

Temperature Rise in Prismatic Polymer Lithium-Ion Batteries: An Analytic Approach

Peyman Taheri and Majid Bahrami
Simon Fraser University

ABSTRACT

A rigorous three-dimensional analytical model is proposed to investigate thermal response of batteries to transient heat generation during their operation. The modeling is based on integral-transform technique that gives a closed-form solution for the fundamental problem of heat conduction in battery cores with orthotropic thermal conductivities. The method is examined to describe spatial and temporal temperature evolution in a sample prismatic lithium-ion battery (EiG ePLB C020), subjected to transient heat generation in its bulk, and various convective cooling boundary conditions at its surfaces (the most practical case is considered, when surrounding medium is at a constant ambient temperature). The full-field solutions take the form of a rapidly converging triple infinite sum whose leading terms provide a very simple and accurate approximation of the battery thermal behavior. A surface-averaged Biot number has been proposed that can simplify the thermal solutions under certain conditions. The presented analytical model provides a fast yet accurate tool for battery thermal management system designs.

CITATION: Taheri, P. and Bahrami, M., "Temperature Rise in Prismatic Polymer Lithium-Ion Batteries: An Analytic Approach," *SAE Int. J. Passeng. Cars - Electron. Electr. Syst.* 5(1):2012, doi:10.4271/2012-01-0334.

INTRODUCTION

Among different types of rechargeable batteries, polymer lithium-ion (Li-ion) cells are well-known for their high energy and power densities (up to 150 Wh/kg), high operating voltage and discharge rate (up to about 4 V), short charging time, minimal memory effects and self-discharge (around 5% per month), and long cycling life [1]. Such desired features have made Li-ion batteries one of the most favoured candidates for portable energy storage systems. More recently, the strategy of electrifying vehicles with Li-ion batteries in order to reduce or remove the contribution of internal combustion engine (ICE) into the powertrain has attracted an intense attention. Nevertheless, the persisting challenge associated with application of Li-ion batteries in hybrid-electric and plug-in electric vehicles (H/PEVs) is their temperature control. It is evident that under high discharge conditions, which involve high rates of Joulean heat generation and exothermic electrochemical reactions, batteries are prone to excessive temperature rise that can initiate swelling [2], thermal runaway [3], electrolyte fire, and in extreme cases explosion [4]. Moreover, exposure of Li-ion batteries to sub-freezing temperatures drastically reduces their energy and power [5]. As a result, design of an efficient battery thermal management system (BTMS) is crucial for batteries' safety, efficiency, and longevity.

An efficient BTMS is required to keep the batteries' temperature within a narrow range (for Li-ion batteries the ideal temperature range is 20 to 30°C), and provide a minimum temperature variation within the battery pack, i.e., a uniform temperature distribution [6]. In order to develop an effective BTMS, accurate thermal models are required to predict thermal response of the batteries under transient and dynamic load cycles [7, 8].

Thermal behavior of batteries is strongly coupled to the electro-chemical processes during charge and discharge cycles [9, 10]. However, for large-scale battery assemblies, e.g., in hybrid and electric vehicles, the collective thermal effects of electro-chemical processes can be approximated from measurements, and then considered as the heat source in a standalone thermal model. Based on this decoupling strategy, there are several battery thermal models available in the literature including one-dimensional [11], two-dimensional [12, 13, 14], and three-dimensional models [15, 16, 17, 18], in which variety of cell designs, modes of operation, and thermophysical properties are considered. For an extensive bibliography on battery thermal models see Ref. [10].

Advanced simulations for Li-ion batteries suggest that owing to their laminated structure, a three-dimensional thermal analysis should be adapted to properly study thermal

response of the batteries during cyclic operation. To the author's best knowledge, all the multidimensional thermal models developed for Li-ion batteries rely on numerical solution; thus, lack of a theoretical method is evident. The only available analytical solution is the work of Newman and Tiedemann [19], where the classical technique of separation of variables is employed to solve the transient heat conduction problem for batteries with a constant heat generation and constant-temperature boundary conditions. In this study, we investigate the same problem featuring transient heat generation and convective boundary conditions that yield a more realistic representation of the operating conditions for Li-ion batteries used in applications such as H/PEVs. In our approach, since both energy equation and boundary conditions involve non-homogeneities, the integral-transform technique [20, 21] is used to obtain a closed form analytical solution.

In the following sections, the analytical thermal model is presented, and its application for a sample polymer Li-ion battery is demonstrated. Thermal behavior of the battery is investigated during galvanostatic discharge processes with different discharge currents, while convective cooling is applied at its surfaces. Heat generation rates within the battery are approximated from voltage drop measurements at constant discharge currents, available from battery manufacturer. Finally, the required convective heat transfer coefficients which must be provided by the BTMS are discussed.

THERMAL MODEL FORMULATION

We consider a three-dimensional rectangular orthotropic solid of length L_1 , width L_2 , and height L_3 . Heat is generated within the solid domain, while heat transfer with surrounding medium is allowed at its boundary surfaces. The temperature distribution inside the solid is described by energy balance equation that only includes conduction terms,

$$\rho c_p \frac{\partial T}{\partial t} = k_1 \frac{\partial^2 T}{\partial x_1^2} + k_2 \frac{\partial^2 T}{\partial x_2^2} + k_3 \frac{\partial^2 T}{\partial x_3^2} + g \quad \text{in} \\ 0 \leq x_1 \leq L_1, \quad 0 \leq x_2 \leq L_2, \quad 0 \leq x_3 \leq L_3 \quad (1)$$

in which, t is time and $\mathbf{x} = (x_1, x_2, x_3)$ represent the components of position vector in Cartesian coordinate system. The density ρ , heat capacity per unit mass c_p , and orthotropic thermal conductivity coefficients (k_1, k_2, k_3) are the thermophysical parameters. The functions $T(\mathbf{x}, t)$ and $g(\mathbf{x}, t)$ represent the temperature field and heat generation rate per unit volume, respectively. It should be noted that in derivation of Eq. (1), the thermophysical properties are assumed to be independent of temperature, which is generally acceptable over a reasonably narrow temperature range of interest, i.e., the desired operating temperature range. This is a key assumption which leads to a linear energy balance equation [cf. Eq. (1)] and allows an analytical solution.

At the boundaries of the domain convective heat transfer is considered,

$$-k_i \frac{\partial T}{\partial x_i} + h_{i0} (T - T_0) = 0 \quad \text{at} \quad x_i = 0 \quad (i = 1, 2, 3) \quad (2-1)$$

$$k_i \frac{\partial T}{\partial x_i} + h_{i1} (T - T_0) = 0 \quad \text{at} \quad x_i = L_i \quad (i = 1, 2, 3) \quad (2-2)$$

where T_0 is the ambient temperature, also the initial temperature of the domain (battery),

$$T = T_0 \quad \text{at} \quad t = 0 \quad (3)$$

In this study, we consider constant ambient temperatures; however, the method allows definition of ambient temperatures as a function of both space and time [20, 21, 22]. At x_i -direction, the convective heat transfer coefficients on surface 0 (the surface at $x_i = 0$) and surface 1 (the surface $x_i = L_i$) are denoted by h_{i0} and h_{i1} ($i = 1, 2, 3$).

The system of initial boundary value problem, described in Eqs. (1), (2), (3), can be transformed into a more convenient form

$$\frac{\partial \theta}{\partial \tau} = \frac{\partial^2 \theta}{\partial X_1^2} + K_2 \frac{\partial^2 \theta}{\partial X_2^2} + K_3 \frac{\partial^2 \theta}{\partial X_3^2} + G \quad \text{in} \\ 0 \leq X_1 \leq 1, \quad 0 \leq X_2 \leq 1, \quad 0 \leq X_3 \leq 1 \quad (4)$$

with boundary conditions,

$$-\frac{\partial \theta}{\partial X_i} + \text{Bi}_{i0} \theta = 0 \quad \text{at} \quad X_i = 0 \quad (i = 1, 2, 3) \quad (5-1)$$

$$\frac{\partial \theta}{\partial X_i} + \text{Bi}_{i1} \theta = 0 \quad \text{at} \quad X_i = 1 \quad (i = 1, 2, 3) \quad (5-2)$$

and the initial condition

$$\theta = 0 \quad \text{at} \quad \tau = 0 \quad (6)$$

In the transformed system, the dimensionless space and time are defined as,

$$X_i = \frac{x_i}{L_i} \quad (i = 1, 2, 3), \quad \tau = \frac{k_1 / L_1^2}{\rho c_p / t} \quad (7-1)$$

and

$$K_i = \frac{k_i / L_i^2}{k_1 / L_1^2} \quad (i = 1, 2, 3), \quad \text{Bi}_{ij} = \frac{h_{ij} L_i}{k_i} \quad (i = 1, 2, 3; j = 0, 1) \quad (7-2)$$

where Bi_{ij} are the Biot numbers. The temperature rise θ , and the source for temperature rise G in temperature unit are

$$\theta = T - T_0, \quad \text{and} \quad G = \frac{g}{k_1 / L_1^2} \quad (7-3)$$

The transformed system (4), (5), (6), which describes the temperature rise with respect to dimensionless space and time, is solved by applying a finite-integral transform technique [20, 21], as described in the [Appendix](#).

STRUCTURE AND THERMOPHYSICAL PROPERTIES OF THE SAMPLE POLYMER LITHIUM-ION BATTERY

Prismatic polymer Li-ion batteries use specific battery architecture; the liquid lithium-salt electrolyte is held within the multi-layered porous structures of electrodes and separator sheets, which are made of solid polymer composites. Application of porous electrodes promotes intimate contact of the electrode material with the electrolyte solution, leading to higher rate of chemical reactions. [Figure 1\(a\)](#) schematically shows the internal multi-layered structure of a prismatic polymer Li-ion battery, in which negative and positive porous electrodes are alternatively wrapped in separator sheets. A battery core as shown in [Fig. 1\(b\)](#), includes several layers of electrodes and separators enclosed in a case (the case is not shown). A unit cell of the battery layered arrangement is depicted in [Fig. 1\(c\)](#), in which lithium ions Li^+ are migrating from anode to cathode during a discharge process.

In order to demonstrate how to apply the proposed thermal model for batteries, ePLB C020 battery fabricated by EiG Corporation (South Korea) is considered as our sample Li-ion battery. This battery uses $\text{Li}[\text{NiCoMn}_2]\text{O}_2$ and graphite as active materials at cathode and anode, respectively. The nominal voltage and capacity the battery are 3.65 V and 20 Ah, with specific energy of $175 \text{ Wh} \cdot \text{kg}^{-1}$. The weight of the battery is approximately 407 g, thus, its energy content is approximately 71 Wh. Mechanical and electrical specifications of the battery are listed in [Table 1](#).

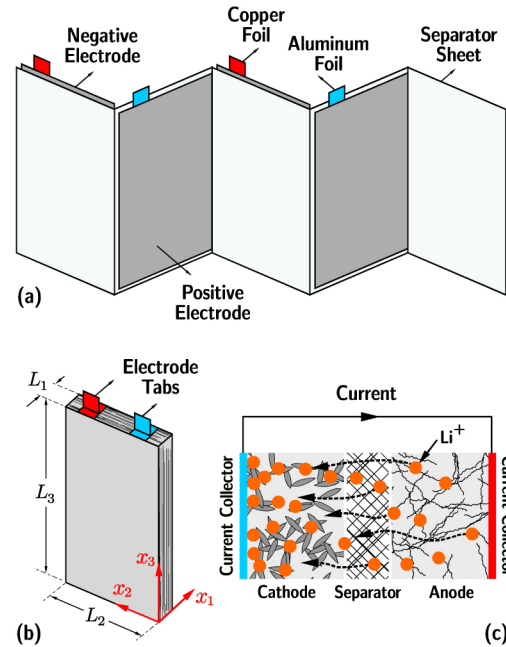


Figure 1. (a) Multi-layered core configuration in a prismatic polymer lithium-ion battery; (b) Core of a single battery pack (the battery case is not shown); (c) A unit cell of the battery including a pair of porous electrodes, a porous separator, and current collectors is shown during discharge process. The pores of polymer components, i.e., electrodes and separator are filled with an electrolyte liquid which allows migration of ions between the electrodes.

The sample battery includes 18 layers of negative electrodes, 17 layers of positive electrodes, and 36 layers of polymer (polypropylene) separator sheets. The electrodes which include current collector foils laminated by thin layers of a polymer (polyethylene oxide) are connected in parallel. Aluminum and copper foils are used as current collectors in positive and negative electrodes, respectively. The polymer layers (electrodes and separator sheets) are porous media soaked in an electrolyte liquid (a mixture of Ethylene carbonate and Dimethyl carbonate) and accommodate active materials required in the battery chemistry. The battery core [[Fig. 1\(a\)](#)] is packed in a polymer laminate aluminum pouch case. The thickness and thermophysical properties of the battery core layers/materials are provided in [Table 2](#). Density, heat capacity, and thermal conductivity of porous polymer layers in the electrodes and separator sheets must be measured after they are soaked in the electrolyte liquid. Since heat capacity and thermal conductivity of wet layers are not reported by the manufacturer, thus we use available data in the literature for a similar battery type [[14](#), [18](#)].

Table 1. Specifications of ePLB C020, EiG battery.

Mechanical characteristics	
Thickness (L_1)	7 [mm]
Width (L_2)	125 [mm]
Height (L_3)	195 [mm]
Weight	407 [g]
Electrical characteristics	
Nominal voltage	3.65 [V]
Nominal capacity	20 [Ah]
Specific energy	175 [Wh kg ⁻¹]
Energy density	370 [Wh L ⁻¹]
Specific power (DOD 50%, 10 sec.)	2300 [W kg ⁻¹]
Power density (DOD 50%, 10 sec.)	4600 [W L ⁻¹]
Operating conditions	
Recommended voltage limit for discharge	3 [V]
Lower voltage limit for discharge	2.5 [V]
Maximum continuous discharge current	5C
Maximum discharge current (peak < 10 second)	10C
Operating temperature	between -30°C and +50°C
Recommended charge temperature	between 0°C and +40°C

Table 2. Thickness and thermophysical properties of battery components.

Material/Layer	Thickness [μm]	Number of layers	Density [kg·m ⁻³]	Heat capacity [J·kg ⁻¹ ·K ⁻¹]	Thermal Conductivity [W·m ⁻¹ ·K ⁻¹]
Aluminum foil	21	17	2702	903	238
Copper foil	12	18	8933	385	398
Separator sheet	25	36	1017 (wet)	1978 (wet)	0.34 (wet)
Positive electrode	70	34	2895 (wet)	1270 (wet)	1.58 (wet)
Negative electrode	79	36	1555 (wet)	1437 (wet)	1.04 (wet)

In order to solve Eqs. (1), (2), (3), it is necessary to determine the thermophysical parameters for the battery core. To avoid complexities associated with its multi-material multi-layered structure, we define average/effective transport properties. The product value of density and heat capacity are approximated based on the volume of each layer (component) [10, 18],

$$\rho c_p = \frac{\sum_{j=1}^N \rho_j c_{p,j} \mathcal{V}_j}{\mathcal{V}} \quad (8)$$

where $\mathcal{V}$ is the total battery volume, $\mathcal{V}_j$ is the volume of the j th component (layer), and N is the total number of components (layers). Furthermore, the concept of “equivalent resistance network” is employed to define effective thermal conductivities in different directions. Based on Fig. 1, there are series thermal resistors in x_1 -direction and parallel thermal resistors in x_2 - and x_3 -directions. Accordingly, through-plane and in-plane orthotropic conductivities are obtained as [8, 10],

$$k_1 = \frac{\sum_{j=1}^N \ell_j}{\sum_{j=1}^N (\ell_j / k_j)} \quad \text{and} \quad k_2 = k_3 = \frac{\sum_{j=1}^N \ell_j k_j}{\sum_{j=1}^N \ell_j} \quad (9)$$

where ℓ_j denotes the thickness of the j th component (layer) in x_1 -direction, and $\sum_{j=1}^N \ell_j = L_1$. It must be emphasized that as a consequence of laminated arrangement of the battery core, interfacial phenomena of contact resistance at porous-porous and porous-solid interfaces must be considered in evaluation of effective thermal conductivities. However, for polymer Li-ion batteries, since the contact interfaces are wet at the presence of the electrolyte liquid, the effects of contact resistance are assumed to be negligible. This simplification is usually justified with the fact that thermal conductivities of electrolyte and polymer compounds are in the same order. Detailed experimental study on contact resistance issue in batteries is not available, and the authors believe that this important phenomenon is overlooked and plan to further investigate this potentially critical issue in depth.