International Communications in Heat and Mass Transfer 71 (2016) 35–43

Contents lists available at ScienceDirect

International Communications in Heat and Mass Transfer

journal homepage: www.elsevier.com/locate/ichmt

Experimental temperature distributions in a prismatic lithium-ion battery at varying conditions☆

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ARTICLE INFO

Available online 17 December 2015

Keywords:
Lithium-ion battery
Electric vehicle
Heat generation
Temperature contour
Thermal management system

ABSTRACT

In this paper, temperature contours are presented for a prismatic lithium-ion battery at 1C, 2C, 3C, and 4C discharge rates and different boundary conditions (cooling/operating/bath temperature) of 5 °C, 15 °C, 25 °C, and 35 °C. The active (water cooling) cooling system is designed and developed based on a prismatic lithium-ion battery using dual cold plates. The battery discharges at constant current rates of 20 Amp, 40 Amp, 60 Amp, and 80 Amp, and the experimental temperature contours are then plotted between the beginning and end of discharge cycle. The results show that a higher temperature distribution is observed over the entire surface of the battery for 4C at 35 °C and a lower temperature distribution is noted for 1C at 5 °C. Furthermore, it is observed that increased discharge rates between 1C and 4C and increased boundary conditions (BCs) between 5 °C and 35 °C result in increased temperature contour of the battery.

1. Introduction

Electric vehicles (EVs), hybrid electric vehicles (HEVs) and plug-in hybrid electric vehicles (PHEVs) are gaining more importance due to increasing gas prices and pollution levels [1,2]. In Canada and in the United States, one of the largest sources of greenhouse gases (GHG) is road transportation. These contributes significantly to urban air quality problems [3], and therefore, the need to lower the vehicle emissions along with the decreasing oil resources is forcing the automotive industry to find pure EVs in order to solve these demands globally [4]. EVs, HEVs, and PHEVs depend on energy storage [5] and improving their lifetime will reduce the runtime and the costs for the vehicle. These technologies have primarily shifted towards lithium-ion batteries for energy storage because the lithium-ion battery is the most advanced battery [6].

Lithium-ion battery is widely used rechargeable energy storage systems for EVs, HEVs, and PHEVs today due to the following: (1) high specific energy and power densities [7,–8] and (2) high nominal voltage and low self-discharge rate for EVs, HEVs, and PHEVs [6]. Apart from automobile, laptops, cell phone or mobiles, toys, and many other consumer products use lithium-ion batteries as the main or secondary power source [9–11]. The precautions during charging and discharging must be taken for these batteries. Exceeding voltage, current, or power limits may result in the battery cell damage. The possibility of thermal runaways also occurs if the care is not taken [12,13]. In addition, lithium-ion polymer batteries must be carefully monitored and managed (electrically and thermally) to avoid safety (inflammability) and performance issues [14–16].

A lithium-ion battery cell consists of two electrodes, anode and cathode, with a separator in between, and current collectors on each side of the electrodes. The cathode is made of a composite material and defines the name of the lithium-ion battery cell [17]. The anode is usually made out of graphite or a metal oxide. The electrolyte can be liquid, polymer, or solid. Several common configurations are available for lithium-ion battery construction. The two prominent types are cylindrical and prismatic. Generally, cylindrical cells designs are limited to below 4 Ah, and prismatic designs are used for higher capacity ratings [18]. Stacked prismatic batteries consist of many individual cells with electrical connections to a common positive and negative current tab [19]. Alternating sheets of positive and negative electrode current collector sheets are stacked between sheets of separator in such a way that the current tab of each positive sheet and each negative sheet are aligned on opposite sides. Both sides of the electrode sheets form electrochemical cells with adjacent electrodes across the separator layers. The current tabs present at the top of each current collector sheets are joined together and attached to a larger output tab that extends to the exterior of the pouch [19].

☆ Communicated by W.J. Minkowycz

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http://dx.doi.org/10.1016/j.icheatmasstransfer.2015.12.004
0735-1933/

Nomenclature

A	area [m^2]
l	lenght [mm]
P	individual component of the surface temperature average
T	Temperature [°C or K]
t	Time [s]
w	width [mm]

Subscripts

avg	average
i	layer index
tot	total
x,y,z	Cartesian coordinates

Acronyms and abbreviations

Act	actual
BC	boundary conditions
BTMS	battery thermal management system
C	discharge rate
CAD	computer-aided design
EV	electric vehicle
EOD	end of discharge
GM	general motor
HEV	hybrid electric vehicle
LFP	lithium phosphate
MOD	middle of discharge
PHEV	plug-in hybrid electric vehicle
SOD	start of discharge
SLE	special limits of error
3-D	three dimensional

Temperature, one of the most important parameter for a battery, can affect both the lifetime and energy of the battery. The battery temperature should be within a temperature range that is considered optimum for the better performance and long life, for both use and storage [20,21]. This temperature range differs between technologies and manufacturers. Therefore, thermal management of batteries is required. However, it is a challenging task in achieving the desired performance in a both the low-temperature and the high-temperature environment. The heat generated inside a battery must be dissipated to improve reliability and prevent failure [22]. At higher temperature ranges, lithium-ion batteries degrade rapidly, while the power and energy output are reduced at cold temperature ranges, thereby limiting the driving range and/or performance capabilities [23,24].

There are two basic types of cooling a system: (1) air cooling and (2) liquid cooling. The main advantage of air cooling systems is their simplicity over liquid coolant systems. Also, there is no direct contact of water with battery and this is considered as the advantage. However, air cooling systems have a lower heat transfer coefficient, making them more difficult to achieve a uniform temperature on the pack. On the other hand, liquid cooling systems are more effective and occupy less volume but have higher complexities, cost, and weight. A battery thermal management system (BTMS) is important for effective performance of battery packs in high-temperature and high-discharge applications in order to keep the average battery system temperature in the range of 20 °C to 45 °C [25]. The lithium-ion polymer battery operates in a range of -30 °C to 60 °C [26].

Given the problems of (1) battery performance, (2) aging or degradation of batteries, and (3) fire issues due to high battery operating temperature, there is strong need to study the thermal behavior of vehicle batteries and assess the performance of EV, HEV, and PHEV batteries undergoing realistic vehicle charge and discharge cycles. To date, a lot of work has been done on battery modeling but limited published experimental studies with varying boundary conditions exists. This has been the main motivation behind this experimental investigation which aims to study the temperature variations in a prismatic lithium-ion battery at varying conditions and evaluate the thermal behavior for each case under different discharge rates of 1C, 2C, 3C, and 4C and various boundary conditions of 5 °C, 15 °C, 25 °C, and 35 °C.

2. Experimental apparatus and procedure

The experimental setup used for thermal characterization of the battery is shown in Fig. 1(a). The components shown on the left side of the picture make up the battery cycling equipment, whereas the components displayed on the right side of the picture comprise the thermal data collection and battery cooling system. The compression apparatus is used to contain and insulate the battery while testing is underway with cold plates. The major components are described in detail in the following sections.

The test stand computer-1 manages a Lab view program (for measurement of charge current, discharge current, number of cycles, maximum voltage at end of charge, and minimum voltage at end of discharge), which records values at one second intervals, and the test stand computer-2 manages the Keithley data acquisition system (for thermal data collection like battery surface temperature 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. The MotoTron controller interfaces via RS232 communication to the test stand computer-1. The battery and cold plate setup is shown in Fig. 1(b) and in Fig. 1(c).

For the active cooling setup, two cooling plates were used: one cold plate was placed at the top of the lithium-ion battery and the other cold plate is placed at the bottom. This type of a cold plate is characterized as having multiple flow channels with nine inlets and nine outlets. The coolant flow paths are symmetrical down the center of the plate such that the flow channels were mirrored about the centerline. The lithium-ion battery was insulated from three sides to prevent heat loss from the battery to the surrounding. The CAD of different views (3-D view, front view, and side view) is shown in Fig. 2. The battery cooling system consisted of a closed loop of tubing connecting two cooling plates to a water bath. Sensors were placed along the flow path to record properties of the fluid. The mass flow rate of water to the upper and a lower cold plate was maintained constant during the experimental work.

A prismatic lithium-ion battery used in GM Chevy Volt (Chevrolet Volt) was selected for this work. It was chosen because it is suitable as a basic block for a large battery pack foreseen for commercial automotive vehicle applications. The prismatic battery has following specifications according to the manufacturer's data sheet: (i) a nominal capacity of 20 Ah, (ii) $LiFePO_4$ as cathode material (known as LFP), (iii) graphite as anode material, (iv) a nominal voltage of 3.3 V, (v) a mass of 496 g, (vi) an internal resistance of 0.5 mΩ, (vii) dimensions of 7.25 mm × 160 mm × 227 mm (as thickness × width × height), and (viii) operating temperature range of −30 °C to 55 °C. For the experimental work, the flow rate was 150 mL/min for both top and bottom cold plates.

2.1. Temperature measurements

For the measurement of battery surface temperature, ten thermocouples were placed on the principal surface of the battery. The locations of these thermocouples are shown in Fig. 3(a). These thermocouples are