

Thermal Management of Lithium-Ion Pouch Cell with Indirect Liquid Cooling using Dual Cold Plates Approach

Satyam Panchal, Scott Mathewson, Roydon Fraser, Richard Culham, and Michael Fowler
University of Waterloo

ABSTRACT

The performance, life cycle cost, and safety of electric and hybrid electric vehicles (EVs and HEVs) depend strongly on their energy storage system. Advanced batteries such as lithium-ion (Li-ion) polymer batteries are quite viable options for storing energy in EVs and HEVs. In addition, thermal management is essential for achieving the desired performance and life cycle from a particular battery. Therefore, to design a thermal management system, a designer must study the thermal characteristics of batteries. The thermal characteristics that are needed include the surface temperature distribution, heat flux, and the heat generation from batteries under various charge/discharge profiles. Therefore, in the first part of the research, surface temperature distribution from a lithium-ion pouch cell (20Ah capacity) is studied under different discharge rates of 1C, 2C, 3C, and 4C. In the second part of the research, the total heat generation from a particular battery is obtained under different discharge rates (1C, 2C, 3C, and 4C) and different boundary conditions (cooling bath temperature of 5°C, 15°C, 25°C, and 35°C). In the third part of the research, the heat flux profile is studied at three different locations on the top surface of the pouch cell (first, near the cathode; second, near the anode; and third, at the center of the cell along the height of the cell) using heat flux sensors. In the fourth part of the research, thermal images from a lithium-ion pouch cell are obtained at different discharge rates to qualitatively evaluate the thermal behaviour and temperature distribution. A "FLIR System" Therma CAM model S60 IR camera is used to obtain thermal images.

KEYWORDS: Lithium-ion Battery, Thermal Management, EVs and HEVs, Heat Generation, Thermal Characteristics, Thermal Image

CITATION: Panchal, S., Mathewson, S., Fraser, R., Culham, R. et al., "Thermal Management of Lithium-Ion Pouch Cell with Indirect Liquid Cooling using Dual Cold Plates Approach," *SAE Int. J. Alt. Power*, 4(2):2015, doi:10.4271/2015-01-1184.

INTRODUCTION

Climate change is the number one threat facing species and habitats today. Curbing climate change means drastically reducing greenhouse gas emissions (GHG). One of the largest sources of GHG in Canada is road transportation, which significantly contributes to urban air quality problems [1]. According to Natural Resources Canada, in 2009, the number of vehicles on Canadian roads increased by 1.7% compared to 2008. Moreover in 2007, there were around 20 million vehicles on Canadian roads, up nearly 2.5 million since 2000. Out of these, 19 million (96.4%) vehicles were light duty, 2% were medium trucks, and 1.7% were heavy trucks. These vehicles travelled some 332 billion kilometers consuming 31 billion litres of gasoline and 11 billion litres of diesel [2]. Canadian GHG emissions can be lowered by replacing gasoline usage with the adoption of alternative fuels, and urban air quality can also be increased. Therefore, demand for electric and hybrid electric vehicles (EVs and HEVs) has increased significantly due to rising costs and environmental concerns [3]. The burning of fossil fuels for gasoline has decreased the number of trees in the world and has also affected the overall air quality for all living and non-living creatures on this planet. In addition, the price of oil

and gasoline has been steadily rising over the decades, making hybrid and electric vehicles a cheaper and more efficient option [3]. Due to environmental benefits and rising oil prices, major automobile manufacturers have spent millions of dollars on the research and development of EVs and HEVs which are becoming more and more environmentally friendly by protecting the eco-system.

Batteries, a major powertrain component of EVs and HEVs, will undergo thousands of cycles during the life-time of a vehicle. Over this lifetime, a battery degrades potentially to the point of requiring replacement. Given the high cost of the battery and its importance in determining electric vehicle range, it is very desirable to postpone battery degradation as long as possible. One element of controlling battery degradation is controlling battery temperature [4, 5]. Understanding vehicle battery temperatures, heat generations, and heat flux profiles during discharge is the focus of this research.

LITHIUM-ION CELL OPERATION

A Li-ion battery cell consists of two electrodes, the anode and the 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 Li-ion battery cell. The anode is usually made out of graphite or a metal oxide. The electrolyte can be liquid, polymer or solid. The separator is porous to enable the transport of lithium ions and prevents the cell from short circuiting and thermal runaway [6].

During discharge the lithium ions diffuse from the anode to the cathode through the electrolyte. The lithium ions will intercalate (Intercalation refers to a reversible chemical process of binding a molecule between other molecules. Deintercalation is the reversible process;) into the cathode, causing the cathode to become more positive. Due to the potential difference between the cathode and the anode, an electric current will flow through the external circuit, supplying power to the load. During charging, the opposite effect occurs. The current will cause the lithium ions to deintercalate from the cathode and diffuse to the anode. At the anode, intercalation of the lithium ions occurs, charging the battery. These processes are shown in Figure 1.

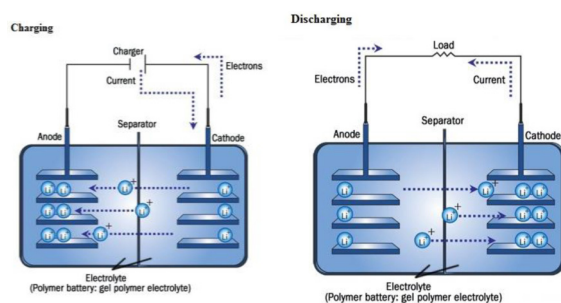


Figure 1. Charge and discharge mechanism in Li-ion battery [7]

HEAT GENERATION & THERMAL RUNAWAY

Heat is generated in a battery cell by (1) ohmic heating (or Joule's effect) caused by current transfer across internal resistances and over potential; (2) entropy change from electrochemical reactions (i.e., reversible endothermic/exothermic part of reaction). For some electrochemical pairs, another electrical energy loss (and thus heat generation) could result from overcharging a fully charged cell.

The heat generation rate in a cell can be calculated from Equation (1) [8,9,10]

$$\dot{Q} = I(E - V) - I \left[T \left(\frac{dE}{dT} \right) \right] \quad (1)$$

The first term in Equation (1), " $I(E - V)$ " is heat generation due to internal resistance (irreversible heat dissipation) and the second term " $-I[T(dE/dT)]$ " is known as reversible heat resulting from changes in open circuit potentials with respect to the temperature at the two electrodes. At practical EV and HEV rates, the second term is usually

small compared to the first term. Hence, the heat is generated and released from the cell during both charge and discharge [9]. Thermal runaway can occur if this heat is not removed properly, as elevated temperatures trigger additional heat generating exothermic reactions [11]. These reactions then further increase battery temperature, creating a positive feedback mechanism that causes battery temperature to climb sharply if heat is not well dissipated. As a result, thermal runaway can occur that results in complete cell failure accompanied by fire or explosive gas release. Furthermore, even if thermal runaway does not occur, significant degradation of battery capacity can occur by consistently operating at an elevated temperature ($>50^\circ\text{C}$) [12].

Current collectors create additional Ohmic heating due to the high current densities that occur in planar prismatic type batteries. In another work, Equation (2) was developed to include two added terms that account for the heat generated in the current collector tabs [13].

$$\dot{Q} = I \left(E - V - T \left(\frac{dE}{dT} \right) \right) + A_p R_p I_p^2 + A_n R_n I_n^2 \quad (2)$$

As heat is generated in the cell during both charge and discharge, the need for adequate cooling arises. The temperature of the cell will continue to increase without adequate processes to remove heat. The heat generation of cell stacks and the collection of stacks into a pack lead to a need for battery pack thermal management. Researchers have achieved thermal control with air or liquid systems, insulation, thermal storage (phase-change material), active or passive approaches, or a combination [14].

EXPERIMENTAL SET UP

A hybrid test stand was designed and modified for this work. Figure 2 shows the modified hybrid test stand used for thermal management. It was modified so that fuel cell components were not connected to the power bus. This enabled the test stand to behave in full EV mode, where only batteries are charged and discharged using the electrical distribution grid of the lab. To allow for significant flexibility, high and low voltage supplies and loads were integrated. The low-voltage supply and load were Lambda ZUP20-40-800 and TDI Dynaload RBL232 50-150-800, respectively. The voltage, current and temperature of the cell are monitored by a MotoTron controller (CTRLPCM00200) which is shown in Figure 2. The MotoTron controller interfaces via RS232 communication to the test stand computer-1. The test stand computer-1 manages a Lab-view program (measurements of battery voltage, current, charge-discharge cycle, cycle number, and time) which records values at one second intervals and the test stand computer-2 manages 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).

There are two E-stop (Emergency shutdown) buttons in the test stand. One is near the MotoTron controller and the other one is near the cell housing and can be easily seen in Figure 2. The E-stop circuit controls the 12V supply to the normally-open contactors, thereby acting in series with the MotoTron control circuit that usually controls the ground path of the contactor control circuit. The E-stop circuit was integrated in the system that caused an immediate opening of the contactors on the power lines in the event that one of two E-stop buttons was hit.

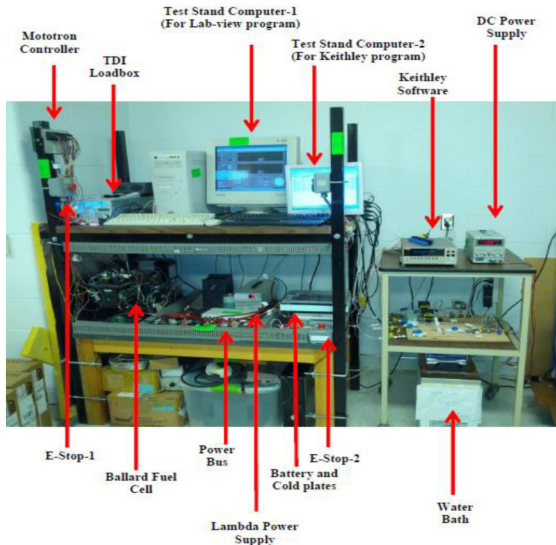


Figure 2. Picture of modified hybrid test bench for thermal management

A set of commercially available battery module cooling plates were selected to remove heat from the battery. The cooling plates were manufactured from two stamped aluminum plates that are joined in a nickel-brazing process. The cooling plate design used is shown in Figure 3. This was named as the “U-turn” cold plate. This plate was characterized as having multiple flow channels with inlets and outlets (9-inlets and 9-outlets) placed on the edges of the plate, near the bottom of the battery. The coolant flow paths are symmetrical down the centre of the plate such that the flow channels were mirrored about the centreline. One cold plate is at the top of the pouch cell and the other cold plate at the bottom of the pouch cell. A Li-ion pouch cell 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.

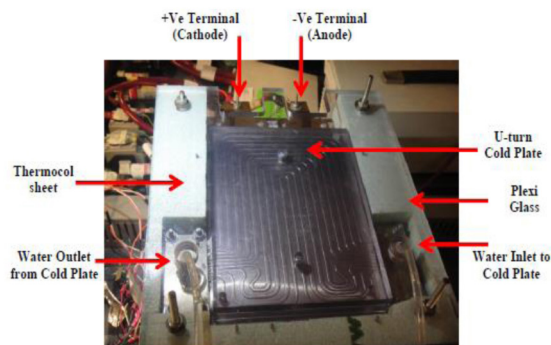


Figure 3. U-turn cold plate set up (Active cooling)

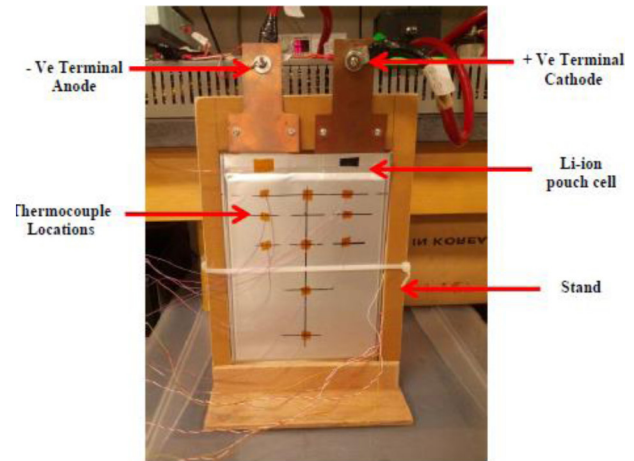


Figure 4. Passive air cooling set-up

Thermocouple Locations

Thermocouples were installed on the principal surface of the battery to measure temperatures at ten discrete points. T-type 30 gauge, special limits of error (SLE) thermocouple wire were used on one side, and three additional K-type thermocouples integral to the heat flux arrays were present on the alternate side. The K-type thermocouple locations are discussed in the next section. The location of T-type thermocouples is shown in Figure 5 and listed in Table 1. Kapton backed adhesive tape was used to adhere the thermocouples to the battery surface.

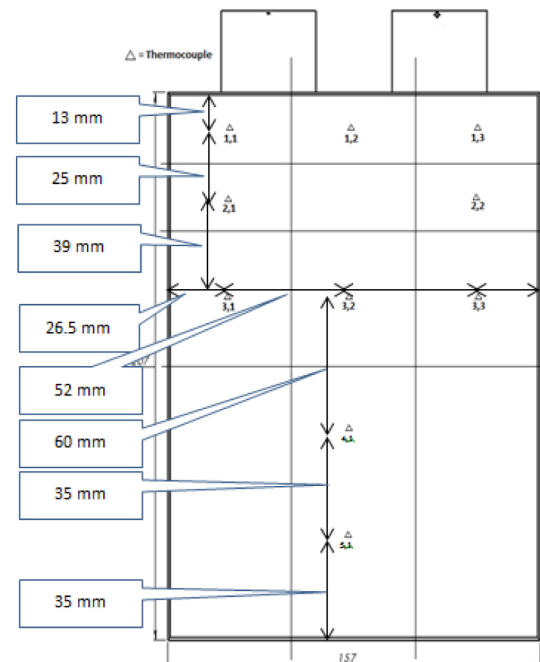


Figure 5. Thermocouples locations on top surface of the cell

Table 1. Distance of thermocouple locations from bottom left corner of the cell surface

Thermocouple	X (mm)	Y (mm)
1,1	26.5	194
1,2	78.5	194
1,3	130.5	194
2,1	26.5	169
2,2	130.5	169
3,1	26.5	130
3,2	78.5	130
3,3	130.5	130
4,1	78.5	70
5,1	78.5	35

Heat Flux Sensors Locations

Three thin-film heat flux sensors were installed on the surface opposite to the locations of the thermocouples. The locations of these three sensors are shown in Figure 6, and the x and y coordinates of HFA centre points are given in Table 2. These sensors function as a self-generating thermopile transducer. They require no special wiring, reference junctions or signal conditioning. The HFS utilizes a multi-junction thermopile construction on a polyimide film laminate. The output of the sensors provides an average measurement of surface heat flux in a 25.4×25.4 mm area (1 inch²).

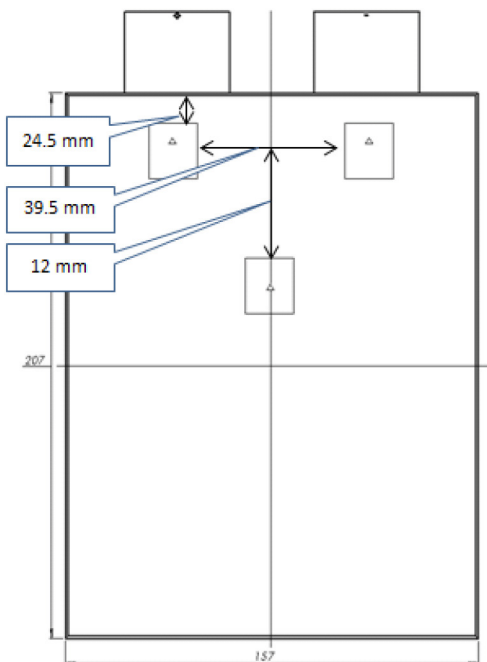


Figure 6. Heat flux sensors locations

Table 2. Locations of heat flux sensor center-points distance from bottom left corner of the cell surface

Heat Flux Sensor	Location	X [mm]	Y [mm]
1	(+) Electrode	104.7	169.8
2	(-) Electrode	52.3	169.8
3	Mid-surface	78.5	122.7

Compression Rig

A special isolating rig was created for tests that include active cooling using the battery cooling. The rig was created to isolate the cell from the ambient thermal environment and maintain compression of the cooling plate/battery surface interface. An exploded assembly of the isolating rig without insulation is shown in Figure 7.

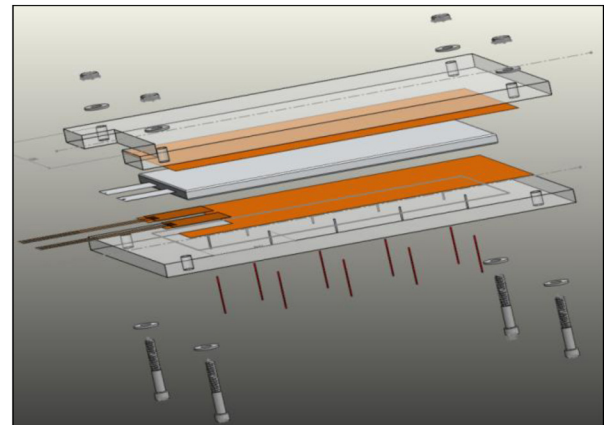


Figure 7. Exploded view of test rig

The rig is comprised of two transparent 12.7 mm thick polycarbonate sheets with the battery and cooling plates sandwiched between the two plates. A hole is present in each corner to allow a threaded bolt to pass through. By tightening down the bolt fasteners, the battery is confined to the assembly by pressure. Spacers were constructed using 9.5 mm thick polycarbonate with dimensions equal to the battery dimensions. These spacers were required to change the distance between the cooling plate and the outer polycarbonate plate so that the inlet, outlet and tubing would fit.

DATA ANALYSIS METHOD

The data produced in the heat generation and cooling requirements experiment consists of electrical data (battery voltage, and current flow) as well as thermal data: surface temperature data (13 channels), heat flux meter output voltages (3 channels), and inlet/outlet cooling system temperatures (4 channels). MATLAB software was used to manipulate the large spread sheets of data. The following energy balance equation was used to determine the actual heat output of the battery.

$$Q_{Total} = Q_{stored} + Q_{removed} + Q_{environment}^{(3)}$$

Sensible Heat (Q_{stored})

Equation (4) is used to evaluate the sensible heat energy stored in the battery when the battery temperature changes from an initial temperature to a final temperature.

$$Q_{\text{sensible}} = m_{\text{battery}} c_{p,\text{battery}} (T_{t_2} - T_{t_1}) \quad (4)$$

A standard method of determining the average temperature across the entire battery surface has been devised to enable sensible heat calculations. For each thermocouple, it is assumed that the measured temperature represents the average of an area extending around the sensor. The areas are determined by defining each area boundary by calculating the x and y midpoint distance between adjacent sensors. Equation (5) is used to evaluate the average battery surface temperature by summing the temperature-area products and dividing by the total area of the surface.

$$T_{\text{surface average}} = \frac{\sum (T_{ij} A_{ij})}{A_{\text{total}}} \quad (5)$$

The ten thermocouples measuring the surface temperatures shown in Figure 5 are each assigned the areas that correspond to their locations as shown in Figure 8. The physical size of the thermocouple areas is presented in Table 3. The rate of sensible heat accumulation is directly influenced by the battery heat generation rate and the heat transfer coefficient out of the system. The temperature of the battery increases as heat is generated due to the finite heat transfer coefficient to the surrounding. The rate of sensible heat accumulation is determined from the rate of change of Equation (6), where dT/dt is the rate of temperature change in the battery.

$$\dot{Q}_{\text{sensible}} = m_{\text{battery}} c_{p,\text{battery}} \frac{dT}{dt} \quad (6)$$

The rate of temperature change is evaluated by measuring the temperature over a time interval and calculating the rate using Equation (7).

$$\frac{dT}{dt} = \frac{(T_{t_2} - T_{t_1})}{t_2 - t_1} \quad (7)$$

The rate of sensible heat accumulation can then be determined via Equation (8).

$$\dot{Q}_{\text{sensible}} = m_{\text{battery}} c_{p,\text{battery}} \frac{(T_{t_2} - T_{t_1})}{t_2 - t_1} \quad (8)$$

Table 3. X and Y component lengths of thermocouple areas

Thermocouple	Area	X [mm]	Y [mm]	Area [m ²] (x10 ⁻³)
1,1	A _{1,1}	52.5	25.5	1.34
1,2	A _{1,2}	52	25.5	1.33
1,3	A _{1,3}	52.5	25.5	1.34
2,1	A _{2,1}	78.5	32	2.51
2,2	A _{2,2}	78.5	32	2.51
3,1	A _{3,1}	52.5	49.5	2.60
3,2	A _{3,2}	52	49.5	2.57
3,3	A _{3,3}	52.5	49.5	2.60
4,1	A _{4,1}	157	47.5	7.46
5,1	A _{5,1}	157	52.5	8.24

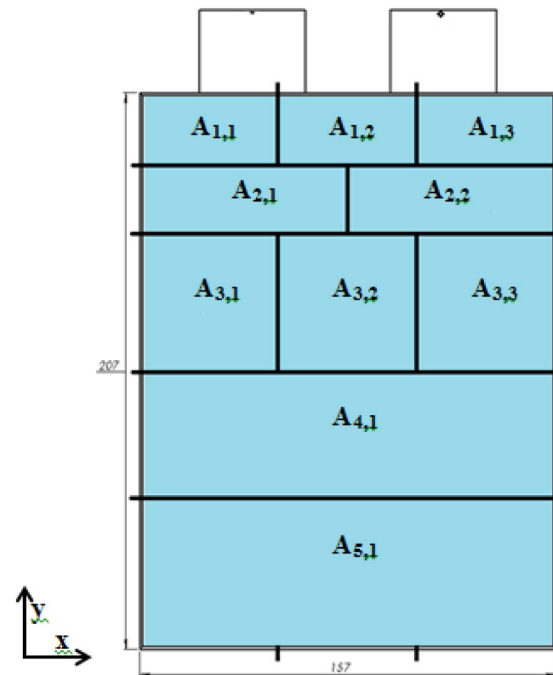


Figure 8. Distribution of areas used to determine average surface temperature

Heat Removed from Battery (Q_{removed})

A fraction of the heat generated by the battery is removed by cooling processes. In one series of testing, the operating battery was placed in a vertical position and ambient air carried heat away by natural convection. In other tests, cooling plates were present that utilized forced coolant flow to remove heat.

Air Cooling

For a fluid at known temperature contacting a surface of known area, heat is transferred via convection and observes Newton's law of cooling.

$$Q_{\text{convection}} = h_c A (T_{\text{surface}} - T_{\infty}) \quad (9)$$