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Research Progress of Nanomaterials in Batter Thermal Management System

Qunchao Lin

Department of Chemical Engineering, University of Manchester, Manchester, UK
qunchao.lin@student.manchester.ac.uk

Abstract. With social development, the process of electrification has accelerated accordingly. However, performance degradation of lithium-ion batteries caused by heat generation remains a major problem that needs to be overcome at present. Because lithium batteries perform best at room temperature on battery thermal-management systems, especially upgrades to interfacial thermal-conductive materials, concerns the battery's efficiency, lifespan, and even safety. This paper reviews heat-generation mechanisms and sorts out three categories of nano-upgraded interfacial thermal-conductive materials: metal-based, phase-change, and fluid-based. The literature indicates that using metal nanowires with special alignment within polymers can enhance interfacial thermal-conductive performance by roughly 100 times. Adding about 1% weight fraction graphene to the matrix can improve the efficiency of the heat-transfer network, while the sensible heat is slightly reduced at the same time. Adding magnetic Fe_3O_4 or CuO to a fluid to construct modules of alternating-magnetic-field nanofluids, forming dynamic heat-conduction chains, can significantly reduce battery-module temperatures. This paper focuses on a comprehensive analysis of four aspects of the experimental materials: thermal-conductivity efficiency, heat-buffering capacity, practicality, and manufacturability. It provides material-level design guidelines for battery cooling systems that are safer, longer-lived, and supportive of faster charging.

Keywords: nanomaterial, battery performance, thermal management system.

1. Introduction

With ongoing social development and progress, energy demand continues to rise, and energy security has attracted increasing attention. At the same time, the combustion of fossil fuels has exacerbated environmental pollution and more than 60% of pollution is attributable to fossil-fuel combustion. These two factors have further accelerated electrification worldwide. The most familiar example is electric vehicles replacing internal-combustion cars. According to the IEA, global EV sales surpassed 17 million in 2024, accounting for over 20% of the market, with year-on-year growth of about 35% in 2025 [1]. This implies that EVs will gradually replace fuel-powered vehicles to become the mainstream in the future.

Furthermore, as sustainable energy sources such as solar, wind, hydropower, and nuclear continue to develop, the demand for electricity transmission and storage is also growing. Owing to advantages such as high energy density, low self-discharge, compact size, ease of maintenance, and a mature industrial supply chain, lithium-ion batteries have become one of the primary global choices for energy storage and energy transport. At the same time, the drawbacks of lithium-ion batteries cannot be ignored that the thermal runaway and limited cycle life are the major of them. Studies show that both thermal runaway and cycle life are closely tied to the performance of the battery thermal management system (BTMS) [2]. Meanwhile, numerous studies have shown that lithium-ion batteries have a narrow optimal operating temperature range, typically cited as 15-35 °C or 25-40 °C [3]. When the battery temperature falls outside this range, its performance deteriorates sharply. When the battery temperature falls outside this range, its performance deteriorates sharply. In low-temperature environments such as below 0 °C, the electrolyte viscosity increases, and lithium-ion diffusion becomes slower which cause a sharp rise in internal resistance and a marked decrease in usable capacity and power output. In high-temperature environments such as above 35 °C, irreversible side reactions, such as decomposition and thickening of the solid-electrolyte interphase (SEI) and electrolyte decomposition will be accelerated, leading to rapid fade of the capacity and a shortened service life [4]. Furthermore, excessively high temperatures can lead to SEI breakdown and a self-accelerating temperature rise, triggering thermal runaway and fires. Because lithium-ion batteries generate substantial heat during operation, the performance of the BTMS is particularly critical.

A BTMS comprises a series of complex components, such as fans, pumps, and evaporators. But the most critical and performance-defining elements are the heat-conducting materials in contact with the cells which is the thermal interface materials (TIMs). For current heat conduction materials, there are three main kinds: metal-based thermally conductive materials, phase-change composite thermally conductive materials, and fluid-based thermally conductive materials. Meanwhile, battery thermal management systems are rarely made up of a single thermally conductive material. They typically combine active and passive cooling system. Normal examples include combining metal-based thermal conduction material with fluid-based thermal conduction material or using metal-based materials together with fan-based air cooling. At the same time, engineers generally want to prevent lateral heat transfer from one cell to neighboring cells, as this increases the risk of thermal runaway. Thus, the following sections of this article will discuss and analyze this issue.

However, the drawbacks of normal conventional materials are also obvious. Metal-based materials have insufficient thermal buffering capacity and limited resistance to thermal expansion and corrosion. In contrast, phase-change materials and fluid-based thermally conductive materials have relatively low thermal conductivity. This is why nanomaterials are increasingly used to enhance the performance in the thermal conduct system. Owing to their excellent physical and chemical properties, nanomaterials can greatly enhance the thermal conductivity or reduce thermal boundary resistance of these materials. Therefore, this paper will focus on analyzing the heat conduction materials currently used in BTMSs and will specifically summarize how nanomaterials improve the thermal-conduction performance of such materials in today’s battery thermal management systems.

2. Nanomaterials in batter thermal management system

2.1. Heat-generation mechanisms: thermodynamic and electrochemical perspectives

Understanding the origins of heat generation inside lithium-ion batteries is crucial for designing efficient thermal management solutions. The first is irreversible heat Qir: This is the main generator of heat, particularly when the charge or discharge rate is high. It originates from the system's internal energy dissipation and primarily consists of two components:

Joule heating: Joule heating is the heat which generated as current flows through resistive battery components, such as tabs, electrolyte, separators, electrode materials, and current collectors. Joule's law states that it scales with the current square. This is the primary source of heat creation overall and the highest fraction of polarization heat.

Polarization heat: Polarization heat is caused by concentration polarization and electrochemical polarization in batteries; when electrochemical reactions occur on the electrode surface, their activation energy barriers will produce electrochemical polarization. However, as for concentration polarization, it is particularly easy to understand. It is the potential difference generated by lithium-ion concentration gradients in the electrodes and the electrolyte. Moreover, this effect becomes more pronounced with low temperatures and high C-rate charge/discharge, which leads to a substantial increase in polarization heat.

The entropy change (ΔS) of electrochemical processes during lithium intercalation and deintercalation in the positive and negative electrodes is linked to entropic heat, which is another name for it. Typically, in the initial stage of a charge or discharge cycle, the cell may exhibit endothermic behavior due to entropic effects, providing a slight cooling effect. As the cycle proceeds, the reaction becomes exothermic.

Meanwhile, battery heat generation is likewise influenced by many operating parameters. The first is the charge or discharge rate, which is also the most critical factor. Because irreversible heat is proportional to the square of the current, when a battery operates at high C-rates, the heat it produces rises sharply. At the same time, the operating temperature affects heat generation: excessively high temperatures accelerate parasitic reactions such as electrolyte decomposition, which increases internal resistance and thus increases heat output. By contrast, under low-temperature conditions, the battery's polarization resistance increases significantly, leading to greater polarization heat during charging or discharging [5].

The above principles clearly explain the root causes of the challenges batteries currently face. As the requirements for storing and transferring electrical energy continue to grow, the expectations for higher battery performance, such as fast charging and discharging, also rise. This indirectly drives exponential growth in heat generation. For example, photovoltaic solar power and offshore wind power are often transmitted at very high voltages. When this energy is stored, the thermal burden on battery packs becomes enormous. This means that relatively traditional air cooling or otherwise inefficient battery thermal-management approaches have become less suitable in certain production settings, as they may increase the risk of thermal runaway. Consequently, there is an urgent market demand for ultra-high-performance thermal management materials and methods.

2.2. Nano-enhanced thermal conduction material

2.2.1. Nano-enhanced thermal conduction material

Metal-based thermally conductive materials generally offer very high thermal conductivity and good mechanical strength. However, their thermal-buffering capacity is typically weak, which causes heat to spread rapidly in the lateral direction. In addition, since metal-based materials are electrically conductive, electrical insulation must be ensured. How to render such materials electrically insulating remains an issue to be solved. Moreover, the surfaces of metal-based materials are often relatively rough, so interfacial thermal resistance requires further investigation. Further still, corrosion during real-world use can undermine the reliability of the heat-conductive components and degrade their thermal performance. Therefore, even in current battery thermal-management systems, it is uncommon to use purely metallic materials for heat conduction. The mainstream approach is to disperse nanoscale metals into organic polymers to form metal-based composites. This not only addresses electrical-insulation and corrosion-resistance needs but also enables the creation of an oriented heat-conduction network by controlling the alignment of the nano-metals during fabrication which reduce lateral heat spreading and mitigate the risk of thermal runaway caused by thermal coupling between neighboring cells.

Under acidic conditions, Jinuk Hwang et al. [6] used graphene oxide (GO) to uniformly coat the surface of aluminum powder, raising the thermal conductivity of pure aluminum from 206.9 to 238 W m^{-1} K^{-1}. The optimal formulation occurred at a GO volume fraction of 0.3%. By forming a nanoscale, uniform GO shell on the aluminum particles, the researchers built a low–thermal-resistance graphene–aluminum composite heat-conduction system. However, excessive GO can increase porosity or cause flake delamination, thereby reducing the thermal conductivity.

Matthew et al. [7] achieved an improvement in thermal conductivity by constructing a three-dimensional thermal-conduction network of silver nanowires (AgNWs) or copper nanowires (CuNWs) in polyvinylpyrrolidone (PVP). The AgNWs had a diameter of about 70 nm and a length of about 40 µm. Using a layered-assembly process, the researchers dispersed these highly thermally conductive one-dimensional nanofillers in the PVP polymer. The metal nanowires were fabricated into composite films aligned along the radial in-plane direction and then stacked layer by layer along the thickness. The thickness of a single layer was on the order of about 10 µm, much smaller than the nanowire length. This means most AgNWs lie in-plane, forming in-plane thermal pathways.

The thermal conductivity of the PVP matrix is 0.23 W m^{-1} K^{-1}, but it increases exponentially with nanowire volume fraction. At $\varphi = 0.025$ (2.5% volume fraction), it reaches 3.2 W m^{-1} K^{-1}. The study ultimately determined that at $\varphi = 0.20$ (20% volume fraction), the in-plane thermal conductivity reached 27.2 W m^{-1} K^{-1}which is an increase of more than one hundredfold over neat PVP. The experiments employed a steady-state DC heating method, and the validity of the one-dimensional heat-transfer assumption was evaluated using finite-variable analysis.

The silver nanowires themselves have very high axial thermal conductivity. By assembling them layer by layer so that they are aligned in the in-plane direction, they effectively form “highways” for heat transfer, markedly reducing thermal resistance in the radial direction. Another reason for the high effective thermal conductivity is the relatively low interfacial thermal resistance in metal–polymer composites which is about one order of magnitude lower than that of carbon-nanotube–polymer interfaces. This means that, during the heat transfer, heat passes more readily from the filler into the matrix, rather than being blocked by countless microscopic contact points. Using effective-medium fitting, this study further back-calculated a total interfacial contact thermal resistance of approximately 6.01×105 K W^{-1}; combining this with an estimated contact area yields an area-specific thermal resistance of (1.32±0.96) ×10^{-8} m^{2} W^{-1}, which is of the same order as independent measurements at single-nanowire contacts.

It can also regard the metallic nanowire network and the PVP matrix as a percolating mesh. As the filler volume fraction increases, the mesh density rises, and the efficiency of the heat-transport network grows in an exponential-like manner. However, with further increases in filler loading, although more nanowire–nanowire junctions are formed, the number of contact points associated contact resistances also increases. As these junctions proliferate, their thermal resistance begins to limit the overall thermal conductivity, so the growth in conductivity progressively tapers off. In short, this class of materials leverages one-dimensional pathways plus low interfacial resistance: aligned metal nanowires deliver heat directly toward the side opposite the battery pack, and the intrinsically low metal–polymer interfacial resistance allows the network to realize its high-k potential without excessive losses at myriad nanoscale contacts. Which means the filler volume fraction cannot simply be pushed ever higher. As contact quality such as filler–matrix adhesion deteriorates, the effective network conductivity also declines, which means an optimal balance must be struck during fabrication [8].

For this type of material, the layer-by-layer stacking process is considerably more complex than for common materials, and the cost of silver is quite high; the equipment R&D needed for mass production is also expensive. At present, large-scale deployment in the short term seems unlikely. In addition, nano-silver is prone to sulfidation and ion migration, so reliability during fabrication still requires further study. These issues can be mitigated by electrostatic protection measures and manufacturing in an inert atmosphere. Because the metallic network is inherently conductive, the thermal interface must be electrically insulated. A common solution is to apply a nanoscale insulating adhesive layer that satisfies insulation requirements while minimizing added thermal resistance. In production, another challenge is achieving uniform radial (in-plane) alignment of the nanowires at scale. This can be assisted by applying electric or magnetic fields. But ensuring low porosity and low contact resistance remains an open problem. A currently feasible approach is annealing under high pressure and controlled temperature to reduce silver-nanoparticle deposition at junctions and to lower the material's porosity.

2.2.2. Phase-change thermal conductive material

Phase-change materials (PCMs) are used primarily in passive thermal management. PCMs typically possess a higher latent-heat storage capacity than other materials, which means they can regulate and control battery temperature more effectively without consuming additional energy. When the battery temperature rises to the PCM's phase-transition temperature, the PCM melts from solid to liquid and absorbs a large amount of heat while its own temperature remains essentially constant. This isothermal heat-absorption feature makes PCMs well suited to batteries with stringent temperature-control requirements.

Among organic PCMs, paraffin waxes are among the most studied because they offer high latent heat, chemical stability, relatively low cost, and a tunable phase-transition temperature. However, conventional PCMs have very low thermal conductivity, which severely limits the application. Therefore, some key research has been focused on how to use nanotechnology to enhance the thermal conductivity of PCMs.

At the same time, since the PCM changes from solid to liquid during the phase transition, leakage will occur which greatly affects the reliability and performance of the thermal-management system. Moreover, once the PCM has liquefied, natural convection may occur near the heat-transfer interfaces, which can further disrupt the uniform dispersion of nanoparticles [9].

Goli et al. [2] added small amounts of graphene as a nanoscale thermally conductive filler to the paraffin matrix to address paraffin's low thermal conductivity and its strong tendency to leak, creating a graphene–paraffin composite PCM. Their goal was to build a percolating heat-conduction network and thereby markedly improve the effective thermal conductivity which is consistent with the metal-based composite strategy discussed above. Typical PCMs have a room-temperature thermal conductivity of only 0.17–0.35 W m^{-1} K^{-1}, orders of magnitude lower than engineering metals. According to their experiments, adding 0.05–0.08% weight fraction graphene to paraffin yielded thermal conductivities of 0.61, 0.81, 0.87, and 0.84 W m^{-1} K^{-1}. Under their conditions, a perfectly and uniformly dispersed 1% weight fraction graphene loading increased thermal conductivity by about 60 times, directly indicating that 2D high-k platelets can form effective pathways even at very low loadings. In a lower-cost variant, ordinary graphite was blended into paraffin: at 3% weight fraction the conductivity reached 0.75 $W\ m^{-1}\ K^{-1}$, and at 7% weight fraction it reached 1.2 $W\ m^{-1}\ K^{-1}$, though the composite's latent heat decreased slightly.

The underlying principle is to use high-aspect-ratio graphene sheets to "bridge" a network within the paraffin matrix, turning the original heat flux into a continuous, low-interfacial-resistance fast lane. As the sheet content approaches the percolation threshold, the effective thermal conductivity increases in an exponential-like fashion which is similar to the mechanism in metal–polymer composites. Thermal transport in polymer composites involves heat-transfer pathways, thermal percolation, and thermoelastic-coefficient–related mechanisms. At low filler contents, most particles are isolated and encapsulated by the polymer, which raises interfacial thermal resistance. As the loading increases, nanoscale fillers form macroscopic heat-conduction paths and networks. For graphene or carbon nanotubes, their intrinsically high thermal conductivity means percolation effects [10] further raise the composite's effective k. A point to note is that as filler concentration rises, the specific latent heat per unit mass declines slightly because the filler contributes no phase-change enthalpy. In the experiments above, each 0.1% volume fraction increase in filler corresponded to a 5.5–6.4 $kJ\ kg^{-1}$ reduction in latent heat. Thus, the formulation must be balanced to meet specific requirements.

The application prospects are broad: graphene-enhanced PCMs can, without major structural changes, transform conventional PCMs into materials that equalize temperature rapidly and reduce heat-flux nonuniformity—promising for EV battery modules to lessen cell-to-cell temperature differences. However, because PCMs transition from solid to liquid, metallic heat-dissipation components such as metal meshes, metal foams, or other porous skeletons should be incorporated to ensure stable heat conduction, improve structural integrity, and mitigate leakage.

2.2.3. Fluid-based thermal conductive material

Among all thermal-management approaches, fluid cooling is one of the most efficient and is typically used in active systems. Compared with metal-based materials, fluids have relatively low thermal conductivity; however, in active systems the presence of pumps allows heat to be removed in a timely manner. How to conduct heat out of the device more effectively, though, remains an open challenge.

To address this, researchers add nanoparticles to conventional fluids to create nanofluids, thereby enhancing the material's thermal-transport capability and offering a new route for extreme heat-dissipation scenarios. A nanofluid is essentially a stable colloidal suspension of nanoparticles in a traditional base liquid, used to increase the convective heat-transfer coefficient.

At the nanoscale, particles are strongly influenced by van der Waals forces and readily acquire surface charge, which promotes mutual attraction and agglomeration; maintaining a stable, free dispersion in the fluid is therefore a key issue. Meanwhile, nanoparticles may adsorb onto pump components, reducing overall cooling efficiency or even causing clogging—problems that also need to be solved.

To address the above issues, Kiani et al. [11] dispersed Fe_3O_4 (magnetite) and CuO nanoparticles in a water-based fluid to prepare nanofluids, and they also applied an alternating magnetic field (AMF). The experiments compared the cooling effects of these nanofluids on a battery module. Relative to pure water, the CuO nanofluid reduced the battery temperature by 12.6%, while the Fe_3O_4 nanofluid achieved a 43.2% reduction. At the same time, the pressure drops increased by 55.2% compared with the base liquid.

In this study, the novel use of an AMF caused the magnetic nanoparticles to instantaneously align into chains or clusters, forming an efficient thermal network and pathway at the macroscopic scale. This allowed the previously disordered convective heat to be removed from the heat-dissipation surface more rapidly, thereby lowering the battery pack temperature. Moreover, the externally applied AMF induces a magnetorheological effect, which increases the nanoparticles' effective volume fraction, thereby raising the effective thermal conductivity. The viscosity also increases, consistent with the observed 55.2% rise in pressure drop. In addition, the AMF repeatedly cycles the chaining and de-chaining of nanoparticles, creating micro-disturbances near the pipe wall and enhancing the convective heat-transfer coefficient.

3. Conclusion

This paper reviews and clarifies that heat generation in lithium batteries consists mainly of two parts: irreversible heat and reversible heat. As society demands higher charge/discharge rates, the problem of battery heating is amplified. Therefore, more efficient thermally conductive materials for battery thermal management systems need to combine high thermal conductivity, high heat buffering, and high stability. Evidence shows that: (1) adding oriented metal nanowires to polymers can construct a rapid heat-conduction network and increase thermal-conduction efficiency by two orders of magnitude; (2) coating metals with graphene oxide can also reduce the metal's interfacial thermal resistance; (3) using a low loading of graphene to reinforce phase-change thermally conductive materials can significantly enhance their thermal conductivity, while the latent heat is slightly reduced, and an anti-leakage scaffold still needs to be designed; (4) nanofluids under magnetic-field assistance can enhance convective heat dissipation, but viscosity and pressure drop increase as well. In general, for interfacial thermal materials in thermal management systems, nano-enhancement can further increase the material's thermal conductivity and reduce the temperature rise of batteries during fast charge and discharge, thereby keeping batteries within an optimal temperature range and improving cycle life and safety.

Future research should address current bottlenecks: ensuring uniform orientation of nano-metallic wires under large-scale industrial production; ensuring electrical insulation in nano-metal-enhanced thermally conductive materials; and achieving uniform dispersion of nanoparticles in nano-enhanced phase-change thermally conductive materials and in nanofluids when produced at scale. In addition, future work can focus on improving the efficiency of industrial production equipment related to magnetized nanoparticles for enhancing battery heat-transfer coefficients, and on further solving leakage and thermal-convection issues in nano-enhanced phase-change materials using nanomaterials. By combining heat-conduction principles with the current state of materials research, this paper provides engineers with a framework and data support for selecting and investigating thermally conductive materials in thermal management systems for the design of safer, higher-power next-generation battery packs.

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