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Optimization of a phase change material based internal cooling system for cylindrical Li-ion battery pack and a hybrid cooling design

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ABSTRACT

An effective and compact thermal management system is essential for modern lithium-ion (Li-ion) battery powered vehicles, which involve rigorous constraints on weight and volume. In this paper, a phase change material (PCM) based battery internal cooling system is proposed by replacing the hollow mandrel in cylindrical battery with a PCM-filled mandrel, and it is tested on a fabricated steel cell. With verifying its effectiveness in cooling, as well as the accuracy of the thermal model, numerical studies are carried out on a Li-ion battery submodule consisting of 40 cylindrical batteries. Variables including PCM species (*n*-octadecane, *n*-eicosane, and *n*-docosane), PCM core size, and PCM core size distribution are used in the simulations to optimize the design by examining the performance indices involving temperature, temperature difference, PCM solidification time, and pack compactness. The numerical results show that the PCM cores can effectively alleviate the temperature rise inside the battery pack, and a uniform temperature distribution can be obtained when thicker PCM cores are embedded in the interior batteries. A pack compactness study indicates that the internal cooling is a space-saving design that facilitates the achievement of the high energy density of the battery pack.

1. Introduction

The mass-market plug-in hybrid electric vehicles (PHEV) and electric vehicles (EV) have one thing in common, employing the lithium-ion (Li-ion) batteries as their power sources. Since the first commercialization in 1991, the Li-ion battery technology shows continuously increasing market share and attracts a significant amount of research interests in producing batteries with higher energy density, longer life, and lower costs. Although a large amount of power can be supplied from a compact Li-ion battery system, the parasitic heat generation at high discharge rate can overheat batteries. Several studies have shown that at elevated temperatures, the depletion of running Li ions and active materials, as well as the increase in internal resistance of Li-ion batteries could be accelerated [1–4], which will ultimately lead to significant performance degradation and reduction in the life expectancy of the system.

In this regard, battery thermal management (BTM) system is designed and employed in battery packs to relieve the rapid temperature rises and to improve the stability and safety of Li-ion batteries during discharges. A qualified BTM system needs to control both the maximum temperature and the temperature difference of a battery pack within the allowable ranges.

Over the past several years, many cooling approaches have been proposed and studied, which mainly include air cooling systems [5–9], liquid cooling systems [10–12], PCM cooling systems [13–18], and heat pipe cooling systems [19–22]. The relevant reviews were also conducted [23,24]. Among the BTM systems, air cooling and phase change material (PCM) cooling systems are extensively researched.

Air cooling relies on the continuous flow of the cold air to extract the heat generated from the battery pack to the ambient, and the relevant research can be classified into two fields, optimizing battery layout and air flow configuration, in achieving better cooling performance. For example, five flow configurations for a PHEV Li-ion battery pack were studied [5]. By employing a tapered manifold and a pressure relief ventilation, the air cooling system attained satisfactory results on the pack with the original battery layout. A trade-off analysis on the temperature, power consumption, and cooling index of a battery pack with cylindrical cells

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arranged in aligned and staggered layouts under an air cooling condition was also performed [7]. In most cases, air cooling system can provide a decent cooling performance, but it will inevitably lead to overheating and uneven temperature distributions during aggressive discharges. In addition, current research on the air cooling systems for cylindrical battery packs paid more attention to the optimization of the battery layout and flow configuration to achieve better cooling performance, with less emphasis on the space utilization ratio of the entire battery module, which in fact is of great importance for applications with rigorous space constraint.

As for the PCM based cooling system, it passively manages the excessive heat generated from batteries with the utilization of its latent heat stored at the solid-liquid phase transition stage. Compared to air cooling, the PCM cooling system is simple in structural design and has no parasitic power consumption, but it will add extra weight to the entire system. Therefore, the PCM cooling system should be designed with using a minimal amount of PCM to manage the temperature of a battery system in an allowable range. Initially, PCM is directly used to surround batteries in BTM systems [13]. However, several works revealed that the low thermal conductivity of PCM could substantially constrain the thorough exertion of its cooling potential. After that, expanded graphite (EG) and metal foams were produced as matrices to absorb the PCM to increase the thermal conductivity of entire cooling systems [16,17]. For instance, the production technique of the PCM/EG composite was elaborately stated and the effectiveness of the BTM system in managing the heat was examined [16]. One merit of this composite is that the liquid state PCM could be well immobilized inside the matrix with the strong capillary force generated by the EG matrix, thus avoiding the leaking problem. Aluminum metal foam has also been manufactured to accelerate the melting process of PCM [17]. However, for PCM-based cooling systems, the utilization of the thermal conductive matrices can lower the latent heat of entire BTM system and increase the manufacturing cost.

In this work, an internal passive cooling design is proposed and studied through replacing the hollow mandrel inside a cylindrical Li-ion battery with a sealed vial filled with pure PCM to achieve a high latent heat. A steel cell is first fabricated and used to test the cooling performance of the proposed design and to validate the thermal model. The feasibility and effectiveness of the cooling system in managing the temperature rise and improving the temperature uniformity is then studied through a series of numerical simulations on a compact 40-cell battery pack: a parametric study using various design variables such as PCM species, PCM core size, and distribution of PCM core size, is carried out to optimize the BTM system; an air cooling system is also integrated with the PCM-embedded battery pack to form a hybrid cooling system, and its cooling performance is examined using a conjugate heat transfer model.

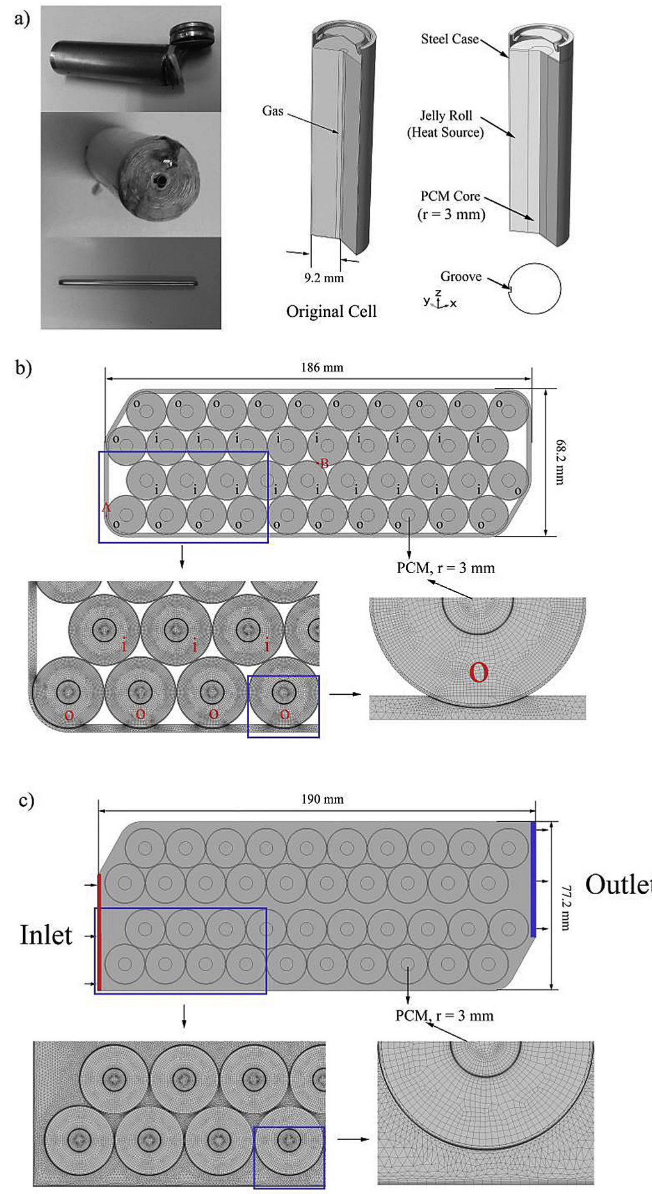

Fig. 1. a) Illustrations of the internal structure of a disassembled 18650 cylindrical battery and the design of a PCM-embedded battery; b) Schematic of a passively cooled 40-cell battery pack; c) Schematic of a hybrid cooling design for the battery pack.

2. Design description

A disassembled 18650 cylindrical battery is shown on the left of Fig. 1a. It is seen that the jelly roll (Li-ion cell) is wrapped around a hollow mandrel (r = 1.25 mm), which is used for electrolyte injection and hazard gas emission at high temperatures. On the right, the PCM internal cooling design is shown, in which the PCM core is inserted in the center of the jelly roll for cooling purpose. In applications, the PCM will be filled in a sealed steel vial to avoid the leaking issue, and a groove will be manufactured on the side of the vial. The PCM filled vial will be wrapped by the jelly roll as same as the hollow mandrel in the original cell. Thus, the compression force and friction between Li-ion cell and the PCM-filled vial will secure the vial in its position during impacts, e.g., falling.

Fig. 1b presents the geometry of a submodule with 40 cells assembled in parallel. Four rows of cells are closely arranged in the battery pack to achieve a high energy density. A 2 mm thick aluminum frame physically retains the cells, and it also serves as the outer surface for convection cooling. The vacancies at the upper-left and lower-right corners of the battery pack are left for wiring and fixation intents. The “o” and “i” in the schematic indicate the locations of the cells in the module and will be discussed in Section 4 for BTM system optimization purpose. In Fig. 1c, a hybrid cooling design is introduced to the battery pack by integrating the air cooling. The red line on the left of the pack indicates the inlet, while the blue line on the right represents the outlet. For these two battery packs, all the relevant dimensions are shown in the figure. Simulations are also carried out on battery pack consisting of original batteries for comparison, in which air is used in the center of the jelly rolls, as shown in the middle of Fig. 1a, and the battery layouts are same with the modified battery pack given in Fig. 1b and c.