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Experimental Investigation on the Lithium-ion Battery Thermal Management System Based on U-Shaped Micro Heat Pipe Array in High Temperature Environment

Ruyang Ren, Yaohua Zhao, Yanhua Diao

***Abstract*—**In this study, a type of active air cooling thermal management system (TMS) based on U-shaped micro heat pipe array (MHPA) is established for the battery energy storage box which operates in high ambient temperature all the year round. The thermal management performance of the active air cooling TMS based on U-shaped MHPA under different ambient temperatures and different cooling conditions is analyzed by the method of experimental research. Results show that even if the battery energy storage box operates at a high ambient temperature of 45 °C, the active air cooling TMS based on U-shaped MHPA controls not only the maximum temperature of the battery in the battery energy storage box below 55 °C, but also the maximum temperature difference in the battery energy storage box below 5 °C during the whole charge-discharge process. The experimental results provide guidance for the application of the battery energy storage box TMS that operates in high temperature areas.

***Keywords*—**Active air cooling, lithium-ion battery, micro heat pipe array, thermal management system.

I. Introduction

As the problems of energy shortage and environmental damage continue to intensify, countries around the world have successively introduced relevant policies for the development of clean and renewable energy [1]. In recent years, photovoltaic power generation, wind power generation and other technologies have been widely used in various fields. However, renewable energy sources such as solar energy and wind energy have the characteristics of intermittency and instability, which can easily cause problems such as frequent grid voltage fluctuations and difficulty in peak regulation [2]. Thus, battery energy storage technology, which can ensure the stability of the power system, improve the power generation and grid-connection capabilities of renewable energy, and provide efficient peak-shaving functions, has been widely used in recent years [3].

Lithium-ion battery (LIB) is widely used in battery energy storage due to their high energy density, low internal resistance, low self-discharge rate, no memory effect, and long cycle life [4]. However, the performance and cycle life of the LIB is seriously affected by the operate temperature. Research has shown that the maximum temperature of LIB cannot exceed 55 °C, and the temperature difference during the operation of LIB cannot exceed 5 °C [5]. In addition, with the widespread popularity of battery energy storage technology, the battery energy storage box inevitably needs to operate in high ambient temperature areas all year round, which further increases the difficulty of the thermal management. At present, air cooling TMS is widely used in the battery energy storage box because of its simple structure, light weight and low cost [6]. However, the low thermal conductivity of air cannot meet the heat dissipation requirements of the storage box that operates in high ambient temperature, and it is easy to cause a large temperature difference in the storage box [7].

MHPA is a flat metal body, which has numerous parallel micro-channels inside the metal body, and each micro-channel has working fluid for heat transfer [8]. The high thermal conductivity and excellent temperature uniformity of the MHPA are achieved through the rapid evaporation and condensation of the internal working fluid. In this paper, based on the patent technology of Zhao et al. in battery thermal management [9], [10], the U-shaped MHPA is combined with air cooling TMS, establishing a type of active air cooling TMS based on U-shaped MHPA. In addition, we apply the TMS to the battery energy storage box that needs to operate in the high ambient temperature all year round. This TMS takes the U-shaped MHPA as the core heat transfer element, owing to the rapid heat transfer characteristics of the U-shaped MHPA, the TMS can not only quickly transfer the heat generated by the LIBs during the charge-discharge process to the outside of the battery energy storage box for heat dissipation, but also ensure that the battery energy storage box has excellent temperature uniformity in the heat dissipation process. In order to accurately analyze the thermal management performance of the active air cooling TMS based on U-shaped MHPA under high ambient temperature, the thermal management performance of the TMS is analyzed through experimental method under different high ambient temperatures and different cooling conditions.

II. Experimental Setup

Fig. 1 shows the structural diagram of the battery energy storage box equipped with the new type of active air cooling

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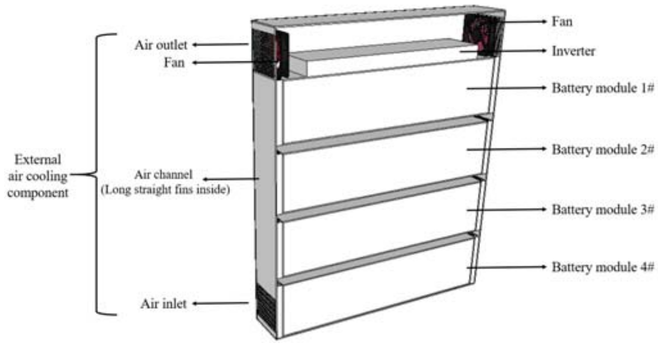
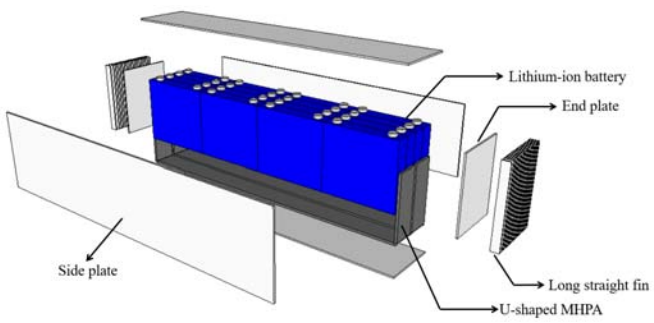
TMS based on U-shaped MHPA. Fig. 1 (a) shows the overall structure diagram of the battery energy storage box, the size of the battery energy storage box is 644 mm × 115 mm × 770 mm (L × W × H). It consists of 4 battery modules connected in parallel, 1 inverter, and 2 external air cooling components on both sides. Fig. 1 (b) shows the structural diagram of the battery module, each battery module is composed of 32 LIBs (2P16S), 2 U-shaped MHPAs, and surrounding end plates and side plates; the type of LIB is lithium iron phosphate, and the nominal voltage and nominal capacity are 3.2 V and 50 Ah respectively (other specific parameters of the LIB can be seen in Table I); so the nominal voltage and nominal capacity of each battery module are 51.2 V and 100 Ah respectively, the nominal voltage and nominal capacity of the whole battery energy storage box are 51.2 V and 400 Ah respectively. In order to improve the space utilization of the battery module, we select the 3 mm thickness U-shaped MHPA as the core heat transfer element, which is composed of 1 evaporation section and 2 condensation sections; the dimensions of the evaporation section and condensation section are 592 mm × 45 mm (L × W) and 128 mm × 45 mm (H × W), respectively. The external air cooling component is composed of long straight fins and a fan; the long straight fins are fitted outside the end plate of the battery module, and combined with the shell of the battery energy storage box to form an air channel; when the fan is turned on, the air flows through the channel to complete the active air cooling.



(a)



(b)

Fig. 1 Structural diagram of the (a) battery energy storage box and (b) battery module

TABLE I
SPECIFIC PARAMETERS OF LIB

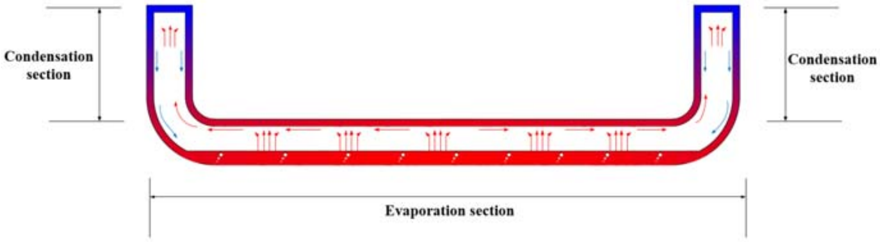
Parameter	Value
Cathode/Anode/Electrolyte	$LiFePO_4$/Graphite/$LiPF_6$
Nominal capacity	50 Ah
Nominal voltage	3.2 V
Operating voltage range	2.0–3.65 V
Charge working temperature	0–55 °C
Discharge working temperature	–20–55 °C

Fig. 2 (a) illustrates the heat transfer schematic diagram of the U-shaped MHPA. The liquid working medium in the evaporation section of the U-shaped MHPA absorbs heat and vaporizes, and the gaseous working medium rapidly rises to the condensation section on both sides under the action of buoyancy; the gaseous working medium liquefies and releases heat after being cooled in the condensation sections, and the liquid working medium returns to the evaporation section under the action of gravity and capillary force to achieve rapid heat transfer from the evaporation section to the condensation sections. Fig. 2 (b) illustrates the heat transfer schematic diagram of the active air cooling TMS based on U-shaped MHPA. The LIBs in the module are placed vertically, and the evaporation section of the U-shaped MHPA is closely attached to the bottom surface of the LIB, so the heat generated by the LIB during charge-discharge process is directly absorbed by the evaporation section of the U-shaped MHPA, and quickly transferred to the condensation sections; then the condensation sections transfer the heat to the end plates on both sides of the battery module, and finally to the long straight fins on the outer surface of the end plates. To sum up, relying on the rapid heat transfer characteristics of the U-shaped MHPA, the heat generated during charge-discharge process is quickly transferred out of the battery module, so as to ensure the safe and stable operation of the battery module. When the U-shaped MHPA alone cannot meet the thermal management requirements of the battery energy storage box, the TMS established in this study can automatically control the fan on the top of the battery energy storage box to turn on, which further strengthen the heat dissipation through the active air cooling.

Fig. 3 shows the experimental system diagram. The charge-discharge process of the s battery energy storage box is completed by the power battery detection equipment. The incubator is used to provide the required ambient temperature for the experiments. Thermistors detect the temperature change of the LIB and transmit the temperature signal to the computer. The measurement error of the equipment can be seen in Table II.

TABLE II
MEASUREMENT ERROR OF THE EQUIPMENT

Equipment name	Specification model	Measurement error
Incubator	-	± 0.5 °C
Power battery testing equipment	IGBT-60V/1000A	± 0.2%
Thermistor	PT100	± 0.15 °C



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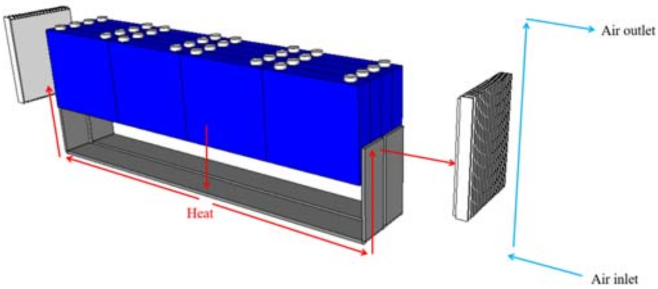


(b)

Fig. 2 Heat transfer schematic diagram of (a) U-shaped MHPA and (b) active air cooling TMS based on U –shaped MHPA

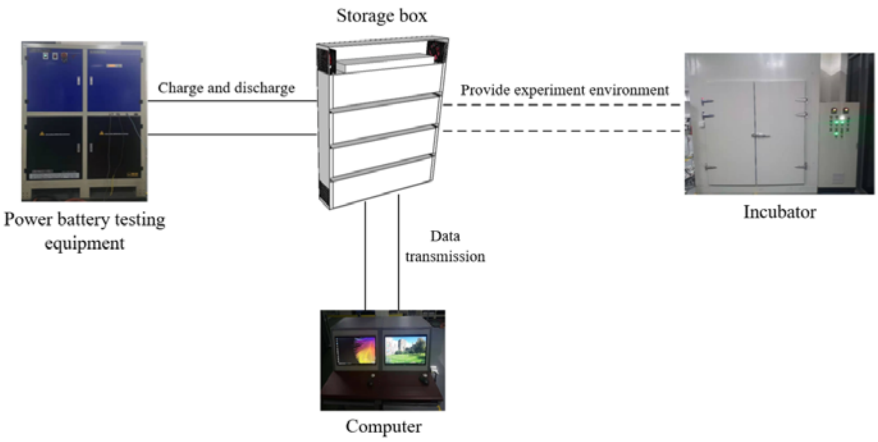


Fig. 3 Experimental system diagram

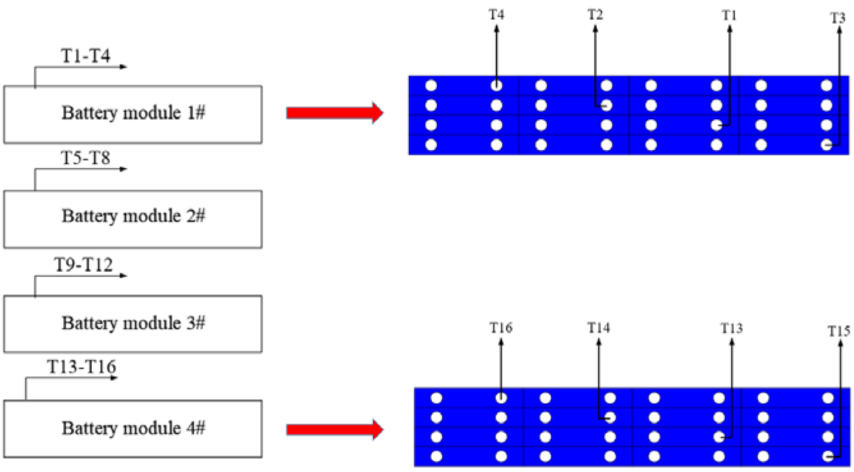


Fig. 4 Layout of the temperature monitoring points

Fig. 4 shows the layout of temperature monitoring points in the battery energy storage box. There are four battery modules in the battery energy storage box, and there are four temperature monitoring points in each battery module; thus, a total of 16 temperature monitoring points in the whole battery energy storage box. Moreover, each temperature measuring point is attached to the surface of the electrode.

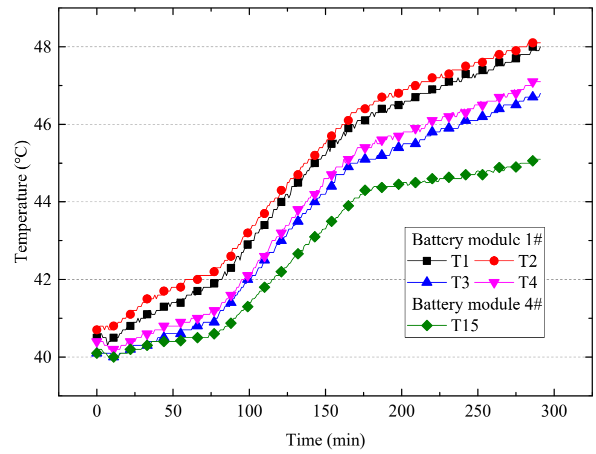
III. Result and Discussion

In order to simulate the working conditions of the battery energy storage box in practical application, the battery modules are completely enclosed in the battery energy storage box during the experiment. During the experiments, the battery energy storage box is first charged at a constant current of 80 A (0.2C), after standing for 5 min, then the battery energy storage box discharged at a constant current of 200A (0.5C). In order to prevent potential safety hazards during the experiments, an alarm signal must be sent once the maximum temperature of the LIB in the battery energy storage box exceeds 55 °C during the charge-discharge process. When the maximum temperature of the LIB in the battery energy storage box exceeds 60 °C, the power must be cut off to stop the operation of the battery energy storage box.

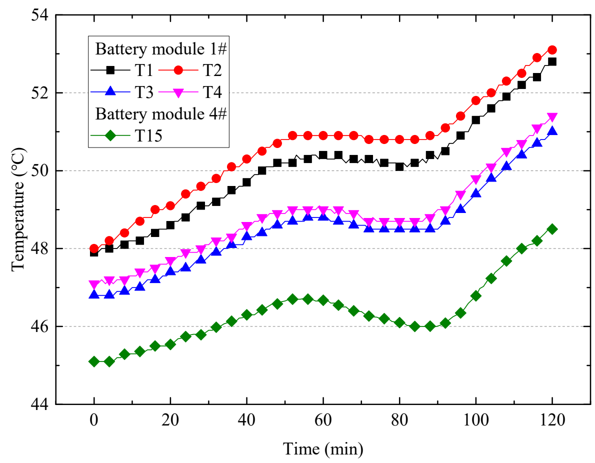
A. Research on Thermal Management Performance of the TMS under Different Ambient Temperatures

In this section, the thermal management performance of the active air cooling TMS based on U-shaped MHPA under different high ambient temperatures is analyzed. Among them, the ambient temperature is 40 °C and 45 °C, and the fans are turned off; that is, the heat dissipation is only performed by the rapid heat transfer characteristics of the U-shaped MHPA without active air cooling.

The four battery modules in the battery energy storage box are arranged at intervals from top to bottom. Affected by the natural convection of the air inside the battery energy storage box, the overall temperature of the uppermost module (module 1#) is the highest among the 4 modules, and the temperature of the lowermost module (module 4#) is the lowest. Therefore, 4 monitoring points (T1, T2, T3, T4) of module 1 # and 1 monitoring point (T15) with the lowest temperature in module 4 # are selected to analyze the performance of the TMS. Figs. 5 (a) and (b) show the temperature change curves of the monitoring points during charge-discharge process when the ambient temperature is 40 °C. During the charge process, the temperature of T2 point is the highest, rising from 40.7 °C to 48.1 °C, with a total temperature rise of 7.4 °C; the maximum temperature difference between the 4 monitoring points of module 1# is 1.6 °C, and the average temperature difference is 1.26 °C; the maximum temperature difference (temperature difference between T2 point and T15 point) of the whole battery energy storage box is 3.1 °C, and the average temperature difference is 2.08 °C. During the discharge process, the temperature of T2 point is still the highest, rising from 48 °C to 53.1 °C, with a total temperature rise of 5.1 °C; the maximum temperature difference between the four monitoring points of module 1 # is 2.4 °C, and the average temperature difference is 2.06 °C; the maximum temperature difference of the whole battery energy storage box is 5.1 °C, and the average temperature difference is 4.22 °C. To sum up, when the battery energy storage box is charged and discharged at an ambient temperature of 40 °C, owing to the rapid heat transfer characteristics of the U-shaped MHPA, the maximum temperature in the battery energy storage box is 53.1 °C, which does not reach the alarm temperature of 55 °C, and further lower than the forced cut-off temperature of 60 °C; besides, the single module's and the whole battery energy storage box's temperature differences are all within an acceptable range, which effectively ensures safe and stable operation of the battery energy storage box.



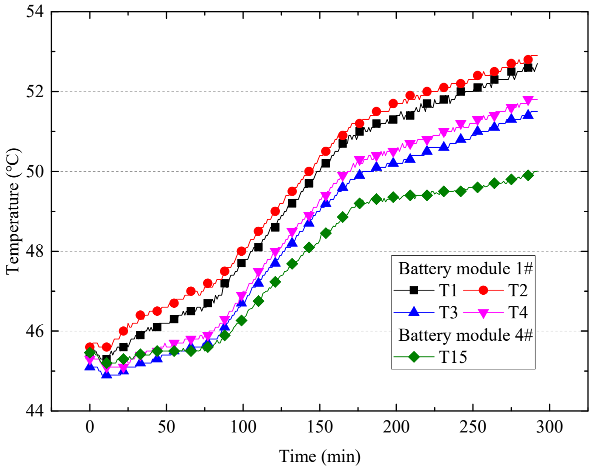
(a)



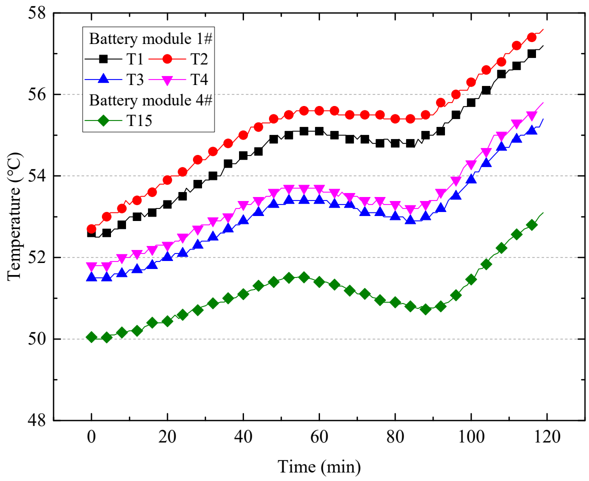
(b)

Fig. 5 Temperature change curves of the monitoring points during (a) charge process and (b) discharge process when the ambient temperature is 40 °C

Figs. 6 (a) and (b) show the temperature change curves of the monitoring points during charge-discharge process when the ambient temperature is 45 °C. During the charge process, the temperature of T2 point is the highest, rising from 45.6 °C to 52.9 °C; the maximum temperature difference in module 1 # is 1.6 °C, and the average temperature difference is 1.29 °C; the maximum temperature difference in the whole battery energy storage box is 3 °C, and the average temperature difference is 1.96 °C. During the discharge process, the temperature of T2 point is still the highest, rising from 52.7 °C to 57.6 °C; the maximum temperature difference of module 1 # is 2.6 °C, and the average temperature difference is 2.14 °C; the maximum temperature difference of the whole battery energy storage box is 5 °C, and the average temperature difference is 4.1 °C. To sum up, when the battery energy storage box is charged and discharged at an ambient temperature of 45 °C, the maximum temperature in the battery energy storage box is 57.6 °C, which has exceeded the alarm temperature of 55 °C, but is still lower than the forced cut-off temperature of 60 °C; in addition, the temperature difference of module 1# and the whole battery energy storage box is still within an acceptable range. Therefore, owing to the rapid heat transfer characteristics of the U-shaped MHPA, even if the TMS operates without active air cooling, the battery energy storage box cannot be forced to cut off when operates at a high ambient temperature of 45 °C.



(a)



(b)

Fig. 6 Temperature change curves of the monitoring points during (a) charge process and (b) discharge process when the ambient temperature is 45 °C

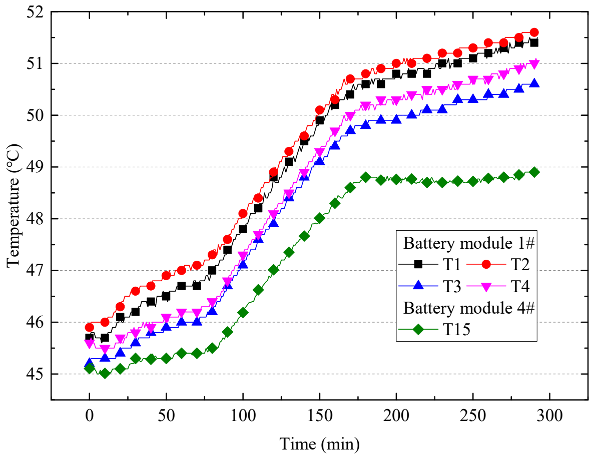
B. Research on Thermal Management Performance of the TMS under Different Cooling Conditions

According to the research in Section III *A*, when the ambient temperature is 45 °C, although the maximum temperature of the battery energy storage box does not exceed the forced cut-off temperature of 60 °C, it has exceeded the alarm temperature of 55 °C. When the temperature of the LIB exceeds 55 °C, it has a great impact on the cycle life and performance; apparently, only relying on the rapid heat transfer characteristics of the U-shaped MHPA cannot meet the thermal management requirements of the battery energy storage box at an ambient temperature of 45 °C. Therefore, this section analyzes the influence of active air cooling on the thermal management performance of the TMS at an ambient temperature of 45 °C.

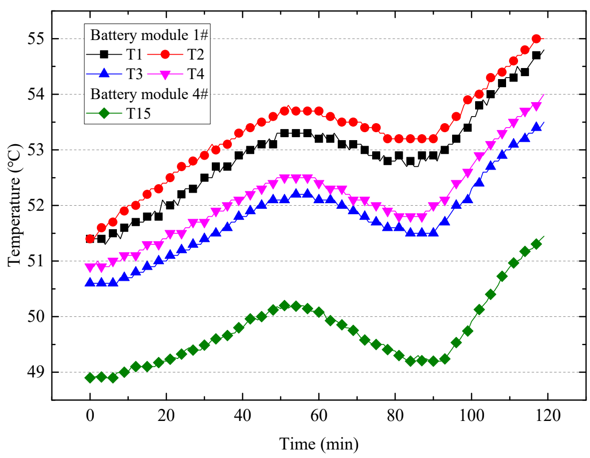
Figs. 7 (a) and (b) show the temperature change curves of monitoring points during charge-discharge process under active air cooling condition and the ambient temperature of 45 °C. During the charge process, the temperature of T2 point is the highest, rising from 45.6 °C to 51.6 °C, with a total temperature rise of 5.7 °C; the maximum temperature difference of module 1 # is 1.1 °C, and the average temperature difference is 0.97 °C; the maximum temperature difference of the whole battery energy storage box is 2.8 °C, and the average temperature difference is 2.0 °C. During the discharge process, the temperature of T2 point is still the highest, rising from 51.4 °C to 55 °C; the maximum temperature difference of module 1 # is 1.8 °C, and the average temperature difference is 1.5 °C; the maximum temperature difference of the whole battery energy storage box is 4.2 °C, and the average temperature difference is 3.56 °C. To sum up, even if the battery energy storage box is charged and discharged at an ambient temperature of 45 °C, owing to the excellent thermal management performance of the active air cooling TMS based on U-shaped MHPA, the maximum temperature in the battery energy storage box is only 55 °C, which does not exceed the alarm temperature of 55 °C, and is further lower than the forced cut-off temperature of 60 °C; in addition, after the fans are turned on, the temperature difference of the single battery module and the whole battery energy storage box are significantly reduced owing to the active air cooling, and ensure the whole battery energy storage box has excellent temperature uniformity. Therefore, the active air cooling TMS based on U-shaped MHPA not only effectively reduces the temperature rise of the LIB in the charge-discharge process, but also ensures the excellent temperature uniformity of the battery energy storage box; apparently, the active air cooling TMS based on U-shaped MHPA effectively solves thermal management problem when the battery energy storage box operates in high ambient temperature, and provides guidance for the application of the battery energy storage box TMS in high ambient temperature areas.

IV. Conclusion

In order to ensure the safe and stable operation of the battery energy storage box in high ambient temperature, a type of active air cooling TMS based on U-shaped MHPA is established in this study, and its thermal management performance under different high ambient temperatures and different cooling conditions are studied through experimental methods. The main conclusions are as follows: (1) Without active air cooling, the rapid heat transfer characteristics of U-shaped MHPA can ensure that the maximum temperature of the LIB in the battery energy storage box far below 60 °C, and the temperature difference of the whole battery energy storage box is also within an acceptable range. (2) Owing to the rapid heat transfer characteristics of U-shaped MHPA and the action of active air cooling, even when the battery energy storage box operates at an ambient temperature of 45 °C, the active air cooling TMS based on U-shaped MHPA can ensure that the maximum temperature of the battery lower than 55 °C, and the maximum temperature difference of the whole battery energy storage box lower than 5 °C.



(a)



(b)

Fig. 7 Temperature change curves of the monitoring points during (a) charge process and (b) discharge process under active air cooling method when the ambient temperature is 45 °C

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References

[1] Chen Z, Yang S, Pan M, Xu J. Experimental investigation on thermal management of lithium-ion battery with roll bond liquid cooling plate, Applied Thermal Engineering, 2022, 206:118106.
[2] Ahmed N, Miyatake M, Al-Othman A. Power fluctuations suppression of stand-alone hybrid generation combining solar photovoltaic/wind turbine and fuel cell systems, Energy Conversion and Management, 2008, 49(10):2711-2719.
[3] Yudhistira R, Khatiwada D, Sanchez F. A comparative life cycle assessment of lithium-ion and lead-acid batteries for grid energy storage, Journal of Cleaner Production, 2022, 358:131999.
[4] Yue Q, He C, Jiang H, Wu M, Zhao T. A hybrid battery thermal management system for electric vehicles under dynamic working conditions, International Journal of Heat and Mass Transfer, 2021, 164:120528.
[5] Jang D, Yun S, Hong S, Cho W, Kim Y. Performance characteristics of a novel heat pipe-assisted liquid cooling system for the thermal management of lithium-ion batteries, Energy Conversion and Management, 2022, 251:115001.
[6] Alihosseini A, Shafaee M. Experimental study and numerical simulation of a Lithium-ion battery thermal management system using a heat pipe, Journal of Energy Storage, 2021, 39:102616.
[7] Luo Y, Tang Y, Zhang X, Wang H, Zhou F, Bai P. A novel composite vapor chamber for battery thermal management system, Energy Conversion and Management, 2022, 254:115293.
[8] Zhao Y, Zhang K, Diao Y. Heat pipe with micro-pore tubes array and making method thereof and heat exchanging system, US, US20110203777 A1.
[9] Zhao Y, Xu H. A movable electric storage box based on micro heat pipe array, CN, CN211480101U.
[10] Zhao Y, Xu H. A safe and energy-saving lithium-ion battery pack dual-mode thermal management system and method, CN, CN110707393A.