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Research progress on cooling methods for lithium-ion batteries in electric vehicles

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Abstract: *The cooling system is the important technological component of the power battery. As a result, this study explains and evaluates the lithium battery pack's heat dissipation and cooling techniques. The battery pack's cooling techniques include liquid cooling, air cooling, phase change cooling, heat pipe cooling, and composite cooling technique. In order to provide some relevant information for the follow-up research on the creation of new energy vehicles, this paper highlights the various techniques of battery cooling and their benefits and drawbacks from a wide range of literature studies.*

Keywords: *lithium-ion battery; heat dissipation; cooling method; cooling effect; heat dissipation efficiency*

1. Introduction

The energy and environmental benefits of new energy vehicles are becoming more and more significant, reflected in energy saving and low pollution. Lithium-ion batteries are being used for hybrid and electric cars (HEV/EV) because of their great cycle stability and high energy density. As long as the temperature maintains within a specified range, the batteries will have increased capacity. The capacity of the battery will diminish at an excessive temperature since irreversible processes proceed more quickly, generates a lot of heat. Additionally, as lithium-ion battery safety concerns worsen due to the pursuit of high energy densities and capacities, there is also a risk of thermal runaway and abuse. [1] Therefore, it is vital to assess the battery's thermal behavior and build an appropriate battery thermal management system in order to guarantee that it runs within a reasonable temperature range (BTMS). Liquid cooling, air cooling, phase change cooling and heat pipe cooling are commonly used in battery thermal management system. They all have their own benefits and drawbacks, whether it is a single cooling method or a number of connected cooling methods. This work compiles pertinent literature, analyzes and explains the heat dissipation methods of lithium batteries in an effort to further increase the heat dissipation efficiency and economy of lithium-ion batteries and give additional references for researchers.

2. Analysis of heat generation mechanism of lithium ion battery

The thermal behavior of Li-ion batteries is influenced by two main sources of heat generation: electric heating and entropy heating.

2.1 Electric heating

Electric heating, is also known as Joule heating or irreversible heating, caused by the overpotential phenomenon. Overpotential results from the resistance of various components in the battery, such as electrodes, electrolyte, separator, and current collectors. The resistance causes energy loss due to the collision and scattering of electrons and ions during charge and discharge processes. Electric heating can be calculated by multiplying the charging current, the overpotential voltage, and the resistance that causes loss. The resistance depends on the state of charge and can be determined by methods such as parameter identification and electrochemical impedance spectroscopy (EIS). Electric heating is an undesirable effect that reduces the battery efficiency and increases the temperature.

2.2 Entropy heating

Entropy heating, is also known as reversible heating or thermodynamic heating, caused by the chemical reactions. These reactions involve changes in entropy, which is a measure of disorder or randomness in a system. Entropy changes can be either positive or negative, depending on how disorderly the system is. Positive entropy changes result in endothermic reactions, which lower the temperature. Negative entropy changes result in exothermic reactions, which raise the temperature. Entropy heating can be calculated by multiplying the charging current and the temperature coefficient of the cell voltage, which is the rate of change of voltage with respect to temperature. The temperature coefficient depends on the SOC of the battery and can be obtained from experimental measurements or literature data. Entropy heating is a reversible effect that depends on the direction of current flow and can be used to regulate the battery temperature.

3. Overview of single cooling method of lithium-ion battery

3.1 Air cooling

Air cooling is popular for cooling the electronics and battery packs of electric vehicles. It has been successfully commercialized and thoroughly researched because to the simple system design and easy access to air. [2] The common methods for BTMS is to use air as the cooling medium, including natural airflow convection and forced airflow convection. In natural airflow convection, the air flow around the battery pack is driven by the temperature difference between the battery and the ambient air, which does not require any external energy input. However, this method may not be sufficient to dissipate the heat generated under high power or high ambient temperature conditions. In contrast, forced airflow convection uses a fan or a blower to create a forced air flow that passes through the battery pack, enhancing the heat transfer coefficient and improving the cooling performance. However, this method also consumes additional energy and increases the noise level of the system. Moreover, the design of the air ducts or tuyeres that guide the air flow into and out of the battery pack is crucial for achieving a uniform temperature and velocity distribution among the battery cells, which can affect the lifespan and efficiency of the battery. It is significant to optimize the design parameters of the tuyeres and analyze their effects on the thermal and fluid dynamics of the BTMS based on air convection cooling.

LIN et al. developed a brand-new design in the form of sleeves. The air travels in the channels in a staggered and reversed manner to improve temperature uniformity. The sleeved cooling channel can reduce the maximum temperature to improve temperature uniformity with A three-dimensional heat transfer model. [3]

Yu et al. [4]proposed a new method to improve temperature uniformity of LiB. In order to decrease heat buildup in the center of the battery modules, the research BTMS has two distinct air ducts for air intake ducts and fans, one for conventionally cooling the batteries and the other for jet cooling. The main goal of bidirectional airflow is to reduce the highest cell temperature to 33°C, with a maximum cell temperature difference of less than 5°C, as opposed to 42.3°C for unidirectional circulation. Therefore, spray cooling can be used to reduce the temperature of the intermediate unit.

3.2 Liquid cooling

Another common method of cooling electronic components, especially batteries, is to use a liquid as a heat transfer medium. Liquid cooling has the advantages of high heat capacity, high heat transfer coefficient, and low pressure drop compared to air cooling. However, liquid cooling also poses some challenges, such as leakage, corrosion, and pump power consumption. Liquid cooling can be divided into direct liquid cooling and indirect liquid cooling based on the contact mode between the battery cells and the cooling liquid. In direct liquid cooling, the battery cells are directly immersed in the cooling liquid, which circulates through the battery pack and removes the heat generated by the cells. This method can achieve a high cooling efficiency and a uniform temperature distribution among the cells. However, it also requires that the cooling liquid has a low electrical conductivity or is electrically insulated from the cells to avoid short circuits or electrochemical reactions. Moreover, the battery pack design must be compatible with the liquid immersion and prevent any leakage or contamination. In indirect liquid cooling, the battery cells are separated from the cooling liquid by a solid wall, such as a metal plate or a heat pipe. The cooling liquid flows through channels or tubes that are attached to the wall, and transfers heat from the wall to the liquid. This method can avoid the potential risks of direct contact between the cells and the liquid, but it also introduces an additional thermal resistance and reduces the cooling performance. Therefore, it is important to optimize the design parameters of the wall and the channels or tubes to enhance the heat transfer rate and minimize the temperature gradient among the cells.

Six mini-channel configurations for the liquid cooling efficiency of pouch battery packs were comprehensively assessed by Monika et al. [5]. Figure 1 depicts several typical micro-channel structures, including straight, serpentine, U-shaped, pumpkin-shaped, helical, and hexagonal ones. The findings showed that while the pumpkin structure displayed decreased pressure and power consumption, the serpentine and hexagonal structures had a favorable impact on thermal uniformity.

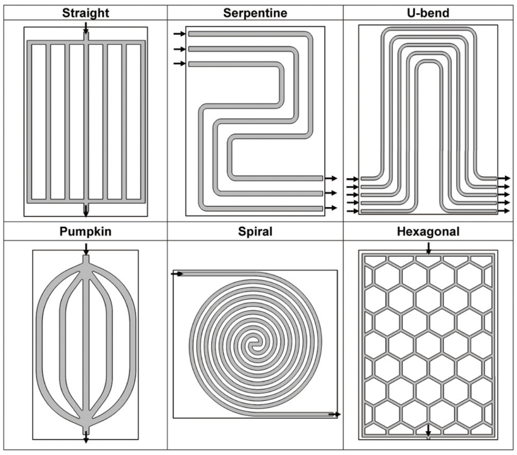

Figure 1: Schematic representation of a typical microchannel structure

A BTMS based on HFE-6120 coolant was employed by Tan et al. [6]. With the proper design parameters, this cooling solution significantly lowers the mass energy and power consumption by 20.3% and 95.3%, respectively.

In conclusion, liquid cooling outperforms air cooling in terms of cooling efficiency, but it also has drawbacks including complex structures, leakage risk, weight, and implementation costs. Furthermore, due to design restrictions, it is challenging to combine thermal control of cylindrical cells with cold plates.

3.3 Heat pipe cooling

The emerging cooling lithium batteries methods is to use heat pipes as heat transfer devices. Heat pipes are passive two-phase heat transfer devices that can rapidly transfer heat from the heat source to the heat sink with minimal temperature difference. They consist of a sealed hollow tube with a porous capillary structure (wick) lining the inner surface and a small amount of working fluid filling the tube. The working principle of heat pipes is based on the phase change and capillary action of the working fluid. When one end of the heat pipe (evaporator) is heated by the battery, the working fluid in contact with the wick evaporates and absorbs a large amount of latent heat from the battery. The vapor then flows to the other end of the heat pipe (condenser) where it is cooled by a heat sink and condenses back to liquid, releasing the latent heat to the heat sink. The liquid then returns to the evaporator through the wick by capillary action, completing the cycle. Heat pipe cooling have been widely used in various fields that require high-efficiency heat transfer, such as electronics cooling, spacecraft thermal control, and nuclear reactor cooling. Heat pipe cooling has several advantages for lithium battery thermal management compared with other cooling methods, such as low thermal resistance, high heat transfer rate, light weight, high reliability and low cost. However, heat pipe cooling also faces some challenges, such as the selection of suitable working fluid and wick material, the optimization of heat pipe geometry and arrangement, and the integration of heat pipes with battery pack structure.

A microheat pipe array-based BTMS with dual functions of chilling in high temperature working settings and heating in low temperature working conditions was created by Ye et al.[7]. When compared to traditional heating, which involves placing a heating film directly on the bottom of the cell, the system performs better at heating.

A unique heat pipe known as an oscillatory heat pipe was created by CHI and RHI [8]for the temperature regulation of lithium-ion batteries used in electric cars. It is easier to maintain since the evaporator is around ten times larger than the condenser. This particular sort of heat pipe has a heating component at the top and a cooling component at the bottom. The advantage of the system is its flat bottom end rather than a regularly curved end, which reduces the complexity. The heat pipe design needs to be optimized in order to provide a BTMS that is inexpensive, small, and effective.

Although there have been many studies on heat pipe cooling in China, due to high cost, complex structure, difficult maintenance, and low cost performance, the research and development of heat pipes is not yet mature in China and has not been widely used.

3.4 Cooling of phase change materials

Phase change materials (PCMs) are materials that can store and release a large amount of latent heat during their phase transition from solid to liquid or vice versa. PCMs can be used for thermal energy storage and thermal management of various systems, such as buildings, solar collectors, and lithium batteries. PCMs can be classified into different types based on their chemical composition, such as inorganic PCMs, organic PCMs, composite PCMs, or other types. Inorganic PCMs are mainly composed of salts or metals, which have high latent heat of fusion and high thermal conductivity, but also suffer from high degree of supercooling and poor thermal stability. Supercooling is the phenomenon where the liquid PCM remains in the liquid state below its melting point, which reduces the effective heat storage capacity and increases the risk of leakage. Thermal stability is the ability of the PCM to maintain its physical and chemical properties after repeated cycles of melting and solidification, which affects the durability and reliability of the PCM. Organic PCMs are mainly composed of hydrocarbons or fatty acids, such as paraffin or acetic acid. Organic PCMs have low degree of supercooling and high thermal stability, but also have low latent heat of fusion and low thermal conductivity. Composite PCMs are a combination of organic and inorganic PCMs, which aim to overcome the drawbacks of each type and enhance the advantages. Composite PCMs have the characteristics of non-corrosiveness, low undercooling, strong chemical stability, etc. Compared with other types of PCMs, composite PCMs can improve the thermal management performance of lithium batteries by increasing the heat storage capacity, reducing the temperature rise and gradient, and prolonging the battery life.

In their research, Chen et al. improved the thermal conductivity of PCM and looked into how cooling it had. The homogenous dispersion of the mixed thermally conductive filler and the aggregation phenomenon on the material surface are improved by the filler. The results show a 264% increase in the thermal conductivity of the PCM with mixed fillers. In comparison to other composite materials in different ratios, the composite phase change material containing 1% few-layer graphene and 2% graphite nanosheets can play a better heat dissipation role in the thermal management of LIB modules.[9]

Compared to other cooling methods, phase change material cooling has unique advantages. In their numerical research, Liu et al.[10]examined the performance of several BTMSs in relation to the Reynolds number, ambient temperature, and current rate. The battery packs were tested using a variety of cooling approaches. It was found that liquid cooling performed better in bringing battery temperatures down while PCM cooling had the best temperature uniformity for the battery modules.

4. Overview of compound cooling methods

The thermal management of battery packs is a challenging task that requires a suitable cooling technique to maintain the optimal temperature range and uniformity of the battery cells. However, the heat dissipation requirements of battery packs may vary depending on the operating conditions, such as power demand, ambient temperature, and state of charge. Therefore, a single cooling technique may not be able to meet the diverse and dynamic thermal needs of battery packs. In order to overcome this limitation, composite cooling techniques have been proposed and developed, which combine two or more single cooling techniques in a synergistic way. Composite cooling techniques can integrate the benefits of different single cooling techniques, such as high heat transfer coefficient, low energy consumption, high reliability, and low cost. Moreover, composite cooling techniques can provide more flexibility and adaptability for the thermal management of battery packs by adjusting the parameters or switching the modes of the single cooling techniques according to the thermal conditions. Some studies have shown that composite cooling techniques performs better than single cooling techniques in terms of temperature reduction, uniformity, and stability.

Zhao et al. [11] suggested a hybrid architecture for cylindrical Li-ion battery packs.The findings indicated that the peak temperature was successfully lowered from 66.9°C to 50°C by this investigation. A hybrid concept was suggested by Wei and Angelin-Chaab [12] by fusing two-phase and air cooling systems. With input and exit channels for the primary coolant (airflow), the design is substantially the

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same as a standard air cooling system. However, there are extra hydrophilic fibers to expose latent heat transfer from the water to the battery. The battery surface's maximum average temperature was lowered by the model from 55°C to 30.5°C. In addition, the battery's internal temperature differential was decreased from 13.5°C to only 2.1°C, a decrease in temperature difference of more than 85%.Hybrid cooling offers a bright future for battery cooling systems since it allows for more flexible usage of several cooling modes to get the battery as cool as feasible. Future cooling capacities often increase as hybrid cooling research continues to progress. [13]

5. Summary

There are benefits and drawbacks to various battery cooling techniques. The liquid-cooled method has a relatively complex structure, relatively high cost, high thermal conductivity, small temperature difference, and high energy consumption; the cooling of the phase change material and the heat pipe depends on its own thermal circulation system, and it has poor control over the temperature uniformity of the battery pack. The cooling of phase change materials may effectively absorb a lot of heat during the solid-liquid phase transition, but the lithium battery's slow heat dissipation and simple leakage are hampered by the low thermal conductivity prior to the phase shift. These issues have not yet been successfully resolved. High thermal conductivity, low thermal resistance, and strong isothermal performance are advantages of heat pipe cooling, but the construction is complex, creating a complex cooling system at a high cost.

To sum up, coupling cooling in multiple ways can solve the problems of a single cooling method and improve the effect of BTMS, This shows that this will be the future of the new trend of automotive development.

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