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Research Paper

Thermal modeling and validation of temperature distributions in a prismatic lithium-ion battery at different discharge rates and varying boundary conditions

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HIGHLIGHTS

- Designed and developed the battery thermal management system.
- Studied average surface temperature distributions with varying boundary conditions.
- Studied the voltage profile at different discharge rates and boundary conditions.
- Developed the battery thermal model using neural network approach.
- Validated the model with the experimental data.

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ABSTRACT

This paper deals with the thermal modeling and validation of temperature rise in a prismatic lithium-ion battery with $LiFePO_4$ (also known as LFP) cathode material. The developed model represents the main thermal phenomena in the cell in terms of temperature distribution. A neural network approach is used for the model development. The proposed model is validated with the experimental data collected in terms of temperature and voltage profiles. In addition to this, the surface temperature distributions on the principal surface of the battery are studied under various discharge/charge profiles with varying boundary conditions (BCs) and average surface temperature distributions. For this, the different discharge rates of 2C and 4C and different boundary conditions (cooling/operating/bath temperature of 5 °C, 15 °C, 25 °C, and 35 °C) are selected. The results of this study show that the increased discharge rates result in increased surface temperature distributions on the principal surface of the battery. Furthermore, it is observed that changing the operating or boundary conditions considerably affect the surface temperature distributions.

1. Introduction

Development of Electric Vehicles (EVs) and Hybrid Electric Vehicles' (HEVs) is gaining traction across all geographies to help meet increasing fuel economy regulations and as a pathway to offset concerns due to climate change [1]. Moreover, the need to lower the vehicle emissions along with the decreasing oil resources has made automotive industry to find pure EVs in order to solve these demands globally [2]. EVs depend on the type of batteries used [3] and improving their life-time will reduce the runtime and the costs for the vehicle. These technologies have primarily shifted toward lithium-ion batteries for energy storage because the lithium-ion battery is the most advanced battery due to its high specific energy, high voltage and low self-discharge rate for EVs and HEVs [4]. It can be said that the battery performance, cost and life affect directly the life and performance of the EVs. Therefore, the need to extend the battery lifetime and to use it at their full capacity is of the most importance.

Thermal management of batteries is critical in achieving the desired performance in a low-temperature environment and the desired life in a high-temperature environment. The heat generated

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Abbreviations: Act, Actual; BC, Boundary conditions; BTMS, Battery thermal management system; C, Discharge rate; DOD, Depth of discharge; EV, Electric vehicle; FEM, Finite element model; LFP, Lithium phosphate; LPM, Lumped parameter model; LPV, Linear parameter varying; MSE, Mean square error; HEV, Hybrid electric vehicle; R, Regression; Sim, Simulation; PDE, Partial differential equation; SLE, Special limits of error.

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inside a battery must be dissipated to improve reliability and prevent failure [5]. Lithium-ion batteries degrade rapidly at high temperatures, while cold temperatures reduce power and energy output, thus limiting their driving range or performance capabilities [6,7]. A thermal management system is necessary in transportation applications in order to regulate the batteries to operate in the desired temperature range; and to reduce uneven temperature distribution [5]. In a battery pack, uneven temperature distribution could lead to electrically unbalanced modules which lower the performance of the pack and vehicle [8].

Many cooling systems, especially active ones, require heat to be rejected outside the vehicle, which in turn requires an additional flow ducting and a heat exchanger. Vehicles have limited physical space available and packaging can become an issue. Some air cooling techniques, such as those in the Toyota Prius, pass cooled cabin air (cooled by the vehicle's air conditioner) through the battery pack. In liquid or fin cooling systems, a secondary refrigeration loop to reject the heat may be needed [5]. The main advantage of air cooling systems is their simplicity over liquid coolant systems. Another advantage is electrical safety. However, air cooling systems have a lower heat transfer coefficient, making it more difficult to achieve a uniform temperature on the pack. Liquid cooling systems, on the other hand, are more effective and occupy less volume, but have higher complexities, weight, and cost.

Active thermal management methods utilize forced fluid convection to absorb heat from individual batteries or subgroups of batteries within a pack. Karimi and Dehghan [9] evaluated thermal management using both air and liquid cooling. A pack, consisting of twenty-prismatic LiCoO2-20 Ah batteries, was modeled with a battery thermal model based on 1) ohmic heating and, 2) reaction entropy changes alone. A flow network model was used to determine the effect of several coolant flows on the final temperature distribution of a pack undergoing constant current discharge. Air and silicon oil were chosen as a cooling medium in a battery pack. Thus, an efficient of battery thermal management system (BTMS) is important for ideal performance in high temperature and high discharge application in order to keep the average battery system temperature in the range of 20 °C–45 °C [10] and the optimum temperature is 45 °C in lithium-ion polymer which operates in a range of –30 °C to 60 °C [11].

As discussed in the first paragraph, due to their high energy density, high voltage, good stability and slow loss of charge when unused, lithium-ion polymer batteries are quickly becoming the most advanced battery technologies for the next generation of EVs and HEVs. Also, these cells are very good for the high rate-of-discharge applications such as acceleration of EVs. Despite these positive aspects, which justify the recent spread of this technology, it is important to notice that during operation, lithium-ion polymer batteries must be carefully monitored and managed (electrically and thermally) to avoid problems related to safety (flammability) and performance [12].

The main parameter, the temperature, has also an important influence on the battery which can affect both the time life and energy of the battery, and automotive drive-ability and fuel economy. For these reasons the battery temperature should be within a temperature range which is considered optimum to achieve good performance and long life, for both use and storage. This temperature range differs between technologies and manufacturer.

Various literature studies are available for thermal modeling of battery, using different approaches like Finite element model (FEM) [13] or lumped parameter model (LPM) [14], Linear Parameter Varying (LPV) model [15], or partial differential equation (PDE) model [16]. In most of the above mentioned models, a thermal model is coupled with an electrochemical model which simulates the battery temperature profile with various operating conditions, cooling rate or geometries. In this paper, the neural network approach is used for the modeling. Neural networks [17] can be used to model the complex relation between the input and output data using a relatively simple construction and algorithm. Neural networks have relatively high tolerance limit to noisy data and they have the ability to discern a pattern even for the data that have not been used to train the model initially, this is one of the main advantages of using neural networks [17,18]. The correctness of the model output function depends extensively on the goodness of the input data being fed into the model; this is one of the essential characteristics of neural networks.

2. Experimental apparatus and procedure

A 20 Ah capacity lithium-ion battery was selected for this work and discharge rates were 2C (40 amp) and 4C (80 amp). The charge/discharge test bench was modified and used for battery charging and discharging and thermal data collection. A picture of the hybrid test bench for the thermal management is shown in Fig. 1. These major components are described in detail subsequently.

The MotoTron controller interfaces via RS232 communication to the test stand computer-1. The test stand computer-1 is used for the Lab View program (measurements of battery voltage, current, charge-discharge cycle, cycle number, and time) which records values at one second intervals. The test stand computer-2 is used for the Keithley-2700 (Data Acquisition) program (measurements of battery surface temperature, heat flux, and water inlet and outlet temperature for top and bottom cold plates). The low voltage supply and the load were Lambda ZUP20-40-800 and TDI Dynaload RBL323-50-150.

A set of commercially available battery module cooling plates was selected to remove the heat from the battery cell or pack. The cooling plates were the manufactured ones from two stamped aluminum plates which are joined in a nickel-brazing process and are shown in water cooling set-up in Fig. 2a. This "zig-zag turn" type cold plate is characterized as having single flow channel with one inlet and one outlet. The single flow channel ran down the length of the plate before turning back on itself, stepping one channel width across the plate with each turn. This flow pattern results in a thermal profile where the coolant temperature gradient is largest across the width of the plate. One cold plate is at the top of the pouch cell and the other cold plate at the bottom of the pouch cell. A lithium-ion battery is insulated from three sides (left, right, and bottom of the pouch cell along the height of the pouch cell) using polystyrene insulation to prevent heat loss from the pouch cell to the surrounding environment.

3. Analysis

3.1. Temperature measurements/thermocouple locations

The thermocouples were installed on the principal surface of the battery to measure temperatures at ten discrete points. Out of ten thermocouples, as shown in Fig. 2b, three were placed near electrodes, three were placed at the center of the battery, and two were placed between the top and the middle of the battery, and two were placed between the center and the bottom of the battery. T-type 30 gauge, special limits of error (SLE) thermocouple wire with uncertainty of 1 °C (according to manufacturer's specifications) was used and the location of T-type thermocouples is shown in Fig. 2b. Kapton backed adhesive tape was used to adhere the thermocouples to the battery surface. Lastly, four additional thermocouples were used to measure the temperature of the water inlet and outlet at the top and bottom cold plates.

A standard method of determining the average temperature across the entire battery surface was devised to enable sensible heat calculations. For each thermocouple, it is assumed that the