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Experimental and theoretical investigation of temperature distributions in a prismatic lithium-ion battery

S. Panchal [a,*], I. Dincer [a], M. Agelin-Chaab [a], R. Fraser [b], M. Fowler [c]

[a] *Department of Automotive, Mechanical & Manufacturing Engineering, Faculty of Engineering & Applied Science, 2000 Simcoe Street North, Oshawa, Ontario, L1H 7K4, Canada*
[b] *Mechanical and Mechatronic Engineering Department, University of Waterloo, 200 University Avenue West, Waterloo, Ontario, N2L 3G1, Canada*
[c] *Chemical Engineering Department, University of Waterloo, 200 University Avenue West, Waterloo, Ontario, N2L 3G1, Canada*

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A B S T R A C T

This paper deals with the surface temperature distributions on the principal surface of the battery at 1C and 3C discharge rates and different boundary conditions (cooling/operating/bath temperature) of 5 °C, 15 °C, 25 °C, and 35 °C. The air cooling and water cooling system is designed and developed based on a prismatic Lithium-ion that has 20 Ah capacity. In addition, the battery thermal model is developed which represents the main thermal phenomena in the battery cell in terms of temperature distribution. The developed model is validated with the experimental data collected including temperature and discharge voltage profile. The results show that the average surface temperature distribution is higher at 3C discharge rate and 35 °C boundary conditions (BCs) and the average surface temperature distribution is lower 1C discharge rate and 5 °C BCs. Furthermore, it is observed that increased discharge rates and increased operating conditions or BCs result in increased surface temperature distributions of the battery.

1. Introduction

Electric Vehicles (EVs) and Hybrid Electric Vehicles' (HEVs) are gaining more importance due to increasing gas prices and pollution levels [1,2]. It is also said that, one of the largest sources of greenhouse gases (GHG) in North America is road transportation, which 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 and HEVs depend on the type of batteries [5] and improving their life-time 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 today in Automobile industry because it possesses high specific energy and power densities, high nominal voltage and low self-discharge rate for EVs and HEVs [6]. Apart from Automobile, laptops, cell phone or mobiles, toys, as well as many other consumer products use Lithium-ion batteries as the main or secondary power source [7–10]. But the drawback of Lithium-ion battery is that precautions during charging and discharging must be taken. Exceeding voltage, current or power limits may be resulted in the battery cell damage. There is a possibility of thermal runaways [11,12]. Also, Lithium-ion polymer batteries must be carefully monitored and managed (electrically and thermally) to avoid safety (inflammability) and performance issues [13].

Temperature is also one of the most important parameter for battery, which can affect both the time life and energy of the battery. The battery temperature should be within a temperature range which is considered optimum for the better performance and long life, for both use and storage. This temperature range differs between technologies and manufacturer. Therefore, thermal management of batteries is required [14]. However, it is a challenging task and critical in achieving the desired performance in a low-temperature environment and the desired life in the high-temperature environment. The heat generated inside a battery must be dissipated to improve reliability and prevent failure [15]. Lithium-ion batteries degrade rapidly at higher temperature ranges, while the power and energy output are reduced at cold temperature ranges, thereby limiting the driving range and/or performance capabilities [16,17].

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

* Corresponding author. Tel.: +1 519 722 4420.
E-mail address: Satyam.panchal@uoit.ca (S. Panchal).

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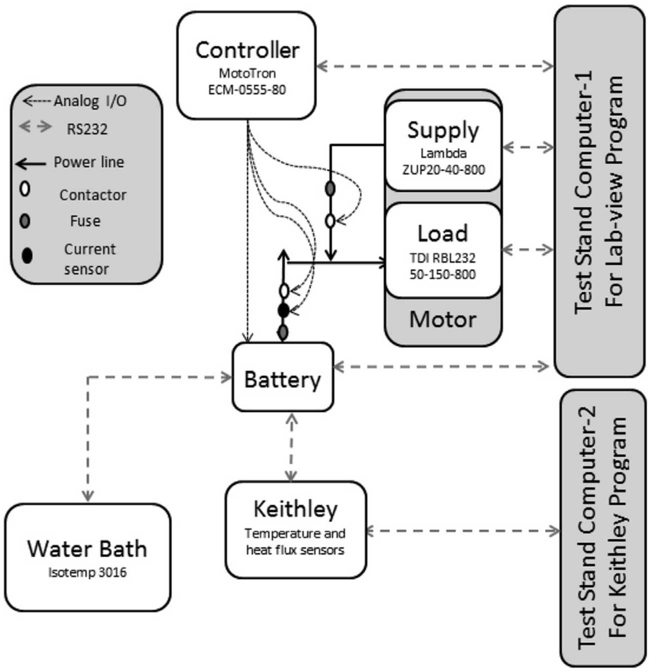

Fig. 1. Schematic of experimental set-up.

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. A battery thermal management system (BTMS) is important for ideal 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–45 °C [18] and the optimum temperature is 45 °C in lithium-ion polymer operates in a range of −30 °C to 60 °C [19].

For the battery thermal modeling numerous papers are available, using different approaches like finite element model (FEM) [20] or lumped parameter model (LPM) [21], linear parameter varying (LPV) model [22], or partial differential equation (PDE) model [23]. 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.

Table 1
Positions of thermocouple locations.

	Thermocouple locations	X (mm)	Y (mm)
1	1,1	26.5	194
2	1,2	78.5	194
3	1,3	130.5	194
4	2,1	26.5	169
5	2,2	130.5	169
6	3,1	26.5	130
7	3,2	78.5	130
8	3,3	130.5	130
9	4,1	78.5	70
10	5,1	78.5	35

2. Experimental apparatus and procedure

The schematic of the experimental set-up used for thermal characterization of the battery is shown in Fig. 1. The components shown on the upper half of the schematic make up the battery cycling equipment. Whereas the components displayed on the lower half of the schematic 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 selected discharge rates were 1C (20 Amp) and 3C (60 Amp). These major components are described in detail in the following sections.

The test stand computer-1 manages a Lab-view program which record values at 1 s intervals and the test stand computer-2 manages the Keithley-2700 data acquisition system (for thermal measurements). 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 air cooling setup is shown in Fig. 2 (a) while the water cooling setup is illustrated in Fig. 2 (b), and the computer-

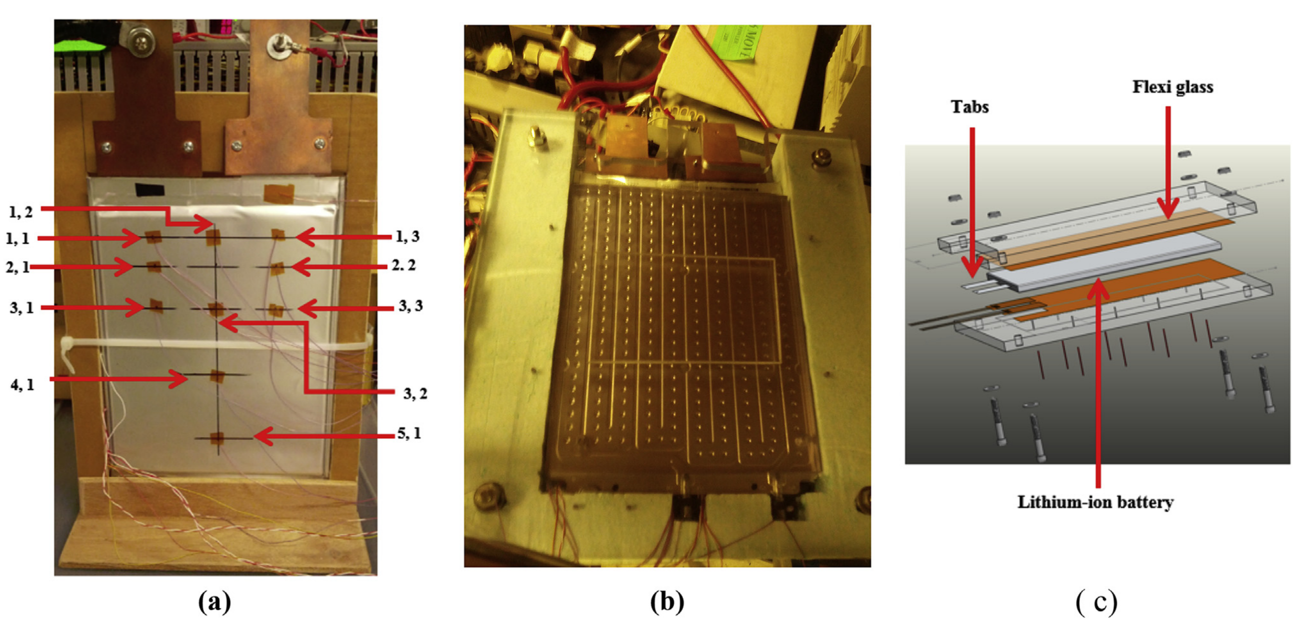

Fig. 2. (a) air cooling; (b) water cooling; and (c) CAD of battery cooling set-up.