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Performance of Flat Plate Loop Heat Pipe for Thermal Management of Lithium-Ion Battery in Electric Vehicle Application

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***Abstract*—**The development of electric vehicle batteries have resulted in very high energy density lithium-ion batteries. However, this progress is accompanied by the risk of thermal runaway, which can result in serious accidents. Heat pipes are heat exchangers that are suitable to be applied in electric vehicle battery thermal management for their lightweight, compact size and do not require external power supply. This paper aims to examine experimentally a Flat Plate Loop Heat Pipe (FPLHP) performance as a heat exchanger in thermal management system of lithium-ion battery for electric vehicle application. The heat generation of the battery was simulated using a cartridge heater. Stainless steel screen mesh was used as the capillary wick. Distilled water, alcohol and acetone were used as working fluids with a filling ratio of 60%. It was found that acetone gives the best performance that produces thermal resistance of 0.22 W/°C with 50°C evaporator temperature at heat flux load of 1.61 W/cm^2.

***Keywords*—**Electric vehicle, flat plate loop heat pipe, lithium-ion battery, thermal management system.

NOMENCLATURE

A : Area, m^2
k : Thermal conductivity, W/m. K
q : Heat transfer rate, W
R : Thermal resistance, °C/W
T_b : Bottom surface temperature, °C
T_t : Top surface temperature, °C
T_c : Condenser temperature, °C
T_e : Evaporator temperature °C.

I. INTRODUCTION

THE shares of electric vehicles in some Northern European countries are assumed comprising 53% of the private passenger vehicle fleet in 2030 [1]. One of the important performance parameters of an electric vehicle is the range or cruising capability, which is mainly determined by the performance of the batteries. Batteries with high energy density are needed to deliver high cruising capabilities. Electric vehicles will rely on lithium-ion batteries according to their high energy density, high power density, long service life and environmental friendliness [2]. Advances in battery technology have resulted in very high energy density lithium-ion batteries. However, this progress is also accompanied by the risk of thermal runaway, which can result in serious accidents such as experienced by the Boeing 787 Dreamliner of All Nippon Airways on January 16, 2013 in Japan [3].

Heat generated by a battery, either at the time of charging or at the time of discharging will increase its temperature. The battery performance and life time are strongly influenced by its working temperature. In general, the performance of electric vehicles is directly influenced by the performance of their batteries [4]. At quite low or high temperatures, the battery performance can be very poor. At very high temperature, lithium-ion batteries can even explode [5]. The desired working temperature range for common lithium-ion batteries is between 25°C and 50°C [6]. For the purpose of energy saving and reduction in the cost of electric vehicles, the batteries should be operated in a proper temperature range [7]. Therefore, an effective thermal management system for battery packs is essential.

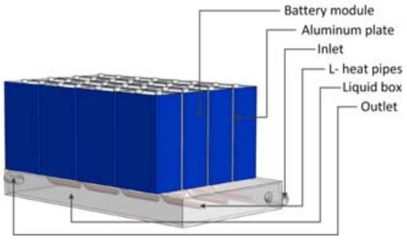

Fig. 1 Thermal management system of electric vehicle battery [15]

Heat pipes are heat exchangers that are suitable to be applied in thermal management of central processing unit (CPUs) and electric vehicle batteries for their lightweight, compact size and do not require external power supply. Studies on heat pipes for electronic cooling have been done by many researches, among which are [8]-[11]. Investigations on flat plate heat pipes in electronic cooling have been conducted by [12]-[14]. Rao et al. [7] have examined the use of straight heat pipes on thermal management system of a LiFePo4 battery. Their experimental results showed that the maximum temperature can be kept below 50°C if the rate of heat generation is below 50 W/cm^2. Wang et al. [15] have investigated the application of heat pipe for thermal management system of electric vehicle battery. In their work, some L-shaped flattened heat pipes were used to transfer heat from the battery to the cooling water as shown in Fig. 1.

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Flat plate loop heat pipes have the potential to be applied as heat exchangers in thermal management system of electric vehicle lithium-ion batteries since most of the lithium-ion battery packs used in electric vehicles have flat surfaces [16]. This paper aims to examine experimentally a flat plate loop heat pipe performance as a heat exchanger in thermal management system of lithium-ion batteries for electric vehicle application.

II. METHODOLOGY

Fig. 2 shows the arrangement of the flat loop heat pipe, conduction plate, battery simulator and insulating box used in the experiment. Battery simulator was made from aluminum alloy. As a heat source, a cylindrical cartridge heater with power of 400 W was placed in the battery simulator. A conduction plate made of stainless steel with size of 105 mm x 40 mm x 15 mm was placed over the battery simulator.

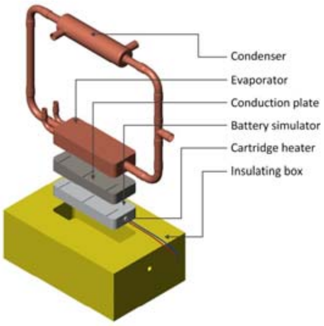

Fig. 2 Flat plate loop heat pipe with battery simulator

The conduction plate was used to determine the conduction heat transfer from the heater to the evaporator by measuring the temperature difference across the plate. Instead of using electric power input, the conduction heat transfer across the conduction plate was used to determine the heat input to the evaporator. The heat input could be determined from:

$$q = (kA/L)(T_b - T_t). \tag{1}$$

The thermal conductivity of the conduction plate which made of stainless steel was assumed to be 25.1 W/m K. The battery simulator and the conduction plate were placed inside an insulating box made of polyurethane. On top surfaces of the conduction plate and the battery simulator, grooves were made for the installation of thermocouples. At the condenser section, an annular heat exchanger was used for heat release to the cooling water.

The evaporator was made of copper with size of 105 mm x 40 m x 15 mm. Each side has 5 mm thickness except the bottom side has 3 mm thickness. To assist the evaporation, 1 mm x 1mm x 60 mm grooves was made on the base surface of the evaporator as shown in Fig. 3.

A stainless steel screen mesh with size of 300 mesh was placed over the grooves to serve as the capillary wick as shown in Fig. 4. The stainless steel screen mesh capillary wick was also placed inside the liquid line to pump back the condensate from the condenser to the evaporator.

Fig. 3 The evaporator

Fig. 4 Stainless steel screen mesh capillary wick

The 0.2 mm k-type thermocouples were used for temperature measurements. Fig. 5 shows the placement of the thermocouples. There were two thermocouples for the evaporator, two thermocouples for vapor line, three thermocouples for condenser, and two thermocouples for liquid line.

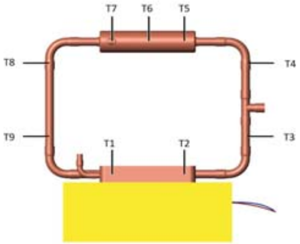

Fig. 5 Thermocouples placement

The flat plate loop heat pipe assembly was then isolated using glass wool. Ceramic blanket, which has higher working temperature, was used for the evaporator insulation. Finally, these insulation layers were covered by the aluminum foil as shown in Fig. 6.

Fig. 6 Flat plate loop heat pipe assembly.

The experimental setup is shown in Fig. 7. The heater power was controlled by adjusting the electric voltage through a voltage regulator. The thermocouple data were send to a NI 9213 data acquisition module installed on a NI cDAQ 9174 chassis. A circulating thermostatic bath was used to simulate cooling condition at condenser side of the heat pipe. The circulating thermostatic bath was set to 28°C with water flow rate of 4 g/s. A DC power supply was used to activate a pressure sensor. The pressure sensor used to monitor the pressure inside the heat pipe was placed in the vapor line.

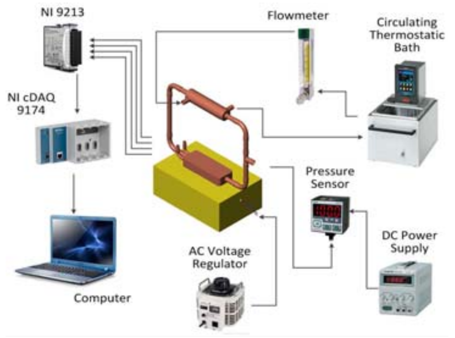

Fig. 7 Experimental setup

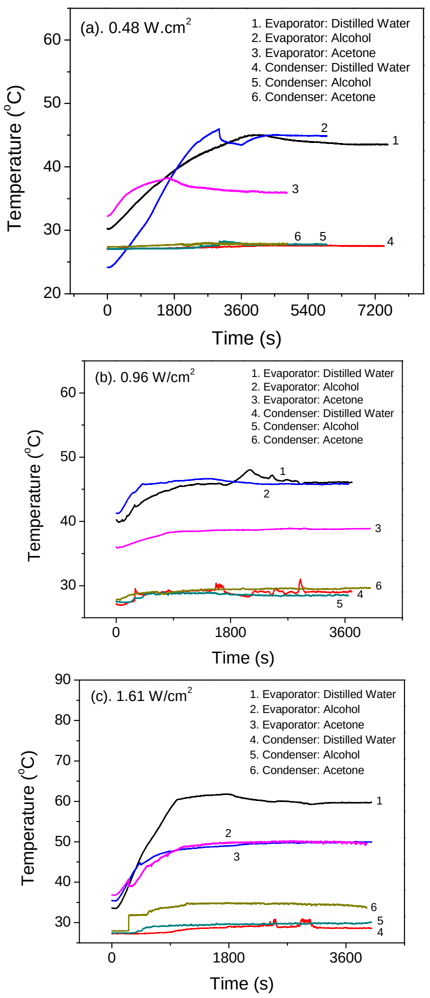

Fig. 8 Transient temperature history

Distilled water, alcohol 96% and acetone 95% were used as working fluids with a filling ratio of 60%. For all working fluids, the experiments used three different heat flux loads, i.e. 0.48 W/cm^2, 0.96 W/cm^2, and 1.61 W/cm^2.

III. RESULTS AND DISCUSSION

A. Transient Temperature History

Fig. 8 shows the transient temperature history curves of the evaporator and the condenser for each working fluid at heat flux load of 0.48 W/cm2, 0.96 W/cm2, and1.61 W/cm^2. These loads may be referred to low heat flux [17]. From the transient temperature curves for evaporator, we can observe the start-up processes. Most of them demonstrate the temperature overshoot that followed by a rapid temperature drop. This overshoot pattern of evaporator temperatures correspond to the boiling of working fluid in the initial state which is accompanied by some superheating [17].

In certain condition where a free “vapor-liquid” interface exists in the evaporation zone, a smooth or stable start-up may proceed without being accompanied by a temperature overshoot [17], [18]. Fig. 8 shows that acetone, at a heat flux load of 0.96 W/cm^2, demonstrates the smooth start-up process. This smooth start-up was probably caused by the higher temperature at the initial condition. The steady state temperatures are achieved at about 30 – 90 minutes depend on the heat flux load. The higher the heat flux load, the shorter the transient period. This quite long transient period can be caused by the high heat capacitance of the system according to the addition of mass such as conduction plate and insulating. When the capacitance of the system is substantially increased, the heat input would affect the transient period very significantly [19]. In addition, it is seen that acetone and alcohol provide shorter transient period for both the evaporator and condenser temperatures.

B. Steady State Temperature Distribution

Fig. 9 shows the steady state temperature distribution along the flat plate loop heat pipe wall. It is seen that at heat flux load of 0.48 W/cm^2 and 0.96 W/cm^2, distilled water and alcohol produce fairly close temperature distribution. However, at a heat flux load of 1.61 W/cm^2, alcohol and acetone provide quite close temperature distribution. At all heat flux load, the evaporator temperature can be kept below 50°C, except for distilled water, which produced evaporator temperature of about 60°C at a heat flux load of 1.61 W/cm^2, For the entire experiment using distilled water, alcohol and acetone as working fluids, acetone provides the lowest temperature difference between the evaporator and the condenser. This may be caused by the fact that acetone has the lowest saturation temperature compared to the distilled water and alcohol.

Fig. 10 shows the steady state temperature distribution along the heat pipe wall at various heat flux loads for acetone as working fluid. The lowest temperature difference between evaporator and condenser was achieved at the heat flux load of 0.48 W/cm^2.

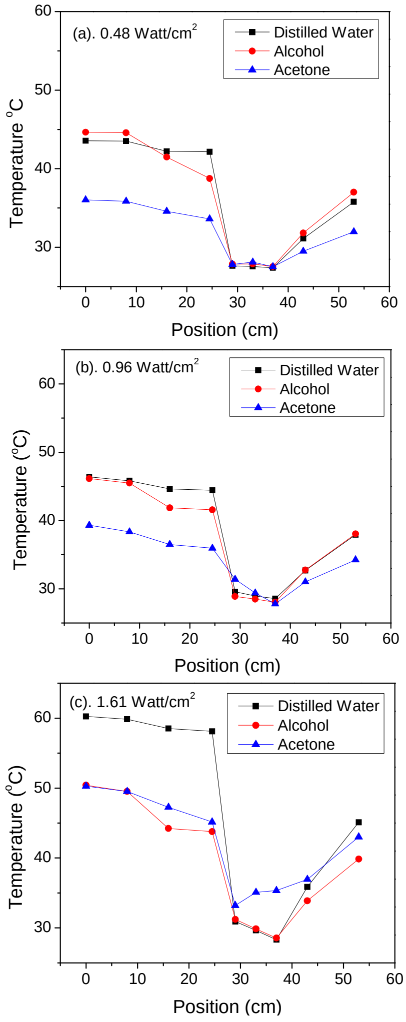

Fig. 9 Steady state temperature distribution

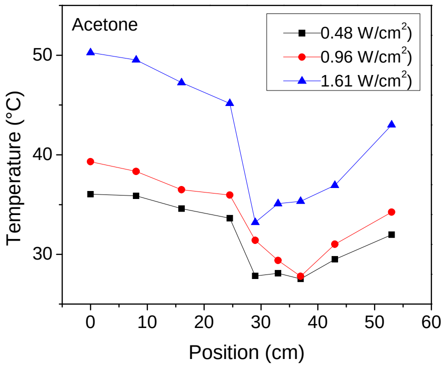

Fig. 10 Steady state temperature distribution for acetone as the working fluid

The performance of the flat plate loop heat pipe can be represented by the thermal resistance, which was calculated by using (1). Fig. 11 shows the thermal resistance of the flat plate heat pipe for the entire experiments. The best performance was obtained at a heat flux load of 1.61 W/cm^2 with acetone as working fluid. The thermal resistance achieved is 0.22 W/°C. The maximum evaporator temperature for alcohol and acetone are about 50°C, which is within the working temperature range of common lithium-ion batteries.

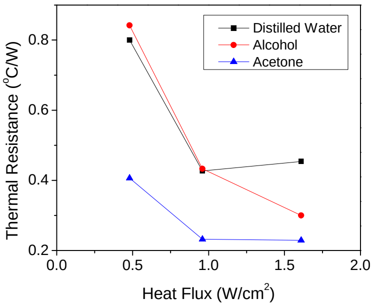

Fig. 11 Thermal resistances

IV. CONCLUSION

The experiments to determine the performance of the flat plate loop heat pipe as heat exchanger for thermal management system of lithium-ion battery have been conducted successfully. We can conclude that:

1. The flat plate loop heat pipe could start-up at heat flux load as low as 0.48 W/cm^2. Temperature overshoot phenomena were observed during start-up period.
2. The best performance of the flat plate loop heat pipe is obtained with acetone used as working fluid with filling ratio of 60% and heat flux loads of 1.61 W/cm^2. The thermal resistance achieved is 0.22 W/°C.
3. The maximum evaporator temperature with alcohol and acetone is about 50°C, which is within the operating temperature range of common lithium-ion batteries.

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