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An experimental study of a lithium ion cell operation at low temperature conditions

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Abstract

Lithium-ion (Li-ion) batteries are widely used for various applications such as telecommunication, automotive, and stationary applications. With their wide range of safe operating temperatures (i.e. -10 °C to 50 °C), the Li-ion is preferred over other types of matured battery technologies such as lead acid and nickel-cadmium (NiCd). Nevertheless, operating the Li-ion batteries at cold climate conditions can potentially harm the batteries and lead to issues such as degradation and reduction in their capacity and power density. This paper aims to experimentally investigate the behavior of a Li-ion cell operating at low temperatures (i.e. -15 °C to 25 °C) with respect to its charging and discharging behavior. It was observed that at sub-zero temperatures (i.e. -5 °C, -10 °C and -15 °C) the Li-ion cell's capacity is reduced due to the impedance effect which then increases the cell's internal resistance. Moreover, at such low temperatures the best state of charge (SOC) of the cell (i.e. during charging mode) has reduced to about 7-23% of its maximum initial SOC (i.e. 100%). To complement the experimental finding, an existing simplified adaptive thermal model was used to obtain the discharge curves at various current rates based on the function of extracted charge (Q_{out}). The discharge curve of equilibrium potential (E_{eq}) is then extrapolated towards zero current in order to obtained the overpotential heat generation curve based on the discharge current of the cell. The result showed a good agreement to the discharge curves that were obtained experimentally. Likewise, with the finding of cell voltage (E), current (I) and temperature (T) that were obtained experimentally, the thermal behavior of the cell in respect of its internal temperature is predicted and represented by comparing both the simulated and experimental cell internal temperatures.

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Keywords: Lithium ion; batteries; cold climatre condition; charging; discharging; heat transfer; theoretical modelling

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1. Introduction

Advanced lithium ion (Li-ion) battery technology is now broadly used in a range of applications such as telecommunication, personal transportation (e.g. e-bikes and scooters), automotive, aerospace, grid, and stationary applications [1-7]. With its wide range of safe operating temperatures (i.e. -10 °C to 50 °C), the Li-ion batteries have gained distinction that is comparable to other types of matured battery technologies such as lead acid and nickel-cadmium (NiCd) batteries [8]. Nevertheless, unlike the simplicity of deploying lead acid battery, the Li-ion batteries require electronic control circuitry to maximize their performances and reinforce their safety that are very important in applications such as telecommunication and electric vehicles (EVs) [2].

In recent years, the thermal management of Li-ion batteries has been the focus of a number of studies as it is a crucial consideration to get them operated at optimum conditions. While both cooling and heating are equally critical, the emphasis of recent studies were mainly towards high temperature applications (e.g. for EV operation in hot climate condition or for remote area power supply (RAPS) system at desert area) with noticeably less attention to their operation in low temperature climate conditions (i.e. particularly for stationary applications). This calls into question on issues relating to the effect of low temperature operation on the performance of Li-ion batteries: for instance reduced energy and power densities of the batteries [9]. It is noteworthy that the Li-ion batteries operate at the same temperature range of human's tolerable range; however, both the high and low temperatures can greatly reduce their performances while overheating can lead to safety issues such as thermal runaway and explosions [10].

As reported by Gering [11], the limitations of the Li-ion batteries can be put into two categories of intrinsic and operational limitations. The intrinsic limitations are due to unavoidable materials-related constraints that are irrespective to the battery usage condition. Examples of the intrinsic limitations include transport characteristics of the electrolyte, charge transfer rates within the electrode materials, and others. Meanwhile, the operational limitations are related to how actively a cell is being cycled under specified state of charge (SOC) and temperature [11]. Hence, it is known that the challenges faced by the Li-ion batteries at low temperature conditions are clearly related to the operational limitations.

Previous research studies have shown that rapid charging of the Li-ion batteries at subzero temperatures can potentially harm the batteries and lead to their degradation [12]. For example the capacity of the Li-ion batteries is greatly reduced as much as 95% when operated at -10 °C rather than at 20 °C [13]. This drop in the capacity is unacceptable in many applications when the Li-ion battery storage system fails to meet the load demand due to aging behavior associated with their operation at extreme cold conditions. It was suggested that such occurrence of performance loss at cold conditions is caused by a significant rise of internal resistance that tends to increase the cell's internal temperature (warming the cell) and potentially degrade the Li-ion in the long run [14, 15]. Hence, among the efforts suggested to improve the Li-ion's performance are advanced thermal behavior study, upgraded electrode materials, improved charging/discharging arrangement and comprehensive battery's thermal management [16-20].

In this paper, the behavior of Li-ion cells is studied based on charging and discharging of the cell at various low operating temperatures. The results of this experimental study will then be used to establish the reliability of an existing simplified thermal model used to predict the performance of Li-ion batteries operated under various temperatures. A small-scale experimental study was carried out on a Li-ion cell at operating temperature ranging between -15 °C to 25 °C. The manufacturer's recommendation of current rate (C-rate) values (i.e. 20C for charging and 5C for discharging) are used to identify the effect of the battery's temperature on its performance.

Nomenclature

m	Mass of cell (g)
C_p	Specific heat capacity ($J.g^{-1}.K^{-1}$)
Q_t^{in}	All processes that generate heat (W)
Q_t^{out}	All processes that dissipate heat (W)
Q_n	Overpotential heat generation (W)
Q_s	Entropic heat generation (W)
Q_c	Heat convection (W)
Q_R	Heat radiation (W)