IJCRT.ORG ISSN : 2320-2882

INTERNATIONAL JOURNAL OF CREATIVE RESEARCH THOUGHTS (IJCRT)
An International Open Access, Peer-reviewed, Refereed Journal

A Review Of The Role Of Phase Change Materials On The Thermal Management Of Li-Ion Batteries

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***Abstract**:* Fossil fuels are a rapidly diminishing energy source that heavily contributes to air pollution. The optimal way to eliminate all the complications caused by fossil fuel vehicles is to use an electric vehicle. The energy source for electric vehicles is a lithium-ion battery. Compared to other battery types now in use, lithium-ion batteries have smaller battery sizes and higher energy densities while maintaining the same storage capacity. A battery will experience thermal runaway and explode if the heat produced during charging and discharging conditions is not precisely controlled. Therefore, careful thermal management of Li-ion batteries is required to increase their lifespan as well as the lives of those who use them. Li-ion batteries' four main cooling and heating methods are air cooling/heating, liquid cooling/heating, phase change material (PCM)-based cooling/heating systems, and hybrid cooling techniques. Every strategy has merits and negative aspects of its own. The current paper critically examines the thermal management of batteries at low and high temperatures, which analyses various approaches to investigating the potential for employing PCM in BTMS. Furthermore, PCM utilization in hybrid thermal management systems is carefully examined. The current paper further expands the evaluations to the potential usage of inorganic composite PCM and Nano-emulsions for Li-ion battery thermal management in the future.

Index Terms **– Electric Vehicles, Batteries, Li-ion battery, Thermal Management, Phase Change Material.**

I. INTRODUCTION

The usage of fossil fuels is expanding globally as a result of population growth and economic development. This will increase the oil demand and contribute to air pollution and global warming. Electric vehicles are one of the finest solutions in this area because they have no exhaust emissions and will contribute to a new global energy economy. Electric vehicles' energy source is lithium-ion batteries. Despite having many advantages over other types of batteries, such as high specific capacity and voltage, no memory, excellent cycling performance, little self-discharge, and a wide operating temperature range, their operation has occasionally led to explosions and fire accidents because of overheating, overcharging, and thermal runaway. The process of charging and draining a battery generates heat. The capacity of a battery is affected by both high and low temperatures. Low temperatures reduce their ability to store energy and accept charges. However, a rise in operating temperature causes a decline in battery performance, a reduction in round-trip efficiency, a reduction in charge acceptance, a reduction in power and energy capability, a reduction in dependability, a reduction in cycle life, and ultimately a rise in cost. That is, the thermal behavior of the batteries and efficient battery thermal management systems (BTMS) in the battery system are relevant to the safety of electric vehicles (EVs).

To maintain the battery's ideal working temperature range (usually 25–40 °C) and reduce temperature variance within the battery, an efficient thermal management system is very necessary. To maximize the performance of Li-ion battery packs and modules and assure safe operation, numerous battery thermal management technologies have been developed. The techniques include hybrid techniques, PCM cooling and heating, liquid cooling and heating, and air cooling and heating. Each of these approaches has advantages and disadvantages and should be employed by the unique needs of the electric vehicle. Despite being less difficult, offering electrical safety, and being less expensive, air-cooling methods are ineffective because of their low heat transfer coefficients. The temperature can be moderately maintained using the forced convection method of cooling, but the cell temperature may not be kept at a safe level. Although water cooling is superior to air cooling, it is less safe, more expensive, and requires more frequent maintenance. Better temperature homogeneity is provided by boiling, although it is less safe to use.

Therefore, PCM cooling is the most often used method of BTMS due to its compactness and isothermal behavior during the charging and discharging processes. It also requires no additional energy or components to work. PCMs are divided into 3 main groups organic (paraffin, non-paraffin compounds such as fatty acids), inorganic (salt hydrates, metallics), and their eutectic mixtures. Organic PCMs are of two main subcategories: paraffin and non-paraffin. Numerous experimental findings demonstrate that PCMs have significant assembly-related stiffness, leakage issues, and low thermal conductivity. Due to their poor thermal conductivity, passive PCM systems are inefficient and prone to failure from repeated severe cycles that cause thermal runaway. However, a battery temperature management system with an active PCM is more effective.

The current review paper examines different ways to use PCM in Li-ion batteries under difficult operating circumstances. The use of composite PCMs (CPCMs), flame-retardant CPCMs, PCM battery modules with fins, inorganic CPCMS, active PCM methods employing nanofluids, nano-emulsions, delayed liquid cooling system, vibration's impact on PCM, cooling arrangement, etc. are all explored. For these systems to be employed in the future efficiently, further research must be done on the utilization of inorganic phase change materials, hydrate phase change materials, PCM capsules, and nanofluid emulsions.

II. DESCRIPTION OF REVIEWED WORKS

This paper reviewed twenty-five works related to the role of phase change materials used in the thermal management of Li-ion Batteries. The thermal management of batteries improves their life span which adds reliability to operation. The purpose of a thermal management system in a battery is to control the level of extreme temperature during the operation and to maintain the temperature difference below a designed safety level. PCM cooling is a more usual method to address this issue. The following sections describe various works related to the role of PCM in the thermal management of Li-Ion batteries. The separate review contents including future direction are included in the following subsections.

1. Li-ion batteries Thermal Management Systems

This paper (Landini, 2019) reveals the content of various types of thermal management systems. Out of the four strategies of Li-ion battery thermal cooling techniques such as air-cooling, liquid-cooling, boiling, and Phase Change Materials, Phase Change Materials (PCM) perform well as passive cooling due to their low-cost TMS.

According to research, 12 mm of PCM material can lower battery temperatures by up to 3^{o}C and temperature gradients between cells by up to 50%, respectively. The technology has many benefits, including cheap operating and maintenance costs, minimal parasitic power consumption (no moving fluid), high efficiency, design simplicity, and the ability to combine PCM with smaller active cooling systems. However, many of the batteries have to operate under extreme conditions, like high ambient temperature, and high discharge rates, PCM are not as good for heat recovery leading to possible thermal runaway. Although flow boiling is hard to operate and necessitates additional pumping, it helps to increase PCM efficiency in extreme environments. Therefore, to maintain maximum temperature and in-cell temperature gradients at a reasonable level, a combination of active PCM systems with liquid cooling and passive PCM is preferable. Due to PCM's many benefits over other traditional systems, combining multiple techniques will increase the effectiveness of current thermal management cooling strategies.

Numerous studies in this field have shown that while they are effective at managing heat, they have poor thermal conductivity. As a result, the potential heat transfer rate can be increased by incorporating high-conductivity materials, such as metal fins, beads, or powders, or by using porous media, such as carbon fibers or composites made of expanded graphite (EG), metal foams with porosity, or cascaded thermal energy systems (CTES) with five stages.

2. Thermal Management System Using Phase Change Material for Lithium-ion Battery

Since PCM can store a lot of heat in a short space without consuming any electricity, this research highlights the significance of a passive cooling system using PCM. This research, (Grimonia, 2021, November.) presents simulation-based results obtained using computational fluid dynamics. To experiment, they used PCM Capric Acid and PCM Hexaoxane in varying thicknesses of 3 mm, 6 mm, and 9 mm. Due to its higher melting temperature, density, specific heat, and thermal conductivity, hexacosane PCM with a 9 mm thickness performs best in terms of reducing heat up to 6.54°K. The simulation's outcome leads to the conclusion that when PCM thickness grows, battery temperature decreases as well because PCM volume and mass increase.

This suggests that it is a viable passive cooling system for Li-ion batteries.

3. A Comprehensive Review of Composite Phase Change Materials (CPCMs) for Thermal Management Applications, Including Manufacturing Processes, Performance, and Applications

This review, (Radouane, 2022) argues that enhanced PCMS can be produced through chemical alterations or the addition of useful additives to support the widespread implementation of PCM. Encapsulated PCMs, the use of a high heat conductivity additive, the insertion of a metal fin, and the embedding of metal foam are some potential methods for enhancing PCM characteristics. Metal foam is crucial in enhancing the thermal performance of PCM as a thermal energy booster.

The current emphasis of research is on the efficiency of PCM cooling and heat absorption at high temperatures. With the spread of new energy vehicles in colder areas, it is vital to further investigate heat storage by CPCMs at low temperatures

4. Optimization of the internal fin in a phase-change-material module for battery thermal management

The usage of fins with PCM to increase the lower thermal conductivity of passive PCM is the major topic of this study (Weng, 2020). Through studies with and without fins, the results are compared. The results show that longitudinal fins with ambient convection currents are better at dissipating heat at the bottom, and adding more fins does not increase this amount because they take up too much space. As a result, the amount of PCM will also decrease, which lowers the PCM's ability to store energy. To achieve a balance between energy storage capacity and energy dissipation capacity, the number of fins should be reduced.

The use of four longitudinal fins displays the highest efficiency for the 18650-battery module in the current work, resulting in a temperature drop from 36.9 to 34.2 °C in the rectangular finned module. As a result, rectangular fins are used in the top portion, while circular fins are used in the lower part to better conduct heat. The number of rectangular and circular fins is set at 4 and 2, respectively, for maximum performance while taking efficiency and the available space into consideration.

This research emphasizes the need to optimize a PCM-based finned module (different fin shapes and appropriate fin numbers) to achieve optimal cooling efficiency and minimal space use. This study sheds light on how internal fins in PCM fin modules for BTMS might be best designed.

These findings may not apply to all practical batteries that operate under challenging operating temperatures because they are based on a single cell with a specific PCM under specific conditions. These results require additional experimental simulation in several areas to be accurate.

5. Performance of a liquid cooling-based battery thermal management system with a composite phase change material

This article, (Zhao, 2020) merges research on a composite phase change material (CPCM) with a liquid cooling-based battery thermal management system (BTMS). For the CPCM, expanded graphite and copper foam served as the structural components. After investigating the experimental temperature behavior of a lithium-ion battery, a two-dimensional model was created. Because it is insufficient for continuous operation and under high current rates, the experimental findings show that using only CPCM (Composite Phase Change Material) is convenient for one charge/discharge condition.

According to research, EG-based CPCM cools more effectively than copper foam-based CPCM. The modeling results indicated that heat conduction played an important role in heat transfer between the CPCM and heat transfer fluid (HTF). That means CPCM alone will not provide effective cooling while the hybrid systems consisting of liquid cooling and CPCM are powerful at high-energy, high-power battery systems. By storing the generated heat and managing the battery temperature with powerful liquid cooling, CPCM minimizes the burden on the cooling pump, lowering the cost and volume of BTMS. By improving heat flow between the cells and the cooling tube, the CPCM controls the temperature of the battery.

The significance of hybrid cooling technology for BTMS is highlighted in this research.

6. Hybrid thermal management of a Li-ion battery module with phase change material and cooling water pipes: An experimental investigation

The thermal performance of several active, passive, naturally ventilated, and hybrid management systems is examined experimentally on a Li-ion module with high-capacity prismatic cells (Hekmat, 2020). The maximum temperature and the maximum temperature differential for each of the seven cases—two naturally ventilated, one passive, two active, and two hybrid systems—are used to evaluate the experimental results. With PCM or silicon oil, the maximum temperature and maximum temperature difference, which are dangerously high with air cooling, are greatly lowered. These hybrid systems can only be used in an EV if the water flow rate is optimized by the typical battery system's discharge rate.

The experimental findings show that the hybrid system outperforms other varieties of BTMS because it delivers a more uniform temperature distribution and requires less time for the cells to cool down than other systems.

7. Development of the inorganic composite phase change materials for passive thermal management of Li-ion batteries: material characterization

The performance characteristics of inorganic PCMs, which have not been acknowledged as a study field in BTMS, are the main emphasis of this paper (Galazutdinova, 2020). This paper describes the development of two inorganic CPCMs based on magnesium chloride hexahydrate and compares their performance as active BTCMS to organic PCM, paraffin wax for both mixes. To improve their thermal conductivity, all three PCMs were impregnated into the enlarged graphite matrix. All three PCMs were subjected to a thermal properties examination, density and viscosity assessments, soaking and compression testing, thermal expansion and conductivity evaluations, and micro-X-ray fluorescence analysis.

The study emphasizes the idea that both inorganic combinations are beneficial for Li-ion battery pack heat management. In comparison to organic PCMs, inorganic PCMs have low melting volume changes, are inexpensive, and are not flammable. The large volumetric latent heat storage capability of inorganic PCMs makes high-density storage possible. Additionally, they may have a thermal conductivity that is twice as high as organic PCM. Therefore, the creation and characterization of appropriate inorganic PCMs to be employed as a passive temperature management system in Li-ion batteries is the primary goal of this study. Three different expanded graphite matrices will be made utilizing paraffin wax, a magnesium chloride hexahydrate mixture, and a bischofite mixture (CPCM wax, CPCM$MgCl_2$, and CPCM bischofite) to study the CPCM performance. Following that, three battery packs made of CPCM wax, CPCM$MgCl_2$, and CPCM bischofite will be put together.

The test findings show that inorganic composite mixtures have thermal, physical, and mechanical qualities that are suitable for Li-ion battery pack heat management. Additionally, the performance of the bischofite/Mg $(NO_3)26H_2O$ mixture demonstrates favorable effects on both economic and environmental issues.

8. Evaluation of fin-intensified phase change material systems for thermal management of Li-ion battery modules

In this work (Fan, 2021), a metal fin-enhanced PCM system for BTMS is proposed. To validate the model, single-cell tests were first carried out. Later, using ANSYS Fluent Software analysis, the thermal behavior of a battery module was assessed in terms of the distribution of fins, their length, and the ambient temperature. It performs exceptionally well because the metal fins increase the heat exchange area and the system creates a multi-channel high thermal conduction network, which would boost the heat dissipation rate and operating time by 98.4% in comparison to the PCM system.

According to the test results, modifying the fin distribution led to more uniform thermal conduction networks, which increased the working duration by up to 15.2%. According to the studies, the length of fins from 7.5 mm to 13.5 mm contributes significantly to an additional 8.3% increase in working time.

The planned fin intensified systems' ability to function accurately even in high-temperature environments was the primary attraction. In comparison to the passive PCM system, the proposed system enhanced the working duration by 1.48, 1.49, and 1.81 times for air temperatures of 20, 30, and 40^{o} C, respectively.

This means that the fin-enhanced PCM systems behave better than the PCM systems.

9. Lithium-ion battery thermal management system with Al2O3/AgO/CuO nanofluids and phase change material

In this work (Kiani, 2020), pouch lithium-ion battery modules were chosen by the authors for investigation, and experiments were carried out using nanofluid-type thermal management systems for the batteries, pure water, and copper foam with paraffin wax as a phase transition material. The suggested system combines active and passive cooling techniques and includes embedded paraffine-metal foam composite, a heat sink, and nanofluid cooling that will assist both systems. The test results demonstrate that the presence of suspended particles in nanofluids improves the system's thermal conductivity, and adding nanofluids to base fluid would increase the convective heat transfer coefficient.

Alumina (Al_2O_3), copper oxide (CuO), and silver oxide (AgO) were the different oxide-nanofluid slurries chosen for the test, and AgO was the best option despite causing some pressure reduction in the working fluid flow. A suitable number of nanoparticles should be carefully selected to ensure system safety because the sedimentation of nanoparticles in the base fluid will decrease efficiency. When compared to battery thermal management systems based on pure water, the AgO/water nanofluid with volume concentration lowers the maximum temperature of the battery by around 4.1 K.

Based on the results of the experiments, it is evident that utilizing an integrated cooling strategy that combines cooling of nanofluids and cooling of phase change materials—metal foam—has greatly lowered the maximum temperature that the battery is permitted to reach.

By changing the liquid channel structure and cooling fluid's properties—which provide prolonged working time at an operational temperature range—the performance of the entire system can be improved in the future.

10. An innovative battery thermal management with thermally induced flexible phase change material

In this paper (Wu, 2020), a novel BTM with thermally induced flexible composite PCM is presented. By using PA/expanded graphite (EG) composites with high porosity characteristics, the PCM leakage issue can be somewhat mitigated. By incorporating highly conductive materials (such as metal foam and porous carbon matrix), the problem of thermal conductivity can be solved. Previous studies mainly focused on foam size and thermal conductivity enhancement without taking into account heat transport, containment, and assembly, which should also be investigated. Due to the classic composite PCM's considerable stiffness, there may be poor installation ease and high thermal contact resistance between the battery and composite PCM.

An innovative "interference fit" concept between the battery and FCPCM is put forth in this study to make the system efficient, and small, and to eliminate the requirement for thermal grease during assembly. The built-in BTM provides superior heat control capabilities. When the battery is depleted from 100% to 0% charge state, it performs significantly better in terms of cooling than in a case without a PCM, especially at high discharge rates.

Long-term PCM latent heat recovery and reduced temperature swings within the range suggest that the suggested system performs better when it comes to battery thermal management solutions.

11. Impact of configuration on the performance of a hybrid thermal management system including phase change material and water-cooling channels for Li-ion batteries

This research (Molaeimanesh, 2020), examines the impact of system configuration on the cooling performance of a hybrid thermal management system composed of phase change material and water-cooling channels. Simulation and analysis are performed on the four configurations, which include parallel, series-1, series-2, and parallel/series. The highest temperature, the temperature difference, and the liquid phase change material fraction are studied. In the Series/Parallel setup, the phase change material melts entirely at 236 S, demonstrating that the PCM has a longer lifespan and a lower maximum surface temperature than in the other three configurations. Series design is superior for generating uniform surface temperature.

According to the study, the parallel/series arrangement enables long-term cell operation with a high rate of heat dissipation, which lowers the maximum temperature and reduces the range of temperature gradients at the cell-to-BTMS interface. For BTMS with lower pressure loss requirements, parallel arrangement is a superior option. The test results indicate that the series-2 arrangement performs better during short operations. The parallel/series design, which allows for 400 seconds of cell operation and a high heat dissipation rate of 1000 kW m when PCM is melted, yields the best test results out of the four. The operating conditions (heating dissipation requirements, pressure loss, etc.) should be taken into consideration while choosing one of these configurations.

This investigation used paraffin wax PCM; the results apply to other PCM materials, and the heat dissipation rate was 1000 kW m^{-3} (rapid charging, uphill climbing), therefore they apply to other worst-case scenarios.

12. Hybrid thermal management of lithium-ion batteries using nanofluid, metal foam, and phase change material: an integrated numerical–experimental approach

This study (Kiani M. A., 2020), focuses on the design and development of a hybrid cooling system that uses copper foam as a passive material and alumina nanofluid as an active phase change material (PCM). According to the experimental data, the nanofluid with a volume fraction of 2% extends the operating period to 900 S, which slows the pace at which the temperature rises. In contrast to nanofluid cooling, which keeps the battery temperature within safe operating limits, water cooling is ineffective at preventing temperature rises, especially under stressful working conditions.

The findings demonstrate that copper foam and paraffin's high latent heat reduce temperature rises. At Reynolds of 420, nanofluid cooling lengthens operation time by 4% and 29% for nanofluid 1% and 2%, respectively. The decrease at the beginning of the paraffin phase shift and the increase in melting time as the volume fraction of nanofluid rises demonstrate the inverse relationship between the Reynolds number and the effectiveness of nanofluid in lengthening the paraffin phase transition time.

Although the alumina nanofluid is an excellent alternative for BTMSs, the fact that it generates a pressure decrease in the canal suggests the need for more research in this area before using it as a useful system.

13. Thermal management technology of power lithium-ion batteries based on the phase transition of materials

This paper (Jiang, 2020), explains two types of BTMS based on the phase transition principle based on the solid-liquid phase transition principle and the liquid-gas phase transition principle. This paper critically points out the importance of the development and building of new thermal management systems or models suitable for future purposes. As per the conclusions by the authors, the Simplified Multi-Particle (SMP) model is more appropriate for higher calculation accuracy and Galerkin's method is the best technique for simplifying order reduction. Hydrate salt with TiO2 nanoparticles has excellent performance characteristics in terms of enthalpy of phase transition and specific heat capacity that could be an alternate thermal management method in the future. Expanded graphite, metal mesh, metal foam, and metal fins are less expensive alternatives to nanomaterials and graphene, improving the thermal conductivity of pure phase transition materials but growing leakage of electricity. Hybrid BTMS can handle high heat fluxes, but they also add weight, complexity, and extra power requirements.

To address the issues with the difficulty and expense of PCM manufacture, the article suggests using hydrate phase change materials and flexible inert metal materials rather than the present organic polymer materials used to make PCM capsules. It also suggests that additional research should be conducted to create PCMS-appropriate nanofluids with high thermal conductivity and low viscosity, as both of these characteristics are necessary for improved heat dissipation and lower pumping power consumption.

14. Delayed liquid cooling strategy with phase change material to achieve high-temperature uniformity of Li-ion battery under high-rate discharge

This research (Cao, 2020), discusses a unique system termed delayed cooling that combines liquid cooling with PCM for a Li-ion battery pack with 40 cylindrical cells. The technology is ideal for high discharge rate situations with low flow rates. The experimental results show that a high inlet water temperature is required to maintain the temperature within the limit. Delayed cooling significantly reduces temperature within the cell and also between cells imparts saving in the power consumption of the system.

This hybrid cooling system is most effective at high-rate discharge conditions. High-rate discharge situations are best for this hybrid cooling system. The battery pack is first cooled by the PCM, and continuous liquid cooling only begins when the battery temperature reaches the phase change temperature of 41 ^{o}C according to this research. Consequently, the maximum temperature is decreased, and the PCM's latent heat is recovered. The PCM is crucial in this stage for regulating the temperature.

The simulation shows that a heatsink with a counterflow can successfully lower the battery pack's temperature. To keep the battery temperature at a safe level of 55^{o}C a high inlet temperature of the cooling water of about 40^{o}C should be the top priority.

15. Numerical analysis of different fin structures in phase change material module for battery thermal management system and its optimization

This study (Choudhari, 2020), compares the thermal performance of battery modules with and without PCM at various current densities. Then, the viability of including various fin forms, such as rectangular, triangular, trapezoidal, I-shape, and T-shape, as well as their quantity, for improving heat transfer. An optimized PCM module is suggested based on the findings, and when compared to a standard PCM module, it is found that the optimized module performs better. Examining the temperature distribution across the PCM's exterior. The PCM's conduction heat transfer and the outer shell's convection heat transfer are both increased by the optimized model.

The main findings of the current work are that PCM-based cooling is only safe at lower discharge rates and that, because of its limited storage capacity and poor thermal conductivity, it performs poorly when discharge rates are large. As a result, various PCM thicknesses were suggested, with 26 mm being the optimum choice for the 18,650 Li-ion battery (Panasonic NCR18650PF, 2.4Ah) employed in the current study.

The test results suggest that triangular fins perform the least efficiently and that I-shaped fins perform best when it comes to heat dissipation capability. The PCM's capacity to store heat is decreased due to its smaller surface area even though the number of fins enhances heat transmission rate. Therefore, the ideal number is restricted to 4 for optimal performance.

Based on these facts, a PCM that is optimized for cooling efficiency is suggested, with the right number of fins, convection current rate, and fin shape. The introduction of specific additives such as expanded graphite, metal foam, or carbon fiber can address PCM's heat conductivity issues. However, the discontinuous density features of these additives could cause them to float to the top or settle at the bottom, which would compromise the structure's homogeneity. To maintain the homogeneity of composite PCM, additional studies should be focused on this area.

Because fins reduce the amount of time PCM takes to melt, they reduce cooling efficiency. In reality, the center zone module pack is more susceptible to high heat than the cells in the outer portions, although the current study solely focuses on a single cell.

To maximize test results, fin placement is therefore extremely important.

16. Experimental investigation of the effect of vibration on phase change material (PCM) based battery thermal management system

This study (Joshy, 2020), looks at how vibration affects a passive battery thermal management (BTM) system. The experiment's applied frequency and amplitude ranges are 20–30 Hz and 30–50 mm/s, respectively. These values are representative of what plug-in hybrid electric vehicles (PHEV) on the road experience during regular operation. The PCM outer surface temperature (PCM in solid state) is unaffected by frequency and amplitude effects at low temperatures.

The vibration of the PCM during its liquid phase can, to some extent, alter the liquid PCM's natural convection circulation and the temperature of the battery's surface. Frequency has a greater impact on temperature rise at low discharge rates. Frequency and amplitude both increase with discharge rate.

The effects of vibration frequency, discharge rate, and amplitude on PCM melting and solidification are no longer effectively presented in the current work. Therefore, it is advised to conduct the same research in a single cell.

17. Experimental and simulative investigations on a phase change material nano-emulsion-based liquid cooling thermal management system for a lithium-ion battery pack

In this study (Wang, 2020), a high-performance liquid cooling thermal management system with PCM with nano-emulsions is discussed. It has great dispersion stability, low viscosity, and strong thermal dependability.

Utilizing liquid cooling based on nano-emulsions considerably reduces the issues associated with using nanofluids. The simulation results show that the 10 wt% OP28E nano-emulsions thermal management quality was superior to that of water due to a discernible drop in Tmax and Tmax with increasing flow rate.

This paper sheds light on the potential for investigation into liquid cooling thermal management systems based on nano-emulsions

18. Effect of coupling phase change materials and heat pipe on performance enhancement of Li-ion battery thermal management system

To address the issues of limited thermal conductivity and huge internal temperature differences in a PCM-based cooling system, the current paper (Yuan, 2021) discusses a novel approach of merging heat pipes, heat-conducting glue, phase change materials (PCM), and micro-channel plates into a TMSs. Furthermore, it is challenging to transfer heat when TMS and PCM are mixed, however, microchannels solve this issue at the moment. The Li-ion battery may be heated and cooled very well using the newly constructed TMS system with an S-shaped microchannel.

The heating capacity of the designed TMS is analyzed for three operating conditions: -20^{0}C, -10^{o}C, and 0^{o}C. According to the present system during the discharging period, the heat pipe transfers the heat generated by the li-ion batteries to the PCM which store the heat, and the micro-channel plate at the bottom cools the PCM. During low temperatures, the direction of heat is opposite to the heat of the battery.

This demonstrates how rapidly the Li-ion battery may reach the safe operating temperature range. The planned TMS can heat the lithium-ion batteries to 20^{o}C at around 1500S. The liquid temperature in the micro-channel will be raised in future studies of this device to shorten the heating time.

19. Liquid cooling with phase change materials for cylindrical Li-ion batteries: An experimental and numerical study

The design of a hybrid thermal management system with liquid cooling and PCM (matrix made of expanded graphite/RT44HC composites) is discussed in this work (Cao J. L., 2020). Water enters the PCM through a cold plate and is then used to cool cylindrical batteries. The study intends to determine the effects of water inlet temperature and flow rate, as well as the PCM content in a battery, on the temperature rise and uniformity of battery temperatures.

The findings indicate that keeping the water temperature below 40 °C and as close to the surrounding temperature as possible would be the optimum control technique. Effective cooling requires an ideal flow rate. Composite PCMs with a high mass percentage of RT44HC operate well under high discharge rates. Along with the contour plot of the PCMs' melting fraction, a numerical model was created to aid in visualizing temperature distribution and explaining latent heat functions.

The study also concludes that due to the high latent heat density, composite PCMs with high PCM mass fractions can achieve minimal temperature rise and minor temperature differences. The system can be further optimized with the use of the present numerical model, which also helps the hybrid thermal management system work better.

20. Computationally efficient thermal network model and its application in optimization of battery thermal management system with phase change materials and long-term performance assessment

For BTMS with phase change material, the present paper created a simple, compact, and accurate 2D thermal network model as well as an analogous electric circuit model (Ling, 2020). These models can save simulation time by 99% when compared to a traditional numerical model. This model aids in optimizing the PCM characteristics to quickly warm up a battery pack in a cold climate. According to the results of the current study, for the PCM to operate at its best, it should have a melting point of about 40°C, a high thermal conductivity of about 5.4W/mK, and a low latent heat storage density of less than 0.0145kJ/m^3. Additionally, during a 10,000-hour charge-discharge cycle, this model is quite effective at forecasting the long-term impact of the thermal management system on the life of a battery module. According to a life span model, lower temperatures and temperature differences decrease a battery module's capacity.

A battery temperature management system with PCMs might be designed and optimized more effectively using this 2D model.

The authors highlight the effectiveness of a 2D model that, using a single electric circuit, can monitor the 2D temperature distribution while simulating the heat generation from the battery, thermal storage in the PCMs, and heat dissipation at the side boundaries. With an average temperature prediction error of less than 1°C. By combining several processing units, this existing 2D model can be expanded to a bigger scale model, which would serve as a strong tool for designing and optimizing a real-size BTMS.

21. Thermo-physical characteristics and application of metallic-oxide-based mono and hybrid nanocomposite phase change materials for thermal management systems

The current study (Arshad, 2020), describes the characterization of a novel nanocomposite phase change material (NCPCMs) comprising TiO2, Al2O3, and CuO nanoparticles for thermal management systems from chemical, physical, and thermal perspectives. Commercial-grade paraffin, specifically RT-35HC, was chosen as the PCM material for the study. Different thermophysical characteristics and chemical interactions of mono and hybrid NCPCMs were researched in the first phase using material characteristic techniques such as ESEM, FT-IR, TGA, DSC, and TCA. The thermal cooling performance was then examined by experimentation in the second phase.

The outcomes demonstrated the uniform dispersion of TiO2, Al2O3, and CuO nanoparticles onto the surface of mono and hybrid NCPCMs without changing the chemical composition of RT-35HC. Al2O3+CuO distributed hybrid NCPCM exhibits maximum latent heat of fusion and highest thermal conductivity of 228.46 J/g and 0.328 W/m K, respectively, when compared to pure RT-35HC. Increases in heat capacity were also reported for NCPCMs, with hybrid NCPCMs in the solid phase exhibiting a 36.47% improvement. Using hybrid NCPCMs, the following observations were made: there was no phase segregation; there was less subcooling; the phase transition temperature was less; and there was greater chemical and thermal stability.

According to the study's findings, hybrid NCPCM can be used successfully and reliably in photovoltaic (PV) module systems, Li-ion batteries, and passive thermal management system electrical devices.

22. Experimental investigation of the flame retardant and form-stable composite phase change materials for a power battery thermal management system

In the present work (Zhang, 2020), a novel flame retarded composite PCMs type battery module was proposed which consists of paraffin (PA), expanded graphite (EG), ammonium polyphosphate (APP), red phosphorus (RP) and epoxy resin (ER). In the micro and macro level investigations are done to confirm the thermophysical and flame-retardant properties. The research results indicate that the proposed composite PCMs with an APP/RP ratio of 23/10 exhibit the optimum flame-retardant performance, so they would be effectively utilized in BTMS, energy storage, and other fields.

Compared with the air-cooled and pure PA cooling systems, the composite flame retardants form-stable PCMs displayed better thermal management effectiveness.

23. The Enhanced Performance of Phase-Change Materials via 3D Printing with Prickly Aluminum Honeycomb for Thermal Management of Ternary Lithium Batteries

The present study (Cao M. H., 2020), introduces a new type of lightweight, shape-stable composite phase-change material (CPCM) which consists of PCM as Paraffin wax (PW), expanded graphite (EG) and high-density polyethylene (HDPE) as support materials, carbon fiber (CF) as a heat-conductive additive, and a 3D printed aluminum honeycomb with a prickly structure (3D Al-Hc) included to enhance the mechanical properties and thermal conductivity of the CPCM. The test results reveal that the CPCM has excellent battery thermal management performance such as good mechanical properties and heat dispersibility.

From the analysis, the degree of supercooling of the prepared PW/EG/CF/HDPE CPCM was reduced by 51.5% and 43.3%, which indicates a short phase change period and also improves the efficiency of the CPCM. The stress-strain analysis results emphasize the point that there is a remarkable increase in compressive strength of the PW/EG/ CF/HDPE due to the addition of the 3D Al-Hc that further improves the thermal conduction and heat dissipation capability of the CPCM.

24. Role of foam anisotropy used in the phase-change composite material for the hybrid thermal management system of lithium-ion battery

The current paper (Bamdezh, 2020), introduces a hybrid BTMS that uses cooling water channels as an active component and a composite of paraffin PCM and aluminum foam surrounding each lithium 18650 cylindrical cell as a passive component. The effect of foam anisotropy—three primary axial, radial, and tangential directions in the cylindrical coordinate system—on its performance is thoroughly investigated. The fact that the hybrid TMS operation consists of two periods of PCM recovery and cell cooling is evident from the results. The first period takes advantage of water's cooling ability to solidify the PCM, while the second period chills the cell using water's cooling ability.

The evaluation's findings show that the average is not affected by axial or radial conductivities. The evaluation's findings show that tangential conductivity improves heat transfer, allowing for quicker PCM solidification and improved average cell temperature control. Axial and radial conductivities have no impact on the liquid fraction or average cell temperature.

According to the findings, the only way to regulate the average cell temperature is to increase tangential conductivity, and the only way to manage the largest temperature differential within the cell is to increase axial thermal conductivity.

25. Characterization and experimental investigation of aluminum nitride-based composite phase change materials for battery thermal management

The present study (Zhang J. L., 2020), focuses on the influence of aluminum nitride (AlN) mass fractions (0 wt%, 5 wt%, 10 wt%, 15 wt%, 20 wt%, and 25 wt%) in composite PCMs. Various properties such as thermal conductivity, mechanical properties, and volume resistivity are examined. The results indicated that 20 wt% mass fractions of AlN in the composite PCMs was an optimal strategy. Through comparison study with an air-cooled battery module, the results indicate that the AlN (Aluminium Nitride) - enhanced composite PCMs-cooled battery module exhibited much better temperature-controlling and temperature-balancing capacities, particularly at a high discharge rate.

The current work focuses on the impact of different aluminum nitride (AlN) mass fractions in composite PCMs ((0 wt%, 5 wt%, 10 wt%, 15 wt%, 20 wt%, and 25 wt%). Examined are several characteristics, including volume resistivity, mechanical characteristics, and thermal conductivity. The outcomes showed that the composite PCMs' 20-weight percent mass fraction of AlN was the best course of action.

According to a study that compared a composite PCMs-cooled battery module with an air-cooled battery module, the AlN (Aluminium Nitride)-enhanced battery module had significantly better temperature-control and temperature-balancing capabilities. This was especially true at high discharge rates.

III. CONCLUSION

Future energy demands and air pollution risks brought on by fossil fuel-powered automobiles are better addressed by electric vehicles. Li-ion batteries are well known for being a great source of power for electric vehicles. Even though Li-ion batteries have high energy densities, higher power densities, long cycle lifetimes, and are relatively inexpensive, thermal management of these batteries is a significant problem because of overheating and thermal runaway. There are several different types of thermal management systems in use, each with its benefits and drawbacks, including air-cooling systems, liquid cooling systems, phase change material (PCM) cooling, hybrid cooling, and heat pipe cooling.

A detailed discussion of Phase Change Material-based BTMSs is included in the current review paper, along with key discoveries about PCM properties at low and high temperatures, usage of composite PCM, organic and inorganic CPCM, flame retarded CPCM, thermally induced flexible CPCM effect of vibration on active cooling, presence of nanofluids and nano-emulsions, PCM with hybrid cooling, cooling configurations, etc. The findings were as follows.

PCM with a thickness of 12 mm is adequate for active cooling, however, it might not be appropriate for high ambient temperatures and high discharge rates. A PCM's efficiency can be increased by adding a liquid cooling system, making a hybrid system the best option in harsh environments.

Hexacosane PCM with a thickness of 9 mm performs exceptionally well among PCM Capric Acid and PCM Hexacosane of 3 mm, 6 mm, and 9 mm thicknesses, indicating a good passive cooling solution for Li-ion batteries.

The major issue of PCMS as a thermal management system is its low thermal conductivity and this can be improved by incorporating high-conductivity materials, such as metal fins, beads, or powders, or by using porous media, such as carbon fibers or composites made of expanded graphite (EG), metal foams with porosity.

Even though the fins increase the PCM's thermal conductivity in a passive cooling system, the right number of fins and their shape must be chosen for efficient thermal management. With efficiency and the available area taken into account, the number of rectangular and circular fins is set at 4 and 2, respectively, for best performance. To better conduct heat, rectangular fins are employed in the top area, and circular fins in the lower portion.

A comparison study based on the use of various fin shapes, including rectangular, triangular, trapezoidal, I-shaped, and T-shaped fins in PCM thermal management systems reveals that conduction heat transfer and the outer shell's convection heat transfer are both increased, triangle-shaped fins perform the least efficiently, the length of fins from 7.5 mm to 13.5 mm improves the working time additionally by 3.3 % of the battery, and I-shaped fins perform the best in terms of heat dissipation capability.

Fin location, appropriate fin thickness, optimal fin shape, and optimal number of fins (four for best performance) must all be considered when using fins in conjunction with a PCM. This means that the fin-enhanced PCM systems behave better than the PCM systems. Further research on the findings is required before this suggestion may be implemented in battery modules and packs.

The introduction of specific additives such as expanded graphite, metal foam, or carbon fiber can address PCM's heat conductivity issues. However, the discontinuous density features of these additives could cause them to float to the top or settle at the bottom, which would compromise the structure's homogeneity. To maintain the homogeneity of composite PCM, additional studies should be focused on this area.

The benefits of employing composite PCM-based battery heat management strategies were also discussed in this paper. Composite PCM-enhanced battery module based on AlN (Aluminium Nitride) (with 20% mass fraction) has much higher temperature-control and temperature-balancing capabilities, and this system performs particularly well at high discharge rates.

The proposed flame retarded composite PCMs type battery module consists of paraffin (PA), expanded graphite (EG), ammonium polyphosphate (APP), red phosphorus (RP), and epoxy resin (ER), the proposed composite PCMs with an APP/RP ratio of 23/10 exhibit the optimum flame-retardant performance, can be utilized in BTMS, energy storage, and other fields.

The nanocomposite phase change material (NCPCMs) comprising TiO_2, Al_2O_3, and CuO nanoparticles for thermal management systems, Al_2O_3+CuO distributed hybrid NCPCM exhibits maximum latent-heat of fusion and highest thermal conductivity of 228.46 J/g and 0.328 W/m K, respectively, when compared to pure RT-35HC.

The usage of hybrid NCPCMs exhibits excellent properties such as no phase segregation, less subcooling, low phase transition temperature, and greater chemical and thermal stability.

Two inorganic CPCMs based on magnesium chloride hexahydrate, and comparing their performance as active BTCMS to organic PCM, paraffin wax for both mixes. The test findings show that inorganic composite mixtures have thermal, physical, and mechanical qualities that are beneficial for Li-ion Li-ion battery pack heat management. The performance of the bischofite/Mg (NO3)26H2O mixture demonstrates favorable effects on both economic and environmental issues.

However, the majority of the research and advancements are based on organic-type composite PCMs, with some study on inorganic CPCMs that needs to be expanded to explore their potential in the future.

The new type of lightweight, shape-stable composite phase-change material (CPCM) which consists of PCM as Paraffin wax (PW), expanded graphite (EG), and high-density polyethylene (HDPE) as support materials, carbon fiber (CF) as a heat-conductive additive and a 3D printed aluminum honeycomb with a prickly structure (3D Al-Hc) has good mechanical properties, thermal conductivity, and heat dispersibility.

The composite PCM alone is not very efficient for high discharge rate applications. As a result, a hybrid cooling approach improves thermal management by using a CPCM, which reduces the load on the cooling pump by absorbing heat, lowering the cost and volume of BTMS and taking advantage of the benefits of a robust cooling capability of the heat transfer fluid (HTF). Conduction is responsible for the heat transfer between the CPCM and HTF.

The experimental findings show that the hybrid system outperforms other varieties of BTMS because it delivers a more uniform temperature distribution and requires less time for the cells to cool down than other systems.

To improve the thermal performance of PCM as a thermal energy booster, it has been discovered that the PCM with nanofluid particles such as alumina (Al2O3), copper oxide (CuO), and silver oxide (AgO) Metal foam is essential. Even if the PCM has low thermal conductivity and leads to leakage in the battery system, extending the battery's working time within an acceptable operating temperature range can be achieved by adjusting the cooling channel structure and cooling fluid's qualities. Nanoparticle sedimentation should also be taken into consideration.

The PCM leakage issue can be somewhat mitigated by using PA/expanded graphite (EG) composites with high porosity characteristics and the problem of thermal conductivity can be solved. By incorporating highly conductive materials (such as metal foam and porous carbon matrix).

In terms of enthalpy of phase transition and specific heat capacity, hydrated salt containing TiO2 nanoparticles has good performance characteristics and may one day serve as an alternative thermal management technique.

The problems associated with using nanofluids are significantly reduced by using liquid cooling based on nanoemulsions that have excellent dispersion stability, low viscosity, and good thermal dependability.

The BTMS is efficient, compact, and requires no thermal grease during assembly owing to an inventive "interference fit" idea between the battery and thermally induced flexible PCM (FCPCM). As a result, the system has better heat control capabilities at high discharge rates.

According to experimental research analysis of different cooling configurations such as parallel, series-1, series-2, and parallel/series, the phase change material melts completely at 236 S in the Series/Parallel setup, enabling long-term cell operation with a high rate of heat dissipation, lowering the maximum temperature and reducing the range of temperature gradients at the cell-to-BTMS interface.

The parallel configuration is the preferable choice for lower pressure loss requirements, whilst the series-2 arrangement performs better during short operations.

In the hybrid cooling system that uses copper foam as a passive material and alumina nanofluid as an active phase change material (PCM), high latent heat reduces temperature rises Although alumina is a great substitute, it causes pressure drops, necessitating further study to resolve the issue at hand.

At high discharge rate conditions, the delayed liquid cooling approach with PCM is the ideal hybrid cooling strategy because it greatly lowers the temperature both inside and between cells, which results in a reduction in the system's power consumption.

The vibration issues can be significant for the passive techniques of battery thermal management systems. Therefore, a passive BTMS using PCM is taken for study and reveals that when the PCM is in its solid phase, the effects of frequency and amplitude on the battery surface temperature are negligible, but when the PCM is in its liquid phase, the surface temperature varies. In this area, more research should be required.

The approach of merging heat pipes, heat-conducting glue, phase change materials (PCM), and S-shaped micro-channel plates into TMSs, helps the Li-ion battery to rapidly reach the safe operating temperature range.

For optimal control over battery temperature, keeping the water temperature below 40 °C and as close to the surrounding temperature as possible and an ideal flow rate is essential.

For the PCM to operate at its best, it should have a melting point of about 40°C, a high thermal conductivity of about 5.4W/mK, and a low latent heat storage density of less than 0.0145kJ/m3.

According to the findings of foam anisotropy used in the phase-change composite material for the hybrid thermal management system of the lithium-ion battery, the only way to regulate the average cell temperature is to increase tangential conductivity, and to manage the largest temperature differential within the cell is to increase axial thermal conductivity.

Many research studies are concentrated on PCM utilization under high-temperature operations. Hence more research should be required on PCM usage in cold environments due to the significant growth of automobiles in these environments.

The main focus of the current paper was a review of design and development methodologies for PCM utilization in Li-ion battery thermal management systems. It is concluded that the PCM utilization can be improved by combining it with liquid cooling systems, nano-emulsion-based cooling systems, using it as a composite PCM (both organic and inorganic), or by using it in active cooling with optimal fin numbers. For BTMS's cooling management to be more effective, the cooling configurations should be carefully chosen.

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