Proceedings of The Joint Canadian Society for Mechanical Engineering and CFD Society of Canada International Congress 2019
CSME-CFDSC Congress 2019
June 2-5, 2019, London, On, Canada

HEAT FLUX ANALYSIS of A LI-ION CELL DURING CHARGING and DISCHARGING PERIODS

A. R. M. Siddique
School of Engineering
University of Guelph
Guelph, Canada
Email: asiddi04@uoguelph.ca

S. Mahmud, S. A. Gadsden, and B. V. Heyst
School of Engineering
University of Guelph
Guelph, Canada
Email: smahmud@uoguelph.ca

***Abstract*—** Due to recent trends in environmental uncertainties and polluted climates, electric vehicles have quickly become the main driving technology to replace gasoline and diesel-powered vehicles. The main power source and storage device for electric vehicles is the rechargeable batteries e.g., Lithium-ion (Li-ion) cell. Excessive heat generation in Li-ion cells during charging and discharging periods reduces the operational lifetime and efficiency of the cell. Extending the operational lifetime of these batteries is critical for the improvement and wide-spread acceptance of electric vehicles. In this article, a series of experimental studies were conducted to analyze the heat flux behavior of Li-ion electric vehicle batteries. Three different temperature-controlled environments were studied: natural convection (in air), inside an enclosed glass jar, and in a liquid (water). Results demonstrate that heat flux changes significantly depending on the environment. The best results are achieved while operating in a controlled environment deployed by a TEC cooling system which also improves the battery operation time. In this study, the heat flux varied between -100 W/m^2 and 300 W/m^2 at 20 ºC to 23 ºC for 9,000 seconds under a 0.5A discharge current.

Keywords-charging cycle; discharging cycle; heat flux; Li-ion cell; thermoelectric cooler (TEC))

I. INTRODUCTION

Electric vehicles have become a reliable mode of transportation, and are a viable alternative to gasoline and diesel-driven vehicles. Since fossil fuels are becoming less abundant and causing environmental pollution, there is a growing demand for smart electric vehicle technology [1]. The electric battery is the key system found within electric vehicles. The performance of the battery depends on many factors, such as electrochemical reactions, heat generation in the cell, surrounding temperature, state of charge and health, operational hours, and so forth [2].

Among various determining factors, heat generation within the cell is also important to study for Li-ion batteries. Different battery thermal management systems (BTMS) have been studied in order to manage the excessive heat generation during high charge/discharge cycle [4-6]. This high amount of generated heat inside the cell causes to reduce battery operation time and efficiency as well. BTMS such as air-cooled system [7], using fins [8], phase change materials (PCM) based cooling system [9], and thermoelectric cooler (TEC) [10] based cooling system are widely used for EVs.

The aim of this article is to study the heat flux behavior of the Li-ion cell during charging/discharging periods in order to identify how much power per unit area does the cell lose during this period. In order to analyze this characteristic, a series of experiments were performed under three different situations that include in natural convection (in air), inside an enclosed glass jar, and inside the water flow with control temperature. A thermoelectric cooler (TEC) was used with a temperature controller to control the water temperature. Surface temperature and voltage profile of the Li-ion cell were also examined.

II. HEAT GENERATION IN LI-ION CELL

Li-ion cell is a chemical power source which mainly linked to the temperature. A complex electrochemical reaction takes place inside the cell during charging/discharging cycle [11]. Heat is generated during the chemical reaction and excessive heat interrupts the normal operation of the Li-ion cell. A general formula of heat generation from a Li-ion battery was developed by Bernardi et al. [12] is given in Eq. (1).

$$q = I\left(U - V\right) - I\left(T\frac{\partial U}{\partial T}\right) \tag{1}$$

where q is the generated heat by the cell, I is the operating cell current, U and V are the open circuits and operating potential of the cell; receptively, and T is the operating temperate of the cell. The first term on the right side of Eq. (1) represents the ohmic loss and the second term presents the irreversible heat generation term [13].

During charging/discharging cycle many complex mechanisms including electrochemical reactions electricity and heat transfer are involved, and are changed due to the state of charge (SOC), state of health (SOH), temperature, time etc.

[13]. The first term is much bigger than the second term in terms of high charge/discharge current rate. Therefore, the second term is negligible for electric vehicles (EVs). The electrochemical reactions and heat generation by a Li-ion cell varies with different environments [12].

III. Experimental Tests and Results

A. *Experimental et-up*

In order to analyze the heat flux and surface temperature during charge/discharge of Li-ion cell at different environmental conditions i.e., in natural air flow, inside a vacuum glass jar, and inside liquid flow, a series of experimental tests were performed. Figure 1 illustrates the experimental set-up for charging a Li-ion cell. A charge/discharge battery tester (Model: iMax B6AC v2, supplier: SKYRC) was used to charge the Li-ion cell (Model: BRC 18650 2200mAh, 3.7 V rated, supplier: Ultrafire) during charging cycle. The voltage of the cell during charging/discharging period was recorded by a data acquisition device (Model: NI USB-6221, supplier: National Instruments). Two K-type thermocouples were used in order to measure the surface and surrounding temperature of the cell by Omega-HH374 thermometer. Heat flux generated by the cell during charging/discharging cycle was measured by a PHFS-01e heat flux sensor (supplier: FluxTeq) which was tightly attached to the surface of the cell. Thermal conductive paste (OT-201-2, OMEGA) was used between the heat flux sensor and the cell to make a good contact.

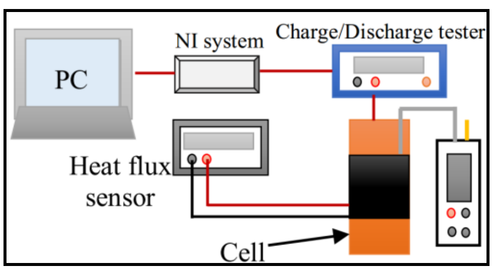

Figure 1. Schematic presentation of the experimental set-up for charging Li-ion cell.

Different environmental situations were considered during the discharging cycle of the cell. A schematic diagram was shown in Fig. 2 to present the experimental set-up in natural air and inside a vacuum glass jar. At first, the Li-ion cell was discharged in the air in normal condition (see Fig. 2(a)). A fixed load (6.75 Ω, which draws around 0.5 A) was used in all cases to discharge the cell. After that, the experimental tests were performed inside a sealed glass jar (see Fig. 2(b)). The bottom part of the glass jar was sealed so that no air goes inside or coming out to make a vacuum environment.

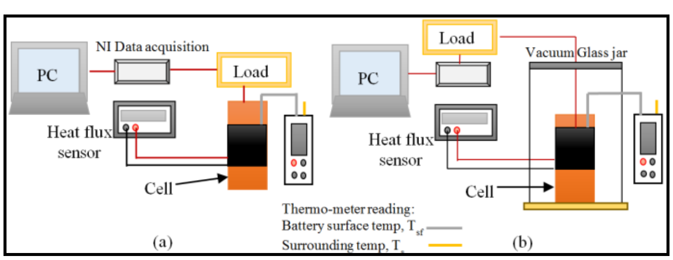

Figure 2. Schematic diagram of the experimental set-up (a) in natural air flow and (b) inside a vacuum glass jar during the discharge period.

Lastly, in order to control the surrounding temperature of the cell, the Li-ion cell was placed inside a cylindrical container full of water as shown in Fig. 3. A thermoelectric cooler (TEC) was incorporated to control the water temperature. TEC is the key component of the cooling module. The cooling module includes a TEC (4 cm×4 cm), fins, a cooling DC brushless fan (12 V, 0.3 A) and aluminum water block (4 cm×4 cm) which was attached to the cooled side of the TEC. A DC brushless pump (4.5 W, Model: DC 30A-123) was used to circulate the water through the container with connecting tubes. The flow rate of the pump was 1852 mL/min. Though it's dangerous to keep the battery without any protection inside the water; however, at first both ends of the battery was soldered and then covered with electrical tape, and then covered by glue so that water cannot go inside.

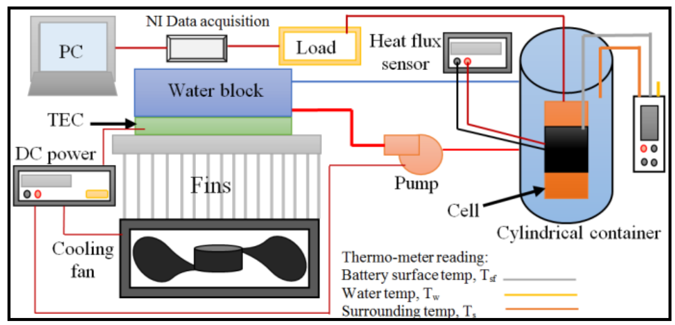

Figure 3. Pictorial diagram of the experimental set-up with the TEC system.

B. *Charging cycle test*

Li-ion cell was charged using the charge/discharge tester using three different current inputs i.e., 1 A, 1.5 A, and 2 A. At first the cell was discharge up to its safety level (2.9-3.2 V) and then it was charged up to nearly 4.1 V. A voltage profile with respect to time was presented in Fig. 4. It is seen that the charging voltage rapidly increases with time. However, there is a sharp rise in the voltage profile starting from 3.8 V to 4.1 V during 2 A and 1.5 A current input whereas it takes more time to go to 4.1 V. As times passes the voltage becomes a steady state.

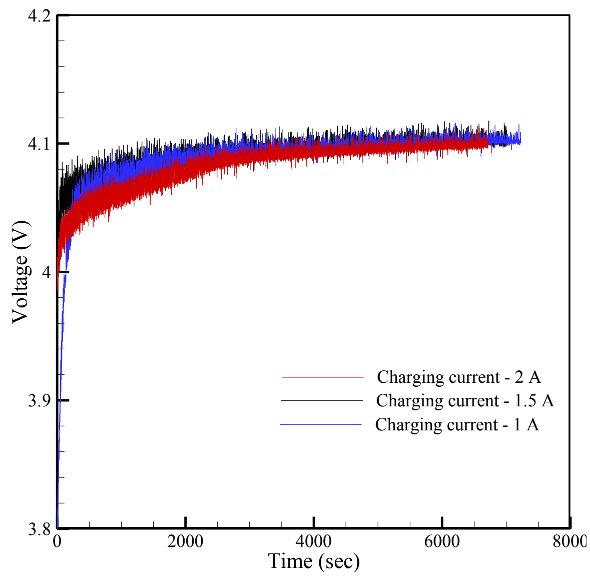

Figure 4. Voltage profile along with time during different charging cycles.

Figure 5 shows the heat flux profile with time under three different current inputs. It is seen that the heat flux and surface temperature increase gradually with time when there is a jump in voltage from 3.8 V to around 4 V. Moreover, when the voltage becomes stabilize (battery was generating less amount of heat) then the heat flux and surface temperature starts to decrease until the cell was fully charged. The heat flux starts from a negative value and as times passes the value varies between 0 W/m^2 to 75 W/m^2 under different charging current. Moreover, it is noticed that the decreasing trends of the heat flux are almost the same for different current input as the cell is generating almost the same heat due to the steady voltage level.

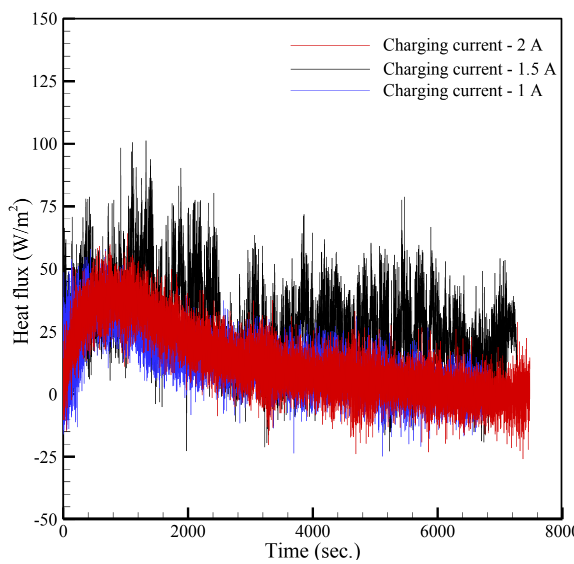

Figure 5. Heat flux pofile along with time during different charging cycles.

C. *Discharging cycle test*

The environmental influence on the cell was tested under the discharging cycle at three environmental conditions. A fixed load of 6.75 Ω (0.5 A) was used to discharge Li-ion cell in this experiments just to identify the characteristics of the cell discharge voltage, the heat flux, and surface temperature at different environmental situations. The surrounding temperature effects on voltage and heat flux was clearly presented in Fig. 6 and Fig. 7. Figure 6 shows the voltage profile during 0.5A discharge current. Though the cell was fully charged; however, when it was connected to the load it started to discharge it's voltage from around 3.9 V and gradually decreases from 3.9 V to 0.6V with time (In total 9000 seconds).

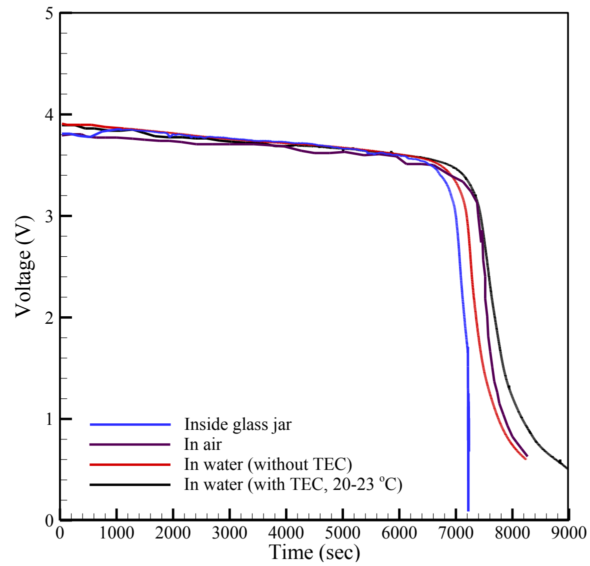

Figure 6. Discharge voltage profile with time under 0.5 A discharge current.

The experimental tests show that it takes longer time to discharge the voltage in the colder environment. The voltage decreases rapidly and takes less time to discharge under vacuum situation due to the effect of the surrounding environment. Since the place was closed, so there was no air flow in or out which means the surrounding temperature was almost fixed with time under normal situation. However, the cell was continuously generating heat during the discharging period which affected the surrounding temperature to heat up. The cell could not radiate heat smoothly as it could do under normal air flow condition. It means the cell heats up itself more and slows down the speed of the chemical reaction which reduces the operation time. In order to control the surrounding temperature, a TEC based cooling system was used with a temperature controller (supplier: INKBIRD). In this experiment, the surround the temperature was controlled between 20 ºC to 23 ºC.

Figure 7 shows the heat flux behavior of Li-ion cell under the natural convection, vacuum place, and inside the water with a controlled environment. The trend of the heat flux increases as the surrounding temperature decreases. Almost similar trend is noticed under natural air, inside the vacuum glass jar, and inside water at 0.5A discharge current. However, this heat flux behavior is completely different for the cell due to the cooling system in a controlled environment. The cell is generating less heat under a cold environment which reduces the heat flux as well.

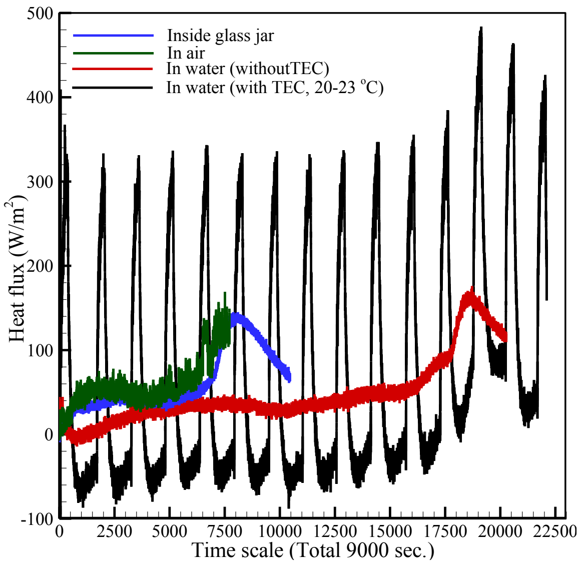

Figure 7. The characteristics of Li-ion cell in terms of generating heat flux with time under different environmental conditions.

Figure 8 presents the temperature profile under different environmental conditions at 0.5A discharge current. Similar trends are noticed under natural air flow and inside the glass jar whereas it is different underwater and in a controlled environment. The surface temperature under natural convection and enclosed glass jar increase gradually; however, it increases rapidly at the end when the battery has does not have enough power to supply. The temperature gradually increases with time without any distortion under water because water has specific heat which helps to keep a steady temperature rise in the cell. Furthermore, the surface temperature of the Li-ion cell fluctuates. The environment temperature is also fluctuating during the test which is seen from the graph by the green line.

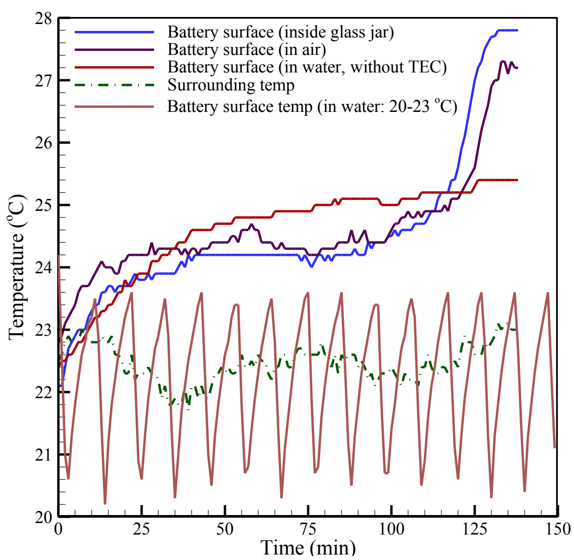

Figure 8. Temperature profile with time under different environmental conditions.

IV. Conclusion

In this paper, the heat flux and the surface temperature behavior of the Li-ion 18650 cell was experimentally studied. Three different environmental conditions (natural air flow, inside the enclosed glass jar, and inside water) were considered to analyze different behavior under charging and discharging cycles. Three different charging current levels (1 A, 1.5 A, and 2 A) were examined to characterize the voltage, heat flux, and surface temperature profiles of the Li-ion cell.

Best results were achieved under the controlled-environment with a TEC cooling module. In other words, fixing the water temperature between 20 ºC to 23 ºC in terms of voltage, heat flux, and surface temperature under 0.5 A discharge current. Moreover, the operational time of the battery increased due to the colder environment. However, heat flux changed more from -100 W/m^2 to 300 W/m^2 than other environmental conditions. Future work will focus on the battery packs of Li-ion cells and characterize its behavior under different controlled-environment temperatures. The TEC based cooling system is a suitable fit for this application and will be utilized and explored further.

References

[1] Conte, F.V., 2006, “Battery and battery management for hybrid electric vehicles: a review,” e & i Elektrotechnik und Informationstechnik, 123(10), pp. 424-431.

[2] Al-Hallaj, S., Kizilel, R., Lateef, A., Sabbah, R., Farid, M., and Selman, J.R., 2005 “Passive thermal management using phase change material (PCM) for EV and HEV Li-ion batteries”, IEEE Veh. Power Propuls. Conf.

[3] Liu, R., Chen, J., Xun, J., Jiao, K., and Du, Q., 2014, “Numerical investigation of thermal behaviors in lithium-ion battery stack discharge”, Appl. Energy, 132, pp. 288–297.

[4] Gadsden, S.A., and Habibi, S.R., 2013, “Model-Based Fault Detection of a Battery System in a Hybrid Electric Vehicle”, Journal of Energy and Power Engineering, 7(7), pp. 1344-1351.

[5] Al-Shabi, M., and Habibi, S.R., 2011, “Estimation Strategies for the Condition Monitoring of a Battery System in a Hybrid Electric Vehicle”, ISRN Signal Processing.

[6] Bustos, R., Siddique, A.R.M., Cheema, T., Gadsden, S.A., and Mahmud, S., 2018, “State of Charge and Parameter Estimation of Electric Vehicle Batteries”, 2018 Canadian Society for Mechanical Engineering (CSME) International Congress, Toronto, Ontario.

[7] Wu, W., Yang, X., Zhang, G., Chen, K., and Wang, S., 2017, “Experimental investigation on the thermal performance of heat pipe-assisted phase change material based battery thermal management system”, Energy Convers. Manag. doi:10.1016/j.enconman.2017.02.022, 2017.

[8] Berthou, Y., 2011, “Étude de parois de bâtiments passifs associant un Matériau à Changement de Phase (MCP) et une super isolation transparents”, phdthesis École nationale supérieure des Mines de Paris.

[9] Kim, S.Y., Lee, K., Park, S., and Kim, J., 2014, “Thermal design analysis and performance test of a 1kW thermoelectric battery cooler”, In: Thermomechanical Phenom. Electron. Syst. -Proceedings Intersoc. Conf., doi:10.1109/ITHERM.2014.6892446.

[10] Zhoujian, N., Li, J., Yong, D., Chao, D., and Xuejiao, L., 2017, “A Review on Lithium-ion Power Battery Thermal Management Technologies and Thermal Safety”, J. Therm. Sci., 26(5), pp. 391-412.

[11] Bernardi, D., Pawlikowski, E., and Newman, J., 1985, “A general energy balance for battery systems [J]”, Journal of the Electrochemical Society, 132(1), pp. 5–12.

[12] Zhao, R., Zhang, S., Liu, J., and Gu, J., 2015, “A review of thermal performance improving methods of lithium ion battery: Electrode modification and thermal\hskip 1em plus 0.5em minus 0.4em\relax Journal of Power Sources, 299, pp. 557-577.

[13] Xia, G., Cao, L., and Bi, G., 2017, “A review on battery thermal management in electric vehicle application”, Journal of Power Sources, 367, pp. 90-105.