REVIEW ON COOLING SYSTEMS IN LITHIUM BATTERY THERMAL MANAGEMENT SYSTEMS

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Abstract - In recent years, electric vehicles (EVs), as the fastest-growing new energy vehicles, have attracted much attention for their energy storage methods. Among them, lithium batteries (LiBs) are the most favored by automakers. LiBs with high energy storage density tend to generate more heat during operation. In EVs, the batteries are arranged in a battery pack (BP), and the arrangement space is small, making it difficult to dissipate heat. Therefore, designing a reliable battery thermal management system (BTMS) has become the focus of the safe development of automotive batteries. BTMS is designed to optimize the temperature change of the battery during the discharge process and reduce the risk of spontaneous combustion of the vehicle caused by a short circuit of the battery. This paper reviews the battery cooling systems in BTMs and different cooling methods in a battery thermal management system, the choice of cooling medium, and the configuration and design of a BP battery/module arrangement, and the latest research results for each cooling method are summarized. It was found that a single cooling method can perform well if an appropriate cooling method and cooling medium (high thermal conductive materials) are developed. The combination of appropriate multiple cooling methods can achieve a better balance of cost and effect.

Keywords - Battery Pack Cooling Systems, Battery Thermal Management Systems (BTMSs), Electrical Vehicles (EVs), Lithium-Ion Batteries (LIBs).

I. INTRODUCTION

There is growing concern about the causes and effects of global warming and climate change. The call to reduce carbon emissions is getting louder. Cars account for a large portion of all carbon emissions. There are approximately 900 million vehicles in the world, 96% of which still run on traditional carbon-based fuels [1]. Althoughelectric vehicles (EVs) do not emit greenhouse gases during operation, they have the potential benefit of reducing daily tailpipe emissions compared to conventional carbon-based fuel vehicles[2,3]. The energy used by EVs usually comes from power plants. In the case of circuit transmission loss, under the same mileage, the carbon emission of EVs is lower than that of traditional carbon-based fuel vehicles. In the future, with the large-scale application of clean energy (such as solar energy, tidal energy, wind energy, etc.), the emissions of EVs can continue to decline. At present, EVs have incomparable advantages in terms of high acceleration capability and lower fossil fuel consumption. Consumers prefer vehicles that consume less energy, which has prompted automakers to develop and offer EVs.

EVs are divided into two categories: pure EVs and hybrid EVs. The former uses only electrical energy as a power source, while the latter uses a conventional gasoline engine running in parallel with a power battery. Pure EVs are more environmentally friendly than hybrid EVs, but typically have shorter battery life. The cruising range of EVs is difficult to reach the level of carbon-based fuel vehicles at the same price. Therefore, the type of battery for EVs becomes an important issue.

At present, the main requirements for EVs are long battery life and long battery cycle, requiring the battery with high energy density, long cycle period, and high discharge rate. The two auto brands with the largest sales of EVs are BYD and Tesla. BYD uses lithium iron phosphate batteries (LFP), commonly known as blade batteries. Tesla's most popular model, the Model 3, uses 21,700 cylindrical ternary batteries and LFP. Clearly, the most common choice in the EV market today is lithium-ion batteries (LiBs). Compared with other rechargeable batteries, LiBs have the advantages of low mass density, low self-discharge rate, high energy density, and not affected by memory effect[2]. LiBs are a relatively balanced choice. This battery has high energy density, long cycle time, and low cost, making it suitable for EVs [4-8].

For LiBs, thermal performance has a great impact on their life cycle, energy density, and performance. At higher temperatures, the high-energy density of LiBs can lead to dangerous situations such as battery short circuit. The large amount of heat energy released by the battery during charging and discharging can damage the battery [9]. For example, under long-term high temperature conditions, a chemical reaction occurs in the electrolyte inside the battery, resulting in the decomposition of the electrolyte [10-13]. The cells in a battery pack (BP) often have uneven temperatures. Too poor temperature uniformity can lead to partial state of charge (SOC), which can also greatly reduce the cycle life of the battery [14,15].

Batteries lose battery energy at low temperature conditions[10]. Doughty and Roth [16] focused on the analysis of factors affecting the safety of LiBs and concluded that temperature is the most important

factor affecting battery safety. Ramadass et al. [17] and Selman et al. [18] conducted experiments on the performance of 18650 LiBs at different temperatures. Ramadass et al. set the temperature and the cycle number as variables and found that the capacity loss of the battery increased with the increase of temperature and cycle time. Therefore, it is necessary to improve the thermal performance of the battery thermal management systems (BTMSs).BTMS is a system that can regulate the temperature of the BP. The main function of the system is to transfer the heat generated during the operation of the battery out of the BP.The heat generated by the LiBs during charging and discharging is caused by the resistance to the movement of electrons and ions in the battery. Motloch et al [19] also confirmed that the battery life will be significantly shortened if the battery is operated outside the optimal operating temperature range for an extended period. They tested that in the operating temperature range of 30-40°C, the battery life will be reduced by two months for every 1-degree increase.

This paper summarized the cooling scheme of BTMSs and analyzed the cooling medium and cooling method adopted by BTMSs. Further research on the comprehensive application of various cooling methods and cooling media in BTMSs will be one of the most important research topics in the future.

II. REVIEW OF COOLING SYSTEMS IN BTMSs

A. Concept of BTMSs

In order to meet the practical needs of electronic devices (such as laptops, smartphones) and EVs, LiBs are designed in different shapes and sizes with different internal structures. High-power charging and discharging will generate more heat and increase the probability of battery spontaneous combustion. To prevent the battery from overheating during high power operation, a temperature limit is generally set, but the temperature limit will greatly affect the performance of the battery. Therefore, a BTMS needs to be integrated in the BP, which keepsthe operating temperature of the battery within a relatively constant safe temperature range [19].

The two main topics that BTMSs focus on are the charge-discharge cycle of the BP and the control of the heat generated during battery operation. BTMSs can prolong the lifetime of LiBs by regulating the temperature level and battery layout distribution, thereby prolonging the lifetime of the battery systems in EVs. A BTMS is an important means to improve battery life, performance, cost per unit power, and safety in existing battery technologies [20-22].

There are many methods to evaluate the cooling performance of BTMSs. Commonly used methods include electrochemical models, mathematical models, BP-based equivalent circuit models, finite element models, and battery thermal models [23-26].

B. Classifications of BTMSs

According to the cooling methods of BTMSs, BTMSs are classified into four types: air-based, liquid-based, heat pipe-based, and phase-change material (PCM)-based [27, 28]. Sub-categorization of BTMSs based on cooling medium can be done as follows: (1): Air (natural or forced (series or parallel) convection; (2) Liquid (indirect (jacketed or mini-channels or tube) or immersion/direct); (3) PCM(material composition or transition phase/integrated); (4) Heat pipe (sintered or loop or pulsating).

C. Air Cooled BTMSs (AC-BTMSs)

In fact, AC-BTMSs are the most common cooling technology and are widely used commercially. It is mostly used for cooling large computer rooms, residential buildings, etc. [29-31]. The air-cooling method is the simplest of the cooling methods by BTMSs. This approach is lighter weight, less expensive to design and produce,and does not require complex modifications to the BP structure. Air-cooling systems fall into two broad categories: active and passive air-cooling systems (also known as forced convection and natural convection), as shown in Figure 1. The main difference between the two cooling methods is mainly in their mode of operation. Forced convection is the flow of additional air into the BP through a separate energy system, such as the vehicle's own HVAC system. In the BTMSs based on natural air convection, the cooling medium enters the BP without consuming additional energy. The structure of the natural air convection BTMSs is simpler, and the manufacturing and maintenance costs are low. The heat transfer coefficient of forced convection BTMSs is higher than that of natural air convection BTMSs, which is sufficient to meet the temperature regulation requirements of most BPs [32, 33].

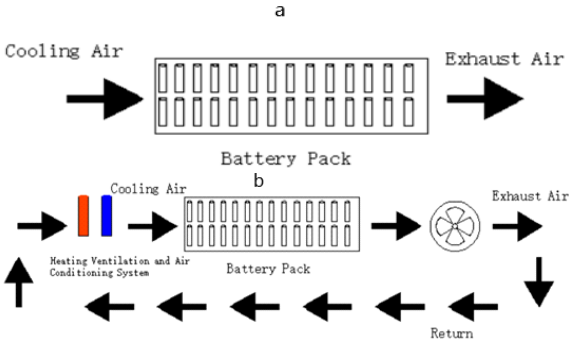


Figure 1. Passive air cooling (a) and active air cooling (b) in BTMSs.

Another way to classify AC-BTMSs is based on the passage of the fluid medium used for cooling. It can be categorized as:(1)Without preconditioning, directly using external air for cooling;(2) EV's battery modules

are cooled by the vehicle's own heating, ventilation, and air conditioning (HVAC) system;(3) Independent of the original vehicle system, in the HVAC system is set independently in the BTMS system [34].

AC-BTMSs take up less space in the car because the coolant in this method is air, which does not need to be stored or recirculated. This is an advantage given the increasing battery capacity and larger battery size of today's EVs. Meanwhile, due to the compact arrangement of the batteries in the BPs of the EVs, the limited airflow through the BP, insufficient air-cooling performance, and the AC-BTMSs will limit the installation position of the BP in the car, etc., currently only relying on the thermal conductivity of air is no longer sufficient. New EVs with certain long-range requirements are needed.

D. Liquid-based BTMSs (L-BTMSs)

As the market demand for EVs gradually increases, some disadvantages of air-cooling technology have begun to appear, such as low heat exchange coefficient between air and battery surface, slow cooling and heating speed, poor sealing of battery box, poor dustproof and waterproof performance, etc. The characteristics of the battery have emerged, and only using air cooling can no longer meet the application of power batteries under complex working conditions. Liquid cooling technology is gradually replacing air cooling technology as the first choice of major car companies. L-BTMSs use a liquid coolant, with a water-glycol mixture most used in BTMSs for EVs.

A three-dimensional model of the liquid cooling system is shown in Figure 2. Since 2017, major automobile manufacturers have begun to use liquid cooling as the first choice for the BTMS of EVs: Tesla's high-performance electric vehicle Model S can accelerate to 100 kilometers per hourin 2.1 seconds, which is comparable to that of a $460,000 Ferrari SF90 supercar [35]. In order to reduce the huge amount of heat generated by the Model S during acceleration, Tesla enabled liquid cooling on this model. The Tesla model S battery cooling system consists of an S-shaped cooling tube in thermal contact with each battery cell. The S-shaped cooling tube adopts a flat shape, while the cooling tube adopts a curved corrugated surface shape.

The battery core is placed in the corrugated groove, and then fits with the cooling tube. The surface shape of the cooling tube matches the outer surface of the battery core to achieve the maximum cooling effect. The batteries are arranged sequentially on the corrugated surfaces on both sides of the cooling pipe. The cooling system of Tesla cars uses a specific G-48 ethylene glycol coolant (HOAT), which can take into account both heating and cooling conditions.

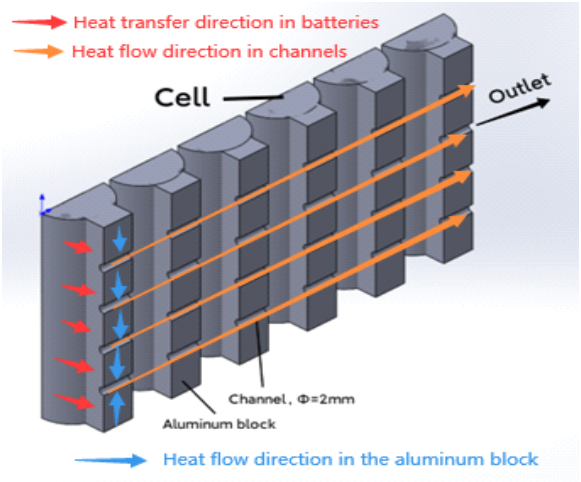


Figure 2.A schematic three-dimensional model of the liquid cooling system.

The BTMS adopts a parallel design, and the motor, car charger, air conditioning system and battery are all managed by a thermal management system. When necessary, the thermal management system can conduct heat exchange between the above components, which also ensures that the temperature of the coolant entering the battery cooling system is similar, avoiding the risk of battery short-circuit. Coolant can be rerouted and pumped in the other direction, ensuring the system is warmed up or cooled down to its optimum operating temperature.

E. PCM-based BTMSs (PCM-BTMSs)

BTMSs can be classified according to whether there is a power assist device, where air cooling usually has a fan and a compressor, and liquid cooling has a heat pump as a power assist device to make the coolant pass through the BP. This type of cooling system is an active cooling system, while the other type is a passive cooling system. The passive cooling system does not need to install a power auxiliary device and can achieve the ideal cooling effect without changing the system parameters [36-39].

A PCM-based system is a passive cooling system. After absorbing heat, PCM will go through three stages: solid state, molten state, and liquid state. At present, the cooling effect of a passive PCM system is not as good as that of the active cooling system. Therefore, many researchers are studying PCM-BTMSs using experiments and simulations to evaluate and improve the performance of such systems [40-42]. Compared with AC-BTMSs and L-BTMSs for which more attention is paid to the internal structure design of BTMSs, and for PCM-BTMSs more attention is paid to the cooling material itself. PCM has the advantages of non-toxic, non-corrosive, good chemical stability, large latent heat of melting, small volume change, high recycling integrity, low cost, and small supercooling degree. Traditional PCMs can be divided into four categories: fatty acid, sugar alcohol, paraffin, salt hydrate [43]. Of these,

paraffin wax is a more common material because of its low vapor pressure when melted. Low thermal conductivity and low thermal energy storage and release rate are significant disadvantages of this system. At present, there are several methods to improve the thermal conductivity of PCM: (1)adding high thermal conductivity materials to PCM, such as: high conductivity nanoparticles, carbon nanotubes, carbon fibers, graphene, aluminum powder, metal particles, etc.;(2) Using porous structure materials such as metal foam or expanded graphite (EG) as the matrix skeleton material of the composite PCM and fill it with PCM such as paraffin.

Compared with L-BTMSs and AC-BTMSs which use sensible heat, the PCM-based systems can use latent heat to extract heat from the battery. Compared with the sensible heat which constantly changes temperature, the latent heat can absorb heat continuously and has stable thermal conductivity, which makes the temperature uniformity of the battery better [44].

F. Heat Pipe (HP) based BTMSs

HP is a cooling structure with high thermal conductivity and compact structure. Compared to a solid metal rod of the same size, a HP can transfer more heat without using moving parts [45]. At present, HPs are widely used in thermal energy storage (TES) systems and electronic thermal management to avoid the inherent intermittency problems of solar power generation devices [46-48]. At present, capillary-driven HPs have been widely used in various thermal control systems of automobiles.

There are three common types of HPs: sintered heat pipes (SHPs), pulsating heat pipes (PHPs), and loop heat pipes (LHPs) [49]. SHPs consist of two parts: an evaporator and a condenser, which are installed at both ends of the HP. After the heat is transferred to the evaporator, the coolant evaporates into a gaseous state, which is then transferred to the condenser. The condenser absorbs heat from the vapor and condenses the vapor into a liquid, which returns to the evaporator. The capillary-driven HPs are commonly used in SHPs. The LHP is mostly used in space applications. In order to balance the pressure difference between the evaporator and the condenser, a capillary structure is installed in the evaporation chamber, which can provide sufficient pressure for the evaporated gas to move. The LHP also adds a compensation chamber that both balances the pressure difference in the circuit and provides cooling liquid to the evaporation chamber. Both LHPs and PHPs are improved based on SHPs.

G. Novel BTMSs

Several common BTMSs have their own advantages and disadvantages. Researchers have begun to develop new BTMSs by using new coolants, changing the system structure, and so on.When designing the new BTMS, the advantages of high temperature uniformity of cooling material based on PCM system and small temperature difference of the BP will be considered, and the characteristics of high heat transfer rate of the liquid and no need to install additional HVAC system based on the PCM system will be also adopted. This scheme arranges cylindrical 18650 batteries into a matrix. The batteries are partially immersed in pressurized saturated liquid ammonia (PSLA). After the heat generated by the batteries is transferred to the PSLA, the PSLA generates steam to take away part of the heat. At the same time, during the steam movement, it touches the battery surface that is not immersed in PSLA and takes away part of the heat [50, 51].

In order to improve the thermal conductivity of L-BTMSs, some researchers opted for emerging coolants instead of commonly used water or ethanol aqueous solutions. The novelty of this solution is that nanofluid is used as the coolant, and liquid metal is used to flow in the cooling circuit, so that the temperature uniformity of the battery is better. In this case, the electromagnetic pump was found to drive the coolant in a L-BTMS more efficiently than the mechanical pump, and the flow direction of the liquid could be changed by changing the direction of the electromagnetic pump current [52, 53]. A schematic diagram of this battery cooling principle is shown in Figure 3.

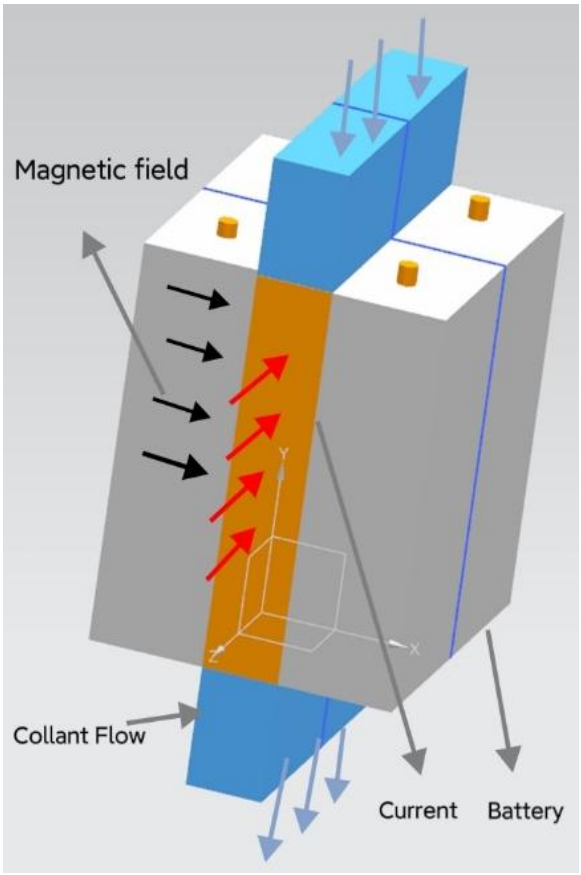


Figure 3.A schematic diagram of a battery module and the cooling liquid driven by an electromagnetic pump.

III. CONCLUSION

This article mainly discusses the latest design of each BTMS, including the selection of coolant and the distribution scheme of the cooling channels.

For AC-BTMSs,improving the air entering the BP and the impact direction of the air and the configuration of the BP are the key points. For L-BTMSs,it is important to improve the thermal gradient generated by the liquid coolant in flow mode and to control the effective contact area between the coolant and the battery. For PCM-BTMSs, further research will be needed to overcome the intrinsic low thermal conductivity of PCM. For HP-based BTMSs, changes to the HP structure and BP design will be considered, including combining HP with other cooling systems for better CP.

While a single BTMS can be improved to meet the cooling needs of the battery pack through research on high thermal conductive materials, the prospects for future improvement are unclear. A better approach is to integrate multiple cooling methods and develop new cooling media to design an integrated BTMS.

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