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Research Progress of Thermal Conductive Materials for Lithium-ion Batteries

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Abstract:

The rapid development of renewable energy and batteries has increased people's demand for lithium-ion batteries. Thermal management plays a very important role in the manufacturing of lithium-ion batteries, as overheating is an inevitable problem when batteries are used for a long time. Moreover, thermal. However, during the charging process, the battery will generate a large amount of heat. This excessive heat will cause the battery's capacity to decrease and also pose a risk of heat runaway. It also plays a crucial role in ensuring the safety, efficiency and lifespan of the battery. This article, however, reviews the latest advancements in thermal conductive materials applied in battery thermal management systems. Using the CAS method, this study systematically analyzed the advantages and disadvantages of carbon-based and metal-based related materials, and particularly emphasized their thermal conductivity and stability. Furthermore, this article also discusses the technologies that enhance conductivity while also reducing costs, as well as the innovations related to this technology, and the future development trends of composite materials. By comparing different materials, this study ultimately concluded that although there is no single material type that can completely solve the problem of thermal management, the use of hybrid materials and new materials still holds potential for the sustainable development of lithium-ion technology.

Keywords: Lithium-ion battery; battery thermal management; battery thermal conductive material.

1. Introduction

Currently, the global demand for clean energy and sustainable development is constantly increasing. This trend undoubtedly highlights the crucial role of energy storage technology. Since fossil fuels are non-renewable resources, as they gradually deplete and in order to alleviate environmental pressure, electrification has now become one of the most promising approaches for the future. Lithium-ion batteries, due to their high energy density, long cycle life and extremely high efficiency, have become the preferred

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batteries for both mobile phones, computers and new energy vehicles. However, despite the numerous advantages of lithium-ion batteries, they still have limitations in terms of thermal safety and battery stability.

During the charging and discharging process, the battery generates a large amount of heat due to resistance and chemical reactions. Without effective cooling methods, the temperature distribution within the battery will become uneven, resulting in a decrease in capacity, reduced efficiency, and even in cases of excessive use, it may lead to out-of-control situations, such as explosions and fires. Therefore, developing a reliable thermal management system is essential for ensuring the safety of batteries. In various studies, thermal management has received increasing attention as it directly affects the efficiency of heat transfer and the stability of the entire system. However, despite these, lithium-ion batteries face significant challenges in terms of thermal and safety.

In recent years, various types of thermal conductive materials have received extensive attention and application. Diverse thermal conductive materials have been investigated. For instance, metal materials such as aluminum and copper possess excellent thermal conductivity, which is the reason why they are widely used. However, they will also be subject to certain limitations such as constraints like cost, weight, corrosiveness, etc. For example, graphite, graphene and carbon nanotubes are lightweight and can be adjusted [1]. However, these materials also have problems when processed and integrated into battery systems. PCMs offer an alternative approach. They absorb and release latent heat, thereby stabilizing the temperature of the battery. However, their inherent low thermal conductivity and leakage problems limit their application. Unless further material improvement measures are taken.

Given these limitations, researchers have increasingly explored methods of blending and compatibility, combining metals, carbon, and phase-change materials to achieve stability, conductivity, cost savings, and further innovation in multi-functional composite material technology [2]. This has also expanded the application of these materials in actual battery management.

This article focuses on the thermal management system of lithium-ion batteries, and discusses the classification of materials, their advantages and disadvantages, as well as their application scenarios. Additionally, this article will also discuss the future development of this type of battery, such as cost reduction, further material innovation, and integration strategies, etc. These strategies can enhance the stability and safety of the battery. Through a comprehensive discussion, this article aims to study how to reasonably select and design thermal conductive materials and provide suggestions for the sustainable development of lithium battery technology.

2. Thermal Conductive Materials in Battery Thermal Management

2.1 Metal-Based Materials

Metal materials have been widely applied in thermal management systems due to their excellent thermal conductivity and mechanical strength. For instance, aluminum, copper and alloys are used as materials for radiators, battery casings and heat sinks, etc.

Conductive metals such as copper and aluminum have excellent intrinsic thermal conductivity, with copper at 400 watts per meter and aluminum at approximately 237 watts per meter. These metals can quickly transfer heat from a single hot spot to the entire metal, avoiding the problem of wire failure due to excessive local temperature [3]. This feature significantly reduces the risk of thermal runaway in lithium-ion batteries and enhances their stability. Metal-based materials not only have excellent electrical conductivity but also offer the functionality of providing hook structures. For instance, by integrating thermal management and mechanical protection in an aluminum shell, the safety and stability of the battery can be enhanced during collisions or external impacts [4]. The production and processing techniques of metals are now highly mature. For instance, rolling, extrusion and welding technologies have made the manufacturing cost of integrating metal components into battery modules much lower than before. Compared with more advanced nanomaterials, this has significant advantages, ensuring reliability and scalability in large-scale production.

Metals such as aluminum and copper have a high degree of recyclability and do not suffer particularly significant performance loss, which helps to form a sustainable production cycle. And reduce the impact on the environment [5]. However, it also has several disadvantages. For instance, Metals, especially copper, have a high density, which increases the weight of the battery. For electric vehicles and the like, lightweight design is crucial for enhancing the mileage and range of electric cars. However, the heavy weight of copper limits the range of electric vehicles.

In humid or chemically corrosive environments, metals are most prone to oxidation and corrosion. For instance, aluminum may react with oxygen to form a protective layer of aluminum oxide, which can affect the long-term thermal properties. While copper requires a protective coating to prevent its own performance from deteriorating, this increases the maintenance requirements.

Although the price of aluminium is relatively low, the prices of copper and special alloys are extremely high. This will increase the overall price of the battery. When large-scale production and application of electric vehicles are carried out, economic barriers usually affect the use and quality of electric vehicles.

Unlike the emerging composite materials, metals mainly offer advantages in terms of chemical, thermal and mechanical properties, such as the lack of heat energy storage, chemical stability and recoverability. As battery performance improves and the demand for solutions increases, the pure metal-based solutions have become outdated. When combined with liquid cooling or phase change cooling strategies, metals may cause problems such as galvanic corrosion or thermal expansion mismatch, which can make the system more complex [6].

2.2 Carbon Based Materials

Carbon-based materials, such as graphite, graphene, carbon nanotubes, and various expanded composite materials, have become a type of material with great potential in the field of thermal management for lithium-ion batteries. They have relatively high thermal conductivity, are lightweight, and have stable chemical properties, providing an attractive alternative to metal-based materials.

The intrinsic thermal conductivity of graphite and graphene sheets can exceed 1000 watts, which is much higher than that of aluminum. This thermal conductivity can be designed in many aspects, such as being used to efficiently guide heat within battery modules. Compared with metals, carbon-based materials are significantly lighter. This advantage is particularly prominent in the automotive and aerospace industries, as reducing weight can enhance energy efficiency and range.

Also, Carbon materials do not need to worry about oxidation and corrosion during operation. However, if metals are used, a protective layer needs to be applied for a long time to isolate carbon dioxide in the air, which ensures the long-term stability of the materials. Although the intraplanar conductivity of carbon-based materials can be very high, their transverse conductivity is very low. This will reduce their efficiency. Unless a very reasonable design is adopted, this poses a potential risk. High-quality graphene and carbon nanotubes require the use of advanced synthesis methods, such as chemical precipitation. These methods are very costly, which limits their large-scale commercial applications. Due to certain issues, such as aggregation and uneven distribution, nanomaterials are difficult to be processed into large-sized and uniform components. This results in a reduction in their effectiveness in practical applications.

Some carbon-based materials, such as graphite sheets, are mechanically brittle and susceptible to fracture under stress. This creates challenges for integration into battery modules that undergo repeated mechanical vibration or impact [7]. Pure carbon-based materials often cannot simultaneously provide high conductivity, structural reinforcement, and thermal buffering. For practical applications, they usually need to be combined with polymers, metals, or phase change materials to form composites [8].

2.3 Phase Change Materials

Phase change materials are substances that can absorb or release energy during the phase change process. This phase change process typically occurs between the solid and liquid states. Because they can regulate temperature and enable batteries to remain within their optimal operating range without the need for complex cooling systems, they have received widespread attention in the field of lithium-ion thermal management. The related materials include organic materials such as fatty acids, paraffin, inorganic materials, and polymer composite materials.

PCMs absorb latent heat during melting and release it during solidification, which allows them to maintain battery temperature within a narrow range. This buffering effect helps prevent overheating during high-rate charging/discharging cycles [9]. Unlike liquid cooling or forced-air systems, PCMs function without pumps, fans, or external power input. This reduces system complexity, lowers energy consumption, and improves overall efficiency [10]. Organic PCMs (e.g., paraffin wax) are inexpensive and chemically stable, while inorganic PCMs (e.g., salt hydrates) provide higher latent heat capacity. This diversity enables material selection according to specific battery system requirements

Their disadvantages are Low intrinsic thermal conductivity most materials, especially organic ones such as paraffin, have relatively low thermal conductivity. If no improvements are made, this will reduce the efficiency of the battery. When the phase change material melts and transforms from a solid state to a liquid state, if proper encapsulation treatment is not carried out, leakage will occur. This not only reduces efficiency but also damages the battery components [11]. While PCMs are effective in buffering short-term heat spikes, they cannot dissipate accumulated heat. Once fully melted, their thermal regulation ability diminishes until they solidify again [12].

3. Future Prospects of Thermal Conductive Materials for Batteriest

The continuous development of electric vehicles, large-

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scale energy storage systems and portable and transportable electronic devices has put forward very high requirements for the thermal management performance of lithium-ion batteries. Meeting these requirements is no easy task. As time goes by, these requirements are getting higher and higher. With the increase in energy density and the continuous increase in output power, the heat generated is also constantly rising. This reveals that the current thermal management systems still have deficiencies. Therefore, the future development of thermal conductive materials lies in achieving thermal conductivity while also increasing mechanical strength, reducing cost, improving safety and ensuring that the environment is not damaged. Only in this way can it continue to develop.

Future research will focus on developing composite materials that can integrate the advantages of existing materials. For instance, metal-carbon hybrid materials can retain the benefits of metals while adding the lightweight and chemical stability of carbon-based materials, thereby enhancing the overall thermal performance of battery systems. Similarly, phase change materials with added conductive fillers (such as graphene) can overcome the issues of low thermal conductivity and chemical leakage. Nanoscale engineering can also play a role in this field. By optimizing surface morphology and improving compatibility, researchers can construct continuous thermal networks to enhance thermal conductivity without sacrificing mechanical stability.

Meanwhile, reducing costs and expanding production remain a significant challenge in the materials field. Although graphene and carbon nanotubes have shown excellent performance in laboratory tests, they cannot be mass-produced due to their high cost and complex synthesis methods. Future processes will continue to follow the approach of low-cost manufacturing and simple methods, such as solution casting, to enhance the feasibility of large-scale application. This is an important criterion. Developing environmentally friendly and recyclable materials, such as bio-carbon-based composites or eco-friendly phase change materials, will help protect the environment and enable large-scale global production.

Furthermore, it is worth noting that future thermal management strategies will increasingly focus on system optimization rather than merely strengthening a specific part or component within the system. Combining passive cooling and active cooling technologies, for instance, by inserting phase-change materials in liquid cooling plates or constructing phase-change enhanced heat sinks, can achieve more stable temperature regulation. Computational modeling and artificial intelligence can accelerate this progress, making it possible to predict material properties based on data and guiding the design of efficient composite materials.

Looking to the future, the development of thermal conductive materials must adhere to the goal of sustainable development and adapt to the continuous updates of technology. Those non-toxic and recyclable materials will become increasingly popular among the public. Moreover, as solid-state and high-pressure batteries become mainstream, the challenges in thermal management will also change. Materials that can withstand a wider temperature range and combine with new chemical materials will be needed. In summary, thermal conductive materials will not be limited to a single discipline but will tend towards interdisciplinary innovation and exchange. They will integrate material science, chemical engineering, mechanical engineering, and computer science to create high-efficiency, low-cost, and sustainable materials. This progress is very important in the global electrification process that is currently experiencing an era of environmental protection.

4. Conclusion

This study examines the research progress of thermal management materials for lithium-ion batteries. It focuses on the composition of the materials, the relationship between thermal properties and the stability of the system. With the advancement of energy storage technology, efficient heat regulation has become a crucial factor determining the safety and durability of batteries. By comparing metal-based, carbon-based, and phase-change materials, this paper highlights the advantages and disadvantages of each material category, and also points out the development and challenges that need to be addressed in the future.

Metal-based materials can still be chosen as this is a mature option. However, the most outstanding feature is its mechanical strength. The corrosion resistance limits its potential for lightweighting. In contrast, carbon-based materials offer new opportunities through nanotechnology, which can reduce their weight and also achieve high thermal conductivity. Moreover, phase change materials provide a new innovative method for passive temperature regulation, capable of absorbing high-temperature energy through conversion. However, they are not yet stable at present and require further optimization in the future. Through interdisciplinary approaches and the integration of experimental and computational insights, future heat-conducting materials will not only extend the lifespan of batteries but also make them less environmentally harmful.

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