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Compact liquid cooling strategy with phase change materials for Li-ion batteries optimized using response surface methodology

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HIGHLIGHTS

- A hybrid battery cooling system is optimized with response surface methodology.
- PCM composition is optimized along with the active cooling structure.
- Effects of battery layout, PCM composition and cooling intensity are studied.
- A compact cooling strategy with composite PCM and liquid cooling is presented.
- The PCM mass and volume have been reduced by 94.1% and 55.6% per battery cell.

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ABSTRACT

The hybrid system that integrates active cooling into phase change materials (PCMs)/expanded graphite (EG) shows great prospects for power battery thermal management. But because of the heavy weight, the system need to be optimized with a balance of the cooling capacity contributed by the active and passive cooling. This study develops an optimization method based on the response surface methodology (RSM) and a numerical heat transfer model to minimize the weight and volume of such a battery thermal management system. With the PCM thermo-physical property models incorporated, the method can optimize the PCM composition along with the active cooling structure – taking the contributions of both the active and passive cooling into account. We minimize the PCM mass of the system with this method, and analyze the effects of the PCM composition, the battery module layouts and the active cooling configuration on the thermal management performance. Then we present an optimal design for this hybrid thermal management system, which helps save the PCM mass by up to 94.1% and the volume by up to 55.6%. The thermal management performance of the design is verified with an experiment. The results show the maximum battery temperature in a 20-battery module during the 1.5C discharge is limited to 37.0 °C while the maximum temperature difference is limited to be smaller than 3 °C. Compared with the conventional liquid cooling system, the hybrid system is not only highly efficient, but lightweight, with simple structure and flexible to the batteries with arbitrary shapes.

1. Introduction

Li-ion battery has become the first choice for the energy storage units of electric vehicles (EVs), because of its high energy and power density. A well-designed thermal management system is critical to ensure a good performance and long cycle life of Li-ion batteries [1,2]. Various thermal management systems have been developed for Li-ion batteries such as air cooling [3–6], liquid cooling [7–10], mist cooling [11], heat pipe cooling [12–14], and cooling via phase change materials (PCMs) [15–21]. The passive thermal management system with the PCMs shows great prospects for battery cooling [22]. Taking advantage of the high latent heat, PCMs can absorb a large amount of heat during the phase change and maintain the battery temperature within a narrow range close to the phase-change temperature [23]. With a simple structure that the PCM directly wraps the battery, the passive system is able to maintain a small temperature rise and small temperature difference in the battery pack [24], and could prevent thermal runaways of Li-ion batteries [25]. The PCM-based thermal management system provides higher cooling capacity than air cooling, has a simpler structure against liquid cooling, and is suitable for the battery with arbitrary shapes compared with heat pipes which can only be attached to a rectangular surface.

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Nomenclature

D	battery spacing (mm)
h	surface heat transfer coefficient ($\mathrm{W\,m^{-2}\,°C^{-1}}$)
m	mass of PCM/EG composite (kg)
c_p	specific heat ($\mathrm{J\,kg^{-1}\,°C^{-1}}$)
k	thermal conductivity ($\mathrm{W\,m^{-1}\,°C^{-1}}$)
q	battery heat generation rate (W)
I	current (A)
E	battery equilibrium voltage (V)
V	battery operating voltage (V)
F	Faraday number (96,485 $\mathrm{C\,mol^{-1}}$)
T	temperature (°C)
ΔS	entropy change ($\mathrm{J\,mol^{-1}\,K^{-1}}$)
hs	sensible heat ($\mathrm{J\,kg^{-1}}$)
Δh	specific latent heat of the melted PCM ($\mathrm{J\,kg^{-1}}$)
ΔH	latent heat (J)
H	enthalpy ($\mathrm{J\,kg^{-1}}$)
T_{max}	maximum temperature rise (°C)
ΔT	maximum temperature difference (°C)
n	nominal direction

Greek letter

γ	specific phase change enthalpy ($\mathrm{J\,kg^{-1}}$)
α	PCM mass fraction (%)
ρ	density ($\mathrm{kg\,m^{-3}}$)
β	melting mass fraction of PCM (%)

Subscripts

s	solid
l	liquid
side	cooling from the side walls
top	cooling from the top and bottom walls

But our previous study shows the PCM would suffer failures in continuous charge-discharge cycles, if heat accumulates in the PCMs [26]. Because the poorly efficient natural convection of air is unable to dissipate the heat stored in the PCM out soon enough before the next discharge starts, the heat accumulation is likely to happen in case of a very short break between two neighboring discharges or a high ambient temperature. As a consequence, the auxiliary active cooling such as air cooling [27] or liquid cooling [28] has to be introduced to PCMs to solve this problem [29,30]. The combination of PCM and active cooling not only improves the long-term reliability for the passive thermal management system, but also helps achieve a high cooling performance for the active thermal management system with a simple structure.

A big problem of the active passive thermal management system is the heavy weight. The PCM thermal management system itself is heavy. As evaluated by Khateeb [31], the PCMs bring in 30% extra weight to the battery. The fans, pumps, and heatsinks used in the active cooling further add the system mass. Therefore, we need to optimize the system structure to avoid overweight of the battery pack. Since the PCM and the active cooling play different roles in battery cooling, we have to balance the cooling capacity for each type of cooling has to reduce the weight and size of the system.

Yet we have not found studies related to the optimization for PCM-based thermal management system. The published works mostly only focus the optimization for the active cooling system. Bauer et al. [32] liquid cooling plate optimization method with the Pontryagin's maximum principle. Severino et al. [33] developed a multi-objective evolutionary algorithm to optimize the layouts of a battery pack that was cooled by air. However, compared with the active cooling only system, the existence of the PCM increases the complexity for optimization. Since the PCM provides large extra cooling capacity for battery cooling, the PCM composition should be optimized so that the PCM can work with the active cooling with the best thermo-physical properties.

The PCM/expanded graphite (EG) composites have great application potentials for battery thermal management [34]. The composite PCM can effectively reduce the temperature difference in battery packs because of the high thermal conductivity and high latent heat [35]. Our previous study has discovered the relations between the PCM constituent (such as PCM mass fraction α and density ρ) and the thermo-physical properties (such as the specific latent heat and thermal conductivity) [36], as well as the effects of the thermal properties on the thermal management performance [37]. With this knowledge, this paper intends to incorporate the optimization of the PCM compositions together with the heatsink structure to maximize the efficiency of both the active cooling and the passive cooling.

But we still need a tool to implement the optimization - as the system optimization involves multiple variables, which at least comes from three sources: (1) The active cooling heatsink structure; (2) The layouts for the battery and the PCM; (3) The PCM constituent. Many previous works adopted parametric studies for optimization battery thermal management system optimization. For example, Fan et al. [38] optimized the battery gap spacing and the air flowrate for a battery pack with eight prismatic batteries. Mohammadian et al. [39] compared the thermal behaviors of the pin fins of different heights, and presented a design with pin fins whose height linearly increase in the flow direction. Ye et al. [40,41] optimized a battery thermal management system with heat pipes through a parametric study on the effects of the number of heat pipes, fin number/fin pitch, and cooling intensity in the condenser sections. The parametric studies works well if the parameter number is small. However, a better optimization tool is required for this multi-parameter optimization of the hybrid battery thermal management.

Response surface methodology (RSM) is a powerful statistical technique for multi-parameter optimization [42]. RSM uses a series of designed experiments via central composite design (CCD) to generate an approximation equation of the objectives against the multiple control variables. We can derive the optimal design from the response surface, which is a polynomial regression equation. The RSM is a simple but efficient tool for multi-parametric optimization. Compared with another commonly used optimization method, the Taguchi method [43], RSM helps find out the global optimal design in a high curvature problem. RSM has been successfully applied for the optimization of a loop heat pipe cooling system for battery [44], the reaction parameters of the co-conversion of waste activated sludge and birchwood sawdust [45], the size of a PV/wind hybrid energy conversion system [46] or other applications across multiple disciplines.

The purpose of this paper is to present an optimization method for the hybrid battery thermal management system and helps design an efficient thermal management system with a simple-structure and lightweight. We combine the RSM with a numerical heat transfer model which incorporates the PCM thermo-physical models as the multi-parameter optimization method. In this way, not just the active cooling structure, the composition of the PCM/EG composite can be optimized simultaneously. Based on the optimization results, a sensitivity analysis will then discuss the effects of density & PCM mass fraction of the PCM/EG composites, the battery gap spacing, and the external cooling intensity on the thermal management system performance. And the thermal management performance of the optimized design for the hybrid battery thermal management system then will be verified with an experiment.