

Design of a Calorimeter for Measurement of Heat Generation Rate of Lithium Ion Battery Using Thermoelectric Device

Yilin Yin and Zhong Zheng
 Auburn University

Song-Yul Choe
 Auburn Univ.

ABSTRACT

Analysis of thermal behavior of Lithium ion battery is one of crucial issues to ensure a safe and durable operation. Temperature is the physical quantity that is widely used for analysis, but limited for accurate investigations of behavior of heat generation of battery because of sensitivities affected by heat transfer in experiments. Calorimeter available commercially is widely used to measure the heat generation of battery, but does not follow required dynamics because of a relatively large thermal time constant given by cavity and a limited heat transfer capability. In this paper, we proposed a highly dynamic calorimeter that was constructed using two thermoelectric devices (TEMs). For the design of the calorimeter and its calibration, a printed circuit board (PCB) with the same size as the battery was used as a dummy load to generate controlled heat. Dynamics were improved using a lead-lag compensator for temperature control and heat generation was estimated using Kalman filter based on a thermal model of the calorimeter. All parameters were optimized using the PCB. Finally, heat generation rate of a large format of pouch type lithium ion battery was measured and compared with theoretical values.

CITATION: Yin, Y., Zheng, Z., and Choe, S., "Design of a Calorimeter for Measurement of Heat Generation Rate of Lithium Ion Battery Using Thermoelectric Device," *SAE Int. J. Alt. Power*, 6(2):2017, doi:10.4271/2017-01-1213.

INTRODUCTION

As energy storage components, lithium ion batteries are widely used in electrical vehicles (EV) and grids because of its high coulombic efficiency, higher power and energy density, and long durability. When lithium ion batteries are charged and discharged, lithium ions flow from cathode to anode and vice versa through the electrolyte, while electrons are transported through an external circuit. The charge transport, chemical reaction, diffusion in the solid and Ohmic's heating produce heat [1], and at the same time, performances of battery are significantly affected by its operating temperature. Charging and discharging lithium ion battery in an elevated temperature accelerates its side reaction and leads to the electrolyte and binder decompositions and reduction of the accessible surface area of the electrode particles. So high operating temperature accelerates power and capacity fade of battery. Santhanagopalan's experiment results at the operating temperatures from 5°C to 45°C showed that the capacity fade of lithium ion battery at 45°C was nine times higher than that at 5°C [2]. And, to minimize the effects of elevated temperature on degradation and other performances and to prevent a thermal runaway, the large amount of heat generated by the battery in a pack or modules should be properly rejected [3]. In order to optimally reject the generated heat, accurate estimation the heat generation rate of lithium ion battery is needed, which is also crucial for its safe operations.

When battery is charged and discharged, the battery's temperature varies due to the internal heat generation [4,5] Heat generation in lithium ion battery consists of two main parts, the reversible heat generated by the change of entropy at a given cell temperature and irreversible heat generated by Joule heat, charge-transfer overpotentials and mass transfer limitations[6, 7]. The heat generation sources are difficult to be estimated based on the thermal model because of temperature-dependent parameters in the thermal model, the changing of electrode resistivity due to current and temperature effects, and the complex behavior of interfacial areas of the electrode and electrolyte[8,9]. Therefore, heat generation rate in the lithium ion battery is preferably measured directly using a calorimeter. There are two known methods: accelerated rate calorimetry (ARC) and isothermal heat conduction calorimetry (IHC) [9]. ARC method measures the heat generation rate of battery based on the increase of battery's temperature and the amount of heat released from the battery to the surroundings. Forgeza used two thermal couples to measure the heat generation rate. One thermal couple was placed into a cylindrical lithium ion battery under an inert atmosphere and another one was placed on the battery surface to measure both inside and outside temperatures [10, 11]. This method measures the heat generation rate accurately but only provides accurate results for the cylindrical batteries that can place a thermal couple inside of a cell. Hong's research team used an accelerated rate calorimeter (ARC2000, Columbia Scientific Industries, Austin, Texas) to

establish the baseline condition which is necessary for measuring the heat effects associated with discharging/charging the cells with the maximum measured heat generation rate of 1.63 W/L [12]. However, the heat generation during charging and discharging is far beyond the measurement range of the calorimeter described before, and it is impossible to follow the dynamics of the heat generation rate that varies fast. The IHC method measures the heat generation rate by using a large heat sink that contacts the surface of the battery to keep the battery at isothermal conditions during measurement [13, 14]. Kim used a commercially available micro-calorimeter (IMC, CSC4400, Calorimetry Science Corp) to measure the heat generation rate of lithium ion battery. However, the IHC method can only measure low heat generation rate because the heat sink cannot extract high rate of heat generation. And, the limited dynamics prevent the measurement of the heat generation rate that changes fast because of a relatively larger thermal time constant.

The lithium ion batteries used for the studies have high power, which generates heat at a high rate during large charging/discharging C-rate.

Therefore, we designed a special calorimeter using two thermoelectric devices that can provide an accurate and fast measurement of the heat generation of the pouch type of lithium ion battery. The calorimeter was modeled and its parameters were identified. Lead-lag compensator was used to keep the temperature of surface of battery to be constant and heat generation was estimated using Kalman filter, which is described in detail below.

MODELING OF CALORIMETER

Calorimeters are commonly used to measure heat generation rate of different kinds of batteries, but they are unable to follow the dynamics of heat generation rate occurring during step or pulse charging and discharging of cells because of a relatively large thermal time constant. To solve the problem, a new special calorimeter was designed using two thermoelectric devices (TEMs).

TEMs are widely used as heat pump in many applications, which includes cooling or heating of an object in control loop [15,16,17]. For control purpose, a mathematical model of TEM was developed, which is a challenging issue because of the nonlinear behavior of TEM. Some researchers proposed a finite element model and finite difference model [18,19]. Neto presented a second order discrete time autoregressive moving average model to describe the TEM [20]. However, these model are too complex to be used to design the controller and heat estimation algorithm.

In this paper, we proposed a simple but accurate model considering the nonlinear characteristics of TEM, which was used to design the controller and heat generation estimation algorithm.

The key components in TEM are the semiconductors (P-N junctions), which are placed thermally in parallel to each other and electrically in series, as shown in Figure 1. The TEM works according to Peltier effect, which occurs whenever electrical current flows through P-N junctions. When a DC voltage is applied to the P-N junctions, the

electrons in the N junctions and the ‘holes’ in the P junctions move from cold side to the hot side and carry the heat from bottom junctions to the top junctions. Depending on the direction of current flow, the junctions either absorb or release heat, so that one side gets colder while the other gets hotter. The hot side is attached to a heat sink to accelerate the release of the heat, shown in Figure 2. The quantity of heat liberated by the holes and electrons per unit of time is proportional to the input current of TEM [22, 23].

$$Q_p = k_1 \cdot I_{TEM} = \alpha \cdot T_2 \cdot I_{TEM} \quad (1)$$

where k_1 is the Peltier coefficient, α is the Seebeck coefficient. T_2 is the absolute temperature of TEM (cold side). I_{TEM} is the input current of TEM. When current flows through a conductor that has a temperature gradient, heat is absorbed or released depending on the direction of temperature gradient and direction of the current, which is called Thomson effect [24, 25].

$$Q_T = \tau \cdot I_{TEM} \cdot \frac{dT}{dx} \quad (2)$$

where τ is the Thomson coefficient and x is the space variable. In our design. The heat generated by Thomson effect is ignored because of the difficulty to measure and negligible amount compared to Joule effect [26].

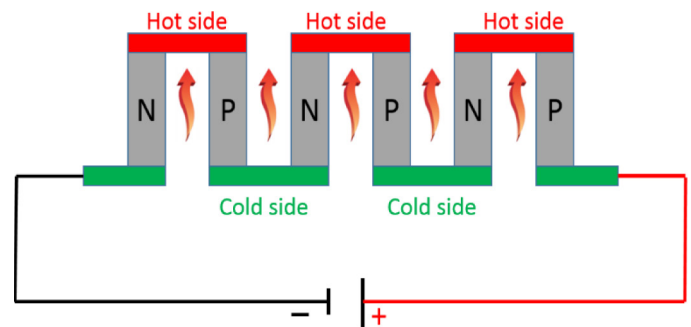


Figure 1. Working principle of TEM

When current flows into TEM, Joule heat is generated due to the resistance (k_2) of P-N junctions inside of TEM,

$$Q_J = I_{TEM}^2 \cdot k_2 \quad (3)$$

Temperature gradient exists between T_2 and T_3 , so there is a heat conduction from the hot side (T_3) to the cold side (T_2),

$$Q_k = k_3(T_2 - T_3) \quad (4)$$

where k_3 is the thermal conduction coefficient. Finally, the heat pump rate of the TEM is given as follows,

$$Q_{pump} = k_1 \cdot I_{TEM} - k_2 I_{TEM}^2 + k_3(T_2 - T_3)$$

When the battery is charged or discharged using pulse or step current, especially for fast charging, the heat generation rate changes abruptly. The dynamics of the calorimeter are limited by the time delay between the input current of TEM and the associated heat pump rate. The dominant time delay is caused by the limited thermal conductivity and thermal capacitance of the metal plate, shown in Figure 2. In order to reduce the effects of the time delay, Kalman filter was used based on the heat transfer model of the calorimeter, which ultimately improves the dynamic response of the designed calorimeter.

The time delay is mainly caused by the metal plate, so only a thermal model of the metal plate was considered and developed. The metal plate is separated into two control volumes, as shown in Figure 3.

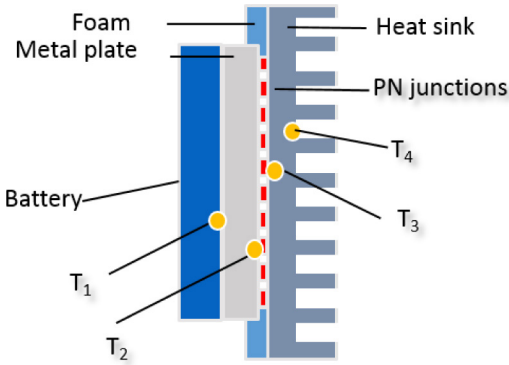


Figure 2. The structure of TEM

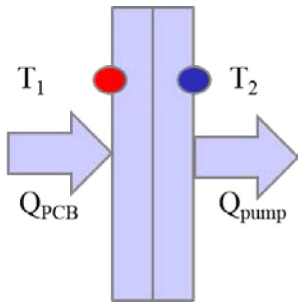


Figure 3. Control volumes of metal plates

Energy equations for the two control volumes of the metal plate is shown below,

$$\left. \begin{aligned} \left(\frac{C_M M_M}{2} \right) \dot{T}_1 &= Q_{PCB} - K (T_1 - T_2) \\ \left(\frac{C_M M_M}{2} \right) \dot{T}_2 &= K (T_1 - T_2) - Q_{pump} \end{aligned} \right\} \quad (6)$$

where C_M is the heat capacity of the metal plate, M_M is the mass of metal plate, K the thermal conductivity of metal plate, Q_{pump} is the heat pump out by TEM. Q_{PCB} is the heat generated by the printed circuit board (PCB).

Using forward difference method, the discretized model of the equation above is written in matrix form as follows

$$\begin{bmatrix} T_1^{k+1} \\ T_2^{k+1} \end{bmatrix} = \begin{bmatrix} 1 - \frac{2K\Delta t}{C_M M_M} & \frac{2K\Delta t}{C_M M_M} \\ \frac{2K\Delta t}{C_M M_M} & 1 - \frac{2K\Delta t}{C_M M_M} \end{bmatrix} \begin{bmatrix} T_1^k \\ T_2^k \end{bmatrix} + \begin{bmatrix} \frac{2K\Delta t}{C_M M_M} \\ -\frac{2K\Delta t}{C_M M_M} \end{bmatrix} \begin{bmatrix} Q_{PCB} \\ Q_{pump} \end{bmatrix} \quad (7)$$

In order to design an algorithm to estimate the Q_{PCB} , combining with equation (5), the above equations can be rewritten in state space form.

$$\begin{bmatrix} T_1^{k+1} \\ T_2^{k+1} \\ Q_{PCB}^{k+1} \end{bmatrix} = \begin{bmatrix} 1 - \frac{2K\Delta t}{C_M M_M} & \frac{2K\Delta t}{C_M M_M} & \frac{2K\Delta t}{C_M M_M} \\ \frac{2K\Delta t}{C_M M_M} & 1 - \frac{2K\Delta t}{C_M M_M} + k_3 & 0 \\ 0 & 0 & 1 \end{bmatrix} \begin{bmatrix} T_1^k \\ T_2^k \\ Q_{PCB}^k \end{bmatrix} - \begin{bmatrix} \frac{2K\Delta t}{C_M M_M} (k_1 I_{TEM} - k_2 I_{TEM}^2 + k_3 T_2) \\ 0 \\ 0 \end{bmatrix} \quad (8)$$

$$y^k = [1 \quad 0 \quad 0] \begin{bmatrix} T_1^k \\ T_2^k \\ Q_{PCB}^k \end{bmatrix} \quad (9)$$

EXPERIMENT

Experimental Setup

The lithium ion battery used for this study is a pouch type lithium ion battery with the dimensions about 20cm×15cm×5mm. The capacity is 15.7Ah and the operating voltage is from 2.5V to 4.15V. A test station was designed to charge/discharge the battery using a DC power supply and an electronic load, and to estimate the heat generation rate of lithium ion battery by TEMs, which are controlled by LabVIEW embedded in a PC, as shown in Figure 4 and Figure 5.

Current was measured by a high-resolution current sensor and the surface temperature was measured by two thermocouples placed at the center of the both sides of the battery surface.

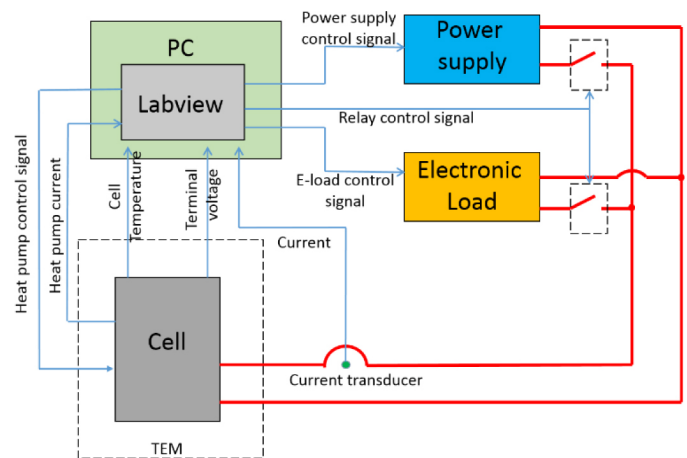


Figure 4. Experimental setup