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An experimental study of lithium ion battery thermal management using flexible hydrogel films

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HIGHLIGHTS

- A flexible hydrogel based battery thermal management (BTM) system is developed.
- The performance of the proposed system is compared with conventional BTM systems.
- Hydrogel BTM system efficiently controls the temperature rise in discharge tests.
- The proposed system can arrest or postpone battery thermal runaway in nail tests.
- The hydrogel BTM system is of low-cost, space-saving, and contour-adaptable.

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ABSTRACT

Many portable devices such as soldier carrying devices are powered by low-weight but high-capacity lithium ion (Li-ion) batteries. An effective battery thermal management (BTM) system is required to keep the batteries operating within a desirable temperature range with minimal variations, and thus to guarantee their high efficiency, long lifetime and great safety. However, the rigorous constraints imposed by the budgets in weight and volume for this specific application eliminate the possible consideration of many existing classical cooling approaches and make the development of BTM system very challenging in this field. In this paper, a flexible hydrogel-based BTM system is developed to address this challenge. The proposed BTM system is based on cost-effective sodium polyacrylate and can be arbitrarily shaped and conveniently packed to accommodate any Li-ion stacks. This BTM system is tested through a series of high-intensity discharge and abnormal heat release processes, and its performance is compared with three classical BTM systems. The test results demonstrate that the proposed low-cost, space-saving, and contour-adaptable BTM system is a very economic and efficient approach in handling the thermal surge of Li-ion batteries.

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1. Introduction

Lithium ion (Li-ion) batteries have emerged as the most promising energy storage technology in recent years due to their higher energy density, lighter weight, no memory effect, and lower self-discharge rate, when compared to other rechargeable battery technologies [1]. Although offering many advantages and benefits, the rigorous requirement for the compactness of Li-ion battery packs in many critical applications (e.g., aerospace and military) usually makes it difficult for the implementation of classical battery thermal management (BTM) systems and often gives rise to some safety issues such as overheating or thermal runaway [2]. Even in safe operation, any increase in temperature may significantly shorten the lifecycles of batteries [3–7]. Therefore, a compact and robust BTM system is critically needed to minimize the temperature rise of Li-ion batteries.

In general, a BTM system can be implemented using either an active cooling system or a passive cooling system. The active cooling system is typically achieved by using fans or pumps to circulate coolants (air [8–10], liquid [11], or CO_2 [12,13], etc.) so that the heat can be extracted from the battery packs. For example in Refs. [14,15], the temperature distribution in battery packs was modified by the forced air convection. The batteries with various types of cell arrangements were designed and the energy consumption was formulated as a function of the pressure drop between the inlet and outlet, from which the optimized arrangements of cells and air flow rates can be obtained. Also the study in Ref. [16] demonstrated the effectiveness of water–

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ethylene glycol mixture in controlling the temperature of battery pack through the implementation of a constant temperature bath. The spatial and temporal temperature variations during the course of discharge were maintained within 0.5 °C, but the mobility of the liquid used as coolant may cause safety issues, such as the short circuit, in practice. Generally, a reasonable cell arrangement, a well-designed circulation system, and a powerful cooling material are essential in an active cooling system; however, these elements may also make the system much bulky and power-demanding, which restricts its application in portable battery packs (e.g., soldier-worn battery packs). The passive cooling system makes good use of the physical properties of various coolants implemented between neighboring battery cells to absorb the heat released during the operation, thereby keeping the battery temperature at a relatively low level. The present passive cooling systems usually rely on phase change materials (PCM) for heat absorption. Al Hallaj has first introduced the PCM to thermal management system for the 18650 battery pack [17]. In his study, the temperature of cells and the temperature distribution across the battery pack were inspected at various depths of discharge, and the comparison with air cooling showed the effectiveness of PCM in battery temperature control. However, the PCM material based passive thermal management system often suffers from the following three inherent limitations: 1) high melting point of the PCMs. The relevant battery cells need to reach the melting points (typically higher than 40 °C) of PCMs to utilize their phase change properties. Such high temperature will shorten the life span of the battery; 2) low specific heat capacity of the PCMs (both solid state and liquid state). This will lead to the dramatic rise in the temperature of the battery pack when the PCM temperature is below the melting range; and 3) poor thermal conductivity of the PCMs. This often results in slow heat dissipation and uneven heat distribution, which is extremely harmful to the health of the battery pack and may even lead to an explosion [18,19]. Although various strategies for PCM matrix optimization based on the PCM/graphite mixture have been reported in recent years [20,21], which can provide higher thermal conductivity, but the specific heat capacity of the PCM matrix will in turn be significantly reduced (below 2 kJ kg^{-1} K^{-1}) when inserted into the graphite. Moreover, the preparation of the PCM/graphite matrix is usually a time-consuming and costly process.

To develop a novel passive cooling system to overcome the limitations associated with the classical PCMs, a flexible hydrogel-based BTM system is proposed in this paper. The proposed system is based on sodium polyacrylate (PAAS) hydrogel, which possesses the following advantages: 1) low cost and high flexibility. PAAS is a type of polymer that has been widely used in daily life for liquid absorption (e.g., diapers). The PAAS-based hydrogel is usually of low cost and can be flexibly packed to accommodate any shapes of battery packs; 2) strong water absorbing capacity. Owing to a great number of hydrophilic groups in the three-dimensional chemical chains, the PAAS polymer has the ability to absorb as much as hundreds of times its mass in water. On one hand, the absorbed water is superior in heat control thanks to its high sensible heat; and on the other, the mobility of water can be well managed in operation; and 3) simple and controllable manufacturing process. The proposed BTM system has been validated through a series of experimental tests: first, the battery packs with two different capacities were tested under normal operations at various discharge currents; second, penetration tests were performed on the charged batteries. The performance of the proposed BTM system is compared with three conventional BTM systems (an active air-cooling system, a passive PCM cooling system, and a natural convection system). The testing results demonstrate that the proposed hydrogel-based BTM system is more effective than the other BTM systems in keeping battery packs' temperature stable within an allowable range in discharge tests and preventing the occurrence of thermal runaway in penetration tests.

Table 1
Specifications of two battery packs.

	Pack 1	Pack 2
Pack operating voltage	3.0–4.2 V $cell^{-1}$ (6–8.4 V $pack^{-1}$)	3.0–4.2 V $cell^{-1}$ (15–21 V $pack^{-1}$)
Pack capacity	1300 mAh	8000 mAh
Total weight of pack		
Ambient	58.7 g	926.75 g
Hydrogel	70.6 g	1178.02 g
PCM	68.66 g	1146.24 g
Cooling fan	240.32 g	1108.37 g
Spacing between cells	2 mm	4.5 mm
Discharge rate	1C, 2C, 4C	1C

2. Experimental

2.1. Constant current discharge tests

Two 1300 mAh and five 8000 mAh pouch Li-ion cells were selected to construct two battery packs in the constant current discharge tests, in which the cells were connected in series and the space between neighboring cells were half the thickness of the cell. Table 1 lists the specifications of two battery packs. Four BTM systems (i.e., PAAS hydrogel, traditional PCM (paraffin wax), air-cooling, and natural convection) were built for the cell packs. The tests were performed in cardboard boxes with a dimension of 29.5 cm × 11.5 cm × 11.5 cm in length, width, and height, respectively, to simulate the real circumstances in military backpack, and every battery pack was placed at the center of each box.

Hydrogel BTM system was obtained by injecting deionized water into the pack on the bottom of which polyacrylate sodium (PAAS) particles were evenly distributed. The content of PAAS is 1 wt.%. Fig. 1 shows the 8000 mAh battery pack with hydrogel coolant embedded in. The specific capacity and heat conductivity of the hydrogel are expressed as follows:

$$\mathrm{Cp_{gel}} = \varepsilon \mathrm{Cp_{PAAS}} + (1-\varepsilon)\mathrm{Cp_{H_2O}}, \tag{1}$$

$$k_{\mathrm{gel}} = \varepsilon k_{\mathrm{PAAS}} + (1-\varepsilon)k_{\mathrm{H_2O}}, \tag{2}$$

where Cp is the specific heat capacity, k is the heat conductivity, and ε is mass content of PAAS particles. As for the PCM cooling system, the battery cells were inserted into the matrix prepared in advance. The air-cooling thermal management was achieved by placing a cooling fan of 8 cm × 8 cm at one side of the battery pack with a distance of 5 cm, and the rotation speed of the fan was set at 1500 rpm.

Before loading, both battery packs were charged at a specific C-rate with the voltage cut-off limits of 8.4 V and 21 V (4.2 V for each cell), respectively, followed by a potentiostatic mode until the current drops to 0.02C. It took 1 h for the battery cells to equilibrate, and then the discharge tests were carried out at different C-rates until the voltage drops to 3 V per cell. In the discharge process, a thermistor was attached at the center of the battery pack (i.e., the position more susceptible to overheating) to measure the temperature variation. The initial temperature inside the test cardboard boxes was kept at 23 °C.

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