International Journal of Heat and Mass Transfer 102 (2016) 315–322

Contents lists available at ScienceDirect

International Journal of Heat and Mass Transfer

journal homepage: www.elsevier.com/locate/ijhmt

Actively controlled thermal management of prismatic Li-ion cells under elevated temperatures

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ARTICLE INFO

Article history:
Received 15 April 2016
Received in revised form 10 June 2016
Accepted 13 June 2016
Available online 25 June 2016

Keywords:
Thermal management
Prismatic Li-ion battery
Elevated thermal environment
Wind tunnel test
Active thermal control

ABSTRACT

This paper reports the experimental study of the active control of the thermal management for prismatic lithium ion (Li-ion) batteries under an elevated thermal environment with temperature above 40 °C. To defray the cost of performing experimental study under such conditions while obtaining meaningful data for a multi-cell battery pack with practical relevance, this study developed an experimental setup using a combination of four real Li-ion cells and 12 dummy cells. The dummy cells were fabricated to have the same geometry as the real cells and embedded with controllable heating elements to simulate, respectively, the aerodynamic and thermal behavior of a multi-cell pack. This experimental setup was then placed inside a wind tunnel so actively controlled cooling tests can be performed under well-controlled flow conditions. During the tests, heating power up to 6×10^4 W/m^3 was generated by the dummy cells, creating and the maximum environment temperature above 40 °C. The major observations obtained from these experiments were twofold. First, besides reducing the experimental cost, the combination of real and dummy cells also offers flexibility to obtain experimental data of a large pack under a variety of conditions for model comparison. Second, a simple on-and-off control strategy was demonstrated to effectively reduce the parasitic power consumption of the cooling systems under the evaluated environmental temperature, even when the Li-ion cells were under dynamic load.

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1. Introduction

Due to their superior properties, lithium ion (Li-ion) batteries represent an important alternative energy source in many areas. Compared to other types of batteries like lead acid and NiMH, the salient features of Li-ion batteries include high power density, high efficiency, and low self-discharge rate, which are all attractive characteristics for the energy storage needs for both mobile and immobile devices [1,2], such as electric vehicles (EV), hybrid electric vehicles (HEV) [3,4], and the grid [5,6]. When deployed as auxiliary or alternative power system in EVs and HEVs, Li-ion batteries have been shown to improve the fuel efficiency and thusly reduce fossil fuel energy consumption and greenhouse gas emission [7]. However, with the increasing applications and demands of Li-ion batteries, it is also important to recognize the limitations they are currently facing [8]. The chemical, thermal, and electrical behaviors of Li-ion batteries need to be better understood, so that they can be applied safely and efficiently under different operation conditions and environments.

Thermal management represents an important issue with both fundamental and practical significance for the applications of Li-ion batteries, especially in EVs and HEVs. The application in EVs and HEVs poses several challenges to the thermal management issue. The heat generation, and consequently thermal management load, is highly dynamic due to the transient vehicle operation, and the environmental temperature under which the vehicles are operated far exceeds the optimum working temperature range of Li-ion batteries. For example, the acceptable temperature range for Li-ion battery operation has been reported to be between −10 °C and +50 °C [9,10], and a narrow range of +20 °C to +40 °C has been reported [11,12] to for performance and lifetime considerations. However, the environmental temperature under with EVs or HEVs are operated can fall significant outside of these ranges, and can cause safety and performance issues to the batteries. Low temperature reduces both the battery capacity and power dramatically [13], while high temperature causes degradation and shortens battery lifetime [14] or even thermal runaway and fire hazards [15].

A variety of thermal management systems have been proposed and developed for battery packs. Both passive and active thermal

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http://dx.doi.org/10.1016/j.ijheatmasstransfer.2016.06.033
0017-9310/Published by Elsevier Ltd.

management systems have been tested, based upon a variety of coolants, ranging from air, liquid, and phase change materials [9,16–18]. However, the thermal management system itself consumes power, and such parasitic power can represent a significant portion of the overall vehicular power portfolio. Different control strategies have been developed and demonstrated to minimize the parasitic power consumption while maximizing the cooling effectiveness. Possible strategies included the control of the cooling flow's direction and pattern [19–21], and the control of the flow rate and direction [22–24]. The ambient temperature has a significant impact on the parasitic power consumption and the difficulty of controlling the battery temperature within the optimal range. It is of particular interest to understand the thermal management systems under extreme ambient temperatures (either extremely cold or hot ambient temperature) because under extreme conditions both the efficiency and also the functionality of the battery pack depend critically on the thermal management systems. For example, past research has reported the capacity fade of Li-ion battery under high ambient temperatures [25] and the warm up issues of Li-ion batteries under sub-zero temperatures [26]. This work focuses on the cooling of batteries under high ambient temperature, even though some of the discussions can be extended to warming up of batteries under extreme low temperatures.

Past studies (especially experimental studies) mentioned above have predominately relied on a single cell and in temperature ranges near room temperature, typically in a range between ~20 and ~30 °C. Based on the fundamental understanding of single-cell behavior, this work aims at investigating the behavior of multiple cells under environmental temperature above 40 °C. This study was motivated by several considerations. First and foremost, the cell-to-cell interactions cannot be easily modeled or extrapolated from results obtained on a single cell. Therefore, it is desirable to have experimental data obtained under controlled-conditions for the development and validation of models for multi-cell battery packs. Second, it is also valuable to examine the performance and reliability of control strategies developed in the past on battery packs consisting of a large number of cells and under elevated temperatures. However, conducting experimental work on a large pack under elevated temperatures is costly. To circumvent the high cost, this work developed a battery pack using a combination of 4 real prismatic cells and 12 dummy cells, resulting in a battery pack consisting of 16 cells. The dummy cells were fabricated to have the same geometry as the real cells to simulate the aerodynamic behavior of a multi-cell pack, and they are embedded with controllable heating elements to mimic the thermal behavior of a multi-cell pack. This customized battery pack was then placed in a wind tunnel. The heating elements heated the dummy cells, which subsequently raised the temperature of the air surrounding the real cells. Thus, by creating a local high temperature region surrounding the real cells, the need to heat up the wind tunnel was avoided, resulted in a significant reduction in the cost. On the other hand, the wind tunnel generated well-conditioned cooling flows and the dummy cells generated the heat in a controllable way (both in terms of the amount and the temporal pattern, resulting in experimental testing under well-controlled and documented conditions. In summary, the dummy cells enabled the experimental study of a large battery pack under elevated temperatures with significantly reduced cost and yet under well controlled conditions.

In the rest of this paper, Section 2 immediately below will describe the experimental setup in detail, including the wind tunnel, followed by the results in Section 3.

2. Experimental setup

Fig. 1 shows the overall experiment platform used in this work. The experimental platform consists of major three components: a wind tunnel, the battery pack, and the data acquisition and control system.

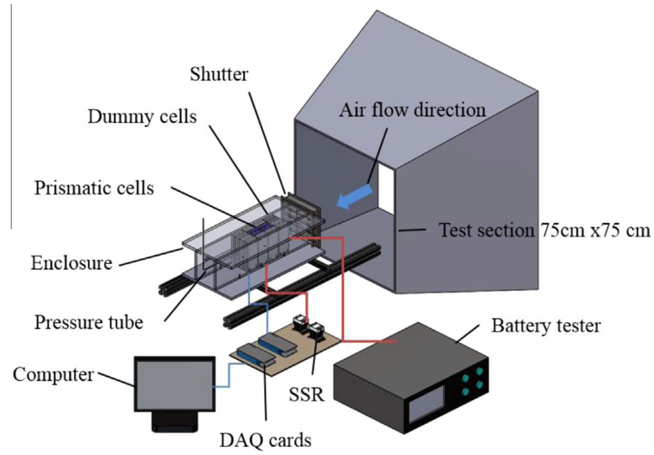

Fig. 1. Schematic of experimental setup.

The wind tunnel used in this experiment is a subsonic open jet wind tunnel as shown in Fig. 1. The wind tunnel provided the cooling air flow at well controlled velocities up to 30 m/s across a test section of 0.7 × 0.7 m. The cooling flow was generated by a centrifugal fan and was conditioned by a diffuser, settling chamber, turbulence reduction screens before entering the test section to ensure its low turbulence and uniformity. The turbulence intensity of the cooling flow was known to have a significant effect on heat transfer rate. The heat transfer increases with the freestream turbulence level [27]. Thus it is important to know the turbulence intensity of the incoming flow. In this test, the turbulence intensity of the incoming flow was calculated from the standard deviation of the velocity divided by the mean velocity. The velocities of the incoming flow were measured by a hot-wire anemometer, and the result shows that the average turbulence intensity of the incoming flow was less than 1%. The battery pack, consisting of 4 real prismatic and 12 dummy cells, was housed in a customized enclosure as shown in Fig. 1 (and the design of the enclosure was detailed in Fig. 2). The target battery pack was instrumented with a pressure tube and multiple thermocouples (as detailed in Fig. 2) to obtain aerodynamic and thermal measurements. A shutter was installed at the entrance of the enclosure (to turn on and off the cooling flow) when tests involving active control were conducted. Two DAQ cards (National Instruments) were used in the experiment, one to collect the temperature data from the thermocouples and the other to control the heating power inside dummy cell (and the operation of the shutter during actively controlled experiments). The heating power of the dummy cell was regulated by a solid state relay (SSR). The loads on the prismatic cells were controlled by a battery tester (Cadex C8000). A computer was used to centralize all the data acquisition and control signals.

Fig. 2 shows a more detailed view (from the top view) of the battery pack and the associate control system. As mentioned above, the battery pack included a total of 16 cells: 4 prismatic Li-ion batteries (3.2 V $LiFePO_4$ from Bioenno Power) and a total of 12 dummy cells with embedded controllable heating elements inside. In the experiments performed in this work, the real cells (labeled C1 to C4 as shown in Fig. 2) were placed in the middle of pack and surrounded by the dummy cells. The nominal voltage of the prismatic cell was 3.2 V and the nominal capacity was 20 Ah. The prismatic cells had the length of 70 mm, width of 27 mm and height of 167 mm without considering the length of terminals. The dummy cells had the same dimension with the prismatic cells. The battery pack was placed in a customized enclosure. The enclosure