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A HYBRID THERMAL MANAGEMENT SYSTEM WITH NEGATIVE PARASITIC LOSSES FOR ELECTRIC VEHICLE BATTERY PACKS

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ABSTRACT

Parasitic power requirement is a key criterion in selection of suitable battery thermal management system (TMS) for EV applications. This paper presents a hybrid TMS with negative parasitic requirements, designed by integrating phase change material (PCM) with thermoelectric devices. The proposed system does not require any power consumption to maintain tight control over battery cell temperature during aggressive use and repetitive cycling. In addition, it can recover a portion of waste heat produced during the typical operation of EV battery packs.

Commercially available $LiFePO_4$ 20 Ah pouch cell has been chosen as a test battery sample for validating the conceptual design presented herein. The commercial battery cells, submerged in a PCM-filled polycarbonate casing, are subjected to a cyclic discharge process to elucidate their heat generation characteristics at 27 °C. Charging and discharging is conducted at 0.5C and 1C, respectively. A thermoelectric circuit is used to recover the heat energy absorbed by the PCM and to convert it to electrical energy. The manuscript further details some of the major findings of this experiment.

Keywords: Battery Heat Generation; Phase Change Materials; Seebeck Effect and Peltier Effect; Thermoelectric Cooler; Abuse Tolerance; Electric Vehicles

INTRODUCTION

Cell temperature is a key parameter that significantly influences the service life and the available energy storage capacity of Li-ion battery packs [1, 2]. Energy efficiency for these systems is maximum at or near the room temperature [3]. Nevertheless, constantly varying ambient temperature and exothermicity of chemical reactions characterizing the charge and the discharge processes of a battery cell can push the cell temperature outside this desirable operating range [4-7]. Thermal energy exchange between neighboring units (cells and modules) of the pack also needs to be controlled so as to minimize the damage caused to the entire battery pack due to propagation of single unit failure events to adjacent battery cells/modules [8, 9]. Consequently, a battery thermal management system (TMS) that would assist in retaining heat generated by battery cells at low ambient temperatures within the battery pack whereas avoiding excessive heat build-up inside in higher ambient temperatures is highly desirable.

Several TMS designs including forced-air cooling [10, 11], jacketed-liquid TMS [12, 13], cold plates [14-16], heat pipes [17-20], phase change materials (PCM) [21-23] have thus been proposed for electric vehicle (EV) battery packs. Details regarding recent advances made in the field of TMS using PCMs are available from [24-28]. Nevertheless, a battery pack of limited energy storage capacity is the only power source available on-board a pure EVs. In view of this, electrical power required for operating a battery TMS, commonly referred as parasitic load, is an important criterion for selecting the thermal management strategy to be employed for managing battery pack performance.

For this reason, conceptual design of a hybrid battery TMS with negative parasitic power requirements is presented in this paper. This novel TMS is based on combination of PCMs and thermoelectric generators. The proposed system cannot only maintain the cell temperature between pre-defined temperature limits without use of any components that consume power, such as a fan, a heat exchanger or a pump but also recover portion of the waste heat to generate electrical power with the aid of thermoelectric devices. The generated power can be used to either support auxiliary systems or drive the electric motor itself, thereby having a significant impact on effective driving range of an EV. More importantly, performance of the proposed system is not affected due to low thermal conductivity and slow regeneration rate of PCMs, which is generally the case with other PCM-based systems [29]. Thus, it would be ideal for EV applications.

EXPERIMENTAL DESIGN

Four commercial 20 Ah lithium iron phosphate (LFP) pouch cells, manufactured by A123 Systems, USA are connected in parallel via copper tabs to form a battery pack, used for demonstrating the novel TMS concept. A 6 mm thick polycarbonate sheet is used for constructing casing for this battery pack. Inter-cellular spacers are also made from the same 6 mm sheet. However, gap in the front and in the rear of the battery pack, i.e. space between the cell surface and the interior surface of the casing, is restricted to 3 mm. Also, a 0.381 mm thick infrared radiation (IR) transmissible sheet, procured from Edmund Optics, Australia, is fitted to the the front surface of the casing. The battery pack is then filled with a PCM having melting point between 27 °C and 29 °C; procured from Rubitherm GmBH, Germany. Heat storage capacity of the selected material (RT28HC) is 250 kJ/kg.

The IR window transmits all radiation in the spectral range of 7.5 – 14 µm. Index of refraction for the window material in IR range is 1.53. The window allows observing melting and solidification of the PCM, triggered by absorption of heat generated during the charging and discharging processes of the battery pack. Trotec IC080-LV thermal imaging camera is used for recording these observations.

At the same time, three TE coolers are connected in parallel to a 2.7 Ω resistor to make a thermoelectric (TE) circuit. TE Resistance value in the TE circuit was determined systematically via calibration for maximum power generation. For calibration purposes, applied temperature gradient across both the sides of the TE circuit was approximately 25 °C.

Subsequently, the TE circuit is carefully arranged over the top edges of the pack casing. Polycarbonate sheet on this side of the casing was intentionally removed so that bottom surface of the TE circuit can make direct physical contact with one side of the battery cells and the PCM matrix. At last, an appreciable temperature gradient across the TE circuit is created by placing an aluminum tray, filled with ice, over its top surface. A photograph of the complete test set-up is presented in Fig. 1.

TEST PROCEDURE

The designed battery pack is connected through a programmable temperature chamber to a 4-channel data acquisition system (Arbin BT2000) for recording the voltage response to the applied current during the test cycle. For charging the pack, constant current - constant voltage (CCCV) regime is used [30]. Accordingly, the pack is charged at 0.5C i.e. with 40 A current until a maximum voltage of 3.6 V is attained. After this, charging current is gradually decreased while maintaining voltage constant at 3.6 V. Charging terminates when the current reduces to 4 A, i.e. equivalent to 0.05C. Battery pack is then left to rest for 12 hours in room temperature environment, nearly 23 °C. This duration isolates the effect of battery heat generation during the CCCV step by allowing time for PCM regeneration.

Testing program or the continuous cycling of the battery pack begins from a fully charged state. Also, the thermal chamber controlling the ambient environment of the battery pack is set to 27 °C prior to starting the continuous cycling test. Then, the battery pack is discharged with a constant current of 80 A, i.e. at 1C-rate. Discharging process is stopped when the pack voltage reaches 2.0 V. It is now declared as fully-discharged. Following a 1 minute rest, CCCV charging sequence, same as above, in the test program begins. Rest phase duration is estimated as the average time needed for EV parking and connecting it to a charging station. The whole discharging at 1C and CCCV charging at 0.5C sequence is repeated twice such that the battery pack is subjected to a total of three galvanostatic discharge steps.

Battery cell temperature variations during the continuous cycling test are monitored with the assistance of two temperature sensors: one of them is attached to the front surface of the first battery cell whereas the second sensor is connected to the third battery cell. Cell numbers are assigned from the side closest to the IR window. In the following text, cell numbers 1 and 3 are described as the outer cell and the internal cell, respectively. Measuring location is 15 mm from the bottom edge of the electrode terminals – on both the cells. In addition, auxiliary voltage sensor of the Arbin battery cycler is used for measuring the terminal voltage created across the TE circuit as a result of the applied thermal gradient.

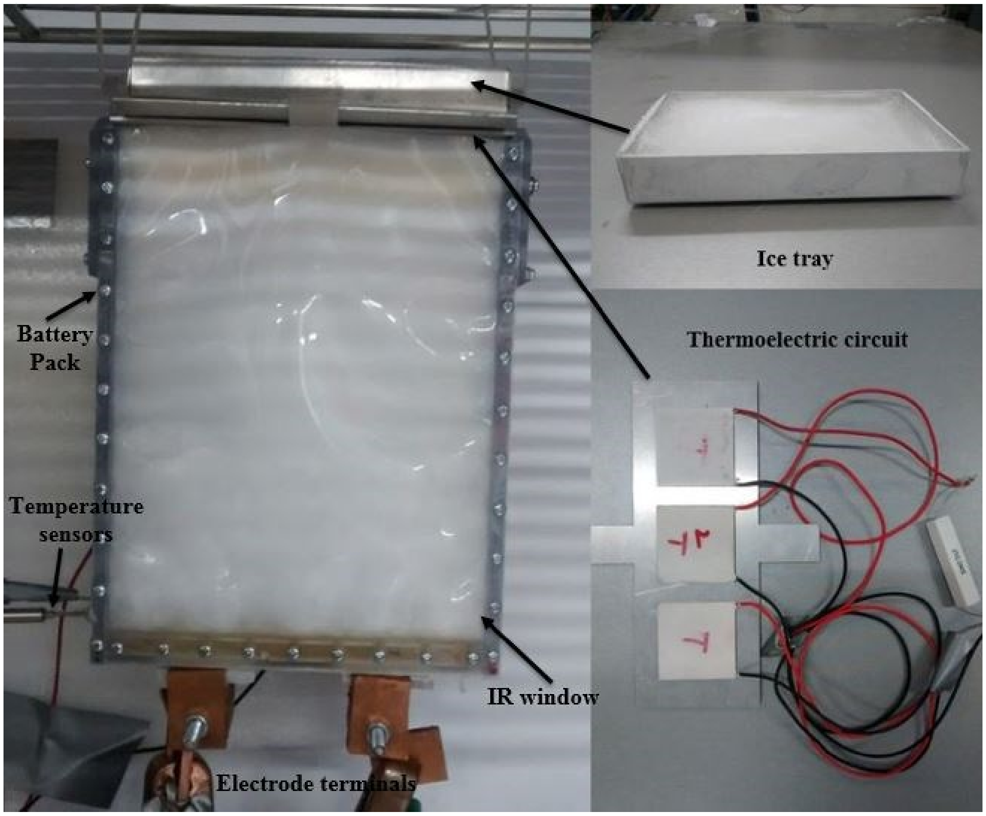
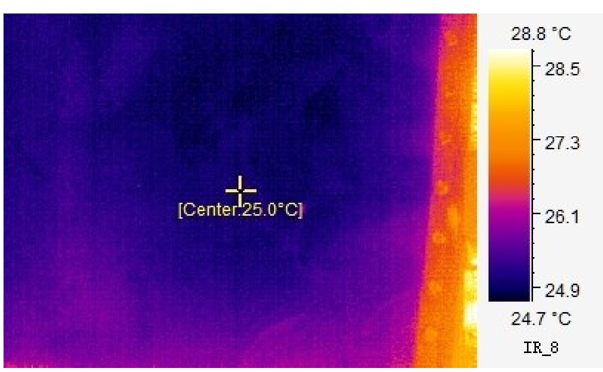


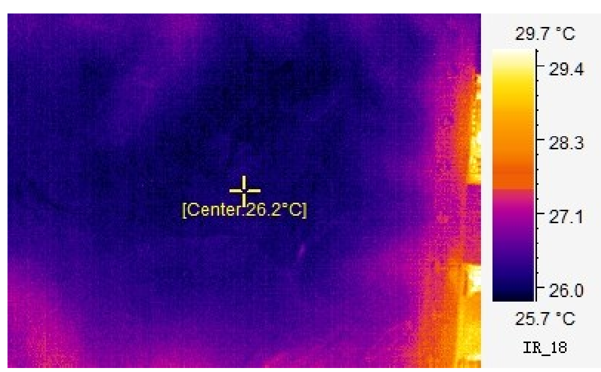
Figure 1 – Experimental set-up showing 80 Ah battery pack filled with RT28HC PCM and a thermoelectric circuit along with an ice tray placed over its top surface [31]

RESULTS AND DISCUSSION

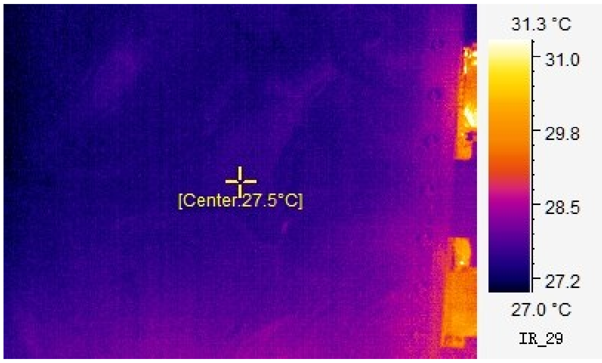
Fig. 2 presents a series of thermal images of the PCM captured at different stages of the continuous cycling test using thermal imaging technique from the IR window fitted to the front surface of the casing. This series of images allow visualizing development of temperature transients and detect hot spots in the PCM matrix in the camera view-frame rather than relying on point measurements provided by a temperature sensor or a thermocouple. Label "Center" in these images indicates temperature in the middle of the view-frame. In the subsequent analysis, this marker is assumed to be a representation of the bulk PCM temperature.



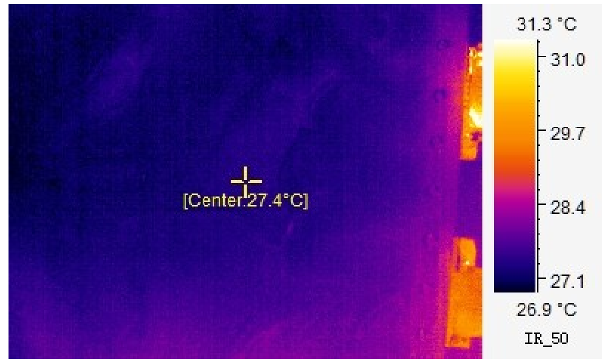
(i) CCD1 – DOD50



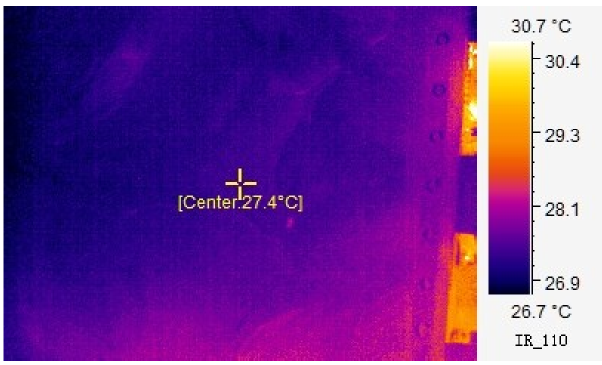
(ii) CCD1 – DOD100



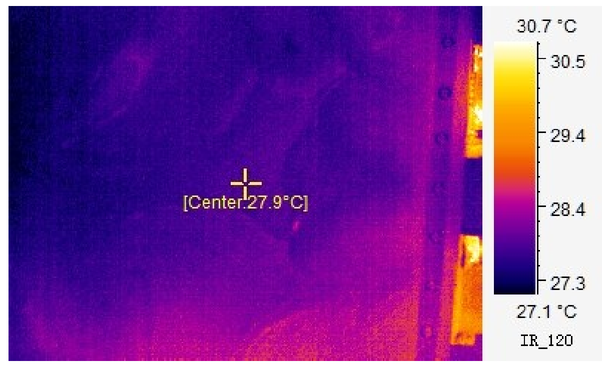
(iii) CCD2 – DOD50



(iv) CCD2 – DOD100



(v) CCD3 – DOD50



(vi) CCD3 – DOD100

Figure 2 – Thermal images of PCM at different stages of continuous cycling test - discharge (@ 1C) and charge (@ 0.5C) of the battery pack in ambient temperature of 27 °C (where, CCD – Constant current Discharge ; DOD – Depth of discharge; and succeeding numerals define the step or stage in the abuse test)

Moreover, detailed information regarding temperature in different regions of the matrix can be extracted from these images by referring to color codes provided on the right side in each thermal image. Increasing intensity of blue, gradually turning purple, indicate low temperatures. In contrast, high temperature areas are shown as orange and yellowish in color.

It is evident from the set of these images that the TE circuit produces a refrigeration effect by recovering a portion of the, otherwise, waste heat from the PCM matrix. This cooling effect can be seen travelling through the PCM matrix from the point of its origin, i.e. section of the casing in proximity of the TE circuit, towards the bottom part or the area closer to electrode terminals. However, relatively small temperature gradient, caused by improper thermal contact between battery cells and the TE circuit, coupled with poor thermal conductivity of PCM limits the rate of heat transfer or propagation of refrigeration effect in the PCM matrix. Benefits of this system cannot be neglected though since the bulk PCM temperature measured at different stages of the continuous cycling test is approximately same. Proposed TMS design facilitates generation of convective heat transferring currents within the battery pack, which increases melting rate for the PCM matrix. As a result, the proposed hybrid TMS design is able to counter the negative effects of lack of regeneration time for PCM, i.e. minimal resting time between the charging and the discharging processes for the battery pack on its performance.

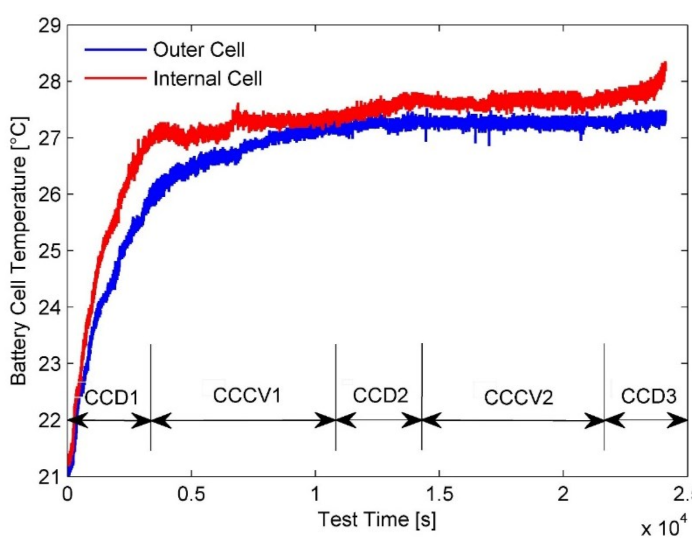


Figure 3 – Cell temperatures of the outer cell and the internal cell measured during the cyclic discharge test of the battery pack; same nomenclature of test steps described above in Fig. 2 caption applies

Fig. 3 shows development of surface temperature profile in real-time for the internal cell and the outer cell of the battery pack. It is evident from this figure that the benefits of the proposed hybrid TMS are two-fold. First, it enables to maintain a uniform cell surface temperature profile during high system usage such as repetitive cycling at quick intervals. Second, it also reduces temperature difference between the outer sections and the core or the inner part of the battery pack.

It can be estimated from the Fig. 2 that temperature of the PCM in the vicinity of the TE circuit fluctuates close to 27 °C whereas ice tray maintains cold side of the TE circuit at 0 °C. Applied thermal gradient of approximately 27 °C induces a voltage in the TE circuit. This voltage is popularly known as Seebeck voltage. Seebeck voltage readings recorded at various instances during the test are shown in Fig. 4.

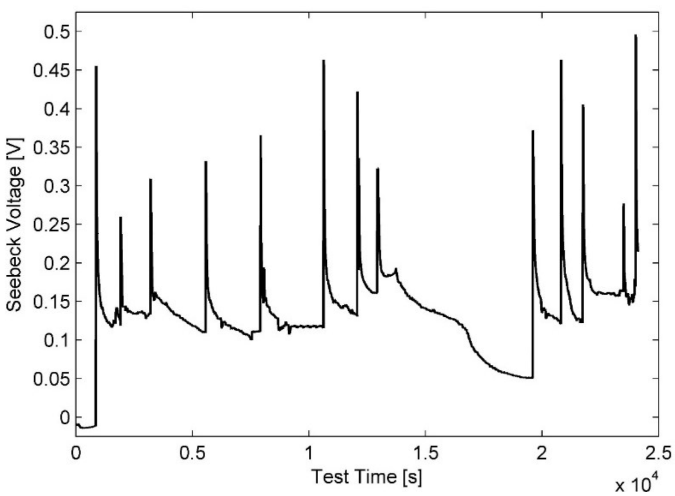


Figure 4 – Seebeck voltage measured across the TE circuit when a thermal gradient of roughly 27 °C exists between its two sides

It is observed that corresponding to thermal gradient of 27 °C, a peak voltage of 496.2 mV is induced across the circuit. However, the Seebeck voltage drops rather quickly as the ice used for creating the temperature gradients starts to melt. It is anticipated that high temperature of the thermal chamber contributes more to the fast melting of ice than the inefficiency of the TE circuit. Ice tray is thus replaced several times, in quick succession, during the cycling test. Multiple voltage peaks of different height whose appearance can be attributed to this need are seen in the voltage spectrum presented in Fig. 4.

Analysis of the data corresponding to time period between $1.4\ x\ 10^4 s$ and $2.0\ x\ 10^4 s$ in Fig. 3 and Fig. 4 reveals that the only effect of not re-filling the ice tray for more than 1.5 hours was a considerable drop in the magnitude of Seebeck voltage. This however did not impact the ability of the proposed TMS to ensure stable temperatures for both the outer cell and the internal cell during this phase. Nevertheless, it is certain that an appreciable amount of waste heat can be recovered from the EV battery packs. Simultaneously, a voltage can be produced. Voltage can be increased either by increasing the number of TE devices in the circuit or by using TE coolers with a higher figure of merit. Figure of merit for the currently available TE devices is reported to be between 0.7 and 1.2 for room temperature applications.

CONCLUSION

This study presents a novel PCM-based TMS suitable for EV battery packs. Experimental results obtained in this study illustrate that thermal management of a battery pack subjected to repetitive cycling with minimal relaxation phase becomes easier by integrating TE devices with PCMs. TE devices produce a refrigeration effect that can, to an extent, compensate for low thermal conductivity of PCMs. Further, it is observed that the TE devices integrated in the proposed system can successfully recover a portion of the waste heat energy from the PCM and transform it to electrical power. The novel TMS presented in this paper has a negative parasitic power requirement. It can thus be regarded to have a visible impact on the driving range of an EV.

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