Experimental Analysis of a Liquid-Based Cooling System for Fast Charging of a High-Power Lithium Ion Cell

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ABSTRACT

An effective thermal management system is necessary for lithium-ion batteries in electric vehicles particularly for fast charging applications to dissipate the excessive generated heat in the batteries. The liquid-based cooling system is one of the most common cooling solutions for batteries due to the compact structure and high cooling efficiency. In this paper, an experimental study is conducted to analyze the effectiveness of a new flat-tube liquid cooling plate for thermal management of a high-power lithium-ion cell during the fast charging process. The cooling plate is made of Aluminum and it is placed at both sides of the battery. A test bench is developed for performing the experimental tests and the temperature of the cell at different points is measured by five thermocouples. The thermal behavior of the cell is investigated at a high C-rate periodic pulse and fast charging current profiles. The results indicate that the cooling system can keep the battery temperature close to the maximum desired temperature range for Li-ion batteries. Moreover, good temperature uniformity is observed on the battery surface. The results of this study demonstrate that the proposed liquid cooling system is an efficient solution in the design of battery systems for fast charging applications.
1. INTRODUCTION

In recent years, due to shortage of fossil fuel resources and air pollution caused by combustion-engine vehicles, the technology of clean energy vehicles such as hybrid electric vehicles (HEVs) and electric vehicles (EVs) have attracted more and more attention. Lithium-ion (Li-ion) batteries are considered as the best energy storage in electric vehicles because of outstanding features such as long lifetime, high energy density, high power, and low self-discharge in comparison with the other battery types [1,2]. However, Li-ion batteries are very sensitive to the working temperature in terms of performance, safety, and lifetime [3]. The desired operating temperature for Li-ion batteries is between 20 to 40 °C [4]. This issue has had a great effect on hindering the fast charging technology development as there is a severe heat generation in Li-ion batteries during the fast charge process [5]. Hence, a well-designed and efficient thermal management system is necessary for battery packs in electric vehicles capable of controlling the maximum temperature of the battery during fast charging applications.

The liquid-based thermal management system is one of the most common methods for batteries in electric vehicles due to the high efficiency and compact structure. Tesla Model 3, Tesla Model S, Audi e-Tron, Chevrolet Volt, and Chevrolet Bolt are such examples of an electric vehicle with the liquid cooling system available on the market. Many researchers have paid attention to the liquid cooling system for thermal management of batteries. Patil et al. [6] studied the thermal performance of a Li-ion pouch cell and pack with a U-turn microchannel cooling plate under high discharge rate. They investigated the effect of coolant inlet flow rate, inlet temperature, channel width, number of cooling channels and the flow pattern layout on the thermal performance. They found that the maximum temperature of a 50 V battery pack could be maintained blow than 40 °C by using the optimized cooling parameters, with the maximum temperature non-uniformity of 4 °C. Panchal et al. [7] investigated the thermal behavior of a lithium-ion battery using a mini-channel cold plate. They found that the temperature of the battery near the electrodes is higher than the temperature at the centre of the cell. Rao et al. [8] presented a novel liquid cooling system for a cylindrical lithium-ion battery module with the variable contact surface. They designed three types of contact surfaces and compared them with the system having a constant surface. They showed that the performance of the system with variable contact surface is better than the system with the constant contact surface. Deng et al. [9] investigated numerically a serpentine-channel cold plate for liquid cooling of a Li-ion battery. They studied the effect of channel number, channel layout and the inlet temperature on the cooling performance of the thermal management system. Their simulation results demonstrated that the cold plate with 5-channels results in the most efficient cooling performance. Tang et al. [10] studied a water-cooling system combined with mini-channel for a Li-ion battery module. They found the best cooling performance with the cold plates at the bottom and on two sides of the module.

Numerous researchers have combined the liquid cooling with passive cooling methods such as phase change materials (PCMs) and heat pipes for thermal management of Li-ion batteries. Cao et al. [11] designed a thermal management system that combines phase change materials with liquid cooling for a battery pack with 20 cylindrical cells. They found that a high water
flow rate can significantly increase the axial temperature difference and power consumption, while it slightly reduces the planar temperature difference and the maximum temperature. Zhang et al. [12] experimentally investigated a hybrid thermal management system using bottom liquid cooling and phase change materials for a large-size battery module. They found that the hybrid cooling system can successfully prevent heat accumulation and maintain the maximum temperature under 50 °C, while the pure PCM cooling is ineffective because of heat accumulation. Hekmat and Molaeimanesh [13] carried out an experimental investigation on PCM and water pipe cooling for a Li-ion battery module with high capacity prismatic-shape cells. They found that combining the water cooling with PCM results in a high-efficient cooling system for batteries.

The literature review of liquid-based battery thermal management systems shows that there is a lack of studies using a liquid-based system for fast charging application. In this paper, an experimental investigation is conducted to evaluate a new liquid cooling system for thermal management of a high-power Li-ion cell at high currents. In this regard, the battery thermal behavior is investigated for two different test profiles including a pulse current test and a fast-charging test. This paper is organized as follows: in section 2, the features of the investigated cell, the structure of the cooling plate and the experimental setup are described. The details and results of the experimental tests are given in section 3, and the conclusions and areas of future research are presented in section 4.

2. EXPERIMENTAL

A commercial high-power lithium-titanate (LTO) battery with a nominal capacity of 23 Ah and a nominal voltage of 2.3 V is investigated in this study. The electrical specifications of the cell are given in Table 1.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Chemistry (-)</td>
<td>LTO</td>
</tr>
<tr>
<td>Geometry (-)</td>
<td>Prismatic</td>
</tr>
<tr>
<td>Nominal capacity (Ah)</td>
<td>23</td>
</tr>
<tr>
<td>Nominal voltage (V)</td>
<td>2.3</td>
</tr>
<tr>
<td>Dimension (mm)</td>
<td>103×115×22</td>
</tr>
<tr>
<td>Weight (kg)</td>
<td>0.55</td>
</tr>
<tr>
<td>Energy density (Wh/kg)</td>
<td>96</td>
</tr>
<tr>
<td>Operating voltage (V)</td>
<td>1.5 – 2.7</td>
</tr>
</tbody>
</table>

The schematic of the cooling system structure is depicted in Fig. 1. The cooling system is comprised of two identical flat-tube cooling plates located at both sides of the battery. The cooling plates are made of Aluminum with a thickness of 3 mm. There is an extruded rectangular channel in the cooling plates with a thickness of 1.6 mm. The height of the cooling plate and channel are shown in Fig. 1(b).
Fig. 1. (a) Cooling system structure, (b) Cooling plate dimensions.

Five thermocouples are employed to measure the battery temperature during the experimental tests. The position of thermocouples on the cell surface is shown in Fig. 2. As it is seen, four thermocouples are attached to the corners of the cell, and the other one is attached to the centre of the cell. Moreover, a gap filler is used between the battery surface and the cooling plate to reduce the thermal contact resistance.

Fig. 2. Position of thermocouples on the cell surface.

The cooling circuit is shown in Fig. 3. The water as the coolant is forced into the cooling plates by a pump, and after absorbing the heat from the battery, it passes through the pipeline and goes to the radiator to release the heat to the environment. It is worth mentioning that the battery surface is covered with an isolating material to reduce the effect of ambient on heat dissipation from the battery. In all experiments, the water flow rate is set to 4 L/min with the inlet temperature of 23 °C.
3. Results And Discussion

3.1. Pulse current test

A pulse current test is carried out in order to investigate the thermal behavior of the cell in the steady-state condition. For this purpose, periodic 8C charge and discharge currents with 2 seconds duration are applied to the cell at 50% of SOC. With this type of load profile, the same battery capacity is extracted and injected to the cell. Therefore, the SOC remains constant during the test and the battery can be heated for a long time to ensure reaching the steady-state thermal behavior. At the beginning of the test, the cooling system is off. After around 6000 seconds when the battery temperature is fully in the steady-state condition, the cooling system is triggered, and the test is continued until reaching the steady-state condition with cooling.

The heat generation in the cell can be calculated as follows:

$$\dot{Q} = (V - V_{OCV}) \cdot I$$

(1)

where $\dot{Q}$ is the heat generation inside the cell, $V$ is the battery voltage, $V_{OCV}$ shows the open-circuit voltage, and $I$ is the working current. It must be noted that the effect of the entropic term in heat generation calculation is not considered because of using a high current. Numerous studies can be found in the literature which demonstrates that neglecting the entropic term in heat generation calculation is reasonable at this high current application as it is very small in comparison with the Ohmic heat generation [14-16].

Figure 4 illustrates the pulse current applied to the battery, the relevant voltage response, and the heat generation in the cell. Since the battery internal resistance increases as the battery temperature decreases, it is observed in Fig. 4(c) that the heat generation in the cell increases after triggering the liquid cooling system ($t = 6000$ s).
Fig. 4. Pulse test results, (a) Current profile, (b) Voltage response, (c) Heat generation.

Figure 5(a) shows the measured temperatures by thermocouples during the pulse test. As can be seen, the battery temperature increases until $t=6000$ s due to the lack of liquid cooling, and after that the temperature drops due to the activation of the cooling system. The maximum temperature corresponds to thermocouple number 3 which is attached to the centre of the cell with the value of 49 °C. It is worth mentioning that depending on the thermocouple, the temperature reduces around 13.5 to 15 °C with the cooling system. The maximum temperature
difference between the thermocouples or the temperature gradient ($\Delta T$) is shown in Fig. 5(b). Before triggering the cooling system, the temperature gradient is around 3.5 °C. When the cooling system is triggered, a high-temperature gradient occurs on the cell with the value around 9 °C. This temperature gradient is gradually decreasing until reaching to steady-state condition with the value around of 5.5 °C.

![Figure 5(a)](image1)

![Figure 5(b)](image2)

**Fig. 5.** Thermal behavior of the cell during the pulse current test, (a) Recorded temperatures, (b) Temperature gradient.

### 3.2. Fast-Charging Test

The objective of this test is to investigate the thermal behavior of the cell under the fast charging process. In order to perform this test in a condition similar to the real operation of an electric vehicle, firstly, the battery is discharged with 4C while the cooling system is off. The 4C discharge causes the battery temperature increase, but the temperature remains below than 40 °C which is still in the desired temperature range of the batteries, and there is no need to the cooling system operation yet. After a short resting period, the battery is charged at 8C and the cooling system is triggered from the beginning of the charging process. The charging process is comprised of two phases including constant current (CC) and constant voltage (CV). In the
constant current stage, the battery is charged at 8C until reaching the upper voltage of 2.7 V, and then this voltage is kept, and the current goes down to reach 0.05 C. Figure 6 shows the current profile, the voltage and heat generation in the battery for this test. As can be seen in Fig. 6(c), the average heat generation during the 4C discharge is around 18 W, while during the CC phase of the 8C charging is around 60 W.
Fig. 6. The procedure of fast charging test, (a) Current profile, (b) Voltage response, (c) Heat generation.
Figure 7 illustrates the measured temperatures by thermocouples as well as the maximum temperature difference between the thermocouples ($\Delta T$) during the fast charge test. It is seen that the same as pulse current test, the maximum temperature is on the centre of the cell. Depending on the thermocouple position, the temperature increases around 11 to 14.5 °C during the 4C discharge. After the rest period, the maximum temperature of the cell (T3) is around 35 °C which as mentioned earlier is in the desired battery temperature range. The battery reaches to its maximum temperature at the end of the CC phase of fast charging process which is around 43.5 °C which is close to the maximum desired temperature for Li-ion batteries (40 °C). Therefore, the temperature increase during the fast charging is around 8.5 °C. Although the average heat generation in the 8C charge is four times higher than the 4C discharge, the temperature increment in the 8C charge is around 6 °C less than the 4C discharge due to the operation of the cooling system. Moreover, as seen in Fig. 7(b) the temperature gradient on the cell reaches its maximum value at the end of charging CC phase which is around 7 °C.
Fig. 7. Thermal behavior of the cell during the fast charge test, (a) Recorded temperatures, (b) Temperature gradient.

4. CONCLUSION

This paper presented an experimental investigation on a liquid-based cooling system for a high-power Li-ion battery at high current applications. The cooling plate which is made of aluminium is placed on both sides of the cell. Two different tests were studied including a pulse current and a fast-charging test both at a high current of 8C. In the pulse test, the cooling system was off at the beginning of the test, and it was triggered when the steady-state temperature of the battery was achieved. It was seen that the cooling system is able to reduce the temperature up to 15 °C. The maximum temperature gradient has occurred at the beginning of cooling phase with the value of 9 °C which gradually decreased during the time until reaching the steady-state value of 5.5 °C. In the fast charging test, the cell was initially discharged at 4C without
cooling. The battery temperature increased during the discharge process, but it was still in the desired temperature range (less than 40 °C). After the discharge process, a rest period was imposed on the cell and then it was charged at 8C. The cooling system was triggered at the beginning of the 8C charge process. Although the heat generation during the fast charging was around 4 times larger than the discharge process, the increase in the cell temperature during the charge was 6 °C less than discharge because of the liquid cooling. The maximum temperature of the cell during the charging process occurred at the end of the CC phase with the value of 43.5 °C which is close to the maximum desired temperature for Li-ion batteries. In the continuation of the present research, the future works will study the same thermal management system on the battery module level along with CFD modeling.

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