Hybrid cooling based battery thermal management using composite phase change materials and forced convection

Mohamed Moussa El Idi, Mustapha Karkri, Mahamadou Abdou Tankari, Stéphane Vincent

Hybrid cooling based battery thermal management using composite phase change materials and forced convection

Mohamed Moussa EL IDI[1,2]*, Mustapha KARKRI[1], Mahamadou ABDOU TANKARI[1], Stéphane VINCENT[2]

[1]Université Paris- Est, CERTES, 61 Av. du Général de Gaulle, 94010 Créteil Cedex, France.

[2]Université Gustave- Eiffel, Laboratoire MSME UMR CNRS 8208, Université Paris-Est Marne-La-Vallée, Marne-La-Valle F-77454, France

*Corresponding author: moussa.elidi@gmail.com

Abstract: *This paper investigates the thermal management performance of a novel system using phase change material (PCM) composite for Lithium-ion battery in cell scale. An experimental platform was developed to study thermal phenomena in Li-ion cell. The system was designed on the basis of heat flux measurements. The cells are embedded in a PCM composite material. The assembly is lodged in an aluminum mold manufactured by 3D printing. The impact of the addition of metal foam and forced convection was evaluated. The results showed that the proposed system allows to keep the temperature of Li-ion cell around the optimal operating temperature, 25°C. It's also found that the addition of an aluminum foam allows a more efficient thermal management of the cell.*

Keywords: Phase change material (PCM), Battery Thermal Management System (BTMS), Metal foam, Li-ion

Nomenclature

C	Specific heat capacity, ($J.\ kg^{-1}.K^{-1}$)	T	Temperature, (K)
ρ	Density, ($kg.m^{-3}$)	k	Thermal conductivity, ($W/m.K$)
Q	Heat flux, (W)		
L_f	Latent heat of fusion ($J.kg^{-1}$)		
t	Time, (s)		

1. Introduction:

One of the main objectives of the world's energy transition is to reduce the amount of CO_2 in the atmosphere. Currently, the global energy is dominated by fossil fuels by about 80% [1]. The transportation sector is among the largest consumers of fossil fuels [2]. One way to reduce carbon emissions in the transportation sector is to replace fossil fuel engines with electric vehicles (EVs) using clean energy sources or hybrid vehicles. Because of their high specific energy density, good stability and low density, Li-ion batteries are generally considered the first choice for EVs [3]. The development of EVs is certainly dependent on that of Li-ion batteries. During charge and discharge cycles, Li-ion batteries experience a rise in temperature, which appears to be the main cause of performance and battery life degradation. The study conducted by Waldmann et al. [4] showed that the high temperatures accelerate the cathode electrode degradation which leads to a decrease of the batteries capacity . This is an agreement with the study made by Ramadass et al [5]. It was found that the capacity of Sony 18650 cells decreases down to 70% after 500 cycles at higher temperatures. In addition to the temperature increasing, the non-uniformity of heat transfer between cells can cause negative effects on the overall performance of the battery. Thereby the development of efficient Li-ion Batteries Thermal Management System (BTMS) appears necessary to ensure better performance, autonomy and optimal lifespan.

The BTMS is currently categorized into three principal categories, active system, passive system, and hybrid system. Amongst them, active cooling systems by air or liquid are the most widely used. However, air systems have its cooling limitations due to its low heat capacity and thermal conductivity. Liquid systems are costly in terms of energy consumption, investment and maintenance. Passive systems are a less expensive alternative. Passive systems can be classified into two principal groups: Heat pipes [6] and Phase Change Material (PCM) composites.

During the solidification and melting process of PCM, they can absorb and release latent heat during the electrical charge and discharge cycles of batteries, while their temperature remains almost constant. In the last two decades there has been a lot of interest in PCM and PCM composites systems [7]. BTMS using PCM systems can present a problem of low thermal conductivity, regeneration or leaks in the liquid state. The regeneration problem can be solved by the addition of an optimized and intelligent active system that only triggers when needed to evacuate the heat stored in the PCM. PCM low thermal conductivity can be improved by integrating a material with high thermal conductivity [8] such as fins [9], porous-graphite [10], expanded graphite [11–13], nanoparticles [14], and high porosity metal foam (MF) [15–20]. Among these solutions, MF have special properties that make them a very good candidate to improve the thermal conductivity of a PCM [21]. MF are porous media with large porosities and large contact areas per unit volume [22].

BTMS using PCM was proposed for the first time by Hallaj and Selman [7]. The authors compared the efficiency of their proposed system with an air system. It was found that the use of PCM allows a more efficient thermal management with a reduction of about 8°C compared to an air system. The use of PCM can be particularly effective to control the temperature of Li-Ion batteries in high temperature environments [23–25]. Wenga and his co-workers investigated the thermal performance of PCM and branch-structured fins for cylindrical power battery in a high-temperature environment [23]. The authors tested different PCM types with different phase change temperatures in a high-temperature environment. It was found that the PCM with a phase change temperature of 46 °C offers the best cooling effect at a high ambient temperature (40°C). In [24] the result showed that the use of PCM - fin structure with optimized design allowed to keep the maximum temperature of the battery under 51°C at high discharge rate of 3C and ambient temperature of 40°C. Ling et al. [26] conducted an experimental and numerical study on the thermal management of a Li-ion battery by an expanded paraffin-graphite composite. They tested paraffin with different melting temperatures (36°C, 44°C and 52°C). The cells were replaced by heating elements that simulate the same thermal behavior of the cells. It was found that PCM composites with high or low phase change temperature are not suitable for battery thermal management systems. Hussain et al. [27] utilized a graphene coated nickel foam saturated with paraffin to study the performance of the thermal management system of Li-ion cell. They compared the system with a system using nickel foam. They found that the cell surface temperature is 17% less using graphene coated nickel foam saturated with PCM compared to using nickel foam. Li et al. [28] conducted an experimental study on the thermal performance of BTMS using a pure PCM and a PCM-MF composite. It was found that the use of PCM-Copper foam composite leads to lower temperatures with a more uniform temperature field compared to pure paraffin.

Recently, some efforts have been focused on the study of hybrid systems for the Li-ion batteries thermal management by adding an active system in order to solve the problems of passive BTMS using PCM composite [29–35]. However, most research has studied numerically this problem. Mashayekhi et al. [34] proposed hybrid system. A paraffin RT44 incorporated in copper foam was used as passive system. For active system the authors proposed an aluminum minichannel containing coolant (Al_2O_3 nanofluid). The evaluation of the thermal performance of the proposed BTMS showed that in high discharge rates passive system was inefficient to keep the battery temperature below the safety limit (60 °C). It's was –also- found that the addition of nanofluid allows to reduce the maximum temperature reached by batteries by 15.5% in active system case and 8.5% in hybrid system case. Bamdezh and Molaeimanesh [30] proposed a hybrid system by combined an air cooling system and a PCM composite. The numerical results showed that the maximum temperature difference of the studied battery was reduced. They do not exceed 1.5°C. Inspired by Tesla cooling system, Lv et al [35] were proposed a novel BTMS using PCM coupled with forced air convection. It's was found that the proposed system compared to passive system can reduce the used PCM composite weight by ~70% and increasing the energy density of the battery module from 107.8 to 121.6 Wh kg^{-1}.

The majority of studies in the literature are numerical or experimental studies simplified by replacing, for example, Li-ion cells with a heating element and focus on maintaining the temperature of the batteries in a temperature range between 40°C and 60°C. However, the optimal temperature range is between 15°C and 35°C [36]. Studies performed in [4] under a current of 1C have shown that the operating temperature for optimal lifetime for 18650 Li-ion cells is 25°C. Below 25°C, the aging rate increases with decreasing temperature, while above 25°C, aging is accelerated with increasing temperature, Figure 1. In this paper we proposed a new BTMS using PCM-MF composite. The aim of the proposed BTMS is to keep cell temperature around optimal temperature of 25°C under a 1C charge/ discharge rate. An experimental platform will be presented and described. The mold intended to house the cell and the PCM composite was manufactured by 3D metal printing. The heat dissipated by the cell has been calculated from the experimental results and by used MATLAB code. The results will be presented and discussed.

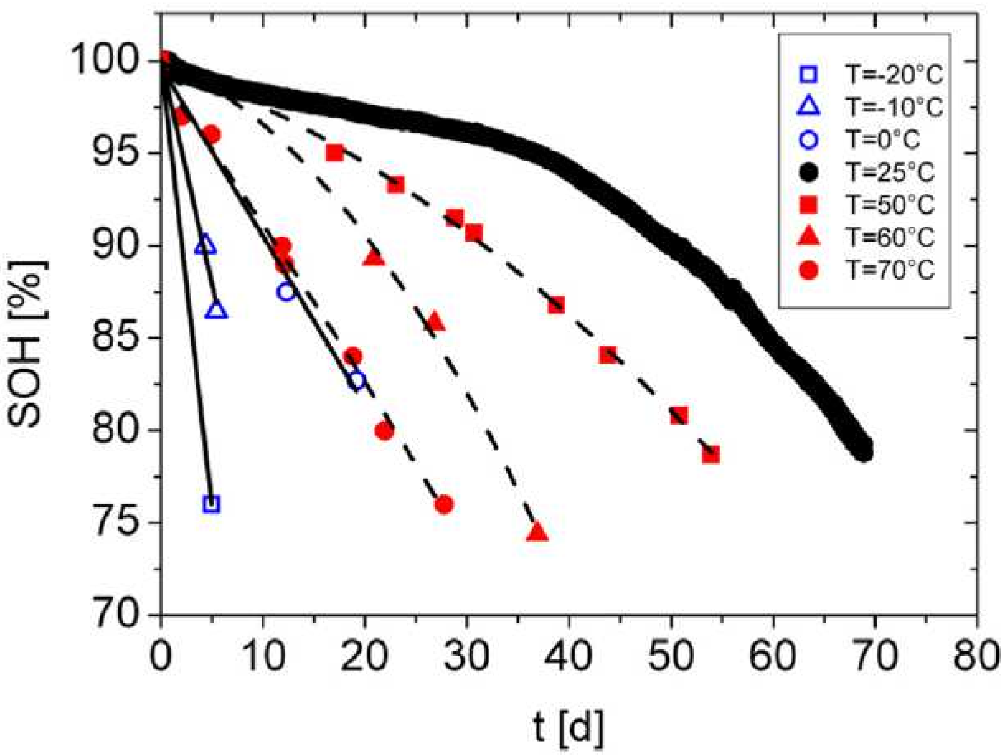

Figure 1: SOH curves measured as a function of time for cycles of 1 C at different temperatures [4].

2. Materials and methods

2.1. Materials

The selected PCM used in this work was paraffin RT27. The phase change temperature of the PCM was around 27°C and specific density, 179 KJ/kg [37]. The metal foam consisted of an Aluminum Foam (AF) with a porosity of 93%. The choice of this foam is the result of our previous work [17,18]. The incorporation of paraffin RT27 in AF was done following the protocol presented in [16]. DSC, Hot- Disk, Transient Guarded Hot Plate Technique (TGHPT) are used to characterize the used materials [16,37]. The elaboration protocol and the experimental devices and characterization methods are well described in our recently published article [16]. The proprieties of paraffin RT27 and paraffin RT27- AF composite used for the present study are given in **Table 1**.

Table 1: Thermophysical properties of paraffin RT27, RT27- Metal foam and aluminum foam.

properties	Paraffin RT27	Aluminum	RT27- Metal foam composite
Density *($kg.m^{-3}$)*	870	2800	1005
Heat capacity–solid *($J.K^{-1}.kg^{-1}$)*	2400	910	1195.68
Latent heat *($KJ.kg^{-1}$)*	179		
Melting temperature *(K)*	300.15		300.15
Dynamic viscosity *($Kg.m^{-1}.s^{-1}$)*	$3.42x10^{-3}$		
Thermal conductivity –solid *($W.K^{-1}.m^{-1}$)*	0.24	237	4.49
Density – liquid *($kg.m^{-3}$)*	760		902
Heat capacity –liquid *($J.K^{-1}.kg^{-1}$)*	1800		
Thermal conductivity – liquid *($W.K^{-1}.m^{-1}$)*	0.15		
β (K^{-1})	$0.5x10^{-3}$		

2.2. Experimental platform

The experimental platform developed in this work to study thermal phenomena in Li-ion cell is shown in ***Figure 2***. The cell is connected to BaSyTec system which ensures the battery charge/ discharge. Commercially available 18650 Li-ion cell with a nominal capacity of 2500 mAh were purchased from VARTRA. The cathode and anode of the Li-ion cells were -respectively- LiNi0.5Co0.2Mn0.3O2 and graphite. Cell electrical and geometrical characteristics are provided by the manufacturer. ***Figure 3 (a)*** shows a picture of the cell used in the present study. It's a cylindrical with dimensions: d=18mm; H=65mm. Thermocouples type K connected to a NI data acquisition system to monitor the cell temperature. A cylindrical sensor encapsulates the cell to measure radial heat flux dissipated by the cell. The instrumented cell is placed in a ESPEC-642 climatic chamber provided by ES Equipements Scientifiques to control the ambient temperature and humidity. The studied cell is suspended in order to avoid thermal exchanges by conduction between the battery surface and the external environment, **Figure 3** (a). The climatic chamber is equipped with a fan which allows to keep a homogeneous temperature in the climatic chamber. This causes a weak forced convection in the case of a constant imposed temperature. All instruments are managed by a LabVIEW program.

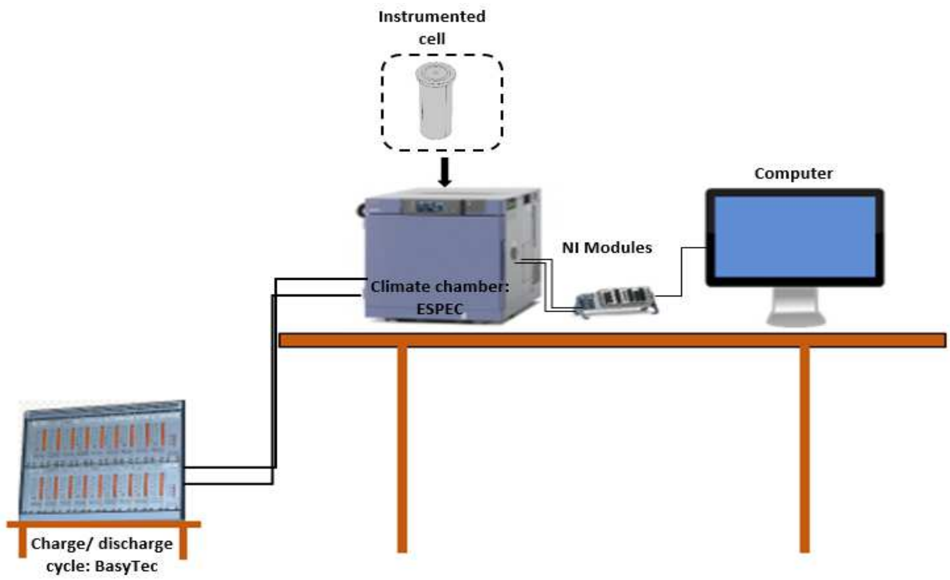

Figure 2: *Experimental testbed*

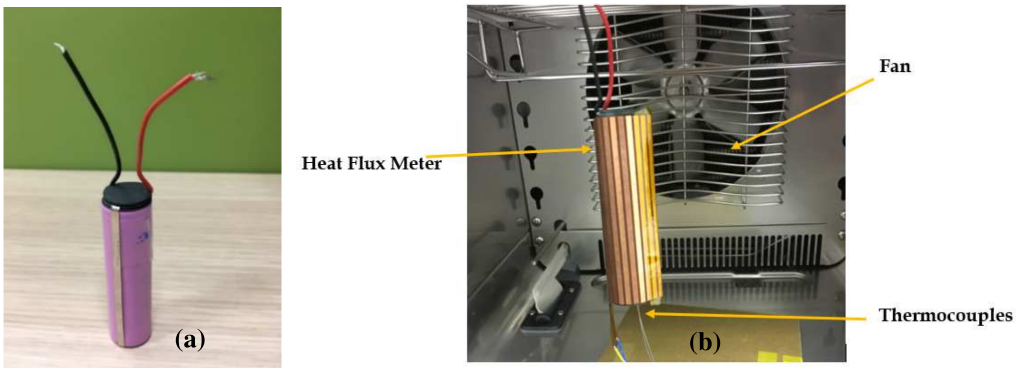

Figure 3: (a) Cell, (b) Instrumented cell in climatic chamber ESPEC-642

3. Results

3.1. Li-ion cell thermal behavior without BTMS

This work is part of the continuity of our recently published works [38]. In the present work we studied axial heat flux density and thermal properties of the cell using Hot-Disk.

The axial heat flux density is measured with a Captec Heat Flux Meter in the form of a disk with a diameter of 18.5mm and a thickness of 0.5mm, **Figure 4**. The disk is glued to the underside of the cell, **Figure 5**. **Figure 11** displays a comparison between axial and radial heat flux density. The results show that the axial heat flux density is higher. Therefore, we can assume that Li-ion cells have higher axial thermal conductivity compared to radial thermal conductivity. To confirm this hypothesis, a characterization of the thermal conductivity of the cells has been carried out.

The thermal properties of the cell were determined using the Hot-Disk transient method [39,40]. The use of Hot-Disk for the thermal characterization of Li-ion batteries is described in [41]. **Figure 7** shows the setup used to characterize the thermal properties of the cells. The measurements were repeated for ten times to ensure the accuracy and repeatability of the results. **Table 2** summarizes the thermophysical properties of the batteries used in this study. It was found that the axial conductivity is 31.2 W/(m.K) and the radial conductivity is 0.2 W/(m.K).

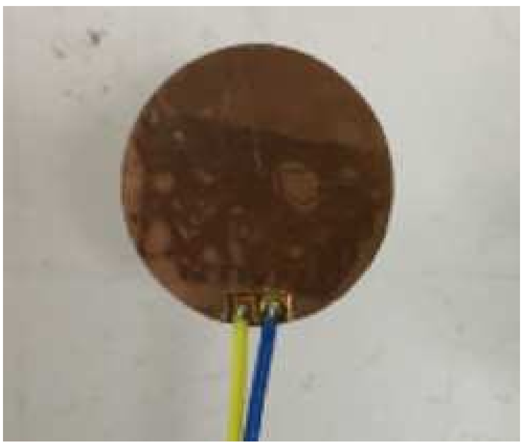

Figure 4 : *Heat Flux Meter, disk*

Figure 5 : Cell instrumented by Heat Flux Meter ''disk''

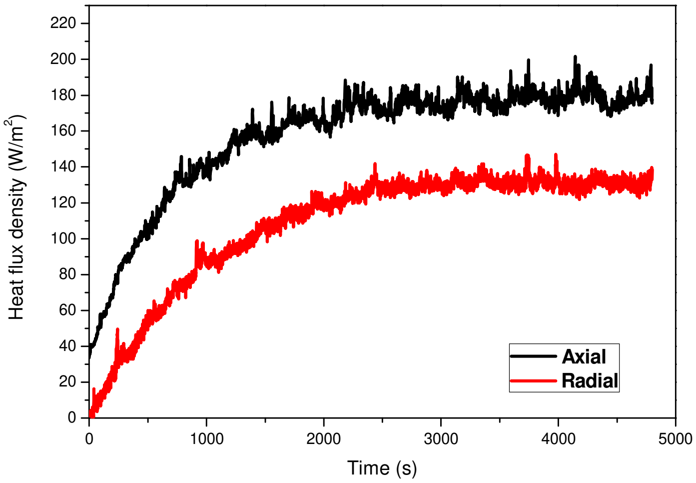

Figure 6: *Radial and axial heat flux density*

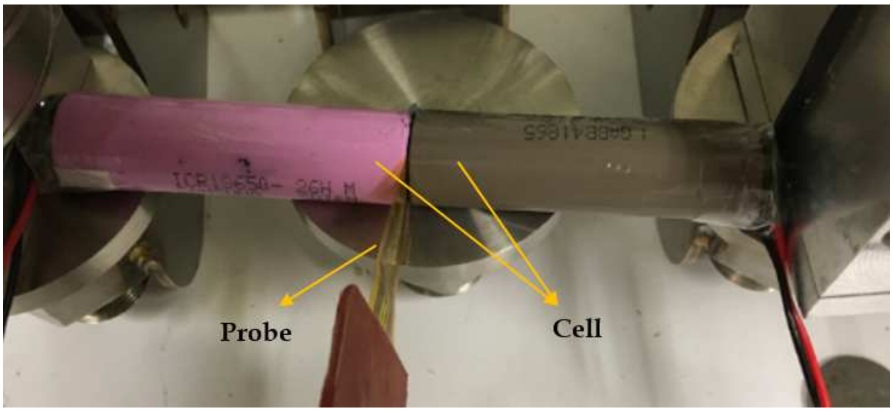

Figure 7: Thermal characterization of the cells by Hot-Disk

Figure 8 shows the temporal evolution of the radial heat flux versus axial heat flux. It can be seen that the axial flow is small compared to the radial flow. In fact, the axial flux represents about 0.9% and the radial flux 99.1%.

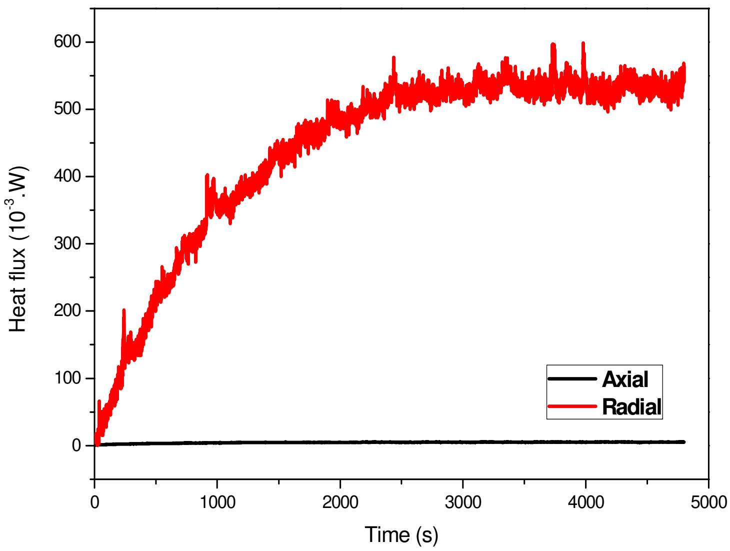

Figure 8: *Radial and axial heat flux*

Table 2: Thermophysical properties of the cell

	k, Axial	k, Radial	C_p	ρ
	$W.m^{-1}.K^{-1}$	$W.m^{-1}.K^{-1}$	$J.kg^{-1}.°C^{-1}$	$Kg.m^{-3}$
Li-in Cell	31.15	0.2	1726	2700
Uncertainties	±0.033	±0.027	±0.021	

The approach we followed to size our system is well described in [38]. The results give a PCM thickness of 2.8 mm. We approximate to 3 mm.

3.2. Li-ion cell thermal behavior with BTMS

The studied cell is placed in an aluminum mold. **Figure 9** shows a photograph of the mold used with the details of its geometrical parameters. The mold takes the form of two hollow coaxial aluminum cylinders, height h and thicknesses e, e_1 and e_2. The inner cylinder has the same diameter as the cell. A PCM composite is inserted between the two cylinders. A groove is provided at the internal cell cylinder interface. It is used to accommodate the temperature sensors and the flowmeter cables. The design of these molds takes into account the volume expansion of the PCM. Aluminum was selected as an acceptable compromise between thermal properties, density and cost. The mold was manufactured by high precision 3D metallic printing.

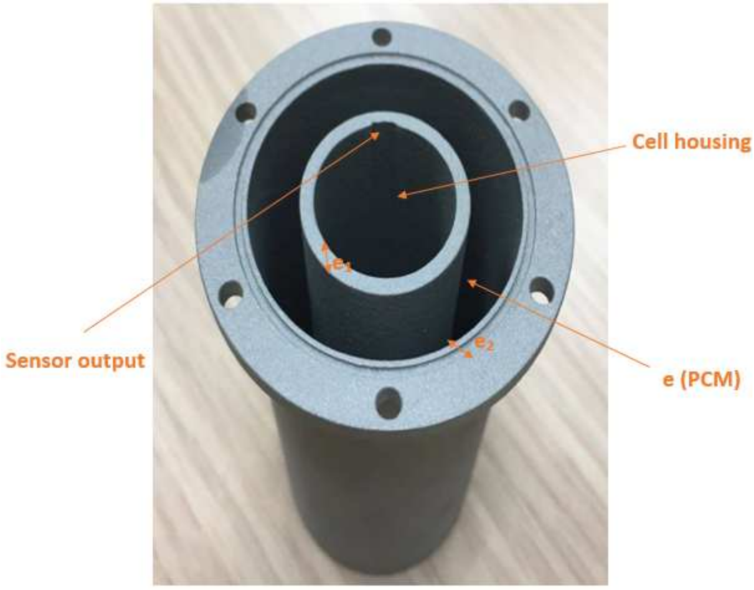

Figure 9: *Aluminum mold used in this study*

Liquid paraffin is injected into the vacuum designed to contain it. After filling, the whole unit is cooled in the climatic chamber to an imposed temperature of 22°C. **Figure 10** (a) provides a photograph during filling, **Figure 10** (b) is after filling and **Figure 10** (c) is after the integration of the cell. Before inserting the cell into the mold, the protection of all connections is necessary to avoid any direct contact between the aluminum mold and the cell connections.

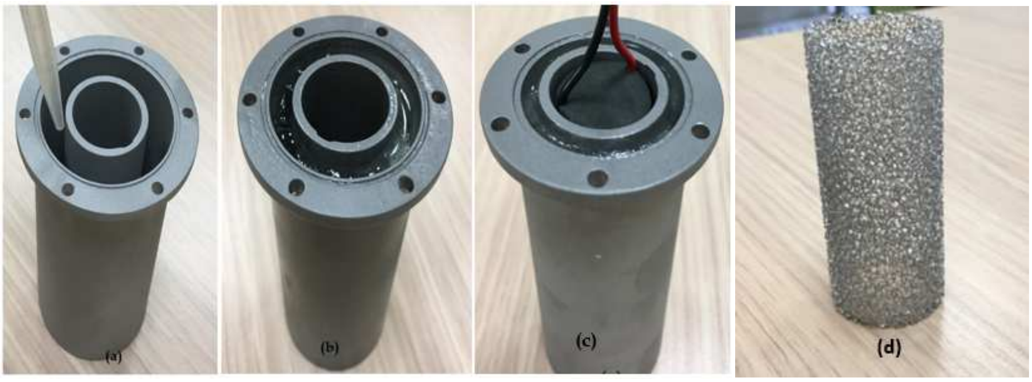

Figure 10: *Experimental protocol*

In the case of an MF-PCM composite, the metal foam is cut by a laser cutting system from the EROSFER company in the form of tubes with dimension h*e, **Figure 10** (d).

The instrumented cell is housed in the climatic chamber. The base of the mold is insulated by expanded polystyrene, **Figure 11**.

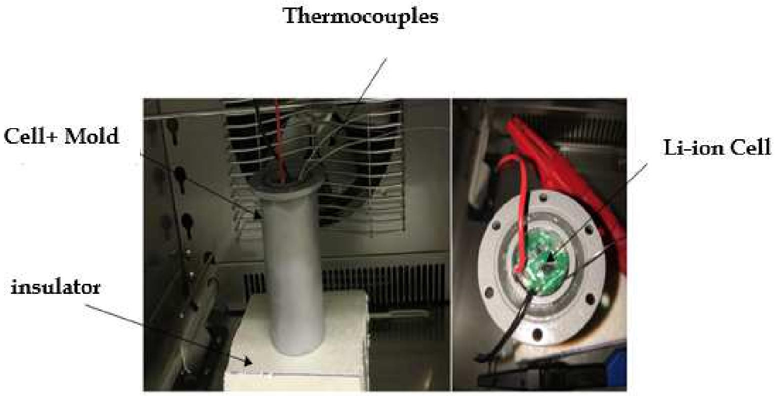

Figure 11: *Cell housed in the climatic chamber*

In order to evaluate the thermal performance of the paraffin RT27 and paraffin RT27- AF composite and their capacities to absorb the heat generated by the cell during successive charge/discharge cycles, the evolution of the radial temperature was monitored at the interfaces thanks to four K-type thermocouples: T_1, T_2, T_3 and T_4. **Figure 12** (a) provides a photo illustrating the location of the thermocouples and **Figure 12** (b) shows a schematic diagram of the location of the four thermocouples.

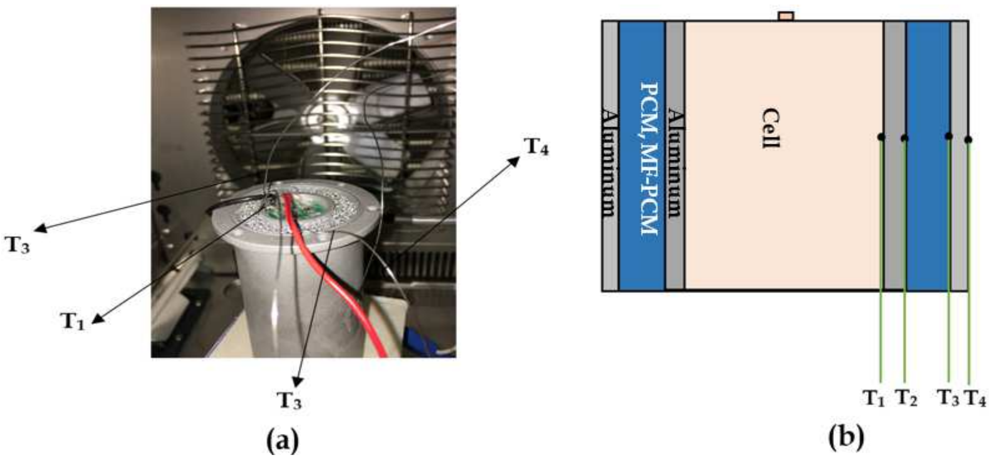

Figure 12: Thermocouple positions (a): Photo, (b): Schematic diagram

3.2.1. Impact of BTMS on cell temperature

Figure 13 shows a comparison of temperature evolution measured by thermocouple T_1 as a function of time. The results presented for the three cases studied include natural convection (cell without proposed BTMS), paraffin RT27 and the AF (porosity 0.93, pore density 40PPI) - paraffin RT27 composite. The solicitation is a current of 1C (2.5A) for ten successive uninterrupted 8-minute charge/discharge cycles. For thermal management with the pure paraffin RT27 and the Paraffin RT27-AF composite, the imposed temperature is 22°C. Ventilation is active to promote heat exchange between the evaporator (or condenser in the case of heating) and the air inside the climatic chamber.

The results show that the proposed BTMS (pure paraffin RT27/ paraffin RT27- AF composite) can significantly reduce the temperature of the cell. The black and blue curves, respectively, show the management of the time evolution of the cell temperature in the cases of pure paraffin RT27 and the Paraffin RT27- AF composite. Both curves show that a steady state is reached after two cycles versus five cycles in the case of natural convection. Comparing the steady state cell temperatures, we observe that the cell temperature of the natural convection reached 36.7°C, while the pure paraffin RT27 reached 26.5°C and thermal management with the paraffin RT27- AF composite (0.93, 40PPI) reached 25.6°C. In conclusion, the pure paraffin RT27 allowed the cell temperature to reduce by 10.2°C (average deviation in the steady state) and the paraffin RT27- AF (0.93, 40PPI) composite reduced by 11.2°C (average deviation in the steady state). The results show that the proposed system can maintain the cell temperature very close to the optimal operating temperature of 25°C.

The comparison of the results of the present study with the studies done by [42–44] points to the role of PCM phase changes temperature on the BTMS performance. In [42] the authors used a paraffin wax with phase change temperature around 44°C. Experiments were carried out for the battery contained in the housing for different heat exchange conditions, natural convection without PCM, pure PCM, and composite PCM and fin structure. The result showed that the proposed system kept the temperature around 55°C in the heat input of 6W case.

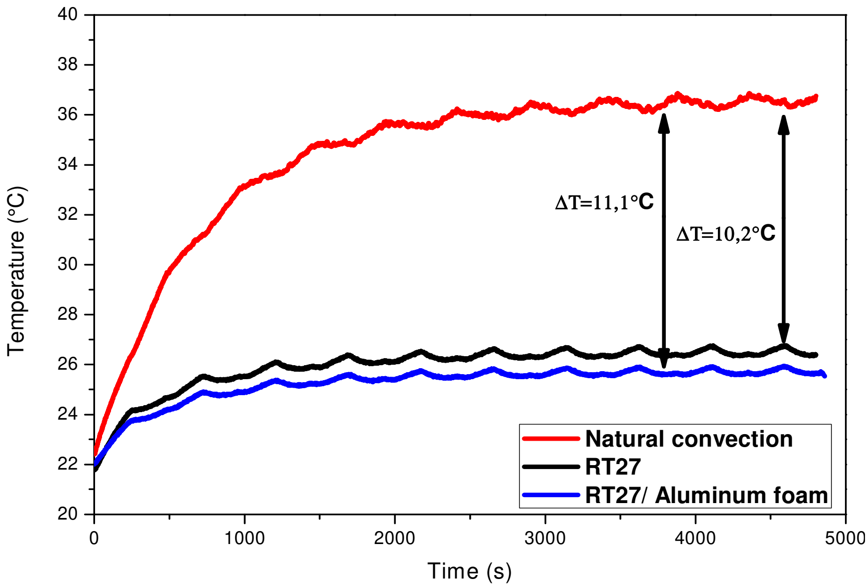

Figure 13: Measured temperature evolution with and without thermal management system

3.2.2. Temperature distribution without forced convection

In order to simulate a cell placed in a very confined area (battery pack of electric vehicle), tests without forced convection are performed. The assembly is placed in the climatic chamber, initially at a thermal equilibrium of 22°C, isolated from any heat exchange with the ambient environment.

Figure 14, and **15**, show – respectively- the temperature evolution in the case of pure paraffin RT27 and paraffin RT27- AF composite. The results show the total melting of the paraffin in both cases. This corroborates the results of our previous numerical study presented in [38]. An underestimation of necessary PCM volume to absorb the heat generated by the cell leads to high temperatures. The results show that the addition of a MF significantly reduced the temperature difference between the cell and the MF-PCM composite due to the improvement of effective thermal conductivity of the MF-PCM composite. The temperature difference between T_1 and T_2 was 2.5°C in the case of pure paraffin RT27 and 1.6°C in the case of paraffin RT27- AF.

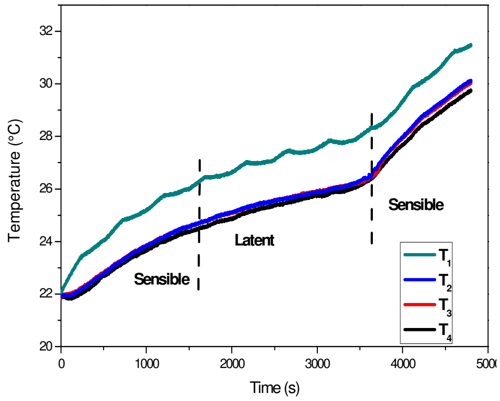

Figure 14: Temperature evolution- RT27, without convection

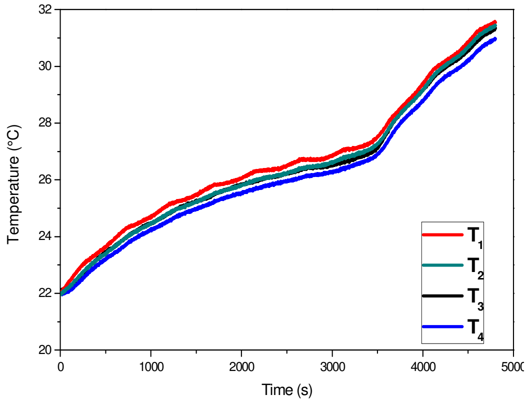

Figure 15: Temperature evolution AF- RT27, without forced convection

3.2.3. Temperature distribution with forced convection

In order to test the effect of convection on the thermal state of the cell, ventilation is activated to ensure a homogeneous temperature in the climatic chamber (22°C). **Figure 16** presents the time evolution of the temperature recorded for the pure paraffin RT27. On the one hand a permanent regime is established after 3 cycles unlike without forced convection. On the other hand, the temperature difference between T_1 and T_2 increased. The results show that the paraffin is not completely melted at the end of the test. This can be attributed to heat losses by forced convection.

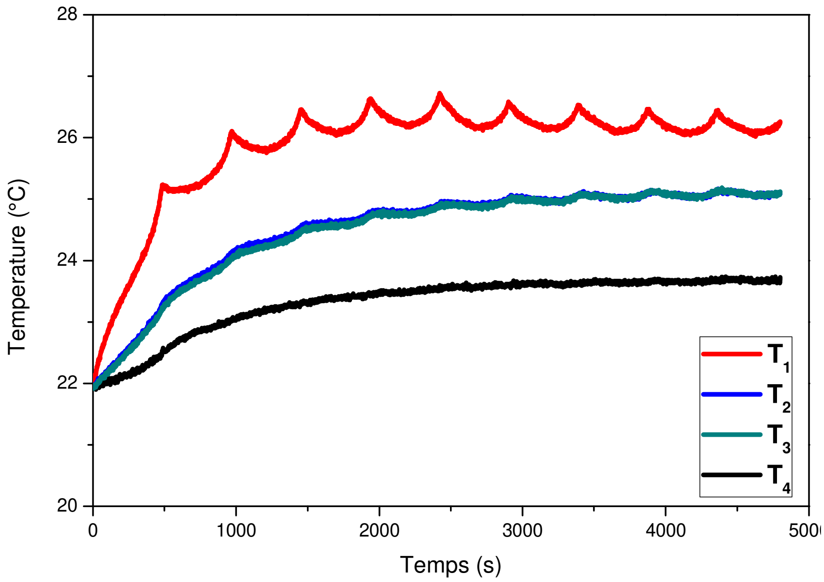

Figure 16: Temperature evolution RT27, forced convection

3.2.4. Impact of the addition of metal foam and forced convection

Figure 17 presents the comparison of the cell temperature evolution (T_1) between pure paraffin RT27 case and paraffin RT27- AF composite case for without forced convection scenario. In this figure it can be seen that the addition of the metal foam reduces the temperature of the cell during the melting process. Indeed, the addition of a conductive foam intensifies the heat transfer. This has, a priori, a greater impact in the presence of forced convection. To confirm or deny this, the temporal temperature of the cell evolution with pure paraffin RT27 was compared to that with paraffin RT27-AF composite in forced convection scenario, **Figure 18**. The comparison shows an average steady-state temperature difference of about 1.2°C between the cell temperature with pure RT27 and the Paraffin RT27- AF composite.

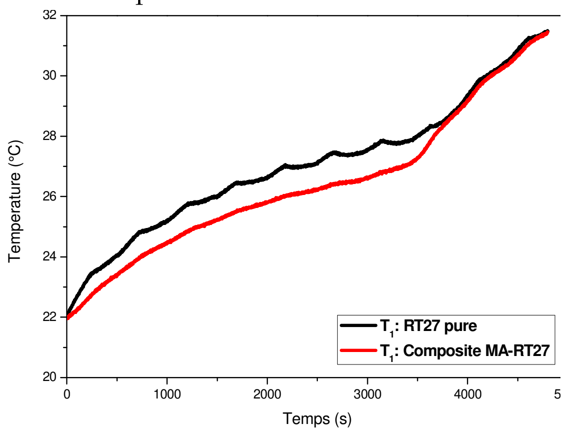

Figure 17: Impact of metal foam on cell temperature, without forced convection scenario

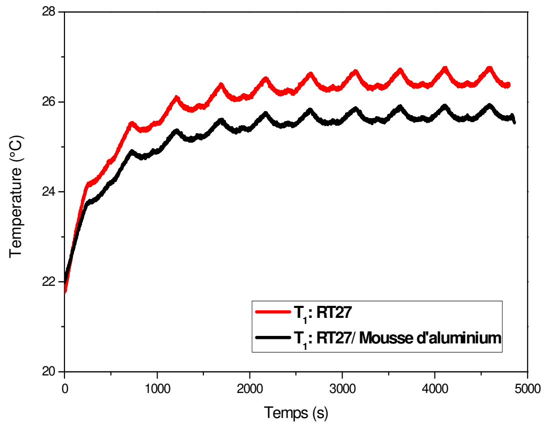

Figure 18: Impact of the addition of a metal foam on the temperature of the cell, with forced convection scenario

4. Conclusion

This paper deals with the study and characterization of thermal phenomena in a Li-ion cell. Cylindrical 18650 cells were used in this study. This type of cell is the most commonly used in electric vehicles. An experimental platform has been developed in CERTES Lab to study the thermal behavior of a Li-ion battery at cell scale. The objective was to propose a new BTMS that guarantees an operating temperature around the optimal operating temperature of 25°C for 1C charge/discharge cycles. The following results were obtained:

- The study of the thermal conductivity of the cell by the Hot-Disk has shown that the axial thermal conductivity is much more important than the radial one.
- The results showed that the PCM can absorb the heat generated by the cell in latent form in solid-liquid phase change. However, its low thermal conductivity limits its performance. The addition of an aluminum foam allows a more efficient thermal management of the cell. The results of the temperature measurements revealed that a temperature difference of about 11°C was recorded on cell surface without the RT27/ Aluminum Foam composite.
- The proposed BTMS system allowed to keep the temperature of the cell very close to the optimal operating temperature

From the above results, we can conclude that the proposed system can be considered as an optimized hybrid system which has the potential to be used for Li-ion batteries cooling of electrical vehicles. Before applying it on the scale of an electric vehicle, this study will be completed by:

- The study of the thermal performance of the proposed system on the scale of a module and then on the scale of a pack.
- Study of the efficiency of the proposed system in the case of severe conditions: fast discharges (2C, 3C,...)

- The study of the thermal response of the proposed system with standard cycles: WLTP (Worldwide Harmonised Light vehicles Test Procedure).
- A Durability study of PCM- MF Composites

References:

[1] Vidadili N, Suleymanov E, Bulut C, Mahmudlu C. Transition to renewable energy and sustainable energy development in Azerbaijan. Renewable and Sustainable Energy Reviews 2017;80:1153–61. https://doi.org/10.1016/j.rser.2017.05.168.

[2] Liu H, Wei Z, He W, Zhao J. Thermal issues about Li-ion batteries and recent progress in battery thermal management systems: A review. Energy Conversion and Management 2017;150:304–30. https://doi.org/10.1016/j.enconman.2017.08.016.

[3] Ren Y, Yu Z, Song G. Thermal management of a Li-ion battery pack employing water evaporation. Journal of Power Sources 2017;360:166–71. https://doi.org/10.1016/j.jpowsour.2017.05.116.

[4] Waldmann T, Wilka M, Kasper M, Fleischhammer M, Wohlfahrt-Mehrens M. Temperature dependent ageing mechanisms in Lithium-ion batteries – A Post-Mortem study. Journal of Power Sources 2014;262:129–35. https://doi.org/10.1016/j.jpowsour.2014.03.112.

[5] Ramadass P, Haran B, White R, Popov BN. Capacity fade of Sony 18650 cells cycled at elevated temperatures: Part II. Capacity fade analysis. Journal of Power Sources 2002;112:614–20. https://doi.org/10.1016/S0378-7753(02)00473-1.

[6] Rizk R, Louahlia H, Gualous H, Schaetzel P. Passive Cooling of High Capacity Lithium-Ion batteries. 2018 IEEE International Telecommunications Energy Conference (INTELEC) 2018:1–4. https://doi.org/10.1109/INTLEC.2018.8612368.

[7] Hallaj SA, Selman JR. A Novel Thermal Management System for Electric Vehicle Batteries Using Phase-Change Material. J Electrochem Soc 2000;147:3231. https://doi.org/10.1149/1.1393888.

[8] Wu S, Yan T, Kuai Z, Pan W. Thermal conductivity enhancement on phase change materials for thermal energy storage: A review. Energy Storage Materials 2020;25:251–95. https://doi.org/10.1016/j.ensm.2019.10.010.

[9] Biwole PH, Groulx D, Souayfane F, Chiu T. Influence of fin size and distribution on solid-liquid phase change in a rectangular enclosure. International Journal of Thermal Sciences 2018;124:433–46. https://doi.org/10.1016/j.ijthermalsci.2017.10.038.

[10] Conductivity particles dispersed organic and inorganic phase change materials for solar energy storage–an exergy based comparative evaluation. Energy Procedia 2012;14:643–8. https://doi.org/10.1016/j.egypro.2011.12.989.

[11] Ren Q, Guo P, Zhu J. Thermal management of electronic devices using pin-fin based cascade microencapsulated PCM/expanded graphite composite. International Journal of Heat and Mass Transfer 2020;149:119199. https://doi.org/10.1016/j.ijheatmasstransfer.2019.119199.

[12] EL IDI MM, Karkri M. Méthode inverse pour la détermination expérimentale des propriétés thermophysiques des matériaux à changement de phase. Congrès Français de Thermique, SFT 2018, PAU, France: 2018.

[13] Boussaba L, Foufa A, Makhlouf S, Lefebvre G, Royon L. Elaboration and properties of a composite bio-based PCM for an application in building envelopes. Construction and Building Materials 2018;185:156–65. https://doi.org/10.1016/j.conbuildmat.2018.07.098.

[14] Sarani I, Payan S, Nada SA, Payan A. Numerical investigation of an innovative discontinuous distribution of fins for solidification rate enhancement in PCM with and without nanoparticles. Applied Thermal Engineering 2020;176:115017. https://doi.org/10.1016/j.applthermaleng.2020.115017.

[15] Dinesh BVS, Bhattacharya A. Comparison of energy absorption characteristics of PCM-metal foam systems with different pore size distributions. Journal of Energy Storage 2020;28:101190. https://doi.org/10.1016/j.est.2019.101190.

[16] El idi MM, Karkri M, Kraiem M. Preparation and effective thermal conductivity of a Paraffin/ Metal Foam composite. Journal of Energy Storage 2020:102077. https://doi.org/10.1016/j.est.2020.102077.

[17] Moussa EL IDI M, Karkri M. Heating and cooling conditions effects on the kinetic of phase change of PCM embedded in metal foam. Case Studies in Thermal Engineering 2020:100716. https://doi.org/10.1016/j.csite.2020.100716.

[18] Mohamed Moussa EI, Karkri M. A numerical investigation of the effects of metal foam characteristics and heating/cooling conditions on the phase change kinetic of phase change materials embedded in metal foam. Journal of Energy Storage 2019;26:100985. https://doi.org/10.1016/j.est.2019.100985.

[19] EL IDI MM, Karkri M. Etude numérique de stockage d'énergie thermique dans un composite : mousses métalliques/matériaux à changement de phase. Congrès Français de Thermique SFT 2019, Nantes, France: 2019.

[20] EL IDI MM, KARKRI M. Melting and solidification behavior of PCM embedded in metal foam. COMSOL CONFERENCE 2020 EUROPE, Grenoble, France: 2020.

[21] Tauseef-ur-Rehman, Ali HM, Janjua MM, Sajjad U, Yan W-M. A critical review on heat transfer augmentation of phase change materials embedded with porous materials/foams. International Journal of Heat and Mass Transfer 2019;135:649–73. https://doi.org/10.1016/j.ijheatmasstransfer.2019.02.001.

[22] Ashby MF, Evans AG, Fleck NA, Gibson LJ, Hutchinson JW, Wadley HNG, editors. Chapter 4 - Properties of metal foams. Metal Foams, Burlington: Butterworth-Heinemann; 2000, p. 40–54. https://doi.org/10.1016/B978-075067219-1/50006-4.

[23] Weng J, He Y, Ouyang D, Yang X, Zhang G, Wang J. Thermal performance of PCM and branch-structured fins for cylindrical power battery in a high-temperature environment. Energy Conversion and Management 2019;200:112106. https://doi.org/10.1016/j.enconman.2019.112106.

[24] Ping P, Peng R, Kong D, Chen G, Wen J. Investigation on thermal management performance of PCM-fin structure for Li-ion battery module in high-temperature environment. Energy Conversion and Management 2018;176:131–46. https://doi.org/10.1016/j.enconman.2018.09.025.

[25] Ouyang D, Weng J, Hu J, Liu J, Chen M, Huang Q, et al. Effect of High Temperature Circumstance on Lithium-Ion Battery and the Application of Phase Change Material. J Electrochem Soc 2019;166:A559. https://doi.org/10.1149/2.0441904jes.

[26] Ling Z, Chen J, Fang X, Zhang Z, Xu T, Gao X, et al. Experimental and numerical investigation of the application of phase change materials in a simulative power batteries thermal management system. Applied Energy 2014;121:104–13. https://doi.org/10.1016/j.apenergy.2014.01.075.

[27] Hussain A, Abidi IH, Tso CY, Chan KC, Luo Z, Chao CYH. Thermal management of lithium ion batteries using graphene coated nickel foam saturated with phase change materials. International Journal of Thermal Sciences 2018;124:23–35. https://doi.org/10.1016/j.ijthermalsci.2017.09.019.

[28] Li WQ, Qu ZG, He YL, Tao YB. Experimental study of a passive thermal management system for high-powered lithium ion batteries using porous metal foam saturated with phase change materials. Journal of Power Sources 2014;255:9–15. https://doi.org/10.1016/j.jpowsour.2014.01.006.

[29] Bamdezh MA, Molaeimanesh GR, Zanganeh S. Role of foam anisotropy used in the phase-change composite material for the hybrid thermal management system of lithium-ion battery. Journal of Energy Storage 2020;32:101778. https://doi.org/10.1016/j.est.2020.101778.

[30] Bamdezh MA, Molaeimanesh GR. Impact of system structure on the performance of a hybrid thermal management system for a Li-ion battery module. Journal of Power Sources 2020;457:227993. https://doi.org/10.1016/j.jpowsour.2020.227993.

[31] Mehrabi-Kermani M, Houshfar E, Ashjaee M. 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 2019;141:47–61. https://doi.org/10.1016/j.ijthermalsci.2019.03.026.

[32] Zhang H, Wu X, Wu Q, Xu S. Experimental investigation of thermal performance of large-sized battery module using hybrid PCM and bottom liquid cooling configuration. Applied Thermal Engineering 2019;159:113968. https://doi.org/10.1016/j.applthermaleng.2019.113968.

[33] Hekmat S, Molaeimanesh GR. Hybrid thermal management of a Li-ion battery module with phase change material and cooling water pipes: An experimental investigation. Applied Thermal Engineering 2020;166:114759. https://doi.org/10.1016/j.applthermaleng.2019.114759.

[34] Mashayekhi M, Houshfar E, Ashjaee M. Development of hybrid cooling method with PCM and Al2O3 nanofluid in aluminium minichannels using heat source model of Li-ion batteries. Applied Thermal Engineering 2020;178:115543. https://doi.org/10.1016/j.applthermaleng.2020.115543.

[35] Lv Y, Liu G, Zhang G, Yang X. A novel thermal management structure using serpentine phase change material coupled with forced air convection for cylindrical battery modules. Journal of Power Sources 2020;468:228398. https://doi.org/10.1016/j.jpowsour.2020.228398.

[36] Pesaran A, Keyser M, Kim GH, Santhanagopalan S, Smith K. Tools for Designing Thermal Management of Batteries in Electric Drive Vehicles. National Renewable Energy Lab. (NREL), Golden, CO (United States); 2013. https://doi.org/10.2172/1064502.

[37] Kraiem M, Karkri M, Nasrallah SB, Sobolciak P, Fois M, Alnuaimi NA. Thermophysical Characterization and Numerical Investigation of Three Paraffin Waxes as Latent Heat Storage Materials 2019. https://doi.org/10.20944/preprints201903.0034.v1.

[38] El Idi MM, Karkri M, Abdou Tankari M. A passive thermal management system of Li-ion batteries using PCM composites: Experimental and numerical investigations. International Journal of Heat and Mass Transfer 2021;169:120894. https://doi.org/10.1016/j.ijheatmasstransfer.2020.120894.

[39] Gustafsson SE. Transient plane source techniques for thermal conductivity and thermal diffusivity measurements of solid materials. Review of Scientific Instruments 1991;62:797–804. https://doi.org/10.1063/1.1142087.

[40] Log T, Gustafsson SE. Transient plane source (TPS) technique for measuring thermal transport properties of building materials. Fire and Materials 1995;19:43–9. https://doi.org/10.1002/fam.810190107.
[41] Hot Disk | Anisotropy Thermal Conductivity Tests of Batteries. Hot Disk n.d. https://www.hotdiskinstruments.com/applications/anisotropy-thermal-conductivity-tests-of-batteries/ (accessed August 7, 2020).
[42] Wang Z, Zhang H, Xia X. Experimental investigation on the thermal behavior of cylindrical battery with composite paraffin and fin structure. International Journal of Heat and Mass Transfer 2017;109:958–70. https://doi.org/10.1016/j.ijheatmasstransfer.2017.02.057.
[43] Weng J, Ouyang D, Yang X, Chen M, Zhang G, Wang J. Optimization of the internal fin in a phase-change-material module for battery thermal management. Applied Thermal Engineering 2020;167:114698. https://doi.org/10.1016/j.applthermaleng.2019.114698.
[44] Choudhari VG, Dhoble AS, Panchal S. Numerical analysis of different fin structures in phase change material module for battery thermal management system and its optimization. International Journal of Heat and Mass Transfer 2020;163:120434. https://doi.org/10.1016/j.ijheatmasstransfer.2020.120434.