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Experimental and Numerical Study of Flat Heat Pipe-Liquid Cooling Battery Thermal Management System

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ABSTRACT

An effective battery thermal management system (BTMS) is of great significance to ensure safety and extend the service life for lithium-ion batteries (LIBs). In this paper, to obtain a more suitable operating temperature and a better temperature uniformity for the battery module, an ultrathin flat heat pipe-liquid cooling BTMS is proposed. The effect of different influence factors are investigated through the numerical simulation and the optimization is conducted on this basis. The results suggest that the heat can removed efficiently through the proposed BTMS, and the maximum temperature can be controlled below 43℃. Additionally, a variable heat pipe length scheme is proposed for the BTMS, which can significantly improve the temperature uniformity of the battery module. The average temperature difference can be controlled below 2℃ under the high discharge and current changing discharge process in comparison with the original system. The study facilitates a guideline for the optimization design of a BTMS.

Keywords: Flat heat pipe, Battery thermal management, Thermal performance, Lithium-ion battery.

1. INTRODUCTION

Electric vehicles (EVs) have gradually become a popular selection. Lithium-ion battery (LIB) has been dominantly utilized in EVs for the high energy density [1]. Nevertheless, the temperature has a significant influence on LIBs, and the optimum operating temperature is generally ranged from 25℃ to 45℃ [2, 3]. Therefore, designing an effective battery thermal management system (BTMS) is of great significance to ensure the operation safety and extend the service life for the whole battery pack.

The BTMS can be generally divided into air based, liquid based, phase change materials (PCM) based, heat pipe based, and the combination of the above methods [4, 5]. Heat pipe is an efficient heat-conducting element with superior thermal conductivity has been widely used in all kinds of cooling systems due to the excellent performance of long service life, flexible geometry, and compact structure [6]. However, since the little contact area between the cells and heat pipes, the heat transfer capability of traditional circular heat pipe is limited [7]. Thus, the flat heat pipe (FHP) is widely applied in BTMSs.

The combination of different cooling methods based on the flat heat pipe has been investigated in recent studies [8]. Zhou et al. [9] designed a sandwich structure consisted of the ultra-thin FHP and batteries. A new structure of FHP combined with fins proposed in [10]. Dan et al. [11] established an equivalent thermal model for a microchannel FHP-air cooling BTMS. Zhao et al. [12] investigated a FHP-wet cooling system to improve the cooling efficiency. The relevant researches of FHP based BTMSs are mainly focus on experiments, and the optimization is merely conducted that various influencing factors are ignored.

In this work, an ultra-thin flat heat pipe-liquid cooling BTMS is proposed in this paper. To obtain a better temperature performance, the numerical simulation cooling model is established and validated by experimental results. The effects of different variables on the battery packs were investigated. On this basis, a variable length cooling strategy is established to improve the temperature uniformity. The study is organized as following: the proposed BTMS is constructed and

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modeled in Section 2. Experiment of the BTMS is carried out in Section 3 to verify the thermal models, and the cooling effectiveness of the BTMS is optimized and analyzed under constant and variable discharge process in Section 4. The conclusions are summarized in the final section.

2. MODEL DESIGN AND VALIDATION

2.1 The proposed heat pipe-liquid cooling BTMS

The proposed flat heat pipe-liquid cooling BTMS is designed as shown in Fig 1. In this design, five commercial pouch lithium-ion batteries (LIBs) are connected in series. The ultra-thin flat heat pipes and cells are stacked alternately to form a compact sandwich structure. The condensation sections of the flat heat pipes are extended to the outside of the batteries and immersed into the cooling channel, and the inlet and outlet are distributed on the downside and upside of the cooling channel.

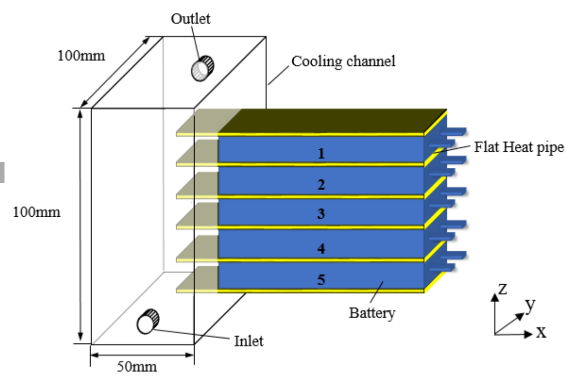


Fig 1 Schematic illustrations of the BTMS

The working process of the BTMS is operated through various heat transfer processes, as displayed in Fig 2. Heat generated from the cell transfers into the evaporation section of the flat heat pipe through the contact surface, then phase change occurs inside of the heat pipe, and the heat is finally taken away by the coolant contact with the condensation section directly through the convection heat transfer.

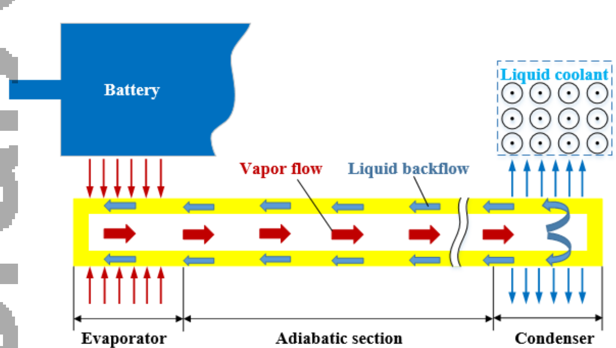


Fig 2 Heat transfer process of the BTMS

The simulation model of the proposed BTMS is constructed and meshed in the commercial CFD software ANSYS Fluent. In this thermal model, the cells and heat pipes are considered as a homogeneous material.

2.2 Experiment and validation

The schematic of the experimental setup is displayed in Fig 3. The battery module is discharged at 2 C and 4 C discharge rate, and the temperature data is recorded in the meantime. The discharge process is finished until the voltage is descended to 15 V.

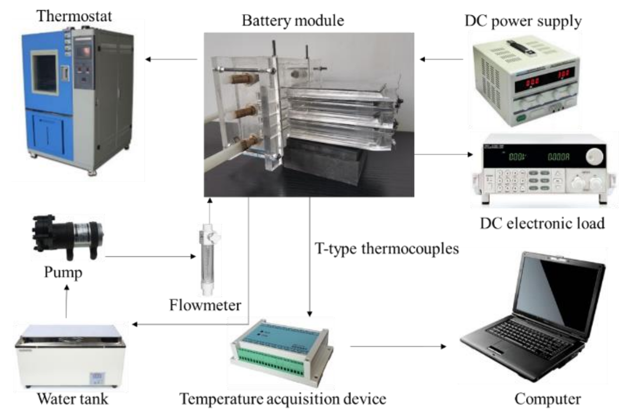


Fig 3 Schematic of the experimental setup

The accuracy of the simulation model is validated by experimental testing at 2 C and 4 C discharge rate, the temperature variation of the computational results and experimental data are shown in Fig 4. As can be seen that the simulation result has a good agreement with the measured data. The maximum relative deviation of the temperature is below 3% at variable discharge process.

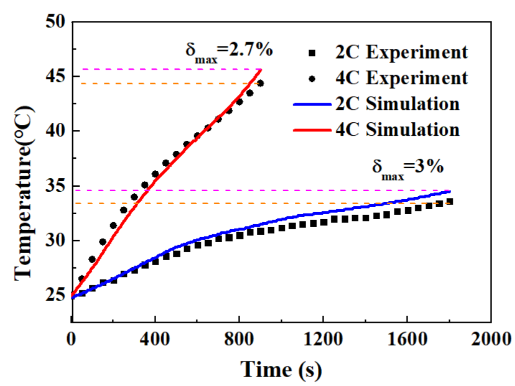


Fig 4 Model validation for the proposed BTMS

3. RESULTS

3.1 Temperature control

Fig 5 shows the computational results of the temperature response for the battery module during the 4 C discharge process. The coolant flow rate is ranged from 0 L min^{-1} to 2 L min^{-1}, and the immersion depth of the heat pipes is changed from 10 mm to 50 mm. The computational results indicate that the maximum temperature is on the decline with the increase of the coolant flow rate and immersion depth of the heat pipes. The maximum temperature can be controlled below 45℃ at 4 C discharge rate. It can be observed that the maximum temperature decreases significantly when the coolant flow rate and immersion depth of the heat pipes is small, and the downward trend gradually decreases as the increase of the influence factors. Consequently, 1.2 L min^{-1} of the coolant flow rate and 30 mm of the heat pipes immersion depth is adopted in this work by considering the energy consumption.

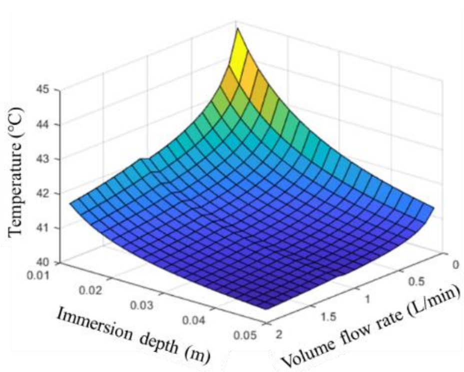


Fig 5 Temperature response of different variables

3.2 Temperature uniformity optimization

The temperature uniformity of the battery module is a critical problem that the temperature difference trends to amplify in large-scale packs. In order to improve the uneven temperature distribution, the variable heat pipe length optimization scheme is proposed as shown in Fig 6. By changing the length of the flat heat pipes, the average temperature difference can be controlled smaller.

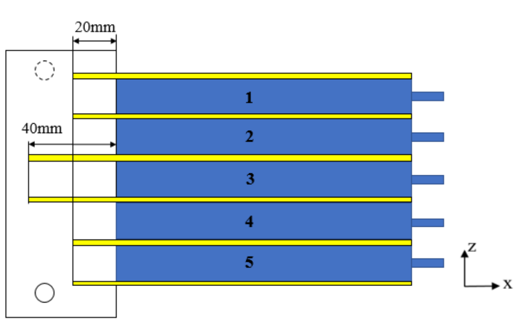
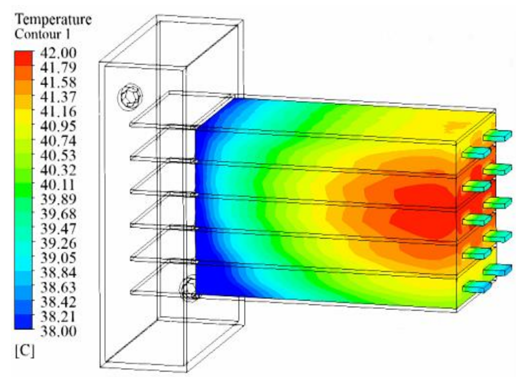
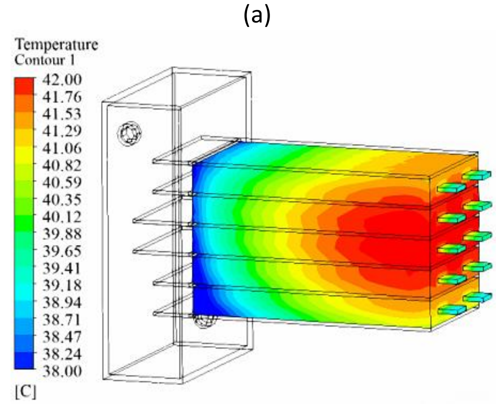


Fig 6 Variable heat pipe length optimization scheme

The detailed temperature nephogram is compared in Fig 7 between the variable heat pipe length scheme and constant length (150 mm) scheme of the proposed BTMS at different discharge rates. It is recognized that the higher temperature appears in the middle area of the battery model, and the surface temperature is reduced as close to the cooling channel caused by the different cooling conditions. As can be noticed from the simulation results, when the variable heat pipe length scheme is adopted, the maximum temperature keep almost unchanged while the temperature uniformity is improved significantly. The average temperature difference is reduced by up to 24% with the application of the variable length scheme, which can be controlled below 2℃ at 4 C discharge rate.



(a)

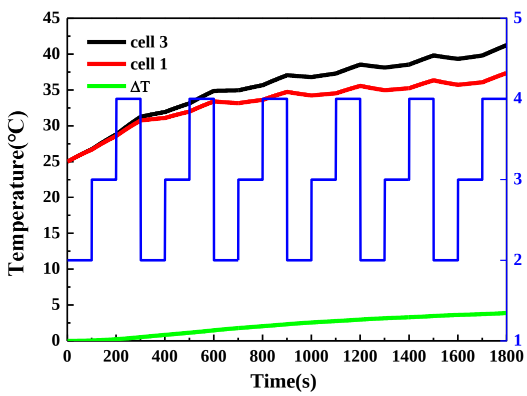


(b)

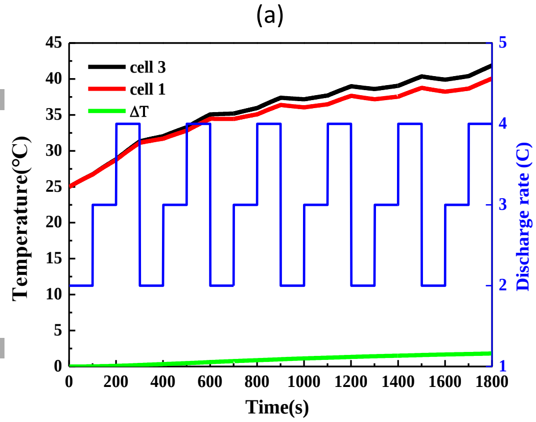
Fig 7 Temperature distribution comparison at 4C discharge rate: (a) original; (b) optimized

The discharge current varies instantaneously in practical application, thus it is necessary to investigate the cooling effectiveness in the variable cycle conditions. Fig 8 depicts the temperature trend of cell 1 and cell 3 on the six cycle under changing discharge rate from 2 C to 4 C. As can be seen that the maximum temperature is kept within the appropriate range on both of the schemes. However, the average temperature difference between the two cells gradually accumulates over time, and ΔT

reaches 3.9 ℃ at the end of the cycles in the original scheme. Therefore, it can be concluded the temperature uniformity of the constant length scheme can not meet the requirements as the further increases of the cycle number. By contrast, the smaller temperature difference appears in the variable length scheme that below 1.8℃ after the transient discharge process. Considering the temperature characteristics of the battery module in multiple cycles, the variable length cooling strategy is more applicable during the variable operating condition.



(a)



(b)

Fig 8 Temperature trend comparison during the current changing discharge process: (a) original; (b) optimized

4. CONCLUSION

In this paper, an effective BTMS based on ultrathin flat heat pipe-liquid cooling method was proposed for the lithium-ion battery module, and the optimization was developed to improve the temperature uniformity. The proposed BTMS can remove the heat effectively. The maximum temperature can be controlled blow 42℃ during the 4 C discharge process. With the application of variable heat pipe length scheme, the average temperature difference is below 2℃ at high discharge rate and transient discharge condition.

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