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Research Article

Experimental Investigation of the Effects of Paraffin as a Phase Change Material on the Cooling Performance of a Battery Thermal Management System

Fikret POLAT [a,*], Suat SARIDEMİR [a]

[a] *Department of Mechanical Engineering, Faculty of Engineering, Düzce University, Düzce, TURKEY*
* *Corresponding author's e-mail address: fikretpolat@duzce.edu.tr*
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ABSTRACT

Internal combustion engines (ICEs) are largely dependent on fossil fuels, and both the risk of depletion of fossil fuels and the harmful exhaust emissions emitted by ICEs have led researchers to become interested in electric vehicles (EVs). As the EV industry develops day by day, battery thermal management systems (BTMS) have become indispensable in solving the high-temperature problem of batteries, which are the most important component of EVs. The cost and reliability of electric vehicles are affected by parameters such as the life cycle, capacity, charging time, durability, and warranty cost of the battery pack used. The heat produced in the battery pack is removed by gas or liquid cooling in active cooling, and by phase change materials (PCM) in passive cooling. The high energy storage density of PCMs and the fact that there is no need for fan or pump power in cooling using PCMs are some of the reasons why PCMs are preferred for BTMSs. In this study, a battery pack consisting of 18 lithium-ion batteries, 6 in series and 3 in parallel, was first charged and discharged without any cooling system and then with the addition of PCM at a current strength of 1C, and the effect of the BTMS was examined. It has been observed that the BTMS has a positive effect of approximately 8% for charging experiments and 23% for discharge experiments in terms of the maximum temperature value in the battery pack.

Keywords: *Battery thermal management system, Electric vehicles, Phase change materials*

Faz Değişim Malzemesi Olarak Parafinin Bir Batarya Termal Yönetim Sisteminin Soğutma Performansı Üzerindeki Etkisinin Deneysel Olarak İncelenmesi

ÖZET

İçten yanmalı motorlar (İYM'ler) büyük ölçüde fosil yakıtlara bağımlıdır ve hem fosil yakıtların tükenme riski hem de içten yanmalı motorların yaydığı zararlı egzoz emisyonları araştırmacıları elektrikli araçlara (EA) ilgi duymaya yöneltmiştir. Elektrikli araç sektörünün her geçen gün gelişmesiyle birlikte, elektrikli araçların en önemli bileşeni olan pillerin yüksek sıcaklık sorununun çözümünde batarya termal yönetim sistemleri (BTYS) vazgeçilmez hale gelmiştir. Elektrikli araçların maliyeti ve güvenilirliği, kullanılan pil paketinin ömrü, kapasitesi, şarj süresi, dayanıklılığı ve garanti maliyeti gibi parametrelerden etkilenmektedir. Batarya paketinde üretilen ısı, aktif soğutmada gaz veya sıvı

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soğutmayla, pasif soğutmada ise faz değiştiren malzemeler (FDM) ile uzaklaştırılır. FDM'lerin enerji depolama yoğunluğunun yüksek olması ve FDM'ler kullanılarak yapılan soğutmada fan veya pompa gücüne ihtiyaç duyulmaması, FDM'lerin batarya termal yönetim sistemlerinde tercih edilmesinin nedenlerinden bazılarıdır. Bu çalışmada, 6'sı seri, 3'ü paralel olmak üzere 18 adet lityum iyon pilden oluşan bir pil paketi, önce herhangi bir soğutma sistemi olmadan, ardından 1C akım gücünde FDM ilavesi ile şarj ve deşarj edilmiş ve batarya termal yönetim sisteminin etkisi incelenmiştir. BTYS'nin batarya paketindeki maksimum sıcaklık değeri açısından şarj deneylerinde yaklaşık %8, deşarj deneylerinde ise %23 oranında pozitif etkiye sahip olduğu görülmüştür.

Anahtar Kelimeler: *Batarya termal yönetim sistemi, Elektrikli araçlar, Faz değiştiren malzemeler*

I. INTRODUCTION

In today's world, with the rapid increase in population, the need for energy continues to increase day by day. It is known that most of the energy needs in the world are met by fossil fuels [1-5]. It has been proven that the use of fossil fuels causes many negative factors such as air pollution and depletion of the ozone layer. Regarding this issue, looking at the data published by the World Health Organization in 2020, it is clear that air pollution causes the premature death of an average of 6.7 million people in the world every year and causes great damage to the economies of states [6,7].

As it is known, conventional vehicles that use only internal combustion engines consume fossil fuels and cause the emission of gases such as CO_2, HC, and NOx. HEVs have been developed and implemented in recent years to overcome the environmental and energy crisis problems caused by conventional vehicles. Although HEV technology has improved fuel economy and caused less emissions compared to conventional internal combustion engine vehicles, it has not reached a satisfactory level, especially in terms of environmental concerns. For this reason, hybrid electric vehicles remain only a temporary step in the transition from internal combustion engine vehicles to electric vehicles. Driven by the imperative to decarbonize personal transportation to meet global targets to reduce greenhouse gas emissions and improve air quality in city centers, the electric vehicle revolution has begun to revolutionize the automotive industry. However, the development of battery packs in electric vehicles, which is the technology of today and the future, has become the most important topic. The most serious problem encountered in battery packs is that the battery cells are negatively affected by sudden temperature increases that occur while the batteries are in operation or when charging and discharging [8-10]. If this heat is not distributed homogeneously in the battery pack and cannot be discharged quickly, results such as deterioration of battery cells and reduced lifespan occur.

As the electric vehicle industry is constantly growing and open to development, researchers have concentrated their work on battery thermal management systems in order to solve the above-mentioned problems. Parameters such as cycle life, capacity, charging time, durability and warranty cost of the battery pack used affect the cost and reliability of electric vehicles [11,12]. These important parameters also largely depend on the BTMS. There are two main criteria to evaluate the performance of BTMS: maximum temperature rise and maximum temperature difference of the battery pack. To maintain optimum performance and extend battery life, the temperature of all cells must be maintained within a narrow range between 20 °C and 45 °C, and the maximum temperature difference between cells must be less than 5 °C [13]. On the other hand, operating below 0 degrees also causes its capacity to decrease. BTMSs include active or passive cooling systems. Generated heat in the battery pack; In active cooling, it is removed by gas or liquid cooling. In passive cooling, it is removed with phase change materials. There are battery thermal management systems in which these methods are used separately or together. Each method has advantages and disadvantages relative to each other. Throughout the literature research, it was concluded that it would not be appropriate to directly compare each system due to differences in the battery type, capacity, charging/discharging rate, and other external conditions used in each study. It should be done according to the battery type, the area in which it will be used, the vehicle, and what kind of need it should meet. As a result, it has been understood that the most appropriate thermal management system to be selected according to criteria such as cost, ease of installation, security risk, and performance will vary depending on the results targeted for the vehicle to be produced.

Phase change materials are materials that show a phase change within a certain temperature range. These materials store or release heat energy during phase change, which ensures that the temperature of the battery remains both homogeneous and at a certain level. PCM-based BTMSs are an innovative approach developed to improve the thermal management of battery technology. These systems provide temperature control of battery packs, increasing the performance of the batteries and ensuring their safety [14-16]. In PCM-based BTMSs, the PCM placed in the battery module begins to melt by absorbing the excessive heat that occurs in the battery during charging and discharging. This process continues until the latent heat value of the PCM is reached. Thanks to the PCM, the temperature is kept constant at the melting point during this time and the temperature rise is also delayed. In other words, the PCM is used as a thermal conductor for the battery pack, thereby increasing system performance. PCMs have been used in the literature due to their advantages such as low operating cost and good temperature homogeneity [17-20].

In a study investigating the effects of PCM thicknesses (3, 6, 9, and 12 mm) around the battery cells on the thermal performance of BTMS, Javani et al found that the maximum temperature and temperature homogeneity in the cell were significantly improved when PCM was used [21]. In another study, researchers analyzed the effects of PCM thickness, melting point, and thermal conductivity on cooling performance by designing different modules consisting of pouch lithium batteries in a computer environment. As a result, they observed that the maximum temperature and maximum temperature deviation decrease, while the thermal conductivity increases when the gap between the modules is increased. In addition, they emphasized that when the melting point of PCM increases, the maximum temperature increases but the maximum temperature deviation decreases [22]. Verma et al. studied the effects of using Capric acid around the battery pack as a PCM. They tested the effect of capric acid as a PCM by conducting research on two ambient conditions, one 294K and the other 323K (desert condition), by forming a PCM layer of different thicknesses, 3mm, 7mm, 9mm, and 12mm, and compared it with conventionally used paraffin. As a result, they declared that the 3 mm thick PCM layer is optimal and reduces the maximum temperature in the battery to 305K [23].

In this study, a battery pack was prepared using 18 lithium-ion batteries purchased from a commercial company. The batteries are connected to each other by spot welding, 6 in series and 3 in parallel. The prepared battery pack was charged and discharged at 1C current power, first without any cooling system, then by adding PCM, and the cooling performance of the battery thermal management system was examined.

II. MATERIAL AND METHOD

In the experimental setup, 18 cylindrical lithium-ion batteries were used. The shape and technical specifications of these batteries can be seen in Figure 1.

Model	18650 Sony VTC6
Chemical	Li-ion
Voltage	3.7 V
Charging Voltage	4.2 V
Discharge Voltage	2.75 V
Capacity	3000 mAh
Power	13,69 Wh
Weight	48.50 gr
Dimensions	18.25 mm x 65.00 mm

Figure 1. *The shape and technical specifications of batteries used in experiments.*

18 batteries, 6 in series and 3 in parallel were punched with the help of strip nickel, and a battery pack was created. In addition, the temperatures of the batteries were measured at the time of charging and discharging with the help of 6 temperature sensors, and data was taken every second via Arduino Nano and recorded on the computer. Power supplies were used to charge the batteries and rheostats were used to discharge them. The final version of the battery pack, charging, and discharging mechanisms are given in Figure 2, Figure 3, and Figure 4, respectively. The created battery pack was enclosed in a battery box obtained with a 3D printer and was made ready for testing. Numbers 1 to 6 in Figure 2 show the location and sequence numbers of the temperature sensors.

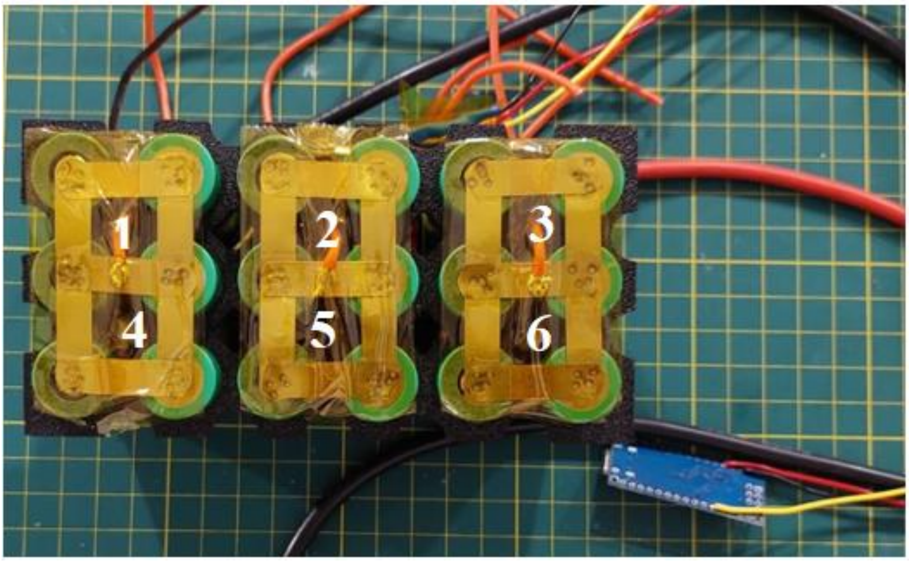

Figure 2. *Final version of battery pack.*

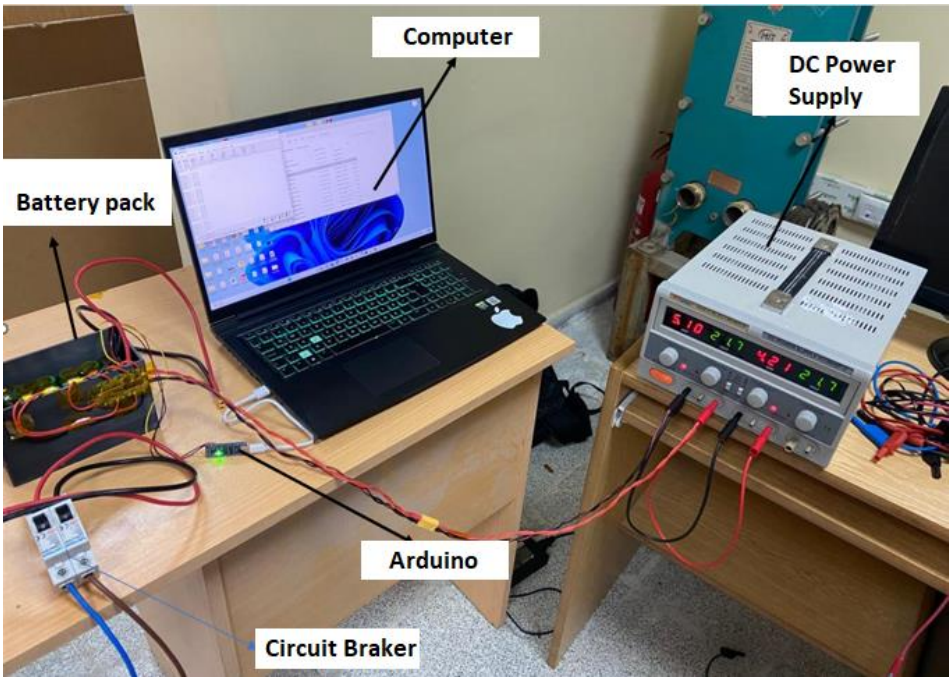

Figure 3. *Experimental setup for charging.*

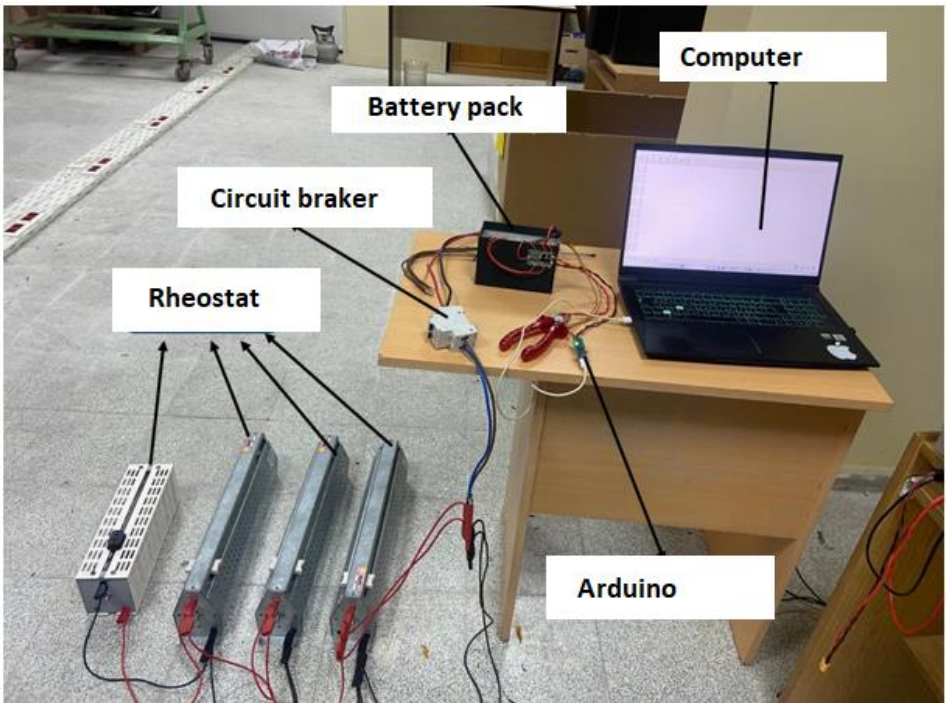

Figure 4. *Experimental setup for discharging.*

First of all, the charging and discharging processes were carried out without any thermal management system, and as mentioned before, the temperature data received from the sensors were recorded on the computer via Arduino. Then, molten paraffin was filled into the battery box and allowed to freeze. After the freezing process was completed, the experiments were repeated under the same conditions as the experiments without paraffin, and the properties of paraffin as a phase change material during the cooling of the batteries were examined. The experiments were carried out at room conditions (22 ^{o}C temperature) and 1 C current intensity. Also, the experiments were repeated 3 times and the data were obtained by averaging the results.

In the charging experiments, the battery pack with 18 V voltage was first charged without paraffin, up to the maximum voltage value of 25.2 V. Meanwhile, the current applied to the battery is 4.2 A. DC power supply was used as the charger. The connections were made with xt60 and the charging process continued until the voltage reached 25.2 V and the current value decreased to 0.06 A in both experiments.

The rheostats to be used in the discharge experiments are each rated at 50 ohms and 1000 W, and 4 of them were used. Each rheostat was set to 1.8 ohms and connected to each other in parallel. The equivalent resistor was set to 1 ohm and connected to the fuse to pass high current. In the first discharge process without using PCM, it was observed that the current passing by using a clamp meter was 23 A. The discharge process started at 25.2 V and ended when it reached 17.85 V. In the discharge experiment using PCM, the discharge process started from 25.2 V to 17.75 V. During these experiments, data was recorded every second thanks to Arduino nano. When the current passing through the cables was measured with the help of a clamp meter, it was seen that 23 A current was passing. Since the variable is only PCM, the equivalent resistance in the rheostats was set to 1 ohm in this experiment.

III. RESULTS AND DISCUSSION

The results from the discharge experiments are shown in Figure 5 and Figure 6. Figure 5 shows the experimental results without any battery thermal management system, and Figure 6 shows the experimental results when using the PCM-based battery thermal management system.

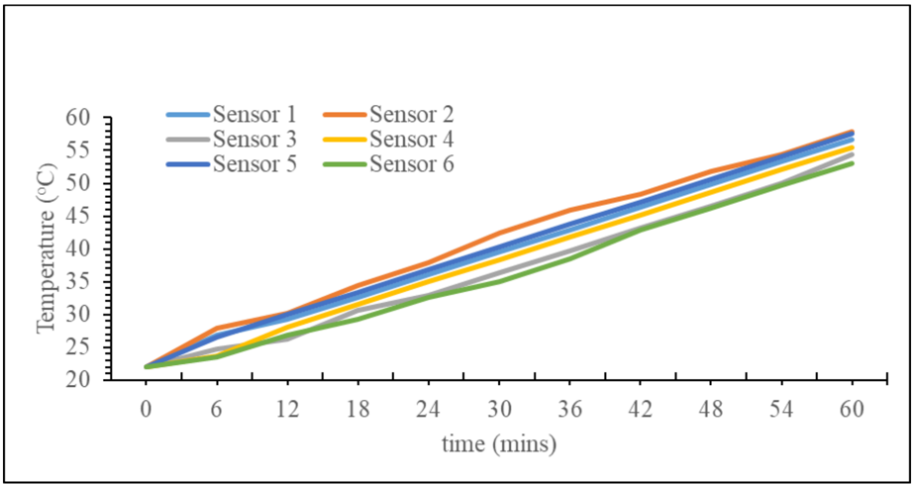

Figure 5. *Experimental results of discharging without battery thermal management system.*

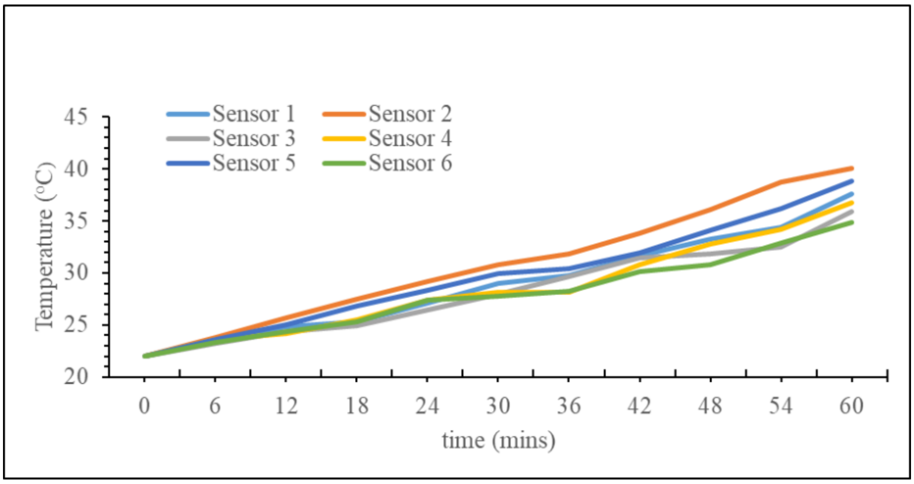

Figure 6. *Experimental results of discharging with PCM-based battery thermal management system.*

In the discharge experiments conducted without PCM and with PCM added, it was observed that the highest temperature values obtained at the end of the discharge process of the battery pack were 57.82 °C and 40.1 °C, respectively as seen in Figure 5 and Figure 6, thanks to the temperature data coming from 6 different sensors. Considering these sensors, it is understood that sensor 2 has reached the highest temperature values. It can be said that the reason for this situation is that this sensor is located in the middle of the battery pack and may be slightly affected by the temperatures of the neighboring battery cells.

The results from the charging experiments are shown in Figure 7 and Figure 8. Figure 7 shows the experimental results without any battery thermal management system, and Figure 8 shows the experimental results when using the PCM-based battery thermal management system.

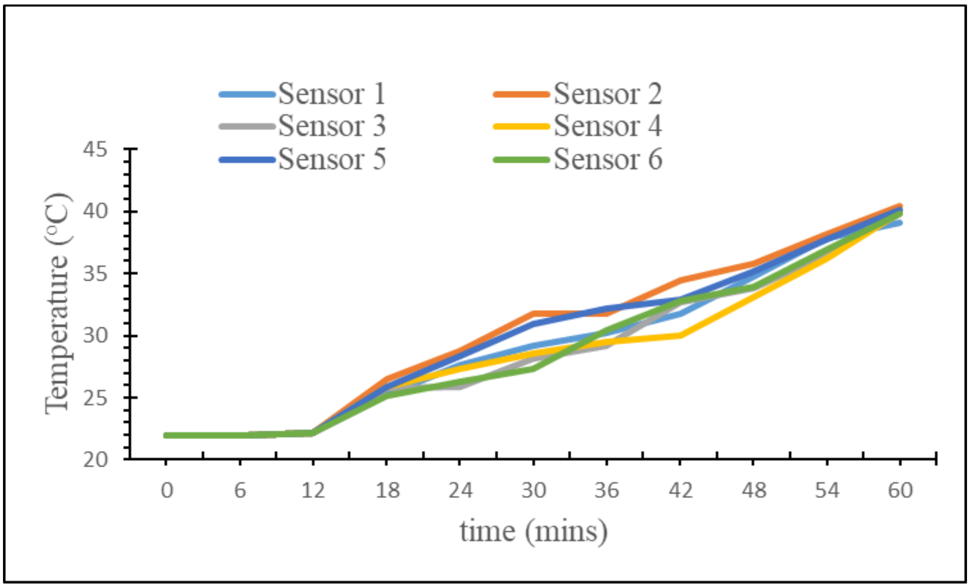

Figure 7. *Experimental results of charging without battery thermal management system.*

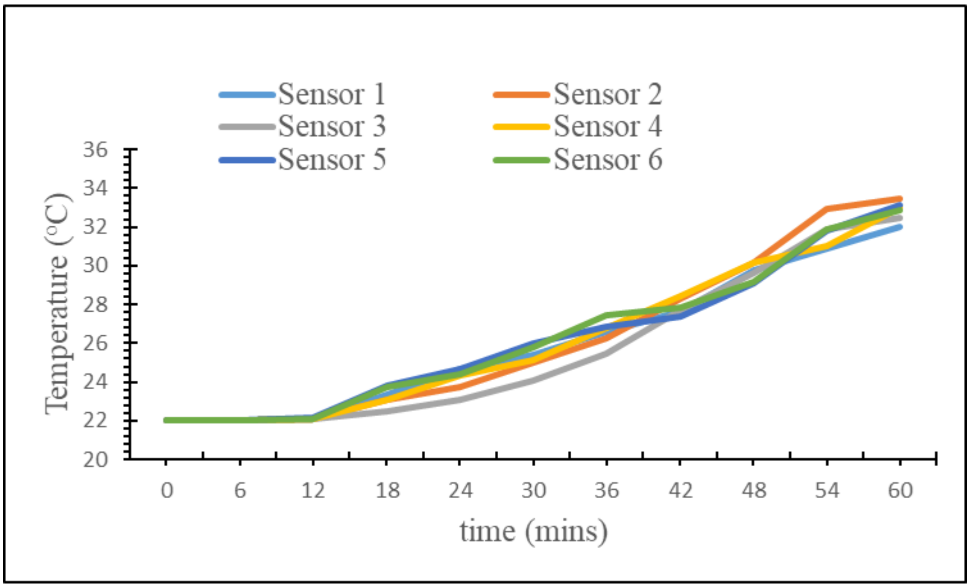

Figure 8. *Experimental results of charging with PCM-based battery thermal management system.*

In the charging experiments conducted without PCM and with PCM added, it was observed that the highest temperature values obtained at the end of the charging process of the battery pack were 40.41 °C and 33.44 °C, respectively as seen in Figure 7 and Figure 8, thanks to the temperature data coming from 6 different sensors.

IV. CONCLUSION

It is known that in electric vehicles, high temperature values occurring in the battery pack during charging and discharging seriously damage the battery cells and directly affect the performance of the battery pack and therefore the performance of the vehicle. For this reason, the necessity of thermal management systems to help battery packs designed for electric vehicles operate efficiently at optimum temperature values has been emphasized by researchers and electric vehicle manufacturers in recent years. In this study, a battery pack was prepared as a prototype and the prepared battery pack was first charged and discharged without any cooling system and then using PCM at 1C current power and the cooling performance of the battery thermal management system was examined. In the literature research on the history and development of battery packs, it was observed that lithium-based batteries provide better results in criteria such as performance, cost, cycle life, capacity, weight and high power. For this reason, lithium ion batteries were used when creating the battery pack in this study. It has been observed that the phase change material-based battery thermal management system positively affects the thermal performance of the batteries. Considering the discharge experiments, it was determined that the maximum battery temperature decreased by approximately 30.65% when a PCM-based battery thermal management system was used. During the charging process, the PCM-based battery thermal management system decreased the maximum temperature by 17.25% compared to without any thermal management system. In addition, it has been observed that thanks to the battery thermal management system, battery temperatures are obtained more homogeneously and the differences between maximum and minimum temperatures are smaller than in experiments without a thermal management system.

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