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Thermal modeling of secondary lithium batteries for electric vehicle/hybrid electric vehicle applications☆

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Abstract

A major obstacle to the development of commercially successful electric vehicles (EV) or hybrid electric vehicles (HEV) is the lack of a suitably sized battery. Lithium ion batteries are viewed as the solution if only they could be "scaled-up safely", i.e. if thermal management problems could be overcome so the batteries could be designed and manufactured in much larger sizes than the commercially available near-2-Ah cells.

Here, we review a novel thermal management system using phase-change material (PCM). A prototype of this PCM-based system is presently being manufactured. A PCM-based system has never been tested before with lithium-ion (Li-ion) batteries and battery packs, although its mode of operation is exceptionally well suited for the cell chemistry of the most common commercially available Li-ion batteries. The thermal management system described here is intended specifically for EV/HEV applications. It has a high potential for providing effective thermal management without introducing moving components. Thereby, the performance of EV/HEV batteries may be improved without complicating the system design and incurring major additional cost, as is the case with "active" cooling systems requiring air or liquid circulation.

Keywords: Li-ion batteries; Thermal modeling; Thermal characterization; Battery safety; Hybrid vehicles

1. Introduction

Lithium-ion (Li-ion) cells have demonstrated excellent performance when operated at ambient temperature conditions. Still, the adverse effect of temperature excursions on lithium-ion cell performance is evident when the cell is operated at temperatures beyond 65 °C [1,3,5] or below 0 °C [2]. As shown in Fig. 1, in most applications, for powering personal electronics or electric vehicles (EV), a number of cells are packed together in various configurations (parallel and/or series connected) to form a module. Several modules are then combined in series or parallel to provide the required voltage and capacity for a specific application (e.g. EV or hybrid electric vehicles (HEV)). Evidently, it is important to keep the battery pack temperature within the fairly narrow temperature range mentioned above, to maintain optimal battery performance and cycle life.

Temperature variation between individual cells in a pack may result from:

1. ambient temperature differences at various points of the pack surface;
2. non-uniform impedance distribution among cells;
3. differences in heat transfer efficiency among cells.

Factor 2 is an unintended condition, but may result from defects in quality control. However, it may also develop during operation of a battery pack, due to differences in local heat transfer rate. Factor 3 depends strongly on pack configuration since some of the cells at the center tend to accumulate heat, while others along the edges are cooled by heat transfer to the environment. This variation may lead to further differences in impedance (factor 2) which amplify capacity differences among the cells. Capacity imbalance may cause some cells to be over-charged or over-discharged during cycling of the pack, and this may result in premature failure. Failure may take the form of thermal runaway or accelerating capacity fading. Both are related to excessive heat generation in individual cells.

Thermal management of a Li-ion battery system can be achieved without excessive complexity by a passive cooling system that incorporates phase-change materials (PCM), as first described in [4]. The PCM integrated in the cell and/or battery will act as a heat sink for heat generated during discharge of the Li-ion battery. Discharge is a highly exothermic process in most commercially available batteries, and the temperature of the cells will exceed that of the PCM so that heat flows from the battery cells into the

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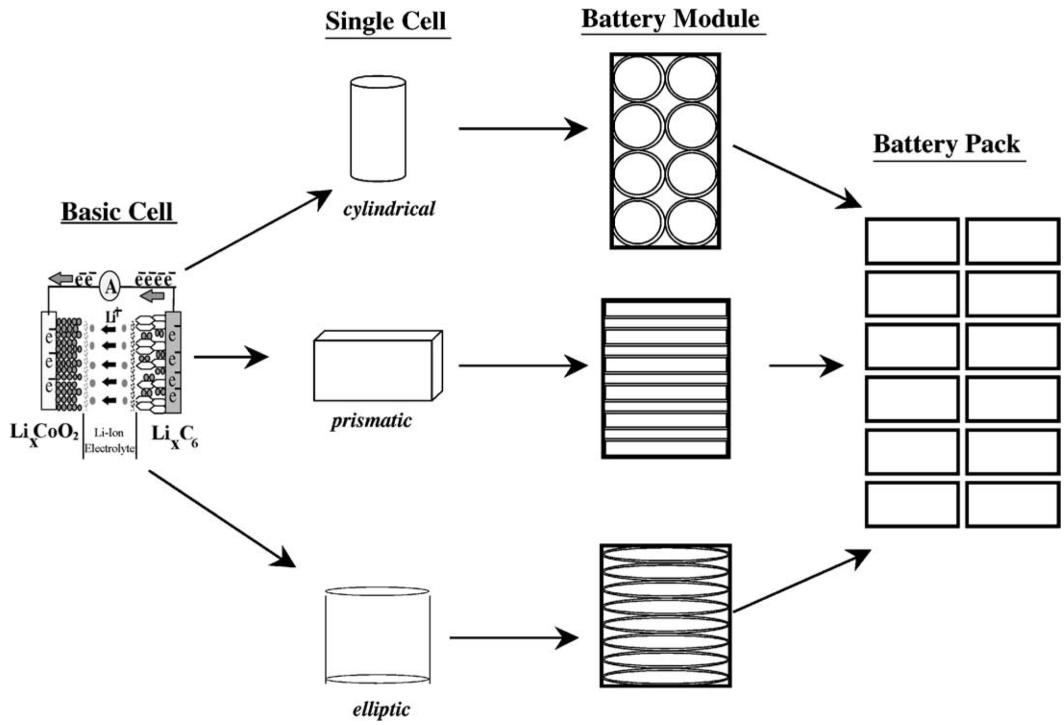

Fig. 1. Schematics of the battery pack design with different cell configurations.

PCM. In a well-designed PCM system, the PCM remains at constant temperature corresponding to the solid–liquid or solid–solid phase-change (phase-change temperature (PCT)). During discharge, the PCM in such a system rejects some heat to the environment, especially under cold weather conditions (i.e. ambient temperature well below PCT). However, the overall net heat flow is toward the PCM, which under normal conditions has enough thermal capacity to accept the total heat developed during discharge, with minimal temperature increase above the PCT. Later, the bulk of the heat stored in the PCM is evolved toward the cell(s) as their temperature drops during charging of the battery. The excess heat remaining in the PCM (net heat effect of discharge followed by charge) is transferred to the surroundings. It follows that the PCM must be chosen such that its functional temperature is above the surrounding temperature. To accommodate extra-cold environments, a parallel heat conduction path may be designed into the PCM system.

2. Scale-up methodology

Fig. 2 summarizes a methodology for scale-up design of Li-ion batteries for EV/HEV applications. The method utilizes experimental data acquired from testing of commercial cells in our laboratory [8]. We used a specially constructed ARC–battery cycler combination (Fig. 3) to measure the rate of heat generation of the cell during charge and discharge under different operating conditions. Details of the experimental procedure and modes of operation may be found in [8].

2.1. Electrochemical–calorimetric measurements

Fig. 4 shows the electrochemical–calorimetric behavior of a typical commercial Type 18650 Li-ion cell during charge at $I = 200$ mA (0.1 C rate) and discharge at $I = 450$ mA (0.18 C rate), under normal operating conditions. Various commercial Type 18650 cells, as shown in Fig. 5, exhibit similar behavior characterized by a weak endothermic heat

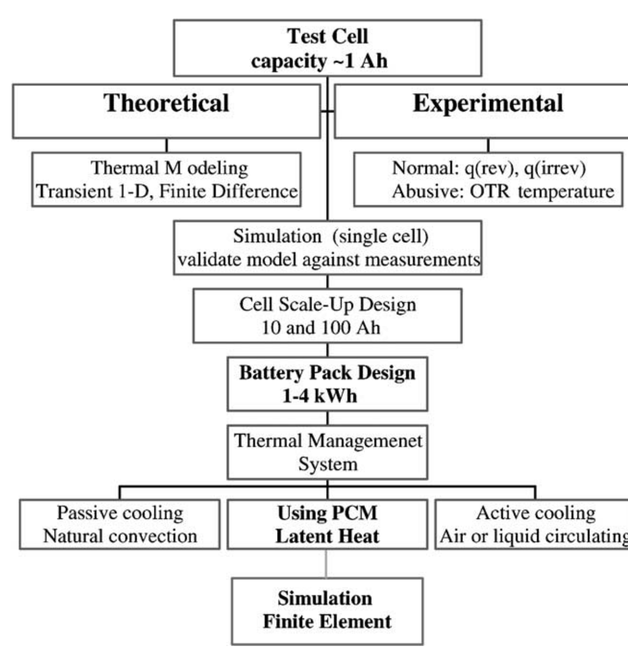

Fig. 2. Proposed methodology for scale-up design of Li-ion batteries.

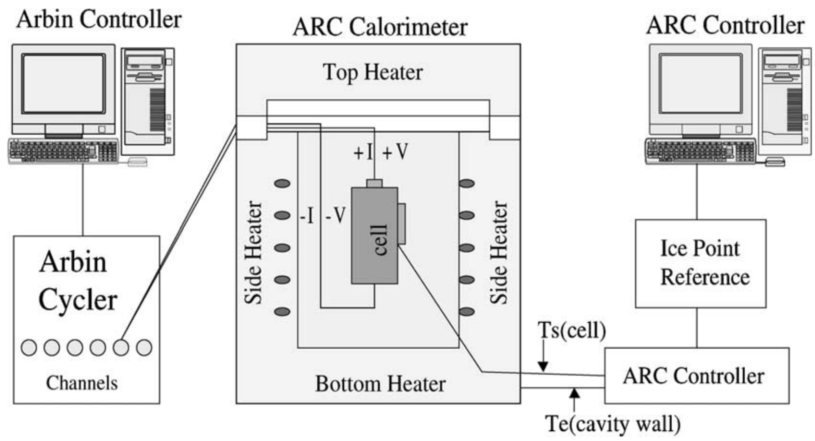

Fig. 3. Schematic of the electrochemical–calorimetric experimental set-up.

effect (cooling) during charge, at rates less than 0.5 C, and a strong exothermic heat effect (heating) during discharge, at all rates [5]. The cooling effect during charge, which our group (using Sony Type US 18650 cells) was among the first to report [8], is caused by the relatively strong reversible heat of reaction of the Li_xC/Li_xCoO_2 chemistry. This conclusion was further confirmed through direct measurement of the entropy coefficient (dE/dT) of several commercial Li-ion cells by electrochemical–calorimetric techniques. Results are summarized in Fig. 6 [3,6].

2.2. Thermal modeling of scaled-up cells

The thermal behavior of commercial Li-ion cells is being simulated by our group using a one-dimensional thermal mathematical model with lumped parameters [13]. This model incorporates experimentally determined thermophysical properties [7] and heat generation data [8] specific to the Li-ion cells and materials being modeled. It is used to simulate temperature profiles under different operating conditions and cooling rates. Results for scaled-up cylindrical lithium-ion cells (Sony Type 18650 chemistry) of 10, 30, 50, and 100 Ah capacity are shown in Fig. 7. It compares the simulated temperature profiles of scaled-up cells at different discharge rates, under natural-convection cooling conditions with an effective heat transfer coefficient of $h = 10 W/m^2 K$. As shown in Fig. 8 for the projected 100 Ah cell, a significant temperature gradient inside the cell was found only at high cooling rates (Biot number expected to be >0.1). At low cooling rates, the cell behaves as a lumped system with uniform temperature [9–13].

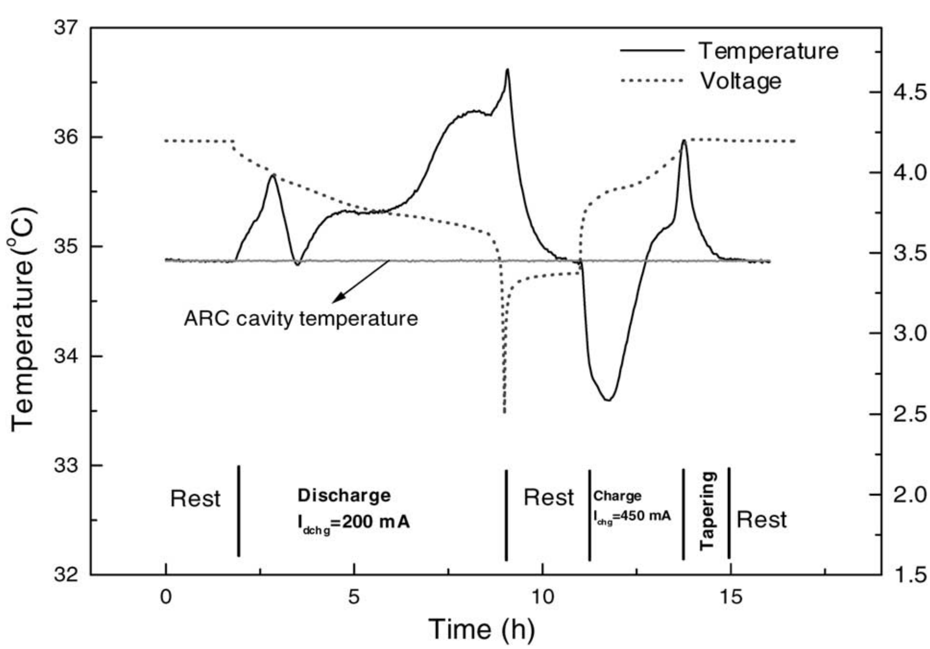

Fig. 4. Typical temperature–voltage behavior of Li-ion cells during charge–discharge cycle under normal operating conditions.

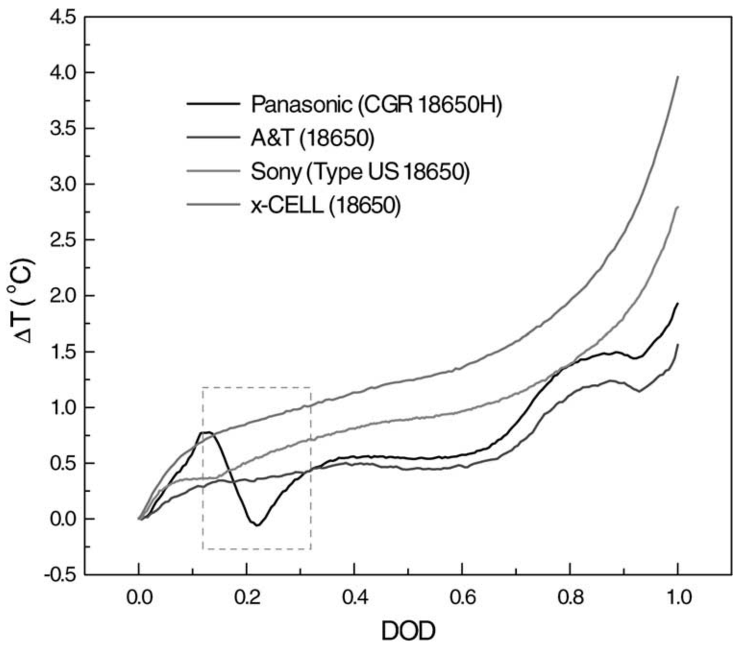

Fig. 5. Thermal behavior of commercial Type 18650 cells during discharge at *C*/6 rate.

2.2.1. Thermal management of battery packs using phase-change material

As shown in Fig. 1, a number of scaled-up cells can be connected in series or in parallel to form a battery module. An EV or HEV battery must have a plurality of modules connected in series to provide a direct current voltage between 60 and 400 V, depending upon the number of modules joined. As explained above, an effective thermal management system must keep the battery pack temperature fairly uniform, in order to achieve an optimum battery performance.

The system described in the work we review here is based on integrating the PCM within the module (but not within individual cells), as shown in Fig. 9. Unlike conventional thermal management systems, the system does not require cooling elements which are normally interposed between adjacent modules to absorb heat generated within the battery pack (see Figs. 10a and b). By utilizing the latent heat of

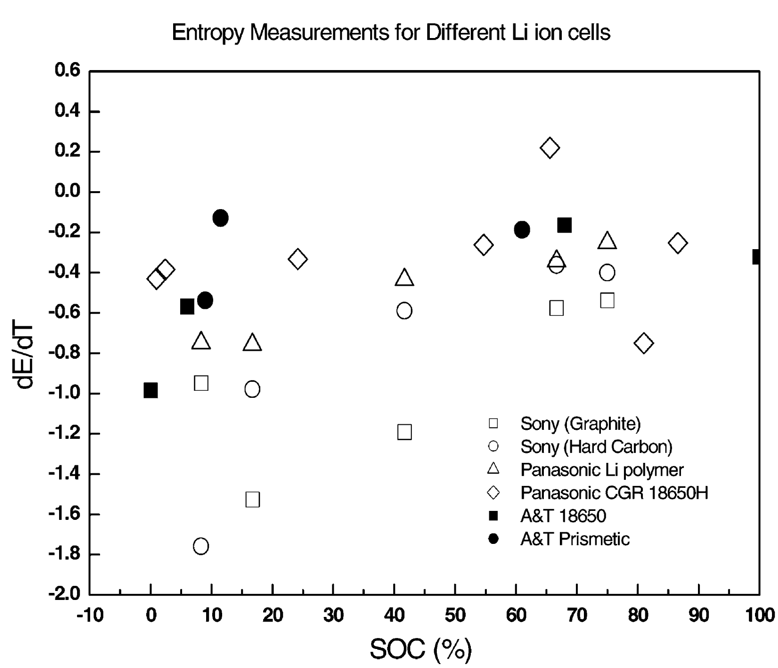

Fig. 6. Measured entropy coefficient (dE/dT) vs. E_{eq} for different commercial secondary lithium cells.

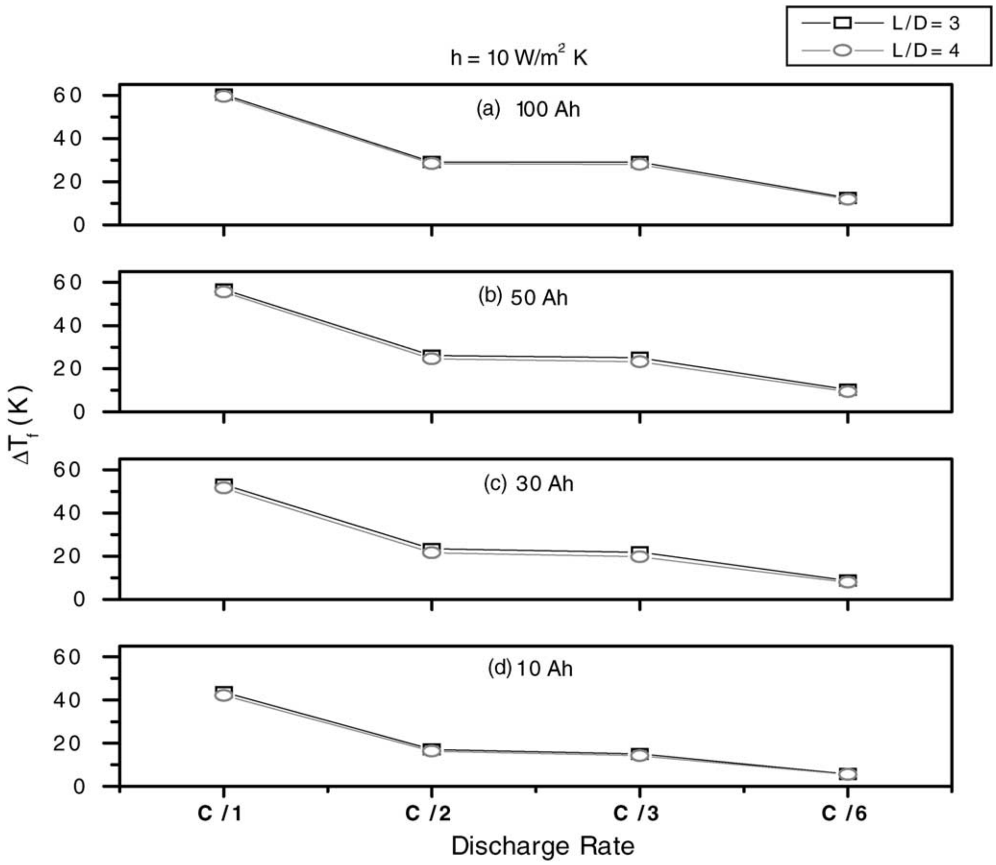

Fig. 7. Simulated temperature profiles for scaled-up Li-ion batteries at different discharge rates under natural cooling conditions ($h = 10$ W/m^2 K).

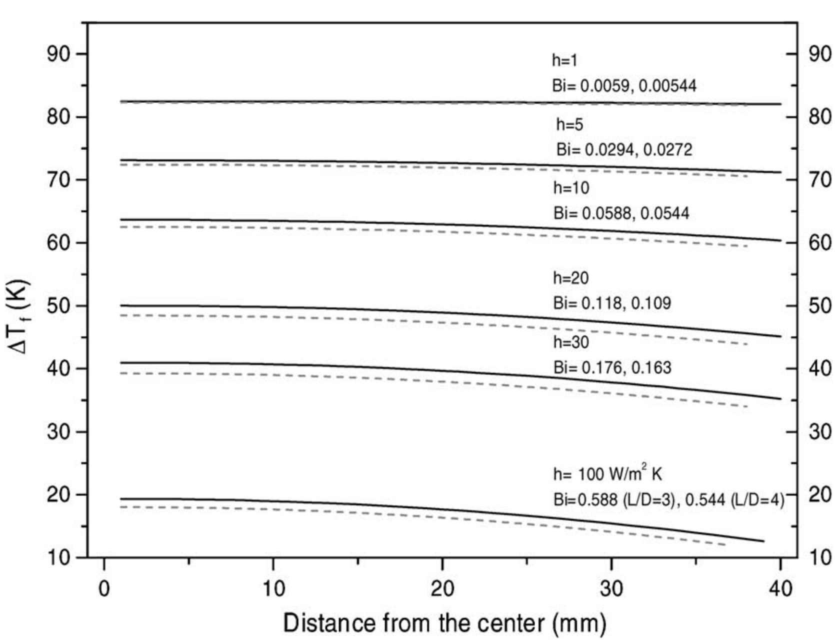

Fig. 8. Simulated temperature profile inside the 100 Ah cell under different cooling conditions, discharge rate = $C/1$. ΔT_f: temperature increase at the end of discharge.

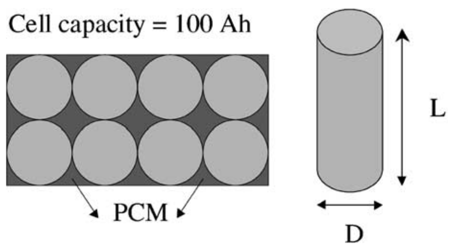

Fig. 9. A Schematic of the proposed EV module with eight 100 Ah cells.

melting/solidification as illustrated schematically in Fig. 11, the PCM thermal management system provides a fully enclosed battery pack which does not include any cooling elements, passageways, or external cooling systems with fluid circulation to transfer heat out of the battery pack. This eliminates the additional costs and control complexities associated with operating the fluid cooling system.

Fig. 12 demonstrates that under near-insulating conditions (i.e. $h = 1$ W/m^2 K) the temperature of a 100 Ah cell in a module with PCM can be maintained at ∼8 °C lower than without PCM, at the end of discharge. As shown in Fig. 13, the PCM system stores the rejected heat in the form of latent heat, in order to use it later when the battery is charged or operated

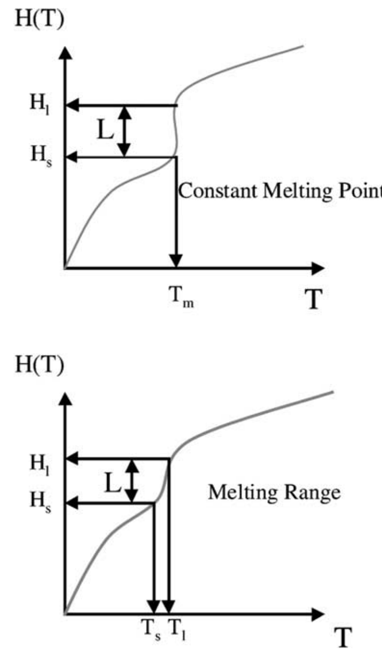

Fig. 11. Schematics of the enthalpy–temperature profile during PCM constant melting point vs. melting range.

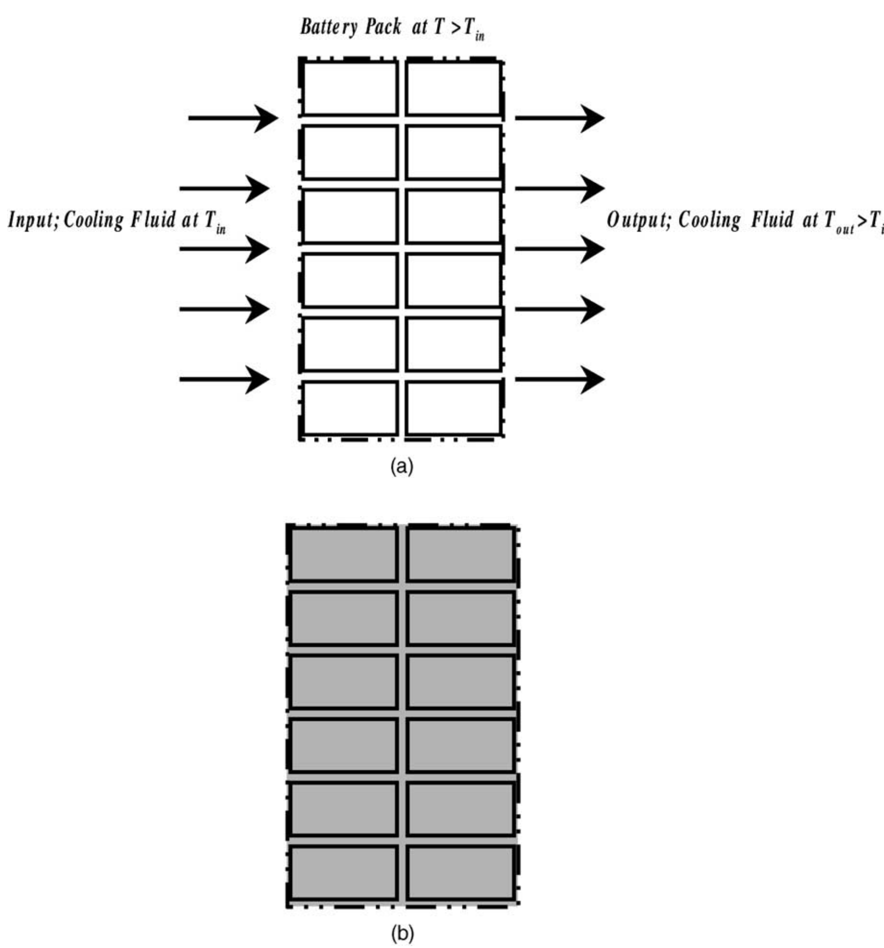

Fig. 10. (a) Battery pack with an external cooling system (i.e. circulating of cooling fluid). (b) Battery pack without an external cooling system (i.e. no flow of cooling fluid).

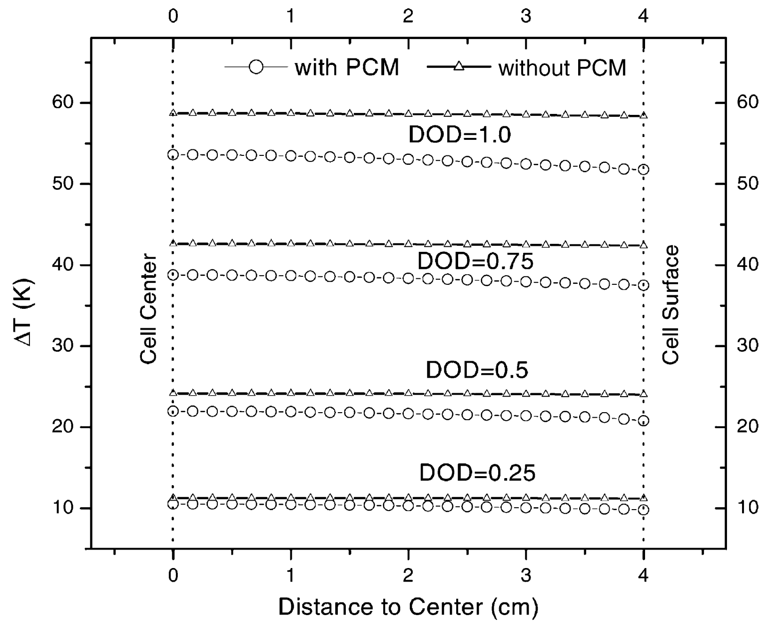

Fig. 12. Radial temperature profile at different DOD for the 100 Ah scaled-up cell at $C/1$ discharge rate with and without PCM at $h = 1\ W/m^2\ K$ cooling rate.

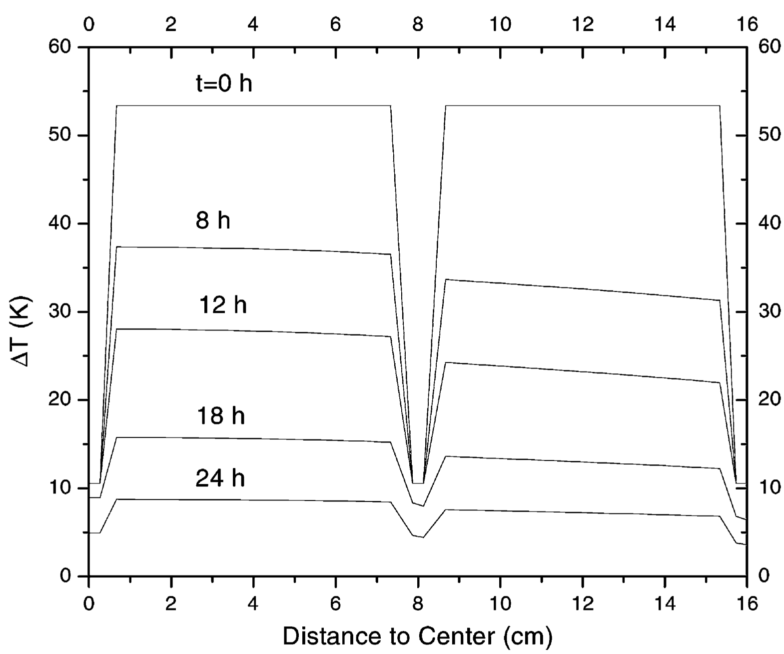

Fig. 13. Temperature profile during relaxation across the center of cells (no. 1 and 2 in the battery module) with PCM at $h = 6.4\ W/m^2\ K$ cooling rate.

in a cold environment (−40 to 0 °C). Therefore, a properly designed PCM system will also reduce the need for battery insulation under these cold conditions which allows further cost reduction and simplification of the battery design.

3. Summary

Unlike most commercial batteries (e.g. lead acid, nickel cadmium, and nickel metal hydride), most commercially available Li-ion batteries exhibit a net cooling effect during charge, and are highly exothermic during discharge. Therefore, an effective thermal management system based on phase-change heat effects is particularly suitable for these batteries. A prototype of such a system is being manufactured to test its suitability for scaled-up Li-ion batteries in EV and HEV applications. In this review, it is shown that the technology base for such a PCM-incorporating battery module, operating as a passive thermal management system, is available and that the design is relatively simple, thereby promising appreciable cost reduction compared to active cooling systems. The PCM-based thermal management system should be especially effective for batteries under very cold ambient conditions, and in space applications.

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