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Thermal management of a large prismatic battery pack based on reciprocating flow and active control

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ABSTRACT

This paper reports the thermal management of a prismatic Li-ion battery pack consisting of a total of 18 cells based on reciprocation flow and active control. Both controlled experiments and accompanying analysis are reported to illustrate the effectiveness of reciprocating cooling flow combined with active control for regulating the cell temperature, reducing temperature non-uniformity, and minimizing parasitic power consumption. Experimentally, a platform with a 3 by 6 prismatic battery module was constructed to perform controlled tests on several competing cooling strategies, including unidirectional cooling flow, reciprocating cooling flow with constant period, and the actively controlled reciprocating cooling flow. The surface and core temperatures of the cells were monitored by the thermocouples during the tests. The major observations from these experiments were twofold. First, the reciprocating cooling flow is effective in reducing the maximum temperature rise and the temperature non-uniformity in the battery pack of practical size. Second, the active control of the reciprocating flow can further reduce both the temperature non-uniformity and the cooling power consumption with a minimal increased maximum temperature rise. Thus through the active control of reciprocating cooling flow, the battery pack can reach a more uniform temperature at the minimum parasitic energy consumption.

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1. Introduction

Thermal management of Li-ion battery pack is one of the key issues for their widespread deployment. Li-ion batteries have been demonstrated as an important power source in a range of applications, such as transportation [1] and energy storage industry [2,3]. In these applications, Li-ion batteries are predominately used in the form a pack of multiple cells, and the formation of large battery pack poses significant difficulty in the thermal management compared to a single cell or a small pack [3]. Challenges of thermal management in a large scale battery pack include high temperature rise or even thermal runaway caused by insufficient heat transfer, excessive cooling power consumption due to increased pack size, the wide range of environmental temperature under which the batteries are used, and the increased temperature non-uniformity along the cooling path due to the pack size. These challenges are compounded by the relatively narrow range of optimal and safe operating temperature for Li-ion batteries, and the thermal management system has to ensure that all the cells in the pack operate within the optimal temperature range. The acceptable operation range for Li-ion batteries is between −10 °C to 50 °C [4,5], and the optimal range is much narrower, approximately from 20 °C to 40 °C [6,7]. Designing a thermal management system that can reliably regulate the temperature of all the cell in a large pack within such a range is a complex issue and has attracted significant research and development efforts [8–12]. Ineffective thermal management can result in efficiency decrease, reduced lifetime, and even catastrophes. For example, batteries working at low temperatures lose significant capacity and power [13], and batteries working at high temperatures degrade faster and have a shorter battery life [14]. In some extreme case, thermal runaway and fire hazards can happen [10]. Besides the optimal working temperature range, the temperature non-uniformity inside the battery pack can also cause problems like different voltage distribution inside pack and different degradation rate [15], which impair the durability and performance of the whole pack.

Due to such significance of the thermal management issues, various cooling methods have been proposed and investigated in the past, including the use of air cooling [16,17], liquid cooling [18,19], and phase change cooling based on heat pipes [20–22] or phase change materials [9,23–25]. These methods all have their

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strengths and limitations. For example, although liquid cooling provides effective heat transfer coefficient, it requires a set of relatively complicated sealing, circulation, and insulating system due to the use of liquid coolant. The use of heat pipe provides a solid-state solution in contrast to the liquid cooling, however, their cost, limited range of operating temperature, and cooling power have limited their widespread application in large scale battery packs [20–22]. The use of phase change material (PCM) can effectively regulate the cell temperature below a critical threshold, but however, only for a finite period of time. Air-based cooling suffers from the relatively low thermal conductivity of air compared to liquid cooling or solid state cooling, however, it enjoys the advantage of system simplicity and low cost [9,23–25]. This analysis of the strengths and weaknesses of existing cooling methods motivates the continued investigation of new and improved thermal management strategies. In this work, a strategy based on reciprocating flow and active control using air as the cooling fluid is described, tested, and analyzed. The results obtained from this work show that this strategy can enable two improvements: the reduction in the temperature non-uniformity in a large pack and the reduction of the parasitic power consumed by the cooling system.

It has been demonstrated in earlier work that the use of reciprocating cooling flow can reduce the temperature non-uniformity in a battery pack [17,26,27]. These past work included simulations using CFD (computational fluid dynamics) a [17], analyses using reduced order models [27], and small-scale experimental tests based on a total of four cylindrical cells [26]. In practice, the battery pack usually consists of more cells and prismatic cells are usually used. The size of the pack and the geometry of the cells can cause increased temperature non-uniformity and maximum temperature rise, and therefore there is a need to test the effectiveness of the reciprocating method under such new conditions. To address this need, this paper studies the reciprocating cooling method on battery pack consisting of a total of 18 prismatic batteries (arranged in a 3 by 6 array). The battery pack consists of 14 dummy cells and 4 real Li-ion cells. The dummy cells were embedded with controllable heating elements to simulate the heating characteristic of the real cells and had the same geometry as the real cells to simulate their aerodynamic characteristics [7,28,29]. Our previous work has shown that such combined use of dummy and real cells as an effective way to experimentally study the behavior of a large battery pack [7].

The second improvement involves the reduction of the parasitic power consumed by the thermal management system. Beside regulating the temperature rise and non-uniformity, the parasitic power consumption of the thermal management system is also an important factor because the parasitic power can be a significant portion of the overall power budget [26,30,31]. As shown in past work based on unidirectional cooling flows, actively controlled cooling can significantly reduce the parasitic power consumption compared to uncontrolled cooling while regulating the temperature rise [7,26,27,32]. Similarly, active control can also reduce the parasitic power consumption when applied to reciprocating cooling flows as demonstrated through numerical models [27] and the experimental test on a small pack consisting of four cylindrical cells [26]. Therefore, it is the goal of this work to explore and assess the effectiveness of active control's ability to reduce parasitic power consumption on a battery pack of practical size when reciprocating cooling is applied.

In the rest of this paper, Section 2 will describe the experimental platform in detail, including the implementation of the reciprocating flow and active control. Section 3 will present the results obtained from this platform, and discuss the effectiveness of reciprocating flow and active control on a battery pack of practical size. Finally, Section 4 will summarize the paper.

2. Experimental setup

The experiment setup used in this work is schematically shown in Fig. 1. The setup consisted of two major components: the battery pack housed within a wind tunnel, and the data acquisition and control system. Fig. 1a shows the top view of the battery pack housed inside a customized wind tunnel. The battery pack consisted of a total of 18 cells, arranged in a 3×6 array as shown. As mentioned earlier, 4 of the cells were real prismatic Li-ion cells (LiFePO4 cell from Bioenno Power) and 14 of them were dummy cells. The dummy cells were fabricated with aluminum, embedded with controllable heating elements inside to imitate the thermal behavior or the real cells, and with outside dimension identical to the real cells to simulate their fluid dynamic behavior [7]. The cells were labeled as Cij as shown in Fig. 1a with *i* denoting the row and *j* the column. Since the dummy cells can simulate the thermal and aerodynamic behavior of the real cells, the location of the cells has no effect on the test results. In this work, the real cells (C22, C23, C24 and C25) were surrounded by the dummy cells. The nominal capacity of each real cell was 20 Ah and the nominal voltage was 3.2 V, so the power capacity of each cell was 64 Wh. The dimension of all the cells was $70 \times 27 \times 167$ mm. The volume of the whole battery pack was 5.68 L, and the power density of this 18 cell pack was 202.77 Wh/L. The total heat capacity of the battery pack was 14.29 kJ/K. Each dummy cell was embedded with the controllable heating element inside so that its heat generation rate can be adjusted independently. The cell to cell distance inside the pack was set to 3 mm as shown. The battery pack was placed in a wind tunnel. The length of the tunnel was 665 mm along the cooling flow direction, the inner width 96 mm, and the inner height 167 mm (which matched the height of the cells). Two fans were installed on each side of the tunnel as shown to generate the cooling flow and alternate its direction. The fan required $\sim$6 s to transition from fully off to fully operational condition.

The data acquisition and control system consists of a temperature acquisition unit, two cell cyclers, and the fan control unit. All the signals from the three units were centralized by a computer as shown. The temperature acquisition unit was formed by a 16 channel temperature measurement module (National Instrument 9213) and 16 K-type thermocouples. The thermocouples were calibrated before use and their accuracy was 0.3 °C at room temperature of 20 °C. The thermocouple locations were shown as red dots in Fig. 1a, with all the thermocouples in the middle of the cell at the vertical direction. The locations of the thermocouples were selected so that the temperature variation can be fully recorded along a row of cells parallel to the cooling channels. Thermocouples labeled as T1 to T4 and T6 to T11 were attached to the surface of the cells to obtain the surface temperatures. However, the core temperatures can be significantly higher than the surface temperatures even with proper cooling flow applied [33]. It is necessary to obtain the core temperature in order to ensure the cells are working in the optimal working temperature range. Previous studies use reduced order models to predict the core temperature of a cylindrical cell through surface temperature and heat generation data [34,35]. Such model provided a non-intrusive way to estimate the core temperatures of cells. In this work, the core temperatures of the prismatic Li-ion cells were directly monitored by five thermocouples: labeled T5 and T12 to T15 during the tests to experimentally evaluate the effectiveness of the cooling strategies and also to provide benchmark data for future modeling work. These thermocouples were inserted in the center of the Li-ions cell through their venting holes on top of the cell, and then the venting holes were properly sealed again after the thermocouples were inserted into the desired locations. The real cells were controlled by a 4 channel cycler (Cadex C8000), each channel providing a maximum charging/discharging current of 10 A and maximum

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