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Numerical Study of Passive Thermal Management of a Cylindrical Lithium-ion Battery

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Abstract. In this paper, a transient model accounting for the conservation of charge, species and energy for a cylindrical lithium-ion battery is solved to evaluate the passive thermal management using PCMs. Two kinds of PCM matrix are considered. The results show that the average temperature of the battery is significantly lowered by the presence of PCM and the local temperature difference is also reduced. In addition, the PCM/Al-foam exhibits a better cooling performance in minimizing the temperature difference due to its higher effective thermal conductivity.

Keywords: lithium-ion battery, thermal management, PCM, mathematical modelling

1. Introduction

Thermal related issues play crucial roles on the battery performance, especially for the large-scale battery system [1]. Large amount of heat generated by the Joule heating and the electrochemical reactions occurring during the charge/discharge processes will lead to an excessive local temperature increase. If the heat cannot be dissipated in time, the temperature will keep increasing and may lead to thermal runaway in worst case. It is therefore necessary to integrate a proper thermal management system into the battery system to maintain the battery to operate within the safe temperature limits. Typically, there are two main thermal management strategies: active approach with air/liquid as cooling medium [2-4] or passive approach by using thermal storage system like phase-change material (PCM) [5-7].The PCM, like a heat sink, has the capability of absorbing large amount of heat generated during the battery discharge process due to its high latent heat of fusion and keep the battery cool enough. Compared to the active method, cooling with PCM has its advantage in minimizing the temperature nonuniformity [8] that in turn can protect the battery from electrical imbalance [9].

Mathematical modelling and numerical simulation can help in getting better understanding of the complex electrochemical and thermal phenomena occurring in the battery and can further assist in the design and optimization of such system. Hallaj and Selman [10] proposed a novel thermal management system that incorporates PCM for electric vehicle batteries and the simulation results show that substantially more uniform temperature profile was obtained for the batteries with a PCM thermal management system during discharge at different rates than without PCM. Khateeb et al. [11, 12] numerically and experimentally studied a lithium-ion battery with PCM thermal management system and the results demonstrate the successful use of the PCM as potential candidate for thermal management solution for the electric vehicle applications. Sabbah et al. [2] conducted a numerical study to compare the cooling performance of high power lithium-ion battery pack with active (air-cooled) and passive (PCM) thermal management system and

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found that the PCM has better cooling performance than the air cooling at stressful conditions, i.e. at high discharge rates and at high operating or ambient temperatures. Moreover, the PCM cooling system can fulfil the operation requirement with the absence of additional fan power. Some other researchers [5, 8, 13, 14] also performed numerical studies to examine the cooling performance for a battery system cooling by PCM. However, these studies failed in resolving the local transport phenomena, electrochemistry and local heat generation. Somasundaram et al [7] developed a coupled thermal-electrochemical model for a cylindrical lithium-ion battery with local resolution in spiral-wound geometries and studied the design and operation of a passive thermal management system based on PCM.

To extend the work on simulating a cylindrical lithium-ion battery in spiral-wound geometries, we present a numerical study of thermal management system by using PCM for a cylindrical lithium-ion battery to examine the electrochemical and thermal behaviour which is resolved in an axisymmetric cross-section. The model considers the conservation of species, charge and energy. Two kinds of PCMs are used in this study and the performance of thermal management system is discussed in terms of average temperature variation and local temperature distribution of the battery under galvanostatic discharge.

2. Mathematical Formulation

Fig. 1a shows a schematic of a commercially available cylindrical (18650-type) spiral-wound lithium-ion battery that is considered in this study. The battery is resolved by an axisymmetric two-dimensional cross-section as displayed in Fig. 1b where the positive electrode (pe), negative electrode (ne), separator (sp) and current collector (cc) are cut into long strips that are wound together like a jelly roll. The dimensions of each functional layer are obtained from a Sony cell reported earlier [15].

The negative electrode ($Li_\chi C_6$ as active material) and the positive electrode ($Li_\eta Mn_2O_4$ as active material) are porous in nature and filled with filler additive, binder and liquid electrolyte. The porous electrodes are separated by the separator. During discharge process, the electrochemical reactions that occur at the electrode/electrolyte interface are as follows:

$$Li_\chi C_6 \rightarrow LiC_6 + \chi Li^+ + \chi e^-,$$
$$Li_{\eta-\chi} Mn_2O_4 + \chi Li^+ + \chi e^- \rightarrow Li_\eta Mn_2O_4.$$

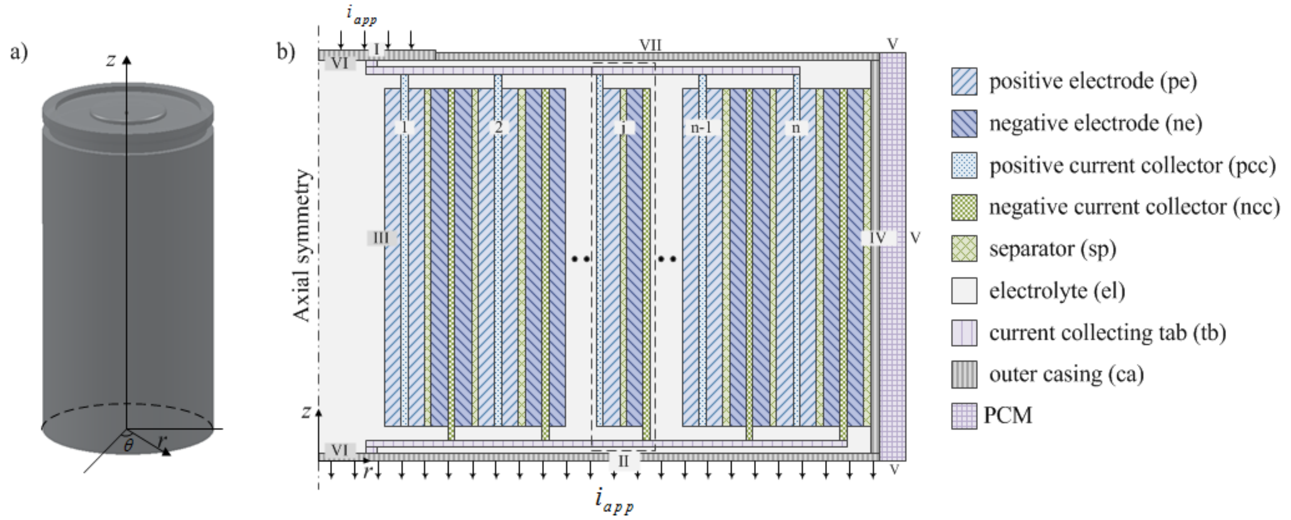

Fig. 1: Schematic of (a) a cylindrical (18650-type) spiral-wound lithium-ion battery, (b) an axisymmetric cross-section of the battery with various functional layers and PCM

The battery is surrounded by the PCM with thickness of 1 mm. Two kinds of PCMs are used in this study; one is the paraffin wax (PCM1)/graphite composite matrix that the wax has a melting range of 315 – 318 K [13]; the other one is aluminium foam (Al-foam) filled with paraffin wax (PCM2) which has a melting range of 314 -317 K [12]. The use of graphite and aluminium with the PCMs is to overcome the low thermal conductivity of the PCMs and enhance the heat transfer between the cell and the ambient [7, 11]. The thermo-physical properties of the PCM/graphite matrix and the PCM/Al-foam are summarized in Table 1, where C_p is the specific heat capacity, k is the thermal conductivity, L is the latent heat, ρ is the density and ε is the porosity of the Al-foam. The calculation of the effective properties for the PCM/Al-foam is given in ref. 12.

The mathematical model is based on the following assumptions: 1. The diffusion coefficient and the transference number are independent of the electrolyte concentration; 2. The active material in both electrodes are assumed to be spherical particles and of same size and uniformly distributed; 3. Side reactions and double-layer capacitance inside the battery are not considered.

Table 1 Thermo-physical properties of PCMs and aluminium foam.

Parameter	Unit	PCM1/Graphite matrix [13]	PCM2 [12]	Al-foam [12]
C_p	$\mathrm{J\ (kg\ K)^{-1}}$	1980	1770	963
k	$\mathrm{W\ (m\ K)^{-1}}$	16.6	0.21	218
L	$\mathrm{J\ kg^{-1}}$	1.85×10^5	1.95×10^5	-
ρ	$\mathrm{kg\ m^{-3}}$	789	910	2700
ε	-	-	-	0.8

The governing equations, boundary conditions and constitutive relations are the same as given in out earlier work [7] and hence are not shown here.

3. Numerics

The generation of computational domain and the simulation were conducted by using the commercial finite-element solver, COMSOL Multiphysics 3.5a [16]. Totally five dependent variables ϕ_s, ϕ_l, c_l, c_s^{avg} and T were solved in the model. The direct solver UMFPACK was used as linear solver with a convergence of 10^{-3}. The computational domain was resolved with around 8×10^4 elements; all the solutions were tested for mesh independence.

In order to ensure convergence, the specific current density, i_{app}, was applied with a smoothed Heaviside function, by which the current density was ramped up from zero to its specified value in a period of time which is much shorter than the overall time of discharge process.

The computations were carried out on a workstation with two quad-core processors (3.07GHz, with a total of eight processor cores) and a total of 24 GB random access memory (RAM).

4. Results and Discussion

The thermal behaviour of the lithium-ion battery during discharge is discussed in terms of average temperature variation. Thereafter, the cooling performance of the battery with a thermal management system of PCM is evaluated and a comparison between the two kinds of PCMs is also presented. The initial and ambient temperature for all the simulations is set to be 298.15 K.

4.1. Average temperature variation

The heat generated during discharge will increase the temperature of the battery. As the solid line shown in Fig. 2, the battery suffers from a significant temperature (increase up to 340 K at the end of discharge under 5 C-rate) when the battery is only with natural convection and radiation, which indicates it is necessary to employ a thermal management system for the battery to operate within its safety limit.

The effect of PCM matrix is simulated for the battery. It is clearly seen from the results (as shown by the dashed and dotted lines in Fig. 2) that the average temperature of the battery is kept at lower temperatures as compared to the case without PCM. The temperature rise of the battery with PCM has dropped by up to around 21 K when compared to the one with only natural convection and radiation. The temperature increases at a constant rate until it reaches the melting point of the PCM after which the rate drops owing to the latent heat of fusion of the PCM [13]. The battery with PCM/Al-foam matrix possesses a slightly lower temperature, around 1 K, when the melting point is reached. This is because the melting point of the PCM2 used in the Al-foam matrix is lesser than the other.

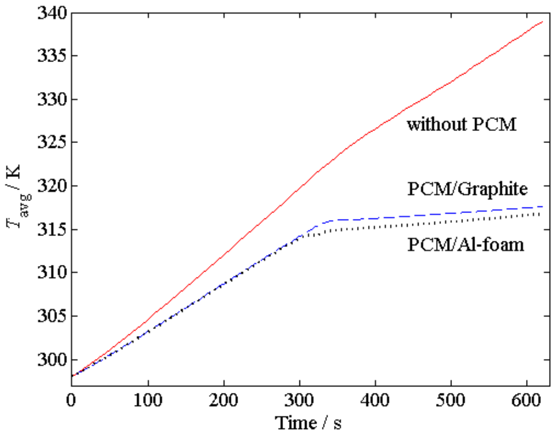

Fig. 2: Average temperature variation of the lithium-ion battery during discharge at 5 C-rate with: PCM/Graphite (dashed line); PCM/Al-foam (dotted line); without cooling (solid line).

4.2. Local temperature distribution

To evaluate the cooling performance of a thermal management system for a battery, one concern is to keep the average temperature of the battery within its safety limit; another concern is to minimize the non-uniformity of local temperature distribution. As depicted in Fig. 3, the temperature difference inside the cell is relatively low which is kept within 1 K for both cases. A closer examination shows that the temperature difference of the battery with PCM/Al-foam is slightly lower (11 % lower than the one with PCM/graphite matrix) which is due to its higher effective thermal conductivity. The slight difference in temperature difference will be accumulated when the battery go through a number of charge/discharge cycles.

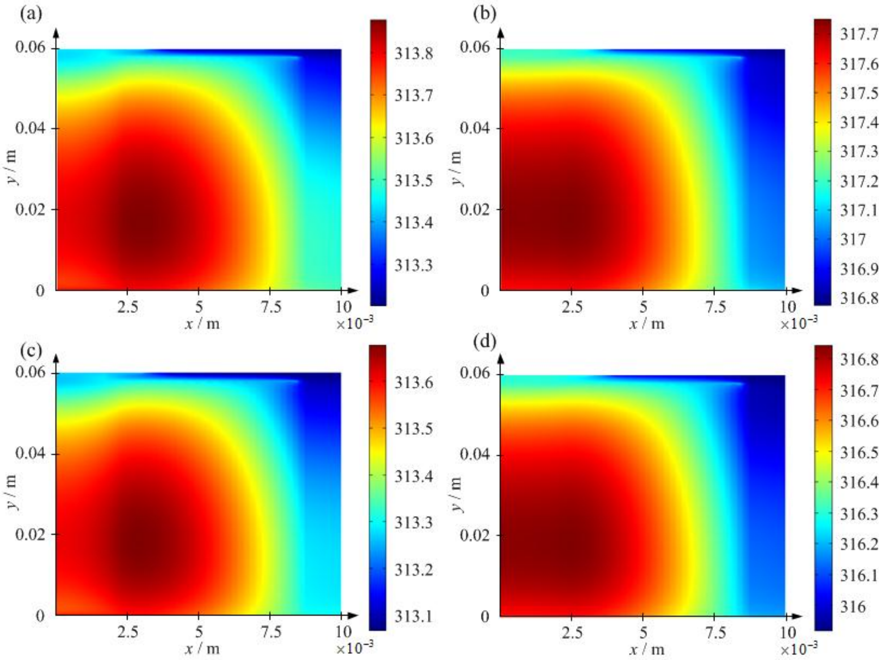

Fig. 3: Local temperature distribution for the lithium-ion battery during discharge at 5 C-rate (PCM/Graphite matrix: (a) t = 290 s, (b) t = .580s; PCM/Al-foam: (c) t = 290s, (d) t = 580s.

5. Conclusions

A numerical study of a two-dimensional thermal-electrochemical model for a cylindrical spiral-wound lithium-ion battery has been carried out and analysed in terms of thermal management with two kinds of PCM matrix. It is found that the presence of PCM can keep the battery with lower temperature (up to 21 K drop in average temperature increase at the end of discharge under 5 C-rate) as compared to the case only with natural convection and radiation. It is also beneficial as the PCM minimizes the local temperature gradient as well.

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