cold plate among the batteries is another factor that is carefully considered and tested under various conditions to evaluate its impact on cooling efficiency and overall system performance. Kim et al. [64] presented two cold

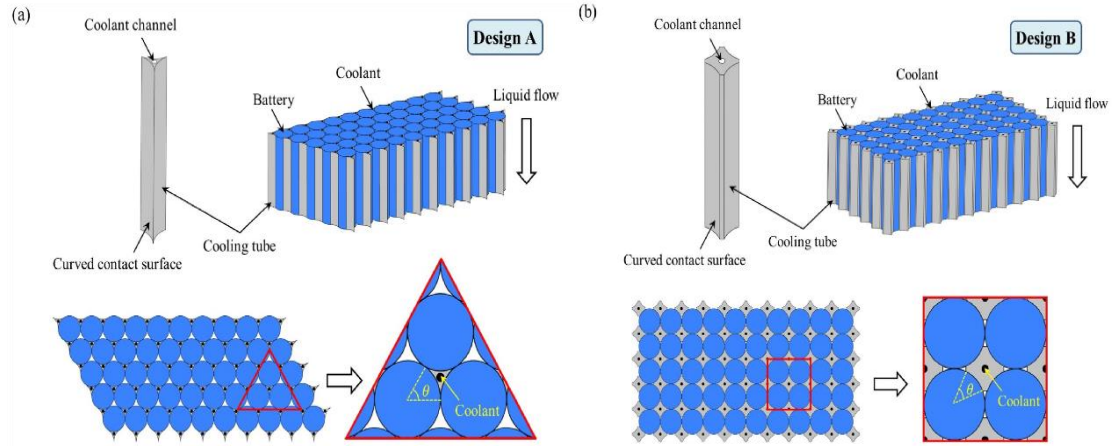


Figure 2.12 Schematic illustrations of the liquid-cooled battery module: (a) Design A showcasing the staggered cell prearrangement, and (b) Design B depicting the aligned cell prearrangement [62].

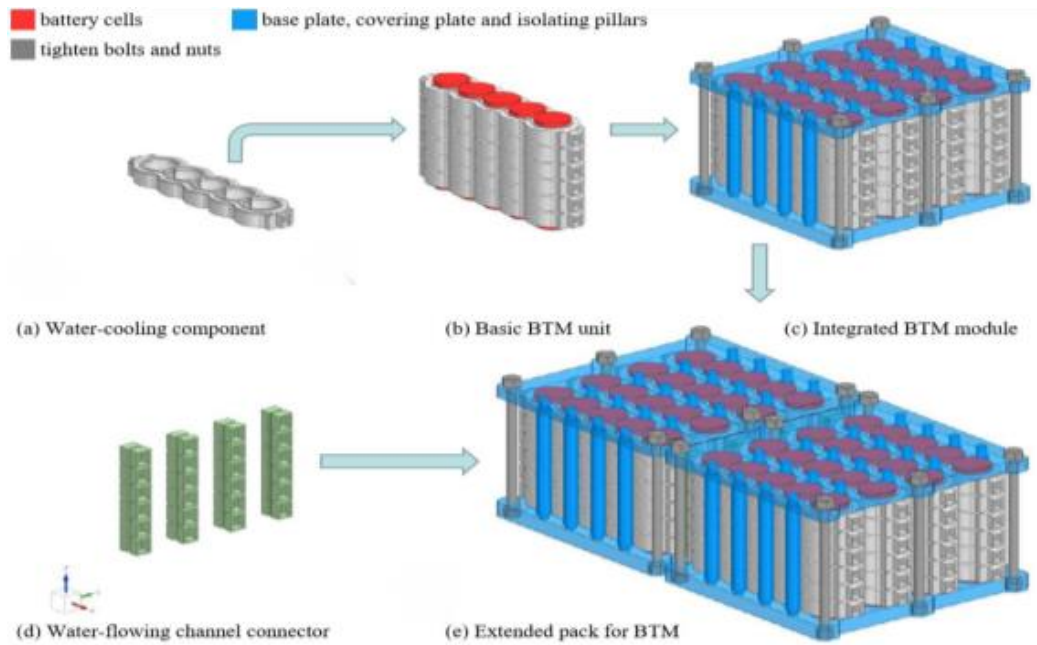


Figure 2.13 Diagram of the proposed battery thermal management solution [63].

plate designs (Type I and Type II) utilizing liquid cooling for the BTMS of Li-ion cells, with the goal of assessing and comparing their cooling efficiency at different C-rates, as shown in Figure 2.14. The system features cylindrical 18650 batteries, where Type I incorporates two cooling channels along the edges, and Type II utilizes four interspersed cooling channels, both integrated with aluminum fins to improve heat transfer. The batteries are arranged in rows, with the cooling channels positioned differently in each

design. Cooling performance was evaluated through experimental methods, with battery temperatures regulated using cooling water at 20°C, as well as MATLAB/Simulink-Simscape simulations to study thermal behavior. The tests were conducted at C-rates from 2C to 10C, with temperature monitoring to assess heat dissipation. The findings reveal that Type II cold plates significantly outperformed Type I, providing superior cooling efficiency, faster temperature regulation, and lower pump energy consumption. Type II more effectively maintained battery temperatures below the critical threshold, consistently demonstrating a thermal resistance of 0.001°C/W, whereas Type I thermal resistance declined with increasing C-rate, indicating reduced overall efficiency.

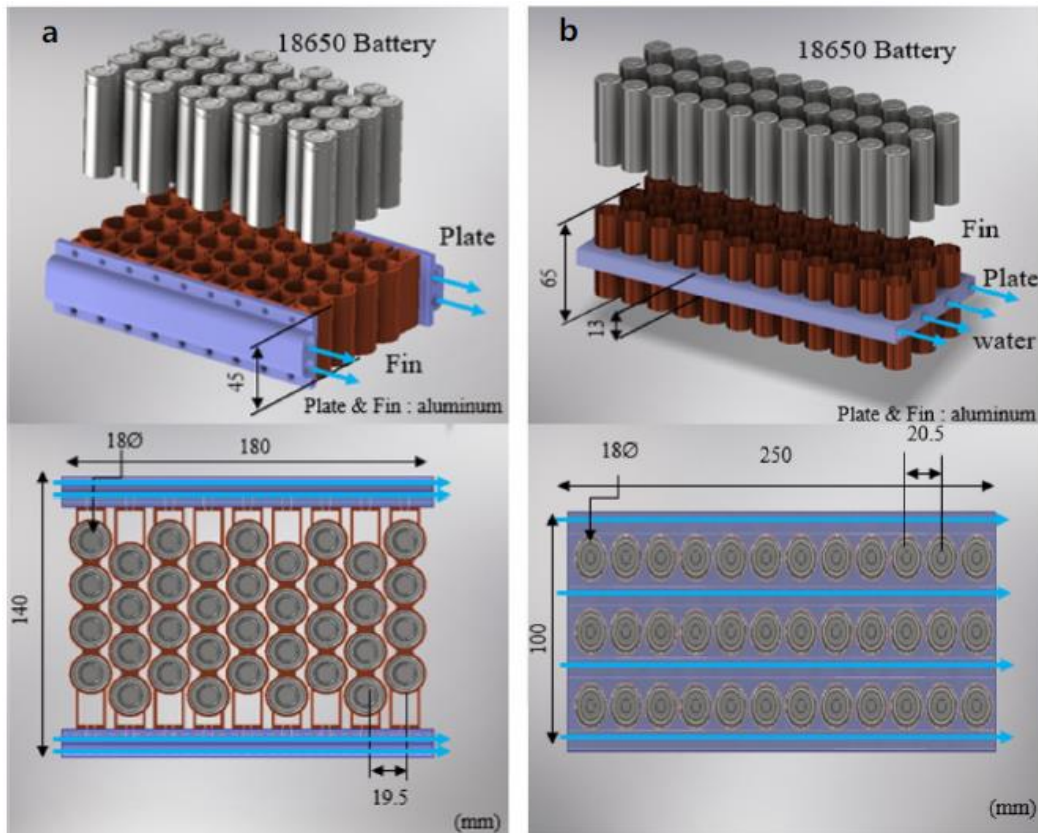


Figure 2.14 cell unit configurations: a) Type I and b) Type II [64].

Researchers anticipated a modification to improve cooling and enhance the heat transfer coefficient, which involves a micro-channel with added baffles. Xie et al. [65] introduced a mini-channel cooling-based structure for cylindrical lithium-ion cell packs, aimed at developing an electrochemical-thermal coupling model to predict heat generation and enhance heat transfer accurately. The system is designed for a Tesla Model S battery module containing 27 NCM 18650 lithium-ion batteries arranged in parallel, with a serpentine liquid cooling channel encircling the module to facilitate heat dissipation. The cooling channels feature aluminum walls and baffles to increase surface contact and promote fluid mixing. Numerical simulations using COMSOL Multiphysics assess the impact of various baffle heights and positions on temperature regulation and cooling performance. Key parameters measured include maximum temperature ($T_{\max}$), temperature difference (ΔT), and pressure drop under high discharge rates and different baffle configurations. Results indicate that the addition of baffles significantly enhances cooling by improving fluid mixing and increasing the temperature gradient within the cooling channels. However, taller baffles result in higher pressure drops, necessitating a trade-off between cooling efficiency and pumping power.

Dielectric immersion cooling is an emerging alternative to conventional BTMS, involving the direct submersion of battery cells in an electrically insulating fluid. This method allows for remarkably high heat transfer rates because of the direct interaction between the cells and the cooling fluid. In immersion cooling, batteries are fully submerged in non-conductive dielectric fluids, such as hydrocarbon oils, silicone oils, or fluorinated hydrocarbons, providing efficient heat dissipation without the risk of electrical conductivity. Zou et al. [66] introduced a thermal management system that combines static

immersion cooling (IC) with liquid cooling tubes (LCTs) to enhance heat dissipation in power battery modules, aiming to reduce energy consumption compared to traditional dynamic immersion cooling methods. The system features a battery module containing seventy-two 18650 cylindrical cells arranged in a 6S12P configuration, immersed in mineral oil, with LCTs placed between the columns of cells, as shown in Figure 2.15. Cooling performance was assessed through numerical simulations under various ambient conditions, testing multiple LCT configurations (ranging from 5 to 14 tubes) and different inlet water velocities (up to 0.6 m/s). Experiments measured the $T_{\max}$ and $\Delta T_{\max}$ at high ambient temperatures (25°C and 40°C) and high discharge rates (up to 3C). Results show that using 10 LCTs provided an effective balance between cooling performance and temperature uniformity, maintaining $T_{\max}$ below 43.39°C at 25°C and 55.72°C at 40°C at a 3C discharge rate. Although increasing the number of LCTs improved heat dissipation, it caused overcooling near the tubes, leading to reduced temperature uniformity. Integrating IC with LCTs connected to the vehicle thermal management system (VTMS) minimized the need for additional circulation systems, thereby improving energy efficiency and system integration. In a similar work, Liu et al. [67] presented an immersion cooling system for a lithium-ion battery module composed of 16 cylindrical 38120-type batteries, which are directly immersed in mineral oil to enhance heat dissipation, reduce maximum temperature, and improve temperature uniformity, as shown in Figure 2.16. The battery module is centrally placed within a sealed ABS plastic shell, with cell spacing varying from 1 mm to 5 mm to examine the impact on cooling performance. Numerical simulations using CFD software ANSYS FLUENT are performed to evaluate cooling efficiency under different cell spacings, coolant flow rates (ranging from 0.05 m/s to 0.35 m/s), and

discharge rates (1C, 2C, 3C), with validation using experimental data from previous studies. The experiment evaluates the $T_{\max}$, ΔT , and pressure drop across various conditions to determine cooling effectiveness. The results show that expanding the spacing between cells from 1 mm to 5 mm reduced the maximum temperature by 29% and lowered the temperature difference from 7.2°C to 5.2°C. Higher flow rates further decreased the temperature rise to 4.07°C, but led to a significant increase in pressure drop, potentially impacting system efficiency. The maximum temperature rises at discharge rates of 1C, 2C, and 3C were 2.67°C, 5.41°C, and 8.69°C, respectively, showing a marked improvement compared to natural convection, with immersion cooling effectively boosting both heat dissipation and temperature uniformity under high discharge rates.

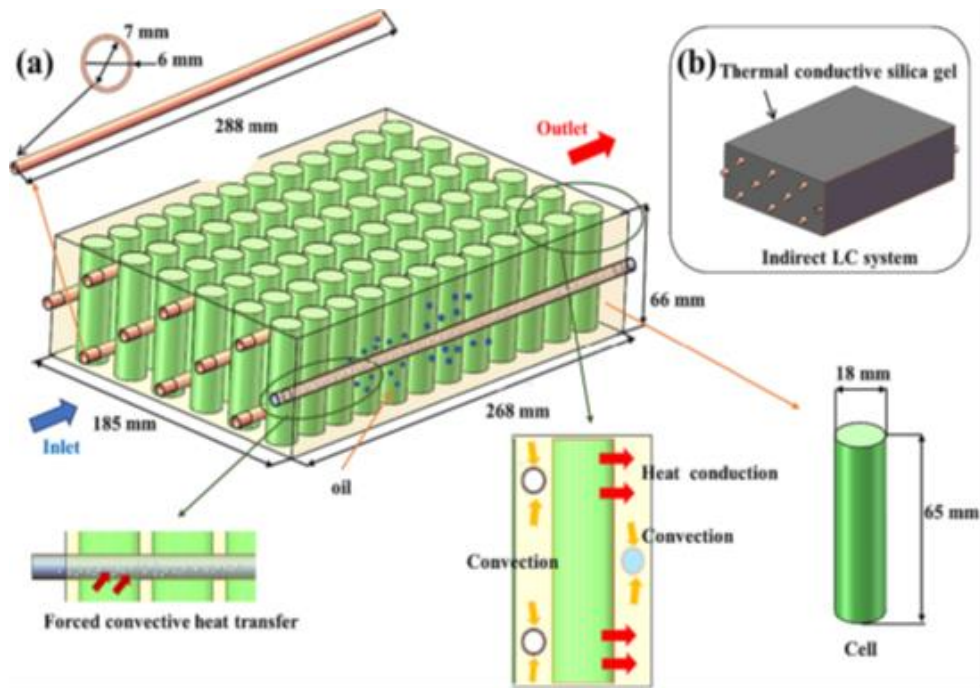


Figure 2.15 Schematic diagram of the battery modules showing (a) the liquid-immersed cooling BTMS and (b) the indirect liquid-cooled BTMS [66].

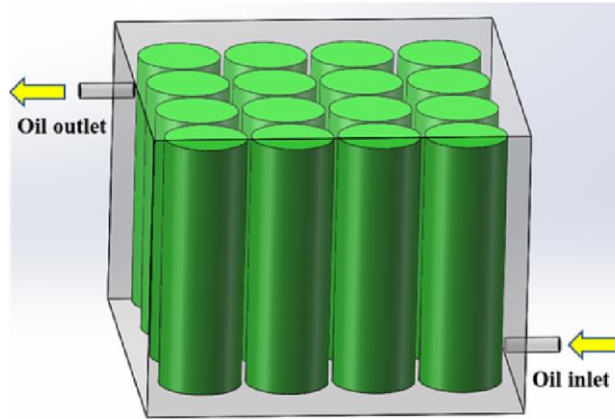


Figure 2.16 Diagram of the geometry model for the immersion cooling system in the study [67].

Nanofluids have developed as a capable enhancement for heat transfer in liquid-cooling systems for BTMSs. Composed of a main fluid with nanoscale particles, nanofluids display superior thermal conductivity compared to traditional coolants. When incorporated into the liquid-cooling structures of lithium-ion batteries, these nanofluids significantly boost heat transfer efficiency, helping to prevent overheating during high-power applications. Touse et al. [68] proposed a novel liquid-cooled BTMS utilizing AgO nanofluid and a copper sheath to enhance heat dissipation in cylindrical Li-ion cell packs, especially under elevated discharge rates (3C, 5C, and 7C). The system contains 12 cylindrical cells arranged in an aligned configuration, with each cell encased in a copper sheath to ensure uniform heat distribution. A unidirectional flow channel made of aluminum alloy, along with separator plates, directs the coolant flow to optimize thermal management. Numerical simulations were conducted to assess maximum temperature ($T_{\max}$), temperature difference (ΔT), and pressure drop across different operating conditions, including discharge rates, nanofluid volume fractions (1%, 2%, 4%), and coolant flow velocities (up to 0.28 m/s). The results indicate that AgO nanofluid significantly reduced $T_{\max}$ and ΔT compared to deionized water, achieving reductions of up to 10.1% and 23.95%, respectively. Increasing coolant

flow velocity further improved cooling performance but also led to a higher pressure drop. While the 21700-type cells exhibited a higher $T_{\max}$ compared to the 18650-type cells, they provided superior energy density and capacity. The system effectively maintained $T_{\max}$ below 305.59 K and ΔT below 1.07 K at high discharge rates, demonstrating efficient cooling performance under optimized flow conditions.

Alumina nanofluid is among the best solutions utilized in liquid-cooling based structures, offering enhanced thermal conductivity and improved heat transfer capabilities. Sarchami et al. [69] introduced a thermal management system for cylindrical lithium-ion batteries that employs a wavy/stair channel liquid cooling system in combination with a copper sheath, aimed at minimizing peak temperatures and enhancing temperature uniformity. The system contains a pack of six 18650 batteries encased in copper sheaths, with coolant circulating through aluminum wavy and stair channels. The batteries are arranged in a staggered configuration, with copper plates assisting in additional heat transfer. The experimental setup features a cooling system equipped with a pump, cooling tank, and flow meters, utilizing alumina nanofluid (at 1% and 2% volume fractions) as the coolant, with flow velocities ranging from 0.2 to 0.4 m/s. The experiments measure maximum temperature, temperature difference, and pressure drop during charge/discharge cycles at different C-rates (0.5C to 5C) to evaluate the effects of nanofluid concentration, flow velocity, and channel design. Results indicate that using a 2% volume fraction of alumina nanofluid significantly decreased maximum temperature and non-uniformity, achieving reductions of 2.6 K and 0.25 K during charging, and 2.33 K and 0.54 K during discharging compared to pure water. The stair channel design outperformed the straight channel, reducing the maximum temperature by 2.8 K during charging and 3.59 K during

discharging. The optimal setup, with a flow velocity of 0.4 m/s and a 2% nanofluid volume fraction, maintained peak temperatures below 305.13 K and temperature differences below 2.01 K during 5C charge/discharge cycles.

Based on the reviewed studies on liquid-cooled BTMS, the efforts to improve the systems focused on several aspects. Researchers optimized cooling channel designs, such as gradient, wavy, stair, and mini-channel cold plates, as well as axially mounted cooling tubes, to enhance fluid flow and heat dissipation. Heat transfer materials, including copper sheaths and aluminum walls, were utilized to improve heat transfer from the battery cells to the coolant. The introduction of nanofluids, like AgO and alumina nanofluids, aimed to enhance cooling efficiency due to their superior thermal conductivity compared to pure water. Hybrid cooling solutions combining static immersion cooling with liquid cooling tubes were also explored to improve efficiency while reducing energy consumption. Electrochemical-thermal coupling models were developed to predict heat generation and optimize temperature control. The systems were tested under different conditions such as varying ambient temperatures, flow rates, and discharge rates to ensure optimal performance in diverse scenarios. Efforts were made to minimize temperature differences between cells and improve temperature uniformity, as uneven temperatures can degrade battery performance. Additionally, weight and energy efficiency considerations were addressed by optimizing the number of cooling components to achieve effective thermal management without excessive system weight or energy consumption. These collective efforts aimed to enhance thermal management capabilities by focusing on efficient heat dissipation, uniform temperature control, effective material use, and overall system integration.

While liquid cooling in BTMS presents significant advantages, numerous drawbacks and limitations have also been noted in the reviewed studies. Increased pressure drops due to added components like baffles and high nanofluid concentrations required higher pumping power, raising overall energy consumption. The inclusion of complex channel designs, such as gradient, wavy, and mini-channels, added to system complexity, affecting scalability and ease of manufacturing. Weight and volume challenges rose from additional components like multiple cooling tubes and copper sheaths, reducing energy density and making the system less suitable for compact applications. In some designs, increasing the number of cooling tubes led to localized overcooling, causing temperature non-uniformity. The use of nanofluids, although beneficial for heat transfer, added significant cost to the system, along with challenges related to maintaining nanoparticle dispersion. Cooling efficiency was also highly sensitive to flow rate and coolant temperature, which required precise control, complicating system management. Some systems showed reduced efficiency at higher ambient temperatures, limiting their effectiveness in hot climates. Additionally, under high discharge rates, many systems faced challenges in maintaining temperature uniformity, especially in densely packed modules, where the increased thermal load was difficult to manage despite enhanced cooling methods. These limitations underline the challenges related to pressure drops, system complexity, weight and space efficiency, overcooling, costs, flow sensitivity, ambient conditions, and uniform cooling at high discharge rates.

2.4 PCM-based BTMS

Compared to conventional thermal management methods, PCM-based thermal management technology has attracted considerable attention due to its ability to eliminate the need for additional components and energy consumption from the battery. This technology operates on the principle that during the phase change process, phase change material (PCM) absorbs or releases a substantial amount of latent heat while maintaining a nearly constant temperature [70]. PCM typically features a high latent heat of fusion and an optimal melting point, enabling effective heat absorption or release. In a PCM-based system, heat produced by the cell is transferred to the PCM and subsequently to the cell casing, which is exposed to ambient air. PCM reduces the need for active cooling for most of the battery's operating time by delaying temperature rise in cooler conditions and keeping the battery temperature below ambient levels in hot conditions, thus providing effective thermal management with minimal energy use. phase change materials that have melting temperature ranges around 20 and 50°C are frequently used in study, as they align with the typical working temperature range of batteries.

Thermal conductivity is a critical property of PCMs, as it influences their ability to transfer thermal energy, with low thermal conductivity often limiting their effectiveness in thermal management applications. Most commonly used PCMs in industry have low thermal conductivities, typically ranging from 0.2 to 0.4 W/(m.K), which adversely affects their performance in heating, cooling, and energy storage systems [71]. To overcome these limitations, researchers have studied numerous strategies to enhance heat transfer in PCMs, such as adding extended surfaces (fins), metal foams, pin-fins, and porous materials, which

help establish conductive pathways and improve thermal conductivity [72]. Additionally, approaches like microencapsulating PCMs and incorporating thermally conductive additives, such as nanoparticles and fiber filters, have become popular for their high thermal conductivity and low density [73]. Nanoparticles, in particular, significantly improve heat transfer by creating low thermal resistance pathways; however, they also increase viscosity, which can amplify buoyancy and viscous forces, leading to both positive and negative effects on PCM performance [74]. Moreover, porous materials can absorb PCMs, forming efficient conduction networks. Despite these advancements, challenges like low form stability, significant volume changes, and the flammability of organic PCMs still need careful attention to ensure the overall efficiency and cost-effectiveness of PCM-based systems. PCMs are typically categorized based on their structure into three basic types: organic, inorganic, and eutectic, which are illustrated in Figure 2.17.

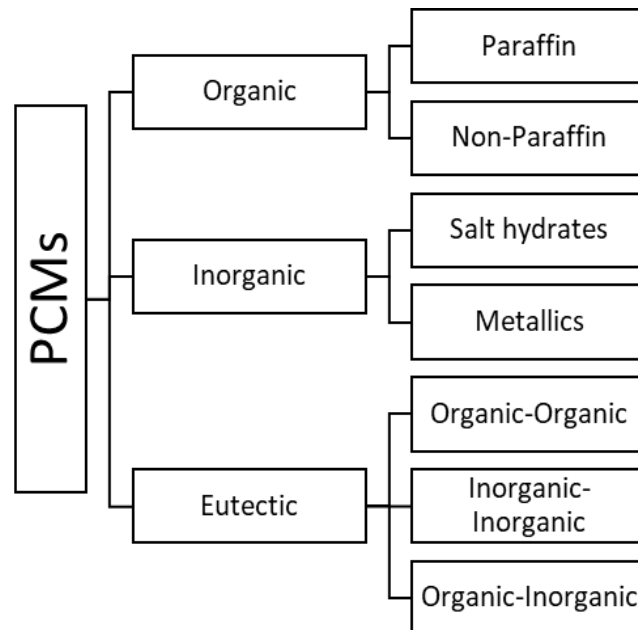


Figure 2.17 Categories of PCM.

2.4.1 Organic PCMs

Organic PCMs are carbon-based compounds divided into paraffin and non-paraffin groups. These materials are relatively stable, safe, and possess a high latent heat of fusion, making them suitable for a broad temperature range (15-45°C) [75]. Organic PCMs exhibit uniform melting characteristics and can be utilized as core materials or coatings without causing corrosion [76].

Paraffin is the most commonly used type of organic PCM for thermal management and energy storage applications, largely due to its wide range of melting temperatures. Contained of straight-chain alkanes, paraffin is characterized by homogeneous melting, core-forming properties, and chemical stability up to temperatures of 500°C [77]. Its non-corrosive nature, easy availability, and cost-effectiveness make it a popular choice for thermal management and energy storage systems. However, paraffin has certain limitations, such as low thermal conductivity, flammability, and incompatibility with plastic casings [78]. These drawbacks can be addressed through modifications to the paraffin wax or adjustments to the storage device.

Non-paraffin PCMs typically include fatty acids, alcohols, esters, and glycols [79]. These materials share similar thermophysical characteristics with paraffin-based PCMs, such as high latent heat, but possess unique properties that influence their applications. Fatty acids, derived from renewable sources like plants and animals, exhibit excellent thermal and physical properties, making them attractive for energy storage. However, non-paraffin PCMs also have limitations, including high flammability, low thermal conductivity, and incompatibility with high temperatures, which limits their applicability in high-heat applications [80]. In spite of these difficulties, extensive research has focused on utilizing

esters, fatty acids, alcohols, and glycols for energy storage due to their renewable nature and diverse properties.

2.4.2 Inorganic PCMs

Inorganic phase change materials, such as salt hydrates and metallic foams, are known for their high latent heat per mass and volume, wide melting temperature range, and advantageous properties like high thermal conductivity, non-flammability, and cost-effectiveness [75]. These features make inorganic PCMs suitable for various thermal management applications, including enhancing the performance of lithium-ion batteries, where they function as structural support materials, thermal conductivity enhancers, and flame-retardant agents [81]. Compared to organic PCMs, inorganic PCMs offer several benefits, such as superior phase change enthalpy, lower cost, and higher thermal stability. However, challenges like corrosiveness, undercooling, phase separation, limited long-term stability, and degradation due to corrosion between PCM and container materials can restrict their use [79]. Salt hydrates, specifically, have high latent heat, minimal volume changes during melting, and high phase homogeneity, but are prone to undercooling, density-driven precipitation, and stability issues [82]. Metallic foams, another type of inorganic PCM, are utilized to improve thermal conductivity, providing good stability and a high ratio coefficient, although the influence of pore size on thermal performance is limited. Despite these challenges, inorganic PCMs show potential for industrial applications, particularly in recovering high-temperature waste heat, though their application in the automotive sector remains largely unexplored in the literature.

2.4.3 Eutectic PCMs

Eutectic phase change materials consist of a combination of two or more components, which can be inorganic-inorganic, organic-organic, or organic-inorganic. These materials are designed to melt and freeze at a specific atomic ratio, resulting in consistent melting and freezing without phase segregation, thereby forming a uniform crystal mixture during phase transition [83]. Examples include organic-organic mixtures like capric-lauric acid, inorganic-inorganic combinations such as Lithium hydroxide-potassium hydroxide, and organic-inorganic blends like naphthalene-benzoic acid. Eutectic PCMs offer advantages such as high latent heat, excellent thermal stability even after thousands of thermal cycles, and the ability to fine-tune the melting temperature by adjusting the composition. This flexibility makes eutectic mixtures particularly appealing for thermal management and energy storage applications, although they tend to be more expensive and less commercially available compared to other PCMs like paraffin wax. The melting and freezing behavior of eutectic PCMs is determined by their composition and the eutectic point, as represented on a phase diagram by the ratio of components and the corresponding eutectic temperature [84].

2.4.4 PCM-cooled BTMS

Many researchers focused on developing a thermal management solution using a PCM-metal foam composite to enhance thermal conductivity and effectively control Li-ion batteries' temperature. El Idi et al. [85] introduced a passive thermal management system that utilizes a PCM-metal foam composite to absorb the heat produced by Li-ion cells, aiming to keep battery temperatures under 27°C throughout charge and discharge cycles. The system features an 18650 Li-ion cell embedded in aluminum foam, which is filled with

paraffin RT27 as the PCM. The experimental setup includes a DC power supply, active charge control, a climatic chamber, and T-type thermocouples for temperature monitoring. The Li-ion cell underwent consecutive charge/discharge cycles at different current rates, with temperatures recorded using the thermocouples. Heat dissipation was calculated from experimental data and simulated using COMSOL Multiphysics and Matlab. The findings indicate that incorporating aluminum foam with the PCM significantly improved heat absorption efficiency, resulting in lower temperatures compared to using pure PCM alone. The study concludes that the PCM-metal foam combination is more effective for managing thermal loads due to enhanced thermal conductivity, whereas increasing the PCM volume beyond a certain threshold had limited additional benefits for temperature control. In a related study, Sun et al. [86] examined a passive BTMS employing a composite of copper foam embedded with paraffin PCM to enhance heat dissipation and temperature control in Li-ion cell modules. The arrangement features a battery pack with 16 cells (simulating 21,700 NMC cells) arranged in a 4x4 grid, with the cells surrounded by either pure PCM or PCM Integrated Copper Foam for cooling, as illustrated in Figure 2.18. The experimental setup included a thermal chamber with controlled surrounding temperatures (25°C and 35°C), a DC power supply for heaters, thermocouples, and a thermal imaging camera for temperature monitoring. The experiment compared free air, PCM only, and copper foam-PCM cooling at a 3C discharge rate. The results demonstrated that the copper foam-PCM composite significantly reduced the $T_{\max}$ from 57.4°C to 51.4°C compared to the PCM only system, and improved temperature uniformity to within 5°C. Additionally, the gravimetric (GCTP) and volumetric (VCTP) cell-to-pack ratios were found to be 53.1% and 45.6%, respectively, highlighting the system's potential for practical applications. In a

similar work, Cheng et al. [87] examined a double-layer battery thermal management system for Li-ion cells using CPCMs to meet the dual demands of effective heat dissipation in high temperatures and heat retention in cold climates, as shown in Figure 2.19. The system features an inner layer composed of an expanded graphite (EG)-based material with high thermal conductivity (POE) and an outer layer made of paraffin wax and olefin block copolymer (PO) with lower thermal conductivity for improved insulation. The batteries are arranged in a 2x8 configuration, surrounded by CPCMs, and tested at discharge rates of 1C, 2C, and 3C. The experimental setup includes a battery cyler, temperature and humidity controls, and thermocouples for temperature measurement, while numerical simulations were performed. The findings reveal that the double-layer structure (Type-C) provided an optimal balance between heat dissipation and insulation. The inner POE layer efficiently conducted heat, while the outer PO layer served as insulation, effectively delaying heat loss in cold conditions. A 4/6 volume ratio of POE to PO was identified as optimal, maintaining thermal uniformity, reducing temperature gradients, and enhancing thermal stability across a wide range of ambient temperatures, while also significantly lowering the risk of thermal runaway.

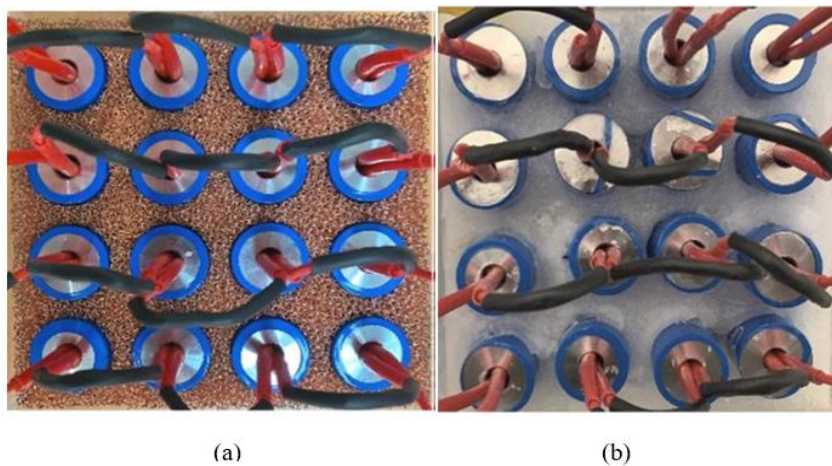


Figure 2.18 Battery pack with cooling medium: (a) copper-foam PCM; (b) PCM only [86].

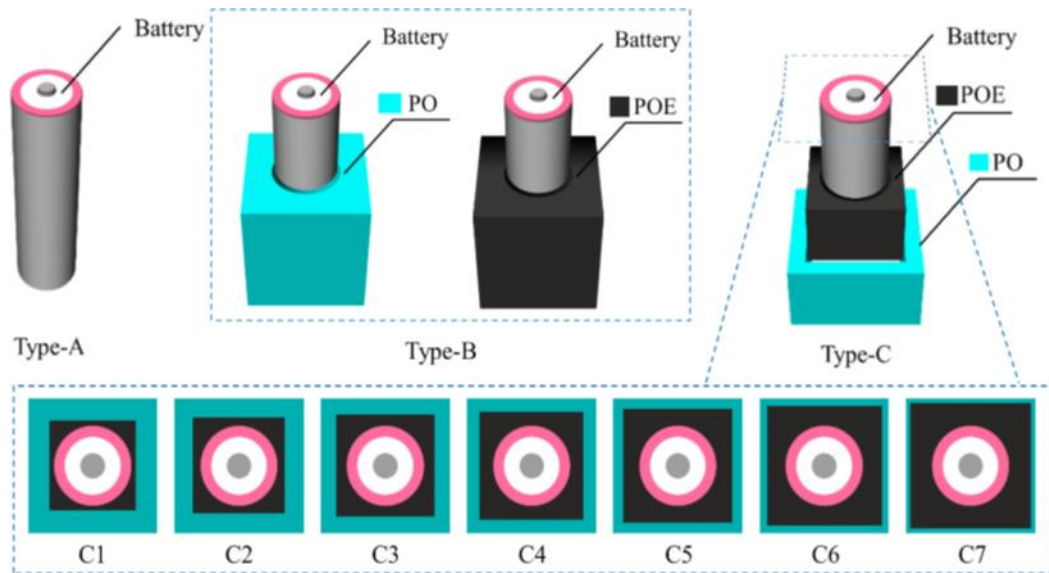


Figure 2.19 Various assembly structures between the battery and the CPCMs [87].

Some researchers have attempted to create analytical models and exact solutions to better comprehend the phase changing progression in such systems and determine optimal working conditions. Kermani et al. [88] introduced a PCM cooling pack using calcium chloride hexahydrate (PCM1) and paraffin wax (PCM2) to manage the thermal behavior of cylindrical 18650 lithium-ion batteries, with a focus on optimizing PCM thickness for effective cooling. The system features batteries arranged in a series, each encased in PCM to absorb heat generated during operation. Thermal analysis was conducted using an analytical approach based on cylindrical coordinates, combined with a thermal resistance method to assess the effects of different PCM types, thicknesses, and ambient temperatures at varying discharge rates (2C to 10C). The temperature distribution was evaluated during both change phases of the PCM, comparing the effectiveness of PCM1 and PCM2 under various conditions. The results indicated that PCM1, due to its higher thermal conductivity, led to significantly lower temperature rise and improved thermal uniformity compared to PCM2. Furthermore, the study concluded that an optimal PCM thickness is crucial for effective heat absorption in the latent phase, reducing sharp temperature increases and

maintaining stable battery performance. In related work, Li et al. [89] presented an optimization approach for a BTMS utilizing an expanded graphite (EG)/paraffin composite PCM to control the thermal Characteristics of lithium-ion cells, aiming to minimize PCM mass while maintaining effective thermal performance. The system contains cylindrical batteries surrounded by the EG/paraffin composite PCM, arranged in varying configurations (single, double, triple, and quadruple units). An experimental setup, including electrical heaters, insulation, K-type thermocouples, and a data logger, was constructed to validate the numerical models used in the optimization. The optimization process examined factors such as cell radius, gaps between cells, heat generation rates, and phase change material thickness, with numerical simulations carried out using computational fluid dynamics. The outcomes indicate that the proposed optimization approach successfully reduced PCM mass while maintaining thermal safety, and parameters like battery radius, inter-battery gaps, and PCM thickness were found to significantly impact cooling performance. The cylindrical BTMS configurations showed greater PCM efficiency compared to cuboid designs, and an optimal PCM thickness was determined for each configuration to achieve optimal thermal performance.

Integrating nanoparticles into PCMs is an innovative approach to improve their thermal conductivity. Karimi et al. [90] explored the thermal management of cylindrical lithium-ion batteries using PCM composites enhanced with metal nanoparticles to improve temperature control and uniformity. The system features a cylindrical cell simulator enclosed in a container occupied with various PCM composites, including macro-doped materials and nano-enhanced PCMs containing silver (Ag), copper (Cu), and iron oxide (Fe_3O_4) nanoparticles. The experimental setup included a constant heat flux heater to

simulate battery heat generation, thermocouples for temperature measurement, and a Plexiglas container. The experiment was conducted in three stages: free convection, PCM cooling, and enhanced PCM composite cooling to assess the thermal performance of each composite. The results indicate that the PCM composite with Ag nanoparticles provided the best cooling, significantly lowering surface temperatures, while the metal matrix-PCM composite exhibited the most uniform temperature distribution. Overall, the PCM composites reduced temperature variations by up to 70% compared to pure PCM, demonstrating enhanced temperature control, and improved thermal management efficiency. In a similar work, Kadam et al. [91] studied a BTMS using paraffin-based PCM enhanced with graphene nanoparticles to enhance the thermal behavior of cylindrical 18650 cells, focusing on enhancing PCM thickness and thermal conductivity. The system contains a 12-cell pack, with the batteries encased in a PCM matrix of varying thicknesses (1 mm, 3 mm, 5 mm, 7 mm, and 9 mm). A 3D model of the battery pack was created in SOLIDWORKS and imported into ANSYS for thermal simulations to analyze the effect of graphene-enhanced PCM on temperature distribution at different discharge rates (1C, 2C, 3C). The results indicate that increasing PCM thickness reduced battery temperature but also added weight, with limited temperature reduction benefits beyond a certain thickness. The incorporation of graphene nanoparticles significantly enhanced thermal conductivity, resulting in more effective temperature management compared to pure paraffin, especially at thinner PCM layers.

Different types of commercial PCMs can be evaluated using a simplified thermal model to assess performance at various discharge rates. This approach helps in determining how effectively different PCMs manage battery temperatures, offering valuable insights into

their suitability for battery thermal management applications under diverse operational conditions. Lamrani et al. [92] presented a passive BTMS applying PCM to improve thermal control during charge and discharge cycles. The system consists of a battery pack containing 24 cylindrical 21,700 lithium-ion cells, arranged in a (6S4P) configuration and surrounded by PCM. Four types of commercial PCMs A-32 H, RT-31, RT-35HC, and A-36 H were analyzed, with PCM A-32 H determined to be the most suitable because of its ideal phase transition temperature and significant latent heat of fusion. A simplified lumped thermal model was employed, incorporating energy balance equations for both the batteries and PCM, with validation from experimental data and previous CFD studies. The thermal performance was assessed over three charge-discharge cycles at a 3C discharge rate and a 0.5 C charge rate. Results indicated that the PCM reduced $T_{\max}$ by up to 3°C in comparison with a battery pack without PCM. Additionally, enhanced airflow around the pack further reduced the maximum temperature by an additional 2.5°C. The model was validated with a maximum relative error of approximately 6%, demonstrating accuracy while offering reduced computational time compared to 3D CFD models.

Determining the optimal PCM thickness is essential for effectively regulating battery temperature and preventing thermal runaway during discharge cycles. An ideal PCM thickness ensures that the heat generated by the battery is efficiently absorbed, keeping the temperature below critical thresholds throughout the discharge process. If the PCM layer is too thin, it may fully melt, causing a sharp temperature rise and increasing the risk of thermal runaway, which can compromise both battery safety and performance. Therefore, achieving the right balance in PCM thickness is crucial for maintaining the safety, reliability, and performance of the BTMS. Bais et al. [93] numerically examined a passive

battery thermal management system using RT-42 paraffin-based PCM to regulate the temperature of an 18650 lithium-ion battery during discharge. The system comprises a single cylindrical battery encased in varying thicknesses of PCM, which is encapsulated in aluminum cylinders for enhanced structural stability and heat dissipation. The objective was to determine the optimal PCM thickness needed to prevent thermal runaway and maintain battery temperature below critical levels. A lumped thermal model was developed using ANSYS Fluent with the enthalpy-porosity approach to simulate PCM melting and solidification during a 3C discharge cycle. The simulations evaluated PCM thicknesses ranging from 1 mm to 7 mm. Results indicated that a PCM thickness of at least 4 mm was effective in maintaining battery temperatures below 50°C, while thinner layers led to complete melting of the PCM and a subsequent sharp temperature rise. The study concludes that a minimum PCM thickness of 4 mm is necessary to ensure effective thermal regulation and prevent thermal runaway during battery discharge. In a similar work, Vashisht et al. [94] investigated the use of phase change material for passive thermal management of 18650 Li-ion cells at various C-rates, focusing on determining the optimal PCM thickness to achieve effective cooling while minimizing excess material usage. The system employs capric acid phase change material to stabilize the cell temperature by utilizing its latent heat during the phase change. Different PCM thicknesses (1.25, 2.50, and 5 mm) were evaluated, with the cell embedded in a cylindrical container filled with PCM. Thermal simulations were conducted using a two-dimensional axisymmetric transient thermal model, and performance was assessed using experimental parameters such as the cell cooling coefficient (CCC) and PCM cooling enhancement factor. The results show that PCM effectively maintains cell temperature below critical thresholds,

with thicker layers providing better thermal regulation. An optimal PCM thickness of 2 mm to 2.5 mm was identified for higher discharge rates (2 C and above), while a thickness of 2.5 mm to 3 mm was ideal for lower rates (1C to 1.5C). PCM layers ranging from 1.25 mm to 5.00 mm reduced battery temperature by up to 10.09°C, demonstrating improved cooling efficiency, though with diminishing returns beyond a certain thickness.

The efforts to improve PCM-cooled BTMS, as described in the reviewed studies, focused on several key aspects. One major effort was optimizing PCM thickness to ensure effective thermal regulation while minimizing excess material use and added weight. Enhancing thermal conductivity was also a priority, achieved by incorporating materials like metal foams, expanded graphite (EG), and metal nanoparticles (such as silver, copper, and graphene) into the PCM. Additionally, the development of composite PCM structures, including double-layer configurations, aimed to balance heat dissipation in high temperatures with heat preservation in cold climates. Metal foams such as copper and aluminum were integrated into the PCM to improve heat absorption by increasing the heat transfer surface area. Advanced simulation and analytical models were employed to predict temperature distribution and optimize PCM design parameters, allowing for accurate and rapid performance assessments. Different PCM materials, including paraffin, capric acid, and commercial PCMs like RT-31, RT-42, and A-32 H, were selected based on their thermal properties to ensure compatibility with specific battery applications. Lastly, PCM performance was evaluated under varying discharge rates (ranging from 1C to 3C or higher) to ensure effective thermal management under different operational conditions. These efforts collectively aimed to improve the efficiency, reliability, and adaptability of PCM-based BTMS.

According to the reviewed studies on PCM-cooled BTMS, several drawbacks and limitations were identified. One common issue is the low thermal conductivity of pure PCMs, such as paraffin, which limits heat dissipation and requires the addition of materials like metal foams or nanoparticles to enhance performance, increasing system complexity. The use of PCM also adds weight and volume to the battery system, which is a significant drawback in applications like electric vehicles where space and weight are critical. PCM performance tends to diminish at higher discharge rates (above 3C), where rapid heat generation can exceed the material's heat absorption capacity, leading to overheating. Additionally, some studies noted PCM degradation over time after repeated charge-discharge cycles, reducing its latent heat capacity and necessitating replacement or maintenance. The slow response time of PCM compared to active cooling systems is another limitation, particularly during rapid charging or discharging. Unequal heat distribution across the battery pack, especially in cases of insufficient PCM thickness or fully melted material, can lead to hot spots and affect battery safety. The inclusion of nanoparticles, while improving thermal conductivity, introduces challenges in terms of cost, stability, and system complexity. Lastly, the use of advanced PCMs, such as those enhanced with expanded graphite or metal nanoparticles, increases the overall cost, potentially limiting the economic feasibility of PCM-cooled BTMS for large-scale commercial use.

2.4.5 PCM-fin Cooled BTMS

PCM-based cooling systems are often paired with fins. Fins are added to the system to overcome the low thermal conductivity of phase change materials. PCMs alone are not effective at rapidly dissipating heat generated by the battery, so fins are incorporated to

improve heat transfer from the cell to the encasing PCM. The fins increase the contact surface area for heat exchange, permitting more efficient and quicker heat dissipation, thus preventing the battery from overheating during high discharge rates. In designing the fins, several considerations are taken into account, including fin thickness, number of fins, length, and the material, to find the optimal configuration that maximizes thermal conductivity while minimizing mass and volume. Dagdevir et al. [95] examined a BTMS that combines helical aluminum fins with CPCM to enhance heat dissipation for a 26,650 Li-ion battery, as illustrated in Figure 2.20. The arrangement features aluminum helical fins surrounding the battery, which is encased in a CPCM made of paraffin mixed alongside the expanded graphite to improve thermal conductivity. The battery is placed within the fin structure, and various configurations with fin widths of 2 mm, 4 mm, and 6 mm, along with 1, 3, and 5 fin rounds, were tested. Numerical simulations using ANSYS Fluent at a 3C discharge rate were conducted. Results indicated that increasing the fin width and number of rounds significantly enhanced heat dissipation, with the 6 mm width and 3 rounds yielding the best performance. An EG fraction of 12% provided the optimal balance, extending the safe operating time by 244% compared to configurations without fins or EG. However, a higher EG content (20%) reduced performance due to a lower latent heat capacity. While the combination of helical fins and CPCM substantially improved thermal management, it also increased the system's mass and volume, making it more appropriate for stationary energy storage applications.

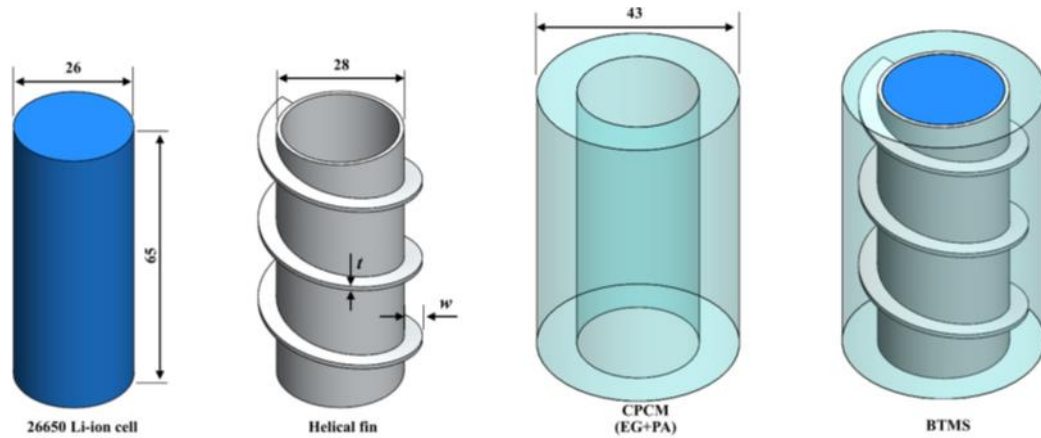


Figure 2.20 Schematic view of BTMS [95].

Optimizing the fin dimensions and arrangements is crucial for improving thermal management, reducing battery temperature, and preventing thermal runaway. Mansir et al. [96] explored the use of triangular extended surfaces placed on cylindrical cells to enhance thermal performance in conjunction with phase change material. The system features three vertically arranged cylindrical batteries surrounded by paraffin-based PCM and equipped with six triangular-shaped fins. The primary goal is to optimize fin dimensions and arrangements to improve heat dissipation and reduce battery temperature. Two fin arrangements (F1 and F2) were tested, with fin widths ranging from 1 cm to 4 cm, as shown in Figure 2.21. Numerical simulations using COMSOL Multiphysics were conducted to evaluate battery temperature, PCM melting, and the heat transfer coefficient over a 50-minute discharge cycle. The results indicate that increasing fin width improved heat dissipation by up to 20% for F1 and 19.4% for F2, with the best results achieved with 4 cm wide fins. The fins reduced the $T_{\max}$ by 2.04°C for F1 and 2.15°C for F2. However, the study also highlighted that excessively large fins could reduce the contact area with the PCM, potentially decreasing overall cooling efficiency. In a similar work, Chen et al. [97] examined a BTMS for cylindrical lithium-ion batteries, intended for aerospace

applications, which uses paraffin wax phase change material along with extended surfaces to enhance cooling efficiency. The system features a cylindrical battery surrounded by PCM, with multiple fins attached to the battery to improve heat dissipation, as shown in Figure 2.22. Numerical simulations were conducted using COMSOL Multiphysics to assess the impact of varying fin numbers and compartment sizes on battery temperature and PCM melting dynamics. The findings indicate that 15 fins provide the most effective PCM melting at the start of the cooling process, while 9 fins result in the lowest maximum temperature overall. Adding more than 9 fins led to an increase in maximum temperature, demonstrating diminishing returns. The study concludes that 9 fins offer the optimal balance between efficient heat transfer and material usage, delivering the best overall cooling performance.

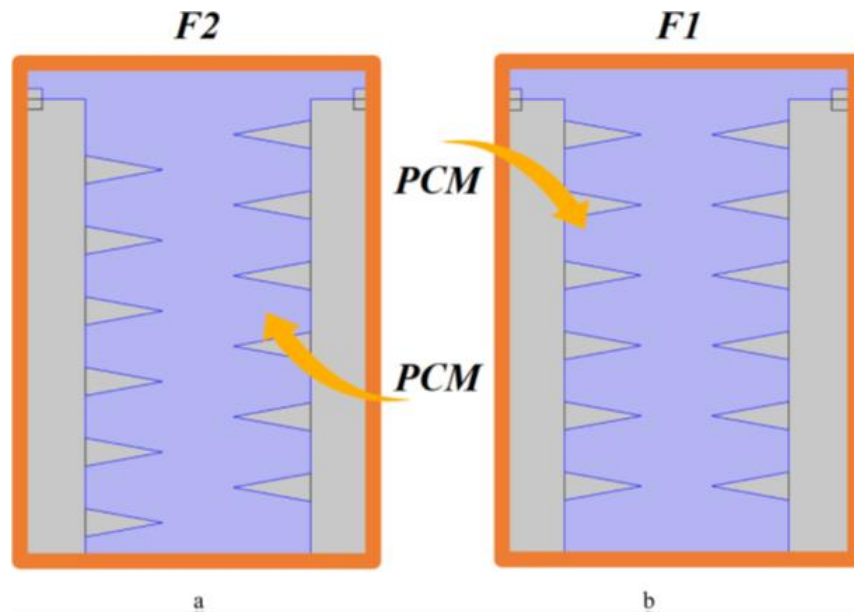


Figure 2.21 Fin configurations on the battery cell: a) F2 configuration b) F1 configuration [96].

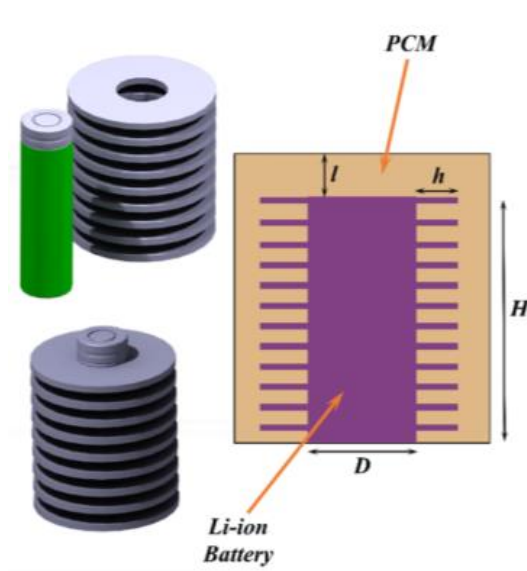


Figure 2.22 Schematic of the studied passive BTMS [97].

Integrating a finned network into the system was explored. Dey et al. [98] investigated the impact of finned networks on a PCM-based BTMS for cylindrical Li-ion cells, introducing a novel hexagonal thermal conduction network with metal fins to enhance heat dissipation and temperature control, as shown in Figure 2.23. The system features a 6S1P battery module, with six 18650 Li-ion cells arranged in a hexagonal aluminum container filled with Polyethylene Glycol (PEG 1000) as the PCM. Two fin designs (D1 and D2) were evaluated: D1 incorporates aluminum rings with vertical fins interconnecting the cells, while D2 adds vertical fins between the aluminum housing and the rings. Numerical simulations using the NTGK model for electrochemical-thermal coupling were conducted at discharge rates of 4C, 6C, and 8C. The findings revealed that the D2 design significantly improved thermal management by delaying PCM melting by 54% and reducing temperature by 75.58%, compared to 71.9% for the base PCM. D2 also maintained thermal stability under stressed discharge rates (up to 6C) and in extreme conditions (8C),

demonstrating the effectiveness of the finned network in enhancing passive cooling for high-performance applications.

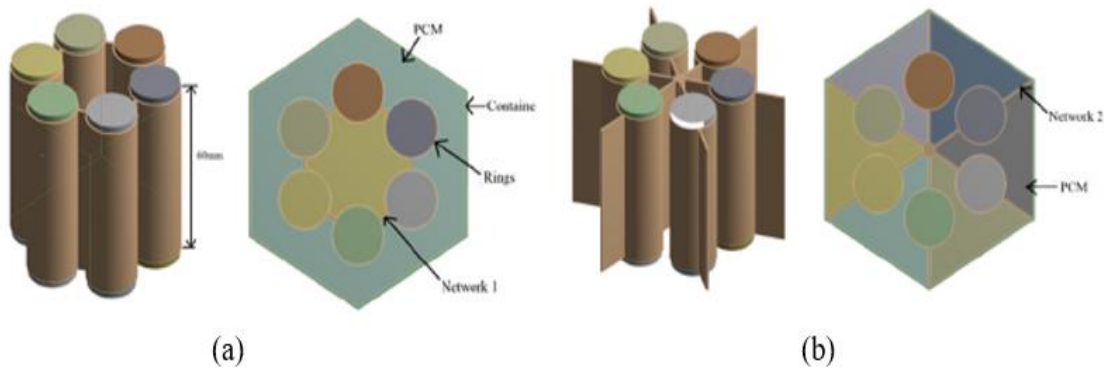


Figure 2.23 Proposed BTMS: a) D1 design; b) D2 design [98].

Metal fins are widely used in the cooling of lithium-ion batteries due to their uncomplicated design and effortlessness in manufacturing, making them a popular choice for thermal management applications. Sun et al. [99] examined a battery thermal management system incorporating phase change material with straight and arc-shaped aluminum alloy fins to enhance heat dissipation for cylindrical 26650 lithium-ion cells, as illustrated in Figure 2.24. The system is designed to improve thermal conduction within the PCM, extending the battery's operational time. A single battery is enclosed in a PCM-filled housing and surrounded by fins, with heat generation simulated using an electrical heater. Experiments were carried out at three discharge rates (8, 12, and 16 W), while numerical simulations were employed to model the phase change process of the PCM. The results showed that the PCM-Fin system extended the battery's working time by 54-90% compared to PCM alone, as the fins created a thermal conduction network that significantly enhanced heat dissipation. Performance was further improved with larger radial distances and longer fins, with copper housing offering the most effective thermal control. In a related study by the same authors, Sun et al. [100] explored a BTMS for Li-ion cells that integrates PCM with

fin structures, including cylindrical rings and longitudinal fins, to enhance heat dissipation. The system involves a cylindrical 26650 Li-ion cell encased in paraffin-based PCM (OP44E) and aluminum fins. Battery heat generation was simulated using a customized electrical heater, while T-type thermocouples tracked temperatures during testing at a heating power of 10 W. Numerical simulations utilizing the enthalpy-porosity method modeled PCM melting behavior, with different fin and ring configurations evaluated. The outcomes demonstrated that the PCM-Fin system significantly improved thermal management, increasing the battery's operational time by 2.1 times compared to a system with PCM alone. The optimal setup featured one cylindrical ring and eight longitudinal fins, with a dimensionless distance of 0.2 between the ring and the battery, as illustrated in Figure 2.25. The arrangement provided excellent temperature control, even at high heat generation rates, outperforming the pure PCM configuration.

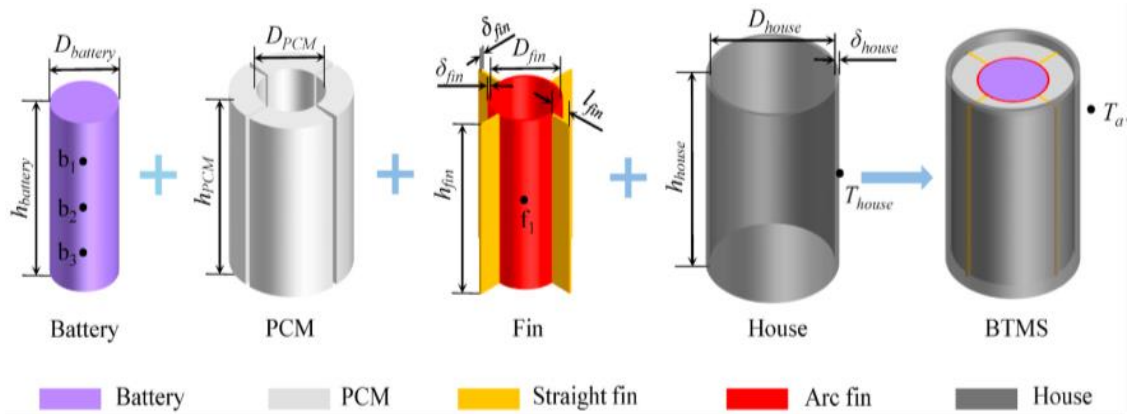


Figure 2.24 BTMS configurations and thermocouple placements [99].

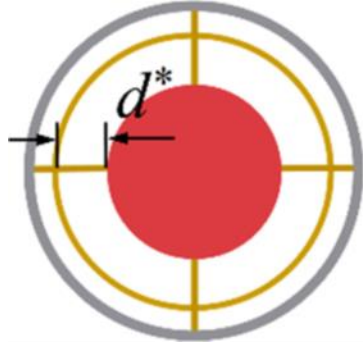


Figure 2.25 Diagram showing the position of the cylindrical ring [100].

The development of a high-performance BTMS to maintain lithium-ion batteries within an optimal temperature range has gathered significant attention in electric vehicle (EV) applications. Najafi Khaboshan et al. [101] examined a battery thermal management system designed for electric vehicle applications, incorporating phase change material, copper metal foam, and copper fins to enhance cooling performance for cylindrical lithium-ion cells, as illustrated in Figure 2.26. The system features a single cylindrical Panasonic NCR18650PF battery encased in n-eicosane PCM, copper metal foam, and five copper fins. The PCM serves as a heat absorber, the metal foam boosts thermal conductivity, and the fins aid in heat dissipation. Numerical simulations were performed at a 3C discharge rate under both normal (300 K) and harsh (305 K) conditions. Various fin shapes (rectangular, triangular, trapezoidal, I-shape, and wavy) were evaluated for their effect on cooling performance. Results indicated that the PCM-metal foam-fin system effectively lower the surface cell temperature by 3 K and delayed PCM melting by 470 seconds, with the fins and metal foam forming a network for even heat distribution. However, the shape of the fins had little influence on the overall cooling performance. In a similar study, Liu et al. [102] proposed a BTMS that combines PCM with innovative spiral fins to improve heat dissipation and temperature uniformity in cylindrical lithium-ion batteries. The system includes an 18650 battery surrounded by paraffin wax PCM and aluminum spiral fins, with

a fixed PCM thickness of 8 mm, as shown in Figure 2.27. Numerical simulations using ANSYS Fluent were conducted at 1C, 2C, and 3C discharge rates, comparing the spiral fin design to traditional circular fins. Results indicated that the spiral fin system reduced the maximum battery temperature by 0.72°C and improved temperature uniformity by 16.8%. Increasing the fin width and the number of spiral turns further enhanced cooling, with six turns delivering optimal performance. The spiral fin configuration also maintained effective cooling at higher ambient temperatures, proving to be more efficient than the circular fin design for PCM-based thermal management.

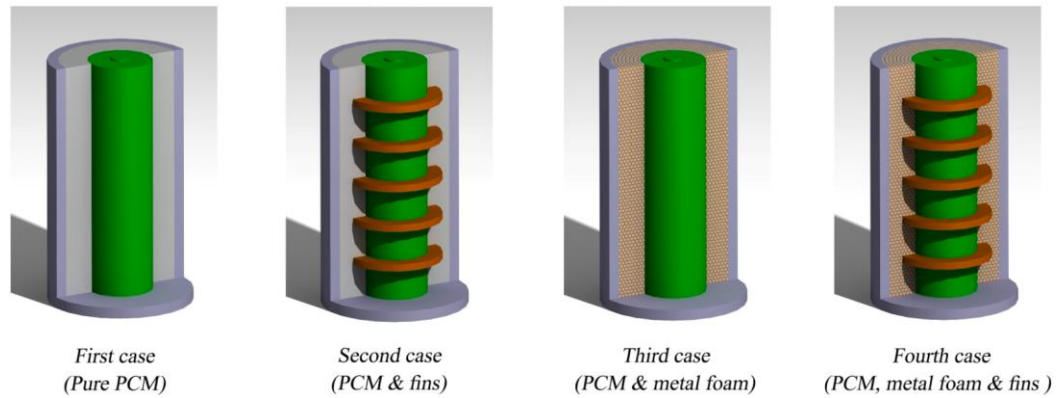


Figure 2.26 Proposed BTMS in the study [101].

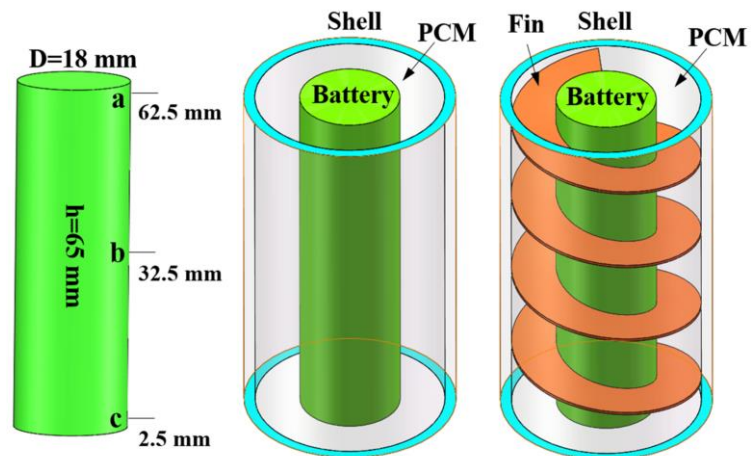


Figure 2.27 BTMS explored in the study [102].

To optimize the BTMS, it is crucial to balance heat dissipation, heat storage, and system mass. External fins are designed to enhance heat dissipation to the surrounding environment, working in tandem with internal fins that improve heat conduction within the phase change material. This combination allows for more efficient thermal regulation, as the internal fins facilitate the movement of heat through the PCM, while the external fins aid in releasing excess heat, ensuring the system remains lightweight and efficient. Such an approach was explored by Zare et al. [103]. The study introduces a BTMS for lithium-ion cells that utilizes external and internal aluminum alloy fins embedded in phase change material to enhance heat dissipation and thermal uniformity, as shown in Figure 2.28. The system is designed for an 18650 cylindrical lithium-ion battery encased in paraffin wax PCM, with four internal-external fins arranged round the cell within a metal housing. Numerical simulations were performed using ANSYS Fluent to model C-rates of 1, 2, 3, and 5C, testing different fin numbers (ranging from 4 to 12) and assessing system performance under constant and transient discharge rates. The simulations analyzed battery surface temperature, PCM melting behavior, heat storage capacity, and fin efficiency. Results indicated that the configuration with four internal-external fins was optimal, reducing the battery surface temperature by 9.90 K at 3C and 17.45 K at 5C in contrast to a pure PCM system. Adding more than four fins yielded diminishing returns, with four fins providing the best balance between heat dissipation, energy density, and PCM melting time.

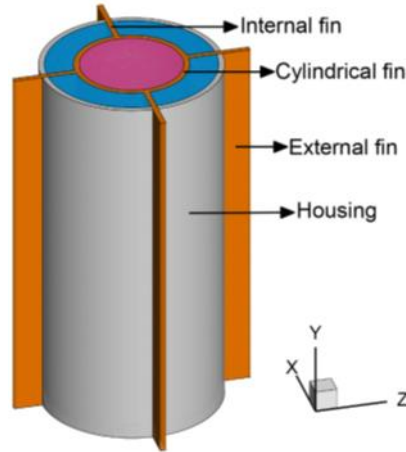


Figure 2.28 The proposed BTMS in the study [103].

While plate fins have been commonly used in previous research for PCM-based heat sinks, some researchers identified that pin fins offer a superior ability to distribute heat more evenly throughout the PCM. This advantage is particularly useful for managing the heat generated by cylindrical lithium-ion batteries under high discharge rates. Pin fins, which are widely used in electronic cooling and latent heat energy storage, were found to be a more efficient structure for thermal management compared to plate fins. Akula et al. [104] introduced a composite heat sink incorporating PCM with pin fins to manage the thermal behavior of cylindrical 18650 Li-ion cells, with the goal of enhancing PCM thermal conductivity and regulating battery temperatures during high discharge rates. The system comprises a cylindrical battery encased in PCM and copper pin fins, housed within an aluminum casing, as shown in Figure 2.29. The pin fins are radially arranged around the battery, and several configurations with varying fin sizes and numbers were tested. Numerical simulations using ANSYS Fluent evaluated the thermal performance of these configurations, and experimental validation was conducted using a custom-made aluminum rod that simulated the heat generation of a real battery. The system's performance was tested at different discharge rates (3C, 4C, 5C) and ambient temperatures,

focusing on average surface temperature and temperature uniformity. Results indicated that pin fins significantly outperformed traditional straight fins, with the optimal configuration consisting of 260 pin fins (each 1 mm in size), providing the best balance between thermal regulation and weight. This configuration effectively reduced battery temperatures, improving temperature control and lowering the risk of thermal runaway, as confirmed by both numerical and experimental findings.

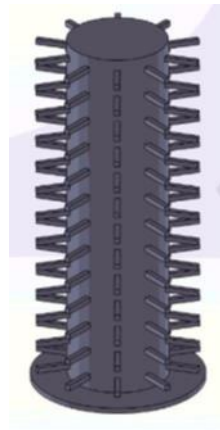


Figure 2.29 A representation of the battery with pin fins [104].

Different fin designs are explored to provide more efficient and uniform heat dissipation, particularly by increasing the surface area in contact with both the cell and phase change material. Zhang et al. [105] proposed a novel thermal management system for cylindrical 18650 lithium-ion batteries that utilizes phase change material enhanced with different fin designs, as shown in Figure 2.30. The system consists of a single battery placed inside an acrylic container filled with PCM, where branch fins are strategically added between the battery and PCM to boost heat transfer. Nine different branch-fin configurations were tested, varying in parameters such as fin coverage area, number, thickness, and arc length. The experimental setup, combined with CFD simulations validated by experimental data, evaluated the thermal performance at different discharge rates (3C, 4C, and 5C). The

results demonstrate that branch fins significantly outperform traditional straight fins, reducing battery temperatures and enhancing heat dissipation. The optimal design reduced battery temperature by up to 7.2 K, improved heat transfer by 15%, extended operational time by 131.5%, and decreased system weight by 10.28%. These branch-fin configurations greatly enhance the efficiency of the BTMS while keeping it lightweight, making it ideal for applications such as electric vehicles, where both efficiency and minimal added mass are crucial. In a related work, Kumar et al. [106] presented an innovative BTMS that integrates triangular and elliptical fins with phase change material to improve heat dissipation. The system features a cylindrical battery mock-up encased in a sleeve filled with PCM, with evenly spaced arrays of either triangular or elliptical fins around the battery. The experimental setup tests the system at three different power inputs (30 W, 50 W, and 70 W) to simulate varying operating conditions, using thermocouples and thermal cameras to capture temperature distribution. Results indicate that the PCM-elliptical fin combination delivered the best thermal performance, extending the battery's operational time by 280% at 70 W compared to the baseline. The elliptical fins outperformed the triangular ones due to their 37% larger surface area, leading to a 20% reduction in battery temperature. The study concludes that PCM paired with elliptical fins significantly enhances battery thermal management, making it appropriate for high-heat generation scenarios, such as electric vehicles.

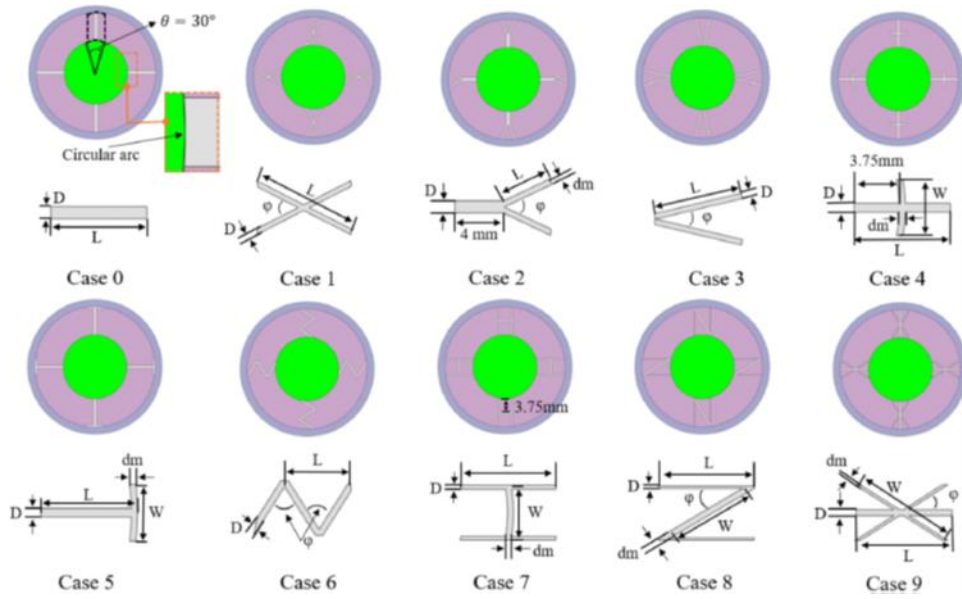


Figure 2.30 Fin design schematic [105].

The efforts to improve PCM-fin systems for the BTMS of cylindrical lithium-ion cells primarily focus on enhancing thermal conductivity, improving temperature uniformity, optimizing fin design, extending operational time, reducing system weight, and maximizing PCM utilization. One of the main challenges is the fundamentally low thermal conductivity of phase change material, which has been addressed by integrating various fin structures, such as pin, helical, triangular, and spiral fins, to facilitate faster heat dissipation. Additionally, several studies have concentrated on achieving more uniform temperature distribution across the battery surface, which is crucial for preventing localized overheating and extending battery life. Different fin geometries, sizes, and numbers have been explored to optimize heat transfer efficiency, with the goal of balancing cooling performance and system complexity. Efforts have also been made to prolong the operational time of the cell by delaying the PCM melting progression, ensuring that the system can maintain a safe temperature for extended periods, even under high discharge rates. Moreover, lightweight designs have been prioritized, particularly for applications in electric vehicles and

aerospace, where minimizing system mass is essential. Finally, improving the efficiency of PCM utilization by preventing premature melting and ensuring that the PCM can absorb as much heat as possible has been a key focus, with fins helping to create multi-path networks for better heat conduction. These combined efforts aim to create more effective, efficient, and reliable BTMS.

The studies reveal several drawbacks and limitations associated with PCM-fin systems for thermal management of lithium-ion batteries. The low inherent thermal conductivity of PCM remains a challenge, even with fins, as PCM alone often struggles to manage heat effectively during high discharge rates. While fins improve performance, they also increase the system's overall weight, which is problematic for mobile applications like electric vehicles, where minimizing weight is crucial. Additionally, increasing the number or size of fins leads to diminishing returns, as excessive fins can reduce PCM volume and hinder heat transfer efficiency. The structural complexity introduced by more complicated fin designs, such as spiral or arc fins, also adds to manufacturing difficulties and space concerns, making the system bulkier. PCM melting is another concern; once the PCM melts, its ability to dissipate heat diminishes, and re-solidification issues may lead to higher temperatures during extended use. In some cases, fins can also reduce natural convection within the PCM, further lowering cooling performance. Lastly, the cost of high-conductivity materials like aluminum or copper for fins and more expensive PCMs poses a financial limitation for widespread adoption. These factors highlight the need for careful optimization to balance fin design, PCM volume, system weight, and complexity to overcome these limitations.

2.5 Hybrid Methods

The hybrid method of thermal management for lithium-ion batteries integrates both active and passive cooling techniques to optimize performance. Active cooling utilizes methods such as air or liquid cooling through fans, pumps, or similar devices, while passive methods depend on natural heat transfer via PCM or heat sinks. This combined approach, known as hybrid BTMS, leverages the strengths of each method to address the limitations of standalone systems. Common examples include the application of PCM alongside liquid or air flow mechanisms, and PCM paired with heat pipes. The hybrid system enhances temperature control, mainly in high-demand or harsh environments, by balancing the efficiency of active methods with the easiness and dependability of passive methods. This ensures improved battery performance, extended lifespan, and increased safety across a variety of operating conditions.

2.5.1 Combining PCM and Air Cooling

By proposing a hybrid system that integrates passive cooling using phase change materials with active cooling through refrigerated air, the author aim to provide an energy-efficient solution that enhances temperature control while minimizing energy consumption during long-term operations. This system mimics a car's air conditioning (AC) system, demonstrating how a practical hybrid BTMS can be seamlessly integrated into real-world electric vehicle (EV) applications without adding significant complexity, weight, or cost. Sajedi et al. [107] proposed a hybrid battery thermal management system that combines phase change material with refrigerated cooling air to enhance thermal control and energy efficiency for cylindrical Li-ion batteries. The battery module consists of three cylindrical

cells arranged in a row, each encased in a thin layer of PCM within aluminum housing, featuring different fin structures (axial, radial, and spiral) to improve heat dissipation. The system incorporates a refrigeration compressor delivering cold air at 5°C, similar to a vehicle air conditioning system, along with high-speed fans to maintain airflow, as shown in Figure 2.31. The experimental setup tested eight hybrid BTMS configurations, as well as passive and active systems, under ambient temperatures of 40°C and 45°C, with heat generation rates simulating battery operation. Results demonstrated that the hybrid system effectively lowered cell temperatures and reduced temperature differences, with spiral fins providing the best performance. Additionally, the hybrid system consumed approximately one-third less energy over extended use compared to active cooling alone, offering a more energy-efficient solution for real-world electric vehicle applications.

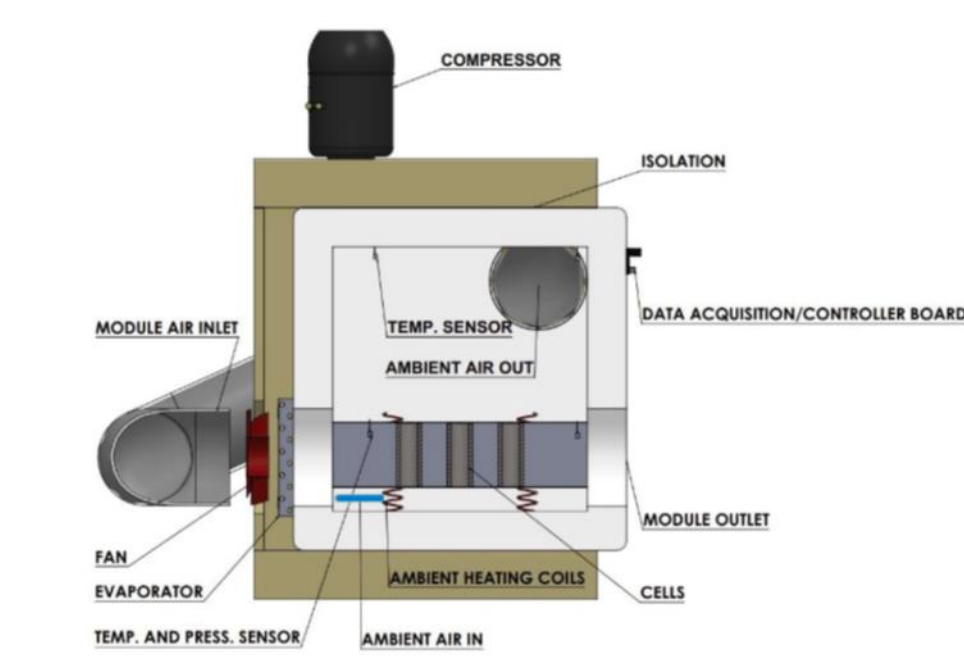


Figure 2.31 The testing unit in the study [107].

The addition of ionic wind enhances the heat transfer throughout the PCM's melting process, addressing the slow heat dissipation problem of pure PCM systems. Kumar et al.

[108] introduced a hybrid BTMS that integrate PCM with ionic wind to enhance heat transfer and maintain safe temperatures for cylindrical lithium-ion batteries during high discharge rates. The system features a cylindrical battery encased in PCM (either fatty acid or paraffin-based) within aluminum housing, with three wire electrodes symmetrically placed around the battery to generate ionic wind and boost convection. The experimental setup simulated battery operation by generating heat and tested different voltages (7 kV, 8 kV, 9 kV) to assess the impact of ionic wind on system performance. Both experimental and simulation methods were used to evaluate PCM melting behavior and the velocity fields of the ionic wind. The results indicated that the hybrid system significantly improved the heat transfer coefficient by 260% at 9 kV, extended the PCM's isothermal plateau by 76%, and reduced the battery's $T_{\max}$ by 54% compared to PCM alone. Of the two PCMs tested, paraffin performed better than fatty acid, reducing the temperature plateau by 14.5% and prolonging the melting time, offering superior thermal management. Additionally, the hybrid system was energy-efficient, with the ionic wind generator consuming only 6% of the total heat generated.

Zhou et al. [109] proposed a battery thermal management system that integrates internal PCM with external air-jet impingement (AJI) cooling to reduce temperature and improve temperature uniformity in cylindrical lithium-ion batteries, as shown in Figure 2.32. The system utilizes paraffin-based PCMs (RT25, RT28, and RT31) placed in the internal void spaces of the jelly rolls, while air jets are directed at the battery surface through optimized nozzles arranged around the cells. The experimental and simulation setup varies nozzle configurations, dimensions, and inlet air velocities to assess their impact on cooling performance, with the batteries discharged at a 4C rate. The hybrid system significantly

outperformed individual PCM or AJI cooling methods, reducing $T_{\max}$ by 44.9% ΔT by 19.7%. Optimizing the nozzle arrangements further improved cooling, achieving a $T_{\max}$ of 34.6°C and ΔT of 1.6°C. Increasing the inlet air velocity from 12 m/s to 21 m/s further reduced $T_{\max}$ to 32.2°C with a slight increase in ΔT . Among the PCM types, RT28 provided the best overall performance for $T_{\max}$, while RT25 minimized ΔT , highlighting the critical role of both nozzle configuration and PCM selection in enhancing battery thermal management.

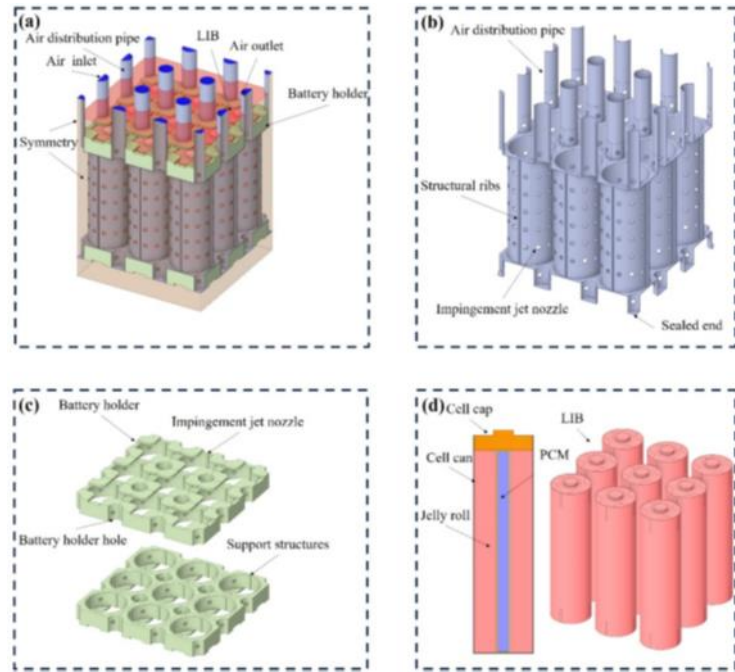


Figure 2.32 Hybrid BTMS model [109].

Maintaining a compact design in the battery thermal management system is important because it directly impacts battery module energy density, which is an essential consideration for electric vehicle and energy storage system applications. A compact design allows for more efficient use of space, enabling higher energy storage capacity within a limited volume. Zhao et al. [110] introduced an optimized internal cooling system for cylindrical batteries, embedding PCM within the hollow mandrel of the batteries,

alongside a hybrid cooling design that incorporates forced air cooling, as illustrated in Figure 2.33. Designed for a 40-cell battery module, the system uses paraffin-based PCMs (n-octadecane, n-eicosane, and n-docosane) to manage heat within the battery's jelly roll core, while an aluminum frame provides external convection cooling. The cells are arranged in four rows, with thicker PCM cores in the center cells ("i" cells) and thinner ones in the edge cells ("o" cells) to enhance temperature uniformity. The study combines experimental tests on a fabricated steel cell with numerical simulations to optimize PCM type, core size, and distribution, as well as evaluating the impact of different inlet air velocities for forced air cooling. The outcomes demonstrate that the PCM-embedded design effectively reduces peak temperature and improves temperature uniformity within the module, with further enhancements when forced air cooling is applied, reducing the peak temperature to 39.38°C and maintaining a temperature difference of 4.7°C. This compact design ensures high energy density and efficient space utilization, making it ideal for applications like electric vehicles, where both space and thermal performance are crucial. In a related study, Ling et al. [111] proposed a battery thermal management system that combines PCM with forced-air convection to effectively regulate the temperature of Li-ion battery packs throughout continuous charge-discharge sequences. The system features a 5S4P configuration of twenty 18650-type cells, surrounded by a composite PCM (RT44HC/EG) and housed within an air tunnel to allow controlled forced-air cooling. The cells, spaced 30 mm apart, are arranged within an aluminum frame placed inside the cooling tunnel. The study compares a passive system using PCM alone with the hybrid system by varying discharge rates (1C, 1.5C, and 2C) and airspeeds (1, 3, and 5 m/s). Both experimental and numerical simulations were conducted to assess thermal performance,

revealing that the hybrid system effectively prevents heat accumulation, keeping battery temperatures below 50°C even at high discharge rates, whereas the passive system fails after two cycles. Forced-air cooling efficiently restores the PCM's latent heat capacity, ensuring reliable performance and temperature uniformity, with the maximum temperature difference remaining under 3°C. The findings emphasize that while PCM controls maximum temperature and temperature differences, forced-air cooling is critical for maintaining system efficiency over prolonged cycles.

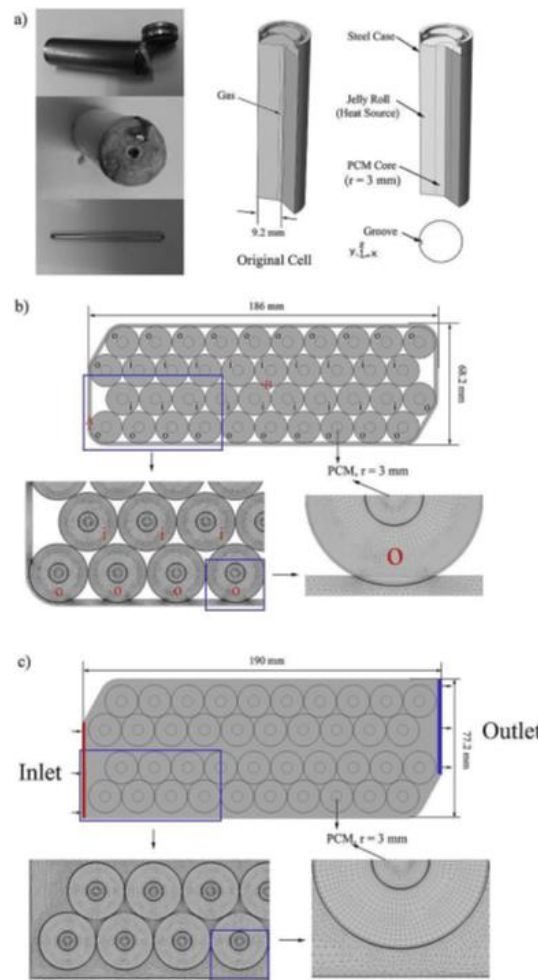


Figure 2.33 a) Diagrams depicting the internal structure of a disassembled 18650 cylindrical battery and the design of a PCM-embedded battery. b) Schematic representation of a passively cooled 40-cell battery pack. c) Schematic illustration of a hybrid cooling design for the battery pack [110].

Traditional PCM-based systems, which use a single PCM with a fixed phase change temperature, are effective only within a narrow temperature range, limiting their cooling capacity under extreme conditions. By using dual PCM layers with different phase change temperatures, the system can maintain effective heat absorption over a broader range of operating conditions, ensuring that the PCM continues to absorb heat at both moderate and higher temperatures. Song et al. [112] proposed a hybrid battery thermal management system that combines dual-layer PCMs with air cooling to improve the thermal regulation of 18650-type cells. The system incorporates two PCM layers with distinct phase change temperatures to optimize heat absorption and dissipation under varying discharge rates and ambient temperatures, all enclosed within an aluminum shell, as shown in Figure 2.34. The battery cells, spaced 7 mm apart, are cooled by airflow through narrow channels around their outer surfaces. Numerical simulations using ANSYS Fluent were performed to evaluate the thermal performance of single PCM, dual-layer PCM, and hybrid systems across discharge rates from 1C to 5C and ambient temperatures of 20°C, 30°C, and 40°C. The outcomes indicated that the dual-layer PCM system exhibited better adaptability to changing conditions, while the hybrid system with air cooling further reduced $T_{\max}$ by up to 13.3°C at higher surrounding temperatures and discharge rates. Additionally, the hybrid BTMS maintained temperature uniformity, with $\Delta T_{\max}$ ranging from 1.1°C to 6.7°C, ensuring safe and efficient battery operation in extreme conditions.

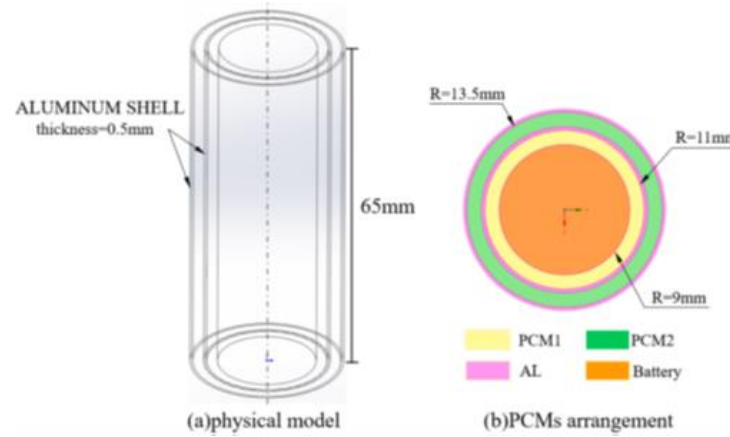


Figure 2.34 Model schematic [112].

2.5.2 Combining PCM and Liquid Cooling

Testing various coolant velocities is essential for identifying the most effective flow rate for heat dissipation. Additionally, the direction of coolant flow plays a critical role in enhancing temperature uniformity across the battery pack. Optimizing both direction and flow rate ensures that heat is evenly distributed and dissipated, improving overall thermal management performance and maintaining battery efficiency. Xin et al. [113] examined a hybrid battery thermal management system that integrates CPCM with counterflow liquid to enhance thermal performance, particularly under high ambient temperatures (40°C) and rapid discharging (5C). The system consists of a 25-cell lithium-ion battery module (26650 type) arranged in a 5x5 grid, with the cells housed in an aluminum frame filled with composite PCM (RT44HC/expanded graphite) to improve heat dissipation, as shown in Figure 2.35. The module also includes 16 liquid cooling pipes to further manage heat. The cells are configured in a combination of parallel and series, with a spacing of 37 mm between them. The study evaluated two system configurations, one using only CPCM and the other a hybrid system integrating both CPCM and liquid cooling. Various flow directions (parallel, counterflow, and alternate) were tested to determine their effects on

thermal performance. Simulations conducted using COMSOL Multiphysics explored the influence of CPCM thickness, coolant flow direction, mass fraction of expanded graphite (EG), coolant velocity, and inlet temperatures. Key findings include an optimal CPCM thickness of 4 mm and an ideal EG mass fraction of 12%, balancing cooling efficiency and heat absorption. Counterflow liquid cooling emerged as the most effective flow direction, offering better temperature uniformity and lower maximum temperatures compared to other configurations. While increasing coolant velocity improved cooling performance, the benefit plateaued beyond a certain point, with 0.01 m/s identified as the optimal velocity for balancing cooling and pump power consumption. Lowering inlet coolant temperatures reduced maximum battery temperature but negatively impacted temperature uniformity when the coolant temperature was reduced to 25°C. Overall, the study outlines the optimal design parameters for an efficient hybrid BTMS, suitable for high-demand operational conditions. In a related study, An et al. [114] introduced an integrated BTMS that combines CPCM with liquid cooling to ensure safe temperatures in lithium-ion battery modules under harsh ambient temperatures and high discharge rates. The system features a 25-cell battery module (Panasonic NCR18650PF, 2.4 Ah) arranged in a 5S5P configuration, housed within an aluminum frame filled with CPCM and liquid cooling channels to enhance heat transfer and prevent PCM leakage. Several channel layouts (Type I, II, III, and IV) and flow velocities (0.02–0.14 m/s) were evaluated using CFD simulations to assess thermal performance. The findings indicate that while increased flow velocity improved cooling, the benefits plateaued beyond 0.08 m/s, with the Type I layout delivering the best performance. A CPCM with 6% expanded graphite reduced the maximum temperature to 46.3°C, maintaining a temperature difference of 2°C, which

demonstrated optimal cooling. Additionally, during continuous charge-discharge cycles, the system with 6% expanded graphite successfully kept operating temperatures safe at a low flow velocity of 0.04 m/s, highlighting its effectiveness in repeated use. The study identifies the ideal configurations for improved heat dissipation and thermal uniformity in hybrid cooling systems for lithium-ion batteries.

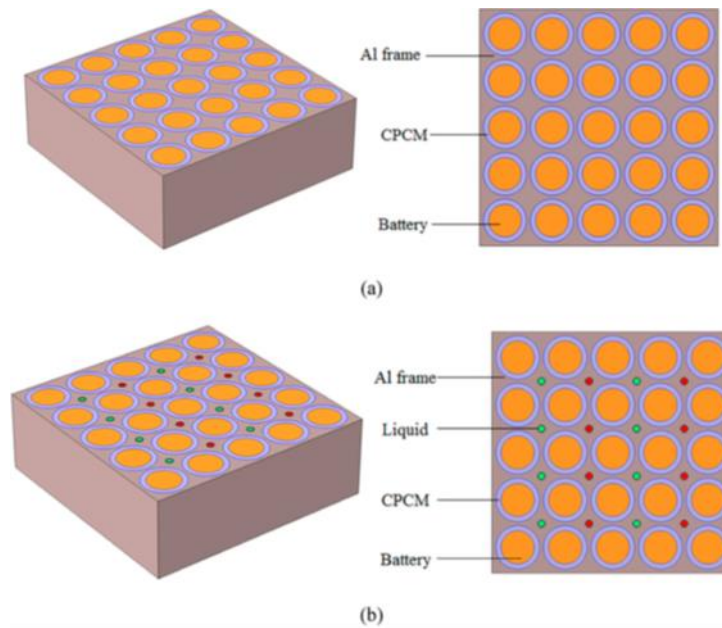


Figure 2.35 Battery pack with only CPCM (a) and hybrid with liquid (b) [113].

Combining hybrid nanofluids and nano-enhanced PCM can significantly improve the thermal performance of lithium-ion cells, enhancing both cooling efficiency and battery performance. Al-Rashed [115] introduced a battery thermal management system that integrates nanofluid (NF) and nano-enhanced PCM to improve heat transfer and reduce battery temperature throughout high charge and discharge sequences, particularly for electric vehicle applications, as shown in Figure 2.36. The system consists of cylindrical lithium-ion battery cells cooled by a combination of hybrid NF flowing through pipes and nano-enhanced PCM surrounding the batteries. The cylindrical batteries are immersed in

the PCM, while cooling tubes with both circular and elliptical cross-sections were tested for their cooling efficiency. The hybrid NF was composed of Al₂O₃ and CuO nanoparticles mixed in water to boost heat transfer through the tubes. Numerical simulations, conducted using COMSOL Multiphysics, evaluated the effects of varying NF velocities and nanoparticle volume percentages (VPNPs) on the PCM's melting and freezing behavior. Results showed that increasing NF velocity improved heat transfer, and adding nanoparticles significantly enhanced the PCM's performance. The optimal volume fraction was 0.02 for melting and 0.03 for solidification, with the circular tube design being the most effective in reducing maximum battery temperature and improving thermal uniformity. Overall, the hybrid cooling system resulted in considerable improvements in thermal management and battery performance.

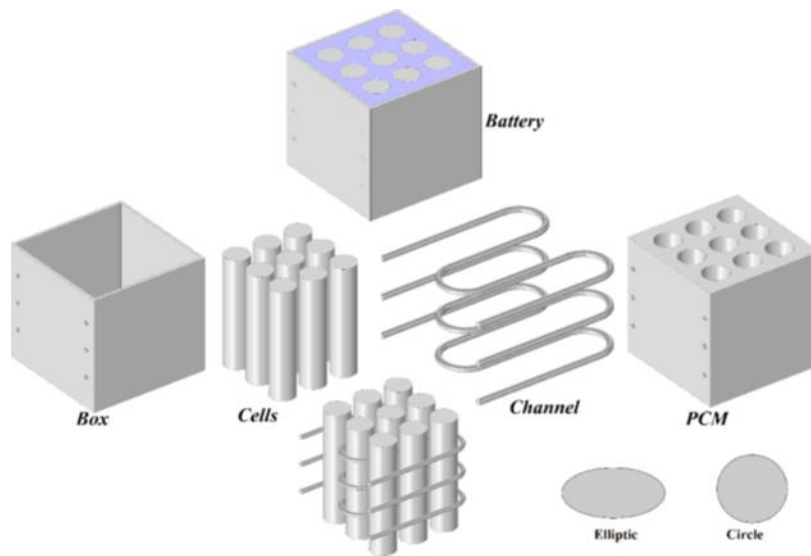


Figure 2.36 A schematic comparison of a conventional Li-ion battery cooling system against the introduced hybrid system [115].

Integrating hexagonal cooling plates, bionic liquid mini-channels, and PCM provides enhanced BTMS for lithium-ion batteries. Yang et al. [116] presented a honeycomb-like system that incorporates cooling plates with bionic liquid mini-channels and PCM to

enhance heat dissipation and ensure uniform temperature distribution in cylindrical lithium-ion batteries, as shown in Figure 2.37. Inspired by the structure of spider webs and honeycombs, the system features 18 lithium-ion cells in a 6S3P configuration, embedded in aluminum cooling plates with PCM-filled heat-conducting columns. Ethylene glycol coolant flows through mini-channels from a central inlet, providing concurrent cooling alongside the PCM. Numerical simulations analyzed the effects of plate shape, tube joints, mini-channel width, and ambient conditions on thermal performance. The hexagonal plates, with an optimal mini-channel width of 2.5 mm, effectively reduced temperature differences and pressure drops compared to rectangular plates, while the internal flow design enhanced temperature uniformity. Additionally, a BP neural network accurately estimated the ideal inlet flow rate, keeping maximum battery temperatures within 312 K and maintaining ΔT of 3.5 K under various cycling conditions. This system demonstrates improved thermal management for Li-ion cells, particularly in high-discharge conditions.

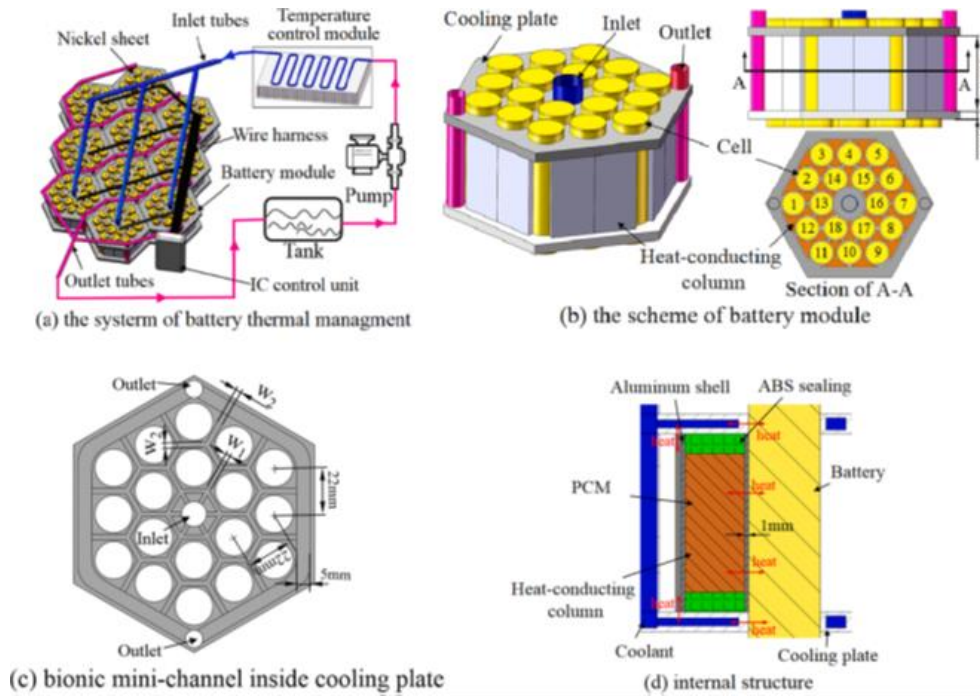


Figure 2.37 Proposed BTMS [116].

Many researchers emphasize the importance of coupling PCM with liquid cooling to achieve superior thermal management in lithium-ion battery modules under high-demand conditions. Xu et al. [117] presented a hybrid battery thermal management system that integrates PCM with liquid cooling to address heat generation in Li-ion cell packs in very harsh C-rate charge-discharge cycles. The system is designed with cylindrical 21700-type batteries arranged with a 3 mm gap between them, which is filled with PCM, while aluminum liquid cooling pipes circulate water to further assist in heat dissipation. Using paraffin-based PCM (RT44HC), the hybrid system ensures temperature uniformity and prevents overheating during prolonged operation. Numerical simulations were conducted to assess the system's performance over three continuous charge-discharge cycles, evaluating various factors such as PCM melting temperature, expanded graphite (EG) content, battery spacing, and coolant velocity to optimize the system. The results indicate that combining PCM with liquid cooling offers significantly better thermal control

compared to using PCM alone. RT44HC, with a melting range of 41-44°C, proved to be the optimal PCM, while the addition of 3% EG improved thermal conductivity. After three cycles, the system's thermal behavior stabilized, with an ideal coolant speed of 0.01 m/s balancing temperature control efficiency and energy consumption. In a related study, Rabiei et al. [118] proposed a novel hybrid battery thermal management system that combines PCM with mini-channels for liquid cooling to optimize thermal efficiency and ensure battery safety during extremely fast charge and discharge cycles. The system features cylindrical 18650-type Li-ion cells organized in a circular configuration, encased by thermally conductive aluminum structures equipped with mini-channels and PCM for efficient heat management, as shown in Figure 2.38. Using Computational Fluid Dynamics (CFD) simulations, the system was tested under different inlet velocities and ambient temperatures, focusing on 5C charge/discharge rates. The results demonstrated that the hybrid BTMS significantly reduced maximum temperatures by 2.15 K compared to traditional liquid cooling, while also requiring 76% less pumping power. Furthermore, the PCM absorbed up to 40% of the generated heat, reducing the load on the liquid cooling system and maintaining safe battery temperatures in the event of cooling failure. Overall, the hybrid BTMS offers superior thermal management, lower power consumption, and enhanced safety during fast charging conditions.

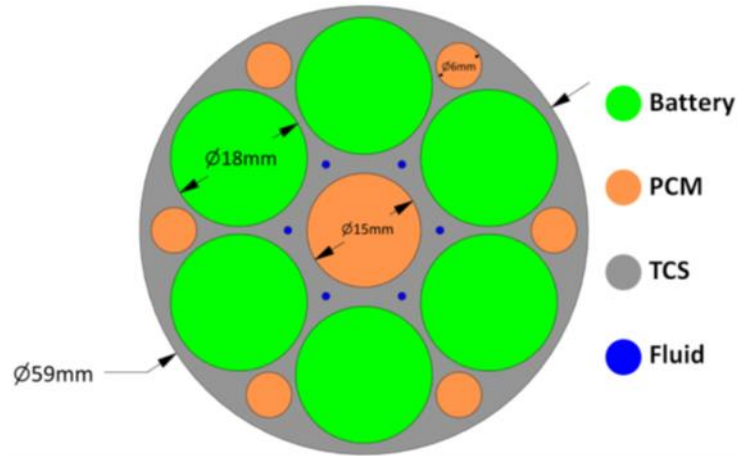


Figure 2.38 Top view of the battery module [118].

2.5.3 Combining PCM and Heat Pipes

Hybrid PCM-liquid cooling systems, while offering enhanced thermal management, tend to be more complex in design and more expensive to manufacture and maintain compared to standalone systems. The integration of liquid channels, mini-channels, and PCM increases the number of components and demands precise control to maintain efficiency, driving up costs in materials and construction. Although liquid cooling can efficiently manage heat, it requires significant pumping power, especially at higher inlet velocities. Hybrid systems alleviate some of this burden by utilizing PCM to reduce the load on liquid cooling, but the need for optimal coolant velocity and the associated energy consumption for pumping still present challenges in achieving a balance between power consumption and cooling efficiency. The limitations of liquid cooling have prompted research into the integration of heat pipes with PCM cooling systems to enhance thermal management efficiency.

Heat Pipes (HP) function as passive thermal transfer mechanisms used in BTMS to improve cooling by efficiently transferring heat from hot sources, such as lithium-ion

batteries, to cooler areas. Designed to manage heat dissipation, HPs work by utilizing a phase-change process, where a working fluid (like water or acetone) evaporates at the hot end, condenses at the cooler end, and returns to the hot end through capillary action, without the need for external power. usually made of thermally conductive materials like aluminum or copper, HPs offer efficient, non-powered heat transfer. Researchers integrate HPs into BTMS to improve heat dissipation, temperature uniformity, and overall cooling performance. When combined with PCMs, HPs enhance the system's capacity to reduce maximum temperatures and delay PCM melting, offering improved thermal stability and safety, particularly in high-performance and high discharge rate applications like electric vehicles. This makes HPs an effective, reliable, and energy-efficient solution for managing battery heat.

The flat heat pipe design increases the contact area, reducing thermal resistance and improving heat conduction. Abd et al. [119] examined a hybrid BTMS that integrates flat HPs with phase change materials to enhance cooling efficiency for lithium-ion batteries during high discharge rates. The system features twelve cylindrical Camelion ICR-18650 Li-ion batteries arranged in a 3-parallel and 4-series configuration, with six flat heat pipes and PCM filling the gaps between the batteries to improve heat absorption and temperature uniformity, as shown in Figure 2.39. Four different BTMS models HP/PCM hybrid, pure PCM, air-cooled, and standalone HP, were tested at 35°C under varying discharge rates (1C, 2C, 3C) and air velocities (2 m/s, 4 m/s). The procedure involved charging the batteries at 0.5C and monitoring surface temperatures during discharge, with thermal resistance calculations used to evaluate heat transfer efficiency. The hybrid HP/PCM system outperformed the others, keeping the maximum battery surface temperature below

50°C at 3C discharge and reducing $T_{\max}$ by up to 21.1% compared to air-cooled and pure PCM models. It also provided superior temperature uniformity, with $\Delta T_{\max}$ staying under 1.8°C. The PCM stored excess heat while the HPs effectively dissipated it, resulting in a more efficient and safer BTMS.



Figure 2.39 Proposed model of HPs [119].

Maintaining a lightweight and compact design for the BTMS is essential because cylindrical lithium-ion cell modules are often used in applications where space and weight are limited, such as in electric vehicles. A compact design ensures that the cooling system fits within the battery module without adding extra volume or weight, which is critical for maximizing the energy density and performance of the battery pack. Additionally, reducing the overall weight of the system contributes to the efficiency and range of the vehicle, while a compact configuration allows for more effective heat dissipation in a limited space, ensuring the system's practicality in real-world applications. Wang et al. [120] presented an state-of-the-art compacted hybrid battery thermal management system for cylindrical Li-ion cell modules, integrating phase change materials with heat pipes to enhance cooling efficiency while maintaining a lightweight and compact structure. The system comprises

40 18650-type lithium-ion batteries arranged in a 4-parallel and 10-series configuration (4P10S), with 14 heat pipes and 13 PCM tubes embedded between them. The experimental setup evaluated five battery module configurations under different ambient temperatures (10°C, 20°C, 30°C, and 40°C) and discharge rates (0.5C, 1C, and 2C). The batteries were charged using a constant current-constant voltage (CC-CV) protocol, with the heat pipes filled with acetone at an optimized 40% charging ratio. Temperature measurements during discharge cycles showed that the hybrid system effectively controlled $T_{\max}$ at 47.7°C and maintained a temperature difference of 2.5°C during a 2C discharge at a 25°C ambient temperature. The heat pipes played a key role in reducing overall temperature rise, while the PCM tubes enhanced temperature uniformity. The PCM tubes' performance was particularly effective in the melting range of 29.89°C to 40.02°C, demonstrating sensitivity to ambient conditions. This system shows significant potential for high-performance thermal management in compact battery applications, such as motorbikes and scooters. In a related study, Peng et al. [121] presented an advanced battery thermal management system integrating PCM with heat pipes to improve heat dissipation and ensure uniform temperature distribution in cylindrical lithium-ion battery modules. The system consists of 40 tightly packed 18650-type batteries, utilizing 14 heat pipes and 13 PCM tubes filled with paraffin wax and acetone as working fluids, as shown in Figure 2.40. A three-dimensional numerical model was developed and validated to assess thermal performance under varying discharge rates (0.5C, 1C, 2C), PCM properties, and continuous discharge-charge cycles. The results reveal that PCM melting occurs non-uniformly, with the outer and top layers melting first, causing slight temperature variations between the batteries, particularly at higher discharge rates. Composite PCM with 12 wt% expanded graphite

(EG) provided the best performance, offering a balance between thermal conductivity and heat capacity. The system effectively maintained safe battery temperatures during high discharge (2C), keeping them within safe operational limits. Extending recovery times and reducing C-rates further enhanced system performance during continuous cycling, demonstrating the PCM-heat pipe system's potential for maintaining effective heat dissipation and temperature balance in battery modules

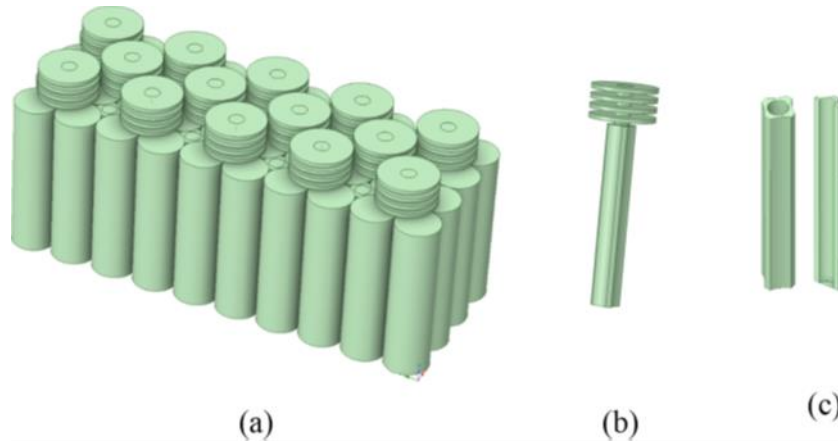


Figure 2.40 Physical model of the (a) BTMS and cell unit, (b) HP, and (c) phase change material tube [121].

The hybrid PCM/HP system shows significant potential in improving thermal management for cylindrical battery modules in electric vehicles. Zhao et al. [122] introduced a hybrid BTMS that integrates PCM with HPs to enhance the cooling efficiency of cylindrical power battery packs used in electric vehicles. The system contains twelve aluminum cylinder battery substitutes encased in PCM, with heat pipes embedded to improve heat dissipation. The PCM, composed of paraffin mixed with expanded graphite (EG), is designed to boost thermal conductivity and stability. Three configurations were tested: air cooling, PCM-based cooling, and PCM combined with heat pipes. The system was evaluated under various air velocities and cooling configurations, focusing on temperature distribution and phase transition behavior. The PCM/HP hybrid system outperformed both air and PCM-

only cooling, keeping the maximum battery temperature below 50°C for extended periods and significantly enhancing temperature uniformity. The PCM alone reduced the maximum temperature difference by 33.6%, and the addition of heat pipes further lowered it by 28.9%. The heat pipes prolonged the phase transition process, allowing the system to absorb and dissipate heat more effectively, leading to improved temperature stability, enhanced battery safety, and increased battery longevity. In another study, Tang et al. [123] proposed a battery thermal management system that integrates composite phase change materials with heat pipes to improve cooling effectiveness in lithium-ion battery modules. The system features a 21,700-type battery pack, where cells are encased in paraffin-copper foam PCM within an acrylic plate shell, and two heat pipes are embedded to aid in heat dissipation, as shown in Figure 2.41. The battery module is configured with six units in series, each containing three cells in parallel. A 3D electrochemical-thermal coupling model was developed and validated with experimental data to simulate temperature distribution under various cooling methods: natural cooling, PCM cooling, and PCM-heat pipe coupling. The PCM-heat pipe system proved to be the most effective, lowering the maximum temperature to 45°C and the temperature difference to 1°C at a 1C charging rate. The heat pipes efficiently removed heat from the center, significantly enhancing temperature uniformity, particularly in high-temperature conditions. At higher charging rates, the PCM's latent heat played a vital role in controlling temperature, although system efficiency decreased under extreme conditions like 3C charging. Additionally, the study found that reducing the distance between battery cells slightly improved cooling but caused a higher temperature rise if the reduction was too great. Overall, the PCM-heat pipe hybrid system provides superior cooling and temperature uniformity, making it an effective

strategy for improving battery thermal control, especially in high-temperature environments.

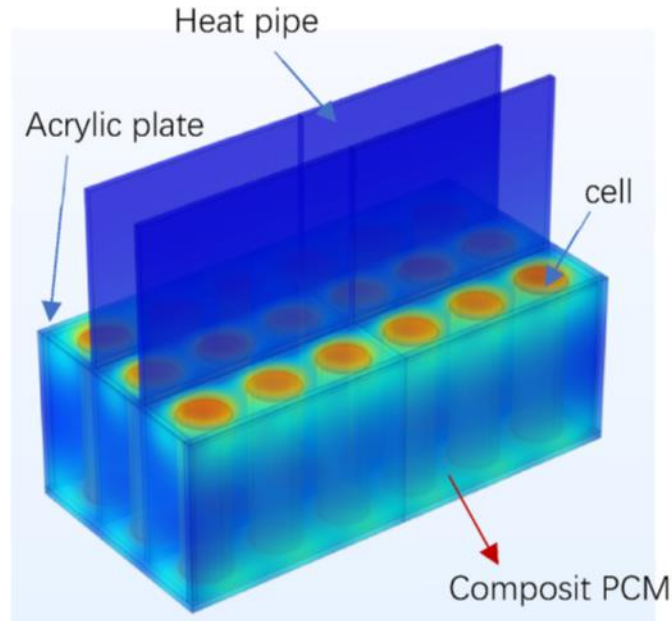


Figure 2.41 Physical model of the proposed system [123].

The hybrid PCM/HP system offers substantial advantages in managing both the $T_{\max}$ and temperature uniformity, making it an effective strategy for improving battery thermal control in high-performance battery applications. Gao et al. [124] introduced a hybrid BTMS that integrates PCMs with HPs to enhance the cooling efficiency of lithium-ion power battery packs. The system consists of 18650-type cylindrical cells, with heat pipes positioned between the cells and PCM filling the gaps, ensuring direct contact between the heat pipes and batteries for improved heat dissipation. A numerical model was developed to simulate the system's thermal behavior under various discharge rates (2C to 4C) and different heat transfer coefficients of the heat pipes. The study compares the PCM-only system with the hybrid PCM-HP system, evaluating maximum temperature ($T_{\max}$), temperature difference (ΔT), and PCM performance during discharge cycles. The hybrid system significantly outperformed the PCM-only system, reducing the maximum

temperature by up to 34.9% and greatly improving temperature uniformity, with ΔT reductions of up to 79.6% at higher discharge rates.

2.6 Summary and Research Gaps

A complete examination of thermal management approaches for cylindrical Li-ion cell modules underscores the critical importance of maintaining optimal temperature ranges to ensure performance, safety, and longevity. Lithium-ion batteries are highly delicate to temperature variations, which can cause a reduced capacity, faster degradation and in extreme cases, safety risks like thermal runaway. Effective thermal management not only prevents overheating but also ensures temperature consistency across the battery module, thereby avoiding changes in cell performance and degradation. Additionally, a lightweight design is a key factor in BTMSs, contributing to the total efficiency and practicality of solutions in various applications.

The examination highlights four primary BTMS: air and liquid cooling, PCM-based solutions, and hybrid techniques. Air-based systems are noted for their straightforwardness and money-saving, making them suitable for low-demand applications. Liquid cooling, known for greater heat dissipation, is highlighted for high-performance environments. PCMs offer passive cooling by absorbing and releasing latent heat to regulate temperature, while hybrid methods combine two or more strategies to optimize thermal management, balancing efficiency, reliability, and performance.

Key findings emphasize advancements in air-cooling strategies, such as optimized airflow patterns and cell arrangements, as well as innovative designs like biomimetic surface structures. These enhancements, focused on factors like airflow outlets, inlet velocities,

and radiator designs, have proven effective in reducing temperature gradients and lowering maximum temperatures, especially in high-power applications. However, research gaps remain, particularly in integrating these strategies into large-scale systems with real-time adaptive control. Future research should explore scalable, cost-effective solutions that minimize power consumption while enhancing cooling performance, as well as hybrid systems that combine air cooling with liquid or PCM-based methods to improve safety and extend battery life.

Further insights highlight the effectiveness of liquid cooling systems, especially with novel designs like gradient channels and immersion cooling. These configurations, utilizing techniques such as variable aluminum block lengths and PCM integration, have demonstrated superior temperature regulation and energy efficiency compared to forced air cooling. However, challenges persist, particularly under extreme conditions such as high discharge rates or fluctuating ambient temperatures. Future research could focus on hybrid cooling techniques and the use of advanced materials, such as nanofluids or composite structures, to develop scalable and cost-effective solutions for large-scale battery systems, ensuring long-term operational durability and safety.

The review also investigates into PCM-based thermal management systems, particularly those enhanced with materials like metal foams or nanoparticles. These systems significantly improve heat dissipation and temperature uniformity across battery packs. Optimizing PCM thickness has shown that thinner layers strike a balance between thermal control and system weight, while excessive PCM adds little benefit. Hybrid systems, combining PCM with expanded graphite or active cooling methods like nanofluids, show promise for managing high discharge rates. Nonetheless, more research is needed to assess

the long-term durability of PCM-metal composites and to optimize hybrid systems for extreme conditions, paving the way for cost-effective, lightweight PCM solutions that address space constraints in electric vehicle applications.

Finally, PCM-fin systems offer notable improvements in thermal management, particularly through the integration of various fin designs, such as pin, straight, spiral, or triangular fins, that enhance the thermal conductivity of PCMs. These designs boost heat dissipation, delay PCM melting, and maintain temperature uniformity, especially under high discharge rates. Studies have shown that while increasing the quantity of fins enhances performance, there is a threshold beyond which the benefits diminish due to reduced PCM volume. High-conductivity materials like aluminum or copper further boost efficiency but at the cost of increased weight and complexity. This highlights the need for optimized designs that balance performance with practicality.

These advancements underline the potential of PCM-fin systems for effective thermal management in applications requiring high thermal control and safety. However, challenges such as reducing system weight and cost remain. This thesis introduces a novel S-shape fin design for the thermal management of cylindrical 26650 lithium-ion batteries, addressing critical gaps in existing PCM-fin systems. Unlike traditional designs, the S-shape fin significantly increases surface area, enhancing heat transfer and improving temperature uniformity. This innovative approach systematically tackles weight and space constraints, providing a lightweight and compact solution ideal for used cases like electric vehicles and portable power systems. By integrating aluminum fins with PCM, the design also prioritizes cost-effectiveness and material feasibility, addressing another key gap in the literature. This work optimizes fin dimensions and spacing through comprehensive

parametric analysis to maximize thermal performance, ensuring prolonged battery operational time while preventing thermal runaway under high discharge rates. Focused on a single cylindrical cell, this research lays the foundation for scalable solutions, offering a systematic and practical approach to enhance the efficiency and affordability of PCM-fin systems in real-world applications. Table 1 highlights the main aspects of the reviewed studies and contrasts them with this work.

Table 2.1 Reviewed studies in comparison with this thesis's proposed work.

Study	Year	Key Focus	Fin Design	Methodology	Research Gap Addressed	How Our Work Differs
Pin fin-PCM composite heat sink solution [104].	2024	Improve PCM thermal conductivity using pin fins	Pin fins	Numerical	Low PCM conductivity	Novel S-shape design for higher surface area and systematic parametric analysis
Branch-fin enhanced BTMS [105].	2023	Branch-fin design to address the problem of the lightweight design	9 branch fins design	Both	Improve heat dissipation	Focus on cost and weight reduction, underexplored in branch designs
Novel fins and PCM [106].	2024	Testing triangular and elliptical fins for cooling performance	Triangular and elliptical fins	Experimental	Testing novel fin shapes	More systematic exploration of fin dimensions with S-shape fin design
Finned networks and PCM [98].	2024	Using finned networks to enhance PCM efficiency	Vertical and diagonal fins	Numerical	Improving PCM efficiency and uniformity	Novel design focusing on space and weight constraints
Three passive methods for PCM cooling [101].	2023	Exploring multiple fin shapes for PCM cooling	Rectangular, triangular, trapezoidal, I-shape, wavy fins	Numerical	Exploring diverse fin shapes	Focused analysis of a single optimized fin shape (S-shape)

Study	Year	Key Focus	Fin Design	Methodology	Research Gap Addressed	How Our Work Differs
Extended surfaces in PCM for aerospace [97].	2022	Application of extended surfaces for aerospace	Extended ring surface	Numerical	Passive cooling for aerospace	Targeting weight and cost feasibility, critical for mobile applications
Helical fin and composite PCM [95].	2024	Enhancing PCM with helical fins and expanded graphite	Helical fins	Numerical	Composite PCM with enhanced conductivity	S-shape fins for better heat transfer and lightweight design
Triangular fins in PCM [96].	2022	Optimization of triangular fin dimensions	Triangular fins	Numerical	Optimizing triangular fin parameters	Increased surface area for better heat dissipation compared to triangular designs
Spiral fin and PCM [102].	2022	Spiral fins to enhance PCM and cooling uniformity	Spiral fins	Numerical	Improving uniformity with spiral fins	More lightweight and cost-effective approach with S-shape fins
Internal-External fin PCM [103].	2024	Internal-external fins to maximize PCM utilization	Internal-external straight fins	Numerical	Maximizing PCM utilization	Cost-effective approach compared to complex internal-external configurations
PCM-Fin composite system [100].	2019	Composite design with cylindrical rings and longitudinal fins	Longitudinal fins and cylindrical ring	Both	Balancing PCM and fin efficiency	Systematic parametric study addressing weight and space limitations
Simulated battery with PCM and fins [99].	2021	Straight and arc fins for prolonged battery operational time	Straight and arc fins	Both	Delaying PCM melting and enhancing operational time	Addressing weight and cost concerns in a systematic manner for S-shape design

Table 2-5 summarizes the reviewed studies on various cooling methods for cylindrical battery thermal management systems, categorizing each study by methodology, cell type, cell count, load, pack arrangement, and study configurations.

Table 2.2 Summary of the studies on air and liquid cooling BTMS.

Author	Techniques	Cell Type	Cell Count	Test Load	Pack Layout	Flow	Coolant	Max Temp. (K)	Temp Diff.	Research Focus
Yang et al. [46]	Exp-Num	18650	36	3C	Parallel (6s6p)	0.1 - 1.5 m/s	Air cooled	308	5	Bionic surface radiator
Kausthubharam et al. [47]	Num	18650	36	1C, 4C	6s6p	0.1 - 1 m/s	Air cooled	304.2	0.4	Optimized radiators and thermal interface material
Yang et al. [48]	Num	18650	37	1C, 3C	Hexagonal	8 - 14 m/s	Air cooled	311	1.7	Air distribution plate and bionic heat sinks
Zhang et al. [50]	Num	21700	36	1C, 3C	4x9	2 - 8 m/s	Air cooled	307.19	1.5	Different airflow pattern
Yang et al. [53]	Num	IFR-38120	20	1C, 2C, 3C	Staggered		Air cooled	310.46	6.6	Reverse-layered airflow system
Lu et al. [54]	Num	18650	12	0.5 C	Staggered	1 m/s	Air cooled	302.6	5	Forced air cooling with different cooling channels
Ji et al. [55]	Exp-Num	18650	49	0.6C	Arithmetic and geometric ratio	0.001 m/s	Air cooled	307.65	3	Optimization
Zhou et al. [49]	Exp-Num	18650	9	3C, 4C, 5C	Aligned	48 L/min	Air cooled	305.7	3	Air distribution pipes with orifices
Liu et al. [51]	Num	18650	10	1C, 3C	Grouped channels	Adaptive control	Air cooled	302		J-type BTMS structures
Kummitha et al. [56]	Num	32700	9	1C, 3C	3x3 grid with baffles		Air cooled	301.5	0.26	Baffles for enhanced airflow cooling
Wang et al. [57]	Num	18650	Various configurations	3C	Rectangular, hexagonal, circular	1 m/s	Air cooled	306.15	3.5	Different cell arrangements
Verma et al. [52]	Exp	18650	28	2C	Aligned	1.5 m/s	Air cooled	314	8	Aligned airflow with staggered arrangements
Rao et al. [58]	Num	18650	6	3C	Linear	0.05 - 0.3 m/s	Water	313	5	Enhancing thermal performance using variable contact surfaces.

Author	Techniques	Cell Type	Cell Count	Test Load	Pack Layout	Flow	Coolant	Max Temp. (K)	Temp Diff.	Research Focus
Gao et al. [59]	Num	18650	32	3C	Symmetric	180 - 900 ml/min	Water	312	6.4	Optimizing gradient channel design for better thermal uniformity.
Li et al. [60]	Num	18650	24	2C	4x6	0.2 - 0.6 m/s	Water	318	5	Evaluating adaptability under varying ambient temperatures.
Li et al. [61]	Exp	18650	21	2C, 3C	7s3p	0.6 m/s	Dielectric fluid	293	1.2	Comparing liquid immersion cooling with forced air cooling for fast charging.
Shan et al. [62]	Num	18650	30	1C, 3C	5x10	0.01 - 0.04 m/s	Water	300.47	2.09	Evaluating cooling tubes for compact and lightweight system design.
Liang et al. [63]	Num	18650	20	3C	Parallel	0.000009 m3/s	Water	312	4.36	Enhancing thermal safety using unitization-based water-cooling components.
Kim et al. [64]	Exp-Num	18650	36	2C to 10C	Rows with cooling plates	0.2 - 0.4 m/s	Water	323.15		Comparing two cold plate designs using experimental and simulation methods.
Xie et al. [65]	Num	18650	27	5C	Parallel configuration with serpentine channel	0.2 m/s	Water	303	4.6	Developing a coupling model to predict heat generation and optimize baffles for fluid mixing.
Zou et al. [66]	Num	18650	72	3C	6s12p	0.6 m/s	Oil	316.5	1.07	Improving cooling efficiency with a hybrid system coupling immersion and cooling tubes.
Liu et al. [67]	Num	38120	16	1C to 3C	Compact grid	0.05 - 0.35 m/s	Oil	308	5	Investigating effects of spacing, flow rates, and discharge on cooling performance.
Tousi et al. [68]	Num	18650/ 21700	12	3C, 5C, 7C	Aligned	0.28 m/s	AgO nanofluid	305.59	1.07	Using AgO nanofluid and copper sheath to enhance performance at high discharge rates.

Author	Techniques	Cell Type	Cell Count	Test Load	Pack Layout	Flow	Coolant	Max Temp. (K)	Temp Diff.	Research Focus
Sarchami et al. [69]	Exp	18650	6	0.5C to 5C	Staggered	0.2 - 0.4 m/s	Alumina nanofluid	305.13	2.01	Evaluating nanofluid cooling and copper sheath for improved temperature uniformity.

Table 2.3 Summary of studies on PCM-cooled BTMS

Author	Techniques	Cell Type	Cell Count	Test Load	PCM Type	Melting point (K)	Thermal Conductivity (W/(m.K))	Max Temp. (K)	Temp Diff.	Research Focus
El Idi et al. [85]	Exp-Num	18650	1	1C	Composite (Paraffin RT27-aluminum foam)	300.15-303.05	0.2 of pure PCM	300	1.5	Using PCM-metal foam composite to improve heat absorption and control battery temperature
Ranjbar Kermani et al. [88]	Num	18650	1	2C-10C	PCM1 (Calcium chloride hexahydrate), PCM2 (Paraffin)	PCM1: 300-305, PCM2: 303-310	PCM1: 1, PCM2: 0.21	323.15	1.5	Analytical study to optimize PCM thickness for effective cooling
Li et al. [89]	Exp-Num	18650	Varied	0.5C to 3C	EG/paraffin composite	317.15	10.8	Not specified	2.9	Optimizing PCM thickness while minimizing PCM mass
Cheng et al. [87]	Exp-Num	18650	16	1C, 2C, 3C	Expanded graphite composite, Paraffin-based composite	320.15, 318.15	6.85, 0.26	328.15	0.7	Double-layer PCM structure for balancing heat dissipation and preservation in various climates
Karimi et al. [90]	Exp	18650	1	2 W	Paraffin + nanoparticles (Ag, Cu, Fe ₃ O ₄)	312-318	Improved by nanoparticles	323	70% reduction in temp difference	Using metal nanoparticles in PCM composites to improve heat dissipation
Kadam et al. [91]	Num	18650	12	1C, 2C, 3C	Paraffin RT58 + Graphene nanoparticles	331	Higher due to nanoparticles	316	Not specified	Using graphene nanoparticles to enhance PCM thermal conductivity
Sun et al. [86]	Exp	21,700	16	1C to 3C	Copper foam-PCM composite	313	Improved by copper foam	324.55	5	Using copper foam to improve heat dissipation and temperature uniformity

Author	Techniques	Cell Type	Cell Count	Test Load	PCM Type	Melting point (K)	Thermal Conductivity (W/(m.K))	Max Temp. (K)	Temp Diff.	Research Focus
Lamrani et al. [92]	Num	21,700	24	3C	A-32 H	304-309	0.22	3K reduction	Not specified	Developing a simplified thermal model to optimize PCM and airflow performance
Bais et al. [93]	Num	18650	1	1C to 4C	Paraffin RT-42	311-316	0.2	320.35	Not specified	Optimizing PCM thickness using numerical analysis to prevent thermal runaway
Vashisht et al. [94]	Exp-Num	18650	1	1C to 3.5C	Capric acid PCM	303.3-306.7	0.22	310	Not specified	Investigating optimal PCM thickness across discharge rates to avoid overdesigning the system

Table 2.4 Summary of studies on PCM-Fin cooled BTMS

Author	Techniques	Cell Type	Cell Counts	Test Load	PCM Type	Melting Temp (K)	Fin Shape	Thermal Conductivity (W/(m.K))	Max Temp. (K)	Temp Diff.	Research Focus
Akula et al. [104]	Num	18650	1	3C-5C	Paraffin	314-317	Pin fins	0.22	331	2.1	Improve thermal conductivity with pin fins
Zhang et al. [105]	Exp-Num	18650	6	3C-5C	Paraffin	311-316	Branch fins	0.2	322	Not Specified	Branch-fin design for temperature uniformity
Kumar et al. [106]	Exp-Num	18650	1	3C	OM-42	317	Triangular and elliptical fins	0.21	333	7.2	Effectiveness of novel triangular and elliptical fins
Dey et al. [98]	Num	18650	6	2C-8C	PEG1000	Not Specified	Vertical and diagonal interconnecting fins	Not Specified	315	4	Finned networks for better temperature control
Najafi Khaboshan et al. [101]	Num	18650	1	3C	n-Eicosane	309.55	Rectangular, triangular, trapezoidal, I-shape, wavy	0.4	318	Not Specified	Combination of PCM, fins, and metal foam
Chen et al. [97]	Num	LiPF6	1	0.5C-1.7C	Paraffin	Not Specified	Extended ring	0.2	315	Not Specified	Extended surfaces for passive cooling in aerospace

Author	Techniques	Cell Type	Cell Counts	Test Load	PCM Type	Melting Temp (K)	Fin Shape	Thermal Conductivity (W/(m.K))	Max Temp. (K)	Temp Diff.	Research Focus
Dagdevir et al. [95]	Num	26650	1	3C-5C	Paraffin + EG	314-317	Helical fins	0.2-10.1	318	5	Helical fin and expanded graphite for enhanced PCM
Mansir et al. [96]	Num	18,650	3	2.4C	Paraffin	Not Specified	Triangular fins	0.358	Not Specified	Not Specified	Optimize triangular fin dimensions and arrangements
Liu et al. [102]	Num	18650	1	1C-3C	Paraffin	311.15	Spiral fins	0.2	314	1.48	Spiral fins for better temperature uniformity
Sun et al. [100]	Exp-Num	26650	1	Not Specified	Paraffin	313.75-317.85	Longitudinal fins and cylindrical ring	0.2	Not Specified	Not Specified	Composite PCM-Fin system with cylindrical rings
Zare et al. [103]	Num	Cylindrical	1	1C-5C	Paraffin	313.75-317.85	Internal-external radial fins	0.21	316	Not Specified	Internal-External fins for PCM utilization
Sun et al. [99]	Exp-Num	26650	1	8,12,16 W	Paraffin	313.75-317.85	Straight and arc fins	0.21	Not Specified	Not Specified	Compound PCM-Fin system for extended operational time

Table 2.5 Summary of studies on hybrid BTMS

Author	Techniques	Cell Type	Cell Counts	BTMS Approach	Load	Max Temp. (K)	Temp Diff.	Main Focus
Sajedi et al. [107]	Exp	18650	3	PCM-Air	6C, 8C	327 (9kV Ionic wind)	5	Effect of extended fins on PCM and air cooling with refrigerated air.
Kumar et al. [108]	Exp & Num	18650	1	PCM-Air	6C, 8C	312.5	0.197	Impact of ionic wind on PCM cooling effectiveness.
Zhou et al. [109]	Exp & Num	18650	9	PCM-Air	4C	307.75	1.6	Air-jet cooling combined with PCM for cylindrical batteries.
Zhao et al. [110]	Exp & Num	18650	40	PCM-Air	1C - 5C	323	4.7	Optimizing internal PCM cooling combined with forced air.
Ling et al. [111]	Exp & Num	18650	20	PCM-Air	1C - 2C	323	3	Integration of PCM with forced-air convection for thermal management.
Song et al. [112]	Num	18650	5	PCM-Air	1C - 5C	312.22 (5C at 20°C T _{amb})	1.09	Performance of dual-layer PCM combined with air cooling.

Author	Techniques	Cell Type	Cell Counts	BTMS Approach	Load	Max Temp. (K)	Temp Diff.	Main Focus
Xin et al. [113]	Num	26650	25	PCM-Liquid	5C	318.4	3.49	Hybrid BTMS with PCM and liquid cooling to handle high ambient temperatures and discharge rates
An et al. [114]	Num	18650	25	PCM-Liquid	3C	319.4	2	Effect of CPCM thickness, coolant flow velocity, and EG mass fraction on hybrid cooling performance
Al-Rashed [115]	Num	Not specified	9	PCM-Liquid	Not specified	312	5	Hybrid cooling with nanofluids and nano-enhanced PCM to improve heat transfer rates
Yang et al. [116]	Num	18650	18	PCM-Liquid	2C-4C	312	3.5	Hybrid cooling with honeycomb structure, mini-channels, and PCM for improved thermal performance
Xu et al. [117]	Num	21700	24	PCM-Liquid	3C-4C	319	4.5	Long-term performance of hybrid cooling using PCM and liquid cooling during high C-rate cycles
Rabiei et al. [118]	Num	18650	6	PCM-Liquid	5C	319	0.8	Hybrid cooling system focusing on safety, efficiency, and real driving cycle performance
Abd et al. [119]	Exp	18650	12	PCM-Heat Pipe	1C, 2C, 3C	323	1.8	Evaluate hybrid BTMS with flat HP and PCM
Wang et al. [120]	Exp	18650	40	PCM-Heat Pipe	0.5C, 1C, 2C	320.8	2.5	Propose compact hybrid BTMS using PCM and HP
Zhao et al. [122]	Exp	18650	12	PCM-Heat Pipe	1C, 2C, 3C	320	5	Study cooling performance of PCM-HP hybrid system
Tang et al. [123]	Num	21700	6	PCM-Heat Pipe	0.5C, 1C, 2C	318	1	Numerically analyze cooling efficiency of composite PCM-HP system
Peng et al. [121]	Num	18650	4	PCM-Heat Pipe	0.5C, 1C, 2C	308	1	Numerically study PCM-HP thermal behavior
Gao et al. [124]	Num	18650	16	PCM-Heat Pipe	2C, 3C, 4C	323	1.73 at 2C, 4.23 at 4C	Improve BTMS performance by combining PCM and HP

CHAPTER 3

METHODOLOGY

3.1 Introduction

In this study, the focus is on enhancing the thermal management of a cylindrical 26650-type Lithium-ion battery using PCM and a novel fin structure. The battery specifications include a diameter of 26 mm and a height of 65 mm. It will be wrapped in paraffin-based PCM (RT50) and confined within a cylindrical nylon casing, which has dimensions of 75 mm in height, a thickness of 2 mm, and an inside diameter of 43 mm.

The fin structure in this study consists of a cylindrical ring and straight aluminum fins, each measuring 65 mm in height and 7.5 mm in length, and designed to be embedded in the RT50 PCM type, as illustrated in Figure 3.1. The investigation will focus on the impact of varying the quantity and thickness of fins on heat dissipation capability. Specifically, configurations will include 4, 8, 12, and 16 fins, with thicknesses of 1, 2, and 3 mm, resulting in a total of 12 simulation cases. Additionally, cases involving PCM only and fin structures without PCM will be examined to assess their comparative effectiveness.

Numerical simulations were performed using a three-dimensional model in ANSYS. These simulations were validated against previous numerical and experimental studies to ensure accuracy. Both grid independence and time independence tests were conducted to optimize the simulations. The battery surface temperature as a function of time was compared across

different cases, and the time step and grid size were chosen based on the need for accuracy and computational time.

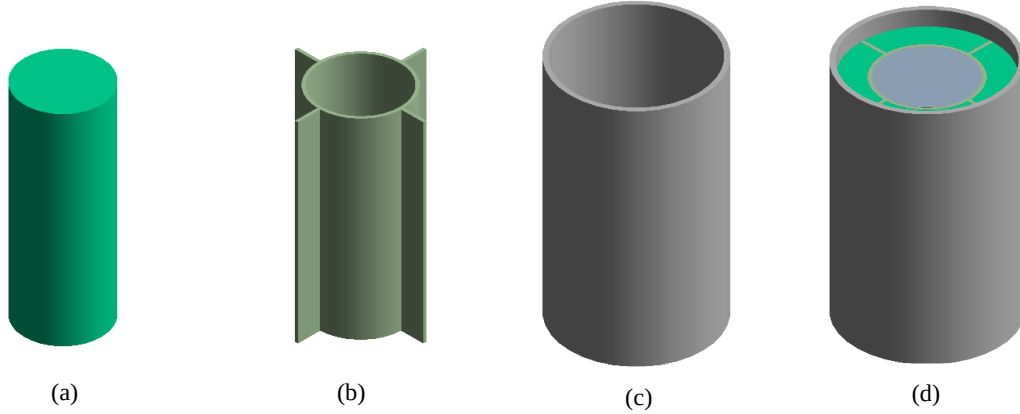


Figure 3.1 BTMS configuration: (a) Battery; (b) Fins; (c) Housing; (d) BTMS.

Ultimately, a novel fin structure is proposed, consisting of a cylindrical ring and an S-shape fins. This design aims to further improve heat dissipation and enhance the battery's thermal control performance. All simulations will assess the thermal management capabilities of these designs, providing a comprehensive understanding of their effectiveness in practical applications. The methodology and key parameters of the study are summarized in Figure 3.2. Additionally, the thermo-physical properties of the housing, fins, battery, and PCM are listed in Table 3.1.

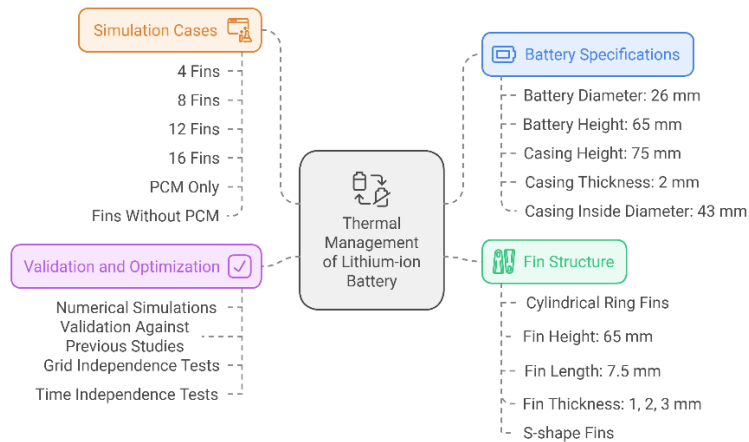


Figure 3.2 Overview of Simulation Cases and Fin Structure for Battery Thermal Management.

Table 3.1 The properties of the selected materials [125-127].

Materials	Properties	Value
Paraffin wax (RT50)	Thermal conductivity, W/(m. K)	0.2
	Specific heat capacity, J/(kg. K)	2000
	Density, solid kg/m ³	760
	Density, liquid kg/m ³	880
	Melting temperature, K	319.15-324.15
	Latent heat, kJ/kg	160
	Dynamic viscosity, Pa.s	0.00251
	Thermal expansion coefficient, K ⁻¹	0.0006
	Thermal diffusivity, mm ² /s	0.134
Al	Thermal conductivity, W/(m. K)	202.37
	Specific heat capacity, J/(kg. K)	871
	Density, kg/m ³	2719
Nylon	Specific heat capacity, J/(kg. K)	1670
	Density, kg/m ³	1140
	Thermal conductivity, W/(m. K)	0.28
26650 Li-ion battery	Density, kg/m ³	1223
	Specific heat capacity, J/(kg. K)	825
	Thermal conductivity, W/(m. K)	0.5

3.2 Numerical Simulations

3.2.1 Governing Equations

ANSYS Fluent is used to solve fluid flow problems involving solidification and melting over a range of temperatures, using an enthalpy-porosity formulation to simulate phase change processes. In this method, the liquid-solid mushy zone, a region where the liquid fraction ranges from 0 to 1, is modeled as a porous medium, with porosity defined by the liquid fraction. As solidification progresses, the porosity in this mushy zone decreases from 1 to 0, resulting in velocity dropping to zero in fully solidified cells. Momentum sink terms (S) are added to the momentum equations to represent pressure drops caused by solid material, while additional sink terms are included in the turbulence equations to adjust for reduced porosity in solidified regions. This formulation is applied in this study to accurately simulate PCM melting, capturing the complex phase change dynamics within the thermal management system.

In this work, governing equations are stated as:

Continuity equation

$$\nabla \cdot (\rho \vec{u}) = 0 \quad (3.1)$$

Momentum equation

$$\frac{\partial(\rho \vec{u})}{\partial t} + \nabla \cdot (\rho \vec{u} \vec{u}) = -\nabla p + \nabla \cdot \tau + \rho_a [1 - \xi(T - T_a)] \vec{g} + S \quad (3.2)$$

Here, u is the velocity vector, τ represents the stress tensor, ξ characterizes the thermal expansion coefficient, and S is the momentum sink because of the lowered liquid fraction. The enthalpy-porosity procedure models the mushy area (partially solidified zone) as a porous medium, where, in completely solidified areas, the liquid fraction is zero, effectively eliminating velocities in those areas. Additionally, ρ is the density, p is the pressure, ρ_a is the density reference at the temperature reference T_a , and g represents gravitational acceleration, selected to be -9.81 m/s in the vertical axis to model free convection within the phase change material. The momentum sink because of the lowered porosity in the mushy zone is expressed as follows:

$$S = \frac{(1-\beta)^2}{\beta^3 + \omega} A_{mush} \vec{u} \quad (3.3)$$

Here, ω is a small constant, set to 0.001, used to avoid division by zero in the calculations, while β represents the liquid fraction. The mushy zone constant A_{mush} set to 10^7 in this work as proposed by Sun et al. [99], characterizes the structure of the melting process and controls how fast the liquid velocity goes zero as solidification occurs. Recommended

values for A_{mush} range from 10^3 to 10^8 , depending on factors such as the specific PCM used, the geometry of the enclosure, and the boundary conditions [128, 129].

Energy balance equations for the fins, cell, housing, and PCM are as follows:

$$\rho_{\text{battery}} C_{p,\text{battery}} \frac{\partial T_{\text{battery}}}{\partial t} = \nabla(k_{\text{battery}} \nabla T_{\text{battery}}) + q \quad (3.4)$$

$$\frac{\partial(\rho_{\text{PCM}} H_{\text{PCM}})}{\partial t} + \nabla \cdot (\rho_{\text{PCM}} \vec{u} H_{\text{PCM}}) = \nabla(k_{\text{PCM}} \nabla T_{\text{PCM}}) \quad (3.5)$$

$$\rho_{\text{fin}} C_{p,\text{fin}} \frac{\partial T_{\text{fin}}}{\partial t} = \nabla(k_{\text{fin}} \nabla T_{\text{fin}}) \quad (3.6)$$

$$\rho_{\text{house}} C_{p,\text{house}} \frac{\partial T_{\text{house}}}{\partial t} = \nabla(k_{\text{house}} \nabla T_{\text{house}}) \quad (3.7)$$

H_{PCM} is expressed as:

$$H_{\text{PCM}} = h_{\text{PCM}} + \Delta H_{\text{PCM}} \quad (3.8)$$

$$h_{\text{PCM}} = h_a + \int_{T_a}^T C_p dT \quad (3.9)$$

$$\Delta H_{\text{PCM}} = \beta L_{\text{PCM}} \quad (3.10)$$

Where β is given by:

$$\beta = \begin{cases} 0, T < T_s \\ \frac{T-T_s}{T_l-T_s}, T_s < T < T_l \\ 1, T > T_l \end{cases} \quad (3.11)$$

Here, h_a is the reference enthalpy at the reference temperature T_a , C_p is the specific heat at constant pressure, L_{PCM} is the PCM latent heat, T_l and T_s are the liquidus and solidus temperatures of the phase change material.

The simulation's initial condition is:

$$T(x, y, z) = T_a; t = 0 \quad (3.12)$$

The BTMS boundary conditions are set at:

$$-k_{battery} \frac{\partial T_{battery}}{\partial n} = -k_{fin} \frac{\partial T_{fin}}{\partial n} = -k_{PCM} \frac{\partial T_{PCM}}{\partial n} = -k_{house} \frac{\partial T_{house}}{\partial n} \quad (3.13)$$

The thermal balance at the interface between the casing and the surroundings can be represented as:

$$-k_{house} \frac{\partial T_{house}}{\partial n} = h(T_{house} - T_a) \quad (3.14)$$

Here, h represents the convective heat transfer coefficient. Under free convection situations, air's convective heat transfer coefficient generally falls between 5 and 10 W/(m².K). Regarding this work, the convection heat transfer coefficient for air was selected to be at 10 W/(m².K) on the external wall of the casing, a value commonly used in PCM-cooled battery thermal management systems studies with free air convection. This higher rate simulates severe environments, implying a higher surrounding airspeed.

To solve the governing equations, the CFD software ANSYS Fluent 24/R1 was employed. The pressure-velocity coupling was addressed using the PISO algorithm. For discretizing the pressure equation, the PRESTO scheme was implemented. The momentum and energy equations were discretized using the second-order upwind scheme. A first-order implicit approach is applied for the transient formulation. The convergence criteria for the computational residuals were established at 10⁻³ for both the continuity and momentum equations and 10⁻⁶ for the energy equation. The solution was considered converged once

these thresholds were satisfied, typically requiring approximately 20 iterations per time step to reach convergence. The computational field was discretized with a structured meshing, which was created using ANSYS MESH.

To simplify the simulation process, several assumptions were made: (a) radiation effects were disregarded; (b) the PCM liquid phase is Newtonian fluid; (c) heat generation from the battery is assumed to be uniform; (d) the volume change of PCM due to phase change was disregarded.

3.2.2 Model Validation

To ensure the accuracy and reliability of my simulation, a validation study was conducted based on the work of Sun et al. [99], who studied the BTMS performance of a PCM-fin arrangement through both experimental and numerical methods. In their setup, a heater generating 16 W of heat was set to mimic the battery-discharging process. It raised the battery temperature from an original 293.15 K (20°C) to 333.15 K (60°C) safety threshold.

For consistency, the complete model and boundary conditions used in their study was replicated, including the same PCM selection. Then, the PCM-fin-based battery thermal management system was simulated, and the results were validated against their findings at a 16 W heat generation rate. As illustrated in Figure 3.3, the comparison of the battery's external surface temperature indicates a high degree of agreement, with a maximum deviation of 5.6%. Additionally, Figure 3.4 illustrates the PCM liquid fraction changes with time, showing trends similar to those in the earlier published study, with a maximum deviation of 0.045. This validation supports the reliability of the simulation model in predicting the thermal behavior of the PCM-fin arrangement.

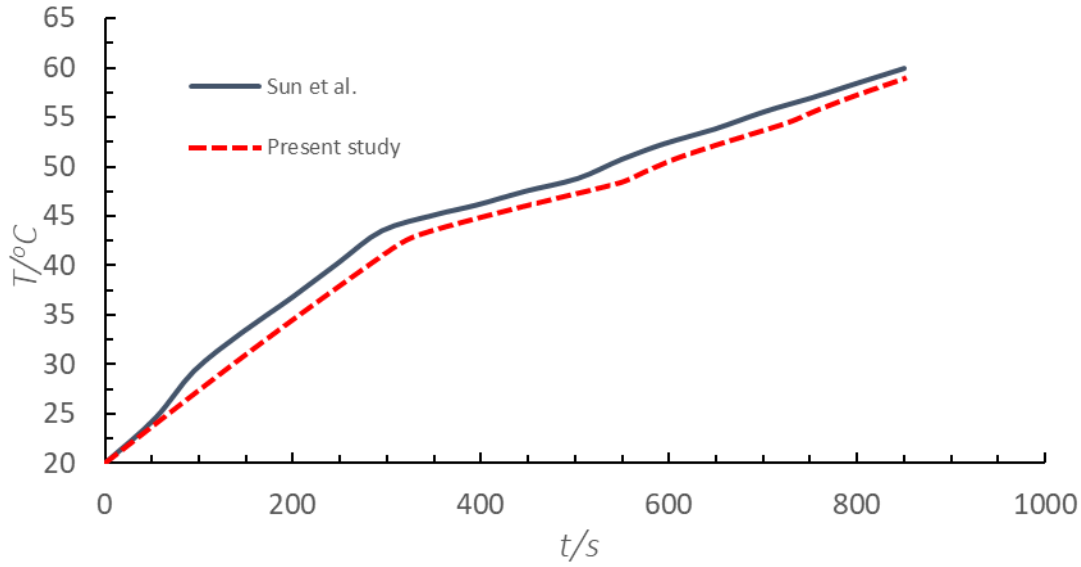


Figure 3.3 Validation of the current study with published study showing total average temperature of the battery external surface [99].

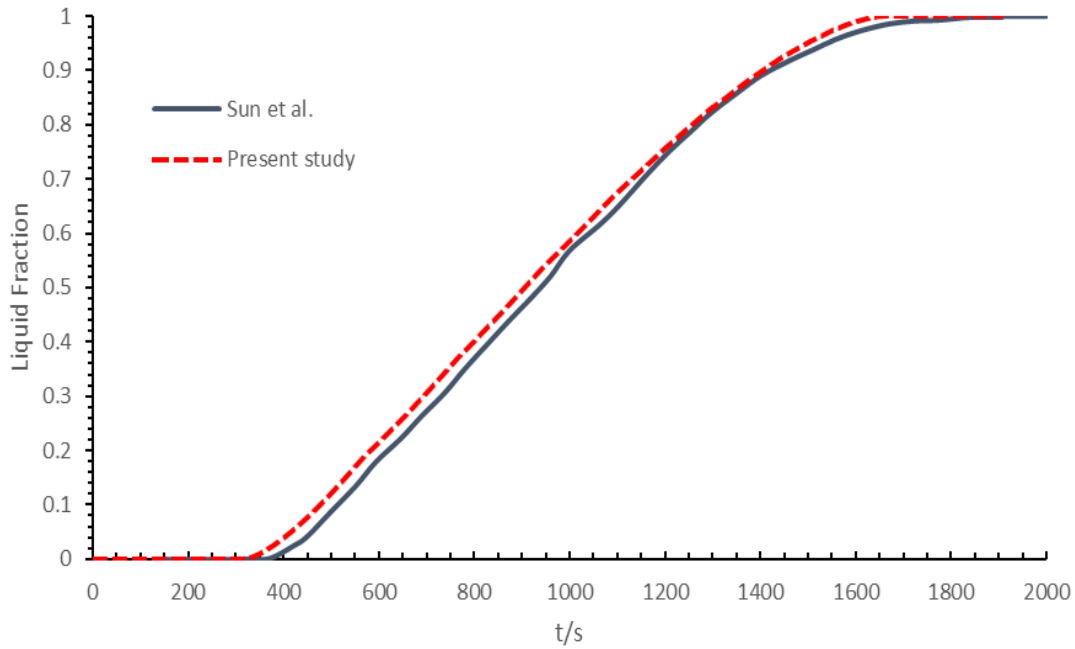


Figure 3.4 Validation of the current study with published study showing PCM liquid fraction [99].

3.2.3 Grid and Time Step Independence Test

The accuracy of numerical work in simulating PCM melting is highly sensitive to grid size and time step. To ensure result independence from these factors, comprehensive grid and time step independence tests were conducted. For the PCM-Fin system with a heat

generation rate of 10 W, four grid sizes 1.2 mm, 1.0 mm, 0.8 mm, and 0.6 mm were tested, corresponding to cell counts of 95,232, 172,046, 279,736, and 681,885, respectively. The mesh generated for the BTMS configurations is illustrated in Figure 3.5 (b), providing a detailed view of the computational domain used in the simulations. This range of grid sizes was selected to ensure a thorough evaluation of mesh independence and its impact on simulation accuracy. The grid independence results, displayed in Figure 3.5 (a), show variations in maximum battery surface temperature, with further details on grid size, element count, and max skewness provided in Table 3.2. As shown in Figure 3.5 (a), the maximum deviation was within 0.7% as the grid size reduced from 1.2mm to 0.6mm, indicating that a grid size of 1mm was suitable for this study.

Table 3.2 Grid information.

Size	PCM-Fin	
	Elements	Max Skewness
1.2 mm	95232	0.696
1.0 mm	172046	0.558
0.8 mm	279736	0.645
0.6 mm	681885	0.462

Given the transient nature of the melting progression, the time step is a vital parameter affecting both computational cost and accuracy in numerical simulations. To ensure accuracy, a time step independence test was executed, comparing time steps of 0.25 s, 0.50 s, and 0.75 s to evaluate their impact on battery surface temperature. As shown in Figure 3.6, the relative errors for these time steps were negligible. Larger time steps were avoided due to their tendency to cause computational divergence; thus, smaller steps were chosen

for reliability. Ultimately, a time step of 0.75 s was selected for all simulations, offering a balanced compromise between computational cost and accuracy.

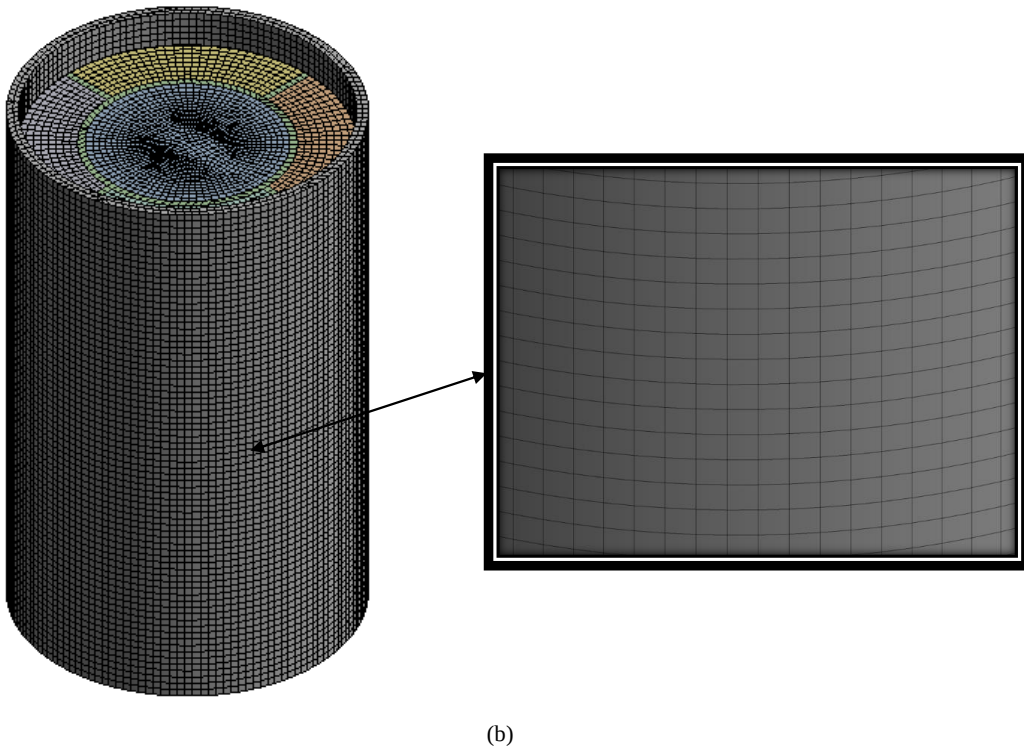
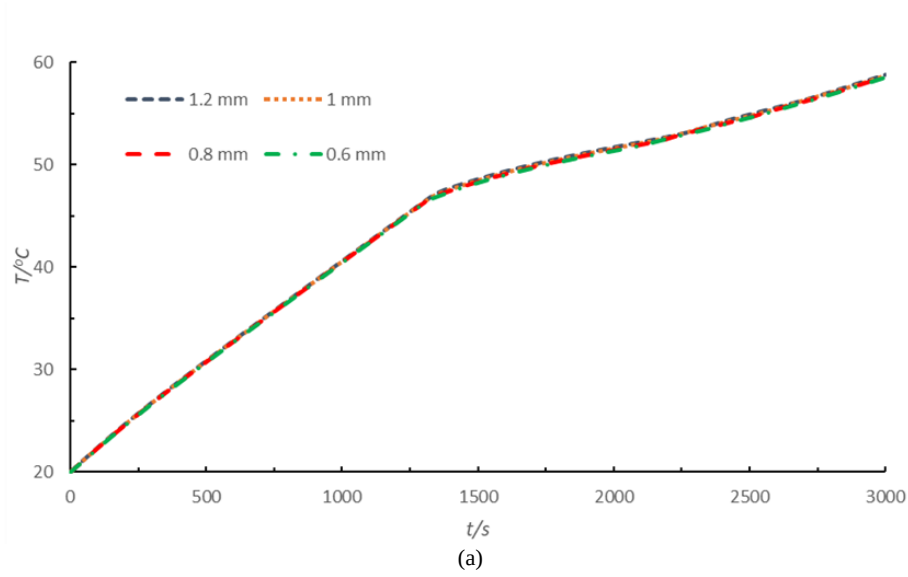


Figure 3.5 (a) Grid independent test by four grid sizes, (b) the generated mesh in the BTMS.

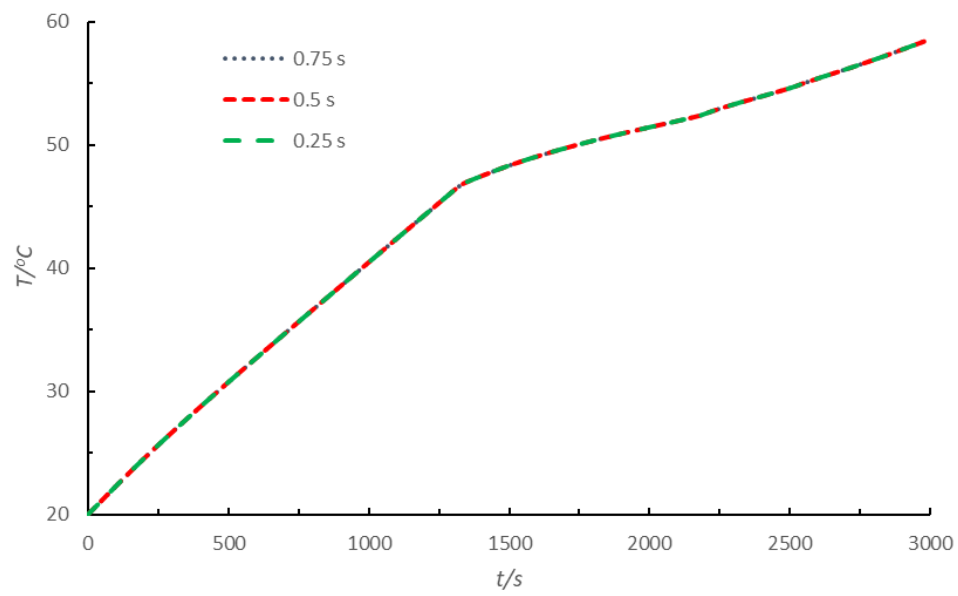


Figure 3.6 Time step independence test.

CHAPTER 4

RESULTS AND DISCUSSION

4.1 Testing of the BTMSs

The performance testing of the BTMSs includes three configurations: the only PCM, the PCM-fin, and the fin system without PCM. Figure 4.1 demonstrates the change in battery surface temperature over time for these configurations. When cooling with natural convection alone, the temperature increases almost linearly, resulting in a battery working time of 546 s. With the help of PCM without fins, the working time increases to 905 s, representing a 65.7% improvement in BTMS performance. This enhancement is attributed to the PCM's ability to capture a significant heat quantity during the melting progression. In the PCM-fin arrangement, the temperature rise rate slows even further, achieving a working time of 1331 s, representing an additional 47% improvement over the pure PCM system. This slower temperature rise indicates that the fins used in this study effectively enhance heat transfer and improve the overall performance of the BTMS. These results underscore the significant role of fins in boosting thermal management efficiency by complementing the heat-absorbing properties of the PCM.

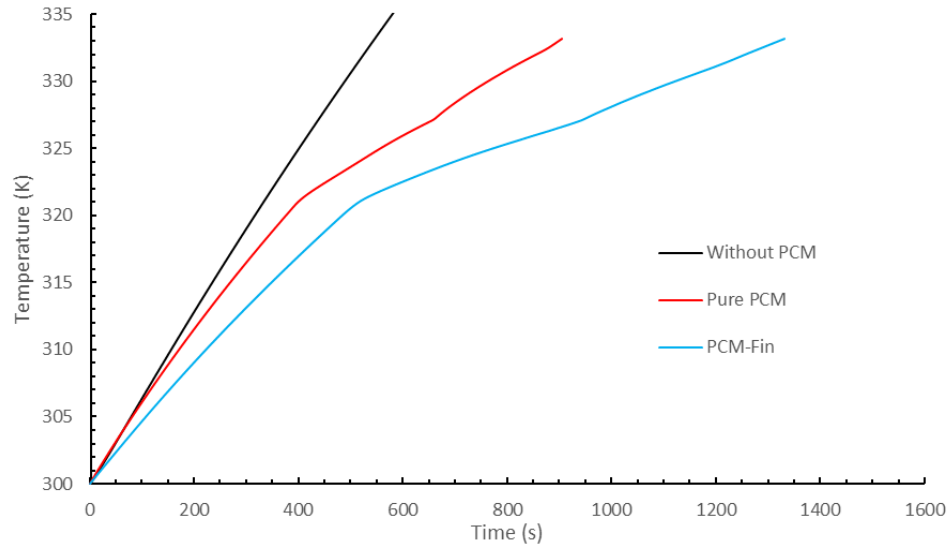


Figure 4.1 Testing of the BTMS.

4.2 Effects of The Number of Fins

Straight fins play a critical role in enhancing the thermal performance of PCM-based battery thermal management systems by providing additional conduction paths that significantly improve thermal management. To determine the ideal quantity of fins for maintaining battery temperature, systems with 0, 4, 8, 12, and 16 straight fins were evaluated under a heat generation rate of 10 W. Figure 4.2 illustrates the various configurations of the PCM-based BTMS with 4, 8, 12, and 16 straight fins, highlighting the different fin arrangements designed to enhance heat dissipation.

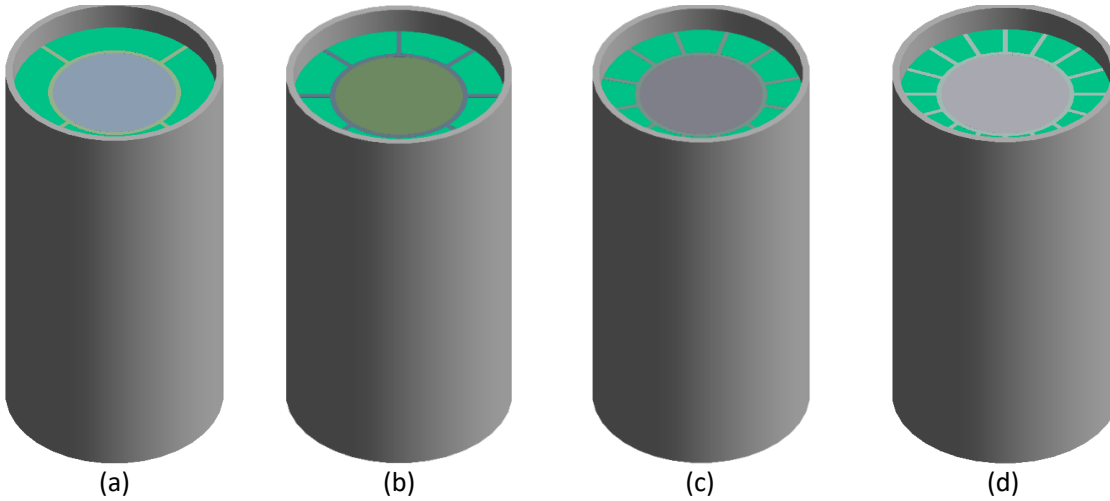


Figure 4.2 The PCM-fin systems with (a) 4, (b) 8, (c) 12, (d) 16 straight fins.

The comparison between different configurations is based on the working time of the selected battery, defined as the duration required for the battery's temperature to reach the safety limit of 60°C (333.15 K). This benchmark ensures a consistent and practical evaluation of the thermal performance of each configuration, allowing for a clear assessment of their effectiveness in maintaining safe operating temperatures. As shown in Figure 4.3, the working times for configurations with 0, 4, 8, 12, and 16 fins were 905 s, 1331 s, 1688 s, 1954 s, and 1999 s, respectively. In the absence of fins, the working time was significantly shorter due to inefficient heat transfer from the cell to the phase change material. Adding fins increased the surface area in contact between the phase change material and fins, improving heat transfer and slowing the rate of temperature rise. However, the improvement in working time is less as the quantity of fins increased from 12 to 16, demonstrating that the heat conduction paths were already adequate for effective dissipation. Beyond this point, adding more fins had a negligible impact on heat transfer and reduced the PCM volume, which negatively affected the overall working time of the

BTMS. Consequently, the battery thermal management system with eight straight fins is recommended for real-world applications.

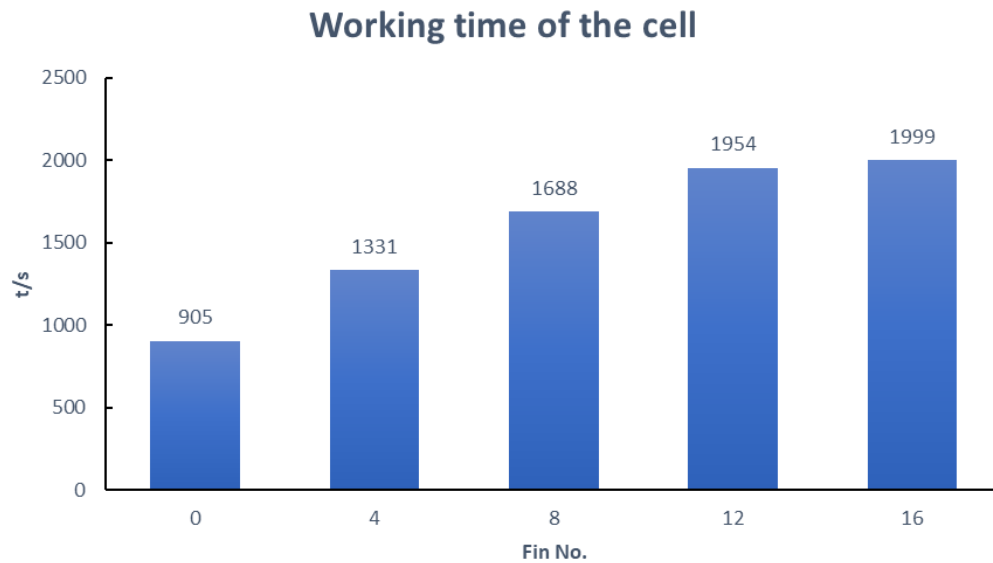
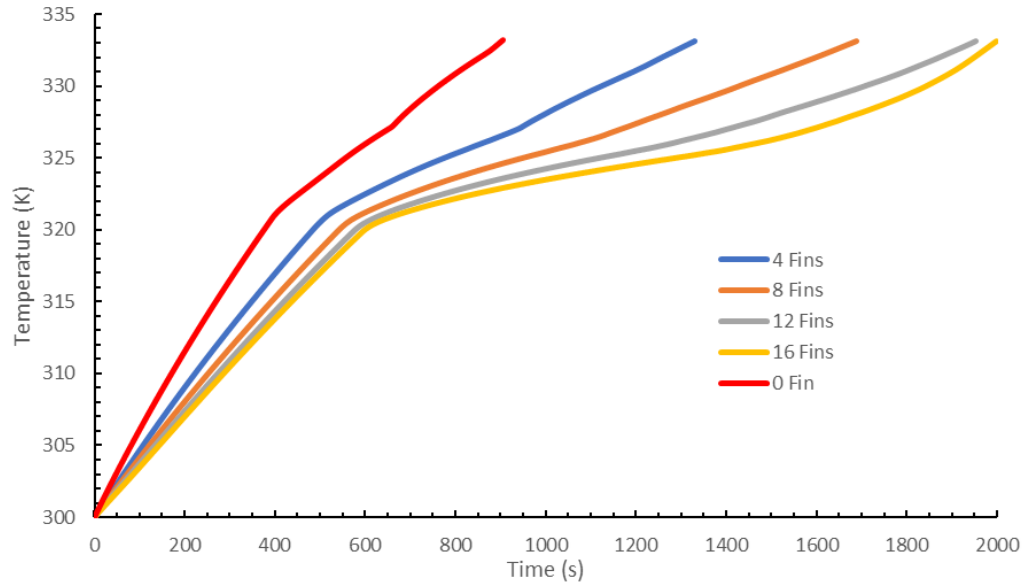


Figure 4.3 The variations in battery surface temperature over time for different numbers of straight fins.

Figure 4.4 depicts the distinctions in the phase change material liquid fraction with time for PCM-cooled battery thermal management systems with different numbers of straight fins, illustrating the melting process until the PCM was fully melted. The addition of fins

delayed the kick of PCM melting by enhancing heat transfer pathways, allowing for a more effective distribution of heat. Consequently, the increased number of fins extended the time needed for the phase change material to get to its phase change point, highlighting their critical role in improving thermal management efficiency and maintaining the system's operational effectiveness.

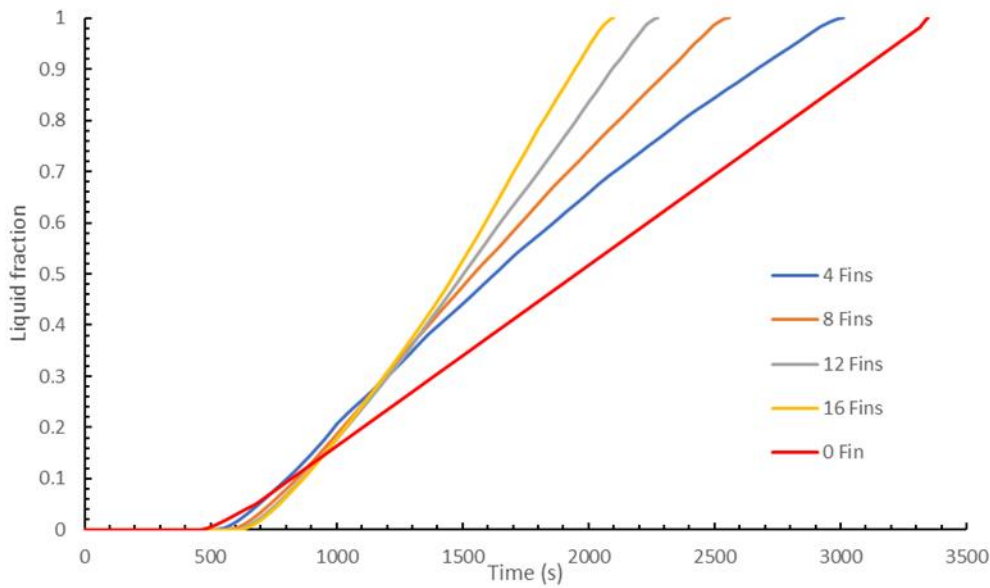


Figure 4.4 The liquid fraction in the BTMSs with time in varying fin numbers under 10 W.

The increased quantity of fins in the BTMS reduces the PCM volume, resulting in faster complete melting of the PCM as the number of fins increases. This trade-off occurs because the additional fins occupy space that would otherwise be allocated to PCM, thereby diminishing the system's latent heat storage capacity. Specifically, the BTMS configurations with 4, 8, 12, and 16 fins reduced the time to complete PCM melting by 10%, 23.55%, 32%, and 37.25%, correspondingly, compared to the BTMS with no fins. Figure 4.5 illustrates the PCM volume in thermal management systems with varying numbers of straight fins, clearly demonstrating the impact of fin inclusion on PCM volume and the corresponding effect on the thermal storage capabilities of the system.

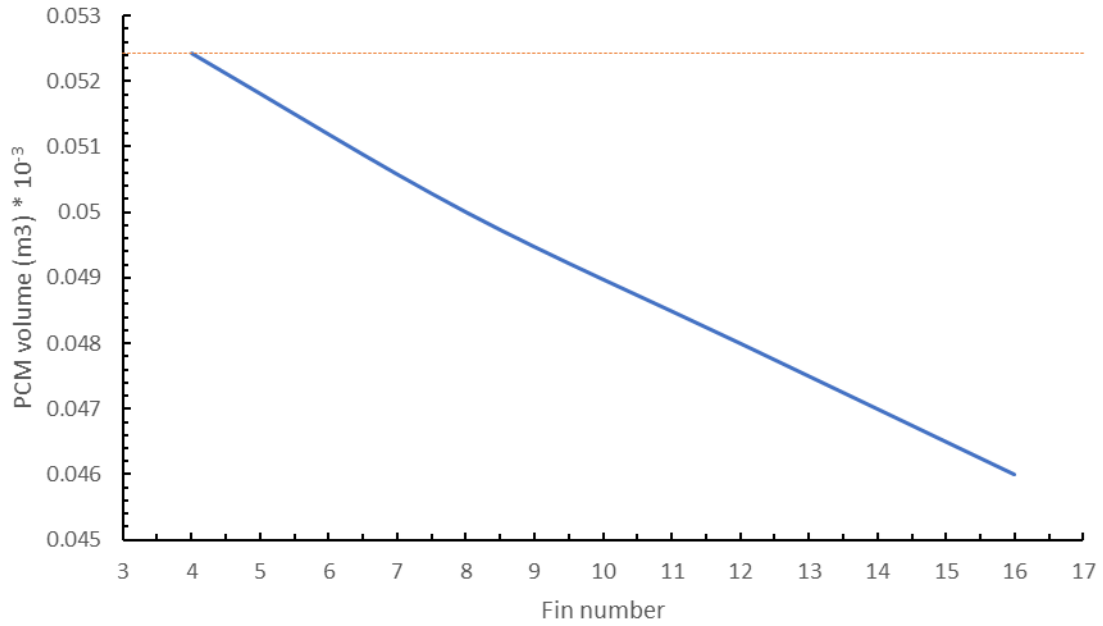


Figure 4.5 The PCM volume in thermal management systems with varying numbers of straight fins.

Figure 4.6 illustrates the liquid fraction distributions in the BTMS for varying numbers of straight fins. The distributions indicate that the inclusion of fins improves the utilization of the PCM correlated to the case with no fins, allowing for more effective use of latent heat as the number of fins increases. However, it should be noted that adding more fins reduces the volume of PCM available, thereby limiting the total latent heat that can be used to mitigate the battery's temperature increase.

This analysis highlights the importance of optimizing the number of straight fins to balance thermal performance and maximize the effective working time of the system. Over-designing with excess fins not only fails to provide additional benefits but also compromises the available PCM volume, highlighting the need for a strategic approach to fin configuration.

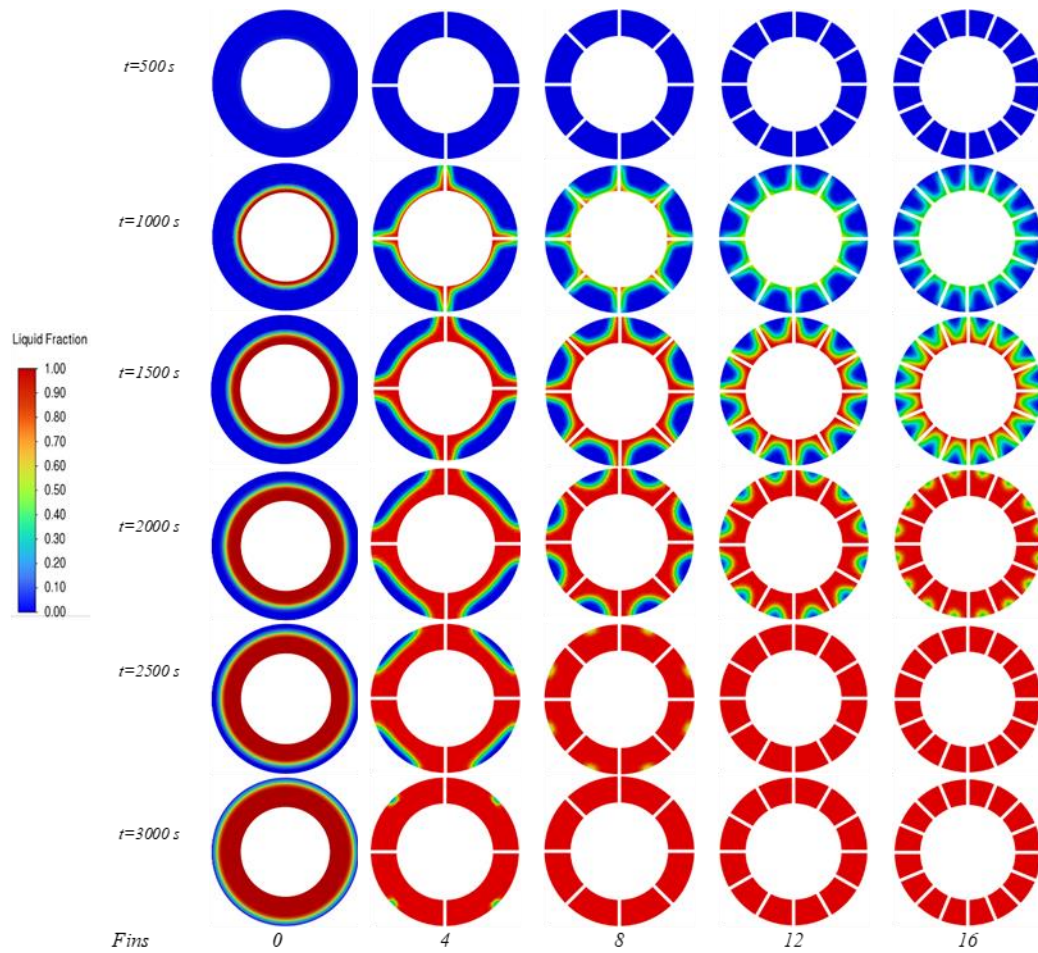


Figure 4.6 Liquid fraction contours inside the BTMS are presented for varying quantities of fins.

4.3 Effects of The Fins Thickness

A study is conducted to evaluate the impact of increasing the thickness of straight fins on the performance of the BTMS. Specifically, the study compares fin thicknesses of 1 mm, 2 mm, and 3 mm across BTMS configurations with 4, 8, 12, and 16 fins. Figure 4.7 illustrates the different fin thicknesses considered in this analysis. The objective is to assess how increasing the fin thickness affects the BTMS's thermal management performance, particularly its influence on the battery surface temperature. This evaluation aims to determine whether thicker fins enhance heat dissipation and improve temperature

regulation or if they introduce trade-offs, such as reduced PCM volume, that could impact overall performance.

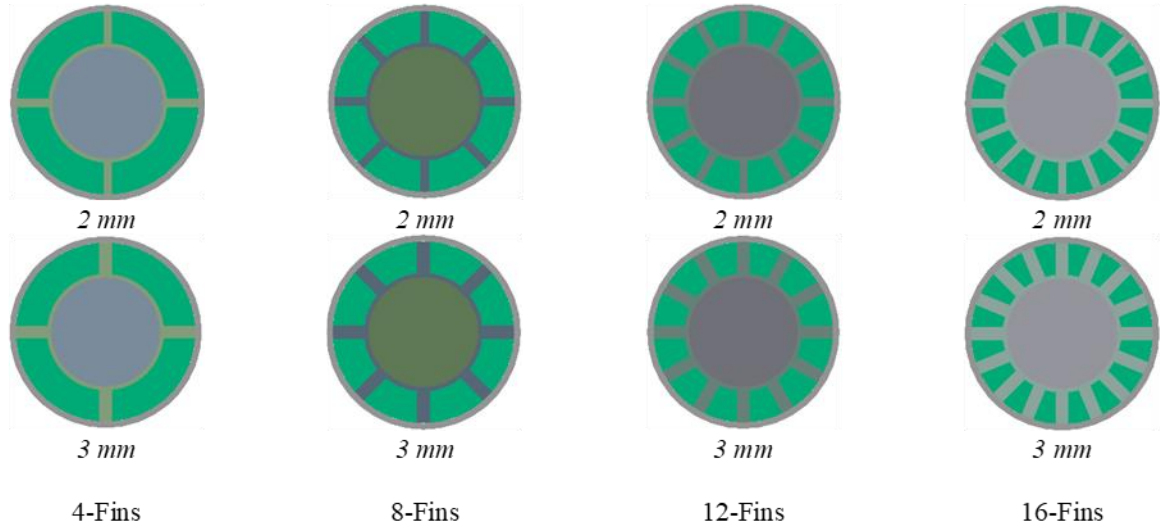


Figure 4.7 Fin thickness considered in the study.

Figure 4.8 illustrates the variation in battery temperature over time for the case of 4 fins with different fin thicknesses. The improvement in battery working time is minimal, with durations of 1331 s, 1342 s, and 1350 s for fin thicknesses of 1 mm, 2 mm, and 3 mm, respectively. This corresponds to a 0.82% improvement from 1 mm to 2 mm and a further 0.59% improvement from 2 mm to 3 mm. Given the marginal gains in working time compared to the added weight of the thicker fins, increasing the fin thickness beyond 1 mm is not a practical solution for enhancing BTMS performance.

Regarding the liquid fraction, it was observed that the initiation of PCM melting was slightly delayed as the fin thickness increased as shown in Figure 4.9. However, the complete melting of the PCM occurred faster with increased fin thickness due to the reduction in PCM volume. Specifically, the complete melting times were 3010 s for 1 mm fins, 2989 s for 2 mm fins, and 2966 s for 3 mm fins. This trend highlights the trade-off

between enhanced heat conduction provided by thicker fins and the reduced latent heat storage capacity resulting from a smaller PCM volume.

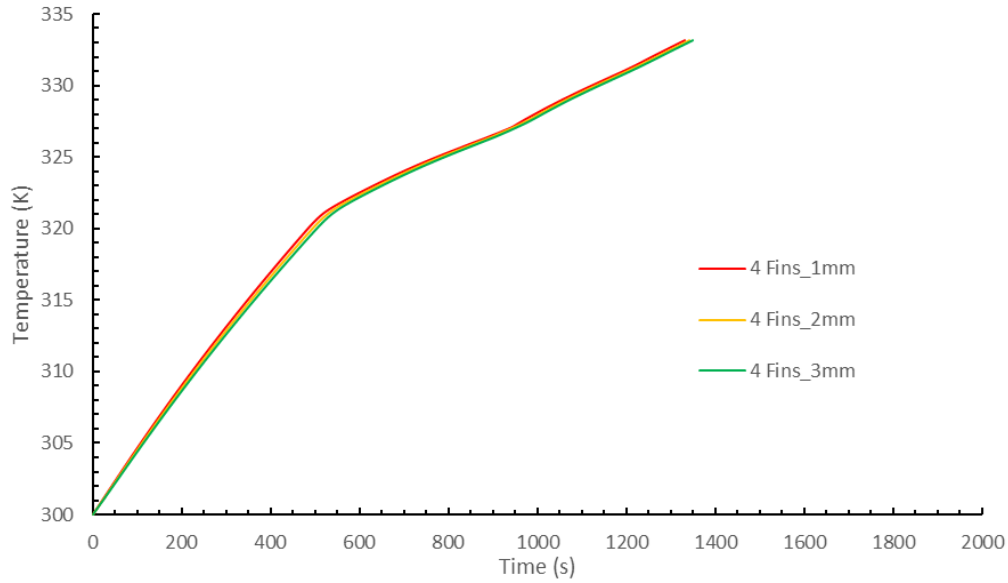


Figure 4.8 Battery temperature variation with time in the case of 4 fins with different fin thickness.

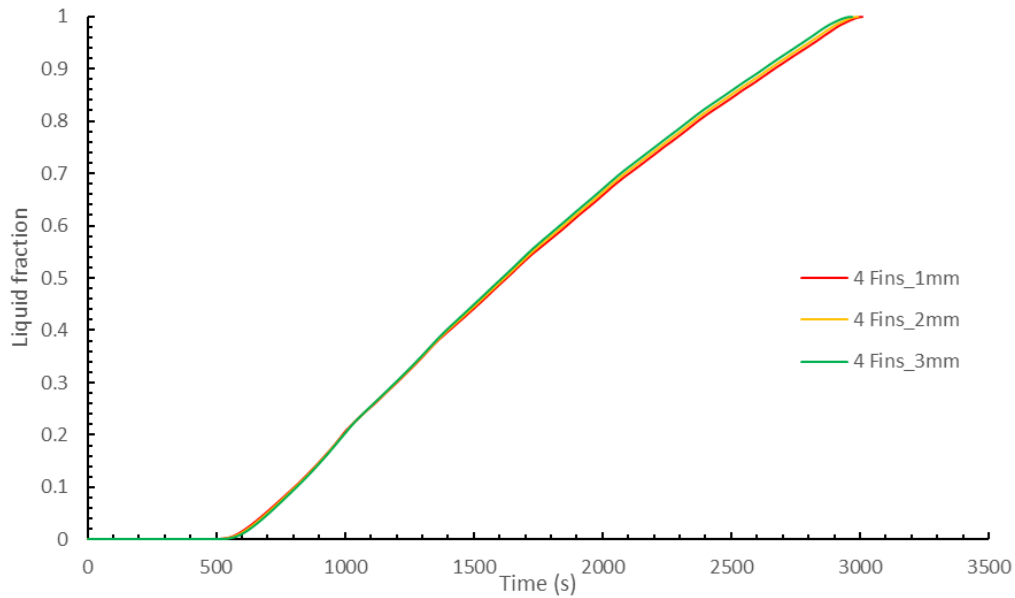


Figure 4.9 Liquid fraction in the case of 4 fins with different fin thickness.

Figure 4.10 illustrates the variation in battery temperature over time for the case of 8 fins with different fin thicknesses. The improvement in battery working time is minimal, with

durations of 1688 s, 1706 s, and 1715 s for fin thicknesses of 1 mm, 2 mm, and 3 mm, respectively. This corresponds to a 1.05% improvement from 1 mm to 2 mm and a further 0.52% improvement from 2 mm to 3 mm. Considering the negligible increase in working time relative to the added weight of the thicker fins, increasing the fin thickness is not a practical enhancement.

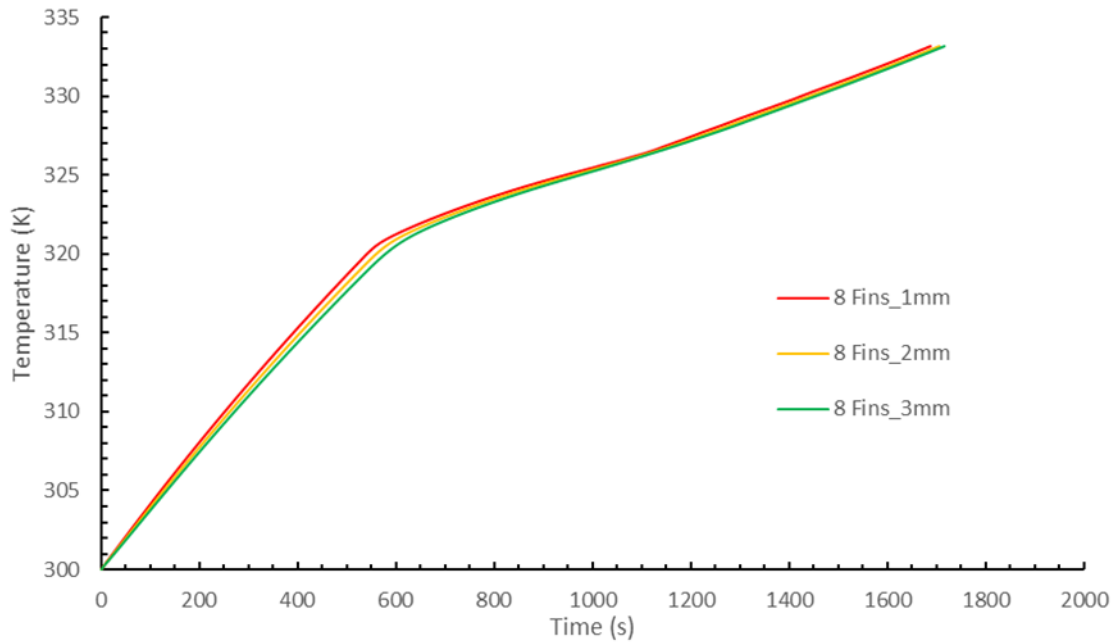


Figure 4.10 Battery temperature variation with time in the case of 8 fins with different fin thicknesses.

As for the liquid fraction, shown in Figure 4.11, the onset of PCM melting is slightly delayed as the fin thickness increases. However, the complete melting of the PCM occurs faster with thicker fins due to the reduction in PCM volume. Specifically, the complete melting times were 2557 s, 2518 s, and 2441 s for fin thicknesses of 1 mm, 2 mm, and 3 mm, respectively. This further underscores the trade-off between improved heat conduction and reduced latent heat storage, suggesting that increasing fin thickness may not yield significant benefits in thermal management performance.

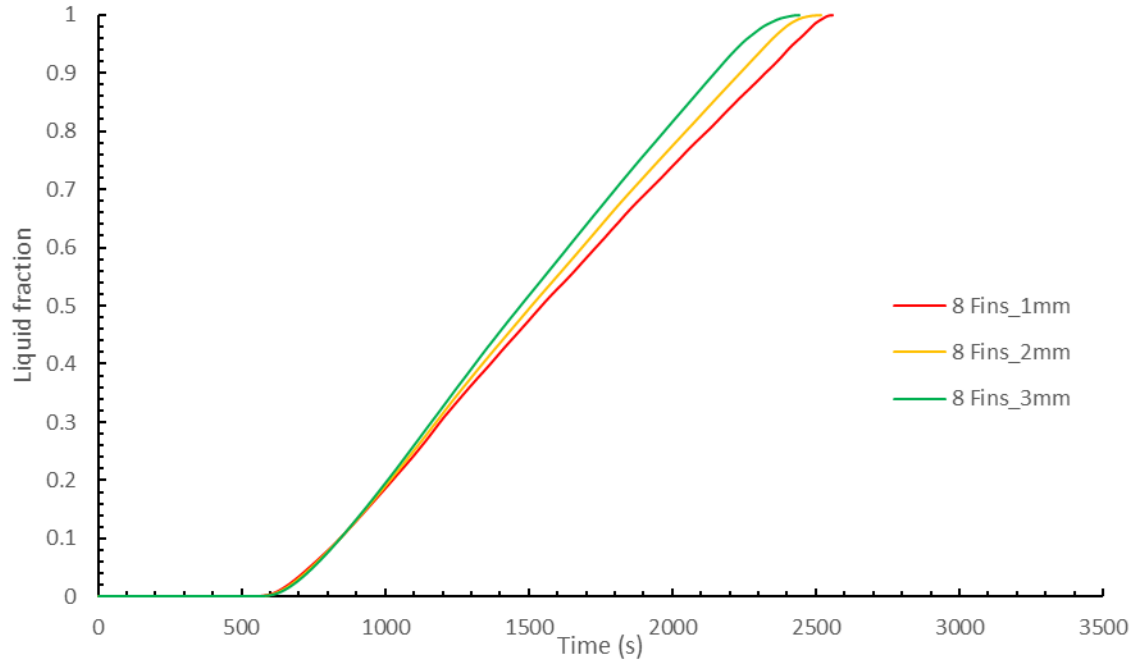


Figure 4.11 Liquid fraction in the case of 8 fins with different fin thickness.

For the case of 12 fins with varying fin thicknesses, as shown in Figure 4.12, it was observed that the working time of the battery actually reduced by increasing fin thickness. This is attributed to the high number of fins, where increasing the thickness further reduces the phase change material volume, diminishing the latent heat capacity and resulting in a shorter working time. Specifically, the working times were 1954 s for 1 mm fins, 1920 s for 2 mm fins, and 1845 s for 3 mm fins.

A similar trend was observed in the case of 16 fins, as illustrated in Figure 4.13. The working time of the battery decreased with increasing fin thickness due to the significant reduction in PCM volume. The working times for this configuration were 1999 s for 1 mm fins, 1897 s for 2 mm fins, and 1780 s for 3 mm fins. These findings highlight that, for systems with a higher number of fins, increasing fin thickness is counterproductive, as the reduction in PCM volume outweighs the potential benefits of enhanced heat conduction.

This underscores the importance of optimizing both fin number and thickness to achieve balanced thermal performance.

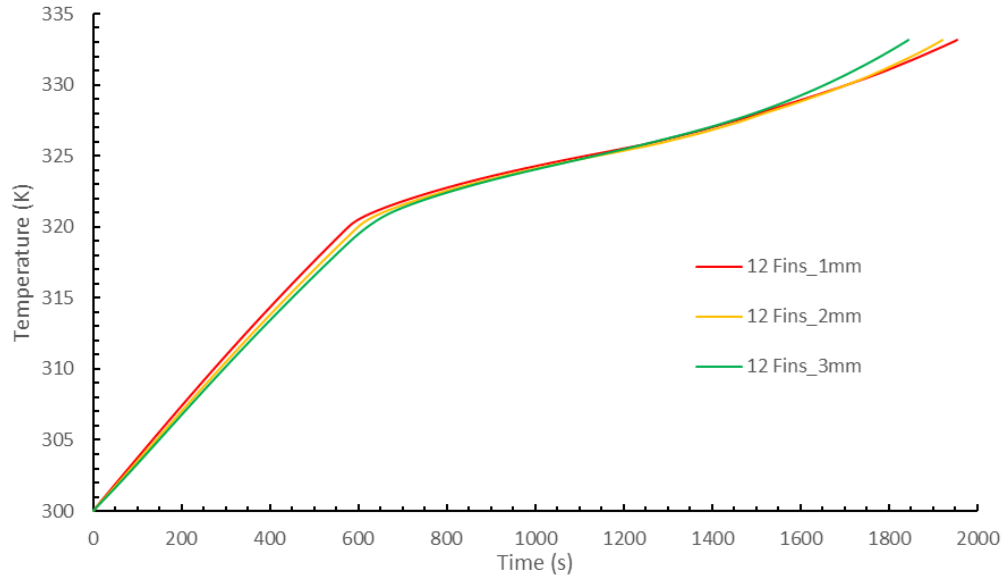


Figure 4.12 Battery temperature variation with time in the case of 12 fins with different fin thickness.

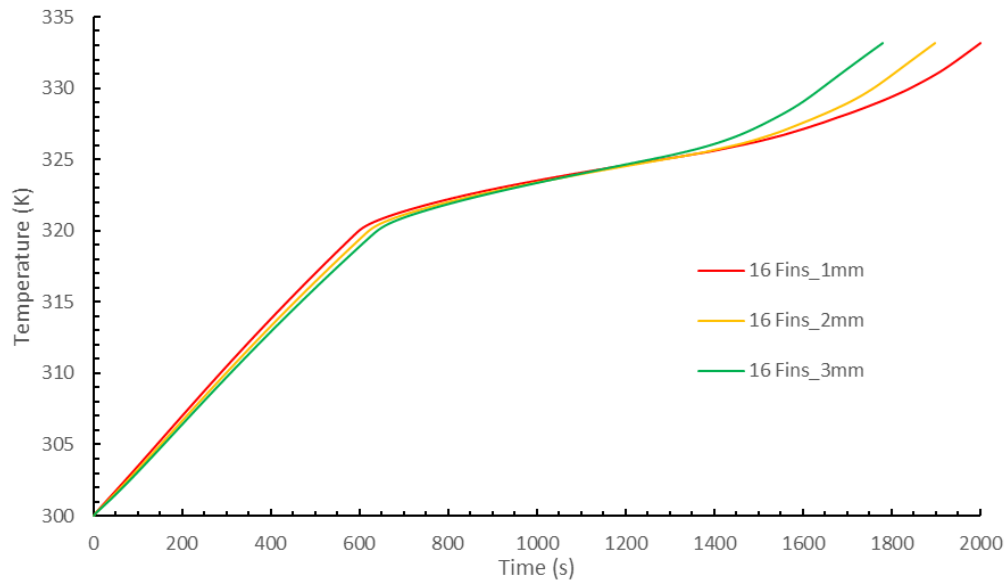


Figure 4.13 Battery temperature variation with time in the case of 16 fins with different fin thickness.

For the liquid fraction in both the 12 and 16 fins cases, similar trends are observed, as shown in Figure 4.14 and Figure 4.15. These trends are consistent with those observed in

the 4 and 8 fins cases with varying fin thicknesses. The beginning of PCM melting is delayed as the fin thickness increases, due to improved heat conduction pathways. However, the complete melting of the PCM occurs faster with thicker fins, owing to the reduced PCM volume. This reduction in volume limits the latent heat storage capacity, accelerating the melting process despite the delayed initiation. These results highlight the trade-offs associated with increasing fin thickness in PCM-based thermal management systems.

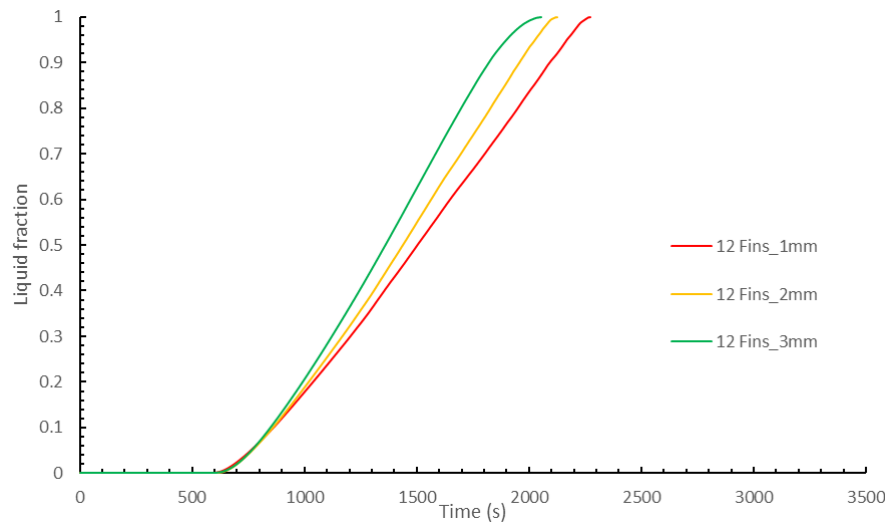


Figure 4.14 Liquid fraction in the case of 12 fins with different fin thickness.

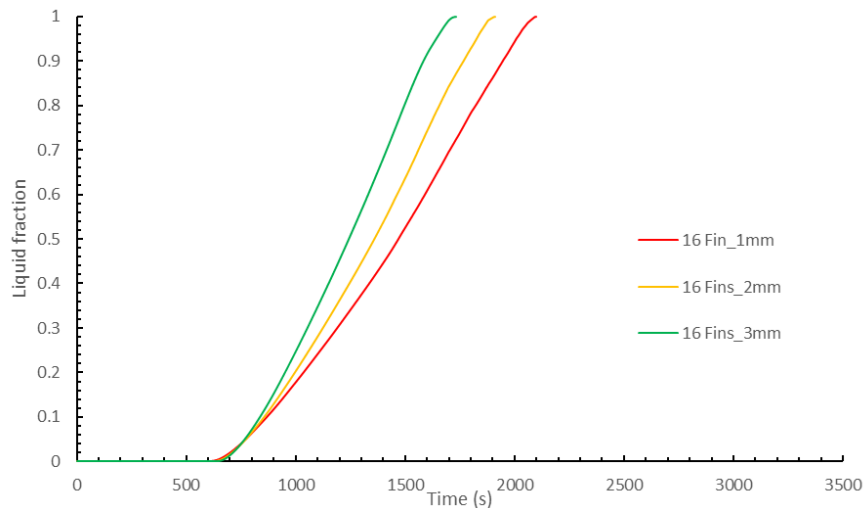


Figure 4.15 Liquid fraction in the case of 16 fins with different fin thickness.

4.4 Proposed S-shape Fins

In this section, the proposed S-shape fin design is studied to evaluate its impact on improving battery working time. A configuration with 4 S-shape fins is considered and compared to the traditional design of 4 straight fins. The choice of 4 fins is based on previous literature, which consistently suggests that 4 fins strike an optimal balance between minimizing added weight to the BTMS and maintaining sufficient PCM volume. The S-shape fin design, as shown in Figure 4.16, offers an increased surface area compared to the straight fins, thereby enhancing the area in contact between the phase change material and fins. This design improvement is expected to further optimize heat transfer and extend the working time of the cell.

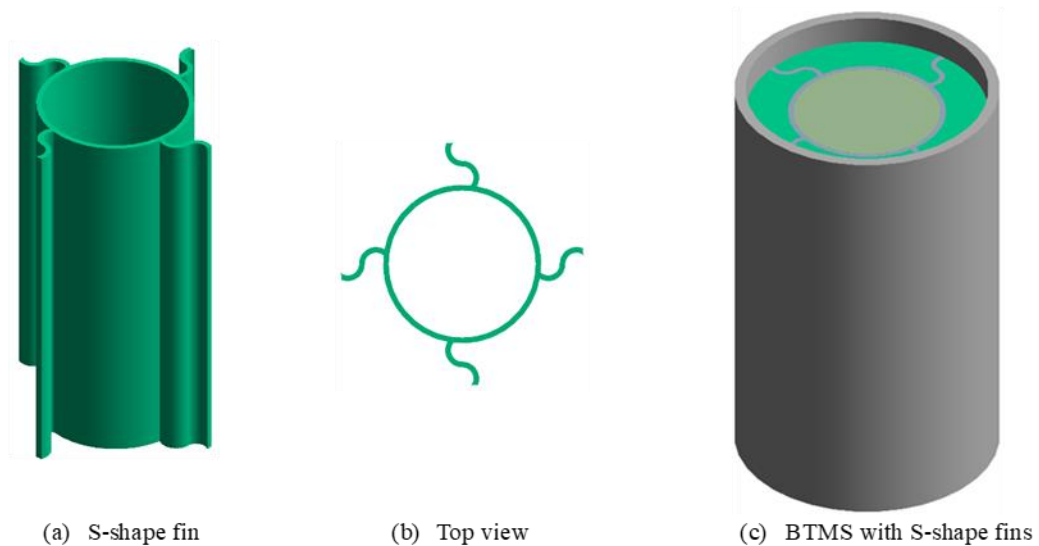


Figure 4.16 The new proposed fin shape in this study.

The performance of the BTMS with the proposed S-shape fin design was evaluated, as shown in Figure 4.17. The results highlight several advantages of the S-shape fin design over the straight fin configuration:

- **More Efficient Cooling:** The enhanced heat dissipation provided by the S-shape fin resulted in a slower temperature rise, effectively improving thermal management.
- **Increased Battery Working Time:** The S-shape fin design extended the battery working time by 169 seconds compared to the straight fin, demonstrating superior thermal performance.

This compact and efficient design shows great promise in the field of BTMS, offering potential applications in future research. Further analysis, as outlined in the following sections, will explore deeper into the phenomena behind this improvement, aiming to provide a comprehensive understanding of the mechanisms contributing to the enhanced performance.

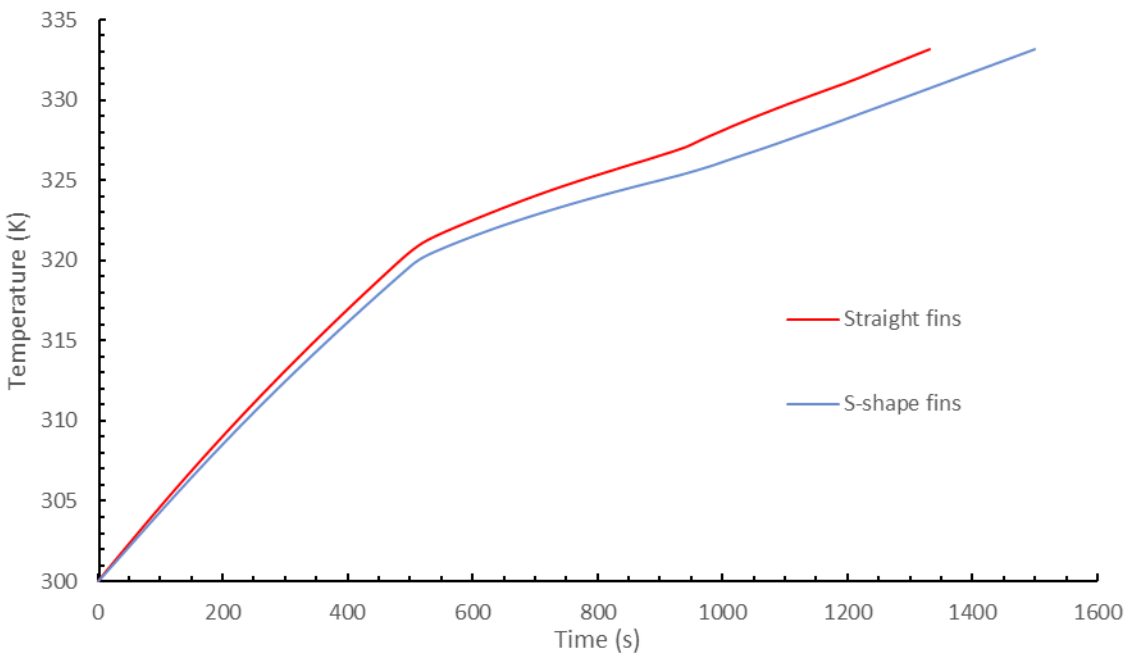


Figure 4.17 A comparison of battery temperature variation over time for straight fins and S-shaped fins.

4.5 Non-Dimensional Analysis for Nusselt Number

The surface-averaged Nusselt number is estimated as [130]:

$$\overline{Nu}(t) = \frac{\bar{h}(t)H}{k} \quad (4.1)$$

Here, $\bar{h}$ represents the surface-averaged heat transfer coefficient, H denotes the characteristic length of the PCM cavity in the battery thermal management system, and k refers to the thermal conductivity of the PCM. These parameters are critical for evaluating the thermal performance of the BTMS, as they influence the rate of heat transfer and the overall efficiency of the system. The $\bar{h}$ can be calculated by the following expression [130]:

$$\bar{h} = \frac{Q_{abs}}{A_t(T_w - T_m)\Delta t} \quad (4.2)$$

Q_{abs} represents the energy absorbed by PCM, which includes both latent heat and sensible heat during Δt . A_t denotes the total heat transfer area between the PCM and the fins. T_w refers to the total averaged temperature of the housing and fins surrounding the PCM, while T_m is the melting point of the PCM.

The Fourier number F_o alone is inadequate for accurately capturing the generalized trend of heat transfer discrepancy as it fails to incorporate the influence of the phase change evolution. The dimensionless time (τ) is expressed as [130]:

$$F_o = \frac{\alpha t}{H^2} \quad (4.3)$$

$$Ste^* = \frac{c_p q'' H}{kL} \quad (4.4)$$

$$\tau = F_o \times Ste \quad (4.5)$$

Here α represents the thermal diffusivity of the PCM, which indicates how quickly heat spreads through the PCM. C_p is the specific heat at constant pressure, describing the amount of heat required to raise the temperature of the PCM by one unit per mass. q'' denotes the heat flux. L is the latent heat of the PCM, defining the energy required for phase change without a temperature rise. The Stefan number Ste^* is a dimensionless quantity, here presented in its modified form, which quantifies the ratio of sensible heat to latent heat in the phase change process. These parameters are critical for understanding and modeling the thermal behavior of the PCM in BTMS applications.

Figure 4.18 depicts the changes in $\overline{Nu}$ against dimensionless time τ for the BTMS configurations considered in this study, tracking the process until the phase change material was entirely melted. The melting heat transfer process in the phase change material can be categorized into three distinct stages: conduction, strong convection, then weak convection, based on the behavior of the Nu over time.

Initially, heat transfer is dominated by conduction as the PCM begins to melt. As the melting progresses, natural convection becomes increasingly significant, peaking during the strong convection stage, where heat transfer efficiency is at its highest. Toward the end of the melting process, natural convection diminishes, transitioning to a weak convection stage as the PCM nears complete melting. This classification highlights the dynamic evolution of heat transfer structure during the phase change material melting progression, providing a valuable understanding of the thermal behavior of BTMSs.

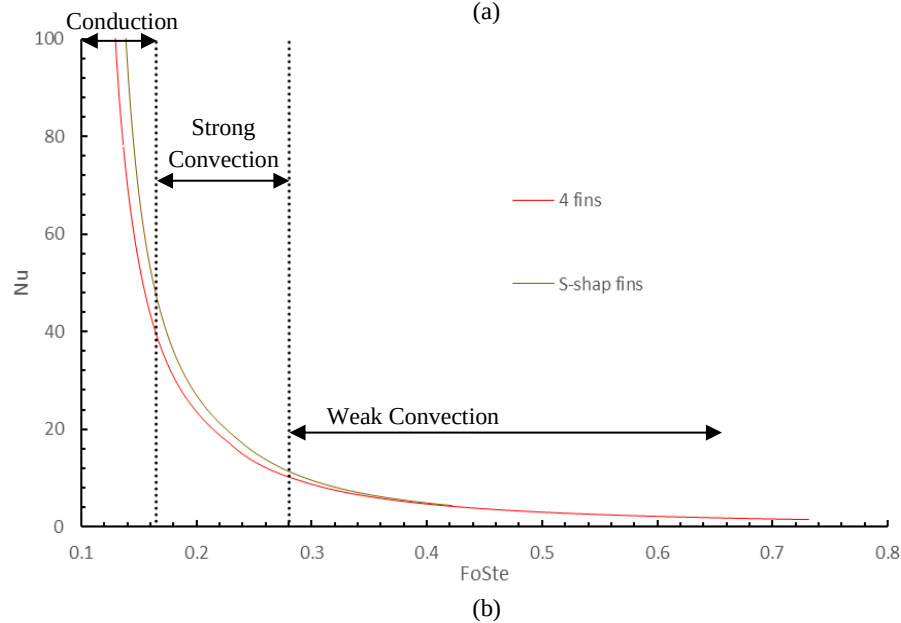
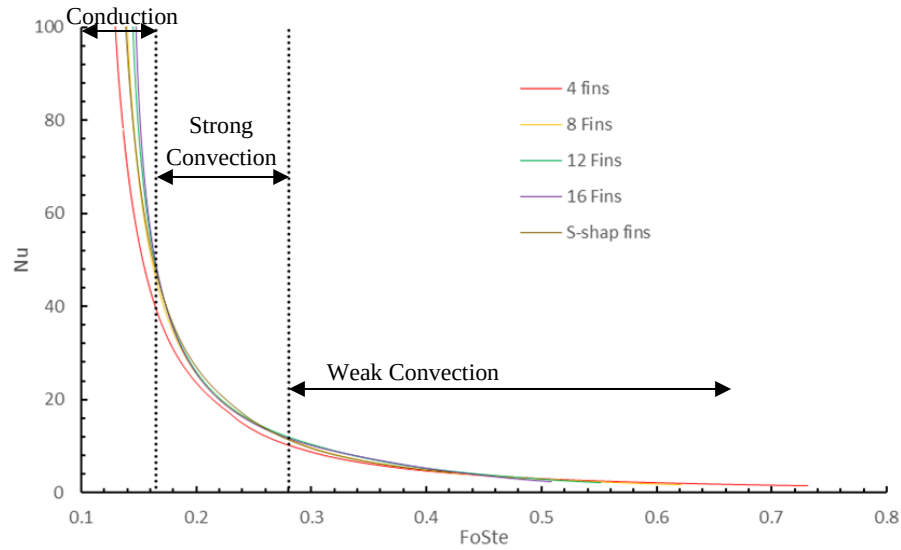


Figure 4.18 Discrepancy of $\overline{Nu}$ against the dimensionless time.

In the heat conduction regime of the phase change material melting process, heat transfer is dominated by conduction, with convection effects being negligible. At the beginning of melting, the Nusselt number reaches its maximum due to the minimal thermal resistance of the initially small liquid phase change material layer. As melting continues, the liquid layer thickens, increasing thermal resistance and causing Nu to decline sharply. During this stage, heat transfer is primarily driven by conduction from the fin surfaces, and adding

more fins slightly increases Nu by expanding the heat transfer area. Over time, as the liquid layer grows and resistance further increases, the heat transfer rate decreases, signaling the gradual transition to the subsequent regime.

Throughout the strong convection area, natural convection becomes the primary heat transfer mechanism within the phase change material, significantly enhancing the overall heat transfer rate. While thermal resistance increases as more phase change material melts, the intensified liquid PCM flow driven by strong convection reduces the impact of this resistance, resulting in a slower decline in the Nusselt number Nu compared to the conduction regime. In BTMSs with a higher quantity of fins, Nu values are higher due to the increased PCM melting rate and the development of more substantial natural convection areas within the PCM silos, further boosting heat transfer performance.

In the weak convection area, Nu continues to decline and reaches significantly lower values than those in the conduction and strong convection regimes. This decrease signifies a reduced heat transfer rate within the BTMSs due to diminishing natural convection currents and a reduced solid-liquid interface. As a result, the weakening convection leads to a rise in battery temperature towards the end of the PCM melting process, indicating a diminished effectiveness of heat transfer during this phase.

Consequently, the PCM-based battery thermal management system with 4 S-shaped fins proved to be more effective in leveraging both conduction heat transfer and natural convection within the PCM to regulate battery temperature compared to the configuration with 4 straight fins.

CHAPTER 5

CONCLUSION AND RECOMMENDATIONS

This study successfully investigated the thermal performance of a battery thermal management system incorporating phase change materials and fin structures for cylindrical 26650 lithium-ion batteries. Using detailed numerical simulations and experimental validation, the performance of different fin configurations was evaluated. The findings confirmed that increasing the number of fins and optimizing their thickness significantly enhances heat dissipation, maintaining the battery's operating temperature within safe limits and extending its working time.

The novel S-shape fin design demonstrated superior thermal management performance compared to traditional straight fins. These improvements are critical for preventing thermal runaway, reducing battery degradation, and ensuring the safe and efficient operation of lithium-ion batteries.

The validated simulation model further underscored its reliability, providing a robust platform for exploring advanced thermal management solutions. This research contributes valuable insights to the field of battery thermal management and serves as a foundation for future studies aiming to optimize battery performance and safety.

Forthcoming research should emphasize on optimizing the configurations of PCM-fin structures by exploring different fin geometries, material properties, and placement strategies. The objective would be to identify configurations that provide the best balance

between thermal performance, weight, and cost, thereby enhancing the practicality of the thermal management system for various applications. Additionally, experimental studies with a variety of phase change materials, including organic, inorganic, and eutectic types, are recommended. This would help identify the most effective PCM for specific operational conditions and environments, further improving the adaptability of the proposed BTMS. The integration of hybrid cooling methods, combining passive systems like PCM and fins with active approaches such as liquid cooling or forced air, should also be explored. Such hybrid systems have the potential to offer superior thermal management for high-discharge and high-temperature scenarios, making them suitable for more demanding applications.

Scaling up the study to include larger battery modules or packs is another crucial area for future work. Testing the system at a module or pack level under real-world conditions and varying operational loads will deliver visions of the scalability and effectiveness of the proposed thermal management design. Furthermore, the use of advanced materials, such as metal foams or nano-enhanced composites, could be investigated to improve heat transfer efficiency while minimizing weight and cost. These materials have the potential to further optimize the performance of the BTMS.

Lastly, a comprehensive lifecycle and economic analysis should be conducted to evaluate the long-term impact of the proposed BTMS on battery performance, operational costs, and environmental sustainability. This analysis would offer a clearer understanding of the viability of the system for widespread adoption in industries such as EVs and renewable storage systems. By addressing these areas, future research can build upon the findings of

this study to develop more effective, efficient, and commercially viable thermal management systems for lithium-ion batteries.

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