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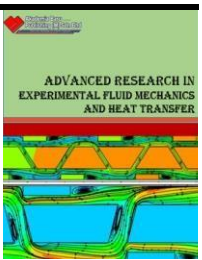

Thermal Management System Based on Phase Change Material (PCM) and Heat Pipe in Lithium-ion Electric Vehicle Batteries

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ABSTRACT

The high working temperature in the battery can cause a thermal runaway, decrease in battery capacity, and reduce the discharge cycle. Therefore, a thermal management system is needed to maintain the temperature of the battery when operated on high-performance electric vehicles, required a reliable thermal management system with light weight, compact size, and able to increase the efficiency of battery performance. So, the aim of the research is to analyze of battery thermal management using PCM and heatpipe, the effectiveness of using PCM and heat pipe. The PCM used in this experiment soy wax with a melting point of 38.49°C. Soywax is expected to absorb and store the heat generated and the heatpipe can help accelerate the heat transfer that occurs in the battery. The simple experimental setup is developed and the series of experiments are conducted with 4 variations, they are the battery without cooling system, cooling using only PCM, cooling using only a heatpipe and cooling using a combination of PCM and heat pipes. The results showed that the thermal management system using only heat pipes was able to reduce the temperature byaround 11°C, from 108.2°C to 97.2°C, Furthermore, with the PCM placed in the heatsink box that surrounds the battery it can result in a temperature drop of up to 40°C from 108.2°C to 68.2°C, the latter, with the PCM placed in the heatsink box that surrounds thebattery and heat pipe it gives a temperature drop of up to more than 50°C from 108.2°C to 58.3°C. The thermal properties of PCM during the discharge process and cycle tests play important role of increasing natural convection and heat conduction in the PCM structure, thereby increasing the efficiency of heat dissipation and reducing the risk of failure in a passive thermal management system using PCM. The utilization of cooling system of PCM and heat pipes can increase the effectiveness of thermal management n battery of electric vehicle.

Keywords:
Battery thermal management system;
phase change material; Soywax; heat pipe

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1. Introduction

Along with the development of life that is increasingly rapid the increase in energy use in the world has also increased continuously every year. Technological advances in the automotive and electronics fields have produced high-tech vehicles but are accompanied by very high heat generation. The increase in the amount of greenhouse gases in the atmosphere is believed to be closely related to the phenomenon of global warming [1]. As a substitute for fossil fuel vehicles,

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electric vehicles (EV) have advantages such as low pollution and high efficiency [2]. Environmental and economic considerations have encouraged the motor vehicle industry to develop electric vehicles. Utilization of electric vehicles is an effective way to reduce emissions of greenhouse gases and other pollutant emissions as well as to save energy consumption [3]. Li-ion battery is an essential component of EV. Improper working temperature (high temperature, low temperature and high differential temperature) will affect performance and battery life [4], greatly affecting EV capability. At high temperatures, capacity / power fading, self-consumption, and other detrimental effects will result in a massive loss of available battery energy [5,6]. Heat generation in motorized vehicles requires a good heat dissipation method to keep the working temperature at an optimal state so that it will provide effective and efficient performance and long battery life [7]. High operating temperatures reduce battery capacity and reduce charge-discharge cycles. Operating high energy density batteries at high operating temperatures carries the risk of causing fires and explosions due to thermal runaway [8].

In extreme situations such as excessive ambient temperature high temperatures will cause thermal runaway and threaten the safety of the EV when overheating from short circuit gets out of control. Low temperature is detrimental to load acceptance [9], capacity / power [10], service life, and alternating efficiency [11]. Electric vehicle battery is generally a battery pack composed of a number of battery modules [12]. The battery is a technical tool whose use will become more widespread and strategic in the future in line with the increasing scarcity of fossil energy sources and the incessant reduction of exhaust emissions to the greenhouse effect on the atmosphere [13]. The performance of this thermal management system, apart from being determined by a good system design, is also largely determined by the heat exchanger used.

Various Methods are used by many researchers to overcome these problems. As conducted by Zhonghao Rao about Experimental investigation on thermal management of electric vehicle batteries with heat pipes, the experimental result showed that the maximum temperature could be controlled below 50°C when the heat generation rate was lower than 50 W [7]; Nandy Putra on the performance of PCM beeswax and heat pipe as a passive battery cooling system for electric vehicles, when use heatpipe decrease battery temperature by 26.62℃.PCM RT 44 Hc decrease battery temperature 33.42℃ [14]; Huan Ling-Liu on Li-on battery performance management using tree-like mini channel heat sinks: Experimental and numerical optimization, the maximum temperature of the Li-ion battery with a tree-type heat sink is 34.2°C, the temperature difference is 5.35°C, and the pressure drop is 11.26 Pa. And the maximum temperature of Li-ion battery is reduced to 33.69°C and the temperature difference is reduced to 4.86°C with a pressure drop of 17.99 Pa. The deviation of below 1% between the multi-objective optimization results [15]; and Muhammad Amin on Thermal Management of electric vehicle batteries using heat pipes and PCM, when heatpipe at 20 W, reduce from 45.5℃ to 37.9℃. Beeswax at 20 W loads, reduce from 45.5℃ to 35.4℃; heatpipe at 50 W, reduce from 79.1℃ to 49.9℃. Beeswax at 50W, reduce from 79.9℃ to 48.1℃ [16].

However, until now the continuous heat loss demands battery thermal management innovations that do not require additional power and are more efficient at absorbing heat. One method of passive heat absorption that has been discussed so far is to use PCM. Phase Change Material (PCM) is a latent energy storage material that is able to release energy for a very long time without the occurrence of temperature changes[17]. PCM can absorb and release heat that occurs when the solid to liquid phase changes or vice versa, so the PCM material can be concluded as a latent heat storage material. The use of PCM provides a higher heat storage capacity and is widely used in building energy conservation [18]. The use of PCM as TES (Thermal Energy Storage) is known to be able to generate latent heat and sensible heat [19]. The many types of PCM that exist, it is required to find the type of PCM that has the best characteristics for cooling applications. However, PCM still lacks its low thermal conductivity and unstable state when PCM undergoes phase changes [20]. So that in this study will provide an option with the cost of an electric vehicle that is economical, reliable with high performance, has a longer service life and reduces serious damage that can cause big losses.

In general, Battery Thermal Management System (BTMS) can be divided into active or passive systems using extra energy sources. For active BTMS, extra energy is consumed to power the fan or pump, which is usually present in air [21] and liquid cooling systems [22]. For passive BTMS, certain structures will be installed on the surface of the battery to achieve a higher heat transfer capacity between the battery and the outer space, such as PCM [23] and heat pipe [24] which are known to increase heat transfer. Heat pipes are very flexible systems with regard to effective thermal control. They can easily be implemented as heat exchangers inside sorption and vapor-compression heat pumps, refrigerators and other types of heat transfer devices[25].The PCM used in this study is soywax which has Heating points 43.92℃ and Cooling Points 38.49℃ to maintain the working temperature of lithium batteries[26]. Therefore, in this research, a battery cooling innovation was carried out using a combination of PCM and heatpipes.

2. Methodology

2.1 Material

Organic PCMs can be aliphatic or other organic. Generally organic PCMs have a low temperature range. They are cheap and have a low average latent heat per unit volume and density. Most of the organic PCMs are flammable in nature [27]. Figure 1 depicted Soy Wax, that used in this study as a PCM material for cooling in battery system. it was chosen by taking into account the melting point and freezing point of the material. Based on research conducted by Titin Trisnadewiet.al, the melting point and freezing point values of soywax were 43.92°C and 38.49°C respectively [26]. Physically, soywax looks like paraffin with a white color when it is solid and when it is melted it has a yellow color. The soywax material is melted into a liquid form before putting it in the battery cooling system. Figure 1 showed the liquification of Soy wax on the electric stove for 12 minutes. After all the soywax material freezes in the battery cooling system, then the test is carried out.

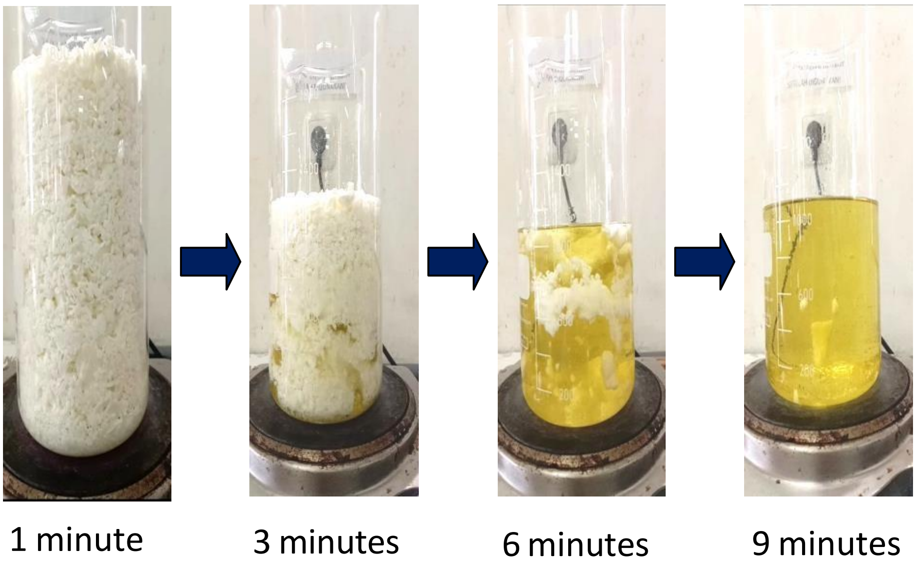


Fig. 1. Phase Change Material (PCM) soy wax melting process hot plate

2.2 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.

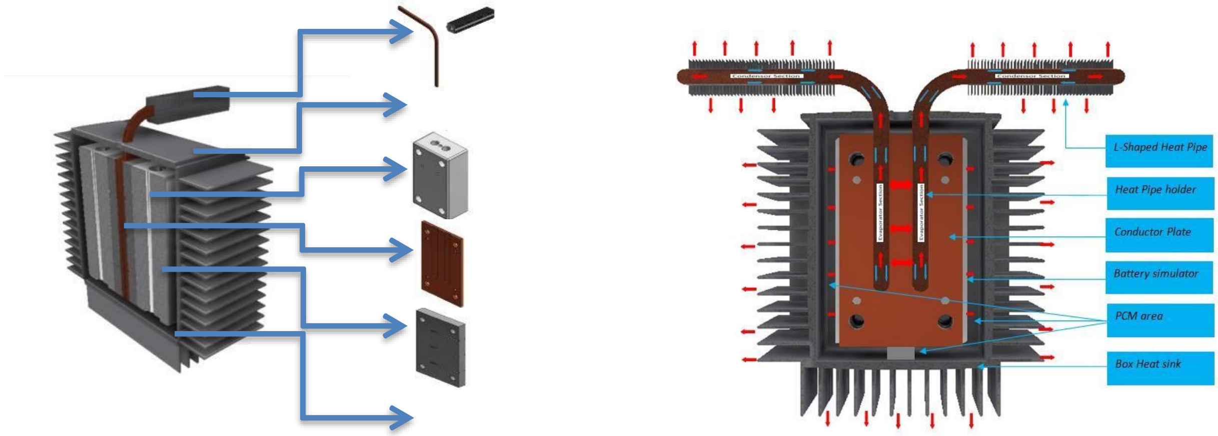


Fig. 2. Construction of the Battery Thermal Management System

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.

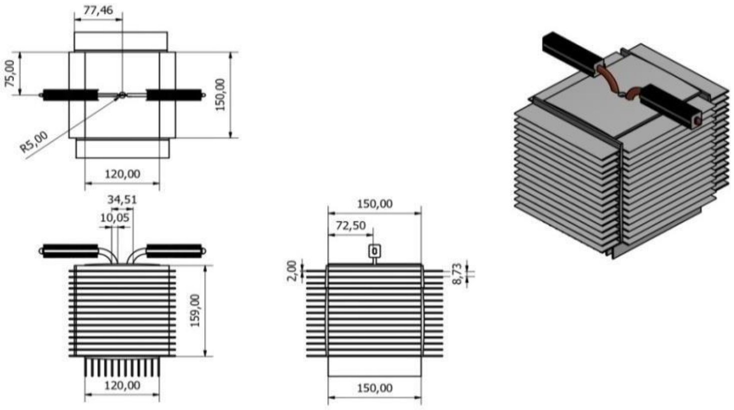


Fig. 3. Box heatsink

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.

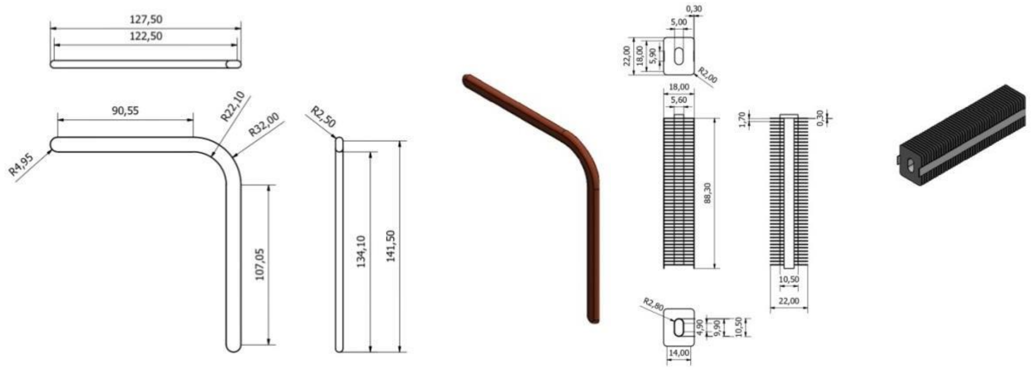


Fig. 4. Heat pipe and fin

2.3 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.

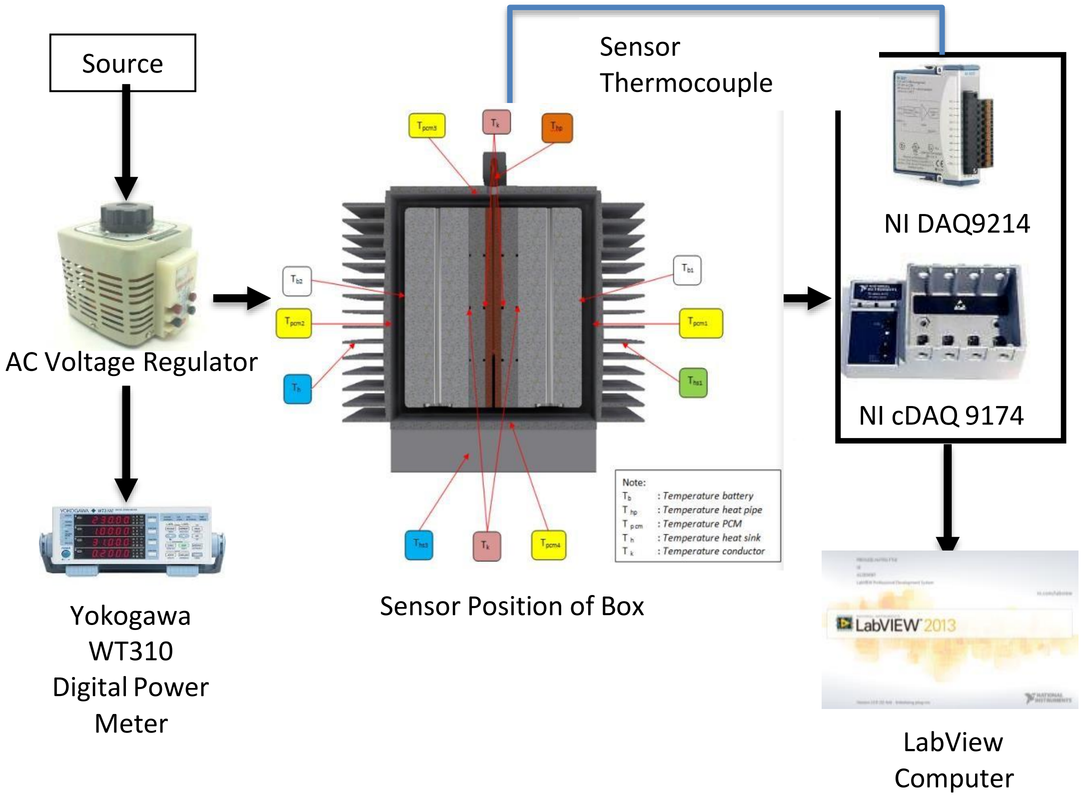


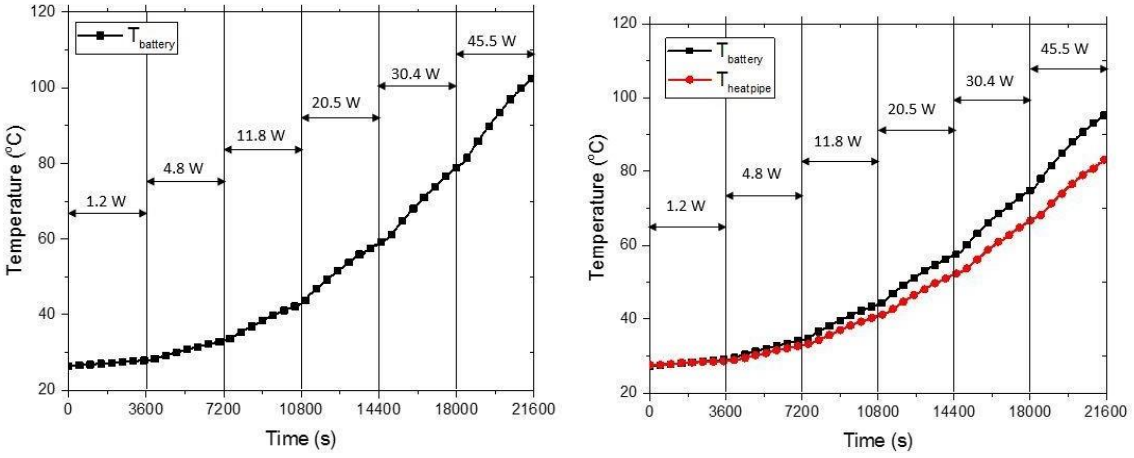
Fig. 5. Schematic system for experiment

3. Results

3.1 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.

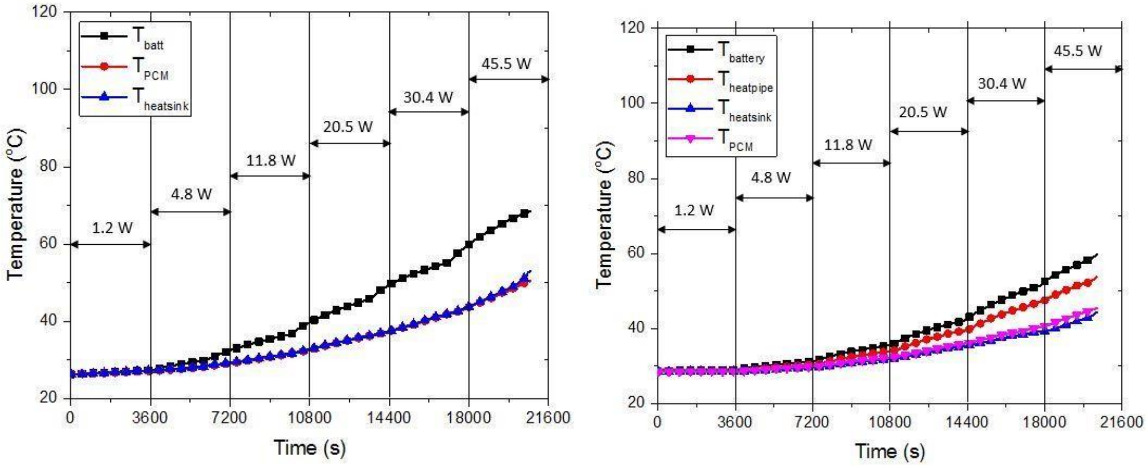
The heat energy supplied by the heater causes the simulator battery temperature rise as the voltage regulator is increased. In this case, BTMS applied 2 heat pipes in between 2 battery simulators. The evaporator side of the heat pipe is placed on the battery simulator and the condenser is placed in the 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

3.2 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°C and at 45.5 W it reaches a temperature of 68.2°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.

3.3 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.

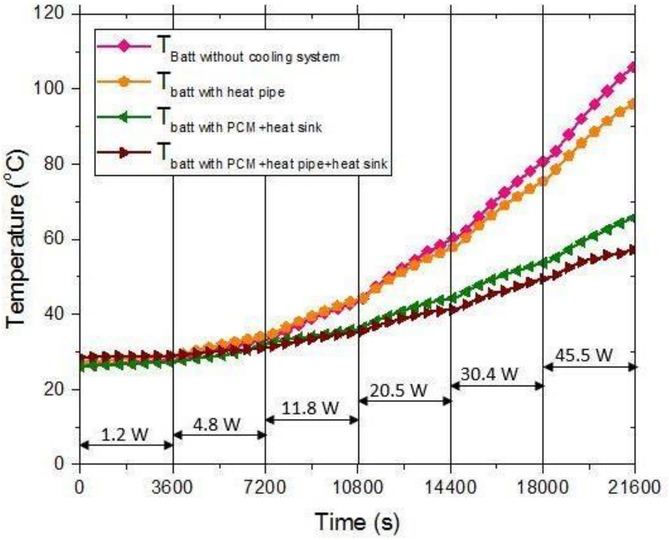


Fig. 9. The difference of electric battery simulator testing without PCM, use heat pipe, use heat sink box, and combination of all

Table 1
The battery surface temperature comparison data

Testing Battery Simulator	**Battery Surface Temperatures with variation of heat load**					
	1.2 W (°C)	**4.8 W (°C)**	**11.8 W (°C)**	**20.5 W (°C)**	**30.4W (°C)**	**45.5 W (°C)**
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

4. Conclusions

The development on the battery thermal management system using Heat Pipe, Phase Change Material (PCM) with a heat sink as a cooling medium has been conducted in this research. The performance of the developed BTMS has been successfully tested and significantly reduce the surface temperature of the battery. The developed BTMS has more compact size without the need for an external power supply to cool the surface battery. The results showed that the thermal management system that only uses heat pipes can reduce the temperature by around 10.1%, from 108.2°C to 97.2°C. Furthermore, placing the PCM in the heat sink box surrounding the battery can result in a decrease in temperature of up to 36.9% from 108.2°C. to 68.2°C, the latter, with the PCM placed in the cooler surrounding the battery and heat pipe providing a more effective reduction as it is able to lower the simulator battery temperature 46.1% from 108.2°C to 58.3°C. From the results of the above research, it was found that the most effective cooling system to reduce battery temperature is by using combination of Heat pipe, PCM and heat sink. The thermal properties of PCM during the discharge process and cycle tests play an important role in increasing the natural convection and heat conduction in the PCM structure, increasing the efficiency of heat dissipation and reducing the risk of failure in passive thermal management systems using PCM. PCM soy wax can be used as an alternative pcm in passive cooling system for electric vehicle batteries in the future.

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