Frontiers in Heat and Mass Transfer (FHMT), 20, 24 (2023)
DOI: 10.5098/hmt.20.24

Global Digital Central
ISSN: 2151-8629

Frontiers in Heat and Mass Transfer

Available at www.ThermalFluidsCentral.org

INVESTIGATION AND OPTIMIZATION OF A THERMAL MANAGEMENT SYSTEM FOR LITHIUM-ION BATTERIES COMBINING CLOSED AIR-COOLING WITH PHASE CHANGE MATERIAL

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ABSTRACT

To maintain the maximum temperature and temperature difference of batteries in electric vehicles within a reasonable range, a battery thermal management system combining closed air-cooling with phase change material(PCM) is proposed and investigated. A three-dimensional numerical model is developed and validated by experiment. The results indicate that the temperature rise of batteries decreases with the increase of ambient temperature. The increasing filling amount of PCM reduces the maximum temperature difference of batteries as well as the effect of the airflow rate on maximum temperature of batteries. The energy consumption is minimum when the filling amount of PCM is 0.28kg.

Keywords: *Lithium-ion batteries, Battery thermal management system, Phase change material, Closed air-cooling*

1. INTRODUCTION

Electric vehicles play a major role in reducing greenhouse gas emission and environmental pollution (Keiner *et al*., 2019; Budiman *et al*., 2022). As the power source of electric vehicles, lithium-ion batteries (LIB) have characteristics of low self-discharge rate, long service life, and high energy density, but the thermal safety is still the main challenge for the development of lithium batteries (Bhattacharjee *et al*., 2018; Jouhara *et al*., 2019). In the abnormal temperature range, the performance and stability of lithium-ion batteries of almost all materials decline rapidly. Therefore, an efficient battery thermal management system (BTMS) is essential to keep the battery temperature within a reasonable range and reduce temperature difference between batteries (Lu *et al*., 2020; Ghiji *et al*., 2021). To maintain the best performance and extend the service life of the batteries, the temperature of all batteries should be maintained within a range of 20°C-50°C. The maximum temperature difference between batteries should be less than 5°C at a high discharge rate (Chen *et al*., 2020).

BTMS is mainly divided into air thermal management, liquid thermal management, phase change material thermal management, and so on nowadays. Of its low cost, the air has become a commonly used working medium (Akinlabi *et al*., 2020). A large number of scholars have studied air thermal management. Fan et al. (2019) found that the air-cooling system with neatly arranged batteries had a good performance. Wang et al. (2021) studied the influence of the parallel plate installation method on battery heat dissipation in air thermal management through simulation, and the results showed that the maximum temperature of the batteries was reduced by 3.42K and the temperature difference was reduced by 6.4K. Wang et al. (2021) studied the influence of adding a spoiler in the airflow channel on the heat dissipation of batteries using simulation and optimized the heat dissipation structure. The results showed that the maximum temperature of batteries was reduced by 2.24K. Lu et al. (2018) studied the influence of different flow channel shapes on the heat dissipation of batteries, and the results showed that the U-shaped flow channel had the best heat dissipation effect. Yi et al. (2020) studied the heat flow of different air outlet modes. The results showed that the heat dissipation performance of the air-cooled batteries could be improved with the increase of the synergy of velocity and temperature gradient. Mohammadian et al. (2015) conducted experiments on forced convection air-cooling of lithium-ion battery modules. The study found that the temperature rise of the battery modules could be reduced by increasing the inlet air velocity or decreasing the distance between the batteries. Xu et al. (2013) studied the heat dissipation performance under different airflow channel modes. It was found that compared with the horizontal battery, the heat dissipation performance of the longitudinal battery was improved because of the shortening of the airflow channel. However, it would cause a large temperature difference between batteries.

To reduce the temperature difference between batteries, phase change materials (PCM) are used for battery thermal management because PCM will maintain a small temperature range during phase transition (Mohammed *et al*., 2022; Zhang *et al*., 2022). Jilte et al. (2021) studied the heat dissipation of batteries with enhanced PCM in different arrangement modes by means of simulation, the results showed that the 7*7*1 arrangement was more efficient than the 7*1*1 arrangement. Lv et al. (2016) constructed a low-fin cooling system of composite PCM and lithium-ion batteries. At the discharge rate of 3.5C, the maximum temperature and temperature difference were below 50°C and 5°C, respectively. Wang et al. (2018) studied a new passive thermal management system (TMS) based on PCM by combining simulation and experiment, and the results showed that passive TMS could keep the battery temperature within 42°C under the discharge rate of 4C. Since the thermal conductivity of PCM is generally low, a lot of research has been done to add fins or heat pipes in PCM. Tian et al. (2020) studied the heat

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transfer characteristics of the fins made of different materials after adding PCM. The PCM with high thermal conductivity had better heat transfer characteristics, and the heat transfer characteristics would be better with a larger fin area. Ji et al. (2018) studied the heat transfer characteristics of adding long and short fins in PCM. When the upper fin was long and the lower fin was short, heat transfer efficiency could be improved. Peng et al. (2022) designed a compact hybrid cooling system of PCM and heat pipes. The results showed that 12% EG(expanded graphite) composite PCM had better heat dissipation performance than pure PCM. This cooling system was especially suitable for small or medium-sized battery modules. Layth et al. (2022) studied the influence of fin shape on heat transfer efficiency when PCM melted. The results showed that the heat transfer efficiency of the V-shaped fin increased by 149.88% when PCM melted.

Since PCM will not cool batteries after completely melting, in order to improve the heat dissipation capacity of the thermal management system, the combination of PCM and air-cooling thermal management mode has attracted more and more attention. Ling et al. (2015) proposed a method for cooling batteries with air and PCM, and the research showed that this method could keep the maximum temperature of batteries below 50°C. Mehdi et al. (2019) experimentally studied the method of combining air and PCM to cool batteries. The results showed that increasing the Re of air could extend the time for the battery temperature to reach 60°C, and PCM with high thermal conductivity had better heat dissipation capacity. Chen et al. (2021) established a heat dissipation model of an air-cooled battery combining PCM with heat pipes and optimized the thickness of PCM. In the optimized model, the temperature difference of the battery was reduced by 30%. LIN et al. (2021) used an artificial neural network (ANN) and genetic algorithm (GA) to optimize the BTMS based on air and PCM. The optimized system slowed down the temperature rise of the battery pack and delay the phase change. Yang et al. (2021) proposed a composite thermal management system for lithium-ion batteries that combined air-cooling and PCM. The thermal performance of batteries in the natural convection, the combination of natural convection and PCM cooling, and the combination of forced convection and PCM cooling were studied. The results showed that the maximum temperature and temperature difference of forced convection and PCM combined batteries were controlled within the ideal range of 2C.

In the studies of air thermal management, many scholars have studied the influence of airflow channels on battery heat dissipation, but this aspect is rarely involved in the studies of the combination of PCM and air-cooling thermal management system. In addition, the filling amount of PCM has a great effect on the weight of electric vehicles and thus on the power consumption, but this is rarely studied. Therefore, a BTMS combining closed air-cooling with PCM is proposed. Firstly, a three-dimensional numerical model is developed and verified by experiment. Secondly, the influence of the filling amount of PCM on the BTMS is analyzed under different ambient temperatures and airflow rates. Thirdly, the airflow channel is changed and fins are added to the BTMS, the influences of the airflow channel and the number of fins on the BTMS are discussed. Finally, the energy consumption caused by different filling amounts of PCM is analyzed and the optimal filling amount of PCM is proposed.

2. THE MODEL

2.1 Physical model

The physical model used in the simulation is shown in Fig. 1. The batteries are staggered and surrounded by PCM. Air flows through the airflow channels between PCM. As shown in Fig. 2, the simplified model in the frame is taken as the research object. The distance between batteries is 6mm and the width of airflow channels is 4mm.

2.2 Numerical model

The continuity, momentum continuity, and energy continuity equations are as follows (Faisal *et al.*, 2021):

$$\frac{\partial \rho}{\partial t} + \nabla \cdot (\rho \vec{v}) = 0 \tag{1}$$

$$\frac{\partial (\rho \vec{v})}{\partial t} + \nabla \cdot (\rho \vec{v} \vec{v}) = -\nabla P + \mu \nabla^2 \vec{v} \tag{2}$$

$$\frac{\partial (\rho C_p T)}{\partial t} + \nabla \cdot (\rho c_p \vec{v} T) = \nabla \cdot (\lambda \nabla T) \tag{3}$$

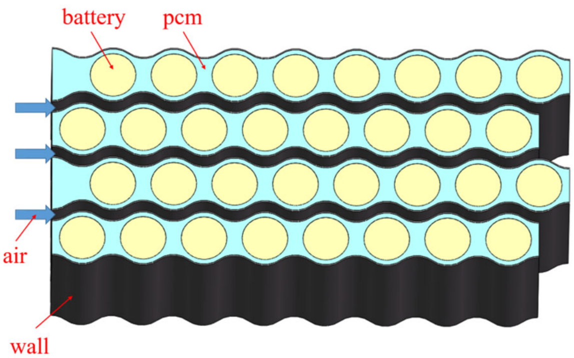

Fig. 1 Physical model

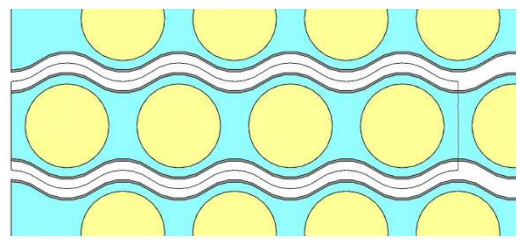

Fig. 2 Simplified model

The physical parameters of air, battery and PCM are shown in table 1 (Xie *et al*., 2021). Since the Reynolds number of air in this model is less than 2300, the laminar flow model is adopted in the numerical simulation.

Table 1 Parameters of air, battery and PCM

Parameter	*Air*	*Battery*	*PCM*
Diameter (mm)	-	18	-
Height (mm)	-	65	-
Capacity (mA·h)	-	2000	-
Density (kg/m^3)	1.1067	2776.3	822
Specific heat capacity (J·kg^{-1}·K^{-1})	1007	1075.9	2130
Thermal conductivity (W/(m·K))	0.0262	Radial:1.473 Axial:29.85	0.2
Viscosity (mPa·s)	0.0187	-	-
Latent heat (kJ/kg)	-	-	180
Phase transition temperature (°C)	-	-	35

The heat generation rate of the battery is calculated as follows:

$$Q_{gen} = I^2 R + IT \frac{\partial U_{ocv}}{dT} \tag{4}$$

$$Q_{ab} = mc_p \frac{dT}{dt} \tag{5}$$

The method used to simulate heat transfer in PCM is as follows (Mat *et al*., 2013):

$$\rho_{PCM} \frac{\partial H_{PCM}}{\partial T_{PCM}} = \lambda_{PCM} \nabla^2 T_{PCM} \tag{6}$$

$$H_{PCM} = \beta L + \int_{T_0}^{T_{PCM}} c_{p,PCM} dT \tag{7}$$

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$$\beta = \begin{cases} 0 & T_{PCM} < T_S \\ \dfrac{T_{PCM} - T_S}{T_L - T_S} & T_S \le T_{PCM} < T_L \\ 1 & T_{PCM} \ge T_L \end{cases} \tag{8}$$

The inlet and outlet boundary conditions are velocity inlet and pressure outlet, respectively. Natural convection due to density changes is ignored and the influence of fluid gravity is not considered. The SIMPLE algorithm is used for pressure-velocity coupling, second-order upwind scheme is used for momentum. Convergent residual index is set as 1.0×10^{-3} in addition to energy and the convergent residual index of energy is set as 1.0×10^{-6}.

In order to research the influence of gird number on the calculation results, five kinds of grid numbers are selected for calculation. Fig. 3 shows the temperature of the battery when the discharge rates are 3C and 4C, respectively. It can be seen that when the grid number reaches 420k, the difference between the calculation results is small.

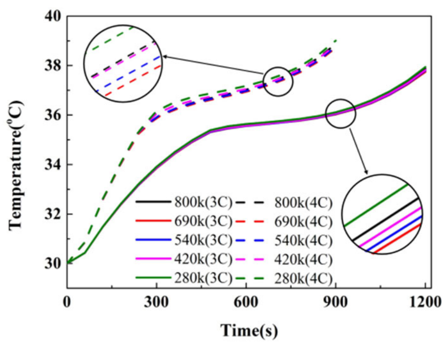


Fig. 3 Temperature of battery in different gird numbers

2.3 Model validation

An experiment was carried out. As shown in Fig. 4, four batteries were formed in series and placed in a container wrapped with an insulation layer. PCM was filled around batteries, and four type K thermocouples were placed around the batteries to measure the temperature. The temperature was recorded by a paperless recorder (MIK-5000C) and transmitted to a computer. The container was placed in an incubator, the temperature in the incubator was set to 30°C, and discharge rates of batteries were set as 3C and 4C through the battery charging and discharging equipment (EBC-A20). The initial voltage of each battery was 4.2V and the discharge stopped at the voltage of 2.8V.

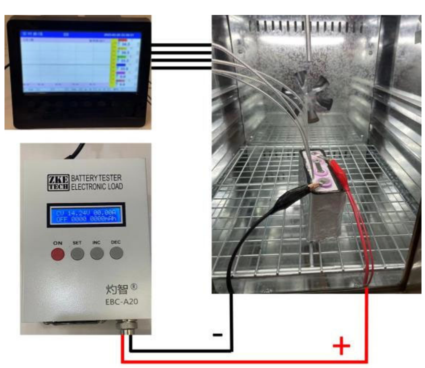
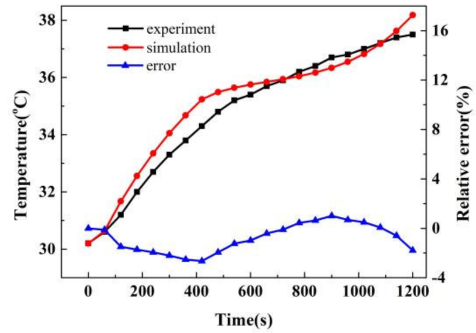


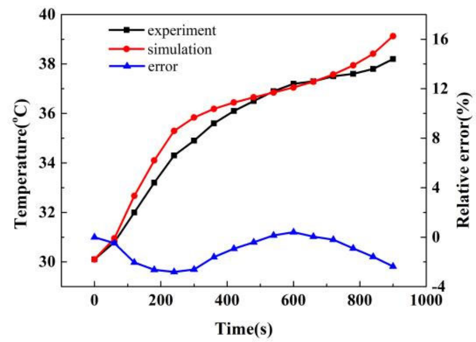
Fig. 4 Experimental system

The experimental results and simulated results are shown in Fig. 5.

As can be seen from Fig. 5, in the process of batteries discharge, the maximum relative errors are within ±3%, indicating the numerical model is valid.



(a) Discharge rate of 3C



(b) Discharge rate of 4C

Fig. 5 Comparison of experimental and simulated results

3. RESULTS AND DISCUSSION

3.1 Influence of filling amount of PCM at different ambient temperatures

Fig. 6 shows the maximum temperature of batteries under different ambient temperatures and filling amounts of PCM, the filling amounts of PCM in case 1, case 2 and case 3 are 22446mm^3, 33678mm^3 and 46158mm^3, respectively.

As shown in Fig. 6, with the decrease of ambient temperature, the temperature rise increases. When the temperature of batteries is higher than 35°C, the PCM begins to melt, and the heat of batteries is absorbed by PCM and air resulting in less temperature rise of batteries. Though the maximum temperature of batteries in case 1 is higher than that in case 3 at the end of discharge, the temperature difference between case 1 and case 3 is less than 0.5°C at the ambient temperature of 25°C and more than 2°C at the ambient temperature of 35°C. The reason is that as shown in Fig. 7, at the ambient temperature of 35°C, the PCM in case 1 has completely melted and the heat of batteries is mainly absorbed by air, while the PCM in case 3 has not completely melted and the heat of batteries is mainly absorbed by PCM, the heat absorption capacity of air is lower than that of PCM.

Fig. 8 shows the maximum temperature difference of batteries at different ambient temperatures and filling amounts of PCM.

As shown in Fig. 8, the temperature difference in case 1 is higher than in other cases at the same ambient temperature, this is because the heat of batteries in case 1 is mainly carried away by air. The specific heat capacity of air is small which resulted in a high temperature difference between air around the first and last battery in case 1 as shown in Fig. 9. With the increase of ambient temperature, the temperature difference decreases. Because PCM melts and absorbs the heat of batteries. Due to the latent heat, the temperature rise of PCM after absorbing heat is small. This results in a small temperature difference between PCM around the first and last battery.

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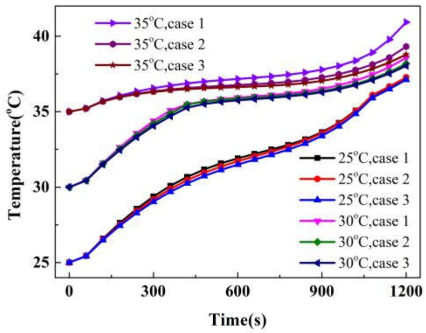
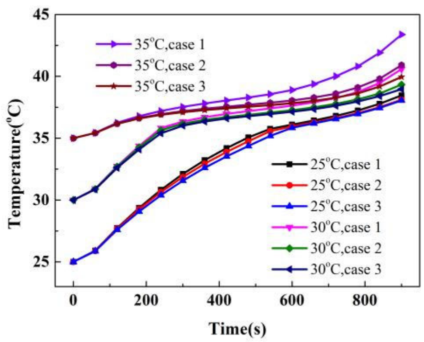


(a) Discharge rate of 3C



(b) Discharge rate of 4C

Fig. 6 Maximum temperature of batteries under different ambient temperatures and filling amounts of PCM

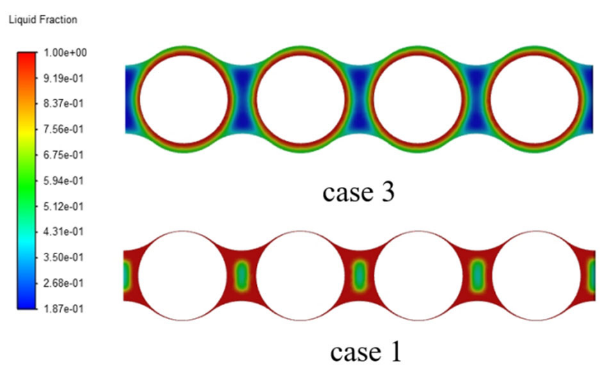


Fig. 7 Liquid fraction of PCM at the end of discharge in case 1 and case 3

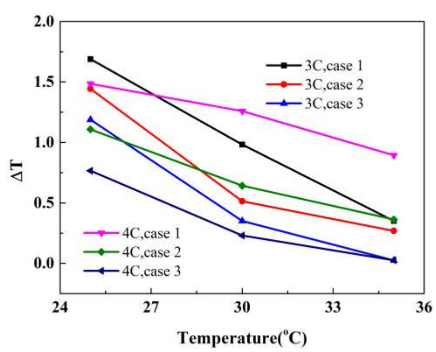


Fig. 8 Maximum temperature difference of batteries at different ambient temperature and filling amounts of PCM

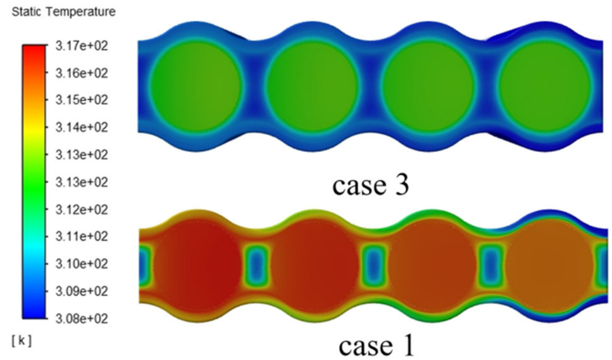
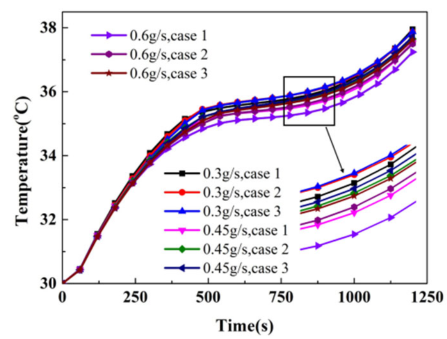


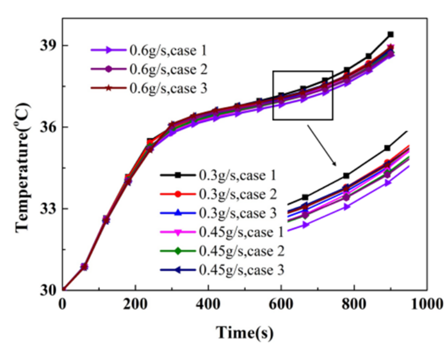
Fig. 9 Temperature cloud diagrams of cases 1 and 3 at the end of discharge

3.2 Influence of filling amount of PCM at different airflow rates

Fig. 10 shows the maximum temperature of batteries under different airflow rates and filling amounts of PCM.



(a) Discharge rate of 3C



(b) Discharge rate of 4C

Fig. 10 Maximum temperature of batteries under different airflow rates and filling amounts of PCM

As can be seen from Fig. 10, with the increase of airflow rate, the maximum temperature of batteries decreases. The increase of airflow rate provides a higher heat transfer coefficient of the air which is beneficial to transfer more heat from batteries to air. In addition, the maximum temperature of batteries decreases by 0.71°C in case 1 and 0.25°C in case 3 at the airflow rate increasing from 0.3g/s to 0.6g/s. The reason is that thermal resistance on the air side in case 1 accounted for more of the total thermal resistance than that in case 3. This results in the reduction of the thermal resistance on the air side having a greater impact on the total

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thermal resistance in case 1 than that in case 3. With the decrease of the filling amount of PCM, the air side thermal resistance becomes more significant for the total thermal resistance, resulting in a greater impact of airflow rate on the temperature of batteries.

Fig. 11 shows the maximum temperature difference of batteries at different airflow rates and filling amounts of PCM.

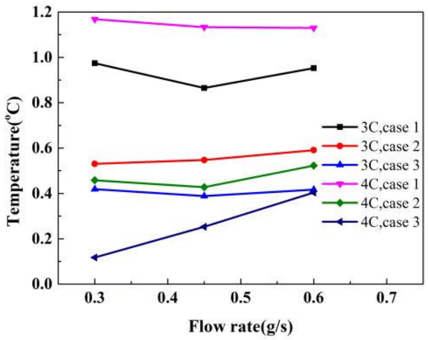


Fig. 11 Maximum temperature difference of batteries at different airflow rates and filling amounts of PCM

As can be seen from Fig. 11, airflow rate has little effect on the temperature difference. Although a higher airflow rate will increase the heat transfer coefficient which causes more heat absorption by air compared with a lower flow rate, the temperature rise of the air is small which resulted in an almost identical temperature difference between air and batteries at high and low airflow rates. As shown in Fig. 12, in case 2, the average temperature difference between batteries and air is 1.46°C and 1.58°C when the airflow rate is 0.4g/s and 0.6g/s.

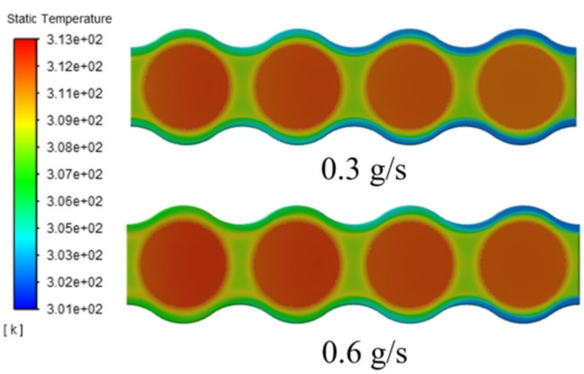


Fig. 12 Temperature cloud diagrams of different airflow rates at the end of discharge

3.3 Influence of different airflow channels

The structures of airflow channels are shown in Fig. 13. The air channels in case 5 and case 6 are more narrow compared with that in case 4.

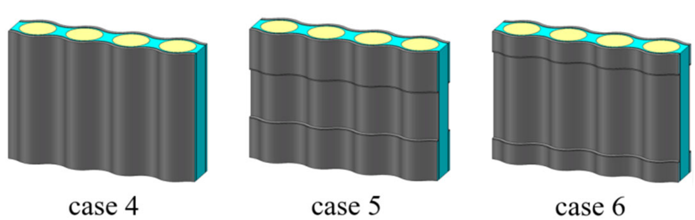
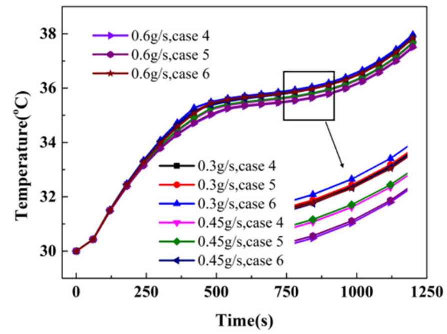
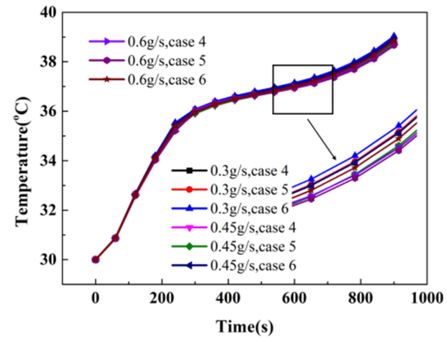


Fig. 13 Airflow channels

Fig. 14 shows the maximum temperature of batteries under different airflow rates and airflow channels.



(a) Discharge rate of 3C



(b) Discharge rate of 4C

Fig. 14 Maximum temperature of batteries under different airflow rates and airflow channels

As shown in Fig. 14, the maximum temperature of batteries is the highest in case 6 and the lowest in case 4. The heat transfer paths in the middle of a battery in case 4 and case 6 are shown in Fig. 15. It can be seen that the heat transfer path in case 6 is longer than that in case 4, which leads to less heat transfer in case 6. In addition, as the airflow rate increases from 0.3g/s to 0.6g/s, the maximum temperature of batteries in case 4 is reduced by 4%, while that in case 6 is reduced by 2%. This indicates that the airflow rate in case 4 has a greater effect on maximum temperature of batteries than that in case 6, which is also ascribed to less heat transfer in case 6.

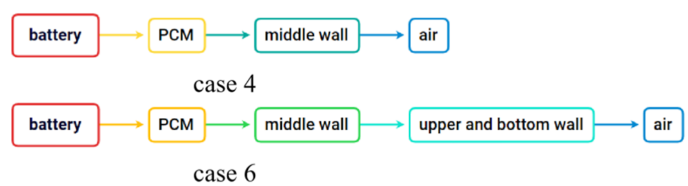


Fig. 15 Heat transfer path

Fig. 16 shows the maximum temperature difference of batteries at different airflow rates and airflow channels.

As shown in Fig. 16, the maximum temperature difference of batteries in case 4 is higher than that in other cases. Air in case 4 absorbs more heat than in other cases, which results in a larger temperature difference between air around the first and last battery. As shown in Fig. 17, the temperature difference between the middle part of the battery in case 6 is small, and the temperature difference mainly comes from the upper part and the lower part.

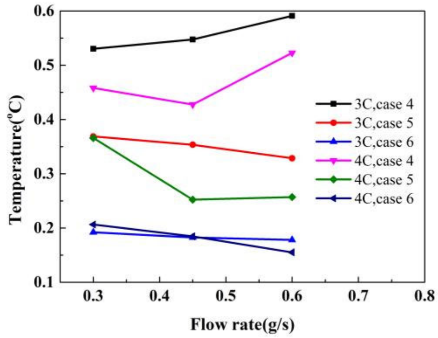


Fig. 16 Maximum temperature difference of batteries at different airflow rates and airflow channels

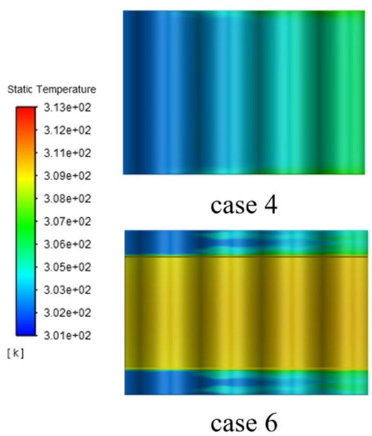


Fig. 17 Temperature cloud diagrams of different cases at the end of discharge

3.4 Influence of different fin structures

The structures of fins are shown in Fig. 18.

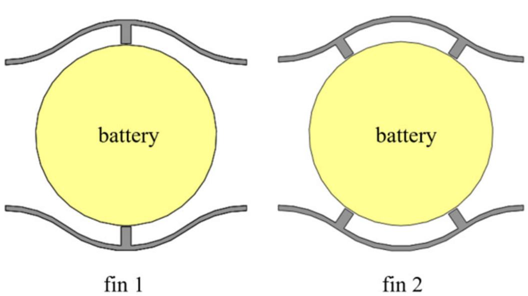
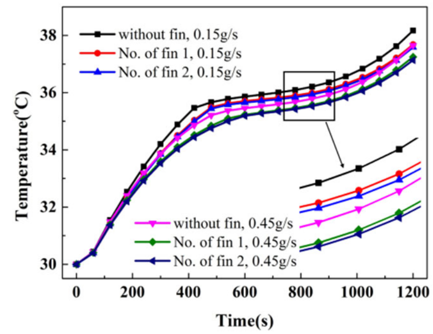


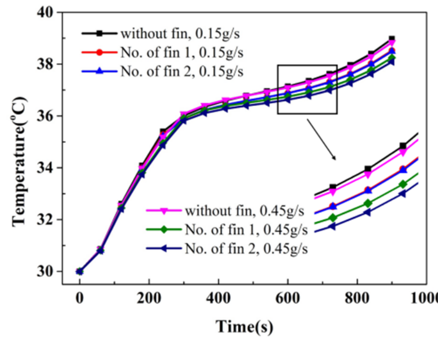
Fig. 18 Structures of fins

Fig. 19 shows the maximum temperature of batteries under different airflow rates and structures of fins.

As shown in Fig. 19, fins reduce the thermal resistance, and more heat is transferred from batteries to the air, so the maximum temperature of batteries is reduced after the addition of fins. When the number of fins increases from 0 to 1, the maximum temperature of batteries decreases by 1%, and when the number of fins increases from 1 to 2, the maximum temperature of batteries decreases by 0.13%, which indicates that when the number of fins is greater than 1, the increase of the number of fins has little effect on the maximum temperature of batteries. When the flow rate is 0.15 g/s, the fins cause the maximum temperature of the battery to decrease by 0.45°C, and when the flow rate was 0.45g/s, the fins cause the maximum temperature of the battery to decrease by 0.52°C, indicating that with the increase of flow rate, the effect of the number of fins on the heat transfer will increase.



(a) Discharge rate of 3C



(b) Discharge rate of 4C

Fig. 19 Maximum temperature of batteries under different airflow rates and structures of fins

Fig. 20 shows the maximum temperature difference of batteries at different airflow rates and structures of fins.

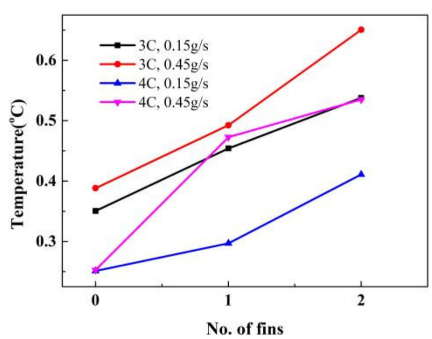


Fig. 20 Maximum temperature difference of batteries at different airflow rates and structures of fins

In Fig. 20, the maximum temperature difference of batteries increases with the increasing number of fins. More fins result in a larger heat transfer from batteries to air, so the temperature difference between air around the first and last battery will be larger, which causes a larger temperature difference between batteries.

4. Optimization of thermal management system

Adding PCM around batteries will increase the weight of the vehicle, and increasing airflow rate will increase the energy consumption of the fan, all of these will increase the energy consumption of the vehicle.

Optimizing the filling amount of PCM and the airflow rate will reduce energy consumption. It is assumed that PCM only leads to the friction resistance of the vehicle and thus increases energy consumption. The energy consumption caused by PCM is calculated as follows:

$$P = \lambda m_{PCM} g v_{vehicle} / 3.6 \tag{9}$$

It is assumed that the airflow rate is changed by changing the energy consumption of the fan. The energy consumption of the fan is calculated as follows:

$$N = V \Delta P / (\eta k) \tag{10}$$

In order to ensure that the maximum temperature of batteries is within a certain limit, appropriate airflow rate is required under different filling amount of PCM. Fig. 21 shows the energy consumption under different filling amounts of PCM when the maximum temperature of batteries is 39°C.

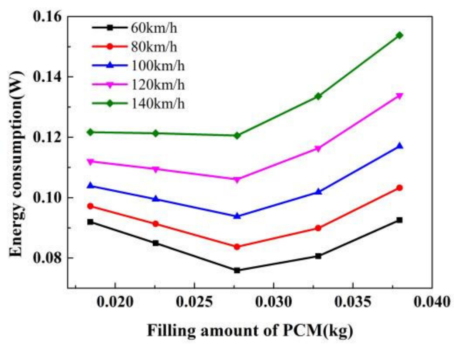


Fig. 21 Energy consumption

With the increase of the filling amount of PCM, on the one hand, the friction resistance of the vehicle increases which leads to an increase in energy consumption, on the other hand, the energy consumption of the fan decreases. When the filling amount of PCM is 0.28kg, the energy consumption is the lowest as seen in Fig. 21. In addition, the increase of vehicle speed will increase the rolling resistance coefficient, thus increasing the effect of filling amount of PCM on energy consumption. As a result, when the vehicle speed is 140km/h, the energy consumption curve first drops slightly and then rises rapidly.

5. CONCLUSIONS

A BTMS combining closed air-cooling with PCM is proposed. A three-dimensional numerical model is developed and validated by the experiment. The influences of ambient temperature, airflow rate, airflow channel, and fin structure on the maximum temperature and temperature difference of batteries are investigated. In addition, the battery thermal management system is optimized to minimize energy consumption. The main conclusions can be drawn:

(1)With the increase of ambient temperature, the temperature rise of batteries decreases because at higher ambient temperatures, the PCM begins to melt and the temperature rise around the batteries is very small. The increasing filling amount of PCM reduces the maximum temperature difference of batteries as well as the effect of the airflow rate on the maximum temperature of batteries.

(2)The airflow channel has little effect on the maximum temperature and temperature difference of batteries. When the number of fins is greater than 1, the increasing number of fins has little effect on the maximum temperature of batteries. The maximum temperature difference of batteries increases with the increasing number of fins.

(3)The energy consumption is minimum when the filling amount of PCM is 0.28kg at different vehicle speeds.

ACKNOWLEDGEMENTS

This work was supported by the Science & Technology Commission of Shanghai Municipality and Shanghai Engineering Research Center of Ship Intelligent Maintenance and Energy Efficiency under Grant 20DZ2252300.

NOMENCLATURE

c_p	specific heat (J/(kg·K))
H	enthalpy (kJ/kg)
I	discharge current (A)
k	motor capacity factor
L	latent heat (kJ/kg)
m	mass (kg)
P	pressure (Pa)
Q	heat (J)
R	internal resistance (Ω)
T	temperature (K)
t	time (s)
U	voltage (V)
V	airflow volume (m^3/h)
v	velocity (m/s)

Greek Symbols

ρ	density (kg/m^3)
μ	viscosity (kg/(m·s))
η	fan efficiency
λ	thermal conductivity (W/(m·K))

Subscripts

ab	absorption
gen	generation
L	liquid
ocv	open-circuit voltage
PCM	phase change material
S	solid

REFERENCES

A.A. Hakeem Akinlabi, Davut Solyali, 2020, “Configuration, design, and optimization of air-cooled battery thermal management system for electric vehicles: A review,” Renewable and Sustainable Energy Reviews, 125, 109815.
https://doi.org/10.1016/j.rser.2020.109815

Abubakar Gambo Mohammed, Karem Elsayed Elfeky, Qiuwang Wang, 2022, “Recent advancement and enhanced battery performance using phase change materials based hybrid battery thermal management for electric vehicles,” *Renewable and Sustainable Energy Reviews*, **154**, 111759.
https://doi.org/10.1016/j.rser.2021.111759

A.C. Budiman, S. M. Hasheminejad, S. Sudirja, A. Mitayani, S.H. Winoto, 2022, “Visualization of induced counter-rotating vortices for electric vehicles battery module thermal management,” *Frontiers in Heat and Mass Transfer*, **19**, 9.
http://dx.doi.org/10.5098/hmt.19.9

Ankur Bhattacharjee, Hiranmay Saha, 2018, “Development of an efficient thermal management system for Vanadium Redox Flow Battery under different charge-discharge conditions,” *Applied Energy*, **230**, 1182-1192.
https://doi.org/10.1016/j.apenergy.2018.09.056

Chenzhen Ji, Zhen Qin, Swapnil Dubey, Fook Hoong Choo, Fei Duan,

2018, "Simulation on PCM melting enhancement with double-fin length arrangements in a rectangular enclosure induced by natural convection," *International Journal of Heat and Mass Transfer*, **127**, 255-265.
https://doi.org/10.1016/j.ijheatmasstransfer.2018.07.118

Dominik Keiner, Manish Ram, Larissa De Souza Noel Simas Barbosa, Dmitrii Bogdanov, Christian Breyer, 2019, "Cost optimal self-consumption of PV prosumers with stationary batteries, heat pumps, thermal energy storage and electric vehicles across the world up to 2050," *Solar Energy*, **185**, 406-423.
https://doi.org/10.1016/j.solener.2019.04.081

Fenfang Chen, Rui Huang, Chongming Wang, Xiaoli Yu, Huijun Liu, Qichao Wu, Keyu Qian, Rohit Bhagat, 2020, "Air and PCM cooling for battery thermal management considering battery cycle life," *Applied Thermal Engineering*, **2020**, 115154.
https://doi.org/10.1016/j.applthermaleng.2020.115154

Hussam Jouhara, Navid Khordehgah, Nicolas Serey, Sulaiman Almahmoud, Stephen P. Lester, Daniel Machen, Luiz Wrobel, 2019, "Applications and thermal management of rechargeable batteries for industrial applications," *Energy*, **170**, 849-861.
https://doi.org/10.1016/j.energy.2018.12.218

Kai Chen, Junsheng Hou, Mengxuan Song, Shuangfeng Wang, Wei Wu, Yanlai Zhang, 2021, "Design of battery thermal management system based on phase change material and heat pipe," *Applied Thermal Engineering*, **188**, 116665.
https://doi.org/10.1016/j.applthermaleng.2021.116665

Kun Zhang, Zhiyong Li, Jia Yao, 2022, "Numerical study on heat transfer characteristics of corrugated tube phase change thermal energy storage unit," *Frontiers in Heat and Mass Transfer*, **19**, 5.
http://dx.doi.org/10.5098/hmt.19.5

Layth M. Jaleel, Hayder M. Jaffal, 2022, "Effect of fin shape on thermal performance enhancement of pcm-based low-grade heat harnessing exchanger," *Frontiers in Heat and Mass Transfer*, **18**, 37.
http://dx.doi.org/10.5098/hmt.18.37

Lin-Li Tian, Xun Liu, Shuai Chen, Zu-Guo Shen, 2020, "Effect of fin material on PCM melting in a rectangular enclosure," *Applied Thermal Engineering*, **167**, 114764.
https://doi.org/10.1016/j.applthermaleng.2019.114764

Matt Ghiji, Ian Burch, Grant Gamble, Vasily Novozhilov, Paul Joseph, Khalid Moinuddin, 2021, "Lithium-ion battery fire suppression using water mist systems," *Frontiers in Heat and Mass Transfer*, **17**, 13.
http://dx.doi.org/10.5098/hmt.17.13

Mehdi Mehrabi-Kermani, Ehsan Houshfar, Mehdi Ashjaee, 2019, "A novel hybrid thermal management for Li-ion batteries using phase change materials embedded in copper foams combined with forced-air convection," *International Journal of Thermal Sciences*, **141**, 47-61.
https://doi.org/10.1016/j.ijthermalsci.2019.03.026

Meiwei Wang, Shiyang Teng, Huan Xi, Yuquan Li, 2021, "Cooling performance optimization of air-cooled battery thermal management system," *Applied Thermal Engineering*, **195**, 117242.
https://doi.org/10.1016/j.applthermaleng.2021.117242

Mengyao Lu, Xuelai Zhang, Jun Ji, Xiaofeng Xu, Yongyichuan Zhang, 2020, "Research progress on power battery cooling technology for electric vehicles," *Journal of Energy Storage*, **2020**, 101155.
https://doi.org/10.1016/j.est.2019.101155

Ningbo Wang, Congbo Li, Wei Li, Mingli Huang, Dongfeng Qi, 2021, "Effect analysis on performance enhancement of a novel air cooling battery thermal management system with spoilers," *Applied Thermal Engineering*, **2021**, 116932.
https://doi.org/10.1016/j.applthermaleng.2021.116932

Peng Peng, Yiwei Wang, Fangming Jiang, 2022, "Numerical study of PCM thermal behavior of a novel PCM-heat pipe combined system for Li-ion battery thermal management," *Applied Thermal Engineering*, **209**, 118293.
https://doi.org/10.1016/j.applthermaleng.2022.118293

Ravindra Jilte, Asif Afzal, Satyam Panchal, 2021, "A novel battery thermal management system using nano-enhanced phase change materials," *Energy*, **219**, 119564.
https://doi.org/10.1016/j.energy.2020.119564

Shahabeddin K. Mohammadian, Yuwen Zhang, 2015, "Thermal management optimization of an air-cooled Li-ion battery module using pin-fin heat sinks for hybrid electric vehicles," *Journal of Power Sources*, **273**, 431-439.
https://doi.org/10.1016/j.jpowsour.2014.09.110

Sohif Mat, Abduljalil A. Al-Abidi, K. Sopian, M.Y. Sulaiman, Abdulrahman Th Mohammad, 2013, "Enhance heat transfer for PCM melting in triplex tube with internal–external fins," *Energy Conversion and Management*, **74**, 223-236.
https://doi.org/10.1016/j.enconman.2013.05.003

Xiaoming Wang, Yongqi Xie, Rodney Day, Hongwei Wu, Zhongliang Hu, Jianqin Zhu, Dongsheng Wen, 2018, "Performance analysis of a novel thermal management system with composite phase change material for a lithium-ion battery pack," *Energy*, **156**, 154-168.
https://doi.org/10.1016/j.energy.2018.05.104

X Lin，X Zhang，L Liu，M Yang, 2021, "Optimization investigation on air phase change material based battery thermal management system," *Energy Technology*, **9**, 7.
https://doi.org/10.1002/ente.202100060

X.M. Xu, R. He, 2013, "Research on the heat dissipation performance of battery pack based on forced air cooling," *Journal of Power Sources*, **240**, 33-41.
https://doi.org/10.1016/j.jpowsour.2013.03.004

Yang, Y., Xu, X., Zhang, Y., Hu H., Li C., 2020, "Synergy analysis on the heat dissipation performance of a battery pack under air cooling," *Ionics*, **26**, 5575–5584.
https://doi.org/10.1007/s11581-020-03676-5

Yi Xie, Xi Wang, Wei Li, Yangjun Zhang, Dan Dan, Kuining Li, Fei Feng, Cunxue Wu, Pingzhong Wang, 2021, "A resistance-based electro-thermal coupled model for an air-cooled battery pack that considers branch current variation," *International Journal of Thermal Sciences*, 159, 106611.
https://doi.org/10.1016/j.ijthermalsci.2020.106611

Youfu Lv, Xiaoqing Yang, Xinxi Li, Guoqing Zhang, Ziyuan Wang, Chengzhao Yang, 2016, "Experimental study on a novel battery thermal management technology based on low density polyethylene-enhanced composite phase change materials coupled with low fins," *Applied Energy*, **178**, 376-382.
https://doi.org/10.1016/j.apenergy.2016.06.058

Yue Yang, Lei Chen, Lijun Yang, Xiaoze Du, 2021, "Numerical study of combined air and phase change cooling for lithium-ion battery during dynamic cycles," *International Journal of Thermal Sciences*, **165**, 106968.
https://doi.org/10.1016/j.ijthermalsci.2021.106968

Yuqian Fan, Yun Bao, Chen Ling, Yanyan Chu, Xiaojun Tan, Shuting Yang, 2019, "Experimental study on the thermal management performance of air cooling for high energy density cylindrical lithium-ion batteries," *Applied Thermal Engineering*, **155**, 96-109.
https://doi.org/10.1016/j.applthermaleng.2019.03.157

Zahraa A. Faisal, Hassanain Ghani Hameed, Dhafer Manea H. Al-

DOI: 10.5098/hmt.20.24
ISSN: 2151-8629

Shamkhee, 2021, “Numerically investigating the effects of feed water preheating tank design on the performance of single slope solar still,” *Frontiers in Heat and Mass Transfer*, **17**, 22. http://dx.doi.org/10.5098/hmt.17.22

Zhao Lu, Xiaoling Yu, Lichuan Wei, Yalin Qiu, Liyu Zhang, Xiangzhao Meng, Liwen Jin, 2018, “Parametric study of forced air cooling strategy for lithium-ion battery pack with staggered arrangement,” *Applied Thermal Engineering*, **136**, 28-40. https://doi.org/10.1016/j.applthermaleng.2018.02.080

Ziye Ling, Fangxian Wang, Xiaoming Fang, Xuenong Gao, Zhengguo Zhang, 2015, “A hybrid thermal management system for lithium ion batteries combining phase change materials with forced-air cooling,” *Applied Energy*, **148**, 403-409. https://doi.org/10.1016/j.apenergy.2015.03.080