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Review of the Merits and Critical Issues of Lithium-Ion Battery Thermal Management Strategies

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Abstract: Most of today's all-electric cars and plug-in hybrid electric cars (PHEVs) are powered by lithium-ion batteries, which would replace vehicles currently powered by fossil fuels and address the energy issue in the transportation industry. Although they have a high energy density, a long lifespan, long-term performance, and low self-discharge, the heat generation in the battery reduces their performance. Therefore, controlling heat and maintaining temperature homogeneity inside batteries is a critical issue in research and development. When used properly, a battery thermal management system (BTMS) can maintain the cell's maximum highest temperature and maximum temperature difference at an ideal level. The strengths and drawbacks of several BTMS types, such as active, passive, and hybrid systems, are critically examined in this study. It also discusses the possibilities of incorporating a waste heat recovery system into BTMS to cut down on power consumption and running costs for both BTMS and hybrid electric vehicles (HEVs). The current review discusses the benefits and drawbacks of employing nanofluids in battery temperature management systems. Additionally, the effectiveness of an optimized Li-ion battery pack's intelligent thermal management system is examined.

Index Terms **– Electric Vehicle, Lithium-Ion Merits and critical issues, Thermal Management, Direct evaporative cooling, Phase change material, Immersion based cooling**

I.INTRODUCTION

The use of fossil fuels is uncontrollable due to vehicle population and mainly dependent on fossil fuels which are a non-renewable energy resource. Moreover, the pollutants from vehicles contribute to air pollution that leads to global warming. Therefore, world transportation sectors face mainly two issues, depletion of fossil fuels that leads to energy crisis and global warming issues due to air pollution from fossil fuels combustion. A viable alternative to fossil fuels is electric vehicles which are operating on battery systems with zero tailpipe emissions. Over time, quite a few types of batteries such as lithium-ion batteries, Hybrid nickel-metal batteries, SLA, or lead acid batteries have been used for electric cars, lithium-ion batteries being the most common due to their high energy capacity, power density, voltage, cycle life, and low self-discharge rate. The demand and research on the development of Lithium-ion batteries is increasing due to its wide range of applications such as electronics, automobiles, aerospace, etc. By 2025, the global demand for Lithium-ion batteries is likely to cress about $100 billion with the automobile sector leading as the fastest growing sector. However, the lithium-ion batteries in electric vehicles have to function within a temperature range because the working environment of EV's varies in different regions. The higher and lower operating conditions will affect the life of the battery. The considerable amount of heat generated in a battery is due to chemical reactions and internal resistance during the charging and discharge process. It is important to control the temperature rise in the cell and also achieve uniform temperature across the module and extend battery life. If the heat is not controlled, that may lead to overheating of the battery and thermal runaway. The ideal working range of the battery is between 15 °C and 40 °C and the temperature difference between cells should lie within 5°C.
The fast degradation of the battery is mainly due to extreme fast charging, and cold climate. Therefore, the most effective battery thermal management systems (BTMS) are crucial for the safe operation of a battery and for improving its lifecycle.

The methods for thermal management of batteries that are now known are generally categorized into three groups: active, passive, and hybrid, which combine active and passive systems. The energy is used immediately for cooling in active methods, such as forced convection airflow cooling systems. The cooling process in passive technologies, such as natural convection heat transfer, heat transfer through heat pipes, and heat management employing phase change material (PCM), is carried out without the use of any external energy.

The current paper primarily focuses on research and reviews made by researchers on heat generation in Li-ion batteries, different types of thermal management systems such as air cooling, liquid cooling, phase change material, phase change material with nanofluids and hybrid systems, direct evaporative cooling, heat pipes, and optimized thermal management systems. Additionally, it focuses on the effectiveness of an intelligent thermal management system, which can save up to 76.4% of energy.

This study comes to the conclusion that more research needs to be done on efficient thermal management techniques using waste heat management systems, since this will increase the performance of Li-ion batteries and Electric vehicles using them.

II. DESCRIPTION OF REVIEWED WORKS

This paper reviewed fifteen works related to Lithium-Ion Batteries. A viable alternative for fossil fuel-powered vehicles that contribute to global warming is an electric vehicle. Future electric vehicles will take over most of the problems caused by traditional, quickly diminishing fossil fuels. The working environment of EV's varies in different regions. Because of this, the lithium-ion batteries in electric vehicles have to operate within a temperature range, which makes the thermal management procedure more difficult. Heat generation is inevitable and it is important to control temperature rise in the cell and achieve more uniform temperature distribution across the module and pack for an extended battery lifetime. A li-Ion battery performs excellently in the heat range of 15-35°C.. Though lithium-ion batteries used in electric vehicles have more energy density, long shelf life, low self-discharge, but the higher and lower operating temperature will seriously affect the life of the battery. Compared to other types of batteries, Lithium-ion batteries have many advantages, making them more promising to use in industries like automobiles, electronics, aerospace and so on. But their performance is declined due to heat generation in the lithium-ion cell. The basic purpose of a battery thermal management system is to maintain the maximum temperature and maximum temperature difference below the safety level.

1. Thermal management for Li-ion batteries

In this study (Shahjalal, 2021) , the authors highlighted the conventional thermal management methods of lithium-ion batteries, including air cooling, liquid cooling, phase change material cooling (PCM), refrigerant cooling, heat pipe cooling, and thermoelectric element. Air cooling and liquid cooling systems are bulky in nature, PCM possess low thermal conductivity, the requirement of an extra cooling system in refrigerant cooling makes it design complex, and heat pipe cooling systems prove to have a high risk of leakage. The present study pointed out the importance of improving the thermal efficiency of the existing systems by mixing one or more of the traditional methods and reducing the thermal resistance of the materials. The paper also included the findings on the cell level, module level and pack level cooling strategies and battery thermal modeling techniques.

2. Thermal management of lithium-ion batteries for electric vehicles

This paper (Zhang, 2022) reviewed the various thermal management techniques of lithium-ion batteries at low and high temperatures and the merits and demerits of various techniques are highlighted. Lithium-ion batteries have problems at low temperature and high temperature. The reviews pointed out the heating methods such as air heating, liquid heating, PCM heating and Peltier effect element (heat pipe) at low temperatures. By comparing different methods of heating, the review highlighted the point that the intermittent self-heating method is the most accepted one since it provides temperature uniformity inside the LIBs. Furthermore, it emphasized the point that the PCM and cold plate cooling technique are effective when operating at very high temperatures. The review comes to the conclusion that PCMs are suitable for both winter heating and summer cooling if the right PCMs are utilized.

3. Effect of heat generation and various thermal management systems for lithium-ion battery used for electric vehicle

This paper (Choudhari, 2020)reviewed the actual mechanism of heat generation and its effect on each component of the lithium-ion cell. The study reveals that total heat generation in a battery is categorized into reversible heat and irreversible heat and it is observed that heat generated at the anode and cathode may be positive or negative depending upon the charging and recharging of a battery cell and for a complete cycle its value is neglected in most of the HEV and EV applications. They further pointed out that more than 70 % of the heat generation in batteries is due to irreversible heat generated at electrodes, electrolyte and current collector. The heat released during charging is higher than the discharging process. Heat generation mainly affects the electrodes, electrolyte and separator and capacity of the battery. Thermal runaway in the battery is due to overheating, overcharging, and short circuits. Various cooling methods are also reviewed in this article by taking the numerical and experimental work done by many researchers. The review shows that the maximum temperature can be reduced up to 30 % by adding metal foam to phase change material since it is a good option as a thermal management system. It also reviewed the challenges in battery technology. The main noticeable challenges are battery life (500 number of cycles), operating conditions (maximum temperature and temperature differences are within 15°C- 40°C and 5°C with a C-rate up to 2°C.), cost and environmental impact.

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

In this study, (Kiani, 2020) the authors analyzed the battery thermal management systems for pouch lithium-ion battery modules. The experiments were conducted for pure water and nanofluid type battery thermal management systems combined with copper foam filled with paraffin wax as a phase change material with massive heat storage potential. It is a combination of active and passive cooling methods comprising nanofluid cooling, heat sink, and embedded paraffin-metal foam composite. The test results indicate that the thermal conductivity of the system is increased due to presence of suspended particles in nanofluids and addition of nanofluids to base fluid will improve the convective heat transfer coefficient. Different oxide-nanofluid slurries were tested and among all AgO was the best candidate. The maximum temperature of the battery is reduced by about 4.1 K by AgO/water nanofluid with %2 volume concentration compared to the battery thermal management systems based on pure water.

The experimental results indicate that the permissible maximum temperature of the battery was significantly reduced by using an integrated cooling method, including, nanofluid cooling and phase change material -metal foam cooling. This study demonstrates that employing nanofluids to increase heat transfer has negative effects, such as a pressure drop in the working fluid flow. The experimental results reveal that out of the three nanoparticles—alumina (Al2O3), copper oxide (CuO), and silver oxide (AgO), AgO nanoparticles have the utmost effect on reducing battery temperature.

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

This article (Patel, 2020) mainly highlighted active, passive and hybrid thermal management systems and major focus is on passive BTMS using phase change material (PCM) and heat pipes. This paper gives an insight into the necessity of the development of practical and economic BTMS with the constraints of limited power consumption, weight and volume. The study reveals that it is difficult to compare the performance of the battery using different BTMS due to different battery types, different capacity, different charging/discharging conditions and ambient conditions. The air/liquid BTMS have limited heat transfer coefficients, thus may not be suitable at extreme ambient conditions and high charging and discharging rate. Even though the thermoelectric BTMS provides better outcomes, research on this area is less and needs more research work to explore its possibilities.

This article gives an insight into the necessity of the development of practical and economic BTMS with the constraints of limited power consumption, weight and volume. The major focus of the study is on PCM and gives the information that PCM based BTMS improves battery thermal performance better than air-based and liquid-based BTMS, but its lower thermal conductivity is a limitation and can be improved by the addition of expanded graphite, carbon fibers, graphene, metal mesh, metal foam or nanoparticles into PCM or providing fins of optimum number and noval shape for better thermal management. The study showed that the size of the PCM affects battery performance, and because of weight and size restrictions, it may be placed inside the battery pack.

The paper also emphasized the requirement of analysis on metal fibers enhanced PCM based BTMS along with the different metals. According to the findings of the present study, among the three types of hybrids BTMS, including PCM with air circulation, PCM with liquid circulation, and PCM with heat pipe, PCM and heat pipe-based BTMS can deliver required battery performance with the least amount of power. This article gives an insight into the necessity of the development of practical and economic BTMS with the constraints of limited power consumption, weight and volume.

6. Emerging challenges in the thermal management of cellulose nanofibril-based supercapacitors, lithium-ion batteries and solar cells

This paper (Zhang Y. H., 2020) highlights the capacity of CNF (Cellulose nanofibrils)-based materials for efficient thermal management of energy storage electronic such as supercapacitors, lithium-ion batteries, and solar cells. The present study is concentrated on the thermal management of Cellulose nanofibrils based lithium-ion batteries and it indicates that adjustable microporous in the CNF-based separator allows lithium ions to pass through while blocking electrons.

The test results show that the CNF-based separator also exhibits adequate liquid absorption and moisture retention capabilities, as well as good electrolyte wettability. The CNF composite film offers excellent mechanical and air permeability qualities and due to its thin thickness, increases the electrode surface area thus decreasing resistance and heat loss. The thorough analysis shows that the CNF-based gel electrolytes have great ionic conductivity and stability, indicating promising application possibilities and providing heat channels to reduce heat accumulation inside batteries.

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

This paper (Jiang, 2020) highlights two types of battery thermal management systems (BTMS) based on the phase transition principle which includes the thermal management system based on the solid-liquid phase transition principle and the thermal management system based on the liquid-gas phase transition principle. Existing models are critically analyzed to project the heat distribution area and temperature rise patterns, as well as to develop and build new thermal management systems or models.

This study reviews and suggests suitable optimization strategies for future battery heat management system research. 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 significantly improved the enthalpy of phase transition and specific heat capacity so that this could be used as a thermal management method in the future. Expanded graphite, metal mesh, metal foam, and metal fins are less expensive alternatives to nanomaterials and graphene, that can greatly increase 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. The nanofluids employed as coolants in the hybrid BTMS active thermal management module are not yet ready for practical deployment. This technology of battery thermal management system based on boiling cooling can effectively reduce the maximum temperature of the battery and the temperature difference of the single cell in the battery module is still in the research stage, and its commercial application is not mature

8. Design of an Optimized Thermal Management System for Li-Ion Batteries under Different Discharging Conditions

An optimized indirect liquid cooling system proposal was made in this paper (Bhattacharjee, 2020) for kW scale Li-ion battery stack. A comparative study on various types of cooling methods is made on a 70Ah, three cell stack Li FePO4 battery at high discharge rates., and arrived at a conclusion that liquid cooling systems are capable of controlling the temperature more than air cooling which can control the temperature to some extent. Refrigerant cooling systems offer promising results with more power consumption. Further improvement in the liquid cooling system can be achieved by increasing the contact area between the coolant and battery, therefore an immersion-based liquid cooling system has been designed.

In this paper, a COMSOL Multiphysics based Li-FePO4 battery stack has been modeled and the temperature rise inside the stack has been observed under different discharging rates. The study reveals that in immersion-based cooling as the battery module is immersed in the coolant maximum heat is dissipated within a short period of time, which improves the life cycle of the battery for long term usage.

9. Thermal management for prevention of failures of Lithium-ion battery packs in electric vehicles: A review and critical future aspects

This paper (Aswin Karthik, 2020) mainly focuses on the safety issues associated with Li-ion batteries and discusses various cooling methods developed to alleviate the problems. The paper also addresses some research gaps related to the recovery and use of low-grade heat produced by the battery pack. The study indicates that the Air-based BTMS is dependent on ambient conditions, hence they may not be efficient at higher and lower ambient conditions and the air-cooling heat transfer coefficient is less resulting in accumulation of heat in the battery pack, but liquid-based systems are better at adverse operating conditions with same power consumption. The flow boiling techniques are preferred over single-phase convection heat transfer to enhance the thermal performance of the BTMs, but the selection of coolants and leakage problems should be considered.

The study also focuses on the Systems based on phase change material (PCM) are better than air and liquid-based systems in terms of weight, power consumption, and thermal performance. PCM's low thermal conductivity can be improved through the use of composite PCMs, which offer better thermal conductivity compared to conventional PCM. Additionally, PCM has low thermal stability over time, which is why heat pipes are used instead of PCM. It also addresses some research gaps related to the recovery and use of low-grade heat produced by the battery pack. In one of the studies, the pool boiling mechanism was implemented in HEVS in such a way that the vapour produced can be used for power generation in the internal combustion engine (IC engine) or to charge batteries through a generator.

The present paper highlights the importance of developing waste heat recovery systems in batteries for reduction in power consumption, and reduction in operating cost of BTMS and HEVs.

10. Cooling capacity of a novel modular liquid-cooled battery thermal management system for cylindrical lithium-ion batteries

A new modular liquid-cooled system for cylindrical lithium-ion batteries has been proposed in this paper (Wang, 2020), and a numerical simulation and carried out an experiment to investigate how coolant flow rates and cooling modes (Serial cooling, parallel cooling) influence battery module thermal behavior. The results indicated that the increased coolant flow rate has a significant effect on lowering the maximum temperature and improving the temperature uniformity of the battery module in a certain flow range. However, beyond certain flow rate values, the higher the flow rate, the less significant the impact on cooling while the power consumption increases. The study confirmed that the flow rate should be selected to maintain the balance between cooling effect and power consumption. The serial cooling mode and parallel cooling mode are compared in this paper and the study shows that parallel cooling maintains the uniformity of temperature in the battery module much better due to faster removal of heat and helps to attain the temperature of batteries to a stable state in a short time. Considerable decrease in temperature difference than decrease in maximum temperature indicates that parallel cooling plays a vital role for keeping temperature uniformity constant.

Three flow direction layouts are designed, and maximum temperature of the flow direction layout III is 35.74 °C, and the temperature difference is 4.17 °C, fulfilling the requirement that the maximum temperature less than 40 °C, and the temperature difference less than 5 °C.

11. Experimental study of a direct evaporative cooling approach for Li-ion battery thermal management

In this paper (Zhao, 2020) an air based BTMS is modified by integrating a direct evaporative cooling (DEC) system that reduces the inlet air temperature for enhanced heat dissipation. The effects of relative humidity and air flow rate on the DEC system are critically analyzed using experimental data from 18650-type batteries and a 9-cell battery pack.

The suggested DEC, forced air cooling, and natural convection cooling are compared in terms of maximum temperature, temperature difference, and battery capacity fading. The experimental results show that the DEC system offers effective cooling performance compared to air cooling due to lower intake air temperature which is caused by the absorption of sensible heat of air during the water evaporation process and low relative humidity is preferred for better cooling. Power consumption and fan noise can be reduced by implementing DEC since it can perform well even at low fan power. A DEC tunnel with reciprocating air flow is constructed and experimental results show that the temperature uniformity is achieved with a maximum temperature difference of 4.5C. The present paper has demonstrated that the proposed DEC system can increase the usage of LI-ion batteries under adverse and challenging operating conditions.

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

This paper (Behi, 2020) proposed the idea of a hybrid thermal management system (TMS), including air cooling and heat pipe for electric vehicles and also forced air cooling and natural air-cooling thermal management techniques are compared. A battery module consisting of 24 cylindrical cells are taken into consideration for the experimental purpose. According to experimental findings, the maximum module temperature for forced-air cooling, heat pipe, and heat pipe with copper sheets (HPCS) reaches 42.4 °C, 37.5 °C, and 37.1 °C respectively. Numerical and experimental results were compared, and the results show that natural air cooling causes the battery temperature to rise above the ideal working range (between 15 °C and 40 °C), and also non-uniform temperature distribution causes the battery module to perform poorly, while forced convection ensures the battery's safety.

According to the results of experiments, adding copper sheets to each heat pipe and cell would enhance the effective contact area, which will speed up heat transmission. According to the experimental outcomes, forced-air cooling, heat pipes, and heat pipes with copper sheets (HPCS) all enhance the temperature uniformity of the battery module by 39.2%, 66.5%, and 73.4%, respectively.

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

In the current study, (Hekmat, 2020) two hybrid TMSs including PCM and cooling water pipes are presented for a Li-ion module with high-capacity prismatic cells. The thermal performance of the active, passive, naturally ventilated and the hybrid thermal management systems are experimentally evaluated. The experimental evaluation is based on the maximum temperature and the maximum temperature difference under seven cases (two naturally ventilated, one passive, two active and two hybrid systems). The maximum temperature and maximum temperature difference are dangerously high during air cooling, significantly reduced with PCM or silicon oil. The experimental results indicate that the hybrid system provides a more uniform temperature distribution and less time is required for the cells to cool down compared to other systems.

The present paper concludes that hybrid TMSs are more superior than all other systems.

14. A Lithium-ion Battery Thermal Management Design Based on Phase Change Material, Heat Pipe and Spray Cooling

The focus of the present work (Lei, 2020) is on the design and testing of a compact and efficient battery-thermal-management system to provide heating and cooling services and be able to protect the battery from low temperature degradation. It is observed that the PCM (hydrated salt) meets the cooling demands, the spray cooling actuates when temperature exceeds beyond 40 C °, thus providing higher heat transfer efficiency. This system offers many advantages over other thermal management techniques such as compact size, reasonable volumetric energy density, and good energy-utilization efficiency.

Test results reveal that the waste heat is recovered and utilized by the battery in low temperature conditions. To use the technology in electric vehicles, more research should be required in the future.

15. An intelligent thermal management system for optimized lithium-ion battery pack

In the present paper (Zhuang, 2021) develops a new battery thermal management system by combining battery pack structure optimization and the cooling strategy design. Battery pack with the hollow spoiler prisms with aligned arrangement improves the heat dissipation capacity and, the reciprocating air flow is applied in this design improves uniformity of temperature in the cells. The cooling performance of the method is based on a series of simulations and indicates that the spoiler prisms have enhanced cooling performance, but poor uniformity in temperature, hence optimal size of the spoiler prism is 8mm.

The reciprocating air flow method provides better uniformity in temperature but consumes more energy when the reciprocation period is too short. The study finds that 400 seconds is the ideal reciprocation period. According to the study, the maximum temperature differential between cells is now only about 0.6 ºC instead of 1.5^{o} C.

In comparison to traditional cooling systems, the current approach can save energy up to 76.4%.

III. CONCLUSION

During the current scenario, electric vehicles play an important role in tacking the energy crisis in transportation sector. The Li-ion battery is the energy storage device in electric vehicles due to its wide range of advantages. The main issue associated with Li-ion batteries is the thermal management for that many types of battery thermal management systems have been developed. The review paper presents the effectiveness of various battery thermal management systems for Li-ion batteries. The merits and challenges of air-cooling system, liquid cooling system, phase change material (PCM) cooling, hybrid cooling, heat pipe cooling, PCM with nanofluids are presented. Heating and cooling are required under lower and higher operating temperatures to improve the life of the battery and to avoid degradation.

Air cooling method is no longer a good alternative due to rise of temperature above normal working range and exhibits poor temperature uniformity while forced convection ensures safety of battery. The air-cooling system efficiency can be improved by increasing the air flow rate but studies in field reveals that increase in flow rate beyond a certain value increases the power consumptions. More research work should be needed in this area to compromise the air flow rate and power consumption for better air-cooling systems.

At low temperature operating conditions, intermittent self-heating method is the most accepted one. PCM and cold plate cooling technique are effective when operating at very high temperatures. PCMs are suitable for both summer cooling and winter heating. The major issues associated with PCM is its poor thermal conductivity.

The thermal conductivity is improved by the BTMS with PCM and nanofluids like Silver Oxide (AgO), however the working fluid flow experiences pressure drops. By reducing the viscosity of the nanofluids to a moderate level, the pressure drop in the working fluid flow can be eliminated, improving the system.

Expanded graphite, carbon fibers, graphene, metal mesh, metal foam, or adding the ideal number and shape of fins to PCM for improved thermal management are all possible additions. However, the cost of graphene and nanomaterials is considerable, and the incorporation of fins reduces the PCM's melting time, which lowers the rate of heat absorption. Immersion-based cooling is a form of modified liquid cooling technique with a very quick heat removal rate that can also be extremely beneficial for Li-ion battery storage applications.

Out of the two modes of cooling, parallel cooling is very effective for temperature uniformity in battery module than serial cooling.

Under adverse and challenging operating conditions, direct evaporative cooling system is better.

PCM and heat pipe-based BTMS can deliver required battery performance with the least amount of power, but heat pipe cooling systems proves to high risk of leakage.

The hybrid system provides more uniform temperature distribution and less time is required for the cells to cool down compared to other systems.

Combining the Phase Change Material, Heat Pipe and Spray Cooling method provide heating and cooling services and able to protect the battery from low temperature degradation.

The paper concludes that, the use of appropriate BTMS under various operating conditions, the use of PCM with additives, direct evaporative cooling strategy, utilizing parallel mode of cooling in various BTMS, combining heating and cooling services, use of hybrid systems, use of waste heat recovery systems, and optimizing battery pack design will all improve heat distribution, allowing the Li-ion battery to be used effectively to meet the requirements of increasing fast charging methods in the future.

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