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Experimental demonstration of active thermal control of a battery module consisting of multiple Li-ion cells

Fan He [a], Haoting Wang [b], Lin Ma [a,b,*]

[a] Department of Mechanical Engineering, Virginia Tech, Blacksburg, VA 24061, USA
[b] Department of Aerospace and Ocean Engineering, Virginia Tech, Blacksburg, VA 24061, USA

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ABSTRACT

This work reports the experimental demonstration of active thermal control of an Li-ion battery module. Corresponding simulations based on computational fluid dynamics (CFD) were also performed to analyze the experimental data. Active control strategies were designed to exploit reciprocating cooling flows to achieve optimal cooling effectiveness, in terms of controlled maximum temperature rise, temperature uniformity among cells, and reduced parasitic power consumption. This work first describes the development of an experimental facility to demonstrate the active control. Second, a CFD model was developed and validated using experimental data. Based on the experimental facility and the CFD model, a number of different cooling schemes and control strategies were investigated. Both the experimental and CFD results suggest that a combined use of hysteresis control and reciprocating cooling flow can achieve the optimal cooling performance among all the strategies investigated. Such a combined strategy dramatically reduced the parasitic power by 84% and cooling air consumed by the cooling system, improved the temperature uniformity among cells, and only with a tradeoff of a slightly increased maximum cell temperature rise.

1. Introduction

Lithium ion (Li-ion) batteries have been identified as a promising solution to meet the increasing demands for alternative energy in electric vehicles (EVs) and hybrid electric vehicle (HEVs) [1]. Energy storage is a key technology for the research and development of EVs and HEVs, and the characteristics of the ideal energy storage solution should include high power density, high energy density, high efficiency, and long lifetime [2,3]. Among various types of energy storage solutions, Li-ion batteries feature relatively high power density, high energy density, stability, and low self-discharge rates [4]. Due to these features, Li-ion batteries show good promise as viable solution for applications in EVs and HEVs. However, the widespread application of Li-ion batteries requires a comprehensive understanding of their behavior. The issue of thermal management is an important aspect of their behavior due to their significant and highly dynamic heat generation in practical use [5,6].

Li-ion batteries can generate a large amount of heat while in use especially at high charging or discharging rates and under high ambient temperature. Such excessive heat, if not removed appropriately from the battery module, can cause shortened battery life, reduced efficiency, or even catastrophes such as fire hazard [7]. Such thermal management issue is further complicated by the wide and dynamic operation range that battery modules encounter in practice. For example, it has been reported that a temperature range between −10 and +50 °C [6] should be the tolerable operation range, and a more restricted range of +20 and +40 °C [8] has been reported for optimal performance and lifetime. However, the ambient temperature under which EVs and HEVs are operated can greatly exceed such preferred ranges. Furthermore, battery modules are charged and discharged according to a dynamic and almost unpredictable pattern in practical EVs and HEVs applications [9,10]. Such dynamic thermal load poses several challenges on the thermal management issue. First, to optimize the cooling effectiveness and minimize the parasitic power consumed by the cooling system, the thermal management should be dynamic correspondingly, which poses challenges on onboard sensing technologies and active control strategies [6,11–14]. Second, the temperature is typically non-uniform across the battery module, compounding the complexity of optimal thermal management when combined with the highly dynamic thermal load [5,15].

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* Corresponding author at: Laser Diagnostic Lab, Room 215 Randolph Hall, Department of Aerospace and Ocean Engineering, Virginia Tech, Blacksburg, VA 24061, USA. Tel.: +1 (540) 231 2249; fax: +1 (540) 231 9632.

E-mail address: linma@vt.edu (L. Ma).

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Non-uniform temperature across different cells cause issues such as non-uniform degeneration rate of cells and local hot spots [10,16,17]. Achieving an approximately uniform temperature distribution among cells within a module can be energy intensive, and various methods have been reported to minimize the energy requirement [5,16].

Due to the importance and challenge of thermal management, considerable research efforts, both modeling and experimental efforts, have been invested to obtain fundamental understanding and also to seek practical solutions. In the area of modeling, computational fluid dynamics (CFD) models have been developed to predict the thermal behavior of battery systems [15,17]. CFD models can predict quantities that are difficult to measure experimentally (such as the detailed temperature distribution throughout the cells and the aerodynamic behavior of the cooling flow) and have been demonstrated as a powerful tool to optimize the design of various thermal management systems [18,19]. In terms of experimental efforts, temperature variations of both the prismatic [20] and the cylindrical cells [21] have been characterized to understand the thermal behavior or batteries from a fundamental level, and also to provide data for model development and validation. The detrimental effects of high thermal load (e.g., the swelling of Li ion batteries) have been investigated experimentally at different charging/discharging rates [22]. To aid the development of models and control strategies, experimental measurements of battery modules have been conducted in controlled wind tunnels [21,23]. Lastly, note that due to the wide range of environmental temperatures encountered in practice, in addition to the study of battery cooling, study of the warm up from sub-zero temperatures is also of interest [24]. In parallel to such modeling and experimental investigations, various techniques have also been proposed and developed for effective thermal management of battery modules, ranging from the use of air or a coolant [6,25–27], to the use of phase change materials (PCMs) [3,28–32], heat pipes [33], and hydrogel [34].

As discussed above, optimal thermal management is expected to involve active control strategies. However, past efforts have been primarily focused on the design of cooling systems and not on the active control of such systems, especially the experimental study of active control methods. Therefore, the primary goal of this work is to report the experimental demonstration of the active thermal control of a battery module consisting of multiple Li-ion cells. This work demonstrated and compared several active control strategies experimentally under well-characterized conditions, and the results illustrate the benefits of active control in terms of reduced peak temperature, reduced parasitic power consumption, and reduced temperature non-uniformity. The rest of the paper is organized as follows. Section 2 describes the experimental setup developed for studying active control of battery modules. Section 3 introduces the computational models used behind the control experiments. Section 4 reports the results obtained from the active control experiments and the analysis of these results using the models introduced in Section 3. Finally, Section 5 concludes and summarizes the paper.

2. Experimental setup

The experimental demonstration was performed using a 4-cell battery module as illustrated in Fig. 1. The experimental setup consisted of three major components: a benchtop wind tunnel, a battery module, and diagnostics and control instrumentations. Fig. 1 illustrates the first two components and the third component is illustrated in Fig. 2.

As shown in Fig. 1, the experiments were performed in a benchtop wind tunnel. The tunnel consisted of three major parts: two identical electric fans (labeled as Fan 1 and Fan 2) that drove the tunnel, a battery enclosure which formed the test section, and two flow conditioning sections that connected the fans to the test section. Two fans were used here to produce the reciprocating flow with various patterns by activating and deactivating them in turns. These fans were electric fans, each with a set power of 0.84 W and a maximum speed of 1200 RPM. The flow conditioning sections were used to guide and shape the flow from the fans to the inlet of the enclosure (i.e., the test section) to reduce the velocity non-uniformity of the flow generated by the fans. The distance between the fan and the enclosure was 150 mm. The enclosure had a cross section area of 60 × 60 mm and a length of 175 mm. The battery module to be tested was housed in the enclosure, and the cooling flow could enter the enclosure either from the left or right (labeled as Inlet 1 and Inlet 2 in Fig. 1) depending on which fan was activated.

As mentioned above, the battery module was placed in the test section. In this work, the module included a total of four cylindrical cells (A123 26650, labeled C1, C2, C3 and C4) arranged in series as shown in Fig. 1. The cells used in this work had a capacity of 2.5 Ah. The diameter and height of each cell were 26 mm and 65 mm, respectively. The distance between C1 and Inlet 1, and the distance between C4 and Inlet 2, were both 25 mm. The distance between two adjacent cells was 7 mm, and the distance between the cell and the side wall of the enclosure was 15 mm. There was no gap between the cells' top/bottom surfaces and the enclosure's top/bottom walls. The enclosure was designed in such a way that all the electronic wires and connectors stayed outside of the enclosure to facilitate the corresponding CFD simulations.

The diagnostics and control instrumentations included 7 K-type thermocouples, a cycler (Cadex C8000 Battery Testing System), a personal computer, and a data acquisition (DAQ) system. The K-type thermocouples were used to monitor temperatures at different locations in the experiments, which were labeled as T0–T6 as shown in Fig. 1. These thermocouples were calibrated before use and their accuracy was determined to be 0.3 °C under the temperature range encountered in this work. The diameter of the thermocouple head was 0.25 mm to minimize the disturbance to the flow. During the experiments, T0 was used to monitor ambient temperature, T1 through T4 to monitor the temperature the four battery cells, and T5 and T6 to monitor the temperature at the inlet of the fans. Note that temperature measured by T0 was not always the "ambient" temperature under the active control cases because the flow was reciprocating. As a result, the temperature measured by T0 was actually the outlet temperature during some time depending on how the controller reversed the flow direction. For T1 through T4, they were placed at the middle of the cells in the height direction and toward the side of Fan 2. During the tests, the Cadex C8000 battery cycler was used to charge or discharge the cells, and to monitor and record the voltage and current data of each cell. The voltage accuracy of the cycler was 0.1% of its full scale range of 36 V, and the current accuracy was 0.25% of its full scale range of 10 A. Therefore, the maximum uncertainties of the voltage and current measurement were 0.036 V and 0.025 A for these experiments, respectively.

Fig. 2 shows a block diagram of the diagnostic instrumentation (panel a) and the control method (panel b). As shown in Fig. 2a, the hardware used here included a personal computer (PC), a portable measurement and instrumentation device (National Instrument myDAQ), two integrated circuits (Texas Instruments L293D), and a temperature DAQ module (National Instrument 9213). The PC served as a digital hysterics controller as well as a signal monitor, and the primary functionalities of the PC included receiving the feedback temperature signal from the DAQ, processing the control model, and sending control signals to the fans via the NI myDAQ module. The myDAQ module had 8 digital outputs, which sent