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A novel thermal management system for improving discharge/charge performance of Li-ion battery packs under abuse

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HIGHLIGHTS

- Novel hybrid battery thermal management system (TMS) is proposed.
- Thermal conductivity of PCM is increased without compromising latent heat capacity.
- Convection current used to improve PCM performance in repetitive cycling conditions.
- Hybrid TMS can recover waste heat and puts negative parasitic load on battery packs.

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ABSTRACT

Parasitic load, which describes electrical energy consumed by battery thermal management system (TMS), is an important design criterion for battery packs. Passive TMSs using phase change materials (PCMs) are thus generating much interest. However, PCMs suffer from low thermal conductivities. Most current thermal conductivity enhancement techniques involve addition of foreign particles to PCMs. Adding foreign particles increases effective thermal conductivity of PCM-systems but at expense of their latent heat capacity.

This paper presents an alternate approach for improving thermal performance of PCM-based TMSs. The introduced technique involves placing battery cells in a vertically inverted position within the battery-pack. It is demonstrated through experiments that inverted cell-layout facilitates build-up of convection current in the pack, which in turn minimises thermal variations within the PCM matrix by enabling PCM mass transfer between the top and the bottom regions of the battery pack. The proposed system is found capable of maintaining tight control over battery cell temperature even during abusive usage, defined as high-rate repetitive cycling with minimal rest periods. In addition, this novel TMS can recover waste heat from PCM-matrix through thermoelectric devices, thereby resulting in a negative parasitic load for TMS.

1. Introduction

Driving range, performance and mass-market appeal of electric vehicles (EVs) are directly associated with energy capacity, power density and cycle life of the battery packs. A key factor that can significantly affect the available energy capacity and the cycle life of a Li-ion battery based energy storage system is the battery cell temperature. Sluggish charge kinetics in sub-zero ambient temperatures on one side and serious safety risks associated with operating Li-ion battery cells at a cell temperature of over 60 °C on another are a cause of major concern for battery pack designers [1,2]. It is suggested that Li-ion battery cells operate at their maximum efficiency near room temperature environment [3]. However, system inefficiency can cause a part of electrochemical energy to transform into heat energy and correspondingly lead to an appreciable deviation in the battery cell temperature from the target value during the charging and the discharging processes [4,5].

Severity of the issue increases as the number of Li-ion battery cells assembled in the battery pack increases due to difficulty in removing heat from central sections of the battery pack [6,7]. Furthermore, heat transfer between neighbouring cells of the battery pack needs to be minimised so as to reduce the probability of single cell failure events cascading to neighbouring cells and damaging the entire battery pack [8–10]. For these reasons, integration of a battery thermal management system (TMS) with the battery pack is essential. This would maintain temperature of the battery within a pre-specified range and also minimise heat transfer between adjacent batteries.

It has been reported that up to 40% of the battery pack's energy

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capacity may be required to support auxiliary electrical loads such as fans, blowers or pumps in forced air-cooling and liquid-cooling TMSs [11]. In view of this, parasitic load is generally one of the key criteria in selection process of the temperature control strategy that should be used to regulate the performance of EV battery packs. This criterion has driven the research requirements for simple and energy-efficient passive TMSs like heat pipes and phase change materials (PCMs) [12,13]. PCMs are preferred over the heat pipes because of their low initial and operating costs and easy integration process [14]. However, PCMs are generally characterised by low thermal conductivities and slow regeneration rates [15]. Long regeneration times can render such systems ineffective under abusive conditions. Standard definition of abuse conditions for battery refers to under/overvoltage, higher than safe operating temperature or current rates higher than the manufacturer stated maximum. However, Rashid and Gupta [16] analysed the effect of length of the rest phase included between successive discharging and charging operations over cell performance and cyclability. Their analysis confirmed that as the relaxation time allowed before charging a battery again decreases, concentration of lithium across the width of anode also decreases. This leads to a significant reduction in the amount of cyclable lithium available and consequently, cell potential over the cell's cycle life. In our previous work, it was demonstrated that commercial grade (lithium iron phosphate) cells, operated in ambient temperature of 27 °C, need a minimum of one hour rest to diffuse the effect of concentration polarisation and attain equilibrium [17]. Therefore, in this study, the standard definition of abusive usage has been expanded to include continuous cycling at fast charge/discharge rates with minimal rest (cooling-down) periods.

Numerous research studies are focussed on investigating methods for improving thermal properties of PCM-based TMSs. For instance, Zhao et al. [18] noted that thermal conductivity of a composite system of paraffin wax (RT58) and copper foam is much higher than the thermal conductivity of paraffin-wax alone. Similarly, Khateeb et al. [19] found that embedding aluminium foam in a PCM matrix can also improve its heat transfer properties. Wang et al. [20] compared the surface temperatures for air-cooled 16.5 Ah $LiFePO_4$ battery cells with surface temperatures for battery cells (a) soaked in paraffin (melting range of 46 °C–52 °C) contained in an insulated quartz container, and (b) embedded in a composite of paraffin wax and four aluminium foams with porosity between 70% and 90%. All the cells were charged at a rate of 1C in an ambient temperature of 20 °C. They reported the maximum battery cell temperatures for the three test cases as 36 °C, 29.5 °C, and 26.1 °C, respectively. Further, the highest surface temperatures recorded for a charging rate of 2C were 46.0 °C, 36.8 °C, and 32.4 °C, respectively. Li et al. [21] also achieved promising results by using a combination of commercial paraffin wax and metallic foam. However, a larger than 3 °C inter-cellular gradient was observed in their experiments.

Cellular structure of metal foams typically resembles a honeycomb. It is suggested that the porous structure of metal foams cannot be refilled uniformly after PCMs go through a phase change cycle. Metal wire mesh plates are thus recommended as a replacement for metallic foam structures in the PCM composite. Azizi et al. [22] positively tested a composite system of polyethylene glycol 1000 and aluminium wire mesh plates with a relatively high voidage as a TMS for Li-ion battery pack made up of $LiFePO_4$ cylindrical (38120) cells operating in the ambient temperatures between 50 °C and 55 °C.

Thermal conductivity of PCM matrix can also be enhanced by addition of highly conductive powders. The powders can be categorised into: (a) macro-doped powders, (b) micro-doped powders and (c) nano-enhanced powders. Macro-doped powders are prepared by injecting PCMs in metallic material matrix. They are however susceptible to heterogeneity as air may sometimes get trapped in the composite. Further, latent heat of the macro-doped powders decreases as the percentage of metallic particles increases [23]. This problem can be resolved by using nano-enhanced materials. Special care is required in preparation of nano-PCM composites though, as percentages typically greater than 1% by weight of nano-particles, e.g. 1.0 wt% for silica (SiO_2) and titania (TiO_2) [24]; 1.5 wt% for alumina (Al_2O_3) [24]; 2.6 wt % for copper (Cu) [25] and 3.0 wt% for copper oxide (CuO) [26] nano-particles, can lead to agglomeration and homogeneity is crucial for efficient functioning of nano-enhanced mixtures [27–29].

It can be seen that these thermal conductivity enhancing techniques involve use of complex fabrication processes and require addition of dead weight in form of metallic/foreign compounds to PCM matrix, which results in partial loss of latent heat storage capacity of the PCMs. Also, it is a common understanding that heat generation sites are non-uniformly distributed across the battery cell surface with more hot spots arising in the top portion, i.e. the area closer to the electrode terminals. Nevertheless, battery cells in the majority of battery pack designs are arranged in an upright position. Such an arrangement suppresses convective heat transfer through the battery pack and affects average thermal conductivity of the PCM-based TMSs.

In this study, we investigate the effect of battery cell orientation on the performance of PCM-based TMSs in abusive conditions. Energy efficient solution is presented that employs convection heat transfer mechanism to improve average thermal conductivity of such systems. Additional improvement to the performance of TMS is made by connecting Seebeck devices, commonly known as thermoelectric coolers, to the battery pack. The thermoelectric coolers reduce the regeneration time for the PCM matrix by recovering a portion of the waste heat and transforming it to electrical energy, which can be used elsewhere. The novel TMS presented in this paper can thus be regarded to have negative parasitic power requirements and a noticeable influence on driving range of the EV. The experiments described in the following sections will present more details of this heat transfer system.

2. Experimental set-up

Commercially available pouch cells of 20 Ah nominal capacity have been selected as test battery cells for substantiating the validity of the TMS design formulated in this study. Subsequently, two different 80 Ah Li-ion battery packs are constructed by connecting four cells in parallel using copper tabs. Battery pack 1, shown in Fig. 1(a), is constructed by arranging the battery cells in a vertically upright position, i.e. electrode terminals projecting through the top surface of the pack. In contrast, the cells are placed in an inverted position in battery pack 2 such that the terminals protrude through 1.5 mm wide slots made in the bottom surface of the battery pack's rectangular casing, as seen in Fig. 1(b).

Casings for both the battery packs are designed with a 6 mm thick polycarbonate sheet because polycarbonate provides excellent visible light transmission and high strength to weight ratio at low price [30]. Inter-cellular spacing in the pack is maintained at 6 mm using spacers made out of the same sheet. On the other hand, gap between internal surface of the casing and front side of the first battery cell in the pack and similarly the gap between the casing's internal surface and rear surface of the last cell in the battery pack are restricted to 3 mm.

Polycarbonate, i.e. the material used for making the battery pack casing in this study, absorbs all radiations transmitted at wavelengths greater than 1.5 μm. An infrared (IR) window that transmits all radiation emitted within the spectral range of 7.5 μm and 14 μm to a thermal imaging camera was therefore installed in the battery pack casing on the face from where the thermal distribution needs to be observed. Front side of the battery pack casing is thus replaced with a 0.381 mm thick IR material window, sourced from Edmund Optics.

The IR window has been molded from a 0.457 mm thick flexible milky white plastic sheet having consistent thickness across the surface. Transmission spectrum of the IR window material for both the visible region and the IR region is presented in Appendix I. Also, important characteristics of the IR window material are presented in Table 1.

The battery packs are then filled with a high capacity paraffin material (RT28HC) sourced from Rubitherm GmBH, Germany. Melting