Sensitivity Analysis of the Battery Thermal Management System with a Reciprocating Cooling Strategy Combined with a Flat Heat Pipe

Tang Wei, Xu Xiaoming,* Ding Hua, Guo Yaohua, Liu Jicheng, and Wang Hongchao

1. INTRODUCTION

At present, the development of EVs and HEVs is mainly constrained by the battery pack, especially the lithium-ion battery cell. However, the performance of the lithium-ion battery cell is limited by the working temperature. If the heat of the lithium-ion battery cannot be dissipated in time, it would lead to excessively high temperature and reduce the temperature uniformity of the battery pack. In a word, an effective BTMS is essential to make full use of each battery cell. The BTMS needs to meet the following requirements: (1) limit the temperature of the battery pack below 60 °C; and (2) minimize the temperature difference of the battery pack within 5 °C.

Up to now, some cooling strategies have been implemented in the BTMS, including the air cooling, liquid cooling, phase change material, heat pipe, and their combinations. Based on its efficient heat transfer performance and light weight, the heat pipe was gradually applied into the BTMS. Xu et al. designed a multistage heat dissipation system based on the flat heat pipe combined with liquid cooling, which successfully controlled temperature of the battery module within the working temperature range. However, it led to a decrease in the temperature uniformity of the single battery cell in the battery module. On this basis, Yang et al. placed the flat heat pipe between the cylindrical battery cells and filled them with a thermally conductive material. The result showed that the BTMS achieved the expected cooling effect, and it could alleviate the problem of excessive temperature difference of the single battery cell. Therefore, the combination of a flat heat pipe and a liquid cooling system could ensure that the temperature of the battery module is kept within the working temperature range.

In addition, the traditional BTMS used a unidirectional flow strategy, which would lead to the inherent temperature gradient problem of conventional BTMS due to the heat exchange between the battery cells and the liquid. In this way, it would further reduce the temperature uniformity of the battery pack. Based on this, a strategy of reciprocating cooling was proposed. At present, there are few studies on the reciprocating cooling strategy, which mainly focused on the use of reciprocating air flow on BTMS to improve the temperature uniformity of the battery pack. They used flip door valves to achieve the reciprocating flow air, in which the unique duct to create reciprocating air would increase the volume and weight of the BTMS, and the flip door valves would greatly affect the service life of the entire system.

To alleviate the temperature gradient problem inherent in traditional battery systems, we used reciprocating cooling strategy in the paper. The reciprocating flow produced by
using a reversible pump is shown in Figure 1. By using a reversible pump, a reciprocating cooling flow could be generated based on the original liquid duct. This paper focuses on analysis of the sensitivity of the switching time (τ) to the effectiveness of BTMS.

2. EXPERIMENTAL SECTION (BATTERY THERMODYNAMIC PARAMETERS ACQUISITION)

In this paper, a 60 Ah lithium-ion battery cell was selected. We adopted a simulation method to obtain the heating power of the battery cell and then conducted experiments to verify the result of simulations.

2.1. The Simulation of the Battery Cell. COMSOL was utilized to simulate the battery cell used in this paper (the electrochemical parameters provided by the manufacturer). The model consisting of a negative electrode material layer, negative electrode current collector, positive electrode material layer, positive current collector, and separator was established in COMSOL. We obtained the temperature and heating power of the battery cell at rates of 1/3, 2/3, 0.8, 1.0, 1.2, 1.5, and 2.0 C.

The temperature distribution of the lithium-ion battery cell at rates of 1 and 2 C is shown in Figure 2. It showed a temperature gradient that diffused from the middle to the surroundings of the battery cell. At a discharge rate of 2 C, the temperature trend was consistent with the discharge rate of 1 C.

2.2. Verification of the Battery Cell Model. The experiment was designed and conducted to ensure the accuracy of simulation results. The test condition was consistent with the simulation condition. Comparing the differences between simulation and experimental results under the same operating conditions, we believed that the final temperature difference range was acceptable within 5% (\(E = |T_1 - T_2|/T_2\), where \(E\) is the temperature difference range, \(T_1\) is the temperature in simulation, and \(T_2\) is the temperature in the experiment).

The ambient temperature was 20 ± 0.5 °C. Eight temperature sensors were arranged in this experiment, including the positive and negative electrodes, the remaining five faces of the battery cell, and the ambient temperature shown in Figure 3. The experiment setting is shown in Figure 4.

The experiment time was 7200 s. The battery cell was charged and discharged at a rate of 1 C. The temperature curves measured by eight temperature sensors are shown in Figures 5 and 6. The surface temperatures of the positive and negative electrodes of the battery cell were slightly higher than...
those of other positions, and the positive electrode surface temperature of the battery cell was higher than the negative electrode surface temperature.

2.3. Comparison of Results and Thermal Characteristics of Battery Cells. Figures 7 and 8 show the temperature difference of the battery cell under simulation and experiment conditions. Under the discharge condition, the temperature difference range was 3.6%; under the charge condition, the temperature difference range was 2.8%, which both meet the demands.

Detailed charge and discharge data for 1/3, 2/3, 1.0, 1.5, and 2.0 C and the specific thermodynamic parameters of battery cells are shown in Table 1.

Table 1. Thermodynamic Parameters of the 60 A h Battery Cell at Difference Rates

| rate  | charge process | discharge process |
|-------|----------------|-------------------|
|       | temperature rise (°C) | heating power (W) | temperature rise (°C) | heating power (W) |
| 1/3 C | 9.75            | 2.06              | 10.01            | 2.56              |
| 2/3 C | 10.73           | 2.95              | 11.15            | 3.12              |
| 1 C   | 12.57           | 5.42              | 15.28            | 7.60              |
| 1.5 C | 18.94           | 10.06             | 23.27            | 15.59             |
| 2 C   | 22.62           | 14.44             | 26.99            | 19.89             |

3. METHODS (DESIGN OF BTMS, GOVERNING EQUATION, AND BOUNDARY AND SIMULATION CONDITIONS)

3.1. Conceptual Design of the BTMS. This paper used numerical calculations to study the sensitivity of switching time ($\tau$) to the temperature distribution of the battery module. We used STAR-CCM+ to simulate the proposed BTMS. Generally, a battery module has 12 battery cells, as shown in Figure 9.

Considering the convenience of calculation and geometric symmetry of the model, the six battery cells shown in Table 2...
The BTMS proposed in this paper consisted of six battery cells, 10 flat heat pipes, five pieces of thermal adhesive, and a unidirectional liquid duct. The relative position relationship between them and their dimension parameters are shown in Figure 11. The flat heat pipe (sintered copper liquid) was inserted into the unidirectional liquid duct. The flat heat pipe and duct were welded to ensure tightness of the entire system. The cooling liquid in the one-way liquid duct flowed through the evaporation end of the flat heat pipe and generated vortices to enhance heat exchange. The 2 mm thick thermal adhesive was placed between two flat heat pipes, which was used to ensure the temperature uniformity of the battery cell located between the two flat heat pipes. In addition, the thermal grease with a thickness of about 0.3 mm was used between the battery cell and flat heat pipe to ensure the insulation and make it as a buffer.

The thermal conductivity of the heat pipe selected in this paper was based on experimental data determined by Ye et al. They experimentally obtained the thermal resistance of the heat pipe (sintered copper liquid) was 9216 W·m⁻¹·K⁻¹ in the present study under the condition.

\[ k_{hp} = \frac{4l_{hp}}{R_{hp}d^2} \]  

Here, \( R_{hp} \) is the thermal resistance of the flat heat pipe. \( l_{hp} \) is the length of the flat heat pipe. \( d \) is the diameter of the flat heat pipe. \( k_{hp} \) is the thermal conductivity of the flat heat pipe.

Additionally, the characteristics of related materials proposed in this paper are shown in Table 3. Among them, the flat heat pipe acted as a heat conductor with effective thermal conductivity, as shown in Figure 12.

### 3.2. CFD Simulation Governing Equation

According to above assumptions, as well as the obtained thermal characteristics of the battery cell, and the thermodynamic parameters of flat heat pipe, the energy conservation equation \(^{24} \) of the BTMS proposed in this paper is as follows:

\[ \rho_b c_{pb} \frac{\partial T}{\partial \tau} = \frac{\partial}{\partial x} \left( k_{hp} \frac{\partial T}{\partial x} \right) + \frac{\partial}{\partial y} \left( k_{hp} \frac{\partial T}{\partial y} \right) + \frac{\partial}{\partial z} \left( k_{hp} \frac{\partial T}{\partial z} \right) + Q \]  

Here, \( \rho_b \) is the density of the battery module, \( c_{pb} \) is the specific heat capacity of the battery module, \( T \) is the temperature of the battery module, \( k_b \) is the thermal conductivity of the battery module, and \( Q \) is the source term that can be calculated as follows:

\[ Q = \frac{Q_{gen}}{V_b} \]

Here, \( Q_{gen} \) is the heat generation power of the battery cell. \( V_b \) is the volume of the battery cell.

The governing equations for liquid include the continuous equation \(^{25} \), momentum conservation equation \(^{26} \), and energy conservation \(^{27} \), which are shown as follows:

**Continuous equation:**

\[ \frac{\partial \rho}{\partial \tau} + \nabla \cdot (\rho \vec{v}) = 0 \]  

**Momentum conservation equation:**

\[ \frac{\partial}{\partial \tau} (\rho \vec{v}) + \nabla \cdot (\rho \vec{v} \vec{v}) = -\nabla P \]  

**Energy conservation:**

\[ \frac{\partial}{\partial \tau} (\rho_c T) + \nabla \cdot (\rho_c \vec{v} T) = \nabla \cdot (k_w \nabla T) \]  

Here, \( \vec{v} \) means the velocity vector, \( P \) means the pressure, \( \rho_w \) means the water density, and \( k_w \) means the thermal conductivity of water.

The heat generation power \( Q_{gen} \) of the battery cell was obtained by simulation, as shown in Table 1.

### 3.3. Boundary and Simulation Conditions

The ambient temperature was set to 20 °C. The inlet of the BTMS duct was set as the speed inlet, the inlet flow was set to 400 L h⁻¹, and the turbulence was 2%. The water inlet temperature was the same as ambient temperature. The outlet of the BTMS duct was set as a pressure outlet. The heat conductivity.
transfer surfaces were set as a coupling surface. In addition, other surfaces were set as heat insulation walls. Additionally, in order to facilitate the numerical simulation, we make the following assumptions: The flat heat pipe was considered as a solid conductor with high thermal conductivity.

During the running of EVs, the charge and discharge rates of the battery pack changed with the driving conditions. Therefore, the charge and discharge strategy shown in Table 4 were formulated to simulate the real operating condition in this paper, verifying the thermal efficiency of proposed BTMS. Among them, working condition A performed charge and discharge with a smaller current, while working condition B was based on working condition A. The charge and discharge currents were doubled, and the simulation time was unchanged.

4. RESULTS AND DISCUSSION

Based on previous research, this paper mainly studied the maximum temperature $T_{\text{Max}}$, the minimum temperature $T_{\text{Min}}$, the maximum temperature rise $T_{\text{Rise}}$, and the maximum temperature difference $T_{\text{Diff}}$ of the battery module as indicators to evaluate the thermal efficiency of BTMS.

4.1. Validation of the CFD Model Using the Unidirectional Flow System.

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4.1. Validation of the CFD Model Using the Unidirectional Flow System.

Table 3. Dimensions of the Battery Cell, Module, and the Working Condition Used for the Simulation and Thermophysical Parameters

| parameters of cells | liquid parameters (at 20 °C) |
|---------------------|-----------------------------|
| $L$ (mm)            | 148                         |
| $W$ (mm)            | 26                          |
| $H$ (mm)            | 97                          |
| $K_i$ (W·m⁻¹·k⁻¹)  | 0.1543                      |
| $C_i$ (kJ·kg⁻¹·k⁻¹) | 2.2071                      |
| $\mu_i$ (kg·m⁻¹·s⁻¹) | 0.00759                    |
| $L_1$ (mm)         | 148                         |
| $D_1$ (mm)          | 324                         |
| $T$ (°C)            | 20                          |
| $t$ (s)             | 7200                        |
| flow rate (L·h⁻¹)  | 400                         |

4.1. Validation of the CFD Model Using the Unidirectional Flow System.

Table 4. Simulation Working Condition Data

| stage | serial number | operation state | time (s) | rate (A condition) | rate (B condition) |
|-------|---------------|-----------------|----------|--------------------|--------------------|
| 1     | 1             | discharging     | 430      | 1/3 C (20 A)       | 2/3 C (40 A)       |
|       |               |                 |          |                    |                    |
|       |               | 2                | shelf    | 20 s               | 20 s               |
|       |               | 3                | charging | 150 s              | 1 C (60 A)         |
|       |               | 4                | shelf    | 20 s               | 20 s               |
| 2     | 1             | discharging     | 430      | 1/3 C (20 A)       | 2/3 C (40 A)       |
|       |               | 2                | shelf    | 20 s               | 20 s               |
|       |               | 3                | charging | 150 s              | 1 C (60 A)         |
|       |               | 4                | shelf    | 20 s               | 20 s               |
| 3     | 1             | discharging     | 430      | 1/3 C (20 A)       | 2/3 C (40 A)       |
|       |               | 2                | shelf    | 20 s               | 20 s               |
|       |               | 3                | charging | 150 s              | 1 C (60 A)         |
|       |               | 4                | shelf    | 20 s               | 20 s               |
| 4     | 1             | discharging     | 430      | 1/3 C (20 A)       | 2/3 C (40 A)       |
|       |               | 2                | shelf    | 20 s               | 20 s               |
|       |               | 3                | charging | 150 s              | 1 C (60 A)         |
|       |               | 4                | shelf    | 20 s               | 20 s               |

4.1. Validation of the CFD Model Using the Unidirectional Flow System.

Figure 11. Relative position relationship and dimension parameters of each component of the model.

Figure 12. Schematic view of the flat heat pipe.

Figure 13. Relative position relationship and dimension parameters of each component of the model.

Table 5. Dimensions of the Battery Cell, Module, and the Working Condition Used for the Simulation and Thermophysical Parameters

| parameters of cells | liquid parameters (at 20 °C) |
|---------------------|-----------------------------|
| $L$ (mm)            | 148                         |
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| $L_1$ (mm)         | 148                         |
| $D_1$ (mm)          | 324                         |
| $T$ (°C)            | 20                          |
| $t$ (s)             | 7200                        |
| flow rate (L·h⁻¹)  | 400                         |
Figure 13. Working condition A.

Figure 14. Temperature distribution of the battery module.

Figure 15. $T_{\text{Max}}$ of the battery module under condition A.

Figure 16. $T_{\text{Min}}$ of the battery module under condition A.

Figure 17. Temperature characteristic curve of the battery module under working condition A.

Figure 18. Temperature characteristic curve of the battery module under working condition B.

Working condition A. Figures 15 and 16 show $T_{\text{Max}}$ and $T_{\text{Min}}$ of the battery module under working condition A. Among them, $T_{\text{Max}}$ of the battery module was 23.7 °C, and $T_{\text{Min}}$ of the battery module was 20.28 °C. Among them, $T_{\text{Max}}$ of the battery module was 23.7 °C, and $T_{\text{Min}}$ of the battery module was 20.28 °C. So, the temperature difference of the battery module was 3.42 °C; excluding the #1 and #6 cells, $T_{\text{Max}}$ of the system was 22.4 °C, $T_{\text{Min}}$ was 20.28 °C, and the temperature difference was 2.12 °C. The temperature distribution on the cell was relatively uniform, which was due to the flat heat pipe thermal conductivity and thermally conductive adhesive designed between battery cells.

It is worth noting that the temperature of the liquid continued to increase during the flow of the liquid in the duct. It could also be seen in Figure 16 that the temperatures of battery cells (#2 and #3) were slightly higher than those of the battery cells (#4 and #5). Based on this, we considered using the reciprocating liquid strategy to optimize temperature distribution inside the battery module.

Figures 17 and 18 show the curve of $T_{\text{Max}}$, $T_{\text{Min}}$, $T_{\text{Max, Rise}}$ and $T_{\text{Max, Diff}}$ under working condition A and condition B. Among them, $T_{\text{Max}}$ of the battery module under working condition A was 23.7 °C; $T_{\text{Min}}$ was 20.28 °C; $T_{\text{Max, Rise}}$ was 3.42 °C; $T_{\text{Max, Diff}}$ was 3.7 °C. $T_{\text{Max}}$ of the battery module under working condition B was 25.31 °C, $T_{\text{Min}}$ was 21.23 °C, $T_{\text{Max, Diff}}$ was 4.08 °C; $T_{\text{Max, Rise}}$ was 5.31 °C.

4.2. Analysis of the Effect of Switching Time ($\tau$) on the Thermal Performance of BTMS. Figure 19a shows that the average temperature of cell #6 was the highest under working condition B, reaching 22.39 °C, which was 0.13 °C higher than that of cell #1. Figure 19b shows that the temperature of cell #6 increased at a faster rate than the temperature of cell #1. This indicates that the use of the reciprocating liquid strategy can effectively optimize the temperature distribution inside the battery module.
higher than the average temperature of cell #1, and there were obvious temperature gradients between these three groups of cells ((#6, #1), (#5, #2), and (#4, #3)). Compared with working condition A, the temperature uniformity of the battery module was further weakened due to the balance between heat generation of the battery module and heat dissipation of the BMTS. At 5400 s, the simulation showed a steady-state convergence trend, and the temperature difference between the battery modules gradually decreased.

Further simulation was performed based on working condition B, and a reciprocating liquid cooling strategy was adopted. This paper identified switching times ($\tau$) of 3600, 1800, and 900 s. It could be seen from Figure 19 that, as the switching time ($\tau$) decreased from 3600 to 900 s, $T_{\text{MaxDiff}}$ between the battery cells decreased, and the temperature uniformity tended to be consistent. In particular, the temperature curves of four battery cells (#5, #2, #4, and #3) in the middle of the battery module were closer, which means that the temperature of four battery cells was basically consistent. Due to the reduction of $T_{\text{MaxDiff}}$ between the liquid inlet and the liquid outlet.

Figure 18. Temperature characteristic curve of the battery module under working condition B.

Figure 19. Average temperature curve of the battery module under different working conditions.

(a) The average temperature curve of the battery module under the B working condition

(b) The average temperature curve of the battery module under the I working condition ($\tau = 3600s$)

(c) The average temperature curve of the battery module under the II working condition ($\tau = 1800s$)

(d) The average temperature curve of the battery module under the III working condition ($\tau = 900s$)
by the using reciprocating liquid strategy. $T_{\text{Max}}^{\text{diff}}$ and $T_{\text{Max}}^{\text{rise}}$ would reduce. Taking cell #4 as an example, as the switching time ($\tau$) decreased, the temperature of cell #4 decreased from 21.875 to 20.875 °C; the performance was obvious.

4.3. Analysis of Single Battery Cell Temperature.

According to the above study, switching the flow of liquid could improve effectiveness of the BTMS. This chapter focuses on the temperature characteristics of each battery cell under the unidirectional cooling strategy and the reciprocating cooling strategy, as shown in Figure 20. This paper analyzed $T_{\text{Max}}$, $T_{\text{Min}}$, $T_{\text{Max}}^{\text{rise}}$, and $T_{\text{Max}}^{\text{diff}}$ of the battery cell. Among these four temperature characteristics, $T_{\text{Min}}$ of the battery cell was most affected by switching times ($\tau$), and its sensitivity was the highest, as shown in Figure 20b.

The sensitivity of other three parameters was lower, and only minor fluctuations occurred. However, once the liquid cooling system changed from a unidirectional flow strategy to a reciprocating flow strategy, the three parameters $T_{\text{Max}}$, $T_{\text{Max}}^{\text{rise}}$, and $T_{\text{Max}}^{\text{diff}}$ of the battery cells would change greatly. Figure 20a shows that $T_{\text{Max}}$ of the battery cell was reduced by 4.6%; Figure 20c shows that $T_{\text{Max}}^{\text{rise}}$ of the battery cell was reduced by 47.11%; Figure 20d shows that $T_{\text{Max}}^{\text{diff}}$ of the battery cell was reduced by 75.6%. This result showed that the reciprocating cooling strategy could greatly improve the performance of BTMS.

We further analyzed the heat dissipation efficiency of the reciprocating cooling strategy taking the battery cells #3 and #4 as examples under initial conditions (unidirectional flow strategy). $T_{\text{Min}}$ of battery cell #3 near the liquid inlet was 21.95 °C, which was higher than the temperature of battery cell #4. With the decrease of switching times ($\tau$), the temperature difference between battery cells #3 and #4 would further narrow. As shown in Figure 20c, when the switching times ($\tau$) = 900 s, $T_{\text{Max}}^{\text{diff}}$ of battery cells #3 and #4 was approximately 2.34 °C. Therefore, as the switching times ($\tau$) decreased, the temperature consistency of the battery module would improve.

5. CONCLUSIONS

This paper proposed a reciprocating cooling strategy to improve the temperature uniformity of the battery module for BTMS of the flat heat pipe and liquid cooling establishing
the thermal model of the 60 A h lithium-ion battery cell and obtaining the thermal characteristics of the battery cell. Through simulations, the influence of switching time (τ) on temperature uniformity of the battery module was studied. Research showed that the reciprocating cooling strategy greatly reduced the temperature difference and the temperature rise of the battery module.

The main work and conclusions of this paper are as follows:

1. Under working condition A, the BTMS of the flat heat pipe combined with liquid cooling using a unidirectional cooling strategy could meet thermal management needs of the battery module. $T_{\text{Max}}^{\text{Diff}}$ of the battery module was 2.04 °C, and $T_{\text{Max}}^{\text{Min}}$ was 3.46 °C. The temperature gradient between the four cells (#3, #4, #2, and #5) did not change significantly.

2. Under working condition B, $T_{\text{Max}}^{\text{Diff}}$ of the battery module was 2.13 °C, and $T_{\text{Max}}^{\text{Min}}$ was 4.98 °C. $T_{\text{Max}}^{\text{Diff}}$ was basically unchanged, but $T_{\text{Max}}^{\text{Min}}$ increased by 43.9%. This was due to the temperature unevenness caused by unidirectional flow.

3. Adopting the switching time (τ) ($\tau = 3600, 1800$, and 900 s), the results showed that, when the switching time was shorter, $T_{\text{Max}}^{\text{Min}}$ of the battery module was lower. Compared with the case of the unidirectional flowing strategy $T_{\text{Max}}^{\text{Min}}$ of the battery module was reduced by 8.7%, and $T_{\text{Max}}^{\text{Diff}}$ was reduced by 13.5%.

4. By analyzing the thermal characteristics of a single battery cell, it was found that the temperatures of four cells (#3, #4, #2, and #5) tended to be consistent with the decrease of switching time. Changing the switching time of liquid flow could greatly reduce $T_{\text{Min}}^{\text{Min}}$ and $T_{\text{Max}}^{\text{Diff}}$ of the battery module.

For existing BTMS, whether it is an air cooling or liquid cooling system. The reciprocating cooling strategy proposed in this paper can be applied to the above BTMS, which can reduce the temperature difference of the battery module by replacing the unidirectional water pump with a reversible pump or replacing the fan with a reversible fan. The BTMS structure in which the scheme of placing a flat heat pipe on the side of the battery proposed in this paper needs further research to reduce the volume of the system in practical applications. This BTMS can be applied to other types of batteries, such as cylindrical batteries. Related research has also studied the unidirectional one-way flow strategy.

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**Notes**

The authors declare no competing financial interest.

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**REFERENCES**

(1) Hao, Y.; Wang, L.; Wang, L. Battery thermal management system with liquid cooling and heating in electric vehicles. *J. Automat. Saf. Energy* 2012, 3, 371–380.

(2) Burban, G.; Ayel, V.; Alexandre, A.; Lagonotte, P.; Bertin, Y.; Romestant, C. Experimental investigation of a pulsating heat pipe for hybrid vehicle applications. *Appl. Therm. Eng.* 2013, 50, 94–103.

(3) Zhao, R.; Gu, J.; Liu, J. An experimental study of heat pipe thermal management system with wet cooling method for lithium ion batteries. *J. Power Sources* 2015, 273, 1089–1097.

(4) Toal, D. J. J.; Keane, A. J.; Benito, D.; Dixon, J. A.; Yang, J.; Price, M.; Robinson, T.; Remouchamps, A.; Kill, N. Multifidelity multidisciplinary whole-engine thermomechanical design optimization. *J. Propul. Power* 2014, 30, 1654–1666.

(5) Hadim, H.; Suwa, T. Multidisciplinary design and optimization methodologies in electronics packaging: state-of-the-art review. *J. Electron. Packag.* 2008, 130, No. 034001.

(6) Wang, J.; Yang, X. P. Thermal management system design and simulation of battery pack for electric vehicles. *Appl. Mech. Mater.* 2014, 494–495, 100–103.

(7) Fathabadi, H. High thermal performance lithium-ion battery pack including hybrid active-passive thermal management system for using in hybrid/electric vehicles. *Energy* 2014, 70, 529–538.

(8) Terada, N.; Yanagi, T.; Arai, S.; Yoshikawa, M.; Ohta, K.; Nakajima, N.; Yanai, A.; Arai, N. Development of lithium batteries for energy storage and EV applications. *J. Power Sources* 2001, 100, 80–92.

(9) Dan, D.; Yao, C.; Zhang, Y.; Zhang, H.; Zeng, Z.; Xu, X. Dynamic thermal behavior of micro heat pipe array-air cooling battery thermal management system based on thermal network model. *Appl. Therm. Eng.* 2019, 162, 114183.

(10) Wang, C.; Zhang, G.; Meng, L.; Li, X.; Sui, W.; Lv, Y.; Rao, M. Liquid cooling based on thermal silica plate for battery thermal management system. *Int. J. Energy Res.* 2017, 41, 2468–2479.

(11) Liu, Y.-P.; Ouyang, C.-Z.; Jiang, Q.-B.; Liang, B. Design and parametric optimization of thermal management of lithium-ion battery module with reciprocating air-flow. *J. Cent. South Univ.* 2015, 22, 3970–3976.

(12) Choi, Y. S.; Kang, D. M. Prediction of thermal behaviors of an air-cooled lithium-ion battery system for hybrid electric vehicles. *J. Power Sources* 2014, 270, 273–280.

(13) Xu, D.; Wang, L.; Yang, J. Research on li-ion battery management system. In 2010 International Conference on Electrical and Control Engineering; IEEE: 2010, 4106–4109.

(14) Andersen, P. H.; Mathews, J. A.; Rask, M. Integrating private transport into renewable energy policy: the strategy of creating intelligent recharging grids for electric vehicles. *Energy Policy* 2009, 37, 2481–2486.

(15) Xu, X.; Tang, W.; Fu, J.; Li, R.; Sun, X. Plate flat heat pipe and liquid-cooled coupled multistage heat dissipation system of Li-ion battery. *Int. J. Energy Res.* 2019, 43, 1133–1141.

(16) Yang, X.-H.; Tan, S.-C.; Liu, J. Thermal management of Li-ion battery with liquid metal. *Energy Convers. Manage.* 2016, 117, 577–585.
(17) Greco, A.; Cao, D.; Jiang, X.; Yang, H. A theoretical and computational study of lithium-ion battery thermal management for electric vehicles using heat pipes. J. Power Sources 2014, 257, 344–355.

(18) Smith, J.; Singh, R.; Hinterberger, M.; Mochizuki, M. Battery thermal management system for electric vehicle using heat pipes. Int. J. Therm. Sci. 2018, 134, 517–529.

(19) Wang, Q.; Jiang, B.; Li, B.; Yan, Y. A critical review of thermal management models and solutions of lithium-ion batteries for the development of pure electric vehicles. Renewable Sustainable Energy Rev. 2016, 64, 106–128.

(20) Huo, Y.; Rao, Z.; Liu, X.; Zhao, J. Investigation of power battery thermal management by using mini-channel cold plate. Energy Convers. Manage. 2015, 89, 387–395.

(21) Mahamud, R.; Park, C. Reciprocating air flow for Li-ion battery thermal management to improve temperature uniformity. J. Power Sources 2011, 196, 5685–5696.

(22) Ye, Y.; Shi, Y.; Saw, L. H.; Tay, A. A. O. Performance assessment and optimization of a heat pipe thermal management system for fast charging lithium ion battery packs. Int. J. Heat Mass Transfer 2016, 92, 893–903.

(23) Nelson, P.; Dees, D.; Amine, K.; Henriksen, G. Modeling thermal management of lithium-ion PNGV batteries. J. Power Sources 2002, 110, 349–356.

(24) Babapoor, A.; Azizi, M.; Karimi, G. Thermal management of a Li-ion battery using carbon fiber-PCM composites. Appl. Therm. Eng. 2015, 82, 281–290.

(25) Goli, P.; Legedza, S.; Dhar, A.; Salgado, R.; Renteria, J.; Balandin, A. A. Graphene-enhanced hybrid phase change materials for thermal management of Li-ion batteries. J. Power Sources 2014, 248, 37–43.

(26) Pesaran, A.; Vlahinos, A.; Stuart, T. Cooling and preheating of batteries in hybrid electric vehicles. In 6th ASME-JSME Thermal Engineering Joint Conference; 2003, 1–7.

(27) Fu, J.; Xu, X.; Li, R. Battery module thermal management based on liquid cold plate with heat transfer enhanced fin. Int. J. Energy Res. 2019, 43, 4312–4321.