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Abstract

The thermal performance of lithium-ion battery under passive cooling (organic PCM) is investigated experimentally. Coconut oil, soy wax and palm wax are used as organic PCM. This study investigates the temperatures at the anode, cathode and midpoint of the battery in natural convection and the effects of passive cooling method on three different organic PCMs located around Li-ion battery during different discharges (1C, 2C and 3C). The results with PCM are also compared with the cases without PCM and the effects of organic PCMs on battery thermal performance are determined. According to the experimental results, it is determined that at the highest discharge rate, coconut oil completely melted, palm wax is in mushy phase region and soy wax does not change phase. Depending on discharge rates, in the case without PCM, while the maximum battery surface temperatures range from 30.7 °C to 48.8 °C, these temperatures range from 25.5 °C to 42.6 °C for coconut oil, 24.8 °C to 41.8 °C for soy wax, and 25 °C to 40.5 °C for palm wax. Battery cooling performance is better in palm wax. In addition, when the surface temperatures of the battery are compared with organic PCMs temperature, it is identified that there is very little difference. These findings indicate that passive cooling can also reduce battery operating temperature and the use of organic PCMs can make positive contributions to battery thermal performance.

Keywords: Organic-PCM, Lithium-ion battery, Thermal Behavior, Passive cooling system.

INTRODUCTION

The importance of energy and its effective use have been one of the most important issues in engineering applications in recent years. The energy required in our daily lives is obtained from renewable or non-renewable energy sources. Renewable energy sources come to the fore due to factors such as the unstable prices of fossil-based energy, lack of confidence in supply and the reduction of CO_2 emissions. One of the most important problems in both renewable and non-renewable energy sources is that energy cannot be stored. Batteries are used to store energy and provide energy in areas that are not accessible. Studies on the chemical, electrical and thermal properties of batteries are still ongoing. Batteries can be divided into two groups, rechargeable and non-rechargeable, depending on their usage areas and capacities. Among rechargeable batteries, the most preferred battery type is Lithium-ion. These batteries are widely used in the automobile-bicycles, household electrical appliances, electronics and aviation industries due to their high efficiency, operating temperature, long life, capacities and low self-discharge rate [1–3]. Capacity is important in batteries used in these devices, and it shows the energy a battery will store and how long it can provide energy at certain discharge currents. However, factors such as ambient temperature, operating current or voltage, discharge rate and sensitivity of the devices directly affect the capacity of the batteries, depending on the battery life. The operating temperature of the battery is an important factor in meeting battery life cycle and power requirements. The operating temperature of the battery is a critical that directly affects its electrical properties such as battery life, capacity and power. Although this undesirable operating temperature is considered as high temperatures, it also negatively affects the battery at operating temperatures below zero [4]. In addition, when the critical temperature is exceeded, it becomes dangerous and unsuitable [5,6]. In this context, depending on the battery characteristics, if it is operated at high currents, the battery temperature is higher depending on the ambient temperature. Cooling is applied to the battery to control the temperature increase of the battery. It is possible to cool the battery in different ways: natural convection, forced convection, coolant circuit, heat pipe, Phase change material (PCM) and hybrid system [7].

PCM stores thermal energy with internal energy of material with temperature change and can transfer this energy to the environment. It is applied in many areas such as textiles, building heating and cooling, cooling of electrical/electronic parts [8]. PCMs can be divided into three groups: organic, inorganic and eutectic. Organic PCMs have properties such as high latent heat of fusion, chemical stability, corrosion resistance and low undercooling. It is possible to classify organic PCMs into two groups: paraffin and non-paraffin. Non-paraffin organic PCMs are preferred in systems operating close to ambient temperature (10-40°C) [9]. Organic PCMs such as paraffin have a negative impact on the environment. Because, paraffin which is petroleum based is toxic to the environment [10]. However, as environmentally friendly bio-based (vegetable oils) organic PCMs, fatty acids are sustainable, non-corrosive and environmentally friendly [10]. Thermophysical properties are investigated depending on the organic PCM cycle in thermoelectric cooling and heating system. While the melting and enthalpy of palm wax remained almost the same depending on the PCM cycle, these values varied in soy wax [11].

Organic PCMs are used in construction materials, heating and cooling systems, etc., and have positive effects. [12–16]. The effect of organic PCMs on thermal management when used as passive cooling in batteries is also among the research topics. However, the application of PCMs in battery cooling is limited due to poor thermal performance, leakage of liquid PCM and challenging temperature control after melting temperatures [17]. However, the most important advantage of PCM is that it does not consume extra power.

Abdulmunem et al. studied the thermal analysis of bio-based PCMs used in lithium-ion battery cooling. The authors used cheap, sustainable and widely available palm fatty acid distillate as PCM. They showed that when bio-based PCM is used in battery cooling, the temperature of the battery is reduced by 10 to 20% and the electrical power is increased by 17 to 43%[18]. Verma et al. investigated the thermal performance of battery in capric acid (PCM) with different thicknesses. The authors investigated the temperature effect of capric acid on battery discharge at two different ambient and compared the results with commonly used paraffin. The capric acid optimum thickness is 3 mm and provides the best cooling performance [19]. John et al. researched the effect of Stearic Acid (organic PCM) which is non-corrosive and has high latent heat, on battery cooling. The authors simulated PCMs with different PCM thicknesses and different amounts of copper oxide (CuO) nanoparticles to optimize. Addition of 4% CuO is the cooling critical value of PCM, above which adding CuO has no effect on the battery temperature decrease. PCMs with phase change temperatures between 310 K and 330 K are much more effective in battery cooling [20]. Ling et al. developed the encapsulated inorganic PCM-sodium acetate trihydrate and studied the thermal performance of this PCM in battery cooling. Expanded graphite is added to improve the thermal conductivity of this PCM. The Authors claimed that the PCM they obtained is not flammable and even protected the battery from thermal runaway and is safer [21]. Goud et al. researched the thermal performance of battery packs using Myristyl alcohol PCM. This PCM provided maximum temperature reductions of approximately 22 to 35%, depending on discharge rates. Passive cooling with Myristyl alcohol is also safe and effective at high discharge rates [22]. Yazıcı studied passive thermal management using PCM/graphite matrix in the battery pack. The temperature changes of the battery in PCM/graphite matrix were evaluated by thermal images, discharge capacity and energy capacity. Graphite PCM increases thermal conductivity by 35 times. Compared to air cooling, while the operating temperature and temperature gradient along the surface of the battery are reduced by 22% to 43%. The energy capacity and operating time are increased compared to natural convection for high discharge rate [23]. Sinha et al. examined the thermal properties of the battery in different terminal designs of prismatic batteries with and without liquid biocompatible phase change material. The authors stated that the counter-flow designed structure has a more homogeneous temperature distribution than the parallel designed terminal. Authors found that there were decreases in maximum temperature values between 6.23% and 12.44% in different currents due to the use of PCM. The authors stated that the use of PCM provides a more uniform decrease in voltage in the discharge states of the batteries, which can increase the performance and life of the battery [24]. Mei et al. used the composite PCM to reduce the thermal runaway of batteries. Authors stated that heating the battery caused high temperature and bright flam. Then, the burning of paraffin increased the duration of a stable flame and concluded that sodium acetate trihydrate efficaciously prevented the burning of paraffin and reduced the burning time by 40.5% [25].

In this experimental study, the effect of organic PCMs which are abundant in nature, have low corrosion effect and biocompatible [26,27] on battery thermal performance is investigated. Palm wax, soy wax and coconut oil are used as organic PCMs. The distance between the battery box and the battery is designed to be at least 2 mm. The battery box is selected as the rectangular prismatic and the battery is placed inside. The battery surface temperature, anode, cathode region temperature, PCM temperature and ambient temperature are measured at three different discharge currents. The changes in these temperatures in the battery box with and without PCM are examined. In cases without PCM, the temperatures of the anode, cathode and midpoints of the battery are measured at different discharge rates and the temperature differences are determined. Because the thermal performance comparison of the organic PCMs, it is taken into consideration that the initial temperatures of the experiments are almost the same. The purpose of this study is to reveal the thermal performances of organic PCMs in wax form in battery cooling.

EXPERIMENTAL STUDY

Materials Preparation

In battery cooling systems, 3 different methods are generally used: active, passive and hybrid. While air or fluid cooling is generally used in active systems, Heat pipe and PCM are used in passive cooling. Hybrid systems are used in both active and passive systems are used together. These cooling systems may vary depending on the place of use and cooling capacity. In this experimental study, the PCM method, which is one of the passive cooling applications, is examined. It is quite preferred because it does not consume additional power for cooling. Inorganic PCMs or paraffin are used in battery applications due to their high heat capacity. However, organic PCMs are also preferred in many studies due to their low cost, accessibility and recyclability. The effect of 3 different organic PCMs which are coconut oil (CO), palm oil wax (PW) and soybean oil wax (SW) on battery thermal management is investigated

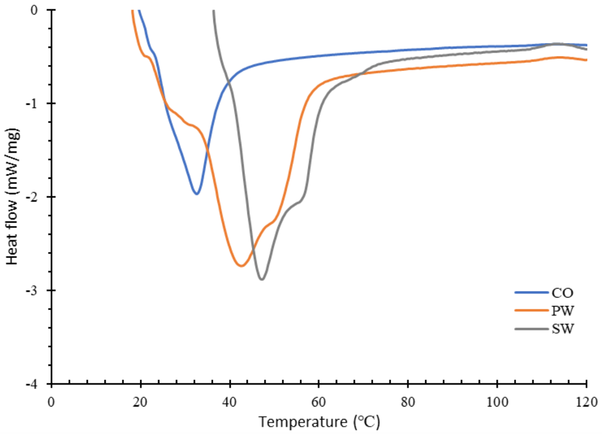


Figure 1. DSC of the organic (Bio-based) PCMs

Organic PCMs in the form of wax are melted and placed in the battery box in liquid phase. Then, the leakage between the battery box and the battery is checked. DSC results of the organic PCMs are given in Fig. 1. The melting behavior of organics PCMs is determined using DSC (Differential Scanning Calorimetry). During the melting times, only one endothermic peak is observed. Therefore, it is seen that the organic PCMs do not consist of eutectic (two or more) PCMs and the phase change temperature is constant values. Thermophysical properties of organic PCMs are given in Table 1.

Table 1. Thermophysical property of organic PCMs

Properties	Coconut oil	Palm wax	Soy wax
Melting Point (°C)	30	42	46
Density (kg/m³)	920 [28]	920 [29]	900 [30]
Latent heat (J/g)	103	135	160
Specific heat capacity (kJ/kgK)	1.55 [16]	2.64 [16]	2.7 [30]

It is seen that the melting temperature starts at the lowest coconut oil 30 °C and increases towards palm wax 42 °C and soy wax 46 °C. The highest density among the PCMs used in this study is soy wax. Latent heat is one of the important parameters to the thermal energy storage capacity of PCMs. It is possible to determine latent heat from the area under the heat flow and temperature curves. The latent heats are listed from lowest to highest as coconut oil, soy wax and palm wax.

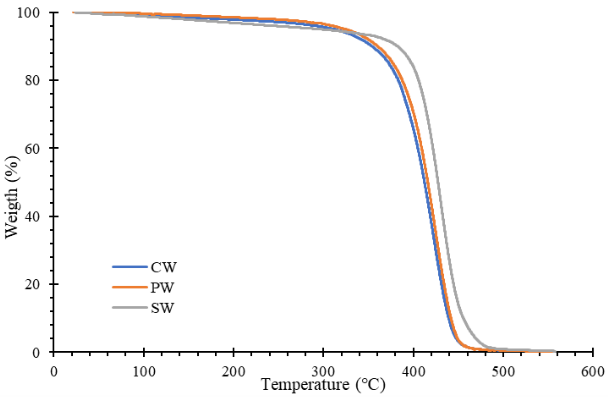


Figure 2. Mass losses of the organic PCMs during heating

In Fig. 2, the mass losses of the PCMs used in the experimental study during heating are given. The melting temperatures obtained from Fig. 1 show that there is a very small mass loss at the transition temperature from solid to liquid state. All three organic PCMs exhibit single-stage decomposition. While coconut oil and palm wax experience a high mass loss during the heating period between 320 and 460 °C, the high mass loss in soy wax is between 360 and 480 °C. This organic PCM may be losing mass due to low moisture content, moisture loss up to 320 °C for palm and coconut, and 360 °C for soy wax, or volatile substances. Because these Bio-PCMs are hydrophobic and have very low water retention capacity [31–33]. It has been observed that the organic PCMs used as battery cooling application reach a maximum temperature of 45 °C and the mass loss in the PCMs at these temperatures is approximately 0.2%. This value is negligible.

Battery Box (Test Chamber)

In this experimental study, the thermal performance of a cell (battery) placed inside the battery box is investigated in different C rates which is discharge currents. The battery is cylindrical with the diameter and height of 18 mm and 65 mm respectively. The battery is in the box and the dimensions of the battery box are 22x22x65 mm. The gap between the battery and the box is at least 2 mm as shown Fig. 3. The battery box is the hollow rectangular prism and it was produced from the 3-D printer. The volume occupied by the battery in the box is 14505 mm³. The total volume of the box is 27588 mm³ and the void volume (PCM) is 13083 mm³. Palm wax, coconut oil and soy wax are used as organic PCMs. The coconut oil placed in the battery box is 12 g, soy wax and palm wax are 15 g.

The battery box is made of 4 mm thick PLA (Polylactic acid) material. The battery box keeps the PCM inside and simplifies the PCM thickness. The thermal conductivity of PLA material is low. Some of the battery boxes used in the application are polymer-based materials. The battery box used in the experiments is given in Fig. 3.

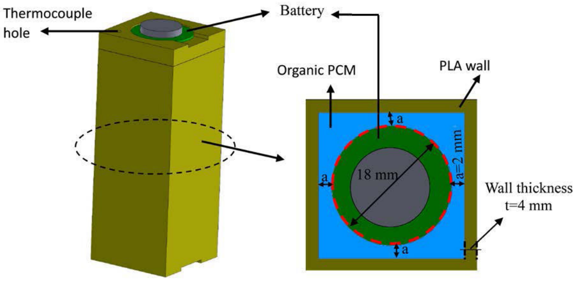


Figure 3. Battery box (Test chamber)

In the study, Orion brand 18650/22 (2200 mAh) model Lithium-ion battery is used. The nominal voltage of the battery used is 3.7 V, the highest voltage is 4.2 V, the cut-off voltage is 2.5 V and the standard capacity is 2200 mAh. The weight, power density and internal resistance of the battery used in the experiment are 45.5g, 8.14 Wh and 35 mΩ, respectively.

Experimental Setup

The battery experimental setup shown in Fig. 4 is established to investigate the effect of using different organic-PCMs on battery thermal performance. The battery experimental setup consists of DC power supply, electronic load, multi-channel temperature recorder, PC and thermocouples, the test chamber consists of the battery box, battery and PCM. The test chamber consists of a cell. The battery (cell) is placed and fixed inside the battery box with equal margins on each side and the anode end on top. DC power supply is used to charge the battery and electronic load is used to discharge it. Since it is a cell, the end of charge/discharge or cut-off voltage stated in the manufacturer's data sheet is not exceeded during charging and discharging. Thus, the battery is not exceeded for the discharge cycle without the need for BMS (Battery Management System) from the applications that cause the battery to be in an unwanted (dead state).

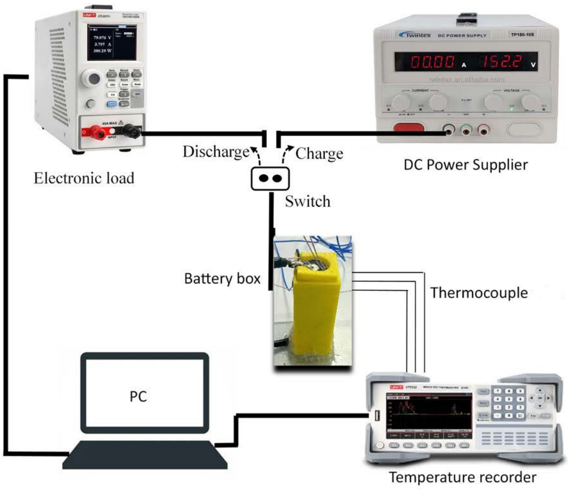


Figure 4. Battery experimental setup

Twintex brand TP150-10S model DC power supply is used to charge the battery. As recommended by the manufacturer, the battery is first current-limited and then voltage-limited to prevent exceeding 2200 mAh. Unit brand UTL8211+ model electronic load is used for battery discharge. Experiments are carried out in 3 different discharge ranges in the electronic load device, with constant current 1C, 2C, 3C discharge rate in the battery module.

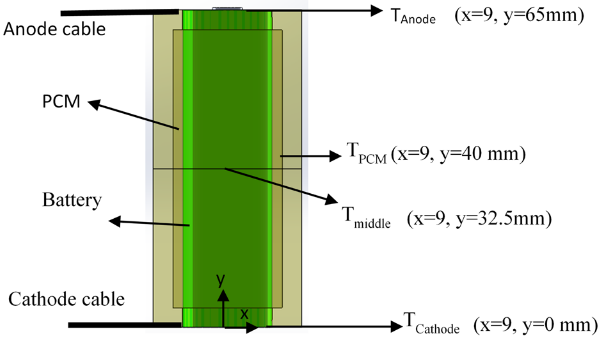


Figure 5. Thermocouple locations

In the experimental study, temperatures are measured from 5 different points, namely the middle, anode, cathode parts of the battery, PCM and ambient temperature. K type thermocouple is used in the experiments. The thermocouple location is given in Fig. 5. In the production of battery surface thermocouples, the thermocouple wires are welded to the surface with the thermocouple-welding device. Thus, it is aimed to minimize the contact resistance. The temperature of the organic PCM is measured from the middle point of the box and 2 mm away from the battery. The ambient temperature is measured approximately 30 cm away from the test chamber. While the temperature data is recorded at different discharge rates, temperature data are taken every second. Temperature data is transferred to the computer via the temperature recorder.

Uncertainty Analysis

Uncertainty analysis can be divided into two categories: measurements and calculations. In this study, there is no uncertainty in the calculations in this study. The measurement uncertainties in the battery experiment are the current and voltage values for both charging and discharging and temperature. The uncertainty of the DC power supply device is 100 mV for voltage and 10 mA for current. The uncertainty of the electronic load device is 0.05%+0.1%FS (full scale) for both current and voltage. The uncertainty of the K type thermocouple is ± 1°C. Therefore, the difference between the measured temperature and the uncertainty of this value is 1 °C. The measured electrical values and their uncertainty are comparatively low and can be neglected.

Governing Equations

The battery is composed of various chemical materials and has a layered structure. Due to this layered structure, the thermal conductivity is not the same in all directions and can be optimal if the battery is cooled differently from the poles or the middle. It is possible to define the physical problem as follows [34,35].

$$\rho c_p \frac{\partial T}{\partial t} = k_b \nabla^2 T + q_{gen} \tag{1}$$

The heat emitted by the battery can be divided into two: the heat resulting from electrochemical reactions and the heat resulting from the battery's internal resistance to current flow [36]. The heat generated in the battery can be defined as shown in Eq. (2).

$$q_{gen} = \frac{1}{V}(I^2 R + IT\frac{\partial U_{ocv}}{\partial T}) \tag{2}$$

Here, represents the heat generation of battery, V is the battery volume, I is the discharge current, T is the battery temperature, R is the battery internal resistance and $\frac{\partial U_{ocv}}{\partial T}$ represents the entropy coefficient. As shown in Eq. (2), the battery temperature and operating current affect the heat generated by the battery. In this study, the current is constant throughout the experiment. The internal resistance of the battery changes depending on its temperature and state of charge. The relation given in Eq. (3) is used to find out the phase of the PCM in the battery box used in the cooling system [35].

$$\lambda_{PCM} = \{ \begin{matrix} 0 & T_{PCM} \leq T_s \\ \frac{T_{PCM} - T_s}{T_l - T_s} & T_l \leq T_{PCM} \leq T_s \\ 1 & T_{PCM} \geq T_l \end{matrix} \} \tag{3}$$

Where λ is the liquid fraction, T_s represents the freezing temperature, T_l represents the melting temperature. Melting and solidification temperature is the property of PCM. PCMs store sensible and latent heat. If the PCM temperature is lower than the melting temperature, the phase is solid and the heat it stores is shown in Eq. (4).

$$Q_{PCM} = m_{PCM} c_{p,s,PCM}(T_{PCM} - T_i) \tag{4}$$

Here is the PCM mass, is the specific heat capacity of PCM (solid phase), is the initial temperature. If the temperature of the PCM is at the melting temperature, PCM is in the mushy region. In this region, PCM is between solid and liquid phase and the liquid fraction is important. the can be expressed as Eq. (5):

$$Q_{PCM} = m_{PCM} c_{p,s,PCM} (T_{PCM} - T_i) + m_{PCM} H\lambda \qquad (5)$$

H is the latent heat and if the PCM temperature is above the melting temperature, the phase is liquid and the heat stored in the PCM is as in Eq (6).

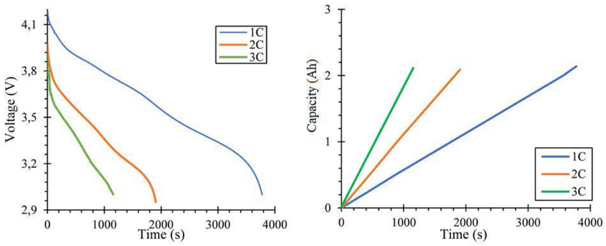
$$Q_{PCM} = m_{PCM} c_{p,s,PCM} (T_{PCM} - T_i) + m_{PCM} H + m_{PCM} c_{p,l,PCM} (T_{PCM} - T_m) \quad (6)$$

Here, is the specific heat capacity of PCM (liquid phase), is the melting temperature.

RESULT AND DISCUSSION

In this article, the effect of organic PCMs on battery thermal performance is examined. Experiments are conducted to examine the temperature difference of batteries at ambient temperature in different current discharge over time. Batteries charged to full capacity are discharged to their full capacity at the constant current thanks to electronic load. Firstly, the battery module test of the electronic load device is performed at different discharge currents. The battery test times are 20 (3C), 30 (2C) and 60 (1C) minutes depending on the discharging rates. C rate is the current of discharge of a battery. These C rates are the current range recommended by the manufacturer of the battery used. The C-rates of the battery used in this experimental study at 1C, 2C and 3C are 2.2, 4.4 and 6.6 A, respectively. Although it was desired to go to high C rates, the technical specification of the battery did not support this data and could not meet the continuous 4C current. The maximum pulse discharge of the battery is 8800 mAh (4C) and is not suitable for use at constant current during discharge. The change of battery voltage and capacity with time at different discharge currents is given in Fig. 6.

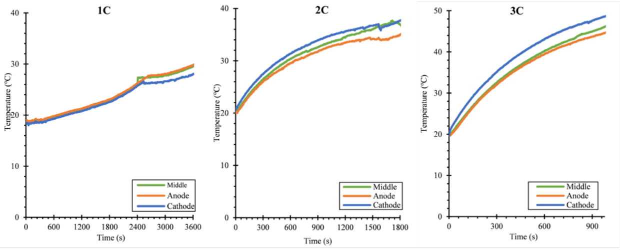
Choosing the right type, battery capacity and C rate is very important for battery use and cycle. A battery with a low C rate is not meet the desired voltage and efficiency in the discharge state. As seen in Fig. 6, as the discharge current increases, the initial voltage suddenly decreases, which affects the battery capacity.



a) b)

Figure 6. Comparison of a) voltage-time b) capacity-time at different discharge currents

The battery surface temperatures which are the anode, cathode and middle of battery were measured from three different points of the battery. These temperatures of the battery are close when these three-temperature data are examined. The battery surface temperatures are given in Fig. 7. Surface temperatures at different points or region of the battery may vary during discharge [37,38]. These temperature differences are generally caused by battery cooling. Each point or region of the battery surface may not be exposed to the same thermal boundary conditions. In this study, in the case of the battery box without PCM, the surface temperatures at each point of the battery differed.

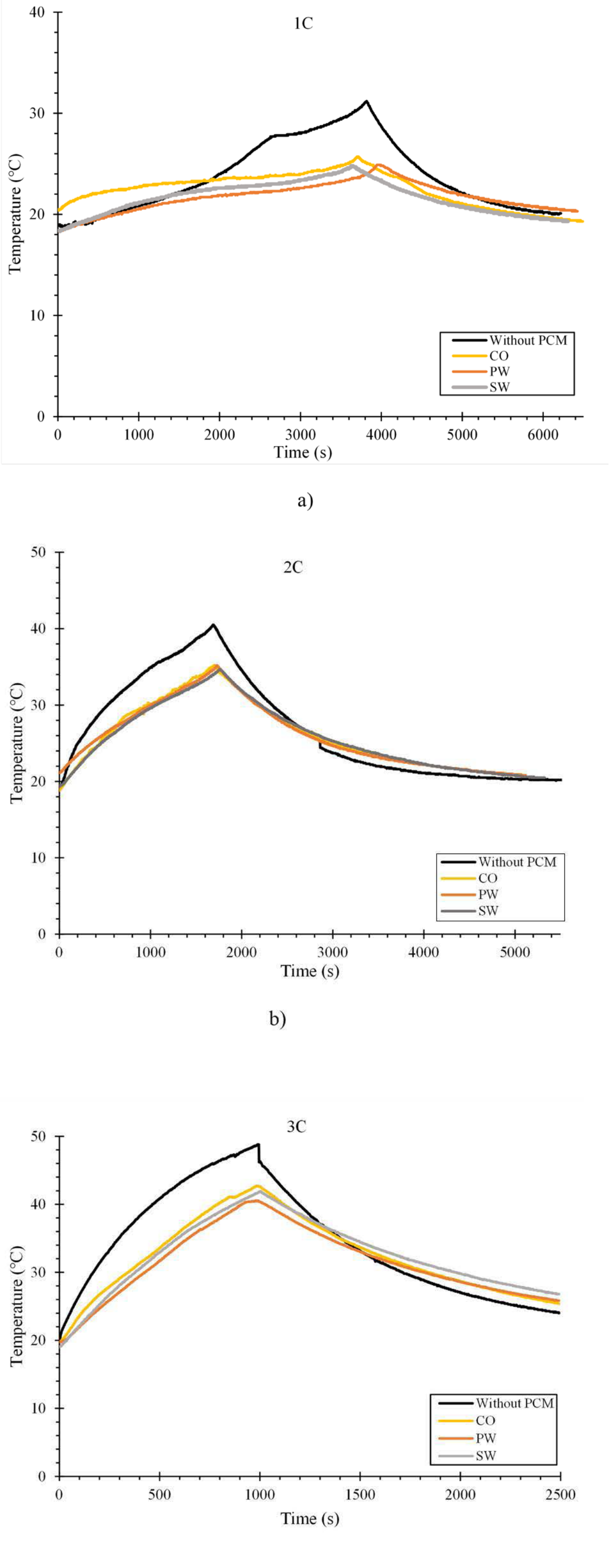


a) b) c)

Figure 7. Battery surface temperature a) 1C, b) 2C, c) 3C

In Fig. 7a, it is seen that the difference between the battery surface temperatures does not change much at low discharge currents. As the discharge currents increase, the battery surface temperatures increase and the difference between the temperatures also increases as shown Fig. 7b and Fig. 7c. This is due to the cooling of the battery. Since the anode part is in contact with ambient air, its surface temperature has increased less. The middle part and cathode region of the battery are not in contact with ambient air. Because these areas are in contact with the air inside the battery box. So, these surface temperatures increase more than the anode part. The design of the cooling system around the battery is very important. If each area of the battery is cooled under different conditions, it can affect the battery life.

Fig. 8 shows the changes in battery surface temperatures over time in different discharge currents with 3 different organic-PCM and without-PCM conditions. The discharge process ended at the peak points of the temperature in the Fig. 8 and heat transfer occurs by natural convection at ambient temperature.



a)

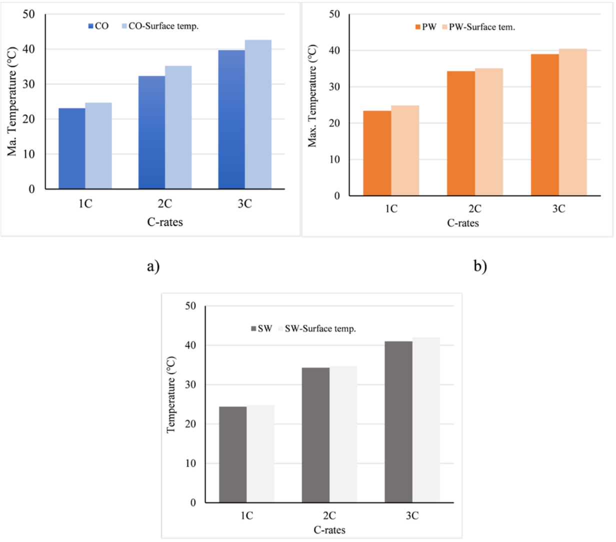
b)

c)

Figure 8. Battery surface temperatures with organic PCM at different discharge currents a) 1C, b) 2C, c) 3C

The initial temperatures shown in Fig. 8 are equal to the ambient temperature. Ambient temperature varies between 19 and 20 °C depending on the experiment day conditions. In the case without PCM, the maximum battery surface temperatures were measured as 30.7 °C, 40.3 °C and 48.8 °C, respectively, depending on the discharge rate which is 1C, 2C and 3C. When the discharge currents are 1C and 2C, it is seen that the batteries in the organic PCMs are at almost the same surface temperatures as shown Fig. 8a and Fig. 8b. Thanks to the organic PCMs, the battery surface temperature of the battery was approximately 5.2 °C and 6.3 °C lower at 1C and 2C rates, respectively, than that without PCMs. As the discharge current increases, battery surface temperatures in organic PCM were changed. In 3C rate, the lowest battery surface temperature is 40.5 °C in palm wax. This is followed by soy wax and coconut oil. The battery surface temperatures of these organic PCMs are 41.8 °C and 42.6 °C respectively. When the phase change of PCMs was examined, coconut oil was completely melted at 2C and 3C discharge rates. Palm wax was not melted but only in the 3C discharge current was the mushy region. However, no phase change was observed in soy wax at all discharge rates. As seen in Fig. 8c, the temperature of battery cools down more slowly due to the high temperatures of the organic PCMs after the discharge is completed. In addition, when the results obtained from the battery box with PCM are compared to the temperature curves from the test chambers without PCM, more homogeneous and non-suddenly rising/decreasing are obtained. This minimizes the sudden temperature changes of the battery and positively affects the life of the battery.

In Fig. 9, the middle battery surface temperature and the highest data of the organic PCMs temperature is given. As seen in Fig. 9a, there is a greater difference between the temperature of coconut oil and the surface temperature of battery, while in Figs. 9b and 9c, the temperature of soy and palm waxes is close to the battery surface temperature.



a)

b)

c)

Figure 9. Maximum battery surface temperature vs. PCM temperature (a) Coconut oil (b) Palm wax c) Soy wax

This shows that the thermal conductivity of these two PCMs may be higher than that of coconut oil. The thickness and mass of PCM directly affect these temperature differences.

In addition, the battery box is made of PLA and its thermal conductivity (k=0.13 W/mK) is very low [39]. This means that the heat absorbed by the PCM cannot be transferred to the environment. Therefore, the temperature of the PCM increases faster.

CONCLUSION

It is very important to be able to meet and maintain the capacity and long battery life of lithium-ion batteries. So, both storage and operating temperature are important and very effective for the battery. Long-term operation of batteries at high temperatures reduces their lifecycle and may cause thermal runaway. High temperature affects the internal structure of the battery. This can lead to great dangers for the battery. In this study, battery surface temperatures were investigated during 3 different discharges (1C, 2C, 3C) of batteries at ambient temperature which is between 19 °C and 20 °C. The experiments were conducted with 3 different organic PCMs and without PCM. In the case without PCM, it was observed that maximum battery surface temperatures vary between 30.7 °C and 48.8 °C depending on the discharge rate. In the case without PCM, sudden changes of temperature were observed in the battery surface temperatures. After placing the organic PCMs in the battery box, the battery surface temperatures vary between 25.5 °C and 42.6 °C for coconut oil, 24.8 °C and 41.8 °C for soy wax, and 25 °C and 40.5 °C for palm wax, depending on the discharge rate. Organic PCMs reduced the battery surface temperature. The lowest battery surface temperature is determined in Palm wax. This was followed by soy wax and then coconut oil. Due to the low PCM amount and the material of the battery box, the PCM temperature and the battery surface temperature are close. However, there are also temperature differences depending on the discharge rates. The box with low thermal conductivity affected the PCM and battery temperature. Palm and Soy waxes exhibited almost similar cooling performance, while coconut oil exhibited slightly lower cooling performance. Compared to without PCMs, sudden changes of temperature were not observed in organic PCM, which positively affects battery life. Although organic PCMs store heat and keep the battery temperature at the desired level, there may be difficulties in temperature control after the phase change due to their generally low thermal conductivity. These PCMs have the low melting point, so attention should be paid to ambient temperature and discharge rates in the application. Temperature measurements from a cell (battery) may not provide sufficient data on thermal behavior. Therefore, more experiments are needed to better understand the thermal performance of organic PCMs in battery groups instead of cell and to reveal the effect of these PCMs at higher charge/discharge currents. Heat storage, heat transfer and melting process properties of coconut, palm and soy wax, an organic PCMs, are discussed in detail in battery applications. In addition, in future studies, more experiments are needed to examine the thermal performance if materials with high thermal conductivity are included in the organic PCM.

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