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Effect of Heat Pipe's Configuration in Managing the Temperature of EV Battery

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ABSTRACT

Because of their high energy density and long cycle life, lithium-ion batteries are commonly employed in electric cars. As battery performance and life are highly dependent on temperature, it is critical to maintain the optimum temperature range. A battery thermal management system (BTMS) is critical for controlling the thermal behaviour of the battery. Air cooling, liquid cooling, direct refrigerant cooling, phase change material (PCM) cooling, and heat pipe cooling are all BTMS strategies. Heat pipes come in a variety of sizes and configurations that can be employed in the BTMS and many studies have proven the feasibility of using heat pipe as the electric vehicles' BTMS. However, there are many aspects of the design and configuration of the heat pipe that could affect the overall thermal performance of the heat pipe BTMS such as its length, diameter, evaporator and condenser lengths, tilt angle, types of heat pipes and working fluids. In this work, a numerical study was conducted to investigate the effect of heat pipe's diameter, number of heat pipes and the types of heat pipes on the thermal performance of the heat pipe BTMS. The diameter of the heat pipe varies between 6 – 12 mm, the number of heat pipes varies from 2 – 10 and the type of heat pipe considered in this work is straight heat pipe. The thermal performance of the heat pipe is measured by the maximum battery temperature and the thermal resistance at different battery heat generation rate in the range of 10 - 30W. The simulation model was validated against experimental data and results indicate excellent agreement between simulation and experimental data. Simulation results shows that the greater the diameter, the lower is the battery temperature. By increasing the heat pipe's diameter, the battery temperature can be reduced by at least 10% or 3.4°C. Temperature reduction of at least 12.7% was observed when the number of heat pipes used in the BTMS increases.

1. Introduction

Tremendous interest in electrified transportation by automotive manufacturers and research and development sector has been spurred by the increasing concerns of the environment, as well as the disturbing fluctuating trends of the crude oil prices. The transportation sector that includes transportation sources such as road vehicles, air travel, rail and marine transportation contributes

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24.5% of the global carbon dioxide (CO_2) emissions in 2017. In Malaysia, this sector is responsible for approximately 28.9% of the nation's total emissions of CO_2 [1]. Volatile oil prices that see the WTI crude oil reached its highest price at slightly above USD$145/bbl in 2008 [2] and the lowest at -USD$37.63/bbl on 20 April 2020 [3], is also the main driver in the aggressive development of electric vehicles. Electric vehicles (EV) have been considered to be part of the solution in addressing the abovementioned concerns as they are producing less or zero-emission. The life of an EV is its energy source, the batteries, whose cost contributes a significant portion of the total EV's manufacturing costs. Analysts at Bloomberg NEF (New Energy Finance) reported that the price of the battery of an electric car accounted for more than half (57%) of the vehicle's production cost in 2015 and 33% in 2019 [4]. Hence it is essential to exercise care and caution in operating the battery to ensure its longevity and ideal performance.

The type of batteries used for EV can be classified according to their battery chemistry; lead-acid, nickel-metal hydride and lithium-ion batteries (LIB), with LIB, dominated the market share. They have been the batteries of choice for EVs as they offer the highest energy density and thus allow the possibility to make the battery size smaller than others while having the same storage capacity. Apart from that, they have long life-cycle and low self-discharge. However, LIB is susceptible to operating temperature, which has been identified as one of the critical factors that affect the performance and lifespan of the battery [5]. Charging and discharging the battery at a high rate would cause the battery temperature to increase too high above its operating limit. Overheating will impact power density and reduce acceleration responses. Uncontrolled high battery temperature will induce an exothermic reaction that would produce a high amount of heat energy, ultimately creating a thermal runway. If temperature control is not adequately undertaken at this stage, there is a high safety risk of fire or explosions. The uncontrolled exothermic reactions could commence at a temperature of around 80–90°C [6, 7].

Therefore, to mitigate the risk of fire and explosion and to prolong the lifespan of the battery, an effective battery thermal management system (BTMS) must be installed with every EV manufactured. An effective BTMS is required to maintain the battery temperature and the temperature difference of the battery pack within the desired operating limit. Most of LIB should be operating at the optimal limit of 20°C – 40°C [8, 9] with an upper limit of safe operating temperature, recommended to be 45°C [10]. Studies indicate that LIB can operate at or below 50°C without any significant effect on charging efficiency and lifecycle [6, 11]. It is also established that the maximum temperature difference within the battery should not exceed 5°C [12, 13].

Several thermal management systems have been employed to control the temperature and the temperature difference of the EV battery within the safe limit, with the main methods being air-cooling and liquid cooling. Commercially, air-cooled battery packs are installed in EVs such as the Nissan Leaf, and liquid-cooled battery packs can be found in Chevy Bolts and Tesla Model 3. Other innovative methods such as phase-change material (PCM) cooling, heat pipe cooling, thermoelectric and hydrogel cooling are still at the stage of producing proof-of-concept and feasibility studies.

Air cooling BTMS is the cheapest and the simplest to install, but they are less effective at maintaining the temperature uniformity within the battery pack as air has low thermal conductivity and heat capacity. The addition of ducts, manifolds and fans increase the parasitic power consumption and cause the overall system to be bulky [14]. BTMS that employs liquid cooling is more suitable for high-performance EVs as they can effectively maintain the temperature of the battery under extreme operating conditions and ambient temperatures. However, the system would incur considerable costs implication as they need bigger space to be implemented, carry a significant amount of weight, and require an increased power to operate. Furthermore, there is a higher risk of leakage [15].

In addition to the excellent thermal management performance of a BTMS, it should also possess other desirable characteristics such as compactness, lightness, low cost, high reliability and easy to maintain [16]. Researchers are investigating different methods of thermal management for EV batteries such as PCM and heat pipe cooling to address all these requirements. Because of the PCM's mechanism of heat absorption and heat rejection, this system requires adequate cooling period to becomes solid. Hence, its application is limited to EVs that is operating intermittently and with short charging-discharging cycles.

The heat pipe is a device that is capable of exchanging heat with its surrounding using the phase-change processes of liquid to vapour and vice versa. Heat pipe is separated into three sections; evaporator where heating takes place, the adiabatic section and the condenser where cooling takes place. The evaporator of the heat pipe is exposed to heat that subsequently causes the vaporization of the working fluid inside the heat pipe. The vapour rapidly moves to the condenser section of the heat pipe due to a pressure gradient created in the heat pipe. At the condenser, the vapour rejects the heat energy and thus condenses to liquid form. Because of the capillary force of the wick inside the pipe or the gravity effect, this liquid flows back to the evaporator, where it will be heated again. Heat pipes are widely used as the thermal management solutions for electronics [17] and solar collectors [18, 19].

The application of heat pipes in EV was first investigated by Swanepoel [17, 20] in 2001, where they use ammonia-filled PHP to manage the temperature of lead-acid batteries and the electrics components of an HEV. Transient simulation works to compare the cooling performance of heat pipes with air cooling was conducted by Wu *et al.,* [21] in 2002. The next work on the usage of HPs in controlling the temperature of the EV batteries would not be conducted until 2012. The investigations on the use of heat pipes in managing the temperature of the EV battery has been spurred by the benefits associated with heat pipe and the corresponding BTMS. These include enhanced thermal conductivity, minimal space requirement, flexibility in system's layout and configuration etc. [22]. From the literature, it can be summarized that the heat pipe BTMS (HPBTMS) employed to manage the temperature of the EV battery can be grouped according to the method taken to cool the condenser section of the heat pipe, either a passive system or an active system. A passive system is when the condenser is cooled by natural convection that does not require any electrical power to work. In active HPBTMS, the condenser of the heat pipe is exposed to external forced convection of a coolant (either air or liquid).

In a study by Deng *et al.,* [23], it is shown that a passive HPBTMS that use L-shaped heat pipes fitted with fins at the condenser is capable of reducing the maximum temperature of the battery by at most 4.9°C (10% reduction) and improving the temperature homogeneity by 62%. The enhanced performance of a passive HPBTMS over a system with no BTMS was also demonstrated in a study by Ye *at al.,* [24]. Superior thermal performance of the HPBTMS as opposed to natural convection (no BTMS) was also reported by Zhao *et al.,* [25] and W. Zhang *et al.,* [26].

Studies have shown that active HPBTMS provides better control of the EV battery temperature and temperature difference within the battery pack compared to the passive HPBTMS. In a study by Dan *et al.,* [27], using air forced cooling for an HPBTMS that employs micro heat pipe (MHP) array manage to reduce the battery temperature to below 40°C as compared to 57°C when using natural convection. Although HPBTMS is capable of maintaining the battery temperature within the desirable limit, the temperature difference within the battery pack is quite tricky to be controlled, especially with a passive system. Liu *et al.,* [28] compared the performance of active and passive HPBTMS for a discharging operation of a prismatic lithium-ion battery at 1 to 3 C. Their results indicate that although the passive system can control the temperature of the battery below the required operating limit, it cannot reduce the temperature difference below 5°C. The similar superior performance of an active HPBTMS is also observed by Zhao *et al.,* [25] and Tran *et al.,* [29, 30].

Water-cooled condensers have been used in the application of HPs in EV BTMS which can be in the form of water cooling loop [31-33] or a more innovative approach; water spray [25]. Under off-normal conditions, *i.e.,* high charging/discharging rate (above 2C), high heat flux, heat pipes with water-cooled condensers is capable of controlling the battery temperature below 40°C. Comparing heat pipes with air forced convection and water-bath at the condenser, Zhao *et al.,* [25] found that the former outperforms the latter. This surprising finding was said to be attributed to the build-up of vapour bubbles at the outer surfaces of the condenser, which consequently reduces the thermal conductivity of the heat pipe and suspends the exchange of heat between the heat pipes and the cooling water.

Thermal performance of HPBTMS is dependent upon the design and configuration of the system. Heat pipes come in a variety of sizes and configurations that can be employed in the BTMS and many studies have proven the feasibility of using heat pipe as the electric vehicles' BTMS. However, there are many aspects of the design and configuration of the heat pipe that could affect the overall thermal performance of the heat pipe BTMS such as its length, diameter [34], evaporator and condenser lengths, tilt angle [35, 36], types of heat pipes and working fluids. Different types of HP used or different methods of condenser cooling employed, or different layout of the setup affects the capability of the HPBTMS in managing the battery of the EV. There are lack of studies in comparing the thermal performance of HPBTMS with different methods of condenser cooling and also in comparing different configuration or layout of the HPBTMS. Therefore, it is the main objective of this work to investigate the effect of different HPBTMS layout on the thermal performance of the BTMS in terms of quantity of the heat pipes and their diameter.

In this work, a numerical model for the HPBTMS was developed and simulated using the steady-state thermal analysis in SOLIDWORK. The result of the base case model was validated with data from previous experimental study. Then, parametric studies on the dimension of the heat pipe (*i.e.,* the diameter) and the number of heat pipes were conducted to determine the optimum heat pipe setup/layout.

2. Simulation Set-Up

2.1 Simulation Model

The simulation base case model for this study was developed from the HPBTMS experimental setup (Figure 1) previously conducted by the author, Nasir *et al.,* [37]. In the experimental work, heat generated by the EV battery cell was managed by using a heat pipe battery thermal management system. Two conventional straight heat pipes were inserted in the gap between two battery cells (Figure 2). The evaporator section of the heat pipe was exposed to the heat generated by the battery and the condenser section was subjected to water cooling. The results from this experimental works were used for validation of the numerical simulation model. The numerical base case model is shown in Figure 3.

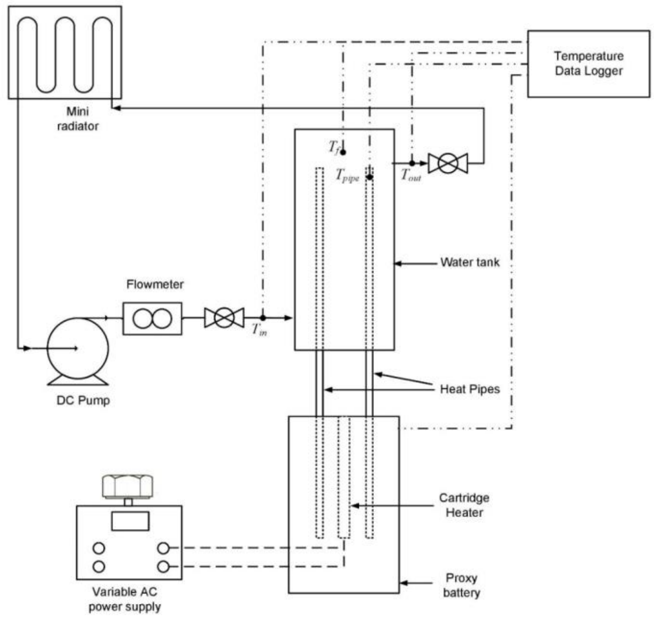

Fig. 1. Schematic diagram for the overall experimental setup

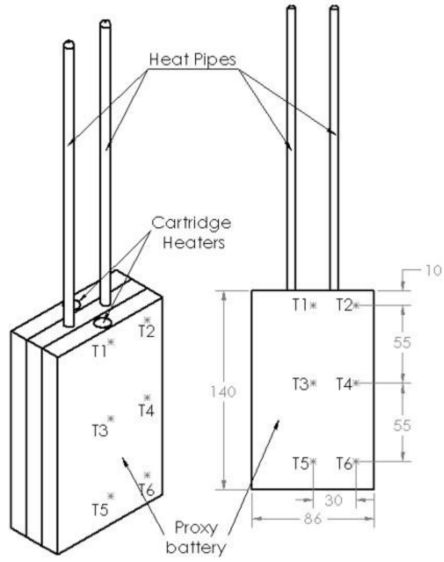

Fig. 2. Battery and heat pipe configuration for the experiment

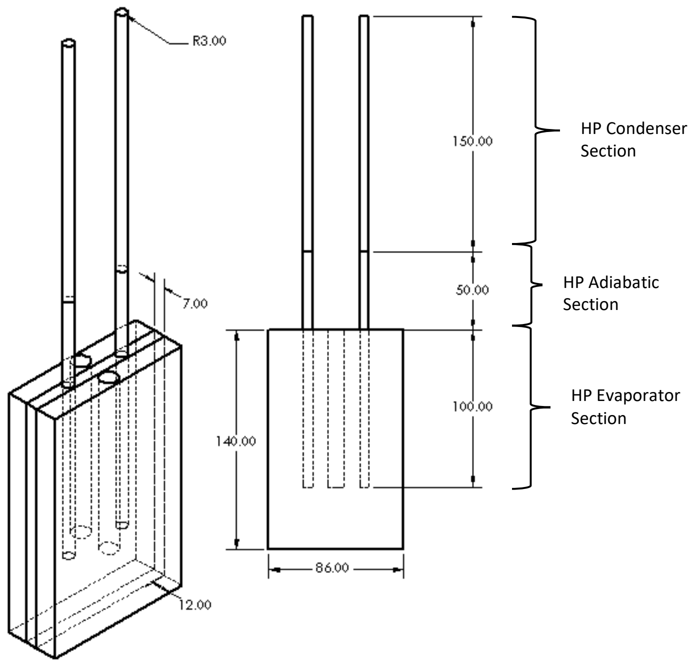

Fig. 3. Simulation base case model for the battery-heat pipe

2.2 Material Specification and Boundary Conditions

The numerical model is simulated using the steady-state thermal analysis of SOLIDWORK. The heat pipe is assumed as a continuum solid body with enhanced effective thermal conductivity of 4000 W/m.K. The material properties for each of the solid body for the numerical model is listed in Table 1.

Table 1
Material Properties for Solid Bodies in the Simulation Model

Solid Body Region	Material	Density (kg/m3)	Thermal Conductivity (W/m.K)	Specific heat capacity (J/kg.K)
Battery Cell and Heat Pipe Holder	Aluminium 6061	2700	170	1300
Heater	Stainless Steel	7700	37	520
Heat Pipe	Copper	8900	4000*	390

The heater is modelled to generate different heat transfer rate in the range of 10 W – 30 W. The evaporator section of the heat pipe is subjected to conduction heat transfer from the heater. The condenser section of the heat pipe is subjected to forced convection heat transfer induced by the water cooling, with the convection heat transfer coefficient, h_{cond} of 3400 W/m^{2}K. The coefficient was determined using the Churchill & Bernstein correlation (Eq. (1)).

$$Nu = \frac{h_{cond} d_o}{k_p} = 0.3 + \frac{0.62\,\mathrm{Re}^{1/2}\,\mathrm{Pr}^{1/3}}{\left[1+\left(\frac{0.4}{\mathrm{Pr}}\right)^{2/3}\right]^{1/4}} \quad (1)$$

The adiabatic section of the heat pipe is under well-insulated condition; hence zero heat flux boundary condition is applied to the section. Similar boundary condition was applied for other exposed surfaces.

2.3 Simulation Validation

The simulation result of the base case model was validated by comparing it with the experimental results described by Section 2.1. The simulated maximum battery temperature at different battery heat generation rate of 10 W - 30 W were compared with the measured maximum battery temperature at the same heat rate. The base case model is validated if the results vary within ±10% from the experiments.

2.4 Simulation Cases

The main objective of this work is to investigate the effect of heat pipe's diameter and the number of heat pipes on the thermal performance of the heat pipe BTMS. The diameter of the heat pipe varies between 6 – 12 mm and the number of heat pipes varies from 2 – 10.

The thermal performance of the heat pipe BTMS is measured by the maximum battery temperature, T_{max} and the overall thermal resistance of the system, R_{th}. The latter is determined from the following Eq. (2):

$$R_{th} = \frac{Tmax - Tmin}{Q} \quad (2)$$

where Tmin is the minimum temperature of the heat pipe BTMS and Q is the heat generation rate of the battery (W).

3. Results and Discussion

3.1 Validation of Simulation Results for Base Case Model

In order to confirm the validity of the numerical model, the simulation results are compared with the experimental data. The parameter being compared to ensure the validity is the maximum battery temperature. The numerical model is deemed validated and verified if its results deviate by less than 10% from that of the experimental works. The results of the comparison are illustrated in Figure 4.

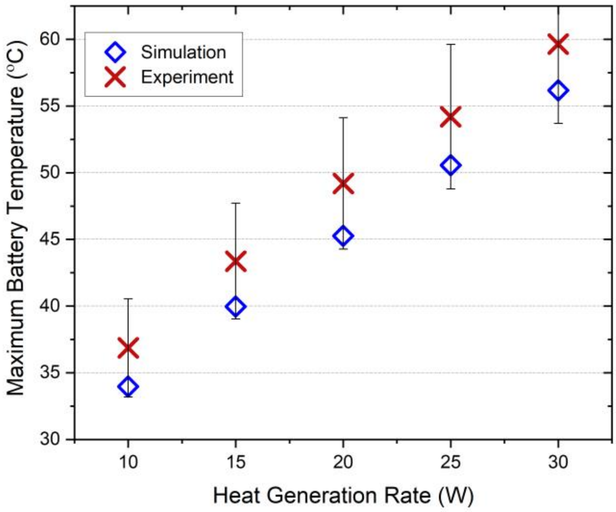

Fig. 4. Maximum battery temperature at different heat generation rate with 10% error bars

As the heat generation increases, the maximum battery temperature also increases. For optimum battery operation, the temperature of the battery should be maintained at less than 50°C. Figure 4 clearly showed that this could be achieved when the heat generation rate is 20 W or less. It can be observed from the figure that the simulation results deviate less than 10% as they are still located within the error bars, indicating excellent agreement between the simulation results and the experimental ones. Hence, it can be concluded that the simulation base case model is validated and can be used for further analysis.

Temperature contour plot for the heat pipe BTMS when the heat generation rate is 30 W is shown in Figure 5. The condenser section of the heat pipe experiences the minimum temperature and the battery surface has the highest temperature. Similar distribution is observed for other heat generation rates.

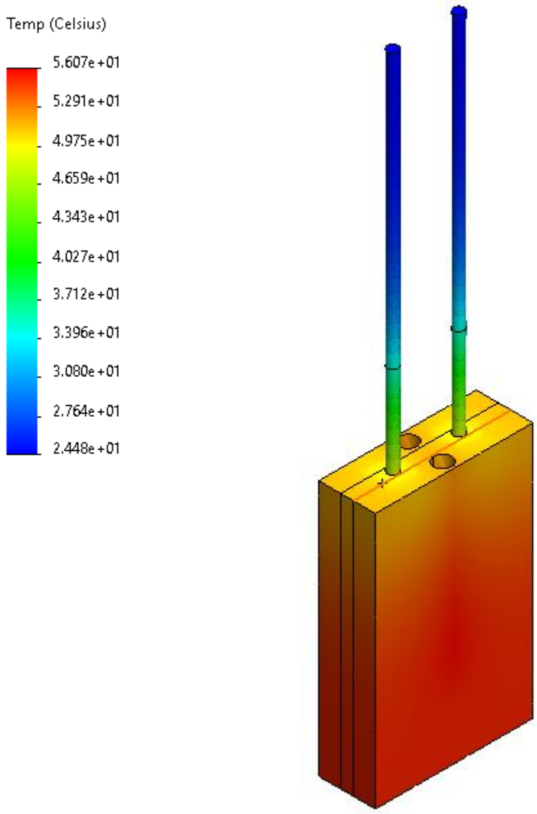

Fig. 5. Temperature contour plot at Q = 30 W

3.2 Effect of Number of Heat Pipes

In the base case model, the number of heat pipes used is two. To determine the effect of this quantity on the heat transfer performance of the heat pipe BTMS, simulation models with 6, 4, 8 and 10 heat pipes were created. The maximum battery temperature at different heat generation rates and the overall thermal resistance were determined for each of the models. Figure 6 depicts the effect of using different number of heat pipes on the maximum battery temperature for different heat generation rate. The temperature decreases exponentially with the increase in the number of heat pipes where no significant improvement can be seen when more than 6 heat pipes are used in the BTMS.

When the number of heat pipes used in the HPBTMS changes from 2 to 4, significant reduction in maximum battery temperature can be observed (Figure 6). At battery heat generation rate of 10 W, the temperature reduces by 4.3°C from 33.97°C and maximum reduction in temperature of 15°C is achieved at heat generation rate of 30 W, as the heat pipes increases from 2 to 4. By increasing the number of the heat pipes, it can be seen that the ability of the HPBTMS to control the battery temperature below the desired operating temperature of 50°C is improved. When only 2 heat pipes are used, the BTMS could maintain the temperature below 50°C when the battery heat generation rate is 20 W or less. However, if 4 or more heat pipes are utilized, the HPBTMS would be able to maintain this desired temperature up to 30 W of battery heat generation rate. The improved performance of the HPBTMS observed as the number of heat pipes increases is attributed by the additional surface area available for heat transfer. Due to the increase surface area, higher amount of heat could be dissipated away from the battery, to the evaporator section of the heat pipe and eventually removed as the condenser section of the heat pipe.

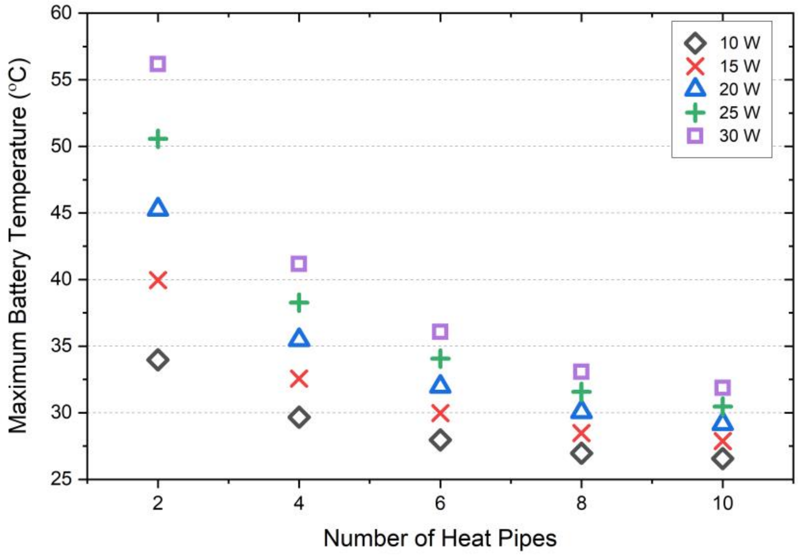

Fig. 6. The effect of the quantity of heat pipes on the maximum battery temperature

Although the battery temperature reduces with the number of heat pipes, there is a limit at which there is no further improvement in temperature can be obtained. From Figure 6, no further improvement in battery temperature can be seen when more than 6 heat pipes were used. This finding is further illustrated by the results of overall thermal resistance for the HPBTMS (Figure 7).

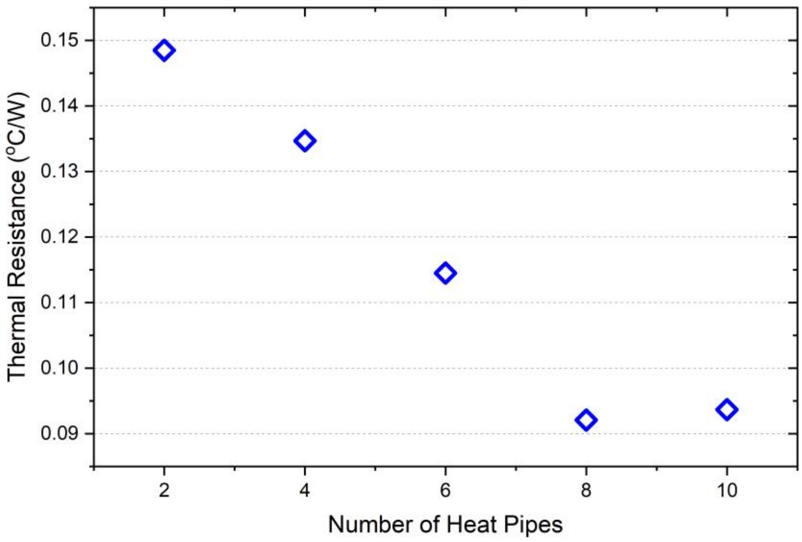

Fig. 7. The effect of the quantity of heat pipes on the overall thermal resistance of the HPBTMS

A high thermal resistance indicates greater resistance to heat transfer, implying that the heat would not be able to flow and dissipate easily. From Figure 7, as the number of heat pipes increases, the thermal resistance decreases linearly. It can also be observed from the figure that the thermal resistance does not differ much when 8 or 10 heat pipes are used, indicating that the optimum number of heat pipes to use is 6. The use of more than 6 heat pipes would make them in a very close proximity with each other, and would cause a reduction in the thermal performance of the heat pipe, particularly due to the poor convection heat transfer at the condenser section.

3.3 Effect of Heat Pipe's Diameter

In the base case model, the diameter of the heat pipe is 6 mm. The diameter is varied to 8 mm, 10 mm and 12 mm to investigate the effect of this parameter on the thermal performance of the HPBTMS. As the diameter is varied, the thickness of the heat pipe holder was also varied to accommodate the change in heat pipe size. Figure 8 shows the effect of heat pipe's diameter on the maximum battery temperature for different heat generation rate for HPBTMS with 2 heat pipes. It indicates that the diameter of the heat pipe has significant effect on the battery temperature, where the temperature reduces with the increase in the diameter.

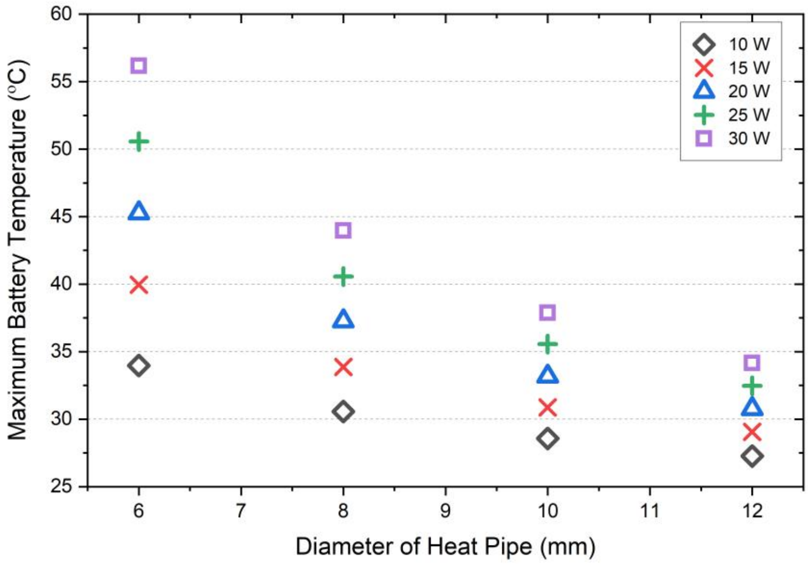

Fig. 8. The effect of the heat pipe's diameter on the maximum battery temperature at different heat generation rates

By increasing the diameter from 6 mm to 8 mm, the maximum battery temperature drops by as low as 3.4°C (at Q = 10 W) and by as much as 12.2°C (at Q = 30 W). Changing the diameter from 8 to 10 mm and from 10 mm to 12 mm produces further reduction of the maximum battery temperature but to a lesser extent. As seen in Figure 8, the base case model with heat pipe's diameter of 6 mm would not be able to control the battery temperature below 50°C for battery heat generation rate of 20 W or less. When the HPBTMS uses 8-mm-diameter heat pipes, the battery temperature is maintained well below 50°C even at the highest heat generation rate of 30 W. Further increase in the heat pipe's diameter would further enhance the ability of the HPBTMS to reduce the battery temperature.

As the diameter of the heat pipe increases, the available surface area for heat transfer at the evaporator and the condenser section increases, allowing greater heat to be dissipated away from the battery. Greater diameter also reduces the resistance to heat transfer, as indicated by the results of thermal resistance in Figure 9. The overall thermal resistance of the HPBTMS decreases linearly with the increase in the heat pipe's diameter. It is the highest at 0.1485 W/°C for heat pipe's diameter of 6 mm and the lowest at 0.0727 W/°C for heat pipe's diameter of 12 mm.

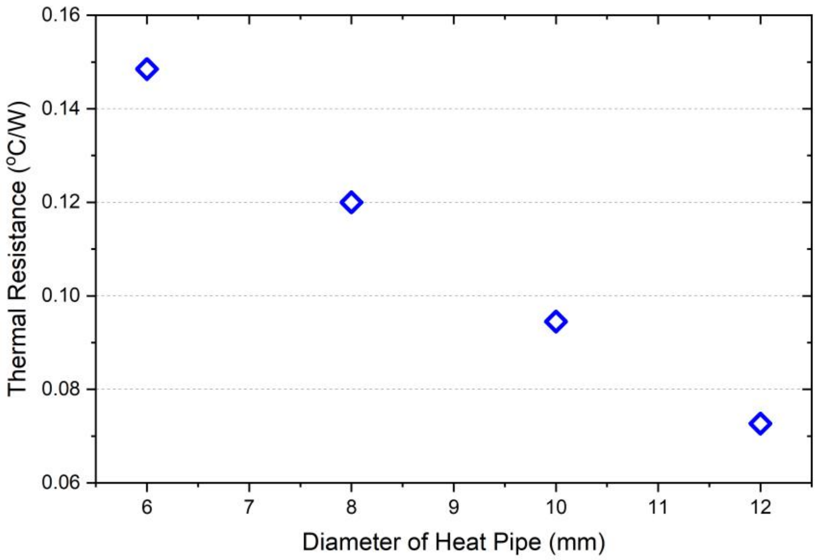

Fig. 9. The effect of the heat pipe's diameter on the overall thermal resistance

4. Conclusions

Due to the sensitivity of the EV lithium-ion batteries on the operating temperature, an effective BTMS must be designed and implemented to ensure that the battery temperature is maintained below the required temperature (less than 50°C). One of the methods used for BTMS is heat pipe cooling and studies have shown that HPBTMS would be able to maintain the battery temperature. The objective of this work is to numerically investigate the effect of the number of heat pipes and its diameter on the thermal performance of the HPBTMS. Using a steady-state thermal analysis, maximum battery temperature and thermal resistance of the system for the numerical models were obtained and validated against previous experimental results. Simulation results showed excellent agreement with the experimental ones as they predict battery temperature within 10% of the actual observations.

The thermal performance of the HPBTMS improves with the increase in the number of heat pipes. However, there is a limit to which further increase in the quantity would hinders further reduction in temperature and thermal resistance. It is found that the limit is 6 heat pipes.

The diameter of the heat pipes has significant effect on the thermal performance of the HPBTMS. The battery temperature and the thermal resistance decreases with the increase in the diameter, from 6 mm to 12 mm. By increasing the diameter from 6 mm to 8 mm, the maximum battery temperature drops by as low as 3.4°C (at Q = 10 W) and by as much as 12.2°C (at Q = 30 W).

The increase in heat pipe's quantity and diameter gives rise to a greater heat transfer surface area, hence allowing higher amount of heat to be dissipated away from the battery. It can be concluded that there are significant effects of the number of heat pipes used and their diameter on the thermal performance of the HPBTMS in managing the temperature of the EV battery. For future studies, it is recommended to pursue the simulation of the heat pipes using multiphase model so as to capture the phase change phenomena occurring in the heat pipe.

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