JJEE
Volume 4, Number 4, 2018
Pages 224-232
Jordan Journal of Electrical Engineering
ISSN (Print): 2409-9600, ISSN (Online): 2409-9619

Performance-Weight Trade for Thermal Management Systems of Lithium-Ion Batteries

Osama M. Al-Hababheh[1], Ahmad M, Jaber[1], Sami M. Halawani[1],
Mustafa A. Al-Khawaldeh[2a]

[1]Department of Mechatronics Engineering, The University of Jordan, Amman, Jordan
[2]Department of Mechatronics Engineering, Philadelphia University, Amman, Jordan
[a]e-mail: malkhawaldeh@philadelphia.edu.jo

Received: October 14, 2018 *Accepted: November 29, 2018*

Abstract— The most important factor limiting the efficiency of Lithium-ion (Li-ion) batteries is their thermal performance. Therefore, the analysis of battery thermal management (BTM) of this type of batteries is of a great interest. This work aims at evaluating the effectiveness of different types of passive and active BTM systems. The electro-thermal behavior of the battery pack is characterized using 3D finite element method (FEM) modeling. The heat generation rate of battery cells during utilization is determined, so that the thermal behavior of the battery pack can be evaluated. The different BTM solutions are evaluated to determine the improvements in the pack thermal behavior. For further improvements, a new mixture of phase-change materials (PCM) is proposed and simulated. The mixture contains 75% of hydrogel and 25% of paraffin wax (PW). The results show that the mixture enables reducing the weight of the BTM material while slightly reducing performance. The end result is reducing the operating cost of the system especially for aerospace applications due to the reduced weight, which is the most important factor. In addition, cooling can be enhanced by the wind.

Keywords— Hydrogel, Li-ion battery, PCM, paraffin wax, thermal management, weight reduction.

I. INTRODUCTION

Li-ion battery is a popular type of rechargeable batteries. It has high energy density, low self-discharge and light weight [1]. It is used in vehicles, laptops, mobile phones, cameras, etc. Energy density and power density are two key battery parameters. Energy density is defined as the amount of energy stored in the battery per unit mass, whereas power density is the amount of power in a given volume. Li-ion batteries provide a compromise between energy density and power density. In batteries, the chemical energy is converted into electrical energy. According to the second law of thermodynamics, any conversion between two forms of energy occurs with an energy loss, which produces battery thermal problems. Therefore, heat is one of the main factors that affect battery efficiency.

It is proven that the temperature of the battery should not be high enough to cause damage. In the meantime, if the temperature of the battery is too low, it would adversely affect its performance. Due to the aforementioned reasons, it is vital to control battery temperature. Due to the importance of this subject, it has received considerable attention from researchers; Anderson [2] investigated how temperature can significantly affect performance and durability of batteries. Ramadass *et al.* [3] studied the capacity fade of Li-ion cells due to cycling at different temperatures.

Various types of PCMs have been studied by researchers; Javani *et al.* [4] conducted Finite Volume simulations for *n*-octadecane wax as a PCM for Li-ion cells; the maximum temperature in the system is decreased by replacing dry foam with PCM-soaked “wet foam”. The addition of PCM also makes temperature distribution more uniform across the cells. The BTM of a cylindrical Li-ion battery is investigated by Greco *et al.* [5] who used compressed expanded natural graphite (CENG) as the PCM. The transient thermal behavior is described

---

Corresponding author's e-mail: malkhawaldeh@philadelphia.edu.jo with a simplified 1-D model. The PCM shows superior transient characteristics to force convection cooling. A BTM system for LiFePO4 battery using expanded graphite matrix as the PCM is developed by Lin *et al.* [6]; a 3-D model of the battery is constructed using ANSYS Fluent®. The PCM cooling significantly reduced temperature during short-time intense use. An experiment as well as two models (lumped and FEA) were conducted by Schweitzer *et al.* [7] who studied the thermal response of a Li-ion battery pack with PCC™ as the PCM. The results predicted a minimal temperature variation for this PCM.

The thermal behavior of Li-ion batteries was studied experimentally by Rui Zhao *et al.* [8] who investigated BTM using different PCMs. They found that the best BTM material is hydrogel. However, since this material is based on water, it is heavier than other alternatives. In an attempt to reduce weight while minimizing the effect on performance, this work proposes a new PCM mixture consisting of 75% hydrogel and 25% paraffin wax. The performance and weight of the proposed mixture are compared to those of rival methods, as weight reduction can lead to cost savings.

II. THEORETICAL BACKGROUND

According to Bernardi [9], battery heat is generated due to two main reasons: irreversible resistive heating and reversible entropic heat. The irreversible ohmic heat loss occurs from internal resistances when the current flows during both charge and discharge. The general equation for the generated heat is [10]:

$$Q = I^2R - IT\frac{dV_o}{dT} \tag{1}$$

Where Q is the heat generated in the battery; I is the cell current, which is positive during discharge and negative during charge; R is the resistance; T is the cell temperature; and V_o is the cell open circuit voltage. The discharge occurs when $I>0$; and the term $\frac{dV_o}{dT}$ is negative. As a result, the second term on the right-hand side of (1) is positive during discharge. If the generated heat in the cell is not removed, it will increase the temperature of the cell, which affects the battery's life and ability to deliver energy. On the other hand, lower battery temperatures lead to decreasing power capability. BTM systems use many techniques for heat dissipation such as: air cooling, liquid cooling, PCMs, heat spreaders and heat sinks. Since the thermal capacity of air is low, the effectiveness of dissipating heat by air cooling is reduced [11].

In order to obtain optimum performance and maximize the useful life of a Li-ion battery cell, the temperature of the cell should be in the range of 20-40 °C. Another critical issue for battery pack is the difference in the temperatures of the cells, which may lead to variations in the charge/discharge performance between cells in the same pack, which may result in electrical imbalance [12]. An effective BTM system must minimize the differences in temperatures between different battery cells in the same pack. An ideal BTM system should be able to maintain the desired uniform temperature in a pack by rejecting heat in hot climates and adding heat in cold climates. BTM system may rely on liquid cooling, which would be more effective than air cooling because it has a higher heat capacity. However, both of these systems involve increasing the complexity and weight of the cooling system [13].

In an effort to simplify the cooling system and reduce its weight, latent heat of the coolant is exploited, converting the heat energy to phase change of the cooling medium. The latent heat exchanged does not affect the temperature of the medium. One of the PCMs used for cooling is paraffin wax. Paraffin waxes are cheap with good thermal energy storage density but low thermal conductivity. Because of the low thermal conductivity, PCM could be liquid at some places inside the pack while being mushy or solid at some other places. From the above discussion, it is noted that BTM systems are divided into two types: active and passive. Active cooling uses fans or pumps which need external power, while passive cooling consumes no power [14].

III. CHARACTERISTICS OF COOLING MEDIA

Different materials can be used as cooling media; the most common one is water. It has high heat capacity, high density and high thermal conductivity, which allow it to transmit heat over greater distances with much less volumetric flow. Water parameters are shown in Table 1 [15].

TABLE 1
THERMAL CHARACTERISTICS OF WATER

Density, kg/m^3	Thermal Conductivity, W/m C	Specific Heat Capacity, J/kg C
997.4	0.604	4179

Water is normally used for active cooling because of the need for pumps to circulate it. Pumps need power which is provided by the battery. This will increase the load on the battery; and affect its performance. Additional heat will be produced as a result. To solve this problem, water can be used for passive cooling if Sodium polyacrylate (PAAS) is added to it. The recommended ratio of PAAS to water is 1%. This operation helps to increase water viscosity, converting it to hydrogel. The hydrogel serves as a passive cooling system or jacket for a battery. The thermal characteristic of the hydrogel is expressed by (2) and (3):

$$Cp_{gel} = \varepsilon Cp_{PAAS} + (1-\varepsilon) Cp_{H2O} \tag{2}$$

$$K_{gel} = \varepsilon K_{PAAS} + (1-\varepsilon) K_{H2O} \tag{3}$$

Where Cp is the specific heat capacity; ε is the mass percent of PAAS in water (1%); and K is the thermal conductivity. The subscript *gel* stands for the hydrogel. Since the PAAS percent in water is too small, the thermal effect of the PAAS is neglected; and the hydrogel is considered as water in a passive cooling system. In general, PCMs melt and solidify at a fixed temperature. Therefore, they are capable of storing and releasing large amounts of energy. Heat storage in PCM can be achieved through (solid-to-liquid), (solid-to-gas), (liquid-to-gas) or (solid-to-solid). However, since (solid-to-solid) phase change is the slowest, it is used in BTM. Solid-to-solid PCMs change their crystalline structure from one lattice configuration to another at a fixed temperature. Therefore, there are no problems associated with handling liquids. The temperature range of solid-to-solid PCM solutions spans from 25-180 °C. An example of PCM is paraffin wax; depending on the Carbon content, the melting point of paraffin wax can be 10-76 °C [16]. The thermal characteristics of paraffin wax are shown in Table 2.

TABLE 2
THERMAL CHARACTERISTICS OF PARAFFIN WAX

Density, kg/m^3	Thermal Conductivity, W/m C	Specific Heat Capacity, J/kg C
900	0.25	2500

Air is considered one of the main methods for BTM, whether as a passive system such as ambient air, or as an active system such as the air forced by a fan. The difference between air passive cooling and air active cooling is the convective heat transfer coefficient (h). In this work, both cases are considered; in the active case, the fan has a diameter of 8 cm at one side of the battery pack with a distance of 5 cm. The rotation speed of the fan is 1500 rpm. The thermal characteristics of air for the two cases are shown in Table 3.

TABLE 3
THERMAL CHARACTERISTICS OF AIR

Parameter/System	Density, kg/m^3	Thermal Conductivity, W/m C	Specific Heat Capacity, J/kg C	Convection Heat Transfer Coefficient, W/m^2 C
Passive	1.1614	0.026	1007	1.25
Active	1.1614	0.026	1007	2.5

IV. MODELING OF BATTERY PACKS

Thermal behavior of Li-ion batteries was studied experimentally by Zhao *et al.* [8] who investigated BTM using different methods and materials. They used two types of battery packs: five cells and two cells. The characteristics of the packs differ in operating voltage, capacity, current, size and spacing between cells as shown in Table 4. In this work, FEM is used to build models for the two types of battery packs using ANSYS®. The FEM models shown in Fig. 1 and Fig. 2 are based on data obtained from Zhao et al. [8]. These models are validated by comparing the simulation results with experimental data obtained from the same reference. The models are used to calculate internal heat generation for each cell. The heat amounts depend on the characteristics of the batteries.

TABLE 4
BATTERY PACKS CHARACTERISTICS

Battery/Property	5-Cells Pack	2-Cells Pack
Pack operating voltage	3.0 – 4.2 V/ Cell (15 - 21 V/ pack)	3.0 – 4.2 V/ Cell (6 – 8.4 V/ pack)
Pack capacity	8000 mAh	1300 mAh
Cell size	0.9 × 4.5 × 17.5 cm^3	0.4 × 2.5 × 7 cm^3
Spacing between cells	0.45 cm	0.2 cm

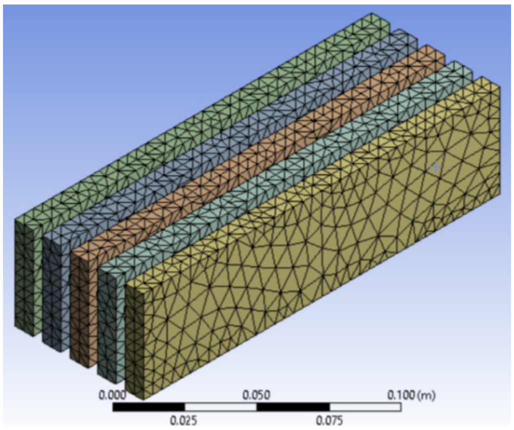

Fig. 1. FEM model for 5-cells battery pack

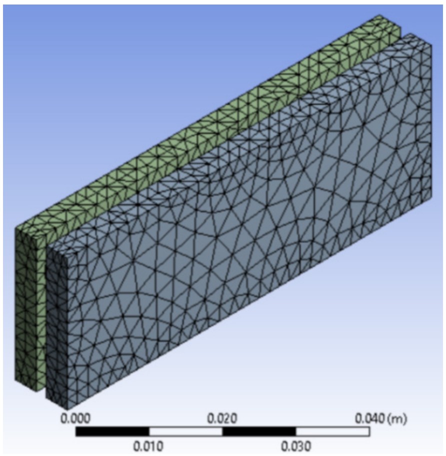

Fig. 2. FEM model for 2-cells battery pack

A) Air Cooling Simulation

Air cooling simulation is made in two stages: passive and active. Passive simulation involves ambient static air surrounding the battery, where transient thermal analysis is conducted so as to determine the air convection heat transfer. The results are shown for the 5-cells pack in Fig. 4. Active air simulation is conducted, where air is driven by a fan. Therefore, the convective heat transfer coefficient will be higher than the passive case because it depends on air velocity. The comparison of simulation results with the experimental data [8] is shown in Fig. 3, which shows the average cell temperature as a function of time. The two curves in Fig. 3 show that the simulation results agree very well with the experimental data [8].

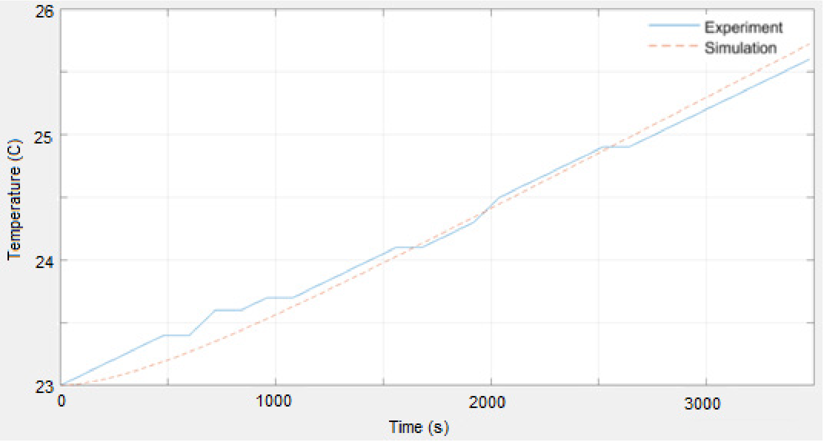

Fig. 3. Comparison of active air simulation and experimental data for 2-cells pack

B) Paraffin Wax Simulation

Paraffin wax is a PCM which is considered a passive cooling system. The average cell temperature as a function of time for the 5-cells pack is shown in Fig. 4.

C) Hydrogel Simulation

In this case, because the PAAS quantity in water is very small (1%), hydrogel is considered to behave thermally like water. The average cell temperature as a function of time for the 5-cells pack is shown in Fig. 4.

V. ASSESSMENT OF BTM METHODS

In this section, the obtained results for different BTM systems are evaluated. The results are plotted in Fig. 4 for the 5-cells packs. The curves show the detailed temperature vs. time profiles for the packs. Heat dissipation capacities of the BTM systems are evaluated based on the temperature rise of the packs. In the figure, the four BTM strategies are plotted together. It is observed in the figure that hydrogel performs much better than other BTM systems in suppressing the temperature rise. It is worth mentioning that these simulation results agree very well with the experimental data obtained by Zhao et al. [8].

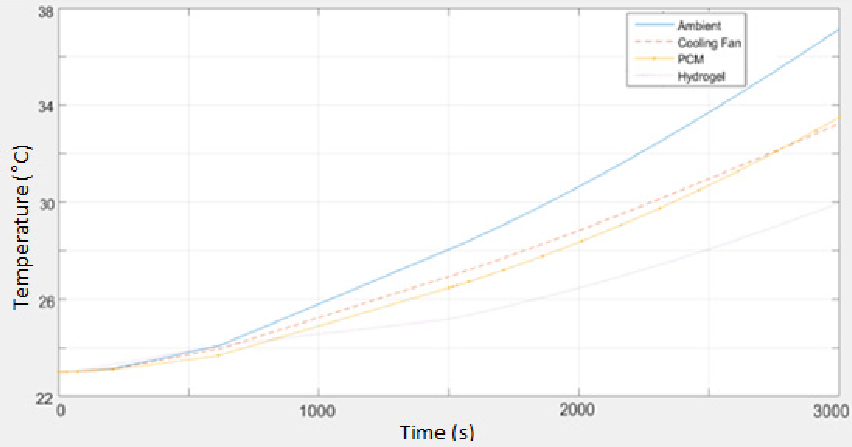

Fig. 4. Comparison of BTM methods for 5-cells pack

VI. PERFORMANCE-WEIGHT TRADE FOR BTM SYSTEM

In this work, a new BTM system is proposed. The proposed system is designed by mixing paraffin wax with hydrogel, where paraffin wax particles are suspended within the hydrogel. Different ratios were investigated in order to find the ratio that has the highest thermal effect on the battery pack and the lowest weight. Thermal characteristics of the proposed mixture are obtained from (4), (5) and (6).

$$\rho_{mix} = \alpha\rho_{gel} + (1-\alpha)\rho_{PW} \tag{4}$$

$$Cp_{mix} = \alpha Cp_{gel} + (1-\alpha)Cp_{PW} \tag{5}$$

$$K_{mix} = \alpha K_{gel} + (1-\alpha)K_{PW} \tag{6}$$

Where ρ is the density; α is the hydrogel ratio; C_p is the specific heat capacity; and K is the thermal conductivity. The subscript "mix" stands for the paraffin wax-hydrogel mixture; and the subscript "PW" stands for "paraffin wax". Three different ratios were investigated. The thermal characteristics of these ratios are presented in Table 5.

TABLE 5
CHARACTERISTICS OF THE PROPOSED BTM SYSTEM

Composition/ Property	**75% gel + 25% PW**	**50% gel + 50% PW**	**25% gel + 75% PW**
Density, kg/m^3	973.1	948.7	924.4
Thermal Conductivity, W/m °C	0.516	0.427	0.339
Specific Heat Capacity, J/kg °C	3759	3340	2920

The three mixtures were simulated on the 5-cells and the 2-cells packs. Temperature distributions corresponding to the (75% Hyd + 25% PW) mixture for the 5-cells and the 2-cells packs are shown in Fig. 5 and Fig. 6, respectively. For comparison purposes, the average cell temperature as a function of time for each of the three mixtures is plotted in Fig. 7 for the 5-cells pack.

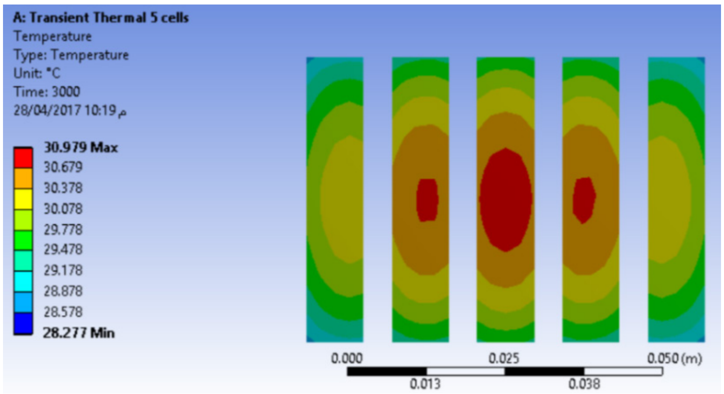

Fig. 5. (75% gel + 25% PW) effect on 5-cells pack

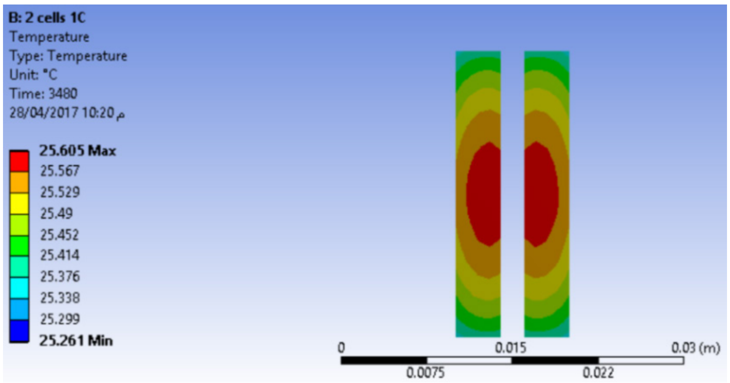

Fig. 6. (75% gel + 25% PW) effect on 2-cells pack

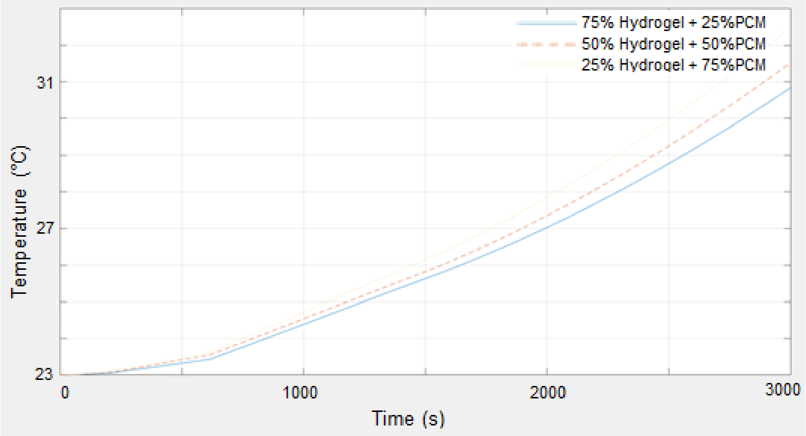

Fig. 7. The three mixtures effects on average cell temperature for 5-cells pack

It is noted in Fig. 7 that the best proposed mixture is the (75% gel + 25% PW). However, this mixture must be compared to the previous results presented in Fig. 4, which showed that hydrogel was the best option. The proposed mixture is compared to hydrogel for 5-cells pack in Fig. 8. In the figure, it is noted that hydrogel is slightly better than the proposed mixture. However, the difference between them is always less than 0.7 °C. On the other hand, hydrogel is heavier than paraffin wax. Using (4) to calculate the density of the mixture yields the data presented in Table 6. The size of BTM material is calculated using Table 4. After calculating the weights of the alternative BTM materials, weight savings are shown in Table 6. Considering the proposed mixture, weight reduction is 3%, while performance loss is 2%. This amount of weight reduction is greater than performance loss.

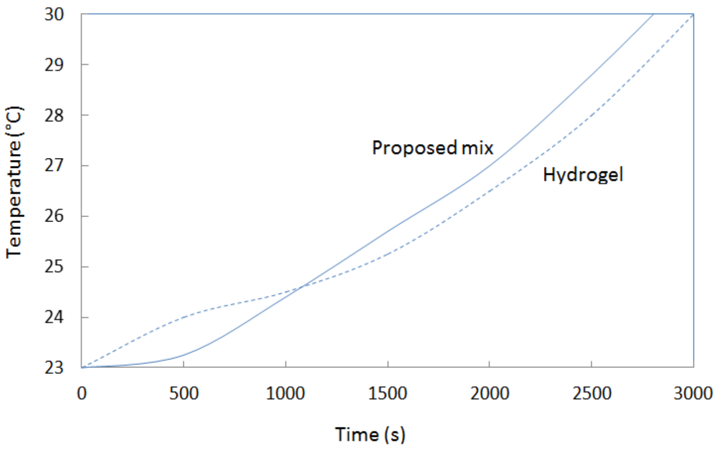

Fig. 8. Proposed mix versus hydrogel for 5-cells pack

TABLE 6
ANALYSIS OF BTM MEDIA FOR 5-CELLS PACK

Property/Material	Density, kg/m^3	Volume, cm^3	Weight, g	Weight Reduction, g	Weight Reduction, %	Performance Loss, °C	Performance Loss, %
Hydrogel	997.4	496	495	0.0	0	0	0
Paraffin wax	900	496	447	48.3	11	1.5	5
Proposed mix	973.05	496	483	12.1	3	0.7	2

VII. CONCLUSIONS

The electro-thermal behavior of the battery packs is characterized using 3D FEM modeling. The heat generation rate of the battery cells during utilization is determined; and the thermal behavior of the battery packs is evaluated. The different BTM solutions were simulated in a comparative study to determine the improvements in the pack thermal behavior. In an effort to reduce the operating cost while maintaining the same level of performance, a new mixture of PCMs is proposed and simulated. The mixture consists of 75% of hydrogel and 25% of paraffin wax. The effectiveness of the mixture in heat dissipation was simulated. The results show that the mixture enabled reducing the weight of the BTM material by 12.1 g, which corresponds to 3%, while slightly reducing performance by 0.7 °C, which corresponds to 2%. The amount of weight reduction is greater than the corresponding performance loss. Therefore, this is one positive point for the proposed mixture. Weight reduction will be reflected on reducing the operating costs of the system, especially in applications where weight is critical such as in aviation. In the meantime, for paraffin wax, performance loss is 5%, which may be unacceptable for some applications, while weight reduction is 11%, which is higher than the proposed mixture. However, the heat conductivity of the paraffin wax is low, which may cause electrical imbalance, whereas the heat conductivity of the proposed mixture is higher, enabling better electrical balance. Further research is needed to optimize BTM materials in terms of cooling efficiency, cooling uniformity and weight, simultaneously.

REFERENCES

[1] H. Khasawneh, J. Neal, M. Canova, and Y. Guezennec, "Analysis of heat-spreading thermal management solutions for lithium-ion batteries," *Proceedings of the ASME 2011 Mechanical Engineering Congress and Exposition IMECE*, pp. 1-12, 2011.

[2] R. Anderson, "Requirements for improved battery design and performance," *Journal of Passenger Cars, SAE Transactions*, vol. 99, no. 6, pp. 1190-1197, 1990.

[3] P. Ramadass, B. Haran, R. White, and B. Popov., "Mathematical modeling of the capacity fade of Li-ion cells," *Journal of Power Sources*, vol. 123, no. 2, pp. 230–240, 2003.

[4] N. Javani, I. Dincer, G. Naterer, and G. Rohrauer, "Modeling of passive thermal management for electric vehicle battery packs with PCM between cells," *Applied Thermal Engineering*, vol. 73, pp. 307-316, 2014.

[5] A. Greco, X. Jiang, and D. Cao, "An investigation of lithium-ion battery thermal management using paraffin/porous-graphite-matrix composite," *Journal of Power Sources*, vol. 278, pp.50-68, 2015.

[6] C. Lin, S. Xu, G. Chang, and J. Liu, "Experiment and simulation of a LiFePO4 battery pack with a passive thermal management system using composite phase change material and graphite sheets," *Journal of Power Sources*, vol. 275, pp. 742-749, 2015.

[7] B. Schweitzer, S. Wilke, S. Khateeb, and S. Al-Hallaj, "Experimental validation of a 0-D numerical model for phase change thermal management systems in lithium-ion batteries," *Journal of Power Sources*, vol. 287, pp. 211-219, 2015.

[8] R. Zhao, S. Zhang, J. Gu, J. Liu, St. Carkner, and E. Lanoue, "An experimental study of lithium ion battery thermal management using flexible hydrogel films," *Journal of Power Sources*, vol. 255, no. 1, pp. 29-36, 2014.

[9] D. Bernardi, E. Pawlikowski, and J. Newman, "A general energy balance for battery systems," *Journal of the Electrochemical Society*, vol. 132, no. 5, pp. 53-63, 1985.

[10] C. Pals and J. Newman, "Thermal modeling of the lithium/polymer battery," *Journal of the Electrochemical Society*, vol. 142, no. 10, pp. 3282-3288, 1995.

[11] A. Pesaran, S. Burch, and M. Keyser, "An approach for designing thermal management systems for electric and hybrid vehicle battery packs," *Proceedings of the Vehicle Thermal Management Systems Conference and Exhibition*, pp. 24.27, 1999.

[12] S. Al-Hallaj, H. Maleki, J. Hong, and J. Selman, "Thermal modeling and design considerations of lithium-ion batteries," *Journal of Power Sources*, vol. 83, no. 1-2, pp. 1-8, 1999.

[13] A. Pesaran, "Battery thermal management in EVs and HEVs: issues and solutions," *Proceedings of the Advanced Automotive Battery Conference*, pp. 1-10, 2001.

[14] R. Sabbah, R. Kizilel, J. Selman, and S. Al-Hallaj, "Active (air-cooled) vs. passive (phase change material) thermal management of high power lithium-ion packs: limitation of temperature rise and uniformity of temperature distribution," *Journal of Power Sources*, vol. 182, no.2, pp. 630-638, 2008.

[15] Engineering Data Sources in ANSYS 16.0 software.

[16] A. Sharma, V. Tyagi, C. Chen, and D. Buddhi, "Review on thermal energy storage with phase change materials and applications," *Renewable and Sustainable Energy Reviews*, vol. 13, no. 2, pp. 318-345, 2009.