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Experimental investigation of heat pipes and liquid cooling based hybrid Battery Thermal Management System

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Abstract
The thermal management system (TMS) for lithium-ion (Li-ion) batteries in electric vehicles (EVs) is an essential requirement to ensure their smooth operation due to the high temperature generated by the batteries during high C rate charging or discharging. In the current study, this paper presents an analysis of the performance of a heat pipe-assisted hybrid cooling battery thermal management system (BTMS) for electric vehicle (EV). Combining a cooling channel and round heat pipes (RHP) at system level, this study examines the vertical position of the RHP under various heat load conditions and liquid temperatures. Moreover, the study also goes through thermal resistance network of the entire system and determines the part with high temperature gap. Experimental results demonstrated that the current design with heat pipes in vertical position is capable of transferring heat released at $1.126\times 10^6 W/m^3$(10W) from heater cartridges. This was enough to keep the battery surface temperature below 59°C and the difference in temperature between them under 2°C. Furthermore, the heater cartridge surface temperature showed 39°C when 5W heat power was released. The two test cases were conducted at 0.33 L/min and 20°C water temperatures which is the average ambient temperature. Finally, it should be noted that the decrease in the temperature of the water from the cooling tower is proportional to the decrease in the temperature of both ends of the heat pipe.

Keywords**:** Electric Vehicles, Battery Thermal Management System, Heat Pipes, Hybrid Cooling,

1. Introduction

Since the 1980s, the use of lithium-ion batteries (Li-ion) have become increasingly popular as a power source for a variety of applications including electronic applications and vehicles, and solar energy storage[1]. This is due to the fact that Li-ion batteries are highly energy dense, reliable, and do not have any memory effect, making them capable of providing a long driving range and high acceleration for transport[2]. In spite of its many advantages, the current battery produces a significant amount of heat during the high C rate, which increases the battery temperature and reduces the performance and lifespan of the li-ion battery. For the reasons stated above, BTMS is an essential requirement for the electric vehicle industry to maintain the optimum operating temperature of the battery pack.

There are two primary requirements of the BTMS: controlling a temperature range within a 25-40°C and maintaining a temperature difference between batteries of less than 5°C[3]. The stated operating temperatures assists the battery function longer and perform more efficiently. In order to complete the task, there are exists four types of the cooling structure applied in the system. They are liquid, phase change material (PCM), air, and heat pipes (HP), as well as a combination of these elements called hybrid cooling.

The most common cooling system is the air-cooling system[4], which is less complex and less expensive than other cooling methods. However, air cooling has certain disadvantages, such as a low heat capacity and low thermal conductivity, which make it unsuitable for reaching high cooling effects. For instance, the cooling system in Nissan Leaf can only operate at low speeds. The drawbacks of the air-cooling system can be neglected if liquid cooling can be replaced as it is capable of high thermal conductivity and more efficient than air cooling[5]. The liquid cooling system is divided into two groups: direct and indirect cooling, and each group consists of several cooling approaches. Despite the advantages of liquid cooling, it has drawback such as the possibility of leaks[6]. Tesla and Chevrolet volt are two examples of vehicles using liquid cooling strategies. After moving through active cooling methods, there exists passive cooling approaches. The PCM is one of them.

A PCM may also suffer from leakage problems depending on the structure of the material used and the temperature range in which it is used[5]. PCM can be used in the cooling system to keep the battery warm during sub-zero weather conditions, since batteries cannot operate at low temperatures. There is also heat pipe passive cooling system, which has a high thermal conductivity, no additional power, is compact, reliable, and requires minor maintenance[7]. A number of heat pipe types exist, such as round, flat, half round, and loop heat pipes (LHP), and some scientists have conducted research using fins to further increase the performance of heat pipes. Different types of heat pipes can be identified based upon the battery shape in order to increase the surface area that is in contact with the battery.

Therefore, in the current study, a round heat pipe assisted hybrid battery thermal management system with heater cartridges are examined in vertical positions with cooling channel. Thermal grease and copper sheets are applied between heat pipes and heater cartridges to improve the contact surface area and heat transfer rate. Finally, the study finds out that heat pipe is capable to keep the surface temperature of the 26650 batteries under 59°C at 8C rate[8], and due to the application of thermal grease, controlling surface temperatures of the batteries under 2°C is also achievable with current design. Heat generation, which considered in this study equivalent to the heat generation by a 26650 battery at 8C rate[8].

2. Experimental setup

The experimental setup shown in Figure. 1a was developed to determine the performance of a vertically oriented heat pipe-based battery thermal management system (HPBTMS). The setup consists primarily of five 300W DC heat cartridges, five $\phi 8mm \times 150mm$ round heat pipes and an octagon-ellipse shape cooling channel. The cooling channel was made with transparent acrylic material to visually monitor the flow pattern of the liquid to ensure the heat pipe under the water. A DC power supply is used to supply power to the heat cartridges while two, 0.5 mm copper sheets are placed between the heater cartridges and heat pipes to enhance the surface contact area. To further improve the heat transfer, thermal grease was applied on either side of the copper sheets. The cooling channel is placed above the heater cartridges as displayed in Figure. 1a. The condenser end of the heat pipes was inserted into the cooling channel from the bottom with an open grommet to prevent leaks, while the evaporation section of those heat pipes was connected to the heat cartridges. When heat pipe is applied in the system, it was arranged as a staggered line as shown in 1b. All the heat pipe parameters are given in the table 2. A cooling tower was used to circulate the water and control the cooling water temperature. A hydraulic control valve was applied to maintain a constant flow rate, preventing any sudden changes in pressure and velocity that could affect the results of the test. A flow meter with valve named Digiten Flow Control is used to measure a volumetric flow rate of the water. This accurately monitors the amount of water passing through the flow valve, ensuring that the right amount of water is circulated during the test.

Moving to the measurement points, the NI9210 and NI9211 modules on the NI chassis were connected to the laptop where LabVIEW software running to receive temperature signals from twelve K-Type thermocouples with 1% uncertainty which are directly applied to the inlet, outlet and evaporation and condensation heat pipe surfaces respectively depending on the flow direction. All the possible uncertainties are given in the table 3 below. A Kapton and insulation tapes were used to completely insulate the heater cartridges and heat pipe system to prevent heat loss. The current test setup was held and maintained in its vertical position by using aluminium extrusion. In the end, the water flows back to the cooling tower to return to the cooling system.

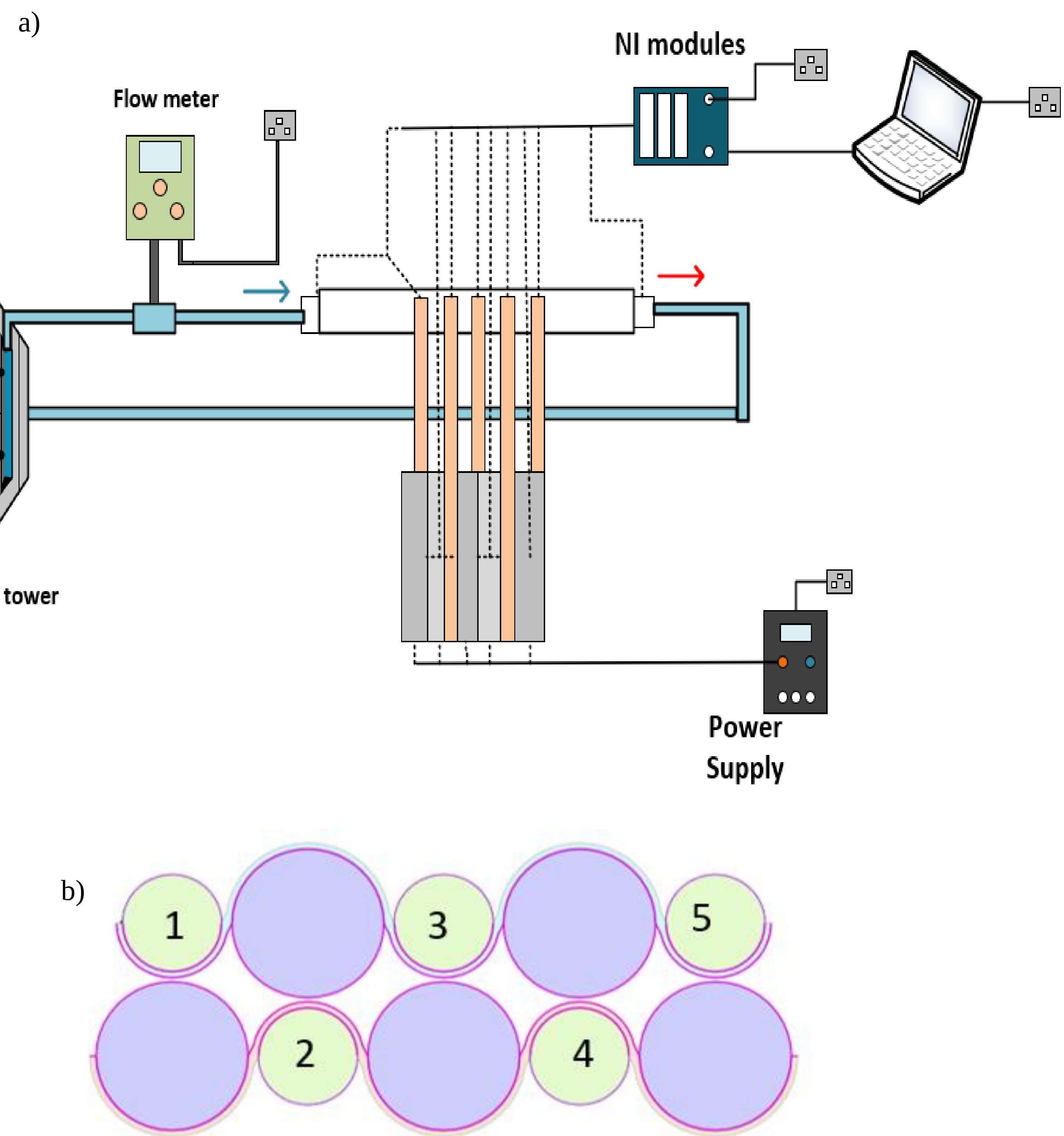

Figure 1. a) Experimental test-rig. b) bottom view of the test setup.

In this study, several tests were carried out by varying heat input and liquid cooling temperatures as outlined by Table 1. The 5W and 10W heat inputs were chosen as 10W heat generation is average maximum heat which typical 18650 and 2170 cylindrical cells generate at 8C rate[9], [10]. For example, 26650 cylindrical batteries generated 8.8W at 8C rate at 20C ambient temperature[8]. Next, the three different most common water temperatures[11] such as 15°C-20°C and 25°C are taken into account, and the water flows with 0.33L/min. The ambient temperature in the room was kept approximately at 20°C.

The cooling process begins with pumping water from the cooling tower with constant temperature and velocity that later reached the flow meter and a hydraulic control valve. The flow valve tracks a volumetric flow rate and send the data to the flow sensor, while flow control valve controls the same liquid volume. Moving to the cooling channel, all the K-Type thermocouples receive temperatures signals from the inlet, outlet and heat pipe surfaces, and the liquid continues to flow to return to cooling tower. Due to the acrylic transparent cooling channel, it was possible to analyse the flow pattern to monitor directly during the process. In the insulated evaporation part of the test rig, the heat released from the heat cartridges transforms to heat pipe surfaces through thermal grease and copper sheets. Then, heat continues to flow up to the condenser end through heat pipes and removes by water liquid for further taken it. The same process continues continuously for all six cases.

Table 1: Test matrix

No.	Heat input	Flow rate	Cooling temperature
1	5W	5W-0.33L/min-0.0055kg/s	20°C
2	10W	10W-0.33L/min-0.0055kg/s	20°C

Table 2: Geometrical properties of round heat pipe

Property	Values (mm)
Outer diameter d_o	8
Adiabatic length,	62
Evaporation length, L_e	75
Condenser length, L_c	13
Total length, L	150

During the experimental test, there were uncertainties of the applied equipment and measurement devices as shown in Table 3. The main uncertainties come to the power, from DC power supply to heat cartridges when the minimum uncertainties are applied for thermocouples and flow meter.

Table 3: Experimental uncertainty

Parameters	Uncertainty
K-type Thermocouples	1%
NI modules	1%
DC power supply	3%
Heat cartridges	3%
Pressure device	1%
Flow meter	1%

3. Results and Discussion

The thermal performance of RHP based BTMS was analysed at various heat inputs for a cooling temperature and volumetric flow rate of water at 20°C and 0.33L/min respectively. Figure 2 shows the variation of maximum temperature at the evaporation and condenser section, and inlet and outlet of the cooling channel at heat input of 5W (536298 W/m3) per heater cartridge. It can be seen that temperature recorded at five points T_1-T_5 in the evaporation section are between 38°C and 39.2°C. A lowest temperature of 38°C was recorded in HP_1 while next three HP_s recorded highest. The trend is explained as three heat pipes in the centre are surrounded by three heater cartridges, while first and fifth heat pipes are only surrounded by two heater cartridges. At the condenser end, the proposed heat pipes' temperatures vary from 29.6°C for the T_1 to 32°C for T_5. The low temperature recorded in the condenser section of HP_1 is associated to the coming flow of cooling water at 20°C, whilst the increase in the temperature of the HP_4 and HP_5 would be a result of heat been absorbed by water. The heat absorbed by the cooling water was determined by equation 1(energy balance equation) and was found to be 24.8W against applied 25W heat input. It is worth to note that outlet temperature is recorded as a point by K-Type thermocouple, and it is assumed the average temperature is slightly lower than 21.08°C, which decreases the absorbed heat value. This shows that there is around 6-7% heat loss from the system to the surrounding.

$$\dot{q} = mC_w * (T_{inlet} - T_{outlet}) \quad (1)$$

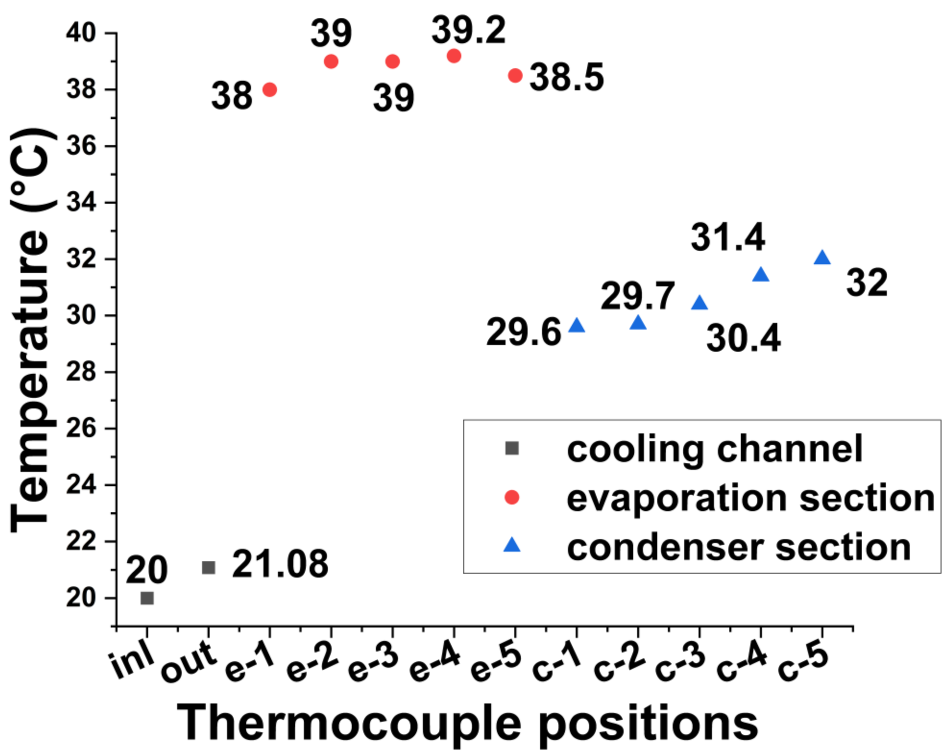

Figure 2: Heat pipe surface point temperature response at 5W heat load

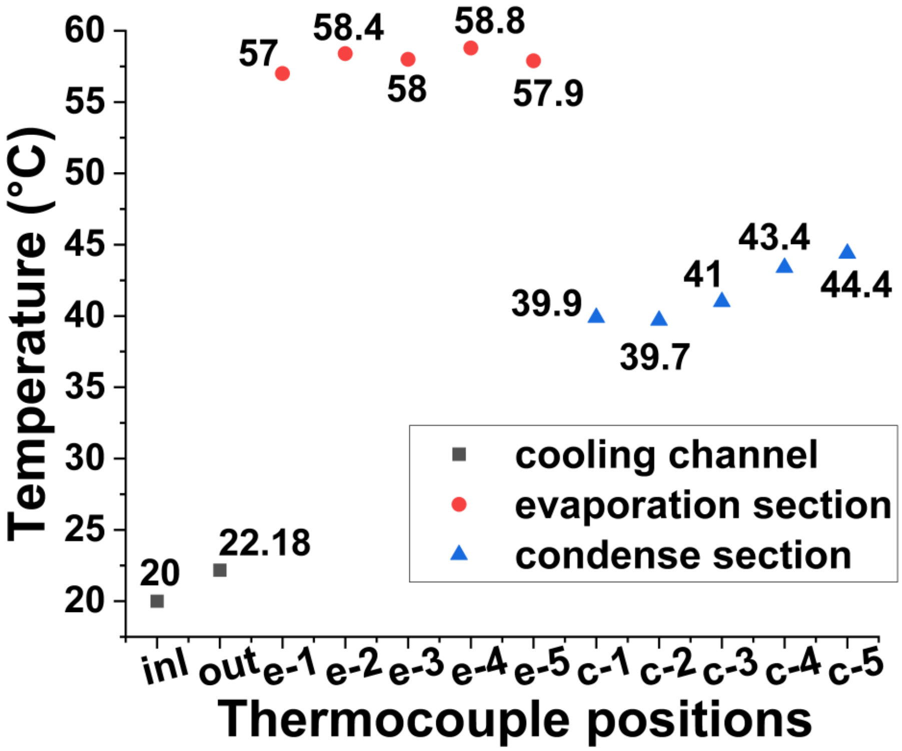

Figure 3: Heat pipe surface point temperature response at 10W heat load

Figure 3 illustrates the maximum temperature variations at the inlet and outlet of the cooling channel, as well as at the evaporation and condenser sections of the five heat pipes, but with a different heat input of 10W (1126596W/m3). For the evaporation section, all five heat pipes' temperatures show between 57°C and 58.8°C respectively which is 17°C higher even though heat input was increased two times than in the 5W test scenario. In addition, the HP_2 and HP_4 have the highest temperatures, 58.4°C and 58.8°C, respectively, since the third and fourth heat pipes are in direct contact with three heat sources. Comparing to the first scenario, the HP_3 is lower despite being surrounded by three heater cartridges. This phenomenon is explained by increasing heat input from 5 to 10W and not equal distribution of the heat load inside the system. In the condenser section, the temperature data shows a highest temperature range of approximately 4°C between 39.9°C and 44.4°C, which still remains within the acceptable range for BTMS. The highest temperatures come from the last two heat pipes (HP_4 and HP_5), with 43.4°C and 44.4°C, respectively. It is likely that the higher temperatures would be due to the increasing absorbed heat by liquid.

The current proposed heat pipe based BTMS is designed to develop the thermal system to increase the performance of the cylindrical shape batteries. Generally, the data shows the current design is capable of transferring heat released from heat cartridges effectively and keep the surface temperature under 59°C when 10W (1126596 W/m3) applied. Moreover, temperature difference between the heat pipes in the evaporation section was under 2°C and 4°C respectively. Comparing with Y Gan's research[12], when water volumetric flow rate was 0.25 L/min, heat load is 5W and water temperature was 20°C that is similar, temperature of the evaporation section shows around 38°C and temperature difference was 5°C for 5W. However, the diameter of the heat pipe was 24 mm and the condenser end length was 24 mm while the current design has only 8 mm diameter and 13 mm length. In order to further increase the performance of the current system, the system will be optimized.

4. Conclusion

An analysis of round heat pipe assisted BTMS is presented in this article with the goal of improving battery thermal performance under a variety of head loads and liquid temperature. A hybrid cooling system with heat pipes in vertical position was examined using the experimental test rig in order to improve battery thermal performance. It is worth to note that experimental test run at 20°C liquid temperature and 0.33L/min volumetric flow rate. Therefore, the results of the experimental study can be summarized as follows:

1) In the 5W (563298 W/m3) applied scenario, the proposed design was able to keep the heat pipe surface temperature in evaporation section below 39 °C and temperature difference between heat pipes are 2°C. The condenser end of the heat pipe showed 7°C lower than evaporation around 32°C.
2) in the 10W (1126596 W/m3) applied scenario, temperatures of the evaporation section reached to maximum 59°C but temperature difference was still under 5°C, which meets BTMS requirements. In the condenser side, temperatures displayed between 39°C and 44°C which is lower 15-17°C than evaporation end.
3) The experimental data clearly shows heat pipe thermal resistance of the heat pipe is not changed significantly by showing 10°C difference at 5W and 17°C difference at 10W. The high temperature range is in the convection heat flow between condenser end of the heat pipe and water temperature. The future research will be focused on increasing contact area in the condenser side and shape of the cooling channel for purpose of increase heat transfer coefficient.

The overall results display that current hybrid cooling system with heat pipe is enough effective to transfer released heat on time and keep the battery temperature under 59°C at 8C rate for 26650 cylindrical batteries[8]. As a next step, the current design will be optimized and adapted for the module level.

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