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A hybrid thermal management system for lithium ion batteries combining phase change materials with forced-air cooling

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HIGHLIGHTS

- Heat accumulation in PCM causes failures of passive thermal management systems.
- The introduction of forced air convection improves the reliability of PCMs.
- Temperature distribution in the hybrid system remains uniform.
- Active cooling and PCMs play separate roles in battery thermal management.
- Numerical results agree with experiment data and give theoretic insights.

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ABSTRACT

Passive thermal management systems using phase change materials (PCMs) provides an effective solution to the overheating of lithium ion batteries. But this study shows heat accumulation in PCMs caused by the inefficient cooling of air natural convection leads to thermal management system failures: The temperature in a battery pack operating continuously outranges the safety limit of 60 °C after two cycles with discharge rate of 1.5 C and 2 C. Here a hybrid system that integrates PCMs with forced air convection is presented. This combined system successfully prevents heat accumulation and maintains the maximum temperature under 50 °C in all cycles. Study on airspeed effects reveals that thermo-physical properties of PCMs dictate the maximum temperature rise and temperature uniformity in the battery pack, while forced air convection plays a critical role in recovering thermal energy storage capacity of PCMs. A numerical study is also carried out and validated with experiment data, which gives theoretic insights on thermo-physical changes in this hybrid battery thermal management system.

1. Introduction

Li-ion batteries are considered as excellent power sources for hybrid or electric vehicles (HEVs/EVs) due to high energy and power density [1]. However, the remarkable deterioration in the performance of Li-ion batteries at elevated temperatures is hampering their practice applications [2–4]. It has been reported that the optimum operating temperatures for Li-ion batteries should range from 20 to 50 °C, and the maximum temperature difference in a battery pack should be kept within 5 °C [5]. Consequently, efficient thermal management systems are highly needed for Li-ion batteries to remove the massive amounts of heat generated in the charge/discharge process.

Forced air convection is a routine solution to thermal management of electronic components. However, forced air convection brings about nonuniform temperature distribution in a battery pack, leading to different degrading rates for each cell [6,7]; As a result, the cycle life of the whole pack would be shortened. Although optimizing the flow ducts for air can improve the temperature uniformity, system complexity is also increased [8–11].

Recently, passive thermal management system using phase change materials (PCMs) have been developed as an alternative to active cooling. Taking advantage of high latent heat, PCMs can absorb the massive amounts of heat generated by Li-ion batteries and keep the temperatures of the batteries within the melting range of the PCMs [12,13], thereby reducing both the maximum temperature and the temperature difference in the battery pack [14–16]. Furthermore, the performance of the passive thermal management systems can be improved via the enhancement in the thermal conductivity of the PCMs by adding some thermal

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conductive materials like metal foams [17,18], graphene [19], or expanded graphite (EG) [20–23]. Mills et al. [20] reported that PCMs decreased the capacity loss rate of Li-ion batteries by more than 50%.

In spite of the high efficiency, PCMs can only absorb heat passively. Running out of the available latent heat under extreme conditions – such as high heat density during the high-current charge or discharge, or high ambient temperature – may cause failures of the thermal management systems [24]. Even under mild conditions (ambient temperature <30 °C and discharge rate <2 C), lack of external cooling may also lead to thermal management system failures. A typical charge–discharge protocol for batteries includes three steps: (1) constant-current charging; (2) constant-voltage charging; (3) constant-current discharging. In continuous operations, most heat is generated by batteries during discharging (Step 3), which is absorbed by PCMs and can only be dissipated to the ambient during charging (Step 1 and Step 2). If natural convection is not sufficient to cool batteries and PCMs down before the next discharge starts, accumulated consumption of latent heat will result in uncontrollable battery temperature rise. Therefore, passive thermal management systems using PCMs are needed to combine with more efficient active cooling to avoid potential failures and improve its reliability. By now, however, only Hassan introduced forced air convection to improve the performance of a passive thermal management system at high ambient temperatures [25].

In the current work, a novel thermal management system that integrates PCM and forced air convection is presented for a 5S4P Li-ion battery pack that charges and discharges continuously without rest. Its thermal management performance is compared with the passive thermal management system using paraffin/EG composite. This hybrid system is supposed to boost the reliability of PCM-based thermal management system without sacrificing its simple structure. Besides the experimental investigation, a numerical study based on the combination of thermal models for batteries [26–28] and the enthalpy-based models for PCMs [29] is also carried out and validated with the experiment data, which gives theoretic insights into thermo-physical changes in this hybrid thermal management systems.

2. Experimental section

2.1. Battery pack

Twenty 18650 Li-ion batteries (Samsung, ICR18650-26FM, 2.6Ah) were connected in the way of 5S4P (five cells in series and four cells in parallel). Specifications of this battery module are listed in Table 1. The spacing between centers of two neighboring cells was 30 mm. As shown in Fig. 1(a), six K-type thermocouples with error less than 0.5 °C were attached to the battery surface (marked in green), to monitor the temperature evolution of batteries. Thermal management performance is judged by two indices: (1) the maximum temperature $T_{\max}$ and (2) the maximum temperature difference ΔT in this pack. In any cases, lower $T_{\max}$ and ΔT are desirable.

Table 1
Specification of Li-ion battery module.

Property	Specification
Cell type	Type 18650
Module capacity	10.4 Ah
Pack operating voltage	13.75–21.25 V
Max. discharge rate	2 C-rate (20.8 A)
Max. Charge rate	1 C-rate (10.4 A)
Operating temperature	20–40 °C

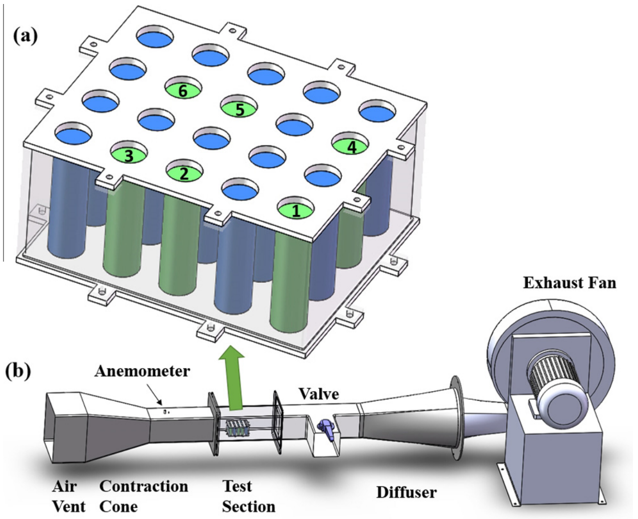

Fig. 1. Schematic of experiment: (a) A 5S4P battery pack, temperature of six cells (marked in green) was measured through K-type thermo-couples; (b) structure of the air channel. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

Table 2
Thermo-physical properties of battery cell.

Property	Value
Density (kg m^{-3})	2700
Thermal conductivity (W m^{-1} K^{-1})	7.14
Specific heat (kJ kg^{-1} $°C^{-1}$)	0.9

The battery pack was charged and discharged by a battery cycler CT2001D, manufactured by Wuhan LAND electronics Co., Ltd, China, current and voltage accuracy of which were ±0.1%. The charge process of the battery module was the same, which first charge the pack in galvanostatic mode at 1 C rate with a voltage cut-off limit of 4.25 V per cell followed by a potentiostatic mode until the current drops to 50 mA per cell. The fully charged battery module was then discharged at constant C-rates – 1 C, 1.5 C or 2 C – with a voltage cut-off limit of 2.75 V per cell. The charge–discharge cycle went on for five times, but would be manually stopped to prevent damages to batteries if the maximum temperature of battery exceeded 60 °C.

2.2. Thermal management systems

Battery performance was tested under two different thermal management systems: (1) completely passive thermal management system; (2) hybrid thermal management system that combined PCMs with force air convection.

In the passive thermal management system, batteries were surrounded by RT44HC/EG composite PCMs. RT44HC (purchased from Ruhr Energy Technology Co., Ltd, Hangzhou, China) was chosen as the basic PCM, due to its proper melting point and high specific phase change enthalpy. RT44HC/EG composites were prepared in the same way as mentioned in [30]. Thermo-physical properties of RT44HC/EG composite are listed in Table 2. Passive thermal management was tested at the ambient temperature around 25 °C.

In the system combining PCM with forced air convection, the battery module that had inserted into RT44HC/EG composites was put into an air tunnel with a rectangular cross section, whose area was 200 × 200 mm^2. The full structure also included: a 500 mm long contraction with the inlet cross section area of