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Research Papers

Machine learning accelerated the performance analysis on PCM-liquid coupled battery thermal management system

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Highlights

- A novel PCM-liquid coupled battery thermal management system is designed.
- The module layout and liquid flow parameters are optimized with monitoring temperature.
- The optimized battery module can improve thermal performance and reduce power consumption.
- The machine learning accelerated regression model can predict the thermal performance.

Abstract

With the increasing prominence of thermal management issues in lithium-ion batteries, the performance of active-passive hybrid battery thermal management systems attracts extensive attention. In this study, a novel phase change material-liquid cooling coupled battery thermal management system was designed. The effects of battery arrangement structure, liquid flow direction, mass flow rate, startup temperature, phase change material melting point, and liquid cooling power consumption on the thermal management performance of the battery module during high-rate discharge were numerically investigated. The results show that the phase change material-liquid cooling system can effectively regulates battery temperature within safe limits under optimal operational conditions. Compared to the module without liquid cooling with an initial temperature of 40 °C, the maximum temperature is reduced by 15.18 °C and 27.5 °C during 3C and 5C discharge, respectively. Lower liquid cooling startup temperature and higher liquid flow rate contribute further to reducing the maximum module temperature, albeit with increased energy consumption. Compared to continuously operating liquid cooling at 0.01 kg/s, adjusting liquid cooling operating point with minimized power usage can drastically reduce energy consumption by up to 94.71 % during 5C discharge and ambient temperature conditions. Additionally, machine learning with three multi-objective regression prediction models were utilized to predict the temperature and energy consumption of the proposed coupled system. The error between the Random Forest model's predicted values and the simulation results was determined to be <5 %.

Introduction

With the rapid development of electric vehicles and renewable energy, lithium-ion batteries have become increasingly important as an energy storage device. However, the thermal management issues have become more prominent [1,2] due to the high temperatures can lead to deterioration of battery performance, shortened life, and even safety risks [3]. Therefore, an effective battery thermal management system (BTMS) is essential to maintaining the battery within the optimal temperature range for safety [4,5]. Generally, these BTMS can be classified into passive or active methods based on the use of extra energy source. Active technologies, such as air and liquid based methods are the most commercially used techniques. Passive approaches include heat pipe and phase change material (PCM) based systems by utilizing the latent heat during phase transition. Notably, each basic BTMS has its own advantages and drawbacks, making it impractical to meet the diverse requirements of various applications by using a single method. Given these trade-offs, it is imperative to develop a coupled thermal management strategy [6].

In recent years, significant progress has been made in the field of coupled BTMS, including the coupling of PCM with air, heat pipe, thermoelectric cooling, and so on [7,8]. The integration of PCM with liquid cooling (LC), in particular, shows great potential in achieving higher thermal performance by combining the advantages of both active and passive cooling modes [9]. On one hand, the PCM-based system utilizes the absorption and release of latent heat during phase change to regulate the battery temperature [10]. On the other hand, LC technology involves circulating coolant (e.g., water or refrigerant) to dissipate heat more effectively to outside environment [11]. Recent literature studies have shown that PCM and LC coupling strategy has shown tremendous potential in BTMS under various conditions [12,13]. For instance, Song et al. [14] investigated a coupled BTMS where heat generated by the battery is transmitted to a microchannel LC plate through PCM and heat transfer column. The results showed that, compared with single PCM or LC, the coupled system reduced the battery steady-state temperature by 13.6 °C at the ambient temperature of 35 °C. Similarly, Kshetrimayum et al. [15] developed a BTMS that combining PCM with cooling plate, effectively limiting thermal runaway and maintaining adjacent cell temperatures below 90 °C through numerical simulations under both normal and stress conditions. Sun et al. [16] proposed a coupled BTMS with LC, foam copper, expanded graphite (EG) and PCM to simulate thermal behavior under 3C discharge and New European Driving Cycle (NEDC) conditions. PCM can effectively maintain temperature rise and uniformity within the ideal range under NEDC condition, and at 3C discharge rate, the average temperature of the whole module could be reduced by 72% under the function of LC. The above studies highlight the effectiveness of coupling BTMS in maintaining batteries within a safe temperature range. However, the complexity of such systems cannot be overlooked, as it involves a multitude of parameters such as flow rates, melting temperature, and operational conditions. Manual optimization of these variables can be arduous and time-intensive, prompting a burgeoning interest in leveraging advanced techniques such as machine learning (ML) to streamline BTMS design and enhance efficiency.

ML algorithms have the potential to analyze complex data, identify patterns, and optimize thermal management system performance in an automated and efficient manner. By employing ML, predictive models can be trained to adapt control strategies dynamically and optimize the system in real-time. The application of ML enables accurate prediction of BTMS performance using learned data samples, reducing experimental costs and time. As a result, integrating ML into BTMS performance prediction has become a prominent focus of research [[17], [18], [19]]. Liu and Zhang [20] studied the design of air-based J-type BTMS through the agent model-based optimization ML algorithm. After optimization, the temperature rise was reduced by 31.18%, and the adaptive control was able to meet the cooling requirements. Yu et al. [21] analyzed and predicted the air cooling technology of $LiFePO_4$ battery pack based on deep learning. Compared with the CFD simulation results, the average absolute errors of the maximum temperature and temperature difference of the deep learning model were 0.046% and 0.99%, respectively. After comparing 765,846 different BTMS structures, the deep learning method is used to determine the best BTMS air cooling design. Kolodziejczyk et al. [22] developed a method combining convolutional neural network (CNN) and finite element analysis to detect the effective thermal properties of composite PCM composed of paraffin and copper foam. The CNN model can robustly with ultrahigh precision estimate the maximum temperature rise in the battery pack, and achieve an average absolute percentage error of about 5%. Shahsavar et al. [23] developed a BTMS with PCM. To accurately estimate liquid fraction, frictional and thermal entropy generation rate, they introduced a novel integrated ML approach, gradient-enhanced decision tree (GBDT), using fin tip and flow time as inputs. The ML-based GBDT model outperformed traditional methods in simulating liquid fraction (R=0.9996, RMSE=1.083E-02 W/K, IA=0.9998) and frictional entropy generation rate (R=0.9985, RMSE=1.547E-12 W/K, IA=0.9992), but had similar performance for thermal entropy generation rate (R=0.9985, RMSE=4.213E-06 W/K, IA=0.9985). Xu et al. [24] proposed a microchannel LC structure BTMS virtual model based on digital twins (DT). The results show that the Gaussian process regression based on DT virtual model is more suitable for analyzing the interaction between multiple factors and obtaining global optimization results. After optimization, the maximum temperature of the system is reduced by 4.02 °C, and the maximum temperature difference is reduced by 5.05 °C. These results demonstrate the effectiveness of ML in designing BTMS.

Based on the literature survey, it is evident that while many studies have been conducted on PCM-LC coupled BTMS, few have focused on the coupling strategy of multi-impact parameters and its intelligent prediction. Especially in practical applications, the complexity and diversity of factors such as module configuration and operational settings pose significant challenges to achieving optimal BTMS performance. Therefore, this paper carries out in-depth research on the performance of PCM-LC coupled BTMS and explores the application of ML in battery temperature control performance prediction. The research in this paper will provide theoretical guidance and technical support for the design and optimization of ML assisted PCM-LC coupled BTMS.

Section snippets

The layout of this paper

The PCM and LC technologies are applied to construct the compact coupled BTMS, where PCM with high latent heat acted as passive thermal buffer to regulate battery temperature, while LC served as active heat dissipation channel to increase the utilization of PCM latent heat and further decrease the module temperature. During the operation, three indexes are adopted to evaluate the thermal performance and energy efficiency: the maximum temperature of the module (T_{max}), the maximum temperature …

Physical system

As shown in Fig. 2a, a prismatic battery [25] (anode: $LiFeO_4$, cathode: graphite) was used, with a nominal capacity of 12 Ah and a size of (Length × Width × Height) 70 mm×27 mm×90 mm. In this paper, PCM and pyrolytic graphite sheets (PGS) are attached to the side of the battery (YZ side). PCM uses paraffin and expanded graphite to compress them into the mold by hot pressing, so as to enhance the thermal conductivity and improve the shape stability of solid-liquid phase transition [26]. PGS …

Performance of different battery module configuration designs

In order to explore the influence of battery module configuration on the temperature control performance of the BTMS, three different LC flow directions were designed: upper nozzle inflow (No. 1), lower nozzle inflow (No. 2), upper and lower staggered inflow (No. 3), as shown in Fig. 4. The combination of the two module topologies (Case1 & Case2) in Fig. 2c and the three LC flow directions can construct six BTMS structures (Case 1.1, Case 1.2…, Case 2.3). The T_{max} and T_{dif} were compared under …

Machine learning models and predictive results

In this study, the BTMS model was used, with ambient temperature, T_{start}, LC mass flow rate and discharge rate as input variables, and T_{max}, T_{dif} and EC_{LC} as output variables. A total of 168 simulation cases with varying input parameters were performed and used as datasets (as shown in Table 2) were obtained by utilizing simulation results. Where, turning off LC is represented by a value of 0 in the input parameters of the dataset. Multiple-objective regression prediction models were …

Conclusions

To improve the cooling performance of battery modules, a novel hybrid BTMS with PCM and LC was developed. This system incorporates temperature monitoring points to regulate the duration of LC activation, ensuring safe module temperatures and maximizing energy savings. The following conclusions were drawn:

1. The arrangement of battery module in a single row demonstrates superior performance in reducing T_{max}, while a double row configuration has better temperature uniformity. Among three flow …

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CRediT authorship contribution statement

Shiwei Xie: Writing – original draft, Visualization, Software, Methodology, Investigation, Formal analysis, Conceptualization. **Chengshan Xu:** Writing – review & editing, Supervision, Methodology. **Wei Li:** Writing – review & editing. **Yue Kang:** Writing – review & editing. **Xuning Feng:** Writing – review & editing, Supervision. **Weixiong Wu:** Writing – review & editing, Supervision, Resources, Project administration, Funding acquisition, Conceptualization. …

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper. …

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