Thermal Management System Of Cooling Technology For Battery: A Review

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ABSTRACT

Electric vehicles (EVs) have become a popular mode of transportation due to their low cost, speed, and energy-efficient battery technology. Among the components of a vehicle, the battery thermal management system (BTMS) is critical in maintaining appropriate battery temperature levels during charging and discharge. Researchers are working on techniques to keep batteries within the temperature range while minimizing temperature fluctuations. Effective cooling solutions can increase battery efficiency, maintain safety, and extend the life of EVs. This review looks at BTMS technologies such as forced airflow liquid cooling techniques (direct and indirect) and heat pipe cooling systems. While air-cooled BTMS systems are simple and reliable, they may be limited in handling high-capacity batteries due to the heat capacity and efficiency of air as a cooling medium. For charging/discharging scenarios, forced air cooled BTMS is used, in which airflow is channelled through channels within the battery packs to cool them. Liquid-cooled Battery Thermal Management Systems (BTMS) are gaining popularity as a cooling solution. To avoid leaks, the sealing cover must be carefully considered throughout the design phase. Incorporating metal plates into the channel configuration can significantly improve cooling effectiveness, but the total weight of the system remains a major concern. Because of their heat conductivity, metals, nanofluids, and boiling liquids are considered excellent solutions for battery cooling. The development of cooling systems that incorporate fins, nanofluids, phase change materials (PCM), and microchannels is predicted to improve battery performance during rapid charging and discharging. The emphasis should be on producing a cost-effective design.

Keywords: *Battery thermal management system; Air-cooling; Liquid cooling; Thermal performance; Temperature effects; phase change material (PCM); Nanofluids; Electric vehicles (EVs).*

INTRODUCTION

The global need for energy sources is increasing as people's living standards and economies improve. This might result in an energy crisis and increased environmental pollution because a big percentage of our energy originates from fast diminishing fuels such as oil, gas, and coal. Recent research indicates that this trend is alarming [1] According to research, oil consumption has increased by 1.9 million barrels per day, with the transportation industry accounting for two-thirds of that expansion. Electric vehicles (EVs) have been developed as a method to combat the use of fossil fuels while mitigating the negative environmental effects of vehicular activities, such as local pollution, ground level ozone generation, and climate change [2]. As a result, it is critical to stabilize energy output by storing it in energy forms, which can be accomplished with the use of battery systems. Batteries store energy in a chemical form, allowing it to be converted into multiple forms as needed for various uses while minimizing environmental impact. As a result, many countries are moving away from internal combustion engine vehicles and toward vehicles in the automotive sector. Experts believe that electric vehicles will account for 15% to 30% of all automobiles within the next five to fifteen years [3–5]. Lithium ion batteries are widely used in industries such as telecommunications, transportation, automobiles, and aircraft. Among the energy storage solutions available, lithium ion stands out due to its high energy capacity, power density, voltage, cycle life, and low self-discharge rate. As a result, these batteries have piqued the interest of both the electrical and electronic industries. Large capacity lithium ion batteries are used to meet power demands [6]. However, the existence of reactive materials and flammable electrolytes continues to offer problems, including thermal instability, high prices, safety concerns, and electronic waste. Manufacturers prioritize safety, which can be enhanced through methods such as safety mechanisms that incorporate positive temperature coefficient elements,

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adding non-flammable substances to the electrolyte solution, implementing overcharge protection measures, including antioxidant additives [7–9].

LITERATURE REVIEW

For years, researchers have focused on the design and development of Li ion battery packs. Most review studies have focused on phase change materials (PCM)-based Battery Thermal Management Systems (BTMS), investigating the thermo characteristics of PCM and the application of additives to increase heat transport and thermal performance of battery packs. In addition, several BTMS studies have mostly examined cooling methods, with a focus on future cooling technologies for rapid charging. There is a paucity of debate of new battery cooling technologies such as natural and forced air cooling, direct and indirect liquid cooling, and heat pipe-based cooling. Few studies have looked at aspects such as installation practicality, sophisticated cooling strategies, and energy usage during the cooling cycle. Researchers also identified shortcomings in conventional battery cooling solutions. Future methods proposed for improved thermal performance include mist cooling, liquid cooling with solid particle suspensions, and the use of battery waste heat for diverse industrial uses. This document presents an overview of scholars' research in this topic.

Rao and Wang [10] studied progress of eco vehicles and advanced high energy batteries was examined, with a focus, on different BTMS approaches those involving phase change materials (PCMs). Nevertheless cooling systems based on PCMs face challenges such as conductivity, increased weight and issues, with leaks. Wang et al. [11] BTMS design aspects were discussed. Four cooling approaches for BTMS were outlined, including air cooling, liquid cooling, PCM, and heat pipe cooling strategies. An et al. [12] After evaluating and contrasting four cooling technologies, it was suggested that the choice of BMTS technology be based on the cooling requirements and intended uses. Liquid cooling was determined to be the best technique for battery applications with rapid charging/discharging circumstances and in high-temperature situations. Yu et al. [13] Using a drying method, a dense holey graphene structure aligned with mesopores was created, with Li4Ti5O12 particles reaching an optimal blend of porosity for rapid Lithium ion movement and high tap density. Our experiments showed that these high-power materials exhibited performance at rates while remaining stable over several cycles. In addition to upgrading materials, we may fine-tune physical properties such as size to build safer, higher-capacity electrodes. Sotomayor et al. [14] Using a powder extrusion molding technique, they created Li4Ti5O12 ceramic cathodes and LiFePO4 anodes. The improved electrode structure was demonstrated to boost energy density per unit weight while keeping production costs low. Kang et al. [15] battery cells were grouped into configurations to obtain the desired cooling results. A study found that the rectangular arrangement outperformed the layout with a lower peak temperature pattern without active cooling. Furthermore, it was discovered that in air-cooled Battery Thermal Management Systems (BTMS), heat transmission relied on conduction rather than thermal convection when the coolant inside satisfied the Rayleigh number requirements. Similar research was conducted by Zhang et al. [16] Batteries' temperature safety was researched, as well as cell designs and spacing. The circular configuration exhibited the best thermal performance, with the highest temperature, biggest temperature difference, and deviation. In contrast, while discharging at 1C, 2C, and 3C speeds, the linear arrangement performed better. It was proposed that the space between cells be at least 7 mm to enable proper cooling.

Qin et al. [17] graphic depicts how a battery operates in forced air cooling mode in a PCM-based thermal management system. It shows performance by maintaining a temperature of 16°C even at high charge/discharge current rates. Huang et al. [18] It was discovered that adding a heat pipe can greatly reduce the buildup of heat in PCM, resulting in a 9% decrease in temperature and a 14% improvement in temperature uniformity when compared to a PCM-based system at 5°C .Numerical and experimental investigations were conducted by Zufar et al. [19] Results were obtained by comparing the performance of OHP charged with Al_2O_3 CuO hybrid nanofluid, SiO_2 CuO hybrid nanofluid, and water. The start-up time of OHP with hybrid nanofluids did not increase with filling ratio due to their ability to absorb heat quickly in comparison to water. Furthermore, using nanofluids as working fluids resulted in increased evaporator temperature and thermal resistance in the OHP system. The introduction of nanomaterials increased OHP performance by lowering evaporator temperature, start-up time/power, temperature difference between evaporator and condenser, and thermal resistance. While there have been advances in improving the performance of nanofluid-based OHP systems, there is little study on their applications, particularly in electric car battery management, leaving much to be investigated.

Mengyao Lu et al. [20] studied battery thermal management systems (BTMS), including air cooling, liquid cooling, and refrigerant direct cooling in BTMS, as well as phase change material-based heat pipe-based and thermoelectric element-based systems in modern BTMS. The goal is to reduce the impact of temperature on battery packs and investigate potential solutions for future BTMS development. Research emphasis and progress objectively examine their strengths and cons, considering practical installation feasibility and economic benefits. suggest appropriate solutions based on current working conditions, forecast future development patterns, and evaluate classic and modern BTMS systems for differences and potential improvements. This analysis intends to guide the creation of optimal BYMS systems that keep batteries within ideal temperature ranges, assure proper operation, improve battery efficiency conversion rates, and provide significant insights for future BTMS research endeavors. Mahesh Suresh et al.[21] the study investigated the cooling effectiveness of Li ion batteries and battery packs in cars equipped with dielectric fluid immersion cooling (DFIC) technology. Experiments showed that a Li ion pouch cell submerged in flowing fluid with tab cooling had cooling performance, lowering the maximum temperature at the positive tab by 46.8% compared to natural convection at a 3C discharge rate. Using a Multi Scale Multi Domain (MSMD) approach and the Newman, Tiedemann, Gu, and Kim (NTGK) model, a mathematical model including thermal aspects was built for the pouch cell immersed in fluid with tab cooling. The numerical projections were within a percentage point of the actual data. During a 5C discharge with an 81.7 W pumping power, the 50 V battery pack maintained a maximum temperature of less than 40°C. Implementing DFIC with tab cooling technology resulted in a 9.3% maximum temperature increase for the battery pack when compared to typical indirect cooling methods, demonstrating improved cooling effectiveness. In the event of abuse owing to a short circuit, the battery pack attained a high temperature of 341.7 °C, although thermal runaway was avoided except for the afflicted cell. The study found that employing DFIC can help cool the tabs, making it a dependable and practical approach for managing heat in dense and large capacity Li ion batteries used in automobiles.

Zhicheng Zhou et al.[22] studied about the heat produced by electric vehicle (EV) batteries during rapid charging and discharging, a novel hybrid heat pipe was developed, combining a copper flat plate evaporator with channels and a capillary copper tube condenser. This arrangement uses an ethanol solution of carbon nanotubes (CNTs), also known as CNT nanofluids, with a 35% volumetric filling ratio. The water-ethanol mixture has a volume ratio of 1:1, and the CNT mass concentration ranges from 0.05 to 0.5 wt%. The experimental results showed that the vertical OHP using CNT nanofluids outperformed an ethanol-water mixture in terms of start-up and heat transmission. With a CNT concentration of 0.2 wt%, the average evaporator temperature and thermal resistance of the OHP reduced to 43.1 ◦C and 0.066 ◦C/W, respectively, with a power input of 56 W, compared to 9.8 ◦C and 0.278 ◦C/W for the ethanol-water mixture. This arrangement allows for an average battery pack temperature below 45°C and a maximum temperature variation of 1°C. The hybrid OHP including water-ethanol mixture based CNT nanofluids offers a method for cooling EV batteries. Rajib and Chanwoo [23] approaches to regulating battery temperature in electric vehicles were investigated with the goal of addressing industry-wide issues. The first section goes into the perspective on battery-powered cars, the principles of Li ion batteries, and the threats they pose to battery safety. The following part discusses methods for modeling efficient battery thermal management, including the thermal fluidic network model, lumped capacitance model, spatial resolution lumped capacitance model, equivalent circuit model, impedance-based model, and data-driven model. Following that, an overview of cutting-edge technologies is provided, including air-based liquid-based PCM-based BTM techniques, as well as heat pipe and module-based solutions. Yulong et al.[24] Four distinct designs, design A, design B, design C, and design D, were investigated for battery management using liquid-cooled plates and microchannels. These designs were proposed for a 35 volt battery pack made up of 12 $LiFePO_4$ pouch battery cells connected in series. A three-dimensional model was developed to quantitatively assess electrical, thermal, and fluid dynamics features. The cooling effectiveness of these designs was assessed using discharge rate, contact resistance, and responsiveness to short circuits. In design D, cooling plates are placed in front of each battery cell. At discharge rates of 0.5C, 1.0C, and 2.0C, design D provided the best cooling performance while using the least amount of electricity of the four designs. The highest temperature recorded for design D was 30°C, with a temperature difference of more than 5°C. Although there were differences in lowering contact resistance for cold plate configurations between the designs evaluated, the overall impact was negligible. In situations involving circuits under harsh conditions in design D, raising the mass flow rate resulted in lowering the maximum temperature by 27.5% from 76.6°C to 55.5°C and reducing the temperature differential by 23.4% from 35.0°C to 26.8°C. Choosing the volume of coolant flow can assist keep the temperature and temperature differential within acceptable ranges for battery pack design D. Increasing the flow rate can boost cooling efficiency. However, for a short circuit, temperatures and temperature differential for the three designs exceeded 90°C and 40°C, respectively. In these circumstances, raising the flow rate only slightly improves performance.

Haowen Wu [25] a simulation model with a cooling structure was investigated. In the cooling circuit for the battery cells, the evaporator exchanges heat directly with them. The study examined the performance of models employing R134a and eco R1234yf without modifying the model structure. The findings show that in temperature settings, the BTMS efficiently controls battery temperature rise to maintain it below 305 K. The difference between the maximum temperature of the battery pack (Tmax) and the energy consumption of the BTMS employing both refrigerants is 2 K and 2.3%. In extreme temperature circumstances, the BTMS can decrease cell temperatures to below 313 K in 66 seconds with a 3.2% power consumption difference. Wiriyasart et al.[26] in this study, an analysis method was employed to investigate how temperature and pressure change as nanofluids move through the micro channel of an EV battery cooling system. The EV batteries in question consist of 444 lithium ion cells (18650 type). It was revealed that temperature changes are strongly impacted by parameters such as coolant flow direction, flow rate, and coolant type. Model II demonstrated cooling performance by using nanofluids as a coolant, resulting in a 28.65% decrease in temperature over Model I, which relies on cooling techniques. However, this improvement is coupled with a decrease in pressure. Furthermore, using nanofluids as a coolant provides more cooling capabilities than using water as one. The findings of this study could potentially improve the thermal control system of electric vehicle batteries across a temperature range.

Mehrdad et al.[27] a new battery thermal management system was created, which included a metal foam paraffin PCM composite, nanofluid cooling, and a heat sink, all influenced by a field. A battery surrogate was utilized to simulate heat generation in the battery, with the goal of preventing runaway and achieving optimal performance. The effects of circumstances on the paraffin wax melting process and the maximum battery temperature were investigated. Additionally, the temperature uniformity of the battery was evaluated with and without medium. At Re = 1250, the best case scenario reduced battery temperature by 7.5 degrees Celsius and enhanced system runtime by 179% when compared to the standard setup. Similarly, when the Reynolds number reached 890, battery cooling increased by 151%. Furthermore, the temperature change in the battery thermal management system averaged less than 4 degrees Celsius. Experimental findings showed that this hybrid system successfully cools the heat generated by the battery and distributes it into its surroundings. Lien et al.[28] designed a cooling system for a lithium ion battery used in electronics. Lithium ion batteries, like other energy sources, can overheat. The purpose was to develop a cooling system for space equipment capable of operating in zero gravity. This equipment serves as a battery and signal booster for spacesuits. It required to cool the batteries without relying on air to remove heat while being lightweight and trustworthy. The idea incorporates carbon nanotubes suspended in water to create a fluid environment. To address the runaway problem with lithium ion batteries, the design includes a failsafe mechanism that turns off the system when the batteries hit a certain temperature threshold. This cooling device uses nano fluids and provides a lightweight option for battery cooling. Fatih et al.[29] a new approach for optimizing the cooling system of lithium-ion battery packs involves inserting a cylinder within the cooling channel, as well as shaped nanoparticles in the base fluid, which acts as the cooling agent. The study assesses performance improvements in a 20 Ah battery utilizing a nanofluid composed of water and boehmite alumina (AlOOH) containing nanoparticles in cylinder, brick, and blade shapes at a solid volume fraction. When the Reynolds number of the cooling agents is increased, both successfully lower peak temperatures and distribute heat uniformly across the battery. This is demonstrated by comparing their relative levels of effectiveness. When compared to a flat channel configuration, adding a cylinder to the tiny channel results in a 2°C temperature drop at Re = 600. A 2% volume fraction of boehmite alumina nanofluid lowers the temperature by 5.1% at Re = 200. Cylinder-shaped nanoparticles raise temperature by 4.93% and 7.32%, respectively, when compared to blade-shaped and brick-shaped particles, according to a shape impact analysis. A cooling system is therefore developed to keep the temperature of the battery packs stable by using a nanofluid containing nanoparticles as a cooling agent in a small channel within a battery thermal management system.

F M Nasir et al.[30] a study was carried out to investigate the usage of Al_2O_3 nanofluid-filled heat pipes to regulate the temperature of lithium ion batteries in electric vehicles (EVs). The heat pipe thermal management system (HPTMS) was portrayed as a body with a high equivalent thermal conductivity. This conductivity was calculated using a thermal resistance network model. The effect of heat inputs and nanoparticle concentrations on HPTMS performance was examined. Simulation results were compared to data, which revealed consistent outcomes. Using 1.5% Al_2O_3 in the heat pipes was found to reduce battery surface temperature and overall thermal resistance by 4.44oC (7.28%) and 15%, respectively. M. Hajialibabaei and M.Z. Saghir[31] study was about investigated layouts and approaches for increasing heat and total thermal efficiency in wavy microchannel heat sinks. Apart from using nanofluids, upgraded designs improve heat transfer efficiency by adding flow. Furthermore, this paper investigates the usage of microchannels as a cooling strategy in the management of lithium ion batteries. This study addresses current challenges. Outlines future study directions. N. Ahmed et al.[32] researchers investigated the characteristics and heat transfer efficiency of a nanofluid composed of deionized water with and without sodium dodecyl sulfate (SDS) surfactants. They used a two-step approach to create three different concentrations of the nanofluid. The tests were divided into dynamic phases. They investigated the characteristics of the nanofluids as well as the heat transfer coefficient using an instrument fashioned after a real heat exchanger for a lithium ion polymer battery compartment. The effect of flow rate and surfactants on heat transfer efficiency in nanofluids was investigated at concentrations of 0.08%, 0.16%, and 0.40%. The results showed that heat transfer efficiency increased significantly with flow rates ranging from 0.5 L/min to 1.2 L/min in the presence of surfactants. The nanofluid comprising 0.40% CuO/deionized water with SDS surfactant demonstrated excellent heat transfer. Hamidreza et al.[33] Investigated the concept of a thermal management system (TMS) for vehicles (EVs) that combines air cooling and heat pipe technologies. Developed mathematical and thermal models to predict the performance of a 24 cell battery module. Investigated thermal management techniques, natural air cooling, and forced air cooling TMS, comparing their efficacy. Suggested enhancements include cell spacing, air speed, ambient temperature changes, and the incorporation of a heat pipe with copper sheets. COMSOL Multiphysics software was used to solve the models using fluid dynamics (CFD) analysis. Validated simulation results against real-world data confirm the efficacy of the suggested cooling technique with HPCS in improving TMS efficiency and providing insights for design improvements in setups. The results revealed that using forced air cooling, heat pipe technology, and HPCS may dramatically lower module temperatures to 42.4 °C, 37.5 °C, and 37.1 °C, respectively, compared to natural air cooling by up to 34.5%, 42.1%, and 42.7%. Furthermore, these approaches resulted in temperature uniformity increases in the battery module by approximately 39.2%, 66.5%, and 73.4% for forced air cooling, heat pipe technology, and HPCS. Pradeep et al.[34] the study discusses cooling technologies used to manage the temperature of battery packs. It covers air-based, liquid-based, and phase change material (PCM) cooling technologies. In addition, it investigates battery pack layouts and different heat generation methods. The study also investigates the use of nanomaterials to overcome challenges in battery packs. It highlights the use of nanomaterials to improve the conductivity of coolants (both PCM and liquid coolant) in order to keep batteries operating at their optimal temperatures.

Yiwei et al.[35] based on constructal theory, researchers developed a new cooling system with double-layered dendritic channels. This system contains heat transfer channels. Collecting channels to balance pressure loss, surface temperature variance, and maximum temperature while managing cooling liquid volume. It used Latin hypercube sampling to get values for cooling plate design features such as branching levels, length factor, height to width ratio, and channel thickness ratio. Then, using a Radial Basis Function (RBF) model, we demonstrated how these design aspects affect system performance. The study improved the system's efficiency by using the NSGA II technique for multi-objective optimization design. Through simulations and comparisons with channel designs such as serpentine and parallel layouts, my optimized design demonstrated significant improvements, lowering the maximum temperature from 52.59°C to 39.3°C, the standard deviation of surface temperature from 5.31°C to 1.96°C, and the pressure drop from 518.6 Pa to 136.5 Pa. The findings may aid in improving the cooling system to function at temperatures while reducing pump power consumption. P.S.N. Masthan Vali and G. Murali [36] The researchers conducted a study to evaluate the performance of a battery pack using various cooling technologies. Three models were created in SolidWorks 2016 to determine the cooling method. In addition, three battery management (BTM) alternatives were selected, investigated, and simulated in Ansys Fluent 19.2 for thermal modeling. The results showed that geometry 2 with ethynyl glycol had better temperature dispersion and a lower maximum temperature than other cooling methods. Furthermore, using channel cooling based on BTMs resulted in temperature distribution, with the highest temperature regulated at 306.66 K and the minimum temperature at 293.20 K. Khaled et al.[37] after thoroughly examining a variety of thermal control methods that cater to both low operating temperatures, including cooling and heating systems, a total of 18 cooling techniques and 64 heating methods were extensively detailed and evaluated based on factors such as complexity, effectiveness, heating or cooling speed suitability for applications, and the specific types and sizes of batteries they are compatible with. The findings serve as a platform for future research endeavors and make recommendations. Husam et al.[38] the temperature of LiB cells is regulated using an innovative cooling system with a Reynolds number ranging from 15,000 to 30,000. The Finite Volume Method (FVM) is used to solve continuity, momentum, and energy equations. ANSYS Fluent, a computational fluid dynamics software, is used to study the flow and temperature fields of 52 LiB cells and evaluate the thermal management system. The arrangement of batteries causes flow patterns and temperature distributions throughout both lower regions of the battery pack. The study investigates the effects of adding SiO_2 to a fluid (water). The findings show that a SiO_2 nanofluid with a 5% volume fraction achieves the temperatures at all Reynolds numbers tested. The new cooling strategy improves cooling performance with SiO_2 concentrations, indicating a 5 vol% concentration for greater diffusion due to higher effective thermal conductivity. Increasing Reynolds number increases flow turbulence, which greatly improves heat transfer efficiency. The results reveal that increasing Re from 15,000 to 22,500 and then to 30,000 causes Nu values to increase by 32% and 65%, respectively.

Liyun et al.[39] a study was done to improve the effectiveness of cooling plates for lithium battery modules used in distributed energy storage systems. The classic serpentine form was changed by adding channels and grooves to produce three different cold plates for the battery module. The cold plate with both grooves and secondary channels had the best balance of performance. Despite the drop in efficiency, pump power consumption was reduced by 92.6%, and the cooling efficiency coefficient improved greatly when compared to the initial design. The cooling targets for the battery pack were set to a temperature (Tmax) below 40°C and an average temperature difference (ΔTavg) less than 3 K. To enhance the cold plate performance, an examination of structural and hydrodynamic parameters' impact on performance indicators was performed, as well as a sensitivity analysis to identify important design elements influencing operational efficacy. The studies demonstrated that differing design parameters could influence eddy currents, hence affecting cooling performance. Notably, velocity (v) and diameter (D) influenced cold plate performance, followed by depth. The number of channels (n) and groove aspect ratio (a) had little effect on cooling efficiency.

Ding et al.[40] the study investigated how the number of channels affects heat dissipation on a liquid cooling panel (LCP). A single channel LCP was discovered to be sufficient for heat dissipation. Following that, an orthogonal test was carried out to optimize the channel width, height, and coolant velocity using the single channel LCP. Following a factor study, the BTMS was upgraded. The heat dissipation performance of the modified BTMS was evaluated across scenarios. An extra LCP was added above the battery module to improve temperature uniformity even further. The improved BTMS can maintain a temperature of 27.7 ◦C and a temperature differential of 1.9 ◦C.

Mahdi and Mohammad [41] a novel cooling system incorporating nanofluids for direct coolant methods was quantitatively investigated. Al_2O_3 water nanofluid and HFE 7100 were chosen as mediums for direct cooling systems, respectively. The study investigated the effects of C rates (3C, 5C, and 7C), inflow velocities (0.2 m/s, 0.25 m/s, and 0.3 m/s), geometric alterations (such as separator plates and corner curvatures), and actual driving cycles on the performance of 21700 cylindrical batteries. Furthermore, a comparison of 21700 batteries with the newer 4680 type LIBs was performed to better understand how different energy-related parameters influence temperature behavior in LIB packs. The numerical results demonstrated that employing a 4%VF Alumina nanofluid with a flow rate of 0.3 m/s resulted in better performance than water with a flow rate of 0.2 m/s as coolants for indirect cooling channels. Additionally, integrating curved cooling channels and integrated separator plates within the channels reduced temperatures and temperature non-uniformity in the LIB bundle by 0.61°C and 0.16°C, respectively. Finally, the study examined two types of lithium ion batteries (21700 and 4680) based on the number of cells and the cooling technique. The data indicate that not only does using 4680 format batteries provide adequate energy, but their thermal efficiency also beats that of 21700 format batteries. Ali and, Manosh [42] study to measure its cooling performance, a model was developed using a cylindrical lithium ion cell with longitudinal and spiral fins on its surface. The effect of parameters such as the number, rotation, thickness, length, and position of the fins was studied at rates. The findings show that the inclusion of fins lowers the cell temperature at lower Reynolds numbers compared to a scenario without fins. However, adding more than three fins can obstruct airflow around the cell, resulting in an increase in battery temperature despite increasing heat transfer area. The orientation of the fin also influences heat transfer between the cell and air cooling; for example, comparing length longitudinal fins results in a 1.5°C temperature rise. Nonetheless, putting fins at various points on the battery surface (top, middle, and bottom) provides little cooling effects. Furthermore, spiral fins were observed to reduce cell temperature by 3.2% when compared to fins, resulting in a 65.6% reduction in material utilization.

Rekabra et al.[43] the environmentally beneficial heat transfer coolant mediums for BTMS have been reviewed, with reference to existing literature. This article discusses coolant media such as air, water, phase change materials (PCM), and hybrid coolants, as well as how to optimize them. It also looks at approaches and materials that may improve the thermal performance of battery packs while simultaneously improving safety and reducing weight, volume, cost, toxicity, and power consumption as compared to traditional heat transfer coolant mediums. The study discovered promising cooling approaches such as cooling, mist cooling, spray cooling, and the utilization of nanofluids. In terms of impact, availability, and non-toxicity, jute emerges as a candidate for inclusion into BTMS systems. This research provides insights into the advancements of innovative cooling mediums aimed at enhancing the BTMS technology. Md Mahmud et al.[44] a review of PCM was conducted for battery thermal management systems. The review delves in. Compares temperature management options for Li ion batteries, highlighting their benefits, limitations, and cost effectiveness. Heating and cooling technologies are discussed. Furthermore, the research investigates developments in the area of improving the thermal management of Li ion batteries in electric vehicles. Verma et al. [45] A study was conducted using a PCM-based system to adjust the temperature of an electric vehicle battery, specifically at 294 K and 323 K. Capric Acid (CA) served as the PCM, with a melting temperature of 302-305 K and a latent heat of 152.7 kJ/kg. The results showed that putting a 3 mm PCM layer to the battery surface helped preserve the battery temperature within 7 degrees of 294 K. Under the increased ambient temperature of 323 K, the PCM could not keep the battery temperature within acceptable operating limits. As a result, it was suggested that an active cooling system based on liquid cooling was required. Several recent research articles have focused on enhancing the performance of battery thermal management systems (BTMS). For example, Zhao and colleagues [46] concentrated on optimizing BTMSs by liquid cooling, whereas Weragoda et al. [47] investigated strategies for improving performance utilizing heat pipes. Ghaeminezhad et al. [48] conducted a review article from a control standpoint, categorizing solutions for Li ion battery packs into feedback-based and non-feedback-based approaches. In another study, Li et al. [49] investigated the use of machine learning approaches to study and optimize BTMSs. The effort to reduce the environmental impact of transportation has fueled breakthroughs in electric mobility technologies. Electric vehicle power sources with voltage, specific energy, portability, low self-discharge rates, temperature tolerance, and long operating life. As explained by

Goutam et al. [51]. Andwari et al. [52] highlight vibration considerations. The performance of Battery Thermal Management Systems is critical in maintaining battery temperatures within electric vehicle systems to avoid damage or danger. Several review papers report the main technology challenges that need to be resolved. Hafiz [53] The practical ramifications were thoroughly investigated. To begin, design issues were analyzed to determine the importance of safety and market potential. The stability was then evaluated in various situations such as runaway, adverse weather conditions, and aging effects. The impact of zero temperatures on charging and discharging speeds, circuit failures, temperature abnormalities, and physical distortions was also considered. Furthermore, the authors' theoretical and practical models for battery temperature management strategies were compared to establish their efficacy in hybrid and electric vehicles. The primary goal of this assessment is to identify issues and substantial gaps in thermal management technologies as envisioned by researchers against the real ways being used by EV manufacturers.

Jiajun et al[54] the researchers investigated the loss coefficients of contracting and diffusing channels, created a model dubbed FRN for predicting velocity in air-cooled systems with changing cross sections, and validated it with fluid dynamics. Using this FRN model, they calculated the width distribution of the diverging duct dependent on flow rate. The diverging deflector's shape was optimized by altering the flow rate distribution and using the model. The results demonstrated a reduction in battery cell temperature differences of over 84% after optimization, with a temperature drop of more than 3.8 K. Furthermore, their optimized system surpassed those used in earlier trials. Experiments were also done to confirm the efficacy of their FRN-based optimization strategy.

Seham and Martin [55] a novel way to regulating heat in a battery module was introduced, which used both air and fluid as coolants to extract heat from a phase transition substance (paraffin). A distinctive cold plate design was created. Located among the cells in a grid pattern. This cold plate has a body that increases the thermal efficiency of the battery module. Experimental experiments were conducted to collect temperature and heat flux data for the battery module. Additionally, a numerical model was created. Validated with the findings. The numerical results closely matched the data within a +2% range. Furthermore, an examination into how nanoparticles can increase water conductivity was undertaken, which revealed that standard liquid cooling methods could not fully harness a 0.32 W/m K increase in conductivity. To improve air cooling, fins were installed in the air duct leading to the plate. However, this is impractical because the pressure drop from adding the fins increased by around 245%, while the battery module's peak temperature fell by only 0.6 K. In conclusion, when applied to a battery pack with a high discharge rate of 7 C, the calculations revealed that the temperature distribution across the pack was consistent at 1.14 K, with a peak temperature of 302.6 K being within the authorized operating range for temperature and uniformity.

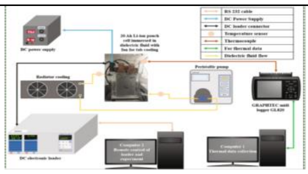
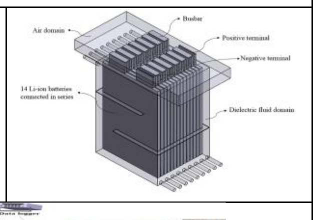
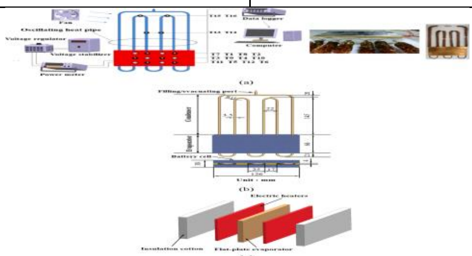
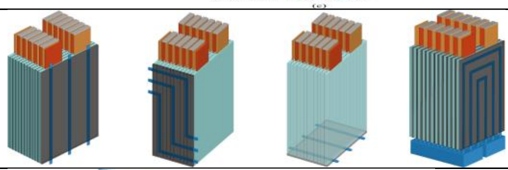
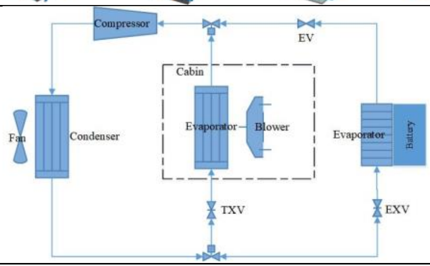
Shengshi et al.[56] investigate how to create an L-shaped heat pipe to properly manage the heat dissipation of batteries and their spatial layout within a battery module. We used the volume of method (VOF). Replicated the working fluid's phase change, flow, and heat transfer processes within the heat pipe. Furthermore, Researchers created a CFD (computational fluid dynamics) model for an 8S1P ternary lithium ion battery module using the NTGK approach. Study goal was to better understand the behavior of the 8S1P battery module at different discharge rates in order to improve thermal management efficiency with L-shaped heat pipes and air cooling. The study found that a battery module model accurately depicts temperature distribution across batteries and temperature variations. The evaporation condensation process within the heat pipe is in equilibrium, ensuring heat transfer via phase transition. By adjusting battery discharge rates from 1C to 3.5C and using forced air cooling with air from air conditioning, we successfully adjusted temperature levels and differences within the module for cooling effects. This study improves the precision of constructing and simulating BTM (battery management) coupled with heat pipes, providing insights into related investigations.

Luttfi et al.[57] a new sort of battery pack has been designed to keep the battery at a consistent temperature, assuring optimal performance. The design includes an airflow system to help maintain the temperature uniform. Initially, a three-dimensional model of the battery cell was created. Tested at room temperature. The results revealed that the temperature distribution was mostly higher, although only slightly, near the cell's core. Additionally, element analysis (FEA) revealed that heat flux across the surface was very consistent, with small fluctuations at the borders. To improve performance further, a network-based machine learning model (NN) was used. Tested to reliably forecast heat flux levels. The model outperformed FEA in terms of time efficiency and prediction accuracy, demonstrating the advantages of employing machine learning for assessments over traditional approaches. Piyapat et al.[58] the study examined how mixing liquid with cooling influences battery management. Several studies were carried out with different types of batteries, liquid flow rates, and battery temperatures using thermoelectric cooling. The experimental results contrasted air cooling (AC), water cooling (WC), and thermoelectric cooling (TEC) with varied water flow rates in the system. It was discovered that employing TEC with a water flow rate of 4.0 l/min was the best cooling method, lowering temperatures by 41.52 percent from the greatest discharge temperatures at rates of 1.0, 1.5, 2.0, 2.5, and 3.0

°C per minute. Furthermore, TEC with water flow rates of 1.0 and 2.0 l/min outperformed cooling solutions in terms of temperature reduction and energy usage while preserving battery temperature.

Mingyi et al.[59] after studying the PCM-based BTMS, it was discovered that carbon-based additives outperformed metal-based additives in terms of density and stability. Additionally, combining polymers and nanoparticles can improve stability and mechanical qualities. However, the flammability of PCM raises the risk of fire and thermal runaway in battery systems. This study focuses on improving PCM's flame retardant properties and their possible applications in BTMS to ensure the usage of LIBs and reduce runaway events. Addressing the difficulty of increasing heat dissipation efficiency and improving TR suppression capabilities in PCM-based BTMS remains a roadblock for progress in this field.

P. Zare et al.[60] Researchers investigated a battery thermal management system (BTMS) that used a phase change material (PCM) with fins to form PCM silos around the battery. This unique design tries to improve the conductivity of PCM. To investigate battery heat generation and PCM melting, the researchers used a lumped capacitance model and the enthalpy porosity technique. Several heat generation scenarios were simulated to evaluate the BTMS, with an emphasis on the impact of fin quantity on management, energy density, heat storage capacity, and PCM melt time. The results showed that the developed BTMS outperformed systems using natural air convection cooling or PCM cooling without fins. At 3C and 5C discharge rates, the BTMS with four fins lowered battery surface temperatures by 9.90 K and 17.45 K, respectively, when compared to a finless PCM system. At temperatures, the BTMS effectively maintained ideal battery surface temperatures while increasing energy density, heat storage capacity, fin efficiency, and total fin effectiveness as compared to systems with more fins. Notably, the suggested BTMS provided cooling across the cell surface—a critical component that is sometimes overlooked in studies on BTMS technology.

Below is a summary of some of the studies cited in this study				
Reference	**Year**	**Study**	**Working fluid**	**Geometry**
[21]	2021	Experimental and Numerical	dielectric fluid immersion cooling (DFIC)	 
[22]	2021	Experimental	Nanofluid	
[24]	2023	Numerical	Liquid	
[25]	2022	Experimental	R134a and R1234y	

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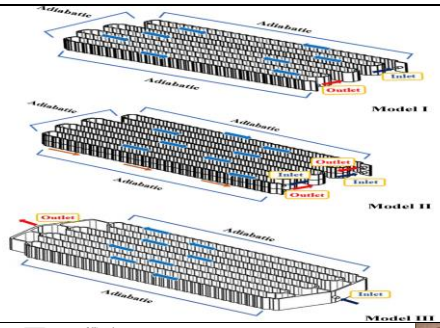
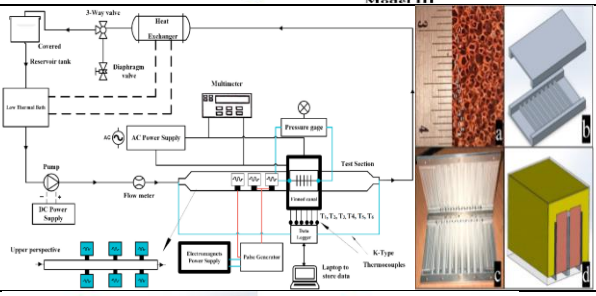
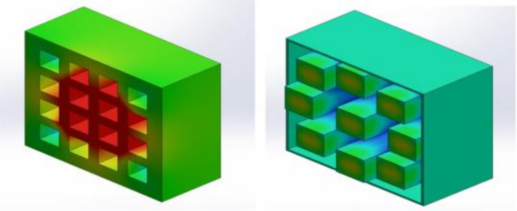
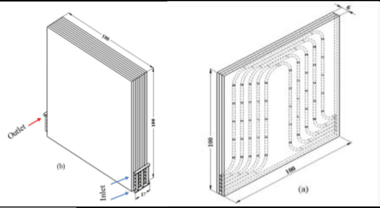
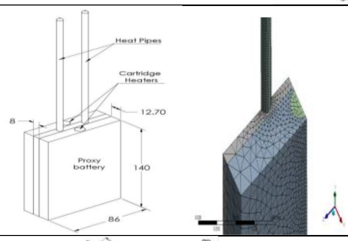
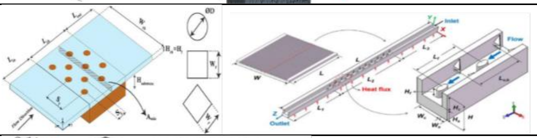
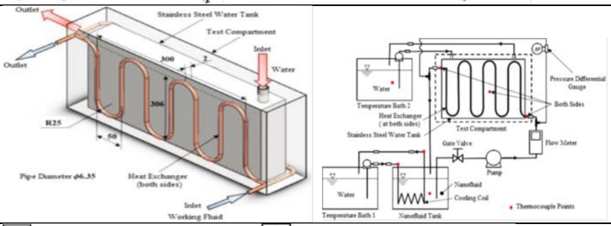
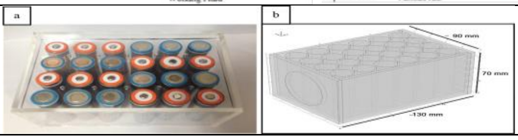
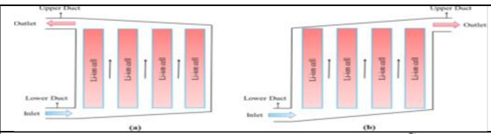
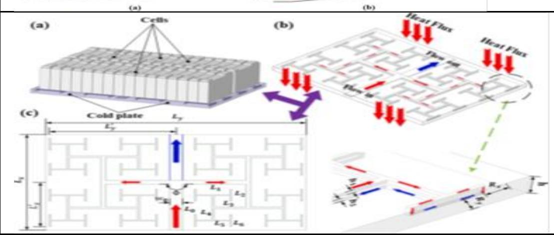
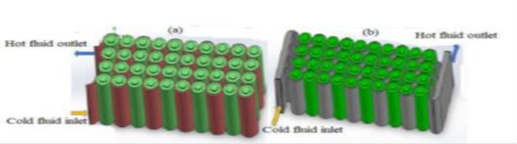
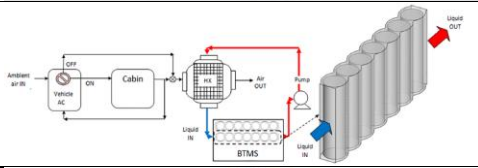
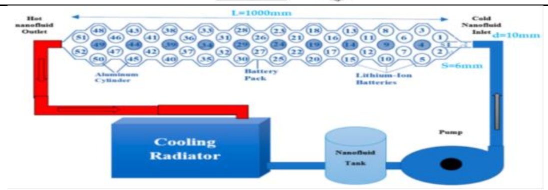
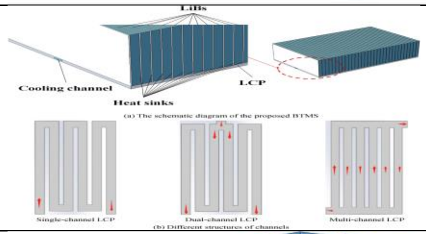
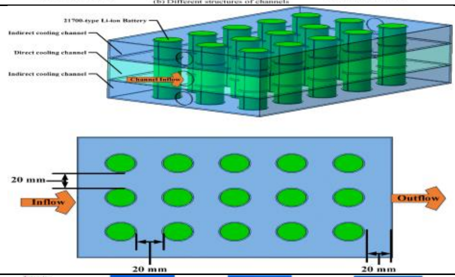
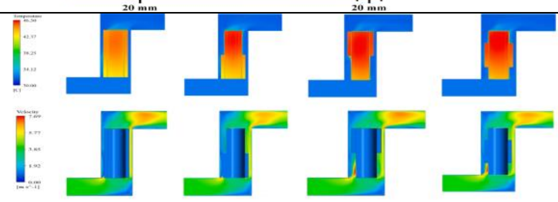
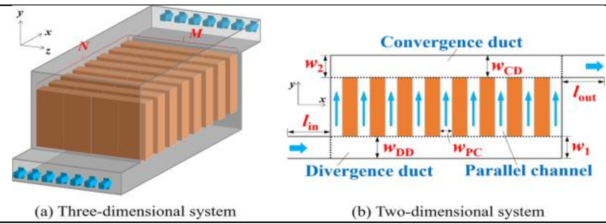
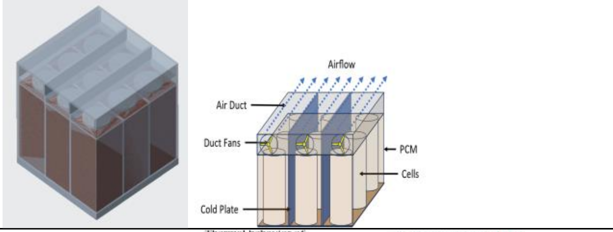
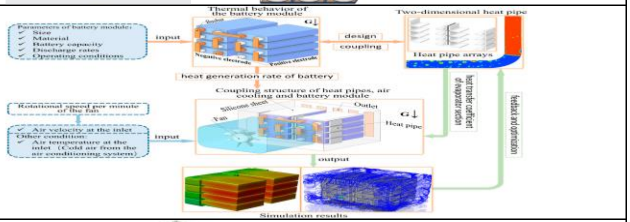
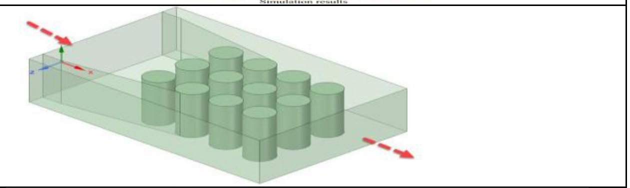
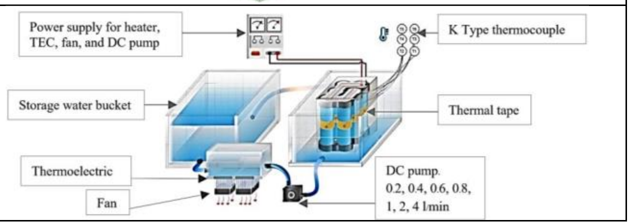
[26]	2020	Numerical	Nanofluid	
[27]	2021	Experimental	Nanofluid	
[28]	2017	Numerical	Nanofluid	
[29]	2023	Numerical	Nanofluid	
[30]	2019	Numerical	Nanofluid	
[31]	2022	Experimental and Numerical	Nanofluid	
[32]	2019	Experimental	Nanofluid	
[33]	2020	Experimental and Numerical	Air	

[34]	2020	Experimental and Numerical	Air	
[35]	2021	Numerical	Liquid	
[36]	2023	Numerical	Liquid	
[37]	2023	Experimental and Numerical	Nanofluid	
[38]	2023	Numerical	Nanofluid	
[40]	2024	Experimental and Numerical	Liquid	
[41]	2024	Numerical	Nanofluid	
[42]	2024	Numerical	Air	
[54]	2024	Experimental and Numerical	Air	

[55]	2024	Experimental and Numerical	Air and Fluid	
[56]	2024	Numerical	Air	
[57]	2024	Numerical	Air	
[58]	2024	Experimental	Water	

CONCLUSIONS

The current review examines research advancements in Battery Thermal Management Systems (BTMS), which includes air cooling, liquid cooling, and heat pipe-based cooling. While air-cooled BTMS have a design and offer safety and durability, their heat capacity and thermal efficiency limit their efficacy in thermal management systems. Forced air-cooled BTMS that makes use of airflow channels within battery packs to take advantage of particular heat capacity and ideal airflow conditions. Liquid cooled BTMS is a cooling system that necessitates careful selection of the sealing cover during the design process to avoid liquid leakage. Incorporating tiny channels can significantly increase cooling efficiency without the need for packing or complicated designs. Metal plates with channels can increase cooling efficiency. The system's weight is an important factor to consider during design. Furthermore, liquid metals, nanofluids, and boiling liquids have demonstrated advantages in liquid-cooled systems due to their thermal conductivity. Because of its superior thermal efficiency, versatility in shape, and compact design, the cooling system that employs heat pipe-based cooling advantages a wide range of thermal management applications. Furthermore, improving cooling via fins, nanofluids PCM, and microchannels can significantly improve battery performance during charging and discharging cycles. It is critical to focus on creating a system with cost effectiveness in mind. Even though battery cooling technologies have advanced over the years, it still takes time and effort from scientists, designers, and manufacturers to increase battery efficiency and heat dissipation in order to maximize electric vehicle performance.

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