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Performance of a Novel Thermal Management System of Li-Ion Batteries Used in Electric Vehicles

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Abstract

The lithium-ion battery is widely used as a subsystem that powers electric vehicles and supplies energy due to its lengthy cycle and high energy density. Maintaining an appropriate temperature is the most important factor that improves battery performance and avoids thermal runaway propagation of lithium-ion power battery modules. *This study presents the performance results of a unique hybrid cooling system for a battery module compared to single-air cooling. A combined battery thermal management system with Composite phase change material RT44HC with forced convection air cooling to enhance the operating performance of the lithium-ion battery pack, a novel structure was proposed and then applied for a four parallel (4P) battery pack, which integrates composite phase change material around every cell of battery and forced-air convection. In the experiment for this system, the designed module achieves a compact cylindrical shape for each single battery, preventing composite phase change material leakage when changing to a liquid state with a one C discharge rate. According to experimental results, the maximum temperature Tmax decreased from 60 ^{o}C at the discharging time of 39 min to The maximum temperature Tmax of 42.7 ^{o}C at discharging time of 47.4 with hybrid forced air and composite phase change material cooling at discharging time of 56 min (complete discharge rate of the battery) and The maximum temperature difference ΔTmax decreased from 5o^{o}C with conventional air cooling to maximum temperature difference ΔTmax 3.5^{o}C which preventing the risk of thermal runaway and enhance the cooling performance of battery thermal manage system for the battery pack.*

1. Introduction

The lithium-ion battery (LIB) is widely used as a subsystem that powers electric vehicles (EVs) and supplies energy due to its lengthy cycle and high energy density. Operating temperature is one of the most important elements influencing LIB's functionality, durability, and safety [1, 2]. To guarantee that the battery pack can function within the suitable temperature range of 20–45 °C and maintain a temperature difference between cells of no more than five °C [2-4]. Due to these criteria, an efficient battery thermal management system (BTMS) is essential. Phase change material (PCM) is an innovative thermal management application that can soak up heat. Meanwhile, the battery temperature is kept constant around the phase change temperature for a while during its phase change

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process. The CPCM-based BTMS offers greater cooling capacity than air cooling, a more straightforward structure than liquid cooling, and a wider use for batteries of various shapes [5]. Multiple studies on the BTMS have been conducted using various heat transfer mediums, including air cooling [6-17], liquid cooling [17-27], thermoelectrical cooling [28-31], and heat pipe cooling [32-38]. Studies have been undertaken to benefit from the advantages of PCM cooling systems [39-47]; for example, Ping Ping et al. [48] experimentally studied PCM-cooled modules with fin structure. The results showed that PCM with fin structure BTMS design enhanced the thermal performance and kept the battery's maximum temperature at less than 51°C at a relatively high discharge rate of 3C. Yantong Li et al. [43] Experimentally Studied composite phase change materials (C-PCMs) paraffine wax with expanded graphite (EX) used to improve cooling properties. The radiuses of the PCM unit in different conditions are identified (R=48,50,15,52mm). The results indicate that the proposed optimization method is effective. The system kept a maximum temperature under 70°C and a temperature difference under 3.4°C. R. Ziyuan et al. [49], Xiaoming Wang et al. [51], and Fereshteh et al. [46] studied adding paraffine wax with carbon fiber to improve the properties of cooling. The results showed that the PCM thermal conductivity was enhanced by adding carbon fiber and the development of maximum temperatures under 55°C,48°C, and 57.2°C, respectively. Deqiu et al. [47] studied C-PCM Paraffin wax using graphene and carbon nanotubes. The results showed that the composite PCM at the multi-walled carbon nanotube carbon nanotubes (MWCNT)/ graphene mass ratio 3/7 could enhance the heat transfer effect. The thermal conductivity was increased by 124% compared to graphene PCM, resulting in a maximum temperature under 55°C.Hybrid air with PCM has gradually been considered the thermal management of LIB due to its widespread application in studying thermal energy storage from latent heat. They are extending the duration of thermal control of the battery module under repeated cycles in PCM-based BTMS. Several studies have been undertaken to benefit from the advantages of hybrid PCM cooling systems with air and liquid cooling [51-61]. For example, Peng Qin. et al. [8] studied integrated PCM hybrid cooling systems designed with forced air. The results showed that PCM's thermal performance under the hybrid mode is superior to that under the only PCM mode, with the influence of maximum temperature under 50°C and temperature difference of 5°C.Fengxian Wang. et al. [21] presented an experimental and numerical study based on simulative investigations on a commercial organic PCM (OP28E), which was compounded with water to prepare two nano-emulsions PCM with different concentrations of OP28E, ten wt%, and 20 wt.%. The results showed that Tmax and ΔTmax were 1.1°C and 0.8°C lower than those based on water, respectively, when a ten wt.% OP28E nano-emulsion was utilized with a 200 mL/min flow rate. Jiahao Cao et al. [62] presented an experimental and numerical study based on Liquid cooling with PCM for cylindrical Li-ion batteries. The result showed that PCM thermo-physical properties significantly impact battery temperature, especially at high-current discharges. CPCM (RT44HC) can reduce Tmax from more than 50°C to 44°C and 42°C. Quantity et al. [47] designed the cooling structure of a LIB coupled liquid cooling with PCM, focused on the coolant's flow rate and the cooling pipe's position, and investigated their influences on the operating temperature. The outcomes demonstrated that this system operated at a flow rate of 0.09 m/s. The most significant fluctuation in temperature was less than 0.25%, and when the unit mass coolant uses the proper flow rate of 0.1 m/s, it may remove more heat. Appropriate cross-section selection with PCM can reduce the temperature difference to near 5K. Wen Yang et al. [27] simulated a novel BTMS-like honeycomb-hexagonal cooling plate with a bionic liquid mini-channel and PCM. The battery module's maximum temperature and the temperature difference are stabilized between 39.0 °C and 3.5 °C. Zhang et al. [63] studied the hybrid cooling of PCM with liquid cooling to improve the cooling properties. It found that the maximum temperature of the battery can be controlled at around 39℃, and the PCM-based BTMS can control the temperature difference of the battery within one ℃. Although many experimental and numerical studies have been undertaken to achieve the advantages of PCM and hybrid PCM with other cooling methods like Liquid, air, and HP-cooled systems, there is still a need to overcome some of the obstacles of PCM-cooled systems. However, two significant challenges restrict the use of PCM-based BTMS. One is that due to its comparatively low thermal conductivity, pure PCM, like paraffin, cannot meet the demands of a fast response to the thermal surge. The other obstacle is leakage during changing to the liquid state, producing problems of the complete PCM melting, which needs a particularly compact system to prevent this phenomenon. In this study, a novel hybrid BTMS based on CPCM and an air-cooling system is designed and constructed by inserting the cylindrical Li-ion battery inside a sealed aluminum cylindric filled with pure CPCM with suitable latent heat of fusion. First, the aluminum cell is made and tested to see how well the suggested design cools. The system's performance in controlling the battery temperature and temperature difference under extreme operating conditions and avoiding thermal runaway propagation under abuse conditions are studied, which increases the ability of time and power during charging and discharging. Furthermore, the influence of CPCM thermal conductivity and the airflow velocity on preventing thermal runaway propagation is further analyzed.

2. Experiments setup

2.1 Preparation of The Experiment.

The battery pack's schematic diagram is shown in Fig.1. Four series of 18,650 Li-ion batteries were linked in parallel, and then six series of batteries were connected in series (6S4P). Commercial LG INR18650-M26 Li-ion batteries were taken into consideration. Device type Li Pro Balance Charger model IMAX B6. This device is a rapid charger with a high-performance microprocessor and specialized operating software. The device's primary function is to balance the batteries used in the module. A CPCM RUBITHERM® (RT44HC) matrix made of paraffin with expanded graphite, aluminum tubes were fitted around each cell of the batteries as a container tube, which was sealed at both ends to prevent leakage problems (see Fig.2). The controlled velocity fan was put to cool the battery, it has a square shape (80 mm * 80 mm), blades with a radius of 35 mm and works on 12 volts, 0.28 Amp to give speed from 3 to 5 m/s. Mini Anemometer with a sensitive digital device used to determine airspeed and temperature. It is used to determine wind speed. By knowing the surface area of the inlet air, one can calculate the volumetric flow rate V (m3/s).

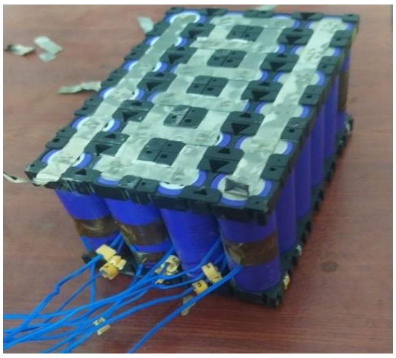

Fig.1 The battery packs without PCM

By knowing the air density, we can calculate the mass flow rate m (Kg/sec) (see Fig.4). Table 1 lists the specific parameters of commercial lithium-ion battery specifications and CPCM RUBITHERM® (RT44HC) used in the experiment.

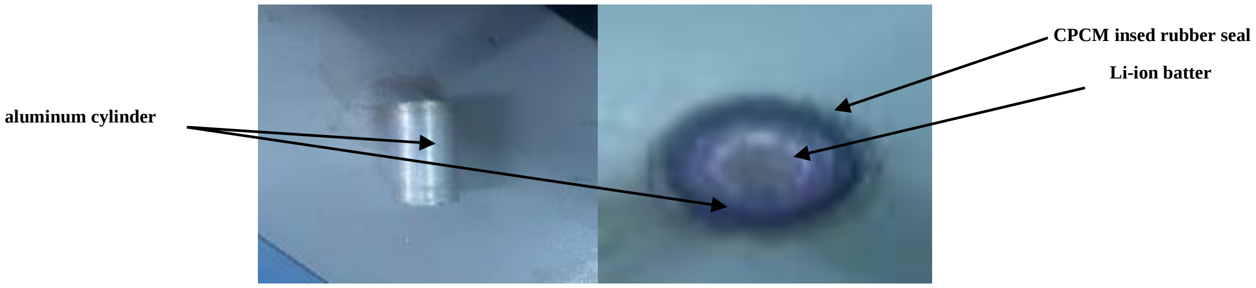

Fig.2 Compact sealed aluminum cylindrical shape around CPCM for each battery

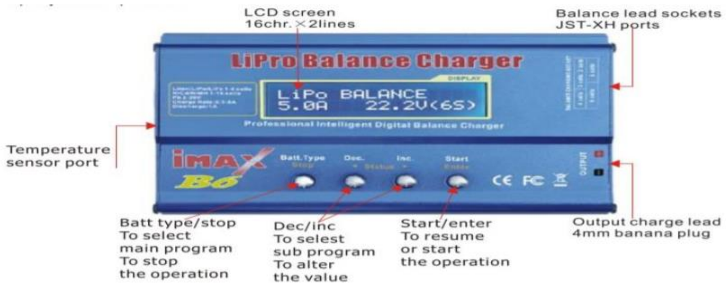

Fig.3 Balance Charger

Fig.4 Mini Anemometer

Fig.5 Batteries and phase change materials unit

Table.1 CPCM RUBITHERM® (RT44HC) and LG INR18650-M26 properties

CPCM RUBITHERM® (RT44HC)		LG INR18650-M26 battery	
Important data	**Typical value**	**Item**	**Specification**
Melting temperature	41-44 ^{o}C	Capacity	Nominal 2. 6. mAh
Congealing area	44-40 ^{o}C		Minimum 2.500 mAh
Heat storage capacity	250 KJ/kg	Nominal voltage	3.6 v
Specific heat capacity	2 KJ/kg.k	Standard charge	0.5 c(1.250 mA), (const current), 4.2 v, (const voltage)
Density solid at 25c	0.8 Kg/l	Max. charge voltage	4.2 v
Density liquid at 80c	0.7kg/l	Max. Charge current	1.0 C(2.500 mA)
Heat conductivity	0.2W/(m.k)	Max. discharge current	10A
Volume expansion	12.5 %	Max temperature limit	75 ^{O}C
Flash point	> 180 ^{o}C	Wight	44 g
Maximum operating temperature	70 ^{o}C	Charge operating temperature	0-45 ^{O}C
		Discharge operating temperature	-20 – 60 ^{O}C

2.2. Experimental Concept

The main components of the experimental system were the test section, thermal performance test subsystem, and battery charge/discharge subsystem. The subsystem of charge and discharge (DC Electronic Load Power Supply Model No.72-13210) included control software and program-controlled DC power supplies and load. This subsystem simulates the battery operation at different charge and discharge rates. The battery was continuously discharged to 18 V at 1 C (20 A) during the discharge procedure. The battery was charged in two stages: first, at a constant current of 33.6 V until the terminal voltage was attained; second, at a constant voltage of 33.6 V and a demand of 0.05 A. The thermal performance test subsystem comprised a JK4000 data questing unit with a high-performance temperature recorder. The JK4000 data acquisition unit recorded all test temperatures every second. The test section was the lithium-ion battery pack comprising 12 single battery cells by the twelve K-type thermocouples used to measure the temperature. As seen in Fig.6, Each cell was composed of a battery core, one tested on both sides and core, and the ambient temperature was controlled and registered. The cylindrical aluminum sheet with two seals protects the PCM from leakage. The thermostatic chamber was filled with the test part positioned vertically. During the trials, the charge/discharge subsystem then charged or drained the battery at a predetermined pace. Concurrently, the battery's temperature, the temperatures of the cells, the outside air, and the voltage and current used for charging and discharging were all noted and stored appropriately. Fig.7 shows the schematics and the photos of the experimental setups.

2.3 Data Error Analysis

Uncertainty and Error Analysis The measurement of the discrepancy between measured and actual values in experimental work is often accomplished by calculating uncertainty. Uncertainty analysis is a systematic approach to determine the cumulative systematic errors resulting from imperfections in the measurement process. Determining uncertainty for any measuring equipment or process may be achieved by conducting numerous trials or extracting the average error readings from the instrument's datasheets or manuals.

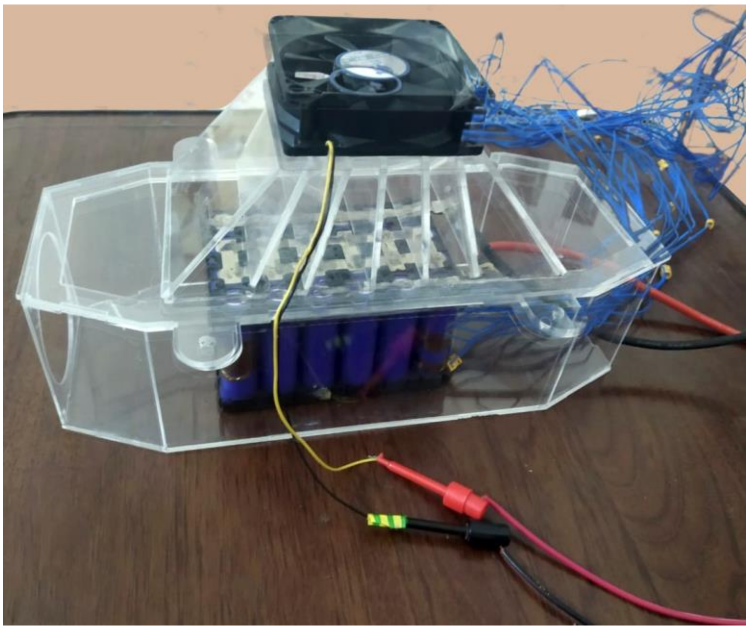

Fig.6 Battery pack with cooling module design

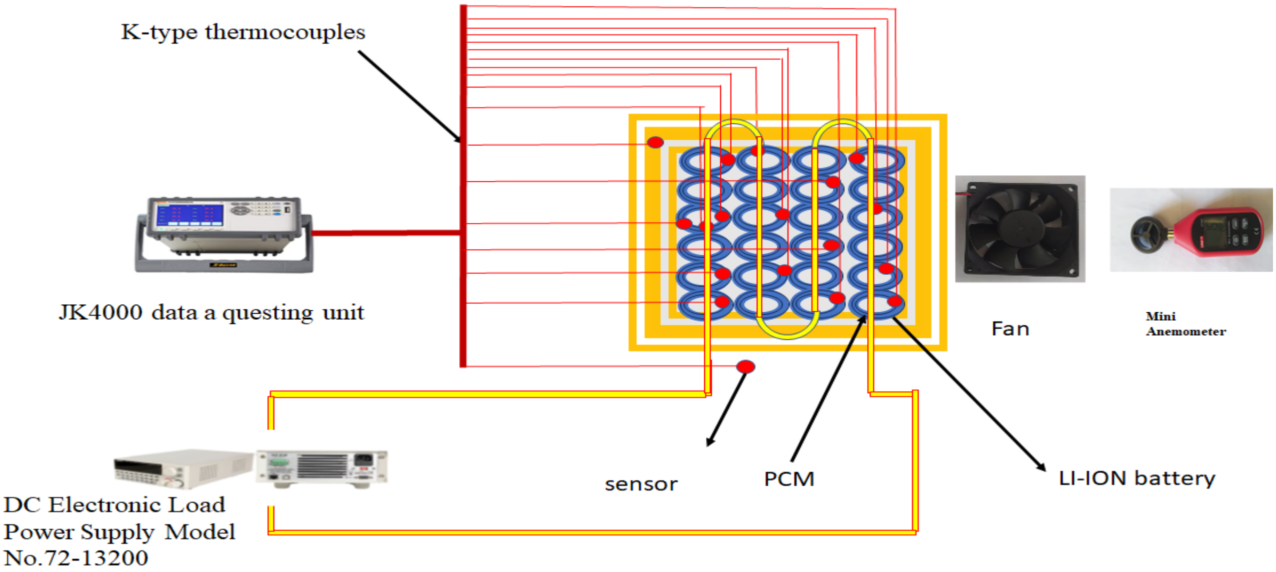

Fig. 7 The battery pack's schematic diagram

In the process of assessing the measurement uncertainty in experimental research, most of the uncertainties associated with the main values of a certain measurement characteristic are approximated using the subsequent function [65]

$$W_R = [(\frac{\partial R}{\partial i_1} W_1)^2 + (\frac{\partial R}{\partial i_2} W_2)^2 + (\frac{\partial R}{\partial i_3} W_3)^3 + \cdots (\frac{\partial R}{\partial i_n} W_n)^n]$$

The function W_R represents the total uncertainty of the experimental components. In this context, W_1, W2, and Wn denote the uncertainties associated with the independent variables, whereas i represents the independent variable corresponding to the property R. This research incorporates several measurement equipment and techniques in its experimental work. For example, the uncertainties associated with the anemometer and K-type thermocouples were determined to be 1.73% and 4.5%, respectively. This investigation demonstrates that each device used in the experiment has a maximum experimental error of ±0.3 m/s and ±0.4.5°C. Hence, the experimental work would have a maximum uncertainty of no more than 6.47%. The JK4000 data acquisition unit with the K-type thermocouples was calibrated using three standard materials: Zero Ice temperature,100°C water boiling temperature, and 56°C acetone boiling temperature, as shown in Fig.6 and Table 2. The error range is between (-0.4°C:0.5°C). The JK4000 data acquisition unit with the K-type thermocouples was calibrated by using three standard materials, which are Zero°C Ice temperature,100°C water boiling temperature, and 56°C acetone boiling temperature as shown in Fig.6, and Table the error range is between (-0.4°C:0.5°C).

3. Result and discussion

Fig. 6 Fig. 7 displays the outcomes of three different BTMS discharging cooling processes: the battery with natural cooling, CPCM cooling, and hybrid CPCM integrated with forced air cooling.

Table 2 Error of measuring temperature.

Channels temperature	Ice			Boiling water			Boiling Aceton		
	St	temp	error	St	temp	error	St	temp	error
1	0.1	0	0.1	100.3	100	0.3	56.2	56	0.2
2	0.3	0	0.3	100.2	100	0.2	56.4	56	0.4
3	0.3	0	0.3	100.4	100	0.4	56.4	56	0.4
4	0.4	0	0.4	100.3	100	0.3	56.5	56	0.5
5	0.2	0	0.2	100.4	100	0.4	56.1	56	0.1
6	-0.3	0	-0.3	100.3	100	0.3	55.7	56	-0.3
7	0.4	0	0.4	100.2	100	0.2	56.6	56	0.6
8	0.4	0	0.4	100.3	100	0.3	56.1	56	0.1
9	0.4	0	0.4	100.1	100	0.1	56.5	56	0.5
10	0.4	0	0.4	100.1	100	0.1	56.2	56	0.2
11	0.4	0	0.4	100.2	100	0.2	56.3	56	0.3
12	0.3	0	0.3	101.4	100	1.4	55.7	56	-0.3
13	0.4	0	0.4	100.2	100	0.2	56.1	56	0.1
14	0.1	0	0.1	100.4	100	0.4	56	56	0
15	0.4	0	0.4	100.4	100	0.4	56.1	56	0.1
16	0.3	0	0.3	100	100	0	56.5	56	0.5
17	0.1	0	0.1	100.3	100	0.3	56.2	56	0.2
18	0	0	0	100.2	100	0.2	56.3	56	0.3
19	0.2	0	0.2	100.2	100	0.2	56.2	56	0.2
20	0.3	0	0.3	100.2	100	0.2	56.3	56	0.3
21	-0.3	0	-0.3	100.2	100	0.2	56.2	56	0.2
23	-0.2	0	-0.2	100.2	100	0.2	56.3	56	0.3
24	0.1	0	0.1	100.1	100	0.1	56.4	56	0.4

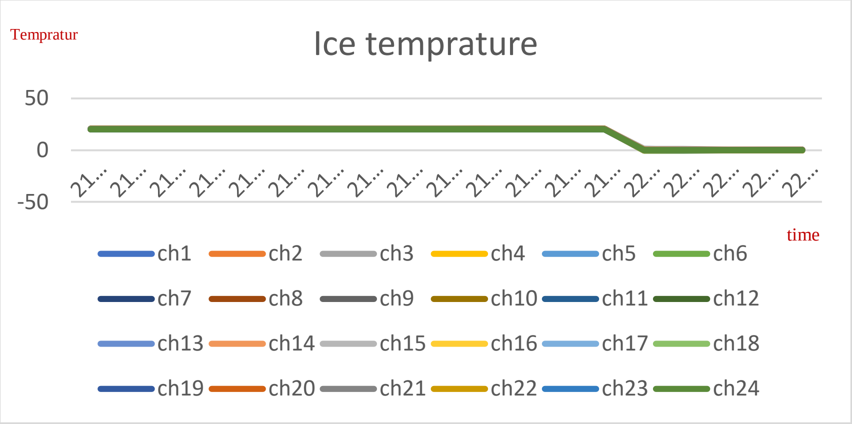

Fig.8 Ice measuring Temperature error

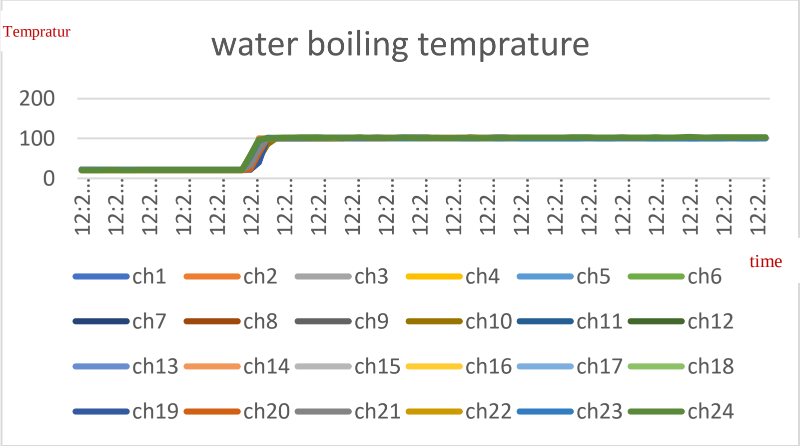

Fig.9 water boiling measuring Temperature error

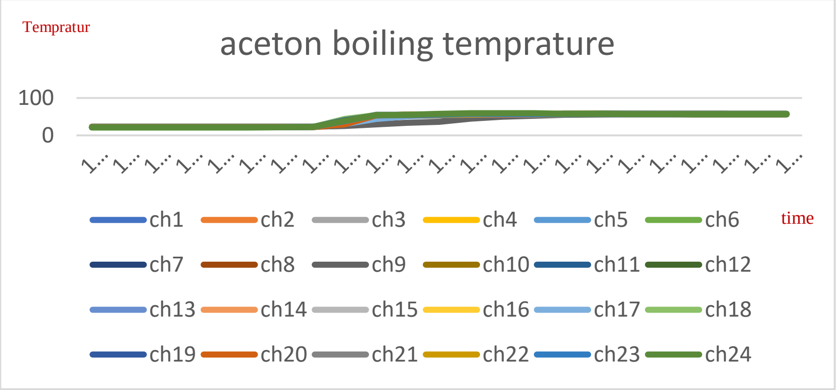

Fig.10 Acetone boiling measuring Temperature error

Several significant parameters exist in evaluating the battery thermal management system under cycling. The figure represents one rate and three cases. Displays the three cases' maximum (T_{Max}) and ambient temperatures (T_{Amb}). Here, T_{max} refers to the maximum temperature among thirteen temperature measuring points (1-13) on the battery surface, three (5-6-7) on both sides, and the center of no nine batteries. As seen in Fig.7, it describes the history of temperature difference (ΔT_{Max}). ΔTMax is the difference between T_{Max} and the minimum temperature of thirteen measuring points

(1-13). The proposed thermal management allows the maximum value of T_{Max} to drop from 60 °C to 47.4 °C to 42.7 °C at 1C, respectively. Meanwhile, the maximum ΔT_{Max} decreased from 5 °C and 3.5 °C at 1C rate separately, as follows:

3.1 The thermal performance of the battery pack under natural convection

As seen in Fig.6, which presents the thermal performance of the proposed BTMS with conventional cooling, the first case shows the thermal performance of the battery pack without any additional thermal management system. It can be easily obtained from Fig. 6 that at 36 min, T_{Max} has exceeded 60 °C, which is the maximum limit of the li-ion battery according to the factor properties of the battery under 1 C rate. Also seen in Fig.7, ΔTm_{ax} climbs over the recommended value (5 °C), which will impair the lifespan of the battery pack. Besides, T_{Max} and ΔT_{Max} both considerably exceed the safety limit of the battery under 1 C rate, and There is a risk of thermal runaway at a cycling rate. Therefore, it is necessary to enhance the cooling performance of BTMS for the battery pack.

3.2 Thermal behavior with a thermal management PCM conventional cooling.

As seen in Fig.6, which presents the thermal performance of the proposed BTMS with conventional CPCM cooling and the temperature of CPCM, the CPCM reached the solid-liquid phase change stage at a cycling rate. It is noted when CPCM temperature exceeds 44 °C in the passive thermal management system. This suggests that the CPCM arrives at the stage of solid-liquid changing, and the latent heat of CPCM has been utilized. This leads to CPCM temperature slightly behind $T_{Max,}$ and the maximum value of T_{Max} drops from 60 °C to 47.4 °C. The efficiency of the designed thermal management system has been proved experimentally. T_{Max} is controlled within the optimum temperature range, also seen in Fig.7, and ΔT_{Max} is maintained below 4.1°C cycling at 1 C rate.

3.3 The effect of forced air with PCM convection cooling

An anemometer estimated the battery pack's entry velocity to be around one meter per second, which triggered the active thermal management system. The heat dissipation in the active mode depends on the forced-air convection. As seen in Fig.6, Comparing the trend of T_{Max} in three thermal management strategies, it can be obtained that the maximum value of T_{Max} occurred differently in the discharging cycle. The maximum value of T_{Max} with active thermal management took place. T_{Max} thus dropped quickly during the laying-aside time. On the contrary, natural convection failed to carry the heat quickly on the laying-side stage. However, the maximum value of T_{Max} in the active mode is approximately lower than 42.7 °C. The forced air, flowing through the surface of the aluminum, carried much heat induced by the battery cells, leading to the difference in thermal performance between active and passive battery thermal management, preventing T_{Max} from exceeding the safe temperature limit (60 °C). At the same time, it is noticed that, as seen in Fig.7, it keeps ΔT_{Max} below 3.5 °C because the high thermal conductivity of aluminum ensures that ΔT_{Max} is minimized under both conditions.

4. Conclusions

This paper proposes a novel hybrid BTMS combining air-forced convection with CPCM (RT44HC). The effectiveness of the designed BTMS was then proved under cycling at a 1 C rate. Within the suggested range, both the maximum and maximum temperature differential are regulated. Meanwhile, the thermal performance between active and passive cooling was compared. Since the

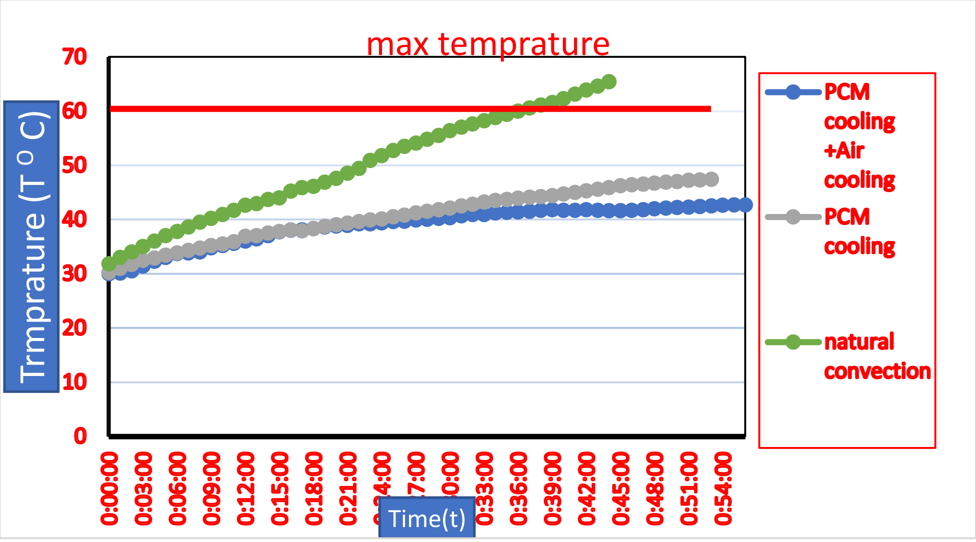

Fig.6. The maximum temperature of the BTMS strategies.

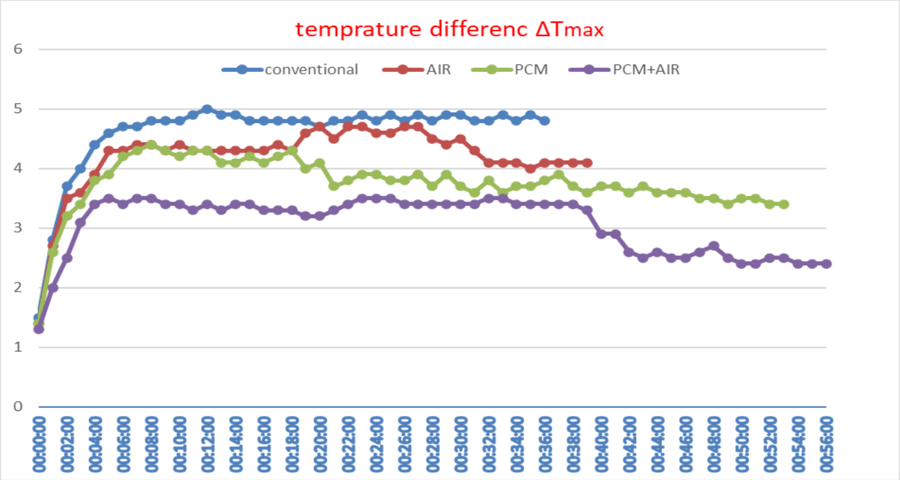

Fig.7. The maximum temperature difference of the BTMS strategies

existence of the active cooling, $T_{Max,}$ and ΔT_{Max} Within the suggested range, both the maximum and maximum temperature differential are regulated. The module's discharging time was increased from 36 minutes with conventional air cooling to 47.4 minutes using passive CPCM cooling. It achieved 56 minutes with hybrid forced air and PCM cooling, raising the power capability consumed at a specific load. The maximum temperature decreased from 60 °C with conventional air cooling to 42.7 °C with hybrid CPCM and forced air cooling, preventing battery temperature from reaching its maximum temperature and thermal runaway propagation. The maximum temperature difference also decreases from 5 °C with conventional air cooling to 3.5 °C with hybrid CPCM and forced air cooling, improving the battery performance.

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