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Study on Battery Thermal Management Systems for Lithium-Ion Batteries

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Abstract: *The increasing adoption of electric vehicles (EVs) as a sustainable alternative to conventional vehicles has highlighted the importance of effective battery thermal management. Lithium-ion batteries, commonly used in EVs, offer advantages like quick recharge times and efficiency but are susceptible to overheating, impacting safety and durability. This project aims to develop a suitable model for battery thermal management using passive and active cooling methods to control and regulate the battery's temperature within a safe range. Implementing an advanced thermal management system enhances battery performance, longevity, and safety, promoting the wider adoption of EVs and contributing to a cleaner and greener transportation future.*

Keywords: electric vehicles

I. INTRODUCTION

In recent years, lithium-ion batteries have become the dominant energy storage technology due to their high energy density, long cycle life, and widespread application in various fields, such as electric vehicles, portable electronics, and renewable energy systems. As the demand for efficient and reliable energy storage solutions continues to grow, the management and control of lithium-ion batteries have become crucial for optimizing their performance, safety, and overall lifespan. A Battery Management System (BMS) plays a pivotal role in monitoring, protecting, and ensuring the efficient operation of lithium-ion batteries. The main objective of the BMS is to maintain the battery cells within safe operating conditions, prevent overcharging, over-discharging, and thermal runaway, and ensure balanced charging and discharging across all individual cells. By effectively managing the battery's state of charge (SoC) and state of health (SoH), the BMS not only enhances the battery's performance but also extends its operational life. One of the critical functions of the BMS is cell balancing. Lithium-ion batteries are composed of multiple cells connected in series or parallel, and slight variations in cell characteristics can lead to an imbalance in charge and discharge rates. The BMS actively balances the individual cell voltages, ensuring that all cells operate within a narrow voltage range, thus maximizing the overall battery capacity and lifespan. The successful design and implementation of a robust BMS are crucial for achieving optimal performance and safety of lithium-ion batteries. Battery Thermal Management of Lithium-ion Batteries refers to the strategies and systems employed to control and regulate the temperature of lithium-ion batteries, ensuring their safe and efficient operation, as temperature extremes can affect battery performance, lifespan, and safety. While there are many ways to store energy, thermal systems find latent heat thermal energy storage (LHTES) with a Nano Fluids to be appealing. Currently, sensible heat thermal energy storage is more prevalent; but, because of its higher energy density, almost isothermal functioning, and smaller size, LHTES may have a larger potential for usage. However, because most PCMs have low thermal conductivities, the usage of LHTES systems has been constrained. As a result, numerous heat transfer augmentation strategies have been developed and applied, including:

1.1 Composite Phase Change Materials

A novel composite phase change material (CPCM) containing nanosilica (NS) has been developed for efficient thermal management of power batteries. The addition of NS improves material stability and reduces leakage and volume change of the CPCM, resulting in enhanced cooling efficiency and durability of battery modules. This breakthrough addresses key challenges in PCM cooling technology for practical applications [1]. The study evaluated two composite phase change materials (PCMs) for battery thermal management. The lower-conductivity PCM extended cooling time but caused uneven temperature distribution in multi-cell packs. The higher-conductivity PCM improved temperature uniformity, reducing voltage differences and enhancing performance, especially in cold conditions. Effective thermal management in battery packs is crucial for maintaining consistent cell temperatures and voltages [2]. A CCFSS/paraffin composite PCM was designed to enhance heat transfer in lithium-ion battery packs. Experimental and numerical analyses demonstrated effective temperature control, validating the composite PCM's performance. Factors like PPI, spacing, and convection coefficient were found to influence battery temperature, providing insights for practical applications of this composite PCM in lithium-ion battery heat dissipation [3]. Graphene and MWCNT-based composite PCM were investigated for lithium-ion battery thermal management. Optimal proportions were determined, enhancing thermal conductivity and controlling temperature rise during heat charge. A composite with 3/7 MWCNT/graphene mass ratio exhibited the highest thermal conductivity, superior temperature control, and potential for efficient lithium-ion battery thermal management [4]. An analysis of PCM cooling for pouch cells revealed improved cooling compared to natural convection. Thermal contact resistance, PCM thickness, and melting temperature were critical factors affecting cooling effectiveness. PCM thickness up to 3 mm increased cooling effectiveness, while lower thermal contact resistance and suitable melting temperature improved performance. These findings guide thermal management and safety designs, with potential for further research on PCM's cooldown effects [5]. Phase change materials (PCMs) offer high thermal energy storage for advanced thermal management. Aluminum and CENG foams enhance thermal charging rates. High pore density aluminum foams outperform due to increased conduction, impacted by PCM viscosity and thermal interface materials. CENG foams exhibit superior thermal charging enhancement due to their high thermal conductivity, low density, and small pore size, guiding thermal battery design for space conditioning [6]. The study proposes an innovative approach to enhance heat transfer in PCM-based thermal management systems for large battery packs. Inverting cell orientation within the pack, combined with convection and thermoelectric devices, improves heat distribution and temperature management during high-rate cycling. This approach preserves latent heat storage capacity and offers potential benefits for electric vehicle driving range and cross-platform technology utilization [7]. The experimental investigation examines copper foam-based heat sinks with embedded phase change materials (PCMs) for electronic device cooling. Varying PCM types and volume fractions influence base temperature reduction at different power loads during charging. PCM/copper foam composites consistently outperform copper foam alone. Thermal control efficiency depends on PCM type, melting temperature, and power load. RT-35HC/Copper foam suits low power levels, while RT-54HC/Copper foam excels at higher loads and set temperatures [8]. The study introduces a hybrid battery thermal management system (PLH-BTMS) utilizing phase change material, liquid cooling, and heat pipes. A surrogate model is developed for cost-effective optimization, enhancing heat dissipation and minimizing temperature differences during discharging-charging profiles. The optimized PLH-BTMS demonstrates superior thermal performance and reduced risk of thermal runaway propagation, establishing a robust solution for battery thermal management [9]. This study focuses on optimizing PCM-based BTMS design through hybrid approaches and thermal conductivity enhancements. Hybrid BTMS with PCM and heat pipes is highlighted as an effective solution, considering factors like material selection, configuration, and reactivity. Thermal conductivity enhancement techniques, including porous foams, are explored. Parameters affecting BTMS performance, such as melting temperature, thermal conductivity, and design considerations, are discussed. Future research should address material compatibility, waste heat recovery, 3D printing, PCM melting points, and cost analysis for improved BTMS design [10]. The combined active and passive cooled battery thermal management system, with a proposed cell-to cell cooling layout and phase change material, effectively keeps cell temperatures stable and uniform even under extreme conditions. Additionally, the modified PCM cooled system allows for easier variation of pack capacity compared to conventional systems [11]. Develop and analyze Phase Change Material (PCM)-based Battery Thermal Management Systems (BTMS) for improving the thermal performance and safety of batteries in electric vehicles. The study focuses on enhancing PCM properties, such as thermal conductivity and latent heat, while considering the trade-offs with other factors like convection, volume, weight, and cost, to achieve efficient and effective BTMS for future applications [12]. Analyze PCM-based Battery Thermal Management Systems (BTMS) to achieve uniform battery temperature distribution. The study explores different approaches to improve PCM properties, such as increasing thermal conductivity and latent heat, reducing melting temperature, and adding carbon materials or metals. The research

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emphasizes the significance of hybrid BTMS and the potential for future improvements in efficiency, energy consumption, volume, weight, and cost-effectiveness of PCM-based BTMS [13]. The performance of an electric vehicle's battery pack is affected by ambient conditions, with extreme temperatures having a more severe impact. The heat generation rate in the battery is influenced by the discharge rate and ambient temperature. Passive cooling using Capric acid (fatty acid) as a phase change material (PCM) effectively cools the battery, especially at low discharge rates, and outperforms paraffin wax in absorbing excess heat in a cost-effective manner. However, at high discharge rates and extreme temperatures, a secondary liquid cooling system may be necessary to maintain optimum temperature conditions [14]. Improve the thermal management of a battery pack by adding Graphene Nanoplatelets (GNP) to paraffin based composites. The addition of 7% GNP significantly enhances the thermal conductivity and delays the temperature increase during discharging, leading to prolonged battery protection time at lower ambient temperatures, while still maintaining acceptable melting latent heat properties for industrial applications [15].

Fig. 1a shows the preparation of the CPCM-NSx based battery module as well as the schematic diagram of the experimental system. First, 6 holes with a diameter of 18.5 mm were drilled on the CPCM-NSx using a milling machine, in which 6 commercial 18,650 Lithium-ion power batteries with a capacity of 2 Ah were placed. Then, all of the cells were connected in 1S × 6P configuration (one cell in series and six strings in parallel) by a laser spot welding machine (Fig. 1b). Finally, the battery module was charged/discharged using a BTS-5V30A-NTF battery testing system with an accuracy of ± 0.01%. 2 T-type thermocouples were mounted on the surface center of two cells in the battery module and connected to an Agilent 34970A Data Acquisition.

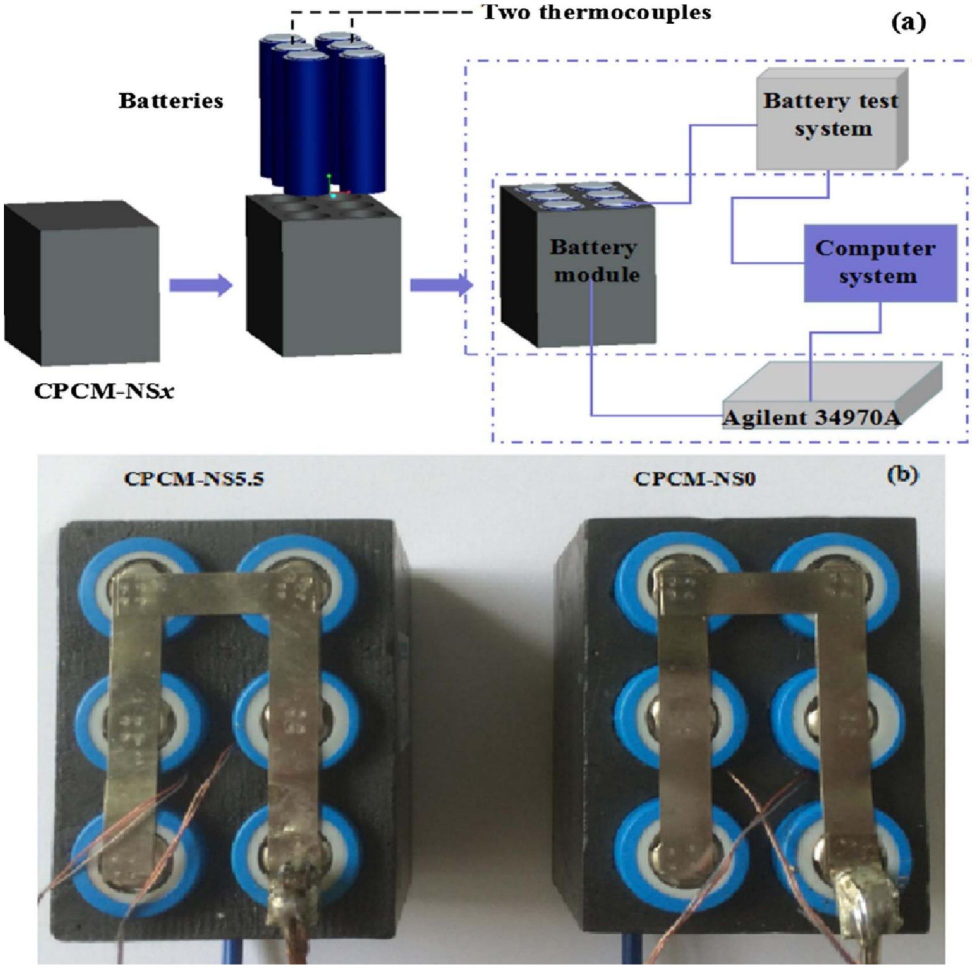

Fig. 1. (a) Schematic diagram for the preparation of the battery module and the experimental system; (b) Photos of the CPCM-NS5.5 and CPCM-NS0 modules.

1.2 Thermal Management with liquid cooling:

Thermal model for an EV battery pack using channeled liquid cooling. The model considers individual batteries, heat generation, and heat transfer. Simulation results show that higher discharge/charge rates increase temperature and non-uniformity. Increasing liquid flow rate improves both. Larger heat exchange areas between batteries slightly help uniformity, while increasing interfacing area with the channel wall reduces max temperature but worsens uniformity [16]. The study introduces a novel AgO nanofluid-based thermal management system for lithium-ion batteries. It maintains optimum temperature and uniformity. Numerical analysis explores the impacts of discharge rate, nanofluid fraction, and flow velocity. Higher velocity and nanofluid fraction decrease max temperature and differences. At 7C discharge rate, optimal conditions keep temperature below 305.59 K and 1.07 K difference. Comparison of 18650 and 21700 battery packs suggests the latter's favorable potential [17]. Thermal management's significance for Li-ion battery packs in EV, HEV, and PHEV applications. Indirect cooling using liquid and aluminum cooling fins is explored for PHEV Li-ion pouch cells. Finite element analysis is used to simulate cell temperature distributions under different cooling setups, indicating the benefits of dual cold plate cooling in providing higher cooling capacity and cooling for cell terminals and busbars [18]. Emphasize the importance of battery thermal management (BTM) systems for electric and hybrid vehicles. The review examines the effects of temperature on battery performance and explores various BTM methods, including air, liquid, and phase change material-based systems. The focus is on optimizing liquid based systems for efficient heat transfer, with potential applications of heat pipes and integration with other vehicle thermal management systems [19]. Present a compact and lightweight liquid-cooled battery thermal management (BTM) system for controlling the temperature of Li-ion batteries during a high discharge rate process. A novel thermal conductive structure (TCS) with three curved contact surfaces is proposed and its structural parameters are systematically discussed to optimize the system's performance. The designed TCS effectively reduces temperature differences and weight while maintaining satisfactory battery temperature control. Additionally, the study explores a parallel TCS setup to homogenize flow rates and maintain temperature uniformity within the battery pack [20]. Battery thermal management system for cylindrical Li-ion battery packs, combining a vapor chamber with a fin structure and integrating air-forced or water cooling. The study concludes that the system with vapor chamber and water cooling is the most effective method for temperature control, providing detailed experiments and a more compact, uniform, and leak-resistant cooling solution for cylindrical Li-ion batteries. Future work will focus on enhancing cooling performance through different refrigerant content and types in the vapor chamber [21].

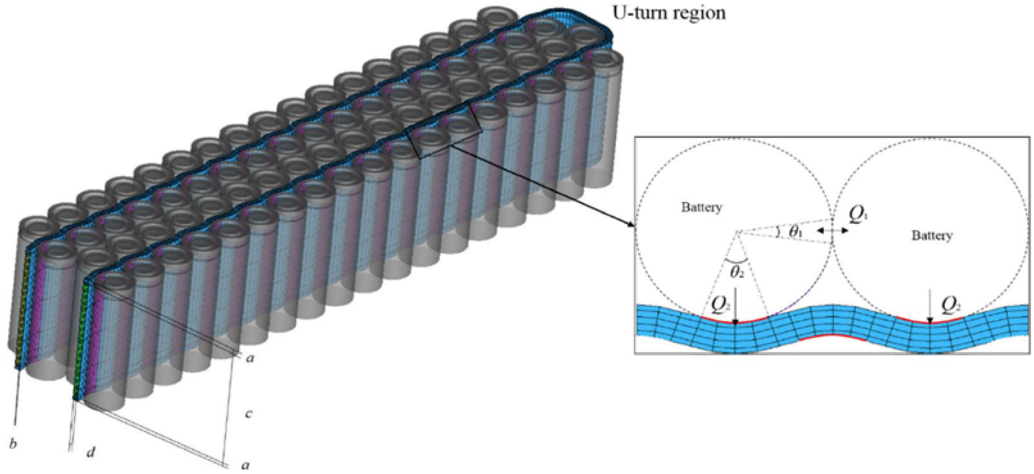

Fig. 2. Schematic of the simulated lithium-ion battery module geometry and the numerical mesh.

The desired battery module should contain batteries densely packed to attain high energy-density. For the sake of ease of operation and better thermal uniformity, the number of batteries in each module should not be too large. This work takes the Tesla Model S pack as a reference and considers a battery module of 71 18650-type LIBs with a wavy channel wound around the batteries acting as the coolant channel, as shown in Fig. 2.

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1.3 Thermal Management with Air cooling:

Reliability design method for lithium-ion battery packs in electric vehicles. It considers thermal disequilibrium and uses cell redundancy. It establishes a multi-physics model, degradation model, and reliability model. The study explores different redundancy strategies and concludes that the optimal system structure is a 6 × 5 parallel-series configuration, with non-monotonic reliability increase due to thermal effects. The impact of cell arrangement and cooling conditions is also investigated [22]. The significance of Battery Thermal Management Systems (BTMS) for EVs and HEVs, focusing on air-cooling methods. It discusses heat generation's impact on powertrains, reviews basic air-cooling BTMS design, explores novel improvements, and highlights enhanced efficiency through simulations and experiments. Future research and solutions for air-cooling BTMS development are suggested [23].

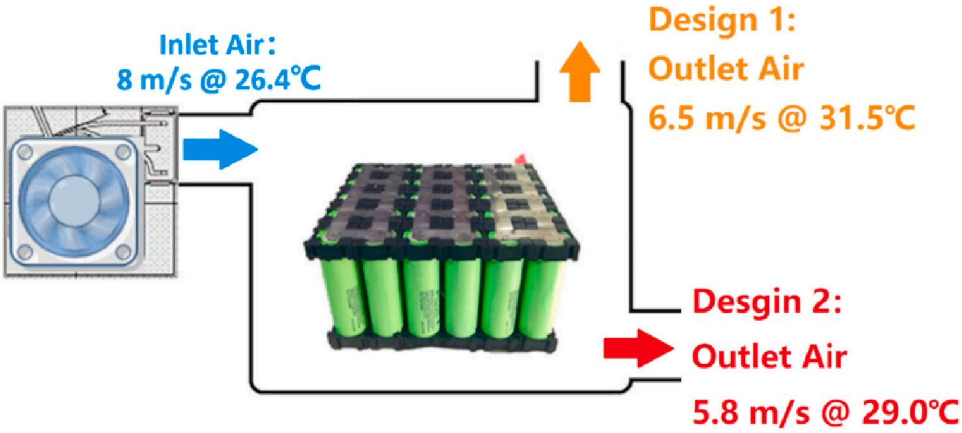

Fig. 3. BTMS designs with different outlets: Design 1: upper outlet; Design 2: bottom outlet.

An active air-cooling BTMS to protect the battery pack from excessive heat accumulation during normal discharging. The overall cooling performance of Design 1, including both the maximum temperature difference and maximum temperature, was better than that of Design 2 as shown in Fig. 3.

1.4 Hybrid Thermal Management

An effective liquid cooling method for rectangular Li-ion power batteries in electric vehicles, using a U-tube shaped cold plate with a serpentine-channel configuration. Analyzing channel layout, number, and coolant inlet temperature, simulation results show that a 5-channel layout along the length direction offers optimal cooling performance, reducing max temperature by 26°C compared to a 2-channel width layout. Considerations of efficiency and safety yield upper limits for channel number and inlet temperature, aiding cold plate design for Li-ion power battery thermal management [24]. The significance of Battery Thermal Management Systems (BTMS) in maintaining optimal working temperatures for lithium-ion batteries (LIBs) in electric vehicles. A heat pipe-based BTMS was designed and tested with L- and I-shaped heat pipes. Results showed the system effectively kept temperatures below 55°C and achieved a temperature difference below 5°C, transferring over 92.18% of generated heat, demonstrating its viability and effectiveness at high heat loads [25]. Heat pipe and wet cooling integrated system for efficient battery thermal management (BTM) in lithium-ion batteries. Ultra-thin heat pipes transfer heat from the battery to cooling ends where water evaporation dissipates it. The system's cooling performance is evaluated on 3 Ah and 8 Ah battery packs with varying cooling end lengths, comparing it to other BTM methods and natural convection. The study introduces a cost-effective combination of natural convection, fan cooling, and wet cooling to maintain battery temperature within a desired range [26]. Enhanced cooling for hybrid electric vehicle battery packs. It proposes a smart thermal management system using heat pipes and a combination of air conditioning and ambient air ventilation. A nonlinear model predictive controller maintains battery temperature using compressor and fan speeds. Simulation results demonstrate effective temperature regulation and heat removal (up to 1135 kJ), adapting to varying conditions. System power consumption is assessed across different modes and ambient conditions [27]. Thermal management system for $LiFePO_4$ battery packs using phase change material (PCM) and liquid cooling. Non-uniform heat generation modeling was verified, and simulations analyzed coolant velocity, pipe position, and ambient temperature effects. Cycle testing demonstrated effective cooling even at 45°C ambient temperature, maintaining battery temperature within 47.6°C and 4.5°C difference. The system improved PCM heat removal and fraction, especially near electrode tabs. Adjusting coolant velocity during charging conserved power while preserving cooling capacity for enhanced battery thermal management under harsh conditions [28]. Classify various Battery Thermal Management Systems (BTMS) for Electric Vehicles (EVs). It highlights the advantages and disadvantages of different BTMS options, ranging from systems utilizing Vehicle Cabin Cooling (VCC) to those without VCC, such as PCM cooling, heat pipe cooling, and thermoelectric element cooling. The goal is to develop more effective BTMS that can handle the increasing thermal load of EV batteries in the future [29]. Thermal management of lithium-ion batteries using a sandwich structure involving a battery, phase change material (PCM), and heat pipe. Experimental investigations and a lumped thermal model reveal coupling mechanisms between battery temperature and phase change. Heat pipes recover PCM latent heat, ensuring low battery temperatures during cycles. Different stages, including sensible and latent heat, solidification, and steady stages, are identified. To balance safe temperatures, energy efficiency, and module density, an optimal PCM melting point and heat transfer coefficient in the condenser are recommended [30].

The test section shown in Fig. 4(a) consisted of the aluminum plates, copper holders, and heat pipes. Aluminum plates were used to simulate batteries, and their dimensions were 173 × 125 × 45 mm. Four heaters were inserted into the four drilled holes with a 14 mm diameter at the top of the plate. The four heaters were used to generate heat. The dimensions of the copper holder shown in Fig. 4(b) was 90 × 40 × 30 mm. It was embedded with inlet and outlet pipes having diameters of 12.7 mm. The inlet and outlet pipes circulated the coolant to and from the re-circulating bath. Fig. 4(b) shows the shapes of heat pipes mounted on the top side of the aluminum plate. Note that the aluminum plate was composed of two plates mounted side by side to form one plate. The sample of a single aluminum plate is shown in Fig. 4(c). The heat pipes shown in Fig. 4(d) were of two types, L-shaped and I-shaped. A side of L-shaped pipe with a length of 60 mm and a width of 7.5 mm, operated as a condenser, whereas another side with the length of 124 mm operated as an evaporator. On the condenser side, the heat pipe was mounted on the copper holder. The I-shaped heat pipe, with a length of 124 mm, worked as an evaporator, with 15 mm working as a condenser, as shown in Fig. 4(e). The evaporator absorbed heat from the aluminum plate's surface and the condenser transferred it to the copper holder. The copper holder contained water as cooling water and transferred the heat to the re-circulating bath. There were 8 heat pipes on the top and 8 heat pipes underneath. All heat pipes were flattened to enhance the thermal contact.

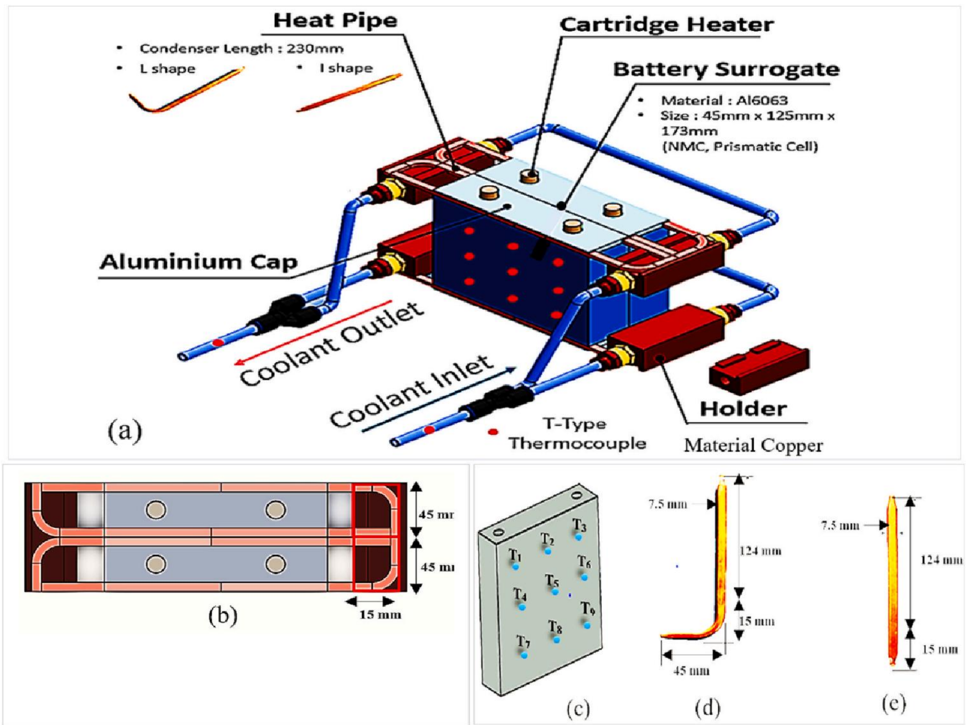

Fig. 4. (a) Test section (b) Arrangement of the heat pipe (c) Location of thermocouples on the aluminium plate (d) L-shaped heat pipe (e) I-shaped heat pipe.

II. CONCLUSION

The collective body of research underscores the critical importance of Battery Thermal Management Systems (BTMS) and Phase Change Materials (PCM)-based solutions for electric vehicle battery packs. These studies collectively reveal several key themes and advancements in the field. Researchers are actively working to improve the thermal properties of PCM materials, such as thermal conductivity and latent heat. These advancements are crucial for achieving efficient and uniform temperature distribution within battery packs, ensuring optimal performance and longevity. The studies showcase a wide range of innovative cooling methods, including channeled liquid cooling, heat pipes, wet cooling, and smart thermal management systems. These approaches offer promising solutions to address the complex thermal management challenges associated with electric vehicle batteries. Hybrid BTMS, integrating multiple cooling techniques and advanced materials like graphene, nanosilica, and copper foam, are emerging as effective solutions. These hybrid systems are designed to tackle the unique thermal requirements of battery packs, particularly under extreme conditions, and are poised to enhance both efficiency and safety. Battery reliability is a paramount concern, and research is focused on developing multi-physics models and redundancy strategies to ensure the robustness of lithium-ion battery packs. These strategies are essential to address complex thermal effects and maintain consistent performance. The field of battery thermal management is continually evolving, emphasizing the need for ongoing research and development. Researchers are exploring various factors, including convection, cost, weight, and environmental conditions, to optimize thermal management systems for electric and hybrid vehicles. These studies collectively highlight the critical role of thermal management in electric vehicle battery packs. They demonstrate a commitment to enhancing battery performance, safety, and durability through innovative PCM-based solutions, advanced cooling techniques, and reliability-driven approaches. As electric vehicles become increasingly prevalent, these advancements will be pivotal in ensuring the continued success and widespread adoption of electric and hybrid vehicles.

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