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Review on Numerical Analysis of Phase Change Materials for Battery Thermal Management Systems

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Abstract: The rapid expansion of electric vehicles (EVs) has intensified the need for efficient battery thermal management systems (BTMS) to ensure safety, performance, and longevity of lithium-ion batteries. Phase Change Materials (PCMs) have emerged as a promising passive cooling solution due to their high latent heat storage capacity and cost-effectiveness. This review presents a comprehensive analysis of PCM-based BTMS, highlighting their advantages, limitations, and enhancement strategies. Key challenges, such as low thermal conductivity, are addressed through composite structures incorporating expanded graphite, biochar, nanoparticles, carbon nanotubes, and metallic coatings, as well as integration with fins for improved heat dissipation. Hybrid cooling systems combining PCMs with liquid cooling, air cooling, and heat pipes are discussed, demonstrating superior thermal uniformity and stability compared to standalone PCM systems. Numerical methods, including finite volume simulations, enthalpy-porosity, and apparent heat capacity approaches, supported by tools such as ANSYS FLUENT, COMSOL Multiphysics, and STAR-CCM+, are reviewed for their role in optimizing PCM-BTMS configurations. Results indicate that hybrid PCM systems significantly reduce maximum battery temperatures, enhance uniformity, and improve exergy efficiency, particularly under high discharge rates. The findings underscore the importance of material innovation, geometric optimization, and numerical modeling in advancing PCM-based BTMS for next-generation EV applications.

1.INTRODUCTION TO BATTERY THERMAL MANAGEMENT SYSTEMS AND PHASE CHANGE MATERIALS

The rapid growth of electric vehicles (EVs) necessitates effective battery thermal management systems (BTMS) to ensure battery longevity, improve performance, and maintain safety [11, 16]. Lithium-ion batteries, widely used as power sources for EVs due to their high energy density and environmental friendliness, are highly sensitive to operating temperature [15, 18]. Factors such as operating temperature, charge/discharge rates, and internal heat generation significantly influence performance metrics like driving range, charge storage capacity, battery cycle life, and the risk of thermal runaway at high temperatures [11]. Therefore, a BTMS is crucial for controlling battery temperature and maintaining optimal operating conditions [11, 15].

Among various cooling methods, battery thermal management systems based on Phase Change Materials (PCMs) have emerged as a safe, inexpensive, and high-performance technology [6, 16, 30]. PCMs are capable of absorbing and storing substantial latent heat within a specific temperature range during phase transition [13, 22]. As PCMs melt, they absorb heat generated by batteries, helping to prolong battery life and improve performance [1, 6]. A cold-energy battery, for instance, utilizes advanced PCM properties to maintain temperature as part of battery thermal management, storing and releasing energy, and can be recharged by placing it in an environment conducive to its phase change properties [21]. Studies on heat transfer and thermal management with PCMs in Li-ion battery cells for electric vehicles have been conducted [2, 4, 5].

2.ADVANTAGES AND CHALLENGES OF PCMS IN BTMS

PCMs offer a distinct advantage as a passive cooling technology, meaning they do not require additional equipment or consume energy, unlike some other cooling methods [24, 26, 32]. This makes them an attractive option for managing the thermal conditions of battery systems, particularly in addressing concerns related to external climatic factors and heat generation during battery operation [12].

However, a significant challenge associated with PCMs, particularly in energy storage applications, is their relatively lower thermal conductivity [13, 14]. This low thermal conductivity can lead to inadequate heat transfer performance, limiting their effectiveness in high-demand applications [13, 14]. Another consideration for PCMs is their material properties; some are suspended in water and are relatively nontoxic, while others are hydrocarbons or flammable materials, or can be toxic, requiring careful selection and application in accordance with safety codes [22].

3.ENHANCING PCM PERFORMANCE FOR BTMS

To overcome the limitations of PCMs, particularly their low thermal conductivity, various strategies have been explored, often involving the creation of "thermal composites" [22]. These composites combine PCMs with other structures, typically solids, to enhance overall or bulk thermal properties [22].

1.1 Composite Phase Change Materials

The primary idea behind thermal composites is to increase thermal conductivity by incorporating a highly conducting solid into the relatively low-conducting PCM [22].

Expanded Graphite: One common approach involves impregnating PCMs into an expanded graphite matrix [6]. This method has been used for both organic compounds like paraffin wax and inorganic composite PCMs based on magnesium chloride hexahydrate, enhancing their thermal conductivity [6]. A study found that paraffin with graphene nanoparticles showed increased cooling and performance for two-wheeler battery packs [18].

Biochar and Nanoparticles: Eco-friendly coconut shell biochar (CSB) dispersed with organic A46 PCM has been synthesized to form green nanocomposites, demonstrating enhanced thermal conductivity (0.39 W/m·K) compared to base PCM (0.22 W/m·K) [13]. Graphene nanoparticles combined with paraffin wax have also been utilized to engineer BTMS [18].

Carbon Nanotubes: The application of carbon nanotubes prepared from waste plastic to PCMs shows potential for battery thermal management [10].

Metallic Coatings: To further enhance both thermal conductivity and mechanical strength, studies have investigated integrating Ni-P and Ni-P-Cu coatings on PCM/expanded graphite structures. Ni-P-Cu-coated composites exhibited a superior thermal conductivity of 27.1 W/mK and higher compressive and tensile strength, also reducing polarization effects and extending operational stability [14].

Integration with Fins
Fins are often integrated with PCMs to improve heat dissipation and thermal management performance.
* Various Geometries: Experimental and numerical investigations have studied the thermal behavior of cylindrical batteries with composite paraffin and fin structures [3, 7]. Studies have explored different fin geometries, such as "I" section fins, which showed a profound beneficial effect on heat transfer [11]. Biomimetic honeycomb fins have also been analyzed for their performance with PCMs [9].
* Effect on Temperature Uniformity: The presence of fins helps reduce the maximum cell temperature and minimizes temperature differences, ensuring more uniform temperature distribution [15, 17]. For example, in a PCM system with rectangular fins, the temperature difference was observed to remain below 1 K [15].

1.2 Hybrid Cooling Systems

Combining PCMs with other cooling methods creates hybrid systems that can offer enhanced thermal performance.
PCM and Liquid Cooling: Numerical analysis has been conducted on BTMS coupling low-thermal-conductive PCM and liquid cooling [8, 12]. Studies involving liquid cooling of batteries encased in PCMs have utilized finite volume methods to analyze battery surface temperature, liquid fraction fields, and average module temperature for different C-rates and PCM types [12]. A numerical study also explored the thermal management of pouch lithium-ion batteries using composite liquid-cooled PCMs with a honeycomb structure [27]. Hybrid systems combining liquid cooling and PCM show exceptional thermal performance, improving temperature uniformity and stability [16].

PCM and Air Cooling: A comparative study investigated BTMS incorporating PCM and air cooling in a cylindrical Li-ion cell with fins, analyzing their effects on maximum and minimum temperature and temperature uniformity [15]. It was found that PCM reduced both maximum and minimum temperatures more effectively than air cooling [15].

PCM and Heat Pipes: Hybrid passive BTMS integrating PCM, heat pipes (HP), and aluminum fins have been evaluated for heat mitigation in Li-ion batteries under high discharge rates [17]. These systems combine axial heat pipe conduction, latent heat absorption from PCM, and fin-assisted lateral dispersion for synergistic thermal control [17, 29, 31]. Such configurations have shown improved maximum temperatures and reduced PCM melting, with temperature differences minimized to less than 1.0 K across the battery pack [17].

Combined Hybrid Systems: Comprehensive reviews indicate that hybrid systems, especially those combining liquid cooling and PCM, or forced air cooling with liquid cooling and PCM, significantly enhance cooling efficiency and energy consumption, proving to be the most effective BTMS methods for EVs [16].

4.NUMERICAL METHODS AND TOOLS FOR PCM-BTMS ANALYSIS

Numerical analysis plays a critical role in understanding and optimizing the performance of PCM-based BTMS.
* **Simulation Techniques:** Finite volume simulations are widely used to examine heat transfer in battery packs [1, 12, 15]. Computational Fluid Dynamics (CFD) is often combined with second law analysis to evaluate and compare new BTMS configurations [1].

* **Modeling Approaches:** The enthalpy-porosity method is a common technique employed to simulate heat transfer efficiency of PCM and thermal behavior of cooling BTMS [20, 23]. Another formulation, the Apparent Heat Capacity method, is also used for such analyses [20].

* **Software Tools:** Numerical analyses are performed using specialized software. ANSYS FLUENT has been used to determine the effect of PCM on heat transfer in battery modules [11]. Other studies have utilized ANSYS software and the finite volume method to evaluate cooling performance [15, 19]. STAR-CCM+ and COMSOL Multiphysics are also employed for numerical studies, with comparisons made between results from the Enthalpy-Porosity method (STAR-CCM+) and the Apparent Heat Capacity formulation (COMSOL Multiphysics) [20]. Two-dimensional energy modeling software is also used to ascertain heat transfer rates of PCM composites [13].

5.CONCLUSION

* PCM Configuration and Parameters: Analysis of double series PCM shells using finite volume simulations showed higher exergy efficiencies compared to single PCM shell systems in most cases [1]. Key parameters like thermal conductivity and melting temperature were identified as important for shell configuration [1]. Exergy efficiency ranged widely (15-85% for single shell, 30-80% for double shell systems), and generally decreased as dead-state temperatures rose [1].

* Thermal Performance: Numerical analysis using ANSYS FLUENT predicted temperature distribution along the battery, demonstrating the beneficial effect of PCM and fins, with "I" section fins showing a profound effect on heat transfer [11]. Studies have also revealed the melting process of PCM for thermal management of cylindrical power batteries through numerical analysis and experimental visualization [4, 25].

* Temperature Control and Uniformity: PCM-only systems can exhibit poor performance at high discharge rates (e.g., 4C), leading to high maximum temperatures and substantial PCM melting [17]. Hybrid systems, such as PCM + Heat Pipe (HP) configurations, significantly improve maximum temperatures and reduce PCM melting, maintaining excellent thermal uniformity with temperature differences minimized to less than 1.0 K [17]. Numerical results show that PCM can reduce both maximum and minimum temperatures compared to air cooling systems [15].

* C-Rate Influence: Numerical investigations have involved three different C-rates for various PCMs (e.g., RT27 and RT31) using the Finite Volume Method, detailing battery surface temperature, liquid fraction fields, and average module temperature [12]. PCM has been shown to effectively stabilize battery temperatures under discharge rates like 1.25C and 2.5C [14].

* Optimization of Design: Numerical simulations for a 3S4P 21700 lithium-ion battery module with varying composite PCM (C-PCM) thicknesses (0 mm, 1 mm, 5 mm, and 10 mm) indicated that a 5 mm thickness for the C-PCM was optimal for stable operation [18]. An optimization method for BTMS using PCM aims to minimize the maximum temperature [28].

* Impact of Natural Convection: Numerical results indicate that while natural convection in the liquid PCM accelerates the melting process, it can lead to a non-uniform temperature distribution, particularly affecting cells in the upper part of the battery pack [20].

* Hybrid System Effectiveness: Numerical findings consistently show that hybrid systems, particularly those combining liquid cooling and PCM, or forced air cooling with liquid cooling and PCM, exhibit exceptional thermal performance, improving temperature uniformity and stability crucial for optimal battery operation [16].

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