Polymeric hollow fibers: a modular heat exchanger for thermal management systems of battery modules in electric vehicles

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Abstract. The liquid-cooling system based on polymeric hollow fibers (ø1 mm) embedded inside durable polydicyclopentadiene is proposed for thermal management of li-ion cylindrical batteries from their surface. In the present work, a dramatically improved design is presented, eliminating the following drawbacks: I) the thermal resistance of the heat exchanger is minimized by bringing fibers into direct contact with the negative terminal/cylindrical shell, II) the fabrication process (combination of extrusion and rapid injection molding) is significantly simplified and accelerated as the essential component of the heat exchanger is nearly planar, and III) inlet/outlet manifolds were refined to enhance modularization of the cooling system of the whole battery pack. The pressure loss of the heat exchanger is favorably low, about 100 Pa, corresponding to 10 l/min of the coolant circulating in the entire battery pack of a virtual electrical vehicle. The heat exchanger was stacked with 18650-type lithium-ion cells, which were repeatedly charged/discharged. With the coolant inlet temperature of 20 °C and the C-rate of 1 C, the maximum temperature of the cells during cycling was between 26 °C and 22 °C in the given range of flow rates (5–45 ml/min). Temperature spreads were 10 °C and 4 °C.

1 Introduction

Well-designed battery thermal management systems (BTMS) ensure optimal thermal conditions for batteries [1]. Temperature variations are caused by heat generation in the battery due to Ohmic losses, concentration gradients (mixing of species), and activation (interfacial energy). Undesired thermal effects, such as capacity/power fade [2], self-discharge [3], thermal runaway [4], electrical imbalance, and low-temperature performance [5], can affect batteries' performance, lifetime, and safety if not maintained at around 25 °C [6]. At elevated and low temperatures, different phenomena accelerate ageing of the battery. As a result, an active BTMS is needed, which involves a cooling system. Many different approaches are known, from which conventional liquid systems, systems with vapor compression cycles (VCC) [7] and air-cooled systems [8] are commonly involved in existing electric vehicles. The air-cooled systems are seen with low/medium power battery packs, those designated for home charging. On the contrary, battery packs of the newest powerful electric vehicles (EV), particularly those demanding super-charging, necessitate discharging a considerable amount of heat; thus, involve the liquid-cooled systems or systems with VCC. In addition, it is more an objective of research than an engineering application to explore the potential of phase-change materials (PCM) [9], heat pipes (HP) [10], thermoelectric coolers [11], and thermo-acoustic refrigerators [12]. Apparently, future developments seem to stay with the liquid-cooled systems, systems with VCC or a combination of both.

A sound design of a heat exchanger, an essential component of the liquid-cooled system, necessarily requires knowledge of the heat generated in the battery. Battery pack designers rely on data from experiments [13] as well as simulations [14].

Mini-channel cold plates, also known as serpentine channels [15] or cold plates [16], are the most used heat exchangers for temperature control of prismatic and pouch cells. Often, the word "serpentine channels" is used when referring to the well-known cooling strategy applied in TESLA cars [17]. Aluminium and even copper are frequently entering ingredients, which are raw materials burdened with a very high carbon footprint. Furthermore, the weight-based standards bestowed on car makers make them literally fight for every gram of a vehicle to meet CO_2 targets. Therefore, plastics may be the way to go due to their favorably low density. Concerns linked with an undesirably increased thermal resistance due to the low thermal conductivity can be overcome, e.g. by considering thinner walls of the heat exchanger. Note that metal heat exchangers often must be lagged with electrical insulators to avoid short circuits, which is unnecessary with plastic counterparts. Further note that the thickness of such thermal insulators is often the same size as the wall

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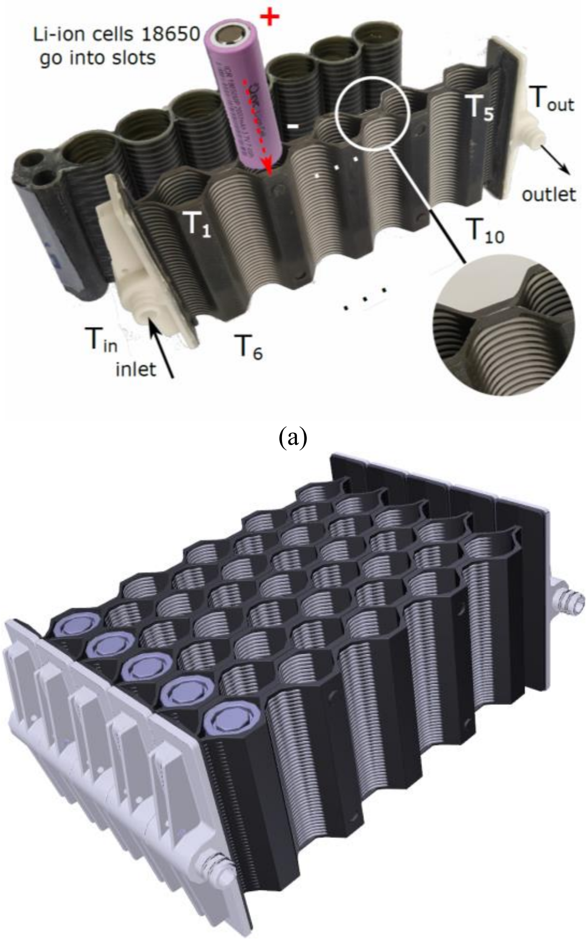
thickness of the polymeric hollow fiber. Therefore, the advantage of highly conductive materials such as aluminium goes to waste. Then, the polymeric heat exchanger offers the same or better thermal performance and more compact dimensions.

In the present work, a plastic heat exchanger is presented for surface cooling of cylindrical 18650-type Li-ion cells (Figure 1). It is a dramatically improved version of the heat exchanger published in [18, 19]. Coolant channels are made of polypropylene hollow fibers [20, 21] with an inner diameter of 0.84 mm, frozen permanently in a polydicyclopentadiene housing. Unlike the preliminary design, the fibers protrude halfway where the cells are in direct contact with the heat exchanger. Redesigned inlet/outlet manifolds promote flexibility of the cooling system. An assembly of several heat exchangers fills the space between the cells completely. The mass-weighted ratio of the heat exchanger-to-battery is just about 1:5. Each cell is firmly clamped within the flexible fibers; moreover, little protrusions in the heat exchanger prevent the cells from slipping out.



(a)

(b)

Fig. 1. A polymer heat exchanger with hollow fibers as coolant channels (a) – the preliminary (back) [18] and the progressed (front) prototype; a compact assembly for a battery module (b) with the first row of Li-ion cells inserted.

2 Experiments, results and discussion

2.1 Pressure drop

As displayed in Figure 2, the heat exchanger reveals favorably low pressure drops in the wide range of flow rates. For example, the flow rate of 15 ml/min would roughly correspond to 1.0 l/min per battery module of TESLA Model S [22] if the battery module was virtually assembled according to Figure 1b. The flow characteristics were examined in the experiment, which is shown in Figure 2. The pressure drop measurements were realized with the BD SENSORS pressure measurements device (max. 1000 Pa of a pressure difference). The pressure drop is extremely low due to many heat exchangers connected in parallel assuming negligible losses in manifolds. The flow distribution into individual heat exchangers is currently a subject of CFD simulations and optimization to improve the manifold design. The goal is to achieve a uniform distribution of the flow and a small pressure drop on manifolds compared to the pressure drop in hollow fibers.

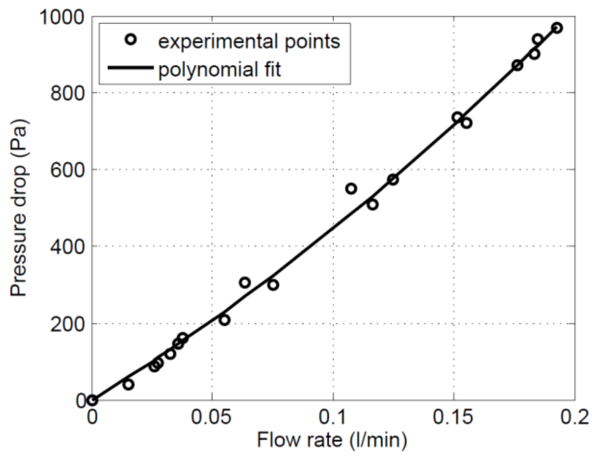


Fig. 2. A pressure drop of the heat exchanger shown in the foreground of Figure 1a.

2.2 Thermal performance

The Li-ion cells (18650 cell type with the capacity of 2200 mAh) connected in series were subjected to a computer-controlled charge/discharge cycling in the entire range of state-of-charge (SOC). The West Mountain Radio Computer Battery Analyzer CBA IV with the 500W amplifier and the charge controller were used for that purpose. A constant current (CC) of 2.2 A, corresponding to 1 C-rate, was considered. 1 C means that the battery is charged to the full capacity exactly in one hour. Charging was stopped when the maximum voltage of 4.2 V of the Li-ion cell was reached. Likewise, discharging was stopped when the voltage dropped to 2.8 V. The voltages are following the manufacturer's specification. The inlet temperature of the coolant (a distilled water) was 20 °C. The flow rates were 5, 10, 20, and 45 ml/min. Such small flow rates were adjusted by the precise flow-regulating needle

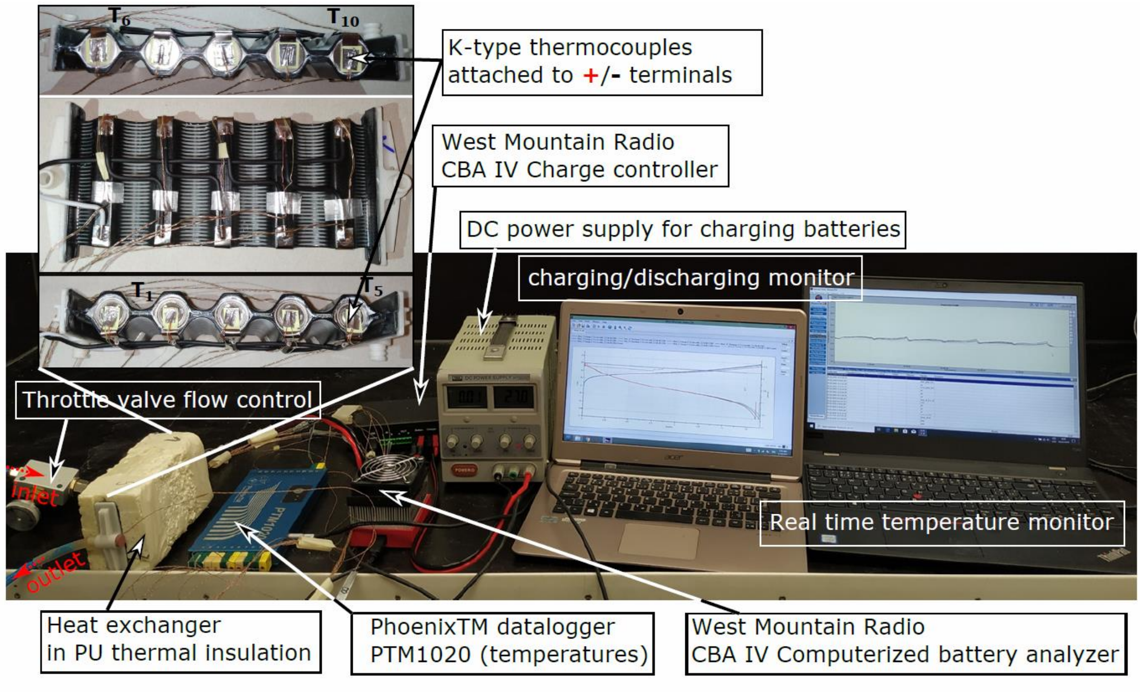


Fig. 3. A photo of the experimental set-up with a detail of wiring Li-ion cells 18650 and the location of K-type thermocouples.

valve (HAM-LET Group H-1300 series), a filtration component, and the KROHNE flow meter VA40V/R. The experimental setup is shown in Figure 3.

K-type thermocouples were used to record temperatures of positive and negative tabs of each 18650, as shown at the right top of Figure 3. The thermocouples were electrically insulated from the tabs to avoid the false reading of the temperatures. As the highest temperatures can be expected to occur at the tabs, the temperature is measured therein. Note that wiring has to have a low enough electric resistance to avoid parasitic Joule heating.

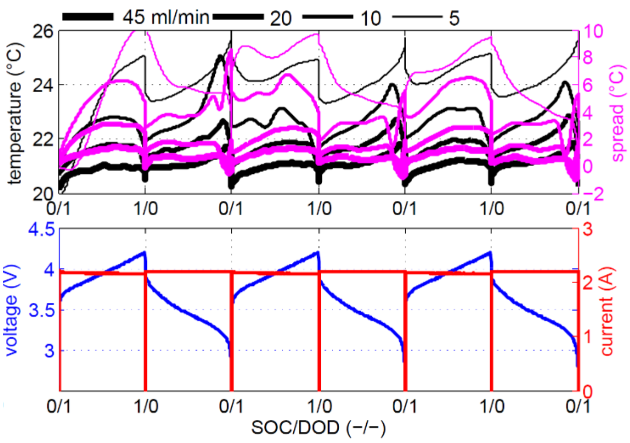


Fig. 4. The thermal performance (at the top) of the heat exchanger assessed by means of the mean temperature (black) and the temperature spread (magenta) of the cells in the range of flow rates (5–45**)** ml/min. Corresponding voltage and current during charging/discharging (at the bottom).

As shown in Figure 4, the cells' mean temperature and temperature spread during cycling were not exceeding 26 °C and 10 °C, respectively, for the lowest flow rate of 5 ml/min. Concerning the highest flow rate of 45 ml/min, the numbers significantly improved, namely 22 °C and 4 °C. In addition to temperature curves, the voltage and the current are shown at the bottom of Figure 4.

3 Further comments and future outlook

To obtain a reliable heat exchanger, particularly ensuring a perfect bonding between the polymeric fibers and the polydicyclopentadiene (PDCPD) thermoset, appropriate parameters of the rapid injection molding (RIM) had to be adjusted. The final quality of the heat exchanger was inspected with the help of computed tomography. A 3D CT scan with a planar section provides a closer look at the crucial fiber-PDCPD interface in Figure 5.

Cylindrical Li-ion cells have by one order of magnitude higher effective thermal conductivity in the axial direction than in the radial direction. Moreover, nowadays battery manufacturers and customers from the EV automotive seem to shift from the type 18650 over the 2170 to the “tabless” 4680. Hence, the increasing tab surface area and the higher conductivity along the axis of the can suggest switching to the tab cooling in the near future.

In the present work, a plastic heat exchanger was introduced for a cylindrical type of Li-ion cells. However, our lab also has an ongoing research on heat exchangers for prismatic or pouch cells. In Figure 6, the first photo shows organized fibers just before the RIM, and the second photo shows the final planar heat exchanger with the precast manifold.

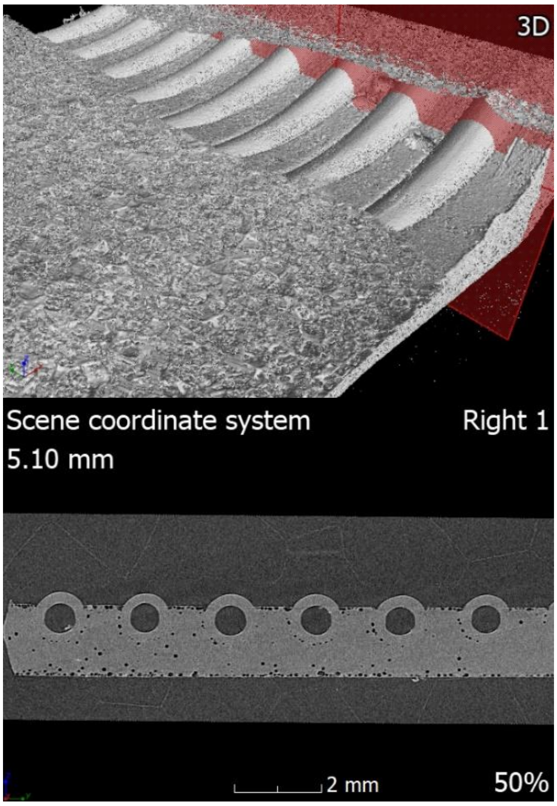


Fig. 5. A detailed view of the 3D CT scan of the heat exchanger, in which the fibers protrude outside the PDCPD matrix (top) and the planar section showing an intact wall thickness of the fibers (bottom).

Fig. 6. Parallel fibers before the RIM process at the top and the final planar heat exchanger at the bottom.

4 Conclusions

A plastic heat exchanger was introduced to be used in battery modules of electric vehicles. Since the aluminium counterparts must be electrically insulated using special foils (~0.1 mm thick), the proposed plastic alternative comprising many polymeric hollow fibers (~0.1 mm wall thickness) provides the same or even more favorable thermal resistance. Hence, the plastic heat exchanger shows a competitive thermal performance and the corresponding dimensions are advantageously smaller.

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