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Research paper

Cold temperature performance of phase change material based battery thermal management systems

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ABSTRACT

This study evaluates performance of passive thermal management system of high power Li-ion batteries in a cold environment. Two different phase change materials (PCM) consisting of pure paraffin and paraffin–graphite composites are considered and compared with a battery module in absence of PCM material. Battery modules are partially discharged for a period and then subjected to different cold time periods representing short and long vehicle stops during winter. Battery performance parameters such as capacity, power, and temperature along with thermophysical properties of each module are recorded, calculated, and compared for different scenarios. Thermal management systems moderate temperature rise during discharge and slow the temperature loss during cold stops but also slow the temperature rise after cold stops. Results show that after a short (10 min) cold stop the paraffin wax offers no advantage by keeping the module warm. Both paraffin and no PCM modules had comparable energy values. On the other hand, during long (2 hours) cold stops a significant detriment (15% reduced energy vs 6% reduced energy) was observed in PCM modules by delaying battery warm up when compared to modules with no PCM. Commercial PCM modules with graphite/paraffin composites performed in-between PCM and no PCM modules (9% reduced energy) after long cold soaks but had no advantage for short cold soaks (2.5% energy reduction) due to higher heat dissipation.

1. Introduction

The depletion of non-renewable energy sources and the environmental pollution accompanying fossil fuel use has become a critical issue across the globe. Using electric vehicles (EVs) instead of traditional vehicles can reduce greenhouse gas emissions up to 40% when the electric power is produced by renewable energy (Rao and Wang, 2011).

Improving the performance and cycle life of Li-ion batteries is a key factor for EV viability. Li-ion batteries need to operate in a temperature range of 20 °C to 40 °C in order to prevent thermal runaway and poor life cycling at high temperatures as well as avoid high resistance at low temperatures. Moreover, uneven distribution of temperature in a battery pack reduces its performance and life (Pesaran, 2002). Given that batteries generate a significant amount of heat at high charge and discharge rates, thermal management systems (TMS) in battery packs in EVs are critical to avoid diverse temperature impacts. Conventional TMS rely on air or liquid, but are too expensive, heavy, and complex (Pesaran, 2001; Hallaj and Selman, 2000).

Another option is to use phase change materials (PCM) that absorb heat through their latent heat during melting. A desirable PCM for a battery thermal management system possesses a melting point coincident with the operating temperature of battery operation, large latent heat of fusion per unit mass, high specific heat, high thermal conductivity, high density, chemical stability, and low cost (Agyenim et al., 2010; Alrashdan et al., 2010). The large latent heat per unit mass requires less PCM to be used, high thermal conductivity allows fast dissipation of heat, and high specific heat allows for greater thermal storage outside of the phase change temperature region. A proper figure of merit can be introduced as the result of multiplying thermal conductivity, specific heat, latent heat and dividing by volume change and density.

TMS using PCM were first developed by Hallaj and Selman and have many advantages over conventional TMS (Sabbah et al., 2008; Hallaj and Selman, 2002). Several studies have examined the suitability of PCM for battery TMS in hybrid and plug-in hybrid electric vehicle systems in stressful conditions such as high power draw at high temperature (Kizilel et al., 2008, 2009; Kim et al., 2008). Other research in this area focused on the material properties such as thermal conductivity to improve performance efficiency of PCM (Alrashdan et al., 2010; Goli et al., 2014).

Nearly all research has been directed towards the study of PCM at high temperatures while their benefits and weaknesses at low

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temperatures have not been as thoroughly investigated. Song et al. (2012) emphasized that battery thermal management is necessary not only at high temperatures but it also significantly affects the battery performance and life in low ambient temperatures. There have been only a few studies in battery thermal management at low temperatures (Song et al., 2012; Shidore and Bohn, 2008; Pesaran et al., 2003). None of these studies have addressed the fundamental question of whether or not PCM materials could be a net detriment to EV battery performance by delaying battery warming after a long cold soak and affecting capacity, temperature and power of battery.

In this study we undertake to answer these questions by assessing the performance of batteries in cold ambient temperature with and without PCM based TMS. Advantages, such as the PCM keeping the battery package warm during short stops, will be compared with drawbacks such as delaying battery warming after a long cold soak.

2. Experimental methods

A Ford Escape Hybrid car can consist of 68 battery modules. Each module contains 20 commercially available 1.5 Ah Type 18650 high power Li-ion cells (Sabbah et al., 2008). A scaled down experiment was employed to induce the required temperature and battery load to the battery module. In this test the battery module consisted of seven high power 2.2 Ah Li-ion battery cells (Interstate Batteries, model 18650, Dallas, TX) assembled in series configuration and connected to a DC power supply (Model 224 Programmable current source, Keithley Instruments Inc, Cleveland, OH), an electronic load (6060B 300 W electronic load, Hewlett Packard, Palo Alto, CA) and a data acquisition system (Model 2000 Digital Multimeter, Keithley Instruments Inc, Cleveland, OH). LabVIEW (National Instruments Corporation, Austin, TX) was used as a communication interface between the battery hardware components and the software used to record temperature, voltage, and power at two second intervals. Battery cell specifications are listed in Table 1.

Table 1
Battery module specification.

Operating voltage		3–4.2V
Cell type		18650
Nominal voltage		3.7V
Operating temperature range	Charge	0 °C to 45 °C
	Discharge	−10 °C to 60 °C
Weight		45g

The individual battery cells were arranged in a hexagonal packing for battery testing (see Fig. 1). To avoid the influence of slight temperature fluctuations between testing on different days the modules were fitted into a waterproof container and placed in a large water bath set to 23 °C. Temperature within the battery modules was monitored via K type thermocouple probes located at the center of the battery module (see Fig. 1). The two Keithley multimeters were used with an error percent of 6% in acquiring temperature. Data acquisition system collects capacity, and power with 5% error. The battery module was charged at 0.1C rate and then discharged at C/1 rate. The C/1 discharge rate represents the normal maximum continuous discharge rate of the 18650 Li-ion cells recommended by the manufacturers in order to prevent overheating.

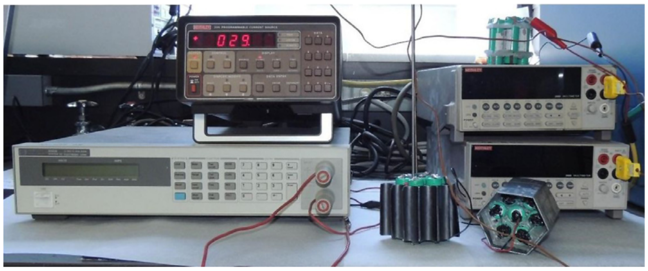

Fig. 1. Illustration of battery test setup.

The battery module was tested with three thermal management conditions; (i) no TMS, (ii) a simple paraffin wax PCM based TMS, and (iii) a commercial paraffin wax and expanded graphite composite PCM based TMS (AllCell Technologies, Chicago, IL). The commercial PCM as discussed by Mills and Alrashdan is made by compacting expanded graphite followed by impregnating it with PCM material such as paraffin wax. This is done in order to more rapidly disseminate heat via the graphite component of the composite. Commercial PCMs have a thermal conductivity of about 30 times of that of the paraffin alone (Alrashdan et al., 2010).

For all three TMS conditions, the battery module was discharged galvanostatically for half an hour at 23 °C before being placed in a cold environment at a temperature of −17 °C to −18 °C for a time period between 10 min and 240 min to represent vehicle stops during winter conditions. Batteries were not discharged during these cold wait periods and the time durations were selected based on statistical average short stops provided by Shahidinejad et al. (2012). After the wait period had elapsed, the battery module was returned to the water bath at 23 °C and was immediately discharged to 21 V. We justify discharging at 23 °C because even in cold winter climates electric vehicles are equipped with an active thermal management system to keep cabin temperature and ambient temperature around battery modules near room temperature) (Pesaran, 2001). The mass of PCM required for passive thermal management of this battery module was calculated using a lumped system analysis where heat discharged by the battery is set equal to the sensible heat of the PCM plus latent heat of the PCM as described in Eq. (1).

$$Q_{discharge} = m_{PCM} C_P (T_m - T_i) + m_{PCM} \lambda \tag{1}$$

where, m_{PCM}, C_P, and λ represent mass, specific heat, and latent heat of the PCM, respectively. T_m and T_i are PCM melting point and initial temperature and $Q_{discharge}$ is the Li-ion battery discharge heat. For commercial PCM ratio of wax volume to pack volume was 80%.

Thermophysical properties such as melting point, latent heat and specific heat was measured using differential scanning calorimetry, (DSC, Netzsch Sirius 3500). Measurements were conducted at a scan rate of 1 K/min at temperature range of 20 °C to 100 °C in a nitrogen atmosphere. Specific heat measurement method based on ASTM E1269 – 11 was selected to analyze the data (ASTM, 2005). Table 2 summarizes the thermophysical properties of the paraffin wax and graphite composite PCM used in this study. Laser flash analysis (LFA, 457 Netzsch) was used to measure the thermal diffusivity of paraffin wax.

3. Results and discussion

3.1. Battery performance after short and long cold soak

In this section the advantages, such as the PCM keeping the battery package warm during short stops, and drawbacks, such as delaying battery warming after a long cold soak, will be quantitatively discussed. From time $t = 0$ s up until $t = 1800$ s the samples are all initially discharged in the water bath and then placed into the cold environment for a specified time. From time $t = 1800$ s up until $t = 3600$ s the samples are removed from the cold environment and allowed to continue discharging in the water