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Combined experimental and numerical study of thermal management of battery module consisting of multiple Li-ion cells

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ABSTRACT

Lithium ion (Li-ion) batteries are promising power sources for hybrid powertrain systems, and the thermal management of batteries has been identified as a critical issue both for safety and efficiency concerns. This work studied thermal management of a Li-ion battery module both experimentally and computationally. A battery module consisting of multiple cells was fabricated and experimentally tested in a wind tunnel facility. Systematic tests were performed under various flow velocities, charging and discharging current, and module configuration. Computationally, a high-fidelity two dimensional computational fluid dynamics (CFD) model was developed to capture the detailed dynamics of thermal management of the cells. Temperature rise of cells and pressure measurements were recorded in the experiments, and compared with CFD model simulations. Reasonable agreement was obtained, confirming the validity of the model. The validated model was then applied to study the power consumption required by the thermal management system. The results obtained in this combined experimental and numerical study are expected to be valuable for the optimized design of battery modules and the development of reduced-order models.

1. Introduction

Due to efficiency and environmental concerns, the importance of hybrid propulsion systems has been recognized for sustainable transportation [1–3]. Secondary lithium ion (Li-ion) batteries are promising for applications in hybrid propulsion systems because of their high energy density, high voltage, good stability, and low charge loss when not in use [4]. To optimize battery safety and life, it is desirable to operate Li-ion battery system in a temperature range of 20–40 °C [4], a relatively narrow range compared to the range of environmental temperature under which the vehicle may operate. Therefore, thermal management of the battery system has been recognized as a critical issue [1–3].

As a result, considerable research efforts have been invested to study thermal management of batteries in recent years. Thermal management has been studied under the context of electronics cooling extensively [5,6]. The governing electro-thermal process in batteries has been modeled based on first-principles [7–9]. Advanced experimental techniques such as neutron imaging are being employed to make *in situ* measurements of lithium concentration to validate these models. Equipped with a fundamental understanding of the governing processes, models are being developed to simulate other aspects of battery operations, including the heat generation in battery cells under different operation conditions and battery geometries using one-dimensional (1D) [10–12], 2D [13], and 3D models [14–16]. These models allow researchers and engineers to investigate various aspects of the thermal management issue of battery modules, with emphasis on two aspects: the uniformity of temperature among cells in a module and the pressure drop [1,17–20]. The temperature uniformity seems to have attracted a significant portion of past efforts. Researchers have studied the temperature uniformity within battery modules both experimentally and numerically [1,17,20], and have investigated various techniques to reduce the temperature non-uniformity including the use of phase change materials for battery [21–24] and the use of various control strategies [25,26]. In addition to the issue of temperature uniformity, the issue of pressure drop is also important. It is directly related to the pump power required in the thermal management system, and subsequently the power available for other vehicle functions. Past efforts have used computational fluid dynamics (CFD) to simulate the pressure drop of various thermal management systems [20,27] in order to seek an optimized balance between cooling effectiveness and pump power consumption. Based on the above understanding of past efforts, several research needs can be identified. First and

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foremost, there is a need for controlled and well-documented experimental data to validate and develop thermal management models. Past efforts have resulted in a range of models, each involving their own empirical parameters, and it is desirable to have an experimental database for validation purposes. Second, there is a need to perform model-based design and optimization. Many aspects for the thermal management of battery systems are difficult, costly, and even infeasible to study experimentally (such as flow friction, temperature non-uniformity, and the effects of cell layout). Hence, it is important to develop and validate models that can be used for such purposes.

This current work therefore focuses on the validation of thermal management models for battery modules, and the application of the validated model to study aspects which are difficult to measure experimentally, such as the power consumption. The uniqueness of this work lies in the combined use of CFD simulations and well-controlled experimental testing, so that the simulations can be validated against experimental data under well-controlled conditions which are directly relevant to practice. Then the validated model can be used to investigate issues that are difficult to study experimentally, as illustrated by some of our ongoing efforts discussed in Section 6. For instance, testing conditions such as air flow velocity of 1 m/s are practical conditions in electrical vehicles and hybrid electrical vehicles [1]. The experimental facility used in this work consists of a wind tunnel, a customized batter module, and a suite of diagnostics. The wind tunnel (an open jet wind tunnel) generates well-controlled cooling air flow with freestream velocity in the range of 0.5–30 m/s (corresponding to ~1.1–67 miles per hour), encompassing conditions expected in most practical applications. The battery module is capable of testing various battery packing geometries, charging and discharging currents, and various cooling air flow velocities. The wind tunnel and battery module are outfitted with a suite of diagnostics to monitor temperature at multiple locations, charging/discharging current and voltage, and also the distribution of pressure drop. Since the experimental facility is capable of carrying out tests under various conditions mentioned above covering all practical conditions, and power batteries of the battery module are A123 26650 cells, which are components of A123 Hymotion™ L5 PCM battery pack [28], tests relevant to practice can be realized under well-controlled conditions.

The rest of this paper is organized as the following. Section 2 described the experimental arrangement and test parameters. Section 3 introduces the 2D CFD model used in this study. Section 4 reports the measurements of temperature rise with direct comparison with CFD results. Section 5 reports the pressure measurements with direct comparison to the CFD, and discusses the pump power consumed by the thermal management system. Section 6 summarizes and the paper and discusses our ongoing efforts.

2. Experimental setup

The experimental setup was similar to that described in [13], with several modifications and upgrades. Here we provide a brief summary of the experimental facility based on Fig. 1 to facilitate the discussion. Panel (a) shows the overall schematic of the experimental arrangements, and Panel (b) the dimensions and configuration of the battery pack, including the position of thermocouples used in the tests. As shown in Panel (a), the experimental facility consists of an open jet wind tunnel, a customized battery module as elaborated in Panel (b), and a suite of diagnostics. The open-jet wind tunnel has a 0.75 × 0.75 m test section and operates with a velocity range of 0–30 m/s. The air flow in the wind tunnel was generated by an AF-600 GE fan, and the flow velocity was controlled by adjusting the speed of the fan. A Pitot tube at the exit of the settling chamber measures the real-time freestream velocity. The battery module consists of a customized enclosure and multiple Li-ion cells. The battery module used a customized enclosure to house the Li-ion cells to be tested, as shown in Panel (b). The enclosure was fabricated using plexiglass because of its good machinability and sufficient mechanical strength. The windward and leeward sides of the enclosure are open and serve as the inlet and outlet of the cooling air flow. The height of the enclosure is 70 mm and the height of the Li-ion cells is 62.5 mm, so that there is space in the height direction (i.e., z direction as shown in Panel (a) to accommodate the wiring of the electronics and thermocouple. The horizontal distance (i.e., distance in the x direction) between the battery cells and the enclosure walls can be adjusted from 3 mm to 17 mm so that the effects of wall–cell distance on cell temperature and pressure drop can be studied during the tests. The cells used in this study are A123 26650 Li-ion cylindrical cells (2.3 Ah 3.3 V), and Panel (b) shows eight of these cells assembled in a 2P × 4S configuration (where P stands for parallel connection and S stands for series connection). The cells are 62.5 mm in height and 25.85 mm in diameter. The battery module was tested in the wind tunnel under air flow velocities of 0 m/s, 1 m/s, 2.5 m/s and 5 m/s. During the tests, the module was rated at 4.6 Ah and 14.8 V with a voltage cut-off limit of 8.0 V. Note that this project focused on generating a basic dataset for model validation under well controlled conditions, and therefore the experiments were intentionally designed to avoid many practical complications. These complications include the geometry of batteries (battery cells of different geometry may have different heat transfer and fluid mechanics properties), layout and packaging of cells, and the various charging and discharging cycles.

The diagnostics outfitted to the test facility include a Pitot tube (to monitor the inlet air flow velocity as mentioned before), thermocouples, a pressure rake, and a charger and discharger to set and monitor the current and voltage of the cells during tests. As shown in Panel (b), five K type thermocouples labeled as T0–T4 were placed in 5 different locations in the module at a height of 30 mm to monitor the temperature of the inlet air and the cells during tests. The thermocouples were calibrated before use and the accuracy of these thermal couples was 0.3 °C under a room temperature of 20 °C. The gap between the cells was small (on the order of ~2 mm) at some places, and therefore the intrusiveness of the thermocouple probes cannot be neglected, causing measurement inaccuracies. Our ongoing efforts, discussed in Section 6, are investigating the use of non-intrusive laser sensors to resolve this issue. A pressure rake was installed on the test rig to measure the total pressure distribution downstream of the battery module for the analysis of aerodynamics of the battery pack. The pressure rake has a total of 28 parallel probes to measure the total pressure at various points simultaneously. In this work, the pressure rake was set at a height of 40 mm and was placed facing the outlet of the battery module enclosure to measure pressure distribution near the outlet.

Two data acquisition (DAQ) systems were used in the tests to log temperature and pressure data. The first DAQ system was a NI 9213 temperature measurement module, which recorded the temperature signal from the thermocouples. In all the tests, temperature measurements were recorded every 10 s (the maximum temporal response of the thermocouple is 0.83 ms). The second DAQ system was an Esterline Model 98RK Pressure Scanning System, which recorded the signal from the pressure rake probes. This scanner is capable of measuring 48 different pressure channels simultaneously, and 28 were used in this study. The pressure data were acquired by scanning the pressure rake in several different positions in the x direction and averaged in a 10 s sampling period.