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Thermal Management Strategies for Safer Lithium-Ion Batteries

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Abstract. Drawing on the superior energy density and endurance of lithium-ion batteries (LIBs), these systems are regarded as essential for electric vehicle and massive energy storage. However, if heat generation within the battery cannot be efficiently dissipated, it can trigger thermal runaway incidents. Therefore, the establishment of strong thermal management framework is still very important. Three major battery cooling technologies are assessed in this paper: air cooling, liquid cooling, and phase-change materials (PCM) and in four categories: thermal transfer capacity, thermal homogeneity, structural intricacy and cost, and deployment scope (including automotive applications and industrial storage applications). Simple and inexpensive, air cooling is not adequate for the high heat removal requirements of liquid cooling, but is used for low power systems and for cost conscious environments. Liquid cooling represents a cooling strategy with high efficiency and superior thermal equilibrium, capable of fulfilling demands for high-power battery assemblies; however, such systems are technically intricate and present a risk of leakage. PCM offers minimal thermal conductivity and thermal saturation challenges, yet it can effectively mitigate temperature spikes as supplementary measures. Each cooling mechanism is not universally optimal for all battery types; selection depends on the battery's power or energy density, environmental conditions, and budgetary constraints. Prospective integrated thermal management architectures combining various cooling methods are expected to achieve a harmony between heat dissipation potential, thermal uniformity and financial feasibility.

Keywords: lithium-ion battery, thermal management, air cooling, liquid cooling, phase change materials

1. Introduction

As a high energy density, long cycle and low self discharge battery, lithium-ion battery has been extensively used in the area such as electric vehicle or large scale energy storage [1]. But, today, lithium ion batteries have a lot of drawbacks. Batteries will get hot when operating. Without being able to disperse heat in time, it will result in such bad outcomes as decreased battery performance, shortened battery life, even thermal runaway accidents [2]. Throughout usage, the capacity retention, charging/discharging performance and cycle lifespan of lithium-ion batteries will noticeably diminish when the operational temperature interval exceeds the ideal thermal zone [3].

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Consequently, the security, productivity and lifespan of lithium-ion cells depend on employing a dependable Battery Thermal Management System (BTMS).

The article mainly discusses three thermal management technologies, including air cooling, liquid cooling, and phase change material (PCM). Firstly, air cooling is cheaper but has poor cooling effect, liquid cooling is efficient but has a complex structure, PCM is energy-saving but has limited thermal conductivity. Each of cooling methods has its own unique strengths and limitations [4]. Recently, most people have chosen composite thermal management schemes that couple different cooling methods. However, research mostly focuses on a single part, lacking comparative studies on three typical cooling methods and the connections between various parts in composite systems.

So this article introduces three common battery thermal management technologies, air cooling, liquid cooling and PCM cooling, which include their working principles, the characteristics of heat transfer, temperature control effects and applicable boundaries. Furthermore, the heat dissipation capability, temperature uniformity, structural complexity/cost and application scenarios are compared from different aspects, which is conducive to the selection and actual application of battery thermal management systems.

2. Heat generation and safety risks

It's inevitable for lithium ion batteries to generate heat during charging and discharging. The heat generated is mainly due to joule heating due to internal resistance, heat due to entropy change and polarization heat [5]. The overall condition of internal heat generation rate (Q_{gen}) and heat dissipation rate (Q_{loss}) of battery is dynamic balance condition and the temperature is stable. If the heat is generated at a higher rate than the heat is lost, then the heat accumulates and the system goes from thermal equilibrium to thermal imbalance.

Overheating and uneven temperature distribution can negatively impact lithium-ion batteries. Elevated temperatures accelerate the degradation of electrode materials and electrolytes, increasing internal resistance and reducing capacity, which shortens battery life [6]. From the safety point of view, the increase of temperature may cause exothermic side reactions, and if the heat generation rate is more than the heat dissipation rate, the system may tend to a thermal runaway at the end [7]. Also, non-uniform temperature distribution between cells can cause non-uniform aging and local over-temperature hot spots, which can also result in thermal runaway.

3. Major thermal management strategies

3.1. Air cooling

Air-cooling is one of the cooling strategies that involves extracting thermal energy generated in the battery by passing air around in the battery. According to the different ways of drawing air, there are two types of air-cooling systems: natural cooling and forced cooling. Natural cooling is a passive cooling system in which the heat is dissipated by natural convection of air. Forced air cooling, however, uses fans and an outside mechanism to increase the flow in and out of the system, which also increases the thermal transfer. Figure 1 shows 2 types of cooling [8].

But because of the low thermal conductivity and specific heat capacity of air compared to liquids, the ability of this technique to dissipate heat is not very effective when there is a high heat load. Furthermore, non-uniform temperature distribution can happen in the battery enclosure during air cooling, resulting in the real thermal performance having a high variation depending on variables like the layout of the airflow channels, the position and geometry of the cells in the assembly.

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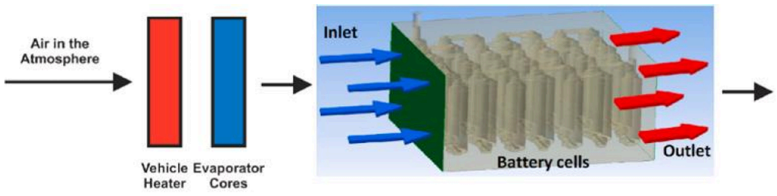
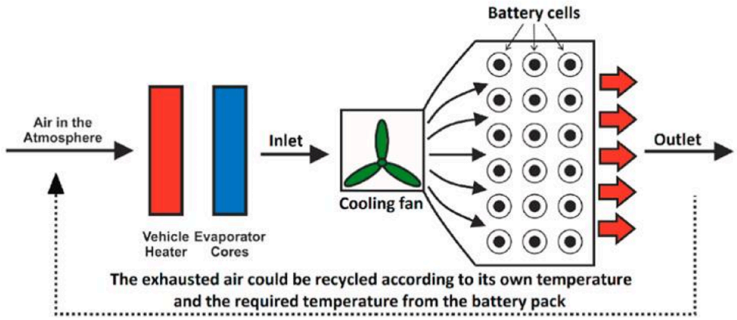


(a) Passive air cooling



(b) Active air cooling

Figure 1. Schematic diagram of air-cooled BMS [8]

The system structure of air cooling technology is simple, the cost is low, and does not need complex equipment like pumps, pipelines, coolant, etc. It is a technology that makes use of wind alone for heat dissipation, has low investment and maintenance costs. Moreover, no leakage of the coolant in the air cooling system is risked [8]. Forced air cooling requires extra power to operate the fans; fan sound and power use depend on type of fan and system design.

The main application of air cooling technology is low power density requirement applications, for example small flying electric equipment, electric bicycles and other light transportation vehicles where cost is a major consideration. The desirable thermal management condition for the air cooling is when the discharge rate is low, the ambient temperature is moderate and the battery pack size is small [9]. One problem is that it can only be so cooling, based on the thermophysical properties of air, and it becomes less effective when it comes to higher energy density or high discharge rate battery systems.

3.2. Liquid cooling

Convective thermal transfer between the fluid coolant and the battery is used as a method of heat dissipation, which is based on fluid circulation. This approach includes two types, that of direct contact liquid cooling and indirect contact liquid cooling. Direct contact liquid cooling (immersion liquid cooling): the coolant and the battery are in direct contact with each other and directly exchange heat with the outer surface of the battery; indirect contact liquid cooling: the cooling medium and the battery are separated from each other by a cold plate, a liquid cooling channel, and other protective measures. In these components, the heat is removed from the battery indirectly by the flow of a coolant [9].

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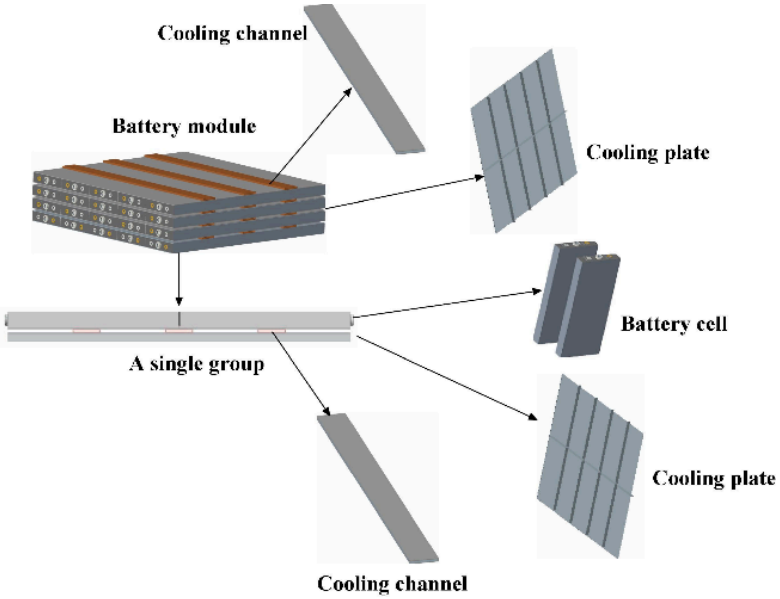

Figure 2. Schematic diagram of liquid cooling system [10]

The indirect contact mode depicted in the following text is exemplified in Figure 2 and is a typical indirect liquid cooling structure that removes the heat from the battery surface by indirect contact through the flow of the cooling fluid in the cold plates.

The liquid cooling has better thermal efficiency than air cooling in high-power situations because of higher thermal conductance and specific heat of liquids than air. However, actual heat removal capacity and cold plate uniformity is related to cold plate coolant flow rates, channel design and the thermal resistance between cells and cold plates. By using liquid cooling in optimal conditions, more consistent temperature can be achieved than by using air cooling.

The drawback of indirect liquid cooling is the chance of leakage, and the construction of the cooling system requires auxiliary equipment like heat exchanger, pipeline and pump, which will increase the weight and electric power consumption of the cooling system. The high sealing and high cost of immersion systems and the heat dissipation problem during driving need to be further solved [11]. The pumping power will vary depending on the characteristics of the coolants and system configurations.

Liquid cooling has been regarded as the primary evolution pathway for battery thermal regulation owing to its merits of effective thermal removal, superior temperature uniformity, etc. Liquid cooling plates are currently utilized in numerous types of EVs, particularly for high-capacity energy density/battery high-power density battery configurations. Immersion cooling is now predominantly applied in the cooling systems of energy storage power stations with elevated cooling demands, and will be extensively utilized in top-tier electric vehicles in the coming years. One of the drawbacks, however, involves the intricate setup and the hazard of leakage, which can only be guaranteed through meticulous fabrication and upkeep for extended operational longevity.

3.3. Phase change materials

The principle of the phase change material cooling is to use the heat absorptive/receptive property of PCM during its phase change process to control the temperature of battery. On one hand, with the rising of battery temperature, PCM absorbs heat and changes its phase, which stores heat in the form of latent heat to reduce the rapid change of battery temperature on the contrary, with the falling of

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battery temperature, PCM releases heat and changes its phase in reverse like solidification, which plays the buffering role. Unlike air or liquid cooling, PCM doesn't move heat away, but rather stores the heat temporarily.

PCM material can effectively suppress the peak temperature of the battery and make the temperature inside the battery pack uniform, as long as the total heat generation does not exceed the PCM's latent heat capacity. PCM can maintain a nearly constant temperature during the phase transition process [12]. However, after the phase transition is completed, that is, when PCM is completely melted, it will lose its ability to absorb heat and experience thermal saturation [12]. The actual thermal performance depends on PCM selection, mass loading, and the effectiveness of auxiliary heat rejection mechanisms.

This can be a passive cooling method without power consumption and can achieve thermal management without energy consumption. Simple and no moving parts system structure. These properties make it an ideal material for applications where a precise temperature control is necessary [12]. However, the thermal conductance of PCM is typically low, and the heat dissipation speed is limited unless it is improved through the incorporation of additives with high thermal conductivity. Furthermore, overflow might occur in certain liquid PCMs, and the PCM will improve the overall quality of the battery assembly [13].

PCM cooling technology is applicable for situations with high demand for temperature uniformity, low power density and is sensitive to energy consumption based on its passive heat dissipation and no requirement of energy consumption and its simple structure. It is preliminarily used in some electronic devices and small power equipment at present. Because of the limited cooling capacity of one PCM, PCM is frequently combined with other cooling methods, like air cooling, liquid cooling or heat pipes. They are combined together and constitute a hybrid thermal management system to cope with the increased power demands [14, 15]. One of the problems is that the PCM when fully melted, can no longer provide cooling until the stored heat is removed through an external cooling source.

One of the example of the use of these composite phase change materials as cooling media is shown in Figure 3, where the composite phase change materials are integrated with soft-pack lithium-ion batteries.

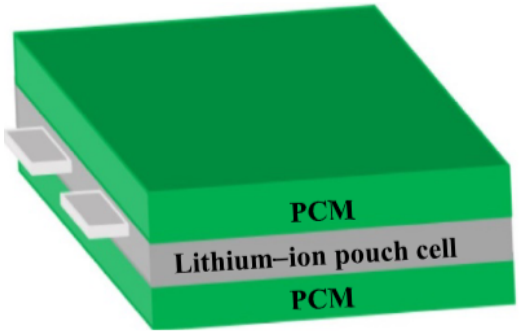

Figure 3. Soft pack lithium-ion batteries cooled by composite phase change materials [16]

4. Comparison and practical selection

The differences between air cooling, liquid cooling and phase change material (PCM) cooling. None of the technologies is inherently better than the other; it will ultimately depend on the specific application requirements (such as thermal load, energy density, operating environment and cost constraint).

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Table 1. Soft pack lithium-ion batteries cooled by composite phase change materials [16]

Evaluation Indicator	Air Cooling	Liquid Cooling	PCM Cooling
Basic Cooling Mechanism	Heat removal through natural or forced air convection	Heat removal through convective heat transfer between the coolant and battery	Heat absorption through latent heat during the phase transition of PCM
Heat Dissipation Capability	Low	High	Moderate
Temperature Uniformity	Poor; prone to temperature gradients	Excellent; relatively uniform temperature distribution	Good; effectively suppresses local temperature rise
Continuous Cooling Capability	Moderate; limited by the heat transfer capability of air	suitable for continuous high heat flux conditions	Limited; thermal saturation may occur after complete phase transition
Cooling Response	Relatively slow	Fast	Moderate
Energy Consumption	Low for natural cooling; moderate for forced cooling	Moderate; pumps and auxiliary components are required	Very low; typically a passive cooling method
System Complexity	Low	High	Moderate
Initial Cost	Low	High	Moderate–High
Maintenance Requirements	Low	Relatively High	Moderate
Coolant Leakage Risk	None	Present	Possible for some liquid or semi-liquid PCMs
Space Requirement	Small	Relatively large; cooling plates and pipelines are required	Relatively large; additional space is required for PCM integration
Applications	Small-scale and low-power energy storage systems	Large-scale and high-power energy storage systems	Small/medium scale energy storage or auxiliary thermal management

Table 1 summarizes the key features and the scope of application of the three technologies to give a comprehensive overview.

Referring to the above comparisons, it can be summarized that for low heat generation per unit area and low cost requirements, the relative simplicity and low cost of the air cooling makes it a viable option, while for high power density applications with constant high thermal loads, the superior and persistent heat dissipation ability of the liquid cooling makes it a better choice than air cooling, and for short-time suppression of thermal peaks, or as a supplementary measure to achieve other cooling objectives, such as uniform temperature, the PCM cooling is more suitable, but it is limited by thermal saturation [13, 17, 18].

Hence, parameters like energy density, operating environment, system cost etc. of the battery should be taken into account, and a proper thermal management scheme should be selected. This comparison shows that the future development of battery thermal management technology can be either one of the aforementioned cooling methods or a combination of different cooling methods because of the different demands, so as to better serve the battery performance.

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5. Conclusion

From the above mentioned discussion, following conclusions may be drawn:

There is no universal refrigeration strategy that can be followed for each and every particular use. There are three cooling modes, namely air cooling, liquid cooling and phase change material cooling (as shown in Figure 1), depending on the thermal demand period and its thermal consistency level, the structural intricacy/price and the usage environments.

Although the poor thermal conductivity and latent heat capacity of air brings a limit to the capacity of air cooling to remove heat, the simplicity of air cooling, the absence of leakage dangers, and the low cost of the system are ideal for low discharge rates, relatively low power densities, and low cost applications. Liquid cooling has better thermal dissipation performance and stable temperature distribution, which is beneficial for high-power-density battery packs, but the liquid cooling system requires strict engineering and there are possible risks of fluid leakage, requiring intensive maintenance. The phase change material (PCM) absorbs heat and can store it passively during the phase change process, which prevents the heat from causing a rapid temperature rise and keeps the temperature close to the phase change point. But, beyond the point of thermal saturation, it still needs external cooling to dissipate stored heat and thus PCM is better suited as an auxiliary to enhance the temperature uniformity and limit the peak temperature in conjunction with air or liquid cooling.

In the future, as energy density of lithium-ion batteries further enhances due to non-stop development, hybrid thermal management systems will be a key development trend. The future research and investigation should focus on the interface between different cooling methods, thermal saturation and effective PCM regeneration methods and safety at the system level under real conditions in the battery pack. Hybrid systems should be a reasonable compromise between the capabilities of each cooling method in order to achieve the best balance of the ability to dissipate heat, uniformity of temperature, energy usage and cost.

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