Thermal Characterization of Advanced Lithium-Ion Polymer Cells

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ABSTRACT

Compact Power Incorporated (CPI) and LG Chem have been developing high-power lithium-ion (Li-Ion) polymer batteries over the past few years. The National Renewable Energy Laboratory (NREL) has supported this development with thermal characterization and analysis of three generations of CPI prototype Li-Ion polymer cells. All generations of the cells use a manganese-dioxide material for their cathode and graphite anodes. NREL measured the heat generation and subjected the cells to thermal imaging. The first- and second-generation cells showed signs of localized heat during thermal imaging underneath the positive electrode during discharge. As the cell was improved and better electrodes designed, the third-generation cell became relatively uniform in temperature and was the most efficient of the cells tested. It exceeded an efficiency of 91% for all currents below 48 amps. In comparison, the second-generation CPI cell was only 78% efficient at 30 amps. CPI is incorporating its latest Li-Ion cells in a stand-alone battery pack for vehicle applications.

1.0 Introduction

The performance, life cycle cost, and safety of electric and hybrid electric vehicles (EVs and HEVs) depend strongly on those of the vehicle's energy storage system. Advanced batteries such as lithium-ion (Li-Ion) polymer batteries are considered viable options for storing energy in EVs and HEVs. Compact Power Inc. (CPI) of Colorado, USA and LG Chem Ltd. (LGC) of South Korea have been developing large Li-Ion polymer cells and batteries for EV, HEV, and other applications. The technology is based on LGC's small Li-Ion cell portable power applications.

Early on, CPI realized that thermal issues are important for operating high-power Li-Ion polymer batteries. Actual data on the thermal behavior of polymer cells, such as heat generation rate and temperature rise under a specified power cycle, were needed to verify the expected thermal performance of the cells and to fine tune the cell and pack thermal management system. Because the National Renewable Energy Laboratory (NREL) has unique facilities and experience [1,2,3], CPI asked the laboratory to conduct tests to evaluate thermal behavior of its polymer cells. NREL's facilities include a unique calorimeter that is large enough to hold multiple cells, high-power battery cyclers capable of simulating any driving cycle, and state-of-the-art thermal imaging and heat transfer equipment. CPI and NREL collaborated to conduct tests to (1) obtain thermal images of cells under load and (2) measure heat generation rate from the cells under various charge/discharge profiles.

2.0 Background

2.1 Compact Power Li-ion Polymer Cell

Figure 1 pictorially shows the cells. Table 1 gives the published characteristics of the three generations of Li-Ion polymer cells.

Figure 1: (Counterclockwise from upper left) CPI Gen I cell, Gen II cell, and Gen III cell.

Table 1: Physical and electrical characteristics of CPI's Li-Ion polymer cells. Upper voltage limit = 4.2 V and lower voltage limit = 3.0 V.

Cell	Ah Cap. (Ah)	Max Dis. Current (Amps)	Mass (grams)	Specific Energy (Wh/kg)	Size (L x W x H) (mm)
Gen I	4.5	45	144.6	118	105x125x3
Gen II	5.0	75	201.3	94	122x118x11
Gen III	8.0	140	300.8	95	243x125x6

The latest version of the cell, Gen III (manufactured by LGC) uses high-capacity artificial graphite anodes and spinel lithiated manganese-dioxide cathodes. The anodes and cathodes are laminated together with the separator and assembled using a proprietary winding-stacking technique. The result is a cell that requires no external pressure and shows exceptional cycle life, very high power (2,000 W/kg), and high specific energy (95 Wh/kg). Figure 2 shows the 18-second discharge power and 2-second regen power capability of the Gen III cell as a function of depth of discharge. The test protocol used to determine the power capabilities is the Partnership for a New Generation of Vehicles (PNGV) Hybrid Pulse Power Capability (HPPC) test [4]. Using the HPPC results for an individual cell, the battery sizing factor, i.e., the number of cells, necessary to meet the PNGV goals of 25 kW on discharge and 30 kW on regen at end of life was calculated to be 75.

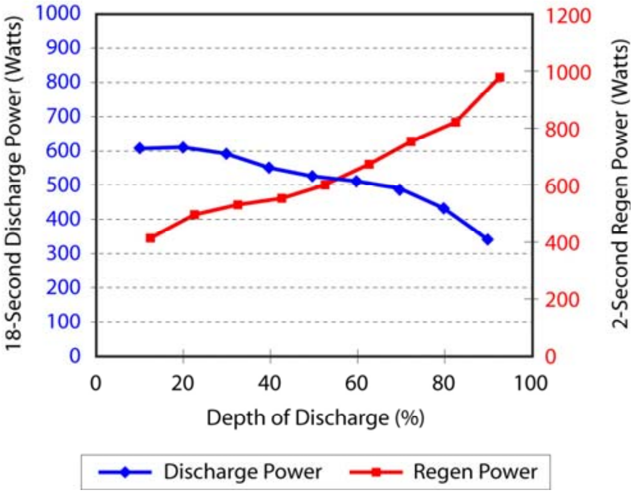

Figure 2: Power capability of the CPI Gen III cell under HPPC profile.

2.2 NREL Calorimeter

NREL uses a custom-made, single-ended, conduction-type calorimeter to measure heat capacity and heat generation from a cell or module [2]. The calorimeter can measure heat as low as 10 J with a heat rate as low as 10 mW. It is designed to measure heat rates as high as 100 W with an accuracy of ±2%. A module in the calorimeter is charged and discharged by a high-power battery cycler.

3.0 Heat Generation Testing

NREL's calorimeter was used to measure the heat generation of the CPI cells. Depending on the cell, the heat generation was measured at 25°C for the following conditions.

1. Constant current discharge at a C/5, C/1, 2C, and 6C rate until voltage reached CPI's specified lower voltage limit (3.0 V) – 100% state of charge (SOC) to 0% SOC.

2. Under CPI's recommended charging scheme, C/2 current was applied to the cell until it reached 4.2 V. The voltage was then held at 4.2 V until the current decayed below 250 mAmps.

The energy efficiency of the cell during constant charge/discharge cycles was determined by the following equation.

$$Eff = \left[1 - \left(HeatGenerated / Energy(Input \ldots Output)\right)\right] * 100$$

The heat generated by the cell is due to the I^2R losses in the cell and the chemical changes within the cell as measured by the calorimeter. The energy (input…output) is the electrical energy supplied or taken away from the cell over the testing cycle. Both the heat generated and the electrical energy are measured in Joules. The average cell heat rate in Watts is determined by the following equation.

$$AverageCellHeatRate = \frac{HeatGenerated}{CycleTime}$$

The heat generated is divided by the cycle time in seconds (the time over which the charge or discharge to the battery was completed). For instance, a C/1 discharge from 100% to 0% SOC takes approximately 60 minutes (3600 seconds).

Figure 3 shows the efficiency of the cells as a function of discharge current at 25°C. Each cell was discharged from 100-0% SOC with 3.0 V representing a fully discharged cell. The efficiency for all generations of cells decreases as the current increases. Furthermore, the Gen III cell has the highest efficiency for any given current. For instance, the Gen III cell has an efficiency of 94.4% at a current of 30.0 amps, whereas the Gen II cell has an efficiency of 78.8% at the same current. Figure 4 shows the average heat rate of the cell as a function of discharge current at 25°C. The heat rate for each cell increases with increasing current. The Gen III cell is the most efficient cell and therefore has the lowest average heat rate for a given current, which indicates improvements between generations. At 30 amps, the Gen III average heat rate was 5.6 W compared to the Gen II cell average heat rate of 21.1 W. The efficiency of the cells was also measured under CPI's recommended charging scheme. The Gen III cell was the most efficient at 99% under the recommended charging scheme compared to an efficiency of 95% for Gen I and Gen II.

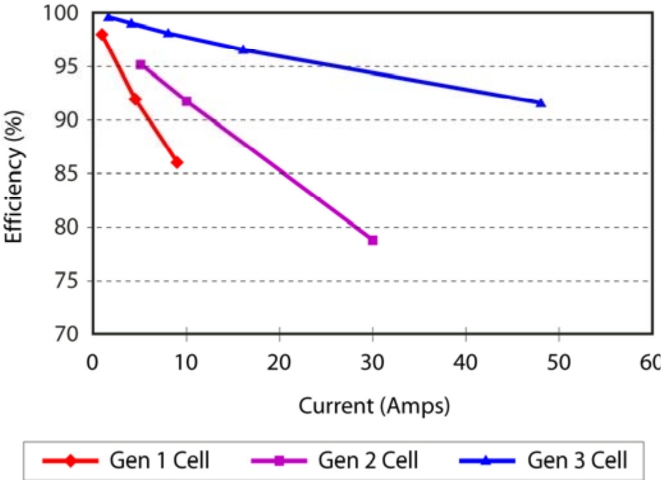

Figure 3: Efficiency data for CPI's Li-Ion polymer cells at 25°C.

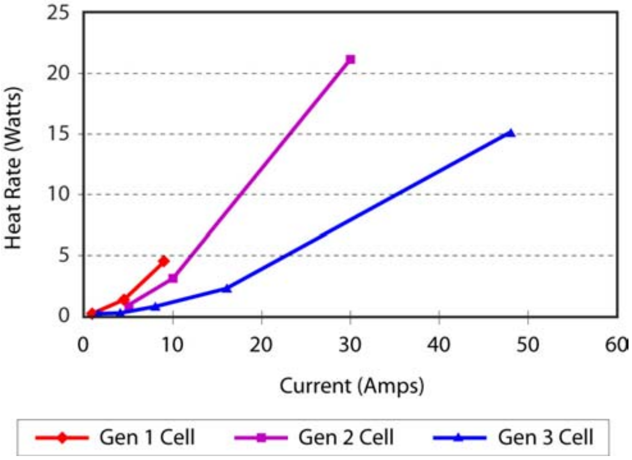

Figure 4: Heat rate data for CPI's Li-Ion polymer cells at 25°C.

Figure 5 shows the calorimeter response and voltage curve of the Gen III cell under a C/5 full discharge. The total discharge lasted approximately 4.5 hours. At the beginning of the cycle, the cell is initially endothermic – a negative heat rate represents an endothermic reaction, heat being pulled from the constant temperature bath surrounding the calorimeter to the battery. The heat rate does not go completely exothermic until approximately 2.5 hours. The cell then peaks at a heat rate of 0.11 W at 3.56 hours and then slightly decreases –possibly because of a phase change. Finally, the heat rate increases at the exact moment that the voltage precipitously dips, 3.95 hours into the test.