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Research Paper

Thermal management for high power lithium-ion battery by minichannel aluminum tubes

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HIGHLIGHTS

- A new design of minichannel cooling is developed for battery thermal management system.
- Parametric studies of minichannel cooling for a cell are conducted at different discharge rates.
- Minichannel cooling can maintain almost uniform temperature ($T_{diff} < 1$ °C).
- Pumping power assumption is only about 5 milliwatt.

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ABSTRACT

Lithium-ion batteries are widely used for battery electric (all-electric) vehicles (BEV) and hybrid electric vehicles (HEV) due to their high energy and power density. An battery thermal management system (BTMS) is crucial for the performance, lifetime, and safety of lithium-ion batteries. In this paper, a novel design of BTMS based on aluminum minichannel tubes is developed and applied on a single prismatic Li-ion cell under different discharge rates. Parametric studies are conducted to investigate the performance of the BTMS using different flow rates and configurations. With minichannel cooling, the maximum cell temperature at a discharge rate of 1C is less than 27.8 °C, and the temperature difference across the cell is less than 0.80 °C using flow rate at 0.20 L/min, at the expense of 8.69e-6 W pumping power. At higher discharge rates, e.g., 1.5C and 2C, higher flow rates are required to maintain the same temperature rise and temperature difference. The flow rate needed is 0.8 L/min for 1.5C and 2.0 L/min for 2C, while the required pumping power is 4.23e-4 W and 5.27e-3 W, respectively. The uniform temperature distribution (<1 °C) inside the single cell and efficient pumping power demonstrate that the minichannel cooling system provides a promising solution for the BTMS.

1. Introduction

While the traditional transportation vehicle with an internal combustion engine contributes about 13% of annual world greenhouse gas (GHG) emissions [1], battery electric vehicles (BEV) and hybrid electric vehicles (HEV) are emerging replacements for traditional vehicles to reduce GHG emissions [2]. EVs and HEVs are not only cleaner and more environmentally friendly, but are also more economically effective as the operating cost is reduced dramatically [3]. Due to their high energy density, high power density, long life, and environmental friendliness, Li-ion batteries are widely used for BEVs and HEVs. However, poor performance at low temperature, degradation of electrodes at high temperature, and safety issues due to thermal runaway associated with the Li-ion batteries will directly influence the performance, cost, reliability, and safety of EVs. Therefore, a battery thermal management system (BTMS) is crucial for the EVs [4–10].

During thermal management study for lithium-ion batteries, adequate knowledge of heat generation and thermal behavior inside the battery is required to predict battery temperature. Studies have been done on the thermal modeling of batteries at different operating conditions, i.e., at normal discharge rates and thermal abuses [8,11–20]. For normal operating conditions, Pesaran et al. [11] developed a lumped capacitance battery thermal model to predict the thermal performance and impact of the temperature on vehicle level performance. Based on this lumped model, the thermal behavior of modules and packs were evaluated. In another study by Chen et al. [12], a detailed three-dimensional thermal model was developed to examine the thermal behavior of a lithium-ion battery, considering the layered-structure of the cell stacks, the case of a battery pack, and the gap between both elements. Using this detailed model, the asymmetric temperature profile and the anomaly of temperature

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distribution on the surface can be simulated precisely. Besides these modeling techniques for normal conditions, different models were also developed for oven exposure testing. A one-dimensional predictive model for a 18,650 lithium-ion cell was developed by Hatchard et al. using the kinetics of jelly-roll material decomposition reactions [13]. To consider geometrical features, a three-dimensional model was developed by Kim et al. to determine the local hot spot propagation through the cell [14]. Their results showed that cell size greatly affected the thermal behavior of a cell due to different heat transfer area per unit volume. Guo et al. proposed another three-dimensional model to predict the thermal abuse performances of lithium-ion batteries with high capacity, and analyzed the temperature distribution under the abuse conditions [15]. The model predictions were compared to experimental test results and a good agreement was observed. For other abuse situations, thermal modeling for the battery pack has also been developed in a one-dimensional lumped model [16] and further in a three-dimensional model [17]. Thermal runaway caused by nail penetration was experimentally studied by Doh et al. [18] and Chiu et al. [19], who also modeled the complex reactions and mechanisms during the thermal runaway.

With profound understanding of the thermal behavior of battery cells at different operating conditions, different battery thermal management systems (BTMS), e.g., air cooling, liquid cooling, and phase change material (PCM) cooling, have been applied to avoid the safety issues from thermal aspect and to maintain the optimal operating temperature. Forced air cooling with different structures has been applied by manipulating the position of the air-inlet and the air-outlet along with longitudinal or horizontal battery packs [21–26]. However, compared with the effectiveness of passive cooling by PCM, the active forced air cooling is not a proper thermal management system to keep the temperature of the cell in the desirable operating range without expending significant fan power [27]. Another advantage of the PCM cooling is that the heat generated during the discharge can be stored as latent heat in the PCM and transferred back to the cell module during the relaxation. Therefore, the battery temperature can be kept above the environment temperature, which can increase the overall energy efficiency of the battery system [28–31]. Compared with the PCM cooling and air cooling, liquid cooling systems can provide more effective heat transfer with different channel designs [32–34]. The cold-plate structure of the S-type with guide plates was introduced by Zhang et al. to avoid the heat concentration and increase the heat transfer area [32]. To enhance the performance of the conventional channel with minimum pressure penalty, an oblique minichannel liquid cold plate was developed by Jin et al. to cool down the EV batteries without over-designing the cooling system [33]. In spite of these studies, a safer and more cost-effective thermal management system is still required.

In the present study, a new battery thermal management system using aluminum minichannel tubes was designed. Different designs of tube systems were parametrically studied at different discharging rates. The numerical modeling of the battery and cooling system design is introduced in the next section. To examine the performance of this BTMS at different discharge rates, different designs of tube systems are applied and the results are shown in the third section. The conclusion on the applicability of the minichannels cooling system is given in the last section.

2. Method

2.1. Physical problem

The computational domain consists of a prismatic geometry as the representative of one single battery cell, the minichannel cooling system, and the fluid. The dimensions for the cell are 173 mm (z: height) by 168 mm (x: width) by 39 mm (y: depth), and the capacity is 55 Ampere-hours. The heat generation inside battery is assumed uniform, but the thermal conductivity is anisotropic. Other properties of the battery are assumed homogenous. The aluminum minichannel tubes wrap around three sides of the battery, as shown in Fig. 1(a)–(d). The geometry of the tubes is shown in Fig. 1(e): the height of channel (h) is 3 mm, and width (w) is 3 mm. The thickness of aluminum between the outer surface and channel (δ) is 1 mm, and the thickness between two neighbor channels will be twice δ [35]. With this minichannel cooling system, the temperature distribution across the battery is studied at different discharge rates. The desired temperature range for battery performance is between 15 °C and 35 °C [36]. If the battery temperature is below this range, battery performance will be lowered due to poor ion transport. On the other hand, a temperature higher than that range will cause faster side reactions, leading to higher dissipation rates of cyclable lithium and active materials.

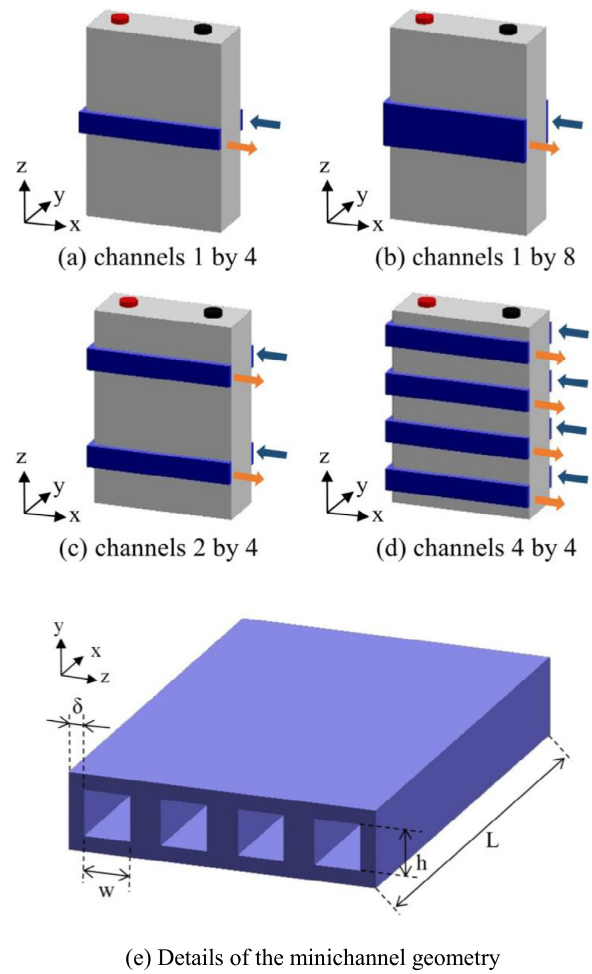

Fig. 1. Different designs of minichannel cooling system: (a) one strip with four minichannels; (b) one strip with eight minichannels; (c) two strips with four minichannels each; and (d) four strips with four minichannels each (blue arrows indicate the inflow direction and orange ones represent outflow direction); (e) details of the minichannel geometry.

2.2. Governing equations

The energy conservation equation of the battery cell is given as follows:

$$\rho_b C_b \frac{\partial T_b}{\partial t} = \frac{\partial}{\partial x}\left(k_x \frac{\partial T_b}{\partial x}\right) + \frac{\partial}{\partial y}\left(k_y \frac{\partial T_b}{\partial y}\right) + \frac{\partial}{\partial z}\left(k_z \frac{\partial T_b}{\partial z}\right) + Q_b \quad (1)$$