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Thermal Management System Based on Phase Change Material (PCM) and Heat Pipe in Lithium-ion Electric Vehicle Batteries

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Research Article

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ABSTRACT

The battery's high operating temperature may result in a thermal runaway, a reduction in battery capacity, and a shorter discharge cycle. Therefore, while operating high-performance electric cars, a thermal management system is essential to control the battery's temperature. This system must be dependable, lightweight, small, and capable of boosting battery performance. Therefore, the purpose of the study is to evaluate the efficacy of employing PCM and heatpipe for battery temperature control. Soy wax, which has a melting point of 38.49°C, was the PCM employed in this experiment. The heatpipe may assist speed up the heat transmission that takes place in the battery, and soywax is anticipated to absorb and retain the heat produced. The battery without cooling system, cooling using just PCM, cooling using only a heatpipe, and cooling using a combination of PCM and heat pipes are the four versions of the basic experimental setup that is built and the series of tests carried out. The findings demonstrated that the thermal management system with just heat pipes could lower the temperature by about 11°C, from 108.2°C to 97.2°C. Additionally, if the PCM was placed in the heatsink box surrounding the battery, the temperature could drop by up to 40°C, from 108.2°C to 68.2°C; if the PCM was placed in the heatsink box surrounding the battery and heat pipe, the temperature could drop by up to more than 50°C, from 108.2°C to 58.3°C. The thermal characteristics of PCM during cycle tests and the discharge process are crucial for boosting natural convection and heat conduction in the PCM structure, which improves heat dissipation efficiency and lowers failure risk in a PCM-based passive thermal management system. The efficiency of thermal management and electric car batteries may be improved by using PCM cooling systems and heat pipes.

High efficiency and little emissions are two benefits of electric vehicles (EVs) [2]. The automotive industry has been motivated to produce electric cars due to economic and environmental factors. Using electric cars is a good approach to conserve energy and cut emissions of greenhouse gases and other pollutants [3]. Li-ion batteries are a crucial part of electric vehicles. EV capabilities will be significantly impacted by improper operating temperatures (high, low, and high differential temperatures), which will also have an impact on battery life and performance [4]. A significant loss of available battery energy will occur at high temperatures due to capacity/power fading, self-consumption, and other negative impacts [5,6]. Heat production in motorized vehicles need a strong heat dissipation technique to maintain the ideal operating temperature for extended battery life and effective and efficient performance [7]. Both battery capacity and charge-discharge cycles are decreased by high operating temperatures. Thermal runaway may result in fires and explosions when high energy density batteries are used at high operating temperatures [8].

Extreme circumstances, such as high ambient temperatures, may result in thermal runaway and endanger the EV's safety when overheating from a short circuit becomes uncontrollable. Load acceptance [9], capacity/power [10], service life, and alternating efficiency [11] are all negatively impacted by low temperature. Typically, an electric vehicle battery is a battery pack made up of many battery modules [12]. As fossil fuels become increasingly scarce and exhaust emissions to the greenhouse impact on the climate are continuously reduced, the battery is a technological instrument whose usage will become more strategic and widespread in the future [13]. In addition to being influenced by a well-designed system, the heat exchanger that is used has a significant impact on the performance of this thermal management system.

Many scholars utilize different approaches to solve these issues. The maximum temperature could be controlled below 50°C when the heat generation rate was less than 50 W, according to Zhonghao Rao's experimental investigation on thermal management of electric vehicle batteries with heat pipes [7]. Nandy Putra's study on the effectiveness of PCM beeswax and heat pipe as a passive battery cooling system for electric vehicles revealed that using heatpipes reduced battery temperature by 26.62°C. PCM RT 44 Hc

33.42°C [14]; Huan Ling-Liu on managing Li-on battery performance using tiny channel heat sinks that resemble trees: The Li-ion battery with a tree-type heat sink has a maximum temperature of 34.2°C, a temperature differential of 5.35°C, and a pressure drop of 11.26 Pa, according to experimental and numerical optimization. Additionally, with a pressure drop of 17.99 Pa, the Li-ion battery's maximum temperature is lowered to 33.69°C

and the temperature differential to 4.86°C. The multi-objective optimization findings [15] and Muhammad Amin's study on the thermal management of electric car batteries utilizing heat pipes and PCM showed a variation of less than 1%, with the heatpipe at 20 W reducing the temperature from 45.5°C to 37.9°C. Heatpipe reduces from 79.1°C to 49.9°C at 50 W; beeswax reduces from 45.5°C to 35.4°C at 20 W loads. Beeswax reduces from 79.9°C to 48.1°C at 50W [16].

However, battery thermal management improvements that are more effective at absorbing heat and don't need more power are still needed due to the ongoing heat loss. PCM is one passive heat absorption technique that has been covered so far. A latent energy storage substance called phase change material (PCM) may release energy for an extended period of time without requiring temperature changes [17]. It is possible to classify PCM as a latent heat storage material since it can both absorb and release heat that arises when the solid to liquid phase shifts or vice versa. PCM is often utilized in building energy saving because it has a greater heat storage capability [18]. It is known that PCM may produce both sensible and latent heat when used as TES (thermal energy storage) [19]. Finding the PCM type with the greatest qualities for cooling applications is necessary given the variety of PCM types available. PCM still lacks its low thermal

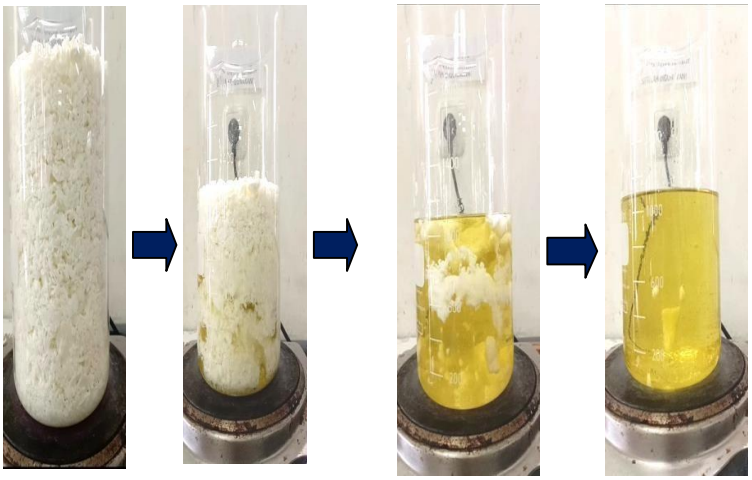
conductivity and unstable state during phase transitions in PCM [20]. In order to minimize major damage that may result in significant losses, this research will provide an affordable, dependable, high-performing electric vehicle choice with a longer service life.

Battery Thermal Management Systems (BTMS) that use additional energy sources may be broadly classified as either active or passive. In active BTMS, additional energy is used to run the fan or pump, which is often found in liquid cooling systems [22] and air cooling systems [21]. In passive BTMS, certain structures—such as PCM [23] and heat pipe [24], which are known to enhance heat transfer—will be placed on the battery's surface to boost the battery's ability to transport heat to space. When it comes to efficient thermal regulation, heat pipes are very adaptable technologies. Refrigerators, sorption and vapor-compression heat pumps, and other heat transfer devices may readily include them as heat exchangers [25].Soywax, which possesses heating points of 43.92°C and cooling points of 38.49°C to maintain the operating temperature of lithium batteries, was the PCM employed in this investigation [26]. Thus, a battery cooling innovation combining PCM and heatpipes was implemented in this study.

Methodology

Material

Aliphatic and other organic PCMs are examples of organic PCMs. Organic PCMs typically have a narrow temperature range. Their average latent heat per unit volume and density is modest, therefore they are inexpensive. The majority of organic PCMs are naturally combustible [27]. Soy wax, which was used in this work as a PCM material for battery system cooling, was shown in Figure 1. It was selected by considering the material's freezing and melting points. According to Titin Trisnadewiet.al's study, soywax has melting and freezing points of 43.92oC and 38.49oC, respectively [26]. In terms of appearance, soywax resembles paraffin and is white while solid and yellow when melted. Before being added to the battery cooling system, the soywax substance is melted into a liquid. Figure 1 depicted the 12-minute liquification of soy wax on an electric cooktop. The test is conducted after all of the soywax material has frozen in the battery cooling system.



1 minute 3 minutes 6 minutes 9 minutes

Fig. 1. Phase Change Material (PCM) soy wax melting process hot plate

Experimental Components

The main component of the developed Battery Thermal Management System (BTMS) is the battery box simulator with its cooling system design. The design of BTMS is made simpler, more compact, and easier to change the PCM material to be used. Figure 2 shows the BTMS consists of several components, namely: (1) two battery simulators with heaters and stainless steel conductors, (2) PCM cooler box, and (3) two L-shaped fin heat pipes.

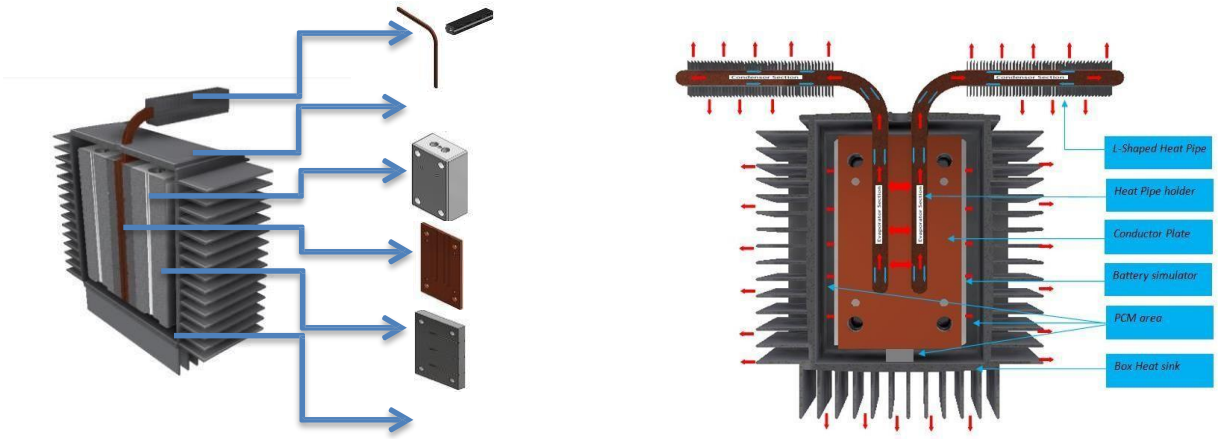


Fig. 2. Construction of the Battery Thermal Management System

The battery simulator is made of stainless steel and has dimensions of 137 × 82 × 46 (mm^3). A heater is placed inside each battery simulator to simulate heat generation in an actual lithium-ion battery. Thus, the battery simulator heat load can be controlled using a voltage regulator. A stainless steel plate is inserted between the heat pipe holder and the battery simulator. In the experiment, two battery simulators and a conductor with a heater are placed inside the air duct. The heat generated by the heater is transferred to the battery simulator and increases its temperature. Then the heat pipe is placed in the heat pipe holder between the simulator batteries.

The heat sink box functions as a PCM storage medium, so that the PCM will be around the battery simulator tool and the heat sink also functions as a heat absorption from the PCM to the environment which can be seen in Fig 3. This box is made of aluminum with a thickness of 2 mm, has dimensions of 150 mm x 120 mm x 159 mm, and an effective volume of PCM is 1100 ml. On the top of the box lid, a hole is placed to place the heat pipe and drain the thermocouple sensor and heater cable.

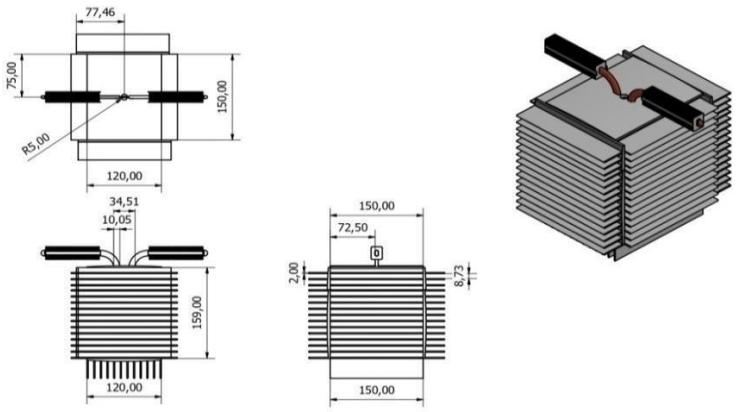


Fig. 3. Box heatsink

Heat pipes have a very high equivalent thermal conductivity because heat transfer involves a phase change in the working fluid. The heat pipe has two components, an evaporator and a condenser, and fluid flow is a two-phase flow. The working fluid is in the liquid phase in the evaporator and in the vapor phase in the condenser. The evaporator sides of the two heat pipes are placed on the copper heat pipe holder to have a good contact surface

between the battery simulator and the heater. Heat pipe performance depends on its properties, i.e. its thermal resistance. Heat pipes with low thermal resistance perform best because they can transfer heat rapidly. The thermal resistance (Res) can be calculated from the temperature difference between the evaporator and condenser and the heat transferred by the heat pipe [29].

The stainless steel conductor plate will be placed between the simulator battery and the L-shaped heat pipe. This aims to determine the amount of heat energy because heat energy will move in all directions. The copper conductor plate will be placed between the conductor connector and the L-shaped heat pipe. There are 45 fins with a distance between the fins of 1.85 mm and a thickness of

0.5 mm made from aluminum. The overall design of the L-Shaped Heat Pipe can be seen in Figure 4.

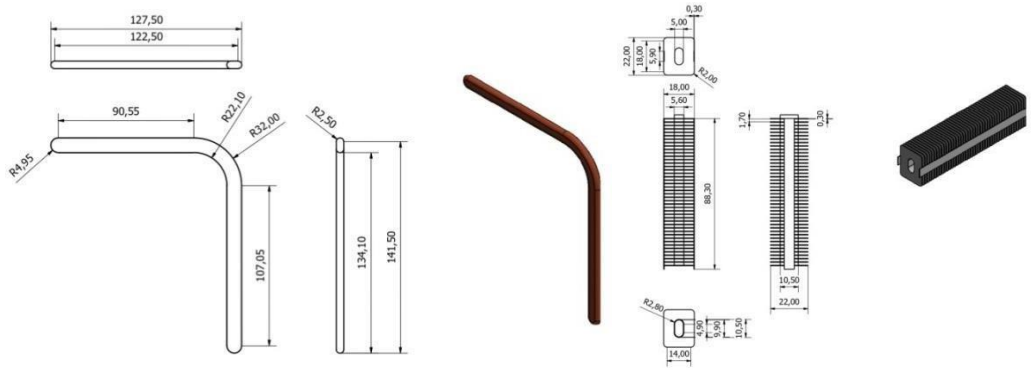


Fig. 4. Heat pipe and fin

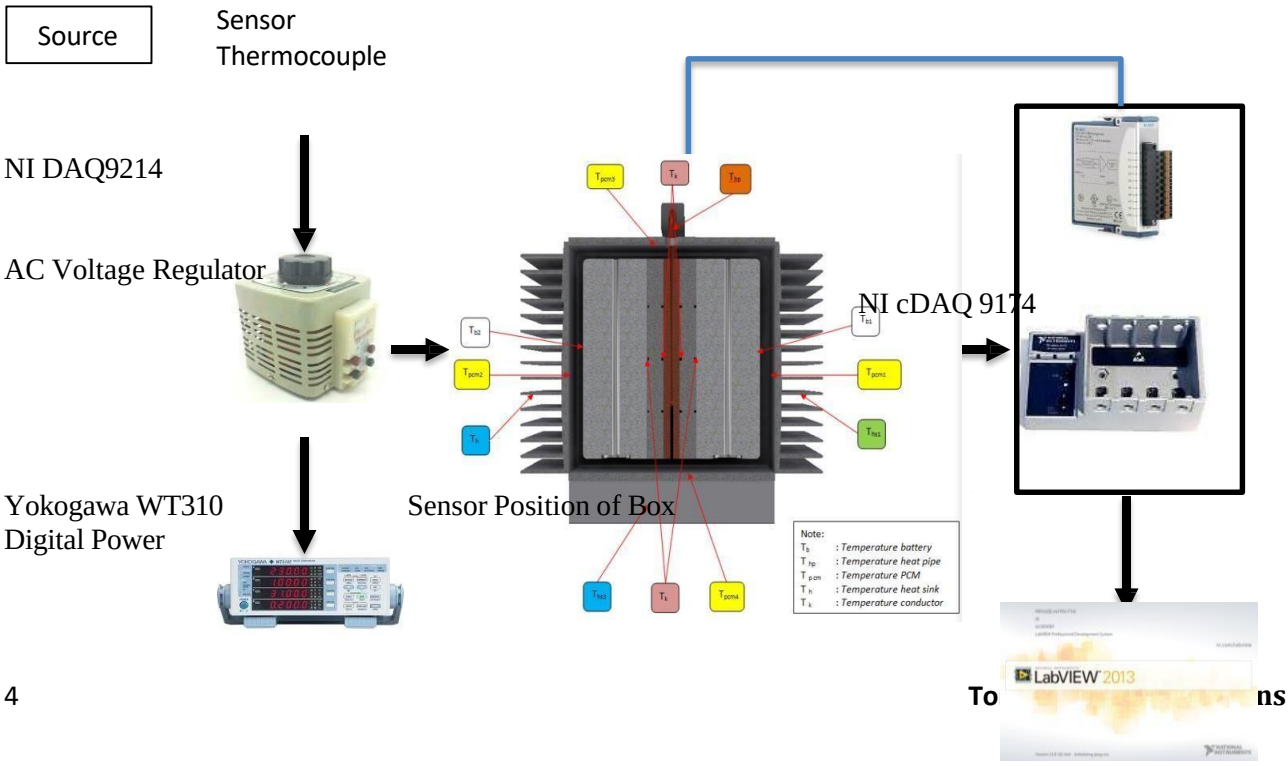
Experimental Setup

The schematic of testing the cooling system in the battery simulator can be seen in Figure 5. Starting with the electric current entering the AC Voltage Regulator, then the current flowing will be read by Yokogawa WT310, the current flowing will heat the heater on the simulator battery covered in PCM and the heat sink box. as a Battery Thermal Management System. The battery temperature data will be recorded via a thermocouple with the National Instruments DAQ 9214 and the measurement results will be stored in the LabView application on the computer.

The heat generated by the battery during charging and discharging will increase the battery temperature to its surface. The variation of the mains voltage to test the simulator battery has an electric current: 1.2 W, 4.8 W, 11.8 W, 20.5 W, 30.4W, and 45.5 W in accordance with the multiple of the battery voltage on an electric vehicle.

The sensor used in this study is a temperature sensor which is used to determine the temperature changes that occur in the system. The temperature sensorswere type K thermocouple with a size of

0.3 mm and have been calibrated. The placement of the thermocouple can be seen in Fig 5 consists of 19 sensors: including 4 sensors on the battery, 2 sensors on the conductor plate, 1 sensor in the holder, 6 sensors on the heat pipe, 5 sensors around the PCM wall, and 1 sensor on the outer surface of the heat sink.



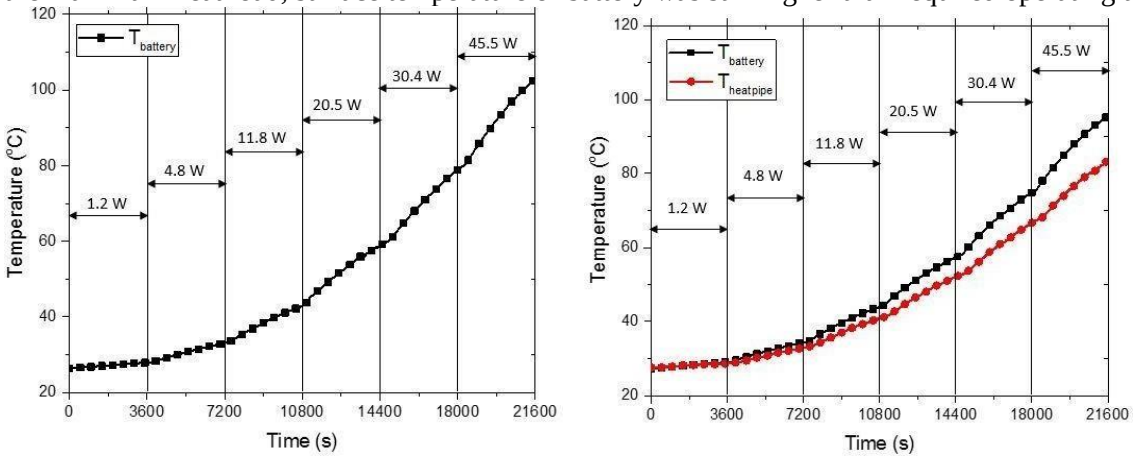
Meter
LabView
Computer
Fig. 5. Schematic system for experiment

Results

Testing of Battery Simulator without Cooling System and with Heat Pipe

As initial reference data, a battery simulation temperature is needed without cooling system treatment by increasing the battery heat load every 1 hour. Based on the test results shown in Figure 7(a), there is an increase in battery temperature along with the increase in voltage. This happens because of an increase in the temperature of the heater. At 1.2 W there is little temperature increase from the battery and it is still around 26.3°C. Then the temperature increase began to occur from the voltage 4.8 W to 45.5 W. Based on the data shown in the graph for the 20.5 W voltage the battery temperature has passed its safe limit until the 45.5 W voltage reaches a temperature of 108.2°C. With this result, it is expected that there will be a decrease in battery temperature when the cooling system is applied so that it has a safe working temperature for the battery.

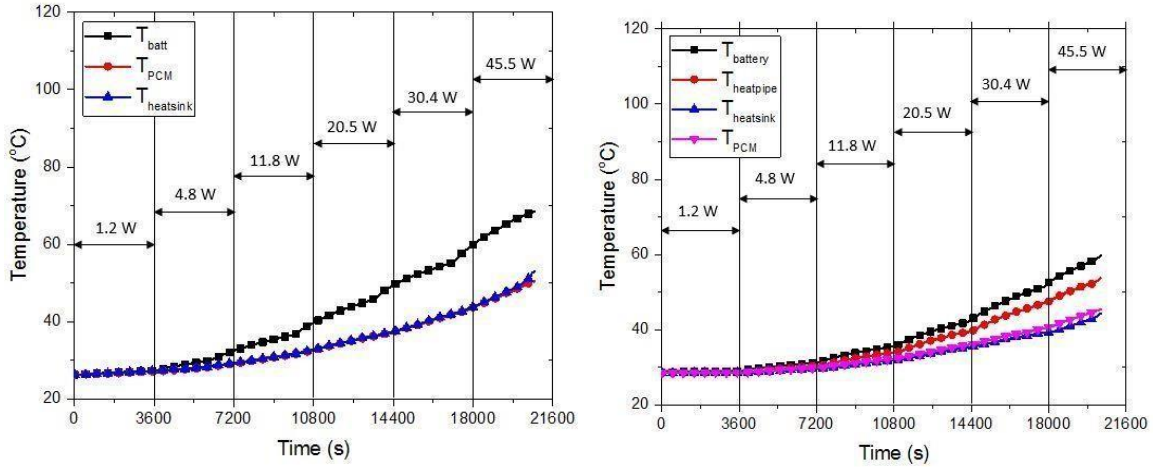
The heat energy supplied by the heater causes the simulator battery temperature rise as the voltage regulator is increased. In this case, BTMS applied 2 heat pipes in between 2 battery simulators. The evaporator side of the heat pipe is placed on the battery simulator and the condenser is placed in the environment in order to release heat from battery to the air. Figure 7(b) shows a graph of the temperature measurements of a battery simulator using only heat pipe. From the graph can be seen that heat pipe can release more heat in the BTMS compare to BTMS without cooling system. Temperature in BTMS with heat pipes decrease significantly around 10°C at the maximum heat load. The temperature decrease is due to the nature of the heat pipe which has high thermal conductivity, and for the range temperature in BTMS, two phase flow in heat pipe occurred, it makes heat pipe worked effectively. But for the maximum heat load, surface temperature of battery was still higher than required operating temperature.



(a) (b)

Fig. 7. (a) Temperature of battery simulator without cooling system, (b) Battery simulator test results with heat pipe

Testing Battery Simulator with Soywax PCM and Box Heat sink and with Heat Pipe, Soy wax PCM, and Box Heat sink



(a) (b)

Fig. 8. (a) Battery Simulator test results with PCM and heat sink Box, (b) Battery simulator test results with PCM, heat pipe and box heat sink

The next test scheme is the cooling system using soywax PCM material which is placed around battery simulator in the heatsink box. In this cooling system, firstly heat will be absorbed by PCM, then heat release using a heatsink around the box. in Figure 8(a) can be seen that temperature measurement at the PCM and heatsink have almost the same increment gradient and but lower than the battery simulator temperature. The battery temperature with heat load 30.4 W has passed the safe temperature limit of the battery of 55.2^{o}C and at 45.5 W it reaches a temperature of 68.2^{o}C. This shows that soywax PCM can absorbing more heat generated by the battery effectively. This occurred because at that temperature PCM has changed from solid to be liquid and at this condition latent heat is dominant. Besides, the addition of a heatsink around the box can help the system to transfer heat with higher the cross-sectional area into the environment, so that the heat transfer generated by the battery can be distributed more quickly.

Figure 8(b), the use of heat pipes combined with PCM soy wax can reduce the heat energy produced by the battery simulator when compared to not using a cooling system. The high thermal conductivity of the heat pipe makes the heat energy produced can be transferred to the air faster, the sensible and latent heat properties of PCM soy wax make the heat energy from the battery simulator absorbed into the PCM Soy wax, and the heat sink box has a forced convection process sink. The temperature of the battery when using a heat pipe combined with PCM Soy wax and a heat sink box at maximum heat load of 45.5 W obtained a temperature of 58.3^{o}C, it means the temperature drop was 46.1% lower than BTMS without cooling system. Amount of heat energy is absorbed by heat pipe firstly, the rest is absorbed by PCM then transfer to heat sink. The use of PCM and heat pipes is very effective in order to reduce temperature of the battery and maintaining the working temperature of the battery.

Comparison of Battery Simulator Cooling with Heat Pipe, Soy wax PCM, and Box Heat sink

Referring to all existing test results, the comparison of battery temperatures with various cooling methods is presented in Figure 9. It can be seen in that the combination of heat pipe, pcm and heat sink has the best performance, which can reduce the surface temperature of battery. At each change in the voltage applied to the battery, there is also a decrease in temperature throughout the cooling system as summarized in Table 1. The results showed that the thermal management system using only heat pipes can reduce the temperature around 11^{o}C, from 108.2°C to 97.2°C, further placing the PCM on the heatsink box surrounding the battery can result in a drop in temperature of up to 40^{o}C from 108.2°C to 68.2°C, the latter, with the PCM being placed in the heatsink box surrounding the battery and the heat pipe providing a temperature drop of more than 50^{o}C from 108.2°C to 58.3°C. Based on the graph results, it can be seen that the highest temperature drop gradient occurs in a cooling system using a PCM and a heatsink box. When compared to the gradient for the increase in battery temperature from 1.2 W to 45.5 W, PCM cooling and heatsink can reduce the temperature by up to 36.9%. whereas using the heat pipe was only able to reduce 10.1% and combination of the heat pipe, PCM and heatsink by 46.1%. So that from the three cooling systems, it is known that cooling using PCM and Heat pipe is effective in reducing battery temperature, and the most optimal cooling system for reducing battery temperature among the other methods.

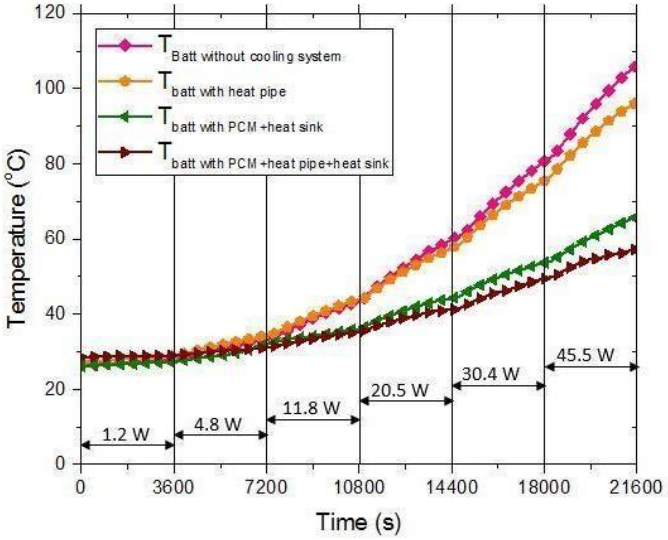


Fig. 9. The difference of electric battery simulator testing without PCM, use heat pipe, use heat sink box, and combination of all

Table 1

The battery surface temperature comparison data

Battery Surface Temperatures with variation of heat load						
Testing Battery Simulator	**1.2 (ºC)**	**W4.8 W (ºC)**	**11.8 (ºC)**	**W20.5 (ºC)**	**W30.4W (ºC)**	**45.5 W (ºC)**
Testing of Electrical Batteries without PCM, Heat Pipe, and Heat sink Box	26.3	34.3	42.6	60.4	80.2	108.2
Testing of Electric Batteries using only Heat Pipes	27.2	34.5	41.3	57.5	76.7	97.2
Testing of Electrical Batteries with PCM and Heat sink Box	26.2	31.4	38.5	47.7	55.2	68.2
Testing of Electric Battery Simulator with PCM, Heat Pipe, and Heat sink Box	28.2	32.1	36.2	42.6	51.7	58.3

Conclusions

In this study, a battery thermal management system combining Heat Pipe, Phase Change Material (PCM), and a heat sink as a cooling medium was developed. The battery's surface temperature has been considerably lowered by the produced BTMS, whose performance has been successfully evaluated. The designed BTMS is smaller and doesn't need an additional power source to cool the surface battery. According to the findings, a thermal management system that just makes use of heat pipes may lower the temperature from 108.2°C to 97.2°C by around 10.1%. Additionally, the temperature can drop by up to 36.9% when the PCM is placed in the heat sink box surrounding the battery, from 108.2°C to 68.2°C. This reduction is more effective when the PCM is placed in the cooler surrounding the battery and heat pipe, as it can lower the simulator battery temperature by 46.1%, from 108.2°C to 58.3°C. According to the findings of the aforementioned study, a combination of heat pipe, PCM, and heat sink is the most efficient cooling method for lowering battery temperature. The thermal characteristics of PCM during cycle tests and the discharge process are crucial for boosting natural convection and heat conduction in the PCM structure, improving heat dissipation efficiency, and lowering failure risk in PCM-based passive thermal management systems. In the future, PCM soy wax may be used as a substitute PCM in passive cooling systems for batteries in electric vehicles.

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