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A Review Of Li-Ion Battery Hybrid Thermal Management Systems

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Abstract: The use of electric vehicles is receiving increased attention due to the environmental problems associated with conventional fossil fuel vehicles and their rising energy demand. The heat the battery produces as it is being charged and discharged and the high and the low operating temperatures adversely influence the battery's lifespan and cause thermal runaway. A battery thermal management system (BTMS) is fundamentally needed to ensure the battery operates safely and extends its lifespan. Numerous BTMS kinds have been developed, including those that use air cooling, liquid cooling, PCM-based cooling, heat pipes, thermoelectric cooling, etc. The development of hybrid BTMS(HBTMS), which combines active and passive systems now in use, was prompted by the fact that each type has distinct advantages and limits. The current research examines several hybrid BTMS configurations and compares them to existing BTMS. The study concentrates on the advantages of adopting HBTMS under high discharge rate circumstances. It provided a critical analysis of the impact of performance-influencing parameters in PCMs with air cooling and PCMs with liquid cooling, as well as the range of such research in developing HBTMS in the future.

Index Terms **– Electric Vehicle, Li-Ion Battery, Thermal Management.**

I. INTRODUCTION

Because fossil fuels are being used up much more quickly than they are being produced, the transportation sector is experiencing an energy crisis. These fossil fuel-powered vehicles also contribute to significant environmental impacts like noise and air pollution. Due to their low emissions and high efficiency, electric vehicles (EVs) can help tackle the energy crisis and the effects of climate change. The lithium-ion battery is a key component that serves as a potential energy source for electric vehicles. Li-ion batteries provide several advantages over other battery types, including high energy density, lightweight, extended life, low self-discharge, and quick charge times. However, as these batteries are being charged and discharged, a significant amount of heat is released.

To prolong the battery's life and reduce the risk of explosions brought on by thermal runaway, this should be removed from the battery promptly. It will influence the battery's performance and cause it to degrade. The cell's temperature shouldn't rise above 333.15 K to ensure the battery's safety. For the battery to operate safely, the heat that has built up inside the cell and the battery pack needs to be appropriately evacuated. To keep the battery operating within the specified temperature range, the battery thermal management systems are crucial in controlling temperature uniformity.

Numerous types of battery thermal management systems have been developed to increase the cooling effectiveness of Li-ion batteries.

Battery thermal management systems are divided into three categories based on the medium: air cooling, liquid cooling, and PCM cooling. They are divided into two groups according to the thermal cycle: BTMS with vapor compression cycles (VCC), which include cabin air cooling, secondary loop liquid cooling, and direct refrigerant two-phase cooling, and BTMS without VCC, which include PCM cooling, heat pipe cooling, and thermoelectric element cooling. The two types of cooling systems are active cooling systems and passive cooling systems, depending on the amount of power they consume.

The power-consuming equipment can speed up cooling or heating in an active cooling strategy. The air-cooling approach is less expensive, but because of its poor heat transfer efficiency, it is only appropriate for low-density batteries. Despite being an efficient cooling method, liquid cooling has a large and complicated operational system. In addition to its many other uses, the PCM also has uses in battery cooling. The BTMS's efficiency is decreased by PCM's low thermal conductivity and volumetric expansion during phase transition, even though they perform better than air cooling and water cooling.

Heat pipes, a different cooling technique, were introduced to overcome PCM's drawbacks. They run without power and have good thermal conductivity, are lightweight, small, quiet, and calm. However, it may not be appropriate for heating operations due to its low capacity, high danger of leakage, high cost, and complicated fabrication. By combining heat pipes with other systems, it is possible to use their high thermal conductivity in battery thermal management systems.

Thermoelectric cooling systems are efficient for both cooling and heating applications. However, because of their reduced conversion efficiency, they are not suited for cooling batteries.

Hybrid battery management systems, which integrate various active cooling systems with PCM, active liquid cooling with PCM, forced air cooling with PCM, heat pipe cooling with PCM, oscillating heat pipe with PCM, etc., have been developed to take advantage of the benefits of both active and passive systems.

II. DESCRIPTION OF REVIEWED WORKS

This paper reviewed twenty-three works related to Li-ion Batteries and their thermal management. The numerous hybrid cooling system types are critically analyzed in the current review. The paper examines several hybrid cooling solutions, and via analysis of prior research, aspects affecting battery performance under liquid and air cooling are examined. The effectiveness of several hybrid techniques, including heat pipes with evaporative cooling, heat pipes with liquid cooling systems, hybrid liquid cooling plates, copper sheets heat pipes with air cooling, PCM heat pipe combinations, HBTM with surrogate models, delayed liquid cooling with PCM, composite PCM with air cooling, PCM with liquid cooling, etc., was thoroughly examined. The current report also discusses upcoming research directions for hybrid battery thermal management systems.

1. Hybrid Battery Thermal Management System in Electrical Vehicles: A Review.

The current paper compares hybrid battery thermal management (BTMS) to conventional BTMS and examines the benefits and prospects of hybrid BTMS. Cost, efficiency, and other factors are carefully examined for the development of hybrid systems in the future to provide design recommendations (Zhao, 2020.).

The review paper points out the advantages and drawbacks of various battery thermal management systems such as active cooling, passive cooling, and hybrid cooling systems are discussed in this paper. Out of the two-air based BTMS, forced air forced-air BTMS is simple and has a low cost, therefore they are enough for relatively low temperatures. Making some design modifications such as the geometry of flow channels, cell arrangement, and airflow configuration would improve the existing system design.

Compared with air cooling BTMS, liquid cooling provides better efficiency due to its high heat-transfer efficiency, and consumes less energy, especially under the high heat load of battery cells. But they have some disadvantages, including complex devices, and high cost (40% more than that of air-based BTMS).

In comparison to alternative BTMS, the heat pipe (HP) has various benefits, including high thermal conductivity, contact structures, and flexible geometry. As a result, they can be used efficiently in hybrid cooling systems.

While active BTMS satisfies higher needs, passive BTMS is ideal for modest requirements (low heat load or short operation time).

The advantages of employing PCM in BTMS are discussed in the current work. These advantages include improved temperature uniformity, high energy usage efficiency because of the latent heat of phase transition, preheating capability to save energy and operational flexibility. To be effective, the PCM is paired with active cooling techniques because they are ineffective under extreme environments.

The greatest option for BTMS development is hybrid BTMS because of its broad applicability, particularly in harsh working conditions.

The current study concludes that at low temperatures, natural convection cooling is adequate for hybrid PCM and HP, but forced convection is needed at high temperatures. Due to the greater adaptability of hybrid BTM, the ideal mix should be chosen to maximize cooling efficiency depending on the circumstance. Heat saturation is one of the limitations of conventional PCM-based BTMS that can be reduced by hybrid BTMS.

2. A state-of-the-art review and future viewpoint on advanced cooling techniques for Lithium-ion battery systems of electric vehicles

The current work (Thakur, 2020.), represents a thorough examination of various BTMS technologies, including natural and forced air-cooling, direct and indirect liquid cooling, heat pipe cooling, the integration of metal plates with mini channels, and the use of liquid metals, nanofluids, and boiling liquids.

High thermal performance, shape flexibility, and compactness make the heat pipe-based hybrid cooling system very useful. When compared to traditional active or passive BTMS, the cost of the system is reduced by using heat pipes made of aluminum or polymer.

The paper concludes the session by concentrating on the development of hybrid cooling systems using fins, nanofluids, and PCM, coupled with microchannel-based cooling to increase the cooling under high charging/discharging rate and also to minimize the cost of BTMS by optimal design.

3. A review of thermal management for Li-ion batteries: Prospects, challenges, and issues

The prevailing thermal management techniques for lithium-ion batteries, including air cooling, liquid cooling, phase change material cooling (PCM), refrigerant cooling, heat pipe cooling, and thermoelectric elements, have been discussed by the authors in the present study (Shahjalal, 2021.).

Air cooling and liquid cooling systems are big, PCM offers low thermal conductivity, refrigerant cooling necessitates additional cooling systems, and heat pipe cooling systems have a high leakage risk.

Even if the system results in complex construction and increased weight with high thermal efficiency, additional research should be focused on the implementation of combinations such as a high thermal conductive system and a combination of more than one traditional cooling system.

The usage of nanoparticles in batteries, cold-plate/PCM/heat-pipe, direct-two-phase/PCM/heat-pipe, and other designs have all been put forth by researchers in this field. By using carbon fiber, aluminum fins, carbon nanotubes, polyurethane foam, metal foams, and expanded graphite, it is possible to address PCM's low thermal conductivity difficulties and make it the most efficient hybrid cooling method.

Another choice is to combine PCM with heat pipe cooling to increase cooling efficiency. Another field of research that requires greater attention in the future is heat pipes with conductive cold plates and cooling systems with conductive nanoparticles.

4. A review of hybrid thermal management of battery packs and their cooling performance by enhanced PCM

To address the shortcomings of battery thermal management systems (BTMS), the present paper studied the implementation of a hybrid Thermal Management System in conjunction with PCM. The use of thermally conductive particles, cellular foams, and encapsulation are some of the PCM's enrichment techniques for thermal conductivity. Cell spacing, PCM mass, PCM thickness, thermal conductivity, and specific heat capacity are among the performance-influencing parameters that are reviewed (Murali, 2021.).

The present work further examined several BTMS kinds. The main negatives of liquid cooling are its high cost, the need for a lot of space, and the demand for a lot more active cooling. To lower the system's high weight, a PCM system and liquid cooling are an alternative.

The study shows that even though heat pipes exhibit excellent thermal performance, efficiency, and high compactness, their application is limited owing to improper contact between the cooling system and the complex heat transfer mechanism.

Due to PCM's high latent heat at low temperatures, PCM-based cooling systems can regulate the temperature between the cells and minimize temperature rise. However, they have issues with thermal conductivity and offer insufficient cooling at high temperatures. By creating a hybrid cooling system or increasing its thermal conductivity, these issues can be somewhat mitigated.

Due to poor performance, PCM with air-cooling hybrid systems requires an external surface like a copper mesh. Even with a 5C discharge, the experimental results of the current technique show good heat dissipation and homogeneous temperature distribution.

Active liquid or air cooling in conjunction with PCM demands additional components that need balance, lowering the vehicle's efficiency in the process. However, PCM with forced air convection performs better in certain circumstances.

The current work focuses on the idea that because PCMs have a big latent heat capacity and Heat pipes (HP) have high thermal conductivity, the two can be combined to produce effective thermal management.

Among the different hybrid BTMSs discussed the PCM with heat pipes operates well at high discharge rates, resulting in a consistent temperature inside the battery without the need for an external power source. But the material for PCM/heat pipes, their size, layout, etc., need to be chosen with more care.

5. A review of air-cooled and air-centric hybrid thermal management techniques for Li-ion battery packs in electric vehicles

The performance of air-cooled and air-centric hybrid battery thermal management systems was examined in the current work (Sharma, 2021.). In addition to comparing them in terms of design and operating temperatures, the study offers recommendations for the creation of an air-cooled hybrid BTMS by utilizing its benefits, such as reduced weight, power consumption, and complexity.

The document also provides information on the battery pack design structure, type of air circulation within the pack, battery cell configurations, and spacing between batteries, all of which are crucial when constructing a reliable BTMS.

To increase the temperature uniformity inside the battery to an ideal range, air-cooling strategies including non-reciprocating (unidirectional) and reciprocating (bidirectional) air-cooling strategies are taken into consideration.

This study also covers operational characteristics such as battery loading, airflow, ambient temperature, maximum internal pack/module temperature, and temperature uniformity.

According to the studies, series airflow across the battery pack results in less temperature homogeneity than parallel airflow along the row of battery cells due to the high convective heat transfer coefficient.

Airflow must be uniform and pressure drops must be kept to a minimum to maximize the performance of the battery modules.

As per the findings, high calorific battery cells should be placed near the entry of airflow, and the battery cell-to-cell distance must be carefully chosen and positioned to provide temperature uniformity.

The battery's design is crucial in ensuring a constant temperature inside the battery. U-type battery modules have the lowest levels of temperature non-uniformity, whereas J-type battery modules have the lowest temperatures. The maximum temperature has been lowered by uneven battery cell spacing.

Cross-battery cell layouts have greater cooling performance and temperature uniformity than aligned, staggered, and cross-battery cell arrangements.

The paper concludes that the future BTMS will be hybrid since it can address the majority of the problems that batteries encounter under extreme ambient/fast charging/discharging circumstances.

To increase the efficiency of BTMS, studies should be expanded to incorporate the use of waste heat. The various design parameters, such as weight, volume, and economic constraints, as well as optimize the design parameters for effective utilization of the battery module/pack volume of EV.

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

In this study (Molaeimanesh, 2020.), the effect of system configuration on the cooling capabilities of a hybrid thermal management system made up of water-cooling channels and phase change materials is investigated.

On the four configurations—parallel, series-1, series-2, and parallel/series—simulation and analysis are conducted. The greatest temperature, the difference in temperatures, and the proportion of liquid phase change materials are investigated.

In the Series/Parallel setup, the phase change material completely melts at 236 S, proving that the PCM has a longer lifespan and a lower maximum surface temperature than in the other three setups. For creating a consistent surface temperature across the battery, a series design is preferable.

The parallel/series configuration promotes long-term cell operation with rapid heat dissipation, which lowers the maximum temperature and temperature gradients at the cell-to-BTMS interface.

According to the experimental findings, the series-2 design performs better during brief operations, whereas parallel arrangement is a preferable choice for reduced pressure loss needs.

The configurations must be properly selected by the working circumstances (heating, dissipation needs, pressure loss, etc.).

The PCM employed in the current experiment was paraffin wax, and the test results can also be used with other PCM materials. Since the study's heat dissipation rate was 1000 kW m-3 (fast charging, uphill ascending), it can also be used in other worst-case scenarios.

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

The current work investigates experimentally the thermal performance of different active, passive, naturally ventilated, and hybrid management methods on a Li-ion module with high-capacity prismatic cells (Hekmat, 2020.).

To assess the effectiveness of the experiment, the maximum temperature and maximum temperature differential for each of the seven cases—two naturally ventilated, one passive, two active, and two hybrid systems—are considered.

The maximum temperature and maximum temperature difference, which with air cooling are extremely high, are considerably reduced using PCM or silicon oil.

These hybrid systems can only be employed in electric vehicles (EVs) when the water flow rate is changed to match the typical battery system's discharge rate. The results of the experiments demonstrate that the hybrid system performs better than other types of BTMS because it provides a more uniform temperature distribution and cools the cells more quickly than other systems.

8. Impact of system structure on the performance of a hybrid thermal management system for a Li-ion battery module

The present paper (Bamdezh, 2020.), critically analyses the e role of the structure of a hybrid TMS with an air-cooling system (as an active TMS) and an embedded phase change material (as a passive TMS). The simulation studies are based on eighteen cases with different cell arrangements, module compactness, and phase change material (PCM) thickness and achieved excellent results in terms of maintaining the maximum temperature difference of the battery module that does not exceed 1.5°C.

The PCM/air combination is simple, less expensive, more dependable, and heavier, while the PCM/liquid combination is an efficient technique to remove heat from battery cells, based on comparison results of three hybrid TMS forms.

In this study, the impact of key structural elements such as cell layout, module compactness, and PCM thickness were thoroughly examined using 3D conjugate heat transfer analysis.

A thin layer of PCM is put around each cell using an aluminum tubular shell because the thickness of the PCM raises the cost of TMSs. This ultimately results in a reduction in PCM usage, weight, and cost of BTMSs.

Simulated cases include 18 with three different PCM thicknesses, three different distances between neighboring cells, and two distinct cell configurations.

Except in an aligned arrangement, all analyzed scenarios show a rise in the average cell temperature that is safe. The average temperature of battery cells is decreased by using PCM with the maximum thickness and maximum compactness. With a 6 mm PCM thickness, there is no discernible difference in the average cell temperature, cell layout, or distances between cells.

The suggested hybrid BTMS has outstanding capabilities of maintaining uniform temperature distribution because the greatest temperature difference between cells in any of the situations investigated never surpassed 1.5°C.

9. Novel thermal management methods to improve the performance of the Li-ion batteries in high-discharge current applications

The performance of an established heat pipe-based air-cooling system to regulate the temperature of the lithium-ion (Li-ion) cell/module in the high current discharging rate is reviewed in the current research (Behi, 2021.). The system's effectiveness was tested for evaporative cooling, natural convection, forced convection, and lack of natural convection. According to the experimental findings, induced and spontaneous convection, both reduce the cell's average temperature by 6.2% and 33.7%, respectively

According to test findings, the evaporative cooling approach is found to be the most effective at enhancing the current cooling system method for further optimization through the use of COMSOL Multiphysics®. The evaporative cooling approach has a 35.8% reduction in the highest temperature of the cell and a 23.8% reduction in the maximum temperature of the module.

The evaporative cooling system exhibits perfect cooling performance and keeps the cell's temperature in the 22°C range.

Due to its better thermal performance, heat pipes have been used in numerous studies to demonstrate their potential as hybrid cooling systems.

The current study demonstrates that, with an inlet velocity of 7 m/s, the evaporative cooling method can maintain the module's maximum temperature within a safe range (25–40°C).

According to test results of the heat pipe-based cooling system, the average cell temperature decreased by 33.7%, from 54.3°C to 35.9°C. The effects of the evaporative cooling approach reduced the cell's maximum temperature by 35.8%, according to the findings. In addition, compared to natural convection, the maximum temperature of the battery module was decreased by 23.8%.

10. PCM-assisted heat pipe cooling system for the thermal management of an LTO cell for high-current profiles

The thermal behaviour of a passive thermal management system (TMS), which includes natural convection, heat pipes, and phase change material (PCM), in a lithium-titanate (LTO) battery cell during a high current discharging process is described in depth in the current study. The analyses make use of the commercial computational fluid dynamics (CFD) program COMSOL Multiphysics®, and the outcomes are contrasted with experimental data with a tolerable margin of error. The outcome shows that for the cooling methods using heat pipes, natural convection, and PCM-aided heat pipes, the maximum cell temperature reaches 56°C, 46.3°C, and 33.2°C, respectively. compared to natural convection, experienced reductions of 17.3% and 40.7% via heat pipe and PCM-assisted heat pipe cooling system.

The LTO cell can be cooled more effectively using the PCM-assisted heat pipe. This is because, during the heat exchange, the heat produced inside the cell is transferred simultaneously through the PCM and heat pipes with essentially no thermal contact resistance (Behi, 2021.).

11. A new concept of thermal management system in Li-ion battery using air cooling and heat pipe for electric vehicles

The concept of a hybrid thermal management system (TMS), incorporating air cooling and heat piping for electric vehicles is revealed in the current research (Behi, 2020.) . Additionally, mathematical and thermal models were constructed to forecast the thermal behavior of a battery module made up of 24 cylindrical cells.

The factors that affect keeping a constant temperature inside the module and regulating the temperature rise, such as cell spacing, air velocity, various ambient temperatures, and inserting a heat pipe with copper sheets, were carefully researched. The computational fluid dynamics (CFD) software used in industry, COMSOL Multiphysics®, solves the mathematical models.

The positive results from the calculations and experiments point to the potential for expanding the study of systems based on heat pipes with copper sheets (HPCS). The maximum module temperature for the cooling strategy utilizing forced-air cooling, heat pipe, and HPCS is found to be 42.4°C, 37.5°C, and 37.1°C, respectively, and can reduce the module up to 42.7%, according to the results. The temperature uniformity of the battery module is 73.4% better in the hybrid mode of heat cooling than it is with natural cooling.

The battery temperature in natural cooling is substantially greater than the ideal range (15 to 40°C), the module's temperature distribution is not uniform, and the inner cells, which are placed close to the module case, are warmer than the outside cells. The battery module's performance could suffer as a result.

The spacing value of 2 mm is preferable for the 4 × 6 cylindrical battery modules when taking heat dissipation and volume into account.

The temperature of the cells is significantly influenced by the surrounding environment.

The local temperature decreases as airflow velocity increases. To promote efficient and consistent cooling, the inlet air velocity should be raised if the ambient temperature exceeds the normal range.

12. A novel liquid cooling plate concept for thermal management of lithium-ion batteries in electric vehicles

The hybrid liquid cooling plate (LCP) described in this study takes advantage of both the advantages of active (liquid) and passive cooling methods by incorporating phase change material (PCM) inside the cooling plate.

The hybrid LCP has good cooling capabilities and heats the battery in cold weather, and it is 36% lighter than a volumetrically identical regular aluminum LCP. The thermal behavior of the hybrid LCP is assessed using a computational fluid model, and it is contrasted with that of conventional aluminum LCP. According to the testing findings, using the novel technology can cut the coolant pump's energy requirements for circulating coolant by up to 30%. Additionally, it enhances temperature uniformity and the hybrid LCP could postpone the temperature drop in an EV's cold stop scenario. As a result, the system uses less energy to heat the batteries after short-term parking.

These suggest that the hybrid liquid cooling plate concept may provide EVs with a promising thermal management option.

Although the hybrid cooling plate rejects latent heat from PCMs more quickly when temperature is reduced, the aluminum LCP is lower at lower ambient temperatures.

Additionally, the hybrid cooling plate's energy release during the phase shift process stops the battery's temperature from dropping more quickly. This energy might help keep the battery module warm, making it useful for brief breaks in cold environments.

The hybrid cooling plate can increase the specific energy of the battery in the electric vehicle and more temperature uniformity in the battery module, according to the cooling performance study conducted under real driving conditions. This reduces the time required for liquid cooling, which ultimately lowers pump energy consumption.

The developed plate would be the best option for the thermal management of battery packs in an electric vehicle based on the hybrid cooling plate's benefits such as lightweight construction, cooling efficiency, and cold temperature performance (Akbarzadeh, 2021.).

13. Hybrid cooling-based battery thermal management using composite phase change materials and forced convection

The thermal performance of a PCM composite for a lithium-ion battery at the cell scale is highlighted in the current work (EL IDI, 2021.), based on heat flux measurements, and the outcomes were assessed.

The results of the experiments show that the suggested system keeps the temperature of cylindrical 18650 Li-ion batteries around 25°C, which is the ideal working temperature, and that the use of aluminum foam enhances the thermal management of the cell.

The findings show that the inclusion of MF greatly decreased the temperature difference between the cell and the MF-PCM composite because the MF-243 PCM composite had improved effective thermal conductivity.

According to the study, axial thermal conductivity is more important than radial thermal conductivity for maintaining the ideal temperature.

The findings demonstrated that the PCM can function superbly with the inclusion of metal foam due to an increase in thermal conductivity.

The existing findings are based on the cell level, but additional research should concentrate on the module/pack level for effective application. Durability studies and the system's performance in harsh environments should also be considered.

14. A novel battery thermal management system coupling with PCM and optimized controllable liquid cooling for different ambient temperatures

The major goal of the current paper is to design a coupled composite phase change material and liquid cooling thermal management system to enhance the lithium-ion battery pack's operational performance in continuous operation at various ambient temperatures.

The PCM serves as the primary heat-dissipating component that maintains the battery's ideal temperature within a safe range, and liquid cooling recovers the latent heat of the PCM during charging.

We check the channel number, coolant velocity, cell-to-tube distance, and cell-to-cell spacing. According to the simulation's findings, the battery's safe working temperature range is within the maximum temperature. To test the effectiveness of the suggested system in practice, the performance of the PCM material is monitored by adjusting the flow velocity and inlet temperature.

The temperature at different locations of the module was noticed and flow velocity was then controlled to effectively utilize the PCM under various ambient operating temperatures.

The increase in the cell-to-cell spacing improves the thermal performance but beyond 5mm there is no significant effect on this coupled system. The longer cell-to-tube distance beyond 2mm brings the better temperature of the battery pack during discharging but as these spacing increases it would not contribute to effective liquid cooling.

The design of the liquid cooling system is crucial to provide a balance between the thermal performance and structural complexity in the coupled system.

The role of the liquid cooling system is different at different ambient temperatures. During discharge conditions, the PCM acts as the main heat-dissipating element when the ambient temperature is less than the phase change interval. The cooling system recovers the PCM latent heat and reduces the temperature difference during charging.

However, the heat produced while charging and discharging and liquid cooling occurs when the outside temperature is greater than or equal to the PCM phase transition interval.

Additionally, because the ambient temperature has a major impact on the thermal performance of the battery pack and the recovery of latent heat from the PCM, it is critical to adjust the inlet temperature of the coolant in the CPLS in response to changes in the ambient temperature (Kong, 2020.).

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

In this study (Kiani, 2020.), a hybrid thermal management system was created by combining passive cooling using saturated copper foam and paraffin as the phase change material (PCM) with active cooling using alumina (Al_2O_3) based nanofluid.

According to experimental findings, the hybrid nanofluid cooling mechanism assures the battery's safe functioning under demanding operating circumstances.

When compared to a water-based cooling system, nanofluid cooling can extend the battery's operational time by 200 s (for nanofluid with a volume fraction of 1%), and 900 s (for nanofluid with a volume fraction of 2%), respectively, at a Reynolds number of 420.

The Paraffin phase transition is efficiently enhanced by the nanofluid, which reduces the rate of temperature increase.

The test results show that although the nanofluid cooling system keeps the battery temperature within the safe limit, the water-cooling system is ineffective under demanding working circumstances. Thermal conductivity and latent heat capacity are both improved by the Paraffin and copper foam properties.

The alumina nanofluid cooling offers improved thermal management outcomes, but it encourages pressure loss in the system, adding to the burden on the coolant pump. More study is needed in this area to address the pressure drop issues that are now present.

16. Development of a hybrid cooling method with PCM and Al2O3 nanofluid in aluminum mini channels using a heat source model of Li-ion batteries

This study (Mashayekhi, 2020.), describes a hybrid mode of BTMS with refined paraffin in block form (P 42-44 #107150) combined with porous copper metal foam as the passive part and aluminum mini-channel containing coolant flow was considered to be the active portion of TMS.

The experimental results show that the maximum temperature decreases with increasing flow rates and that both passive and active cooling techniques failed to keep the battery temperature below the 60°C safety limit at high discharge rates, whereas HTMS performed appropriately thermally under the same conditions.

In active and hybrid techniques, respectively, the impact of nanofluid reduces the maximum temperature of batteries by 15.5% and 8.5%. The nanofluid increases the liquid's thermal conductivity and convective heat transfer coefficient.

Battery temperature response was examined for passive, active, and hybrid thermal management systems.

Because of its weaker convection heat transfer coefficient, the passive approach produces poor outcomes. The active approach was unable to maintain temperature uniformity at higher heat generation power levels, but it can keep the temperature at a steady state level of 44.5^{o} C at 3.7 W.

When operating at a high-power level, the mass flow rate plays a crucial role. The HTMS claims to operate more effectively than active and passive techniques, and it can lower the battery's steady-state temperature by 19.5%.

17. Recent developments in the passive and hybrid thermal management techniques of lithium-ion batteries

The current article (Patel, 2020.), analyses several active and passive BTMS that utilize phase change materials (PCM) and heat pipes and offer superior thermal management outcomes regarding PCM and heat pipe-based BTMS's ability to offer better thermal management without consuming any power.

The current paper provides additional insight into the creation of practical and affordable BTMS with constrained power, volume, and weight.

The two types of BTMS were examined. Internal BTMS modifies the battery's interior to lower internal resistance, but it also reduces the battery's ability to store energy, making it unsuitable for modern use.

Active, passive, and hybrid BTMS are the external BTMS.

The air-cooled BTMS is simple in design and simple to place inside the battery pack, but it is more expensive since it has poorer thermal conductivity, a slower rate of heat removal, and a higher airflow rate required under intense charging and discharging circumstances.

Air cooling is more effective for BTMS, however liquid cooling adds volume, complexity, leakage issues, and costs.

It is necessary to conduct more studies on the application of thermoelectric BTMS, which have a small, affordable, and effective design and can heat or cool batteries.

Hybrid BTMS is required to improve the battery thermal management systems by using the following combinations, such as a PCM with air circulation, a PCM with liquid circulation, and a PCM with a heat pipe. Active and passive systems both have benefits and drawbacks.

The PCM with air cooling is effective at low temperatures, but they are unsuitable at higher ambient temperatures.

Although the PCM and liquid combination is more efficient at lowering battery temperature, the weight is very high because of the PCM and the pumping equipment that is utilized to move the liquid.

When compared to PCM-based BTMS, the installation of a heat pipe reduced battery temperature by 10–40% more. Additionally, the PCM and heat pipe can function as a passive BTMS since neither a pump nor a fan is needed.

It is extremely difficult to compare various types of BTMS because so many researchers used different battery types, charging/discharging rates, battery capacities, and environmental conditions.

The PCM and heat pipe-based hybrid BTMS, one of three varieties, can deliver the required battery performance with the least amount of electricity.

Since only the condenser portion of the heat pipe needs to be cooled, electricity isn't needed to make the flow of liquid or air across the battery pack as it is in other hybrids with BTMS.

18. Design and optimization of a hybrid battery thermal management system for electric vehicles based on a surrogate model

In this study (Zhang, 2021.), a hybrid thermal management system that combines liquid cooling, heat pipes, and phase change materials (PCM) is built initially, and a numerical heat transfer model is established afterward. A surrogate model of the thermal management system is built using the Adaptive-Kriging-High-Dimensional Model Representation (HDMR) approach, and the optimization design of the hybrid thermal management system is also carried out.

According to the experimental findings, the maximum temperature and temperature differential of the battery system are significantly influenced by the thermal conductivity of PCM, its thickness, the length of the heat pipe, and the velocity of the incoming water.

According to the optimization results, the optimized TMS has the best capacity to disperse heat, maintain temperature uniformity, and avoid the spread of thermal runaways under thermal abuse situations.

The significance of engineering design and TMS optimization for electric vehicles is demonstrated by this study.

19. Investigation on battery thermal management system combining phase changed material and liquid cooling considering non-uniform heat generation of battery

The prismatic $LiFePO_4$ battery pack is discussed in this study along with a novel coupled heat management technique using phase-changing material (PCM) and liquid pipes.

The temperature distribution was then determined using the heat generation model for the battery, and the impact of coolant velocity, pipe position, and ambient temperature on coupled system cooling performance was also examined.

Cycle tests at high rates were considered as a way to evaluate the system's thermal performance and optimize it.

The simulation results demonstrate that the current technology performs better in terms of cooling even at 45°C.

When compared to CPCM, the liquid-cooled battery pack performed better thermally, resulting in a smaller temperature gradient from top to bottom of the battery pack and better control of the maximum temperature (Tmax ≤ 50°C) of the batteries.

The highest temperature of the batteries with CPCM was 54°C, but it was 47°C with PLPS, demonstrating that it is possible to lower the temperature using the PCM-liquid pipes system (PLPS).

Additionally, the liquid percentage was less than 30%, which indicates that the collected heat is eliminated by the liquid cooling system, relieving the heat buildup in the PCM and further enhancing cooling effectiveness.

These findings showed that even in challenging operating conditions, PLPS performs better at cooling the batteries and expelling heat buildup from the PCM. The performance of a BTMS will be significantly impacted by design factors such as liquid velocity (0.2 m/s for the existing system) and pipe positioning; therefore, additional research should focus on this area to optimize BTMS performance for greater cooling efficiency.

The experimental findings of the study show that the position of pipes has a significant impact on the thermal performance of the battery pack and that changing the position of pipes may enhance system efficiency.

The Tmax and $\triangle T$ of the battery pack were decreased by increasing the liquid's velocity in PLPS, however, under discharge conditions, velocities greater than 0.2 m/s did not contribute to any improvement in heat dissipation.

The liquid fraction of PCM at the top was improved and a higher pipe further decreased the Tmax.

The influence of ambient temperature on the thermal performance of PLPS was mainly reflected in the initial state of PCM. Following that, it no longer plays a substantial role because of the air convection heat transfer (Ping, 2021.).

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

For a Li-ion battery pack with 40 cylindrical cells, this paper proposes a novel technology known as delayed cooling that blends liquid cooling with PCM. The technology is perfect for low flow rate, and high discharge rate scenarios. The experimental findings demonstrate that to keep the temperature under the limit, a high inlet water temperature is needed (Cao, 2020.).

The system's power consumption is reduced by a large amount as a result of delayed cooling because it lowers the temperature both within and between cells.

High-rate discharge situations are best for this hybrid cooling system. According to this research, the PCM cools the battery pack first, and continuous liquid cooling doesn't start until the battery reaches the phase transition temperature of 41^{o}C. As a result, the maximum temperature is lowered and the latent heat of the PCM is recovered. In this step, the PCM is essential for controlling the temperature.

The simulation demonstrates that the temperature of the battery pack can be successfully decreased by a heatsink with a counterflow. A high inlet temperature of the cooling water of about 40^{o}C should be the top priority to maintain the battery temperature at a safe level of 55^{o}C.

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

This study (Cao, 2020.), discusses the design of a hybrid thermal management system that uses PCM (matrix comprised of expanded graphite/RT44HC composites) and liquid cooling. Water cools cylindrical batteries after entering the PCM through a cold plate.

The goal of the study is to ascertain how a battery's PCM content, water inlet temperature, and flow rate affect temperature rise and battery temperature uniformity.

Keeping the water temperature below 40 °C and as close to the ambient temperature as possible would be the best control strategy, according to the results.

A desirable flow rate is needed for effective cooling. High mass percentage RT44HC-containing composite PCMs function effectively at high discharge rates. A numerical model was developed to help understand temperature distribution and clarify the roles of latent heat in addition to the contour plot of the PCMs' melting fraction.

The study also concludes that composite PCMs with high PCM mass percentages can only accomplish a minimum temperature rise and slight temperature changes because of the high latent heat density. The existing numerical model can be used to further optimize the system, which also improves the performance of the hybrid thermal management system.

22. Effect of channel configurations on the thermal management of fast discharging Li-ion battery module with hybrid cooling

For pouch cell Li-ion batteries, a unique BTMS with liquid cooling and a PCM integrated with cold plates grooved with a converging serpentine microchannel is designed in the current study. This paper (Faizan, 2023.), thoroughly examines the impact of various channel cross sections, including square, elliptical, slot, hexagonal, and kite, mass flow rate, and volume fraction of nanofluid on maximum temperature and maximum temperature difference.

Excellent findings from the experiment show that, even under challenging operating conditions, hybrid cooling maintains the module temperature below the safe operating level.

Better cooling performance is provided by the serpentine microchannel cross-section compared to the kite cross-section. The maximum temperature and temperature difference inside the battery pack are both dramatically decreased by the nanoparticles.

The thermal safety of Li-ion batteries, particularly those operating at high discharge rates, is also examined in the current study. Channel grooves are constructed on cold plates to achieve temperature rise and uniform temperature under a safe value.

23. Novel hybrid thermal management system for preventing Li-ion battery thermal runaway using nanofluid cooling

An effective energy-saving BTMS using PCM cooling, nanofluid cooling, and heat insulation materials is suggested in this research to lower the likelihood of thermal runaway propagation.

The analysis was completed by merging the electrochemical, thermal, and fluid models, and the model's applicability was examined. A study is done on the impact of nanoparticle volume fraction and flow rate (Ouyang, 2023)

To prevent the spread of thermal runaway between batteries, this work examines the balance between heat insulation and dissipation. To prevent the prompt and quick transmission of heat that has been collected in the system, flexibility in the system's architecture is required.

III. CONCLUSION

The automotive industry is steadily shifting toward new technologies because of the quick depletion of fossil fuels and climate problems brought on by the transportation sector. The transition to electric vehicles is one of the promising answers for the transportation sector's energy crises and climate challenges. The Li-ion batteries, which are the primary component of an electric vehicle, have numerous obvious advantages over other types of batteries now in use. However, it is sensitive to external factors, and heat generated during charging and discharging would shorten the battery's lifespan and eventually cause thermal runaway. Battery thermal management systems (BTMS) are therefore essential for maintaining a constant temperature in battery cells, modules, and packs as well as for managing the greatest temperature development.

Many different battery temperature management technologies, including active, passive, and hybrid cooling, have been created. Due to the benefits of using multiple approaches, the hybrid BTMS is beneficial in regulating and maintaining the consistency of temperature in the battery. Hybrid BTMS is receiving more attention as a result of expanding research into various battery thermal management systems and the fact that these systems provide a superior response to many harsh conditions.

Reviewing research and development in the field of hybrid management cooling systems is the primary goal of the current work. The main conclusions are:

Despite having a simple design, air-based systems are unsuitable for applications requiring high temperatures. Liquid cooling methods have a higher heat transfer efficiency than air-based systems, but they are large and raise the price of battery thermal management systems. The advantages of passive cooling methods like PCM and heat pipes allow for their efficient use in hybrid systems.

Heat pipe and air/liquid, PCM and heat pipe, PCM and air/liquid, Liquid and air, and thermos electric coolers (TEC) among others are some of the different hybrid system combinations.

Hybrid cooling systems utilizing fins, nanofluids, and PCM, coupled with microchannel-based would decrease the cost and would be a better solution in this field under high charging and discharging situations.

Researchers in this subject have proposed several different combinations, including the use of nanoparticles in batteries, combining cold-plate/PCM/heat-pipe, direct-two-phase/PCM/heat-pipe, and other ideas. The main problems PCMs suffer because of their low thermal conductivity difficulty can be somewhat mitigated by the use of carbon fiber, aluminum fins, carbon nanotubes, polyurethane foam, metal foams, and expanded graphite.

Cell spacing, PCM mass, PCM thickness, thermal conductivity, and specific heat capacity are all performance-influencing factors that should be carefully optimized.

Since their combination performs well at high discharge rates, the PCMs' large latent heat and the high thermal conductivity of heat pipes should be effectively utilized to create an optimum thermal management system. Instead, PCM/heat pipes should be properly chosen in terms of material, size, and layout.

The battery pack design structure, the type of air circulation within the pack, battery cell topologies, and battery spacing are all crucial factors for building a reliable BTMS.

When the airflow is uniform, a hybrid thermal management system with air cooling operates effectively, and parallel air flow enhances the heat transfer by raising the convective heat transfer coefficient.

The greatest methods for obtaining the best cooling performance are cross-battery cell arrangements, J-type battery shell modules, parallel airflow, and uneven battery cell spacing.

For PCM-based hybrid cooling with water channels, a series/parallel design works well. With this combination, PCM's lifespan is increased while its maximum surface temperature is decreased. It lowers the maximum temperature and temperature gradients at the cell-to-BTMS interface.

The water flow rates for PCM and cooling water pipes based on HBTMS should be modified by the battery discharge rate.

To increase performance the performance of the hybrid method using PCM with an air-cooling system, cell architecture, module compactness, and PCM thickness should be carefully selected.

The evaporative cooling system performs successfully in a hybrid cooling system with heat pipes, maintaining the cell's temperature in the 22 range. According to the experimental findings, a heat pipe-based cooling system using an evaporative cooling technique decreased the maximum temperature at the module by 23.8% and the maximum temperature at the cell by 35.8%.

Utilizing the PCM-assisted heat pipe, which results in a 40.86% heat reduction, will allow the lithium-titanate battery cell to be cooled more efficiently. This is because, during the heat exchange, virtually no thermal contact resistance is present as the heat generated inside the cell is concurrently transported through the PCM and heat pipes.

Since the temperature uniformity of the battery module is 73.4% better in the hybrid mode of heat cooling than it is with natural cooling, the air cooling and heat pipe with copper sheets type hybrid BTMS widens the potential for improving the performance of the existing heat pipe hybrid system.

The inlet air velocity should be raised if the ambient temperature exceeds the normal range for efficient cooling in BTMS.

The hybrid LCP is 36% lighter than a volumetrically identical normal aluminum LCP and has good cooling characteristics as well as the ability to heat the battery in cold weather. The greatest alternative for BTMSs is because of their lightweight structure, effective cooling, and cold temperature performance. It also decreases pump energy usage.

Due to an increase in thermal conductivity, the addition of metal foams to PCM-based hybrid cooling increases the cooling effectiveness of BTMS.

In a PCM-based optimized controllable liquid cooling system design the cell-to-cell spacing, cell-to-tube distance, channel number, and coolant velocity are checked for optimum performance. The results observed that optimum cell-to-cell spacing is 5mm but cell-to-tube distance is limited to 2 mm.

Additionally, because the ambient temperature has a major impact on the thermal performance of the battery pack and the recovery of latent heat from the PCM, it is critical to adjust the inlet temperature of the coolant in the CPLS in response to changes in the ambient temperature.

At a Reynolds number of 420, nanofluid cooling can increase the operational time of the battery by 200 s (for nanofluid with a volume fraction of 1%), and 900 s (for nanofluid with a volume fraction of 2%).

Although pressure loss in the system is encouraged by the alumina nanofluid cooling, which improves thermal management outcomes, it places additional stress on the coolant pump. For a better improvement in the pressure drop induced by nanofluids, additional study should be required in the inclusion of nanofluids in hybrid BTMSs.

The hybrid mode of BTMS with refined paraffin in block form (P 42-44 #107150) combined with porous copper metal foam and aluminum mini-channel containing coolant flow lowered the battery's steady state temperature by 19.5%.

Because the condenser section of the heat pipe only needs to be cooled, the PCM and heat pipe-based hybrid BTMS may provide the necessary battery performance with the least amount of electricity.

The peak temperature of the batteries with the PCM-liquid pipes system (PLPS) was 47°C, whereas it was 54°C with the CPCM, proving that the temperature may be lowered.

Increasing the liquid's velocity in PLPS reduced the Tmax and T of the battery pack, although the best results were attained at a coolant velocity of 0.2 m/s. Only the initial state of PCM is significantly affected by ambient temperature, while greater pipe decreases the maximum temperature.

The system's power consumption is significantly reduced by the delayed liquid cooling method, which also results in significantly lower temperatures inside and between cells. This can therefore handle instances of high-rate discharge.

Even at high rate discharged conditions, the liquid cooling and a PCM coupled with cold plates grooved with a converging serpentine microchannel hybrid system offer improved cooling performance.

The construction of channel grooves on cold plates should be done with the utmost care to achieve a temperature rise and uniform temperature below a safe value.

According to studies, utilizing a hybrid cooling system with PCM cooling, nanofluid cooling, and heat insulation materials is a better strategy to reduce the risk of thermal runaway since it efficiently balances thermal insulation and dissipation.

The review article concludes that the best way to keep the battery temperature at a safe level is to use a hybrid thermal management system (TMS), which combines an active TMS and a passive TMS.

It also concludes that a hybrid system made up of heat pipes, phase change materials, and nanofluids enables long-term battery operation at high discharge rates. Thus, future research should appropriately take into account the pressure loss issue with nanofluids.

When developing battery thermal management systems, it is important to pay closer attention to the ambient temperature, air velocity, coolant velocity, cell spacing, PCM mass, PCM thickness, thermal conductivity, specific heat capacity, battery pack design structure, the type of air circulation within the pack, and battery spacing.

The performance of current battery thermal management systems is considerably increased by optimizing these elements in conjunction with a hybrid cooling technique. To create an efficient battery thermal management system in the future, further research should be concentrated on PCM and heat pipe-based hybrid cooling systems by taking into account all performance-influencing aspects.

Thermal runaway risks could be reduced by properly balancing heat insulation and dissipation in BTMS, which should also be considered when designing BTMS.

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