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Battery thermal management system using loop heat pipe with LTP copper capillary wick

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Abstract. Loop heat pipes (LHPs) with Lotus-Type Porous Copper (LTP Copper) capillary wick are expected to be applied to battery thermal management systems for safe operation at high performance with a long service life. Sintered LTP Copper is a high permeability porous metal with an excellent capillary pumping characteristic. The objective of this work is to determine the performance of the battery thermal management system using LHP with sintered LTP Copper capillary wick experimentally. The experiment used two battery simulators made of aluminum. The heat generation of the battery was simulated using cartridge heaters. The LHP was made of 10 m OD copper tube, and the sintered LTP Copper capillary wick was placed in the liquid line. Water was used as working fluid with filling ratio of 50%. The evaporator section of the LHP was inserted between the battery simulators surfaces. A thermostatic bath was used to regulate the condenser cooling fluid temperature. K-type 0.3 mm thermocouples were used for temperature measurement, and a digital power meter was used to measure the electric power. Experiments were conducted with various heating power with the condenser cooling fluid temperature was kept at 28°C. At a heat generation of 20 W, the LHP was capable of maintaining the battery surface temperature below 50°C. At a heat generation of 40 W, the utilization of LHP with LTP Copper can reduce the average battery simulator surface temperature from 93°C to 65°C.

1. Introduction

The development of battery technology for electric vehicles has produced lithium-ion batteries with high energy density. However, this progress is accompanied by the risk of thermal runaway which can cause serious accidents such as that experienced by a commercial aircraft Boeing 787 Dreamliner on January 16, 2013, in Japan [1]. Chemical reactions that occur in a lithium-ion battery, either at the time of charging or discharging, are always accompanied by the generation of heat that causes the rise in battery temperature. Thermal runaway begins when the high battery operating temperature triggers a damage to one cell and causes a sharp rise in the temperature of the cell. In the absence of an effective heat release mechanism to the surrounding, the increase in temperature of the cell may propagate to the neighboring cells, causing an uncontrollable chain reaction and may cause the battery to burn and explode. Figure 1 shows the Boeing 787 Dreamliner of All Nippon Airways battery, which burned and exploded caused by thermal runaway [1]. Also, overly high operating temperatures can lead to lower initial battery capacity and shorten battery life [2].

Conventional thermal management systems such as vapor compression cycles or heat exchangers that use circulated cooling fluid will increase battery power consumption to reduce the cruising range of electric vehicles. The battery operation at a safe temperature range which delivers high performance with long service life requires a reliable thermal management system with compact size, light weight, and energy-saving.

Figure 1. The burned and exploded Boeing 787 Dreamliner battery [1].

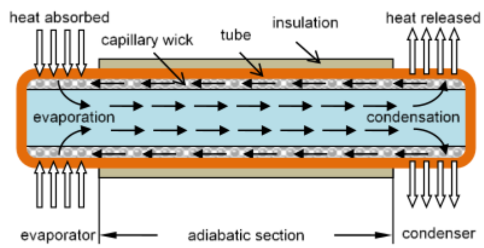

Figure 2. Straight heat pipe [3]

A heat pipe is a thermal device made of a closed tube comprising the evaporator, adiabatic and condenser section. The heat absorbed at the evaporator causes the working fluid to boil, and the vapor then flows through the adiabatic section toward the condenser section. In the condenser section, there is a release of heat to the surroundings and causes the working fluid to condense. The condensate fluid is then pumped back to the evaporator section via a capillary wick located on the inner surface of the tube as shown in figure 2 [3]. The heat pipe has a high heat transfer per unit area capacity because it involves the phase change of the working fluid. A heat pipe has a compact size and lightweight because it requires only a small amount of working fluid and does not require a pump or compressor to circulate it. Moreover, the heat pipe is a passive thermal device because it does not require an external power supply to circulate its working fluid.

The performance of a heat pipe depends on the design of the structure, the working fluid, and the capillary wick structure. LHPs have a higher cooling capacity compared to straight pipes [4]. The addition of nanoparticles to the working fluid can improve the performance of a heat pipe [5-7]. Putra et al. have found that a capillary wick made of corals combined with a nanofluid can significantly improve an LHP performance [7]. The smooth, uniform and continuous pore structure of the coral provides high permeability and capillarity to provide high capillary pressure with high mass flow rates [8]. However, the environmental consideration limits the use of coral. Supriadi et al. have succeeded in making Lotus Type Porous (LTP) Copper through slip casting and sintering techniques to mimic the coral pore structure [9]. In this study, LTP Copper is applied as a capillary wick of an LHP that is used in a battery thermal management system. The objective of this study was to determine the performance of battery thermal management system using LHP with LTP Copper capillary wick experimentally.

2. Methods

The manufacture of Lotus-type porous copper (LTP Copper) using Gasar method is quite complicated and requires expensive equipment [10, 11]. To simplify the manufacturing process, LTP Copper was made through slip casting and sintering process according to the method developed by Supriadi et al. [9]. This method used pore former such as implemented in bi-porous capillary wick manufacturing techniques performed by Li et al. [12]. However, instead of using Natrium Carbonate, Supriadi et al. use nylon threads as a pore former to produce directional pore structure. In this study, the LTP copper wick was fabricated using 200 mm copper powder and 120 mm nylon threads pore former. The copper slurry was poured into a cylindrical copper tube of 10 mm in diameter and 60 mm in length. After drying, the green product was sintered at 850°C for 60 minutes. The final product of LTP Copper wick is then installed as part of the liquid line section of an LHP as shown in figure 3.

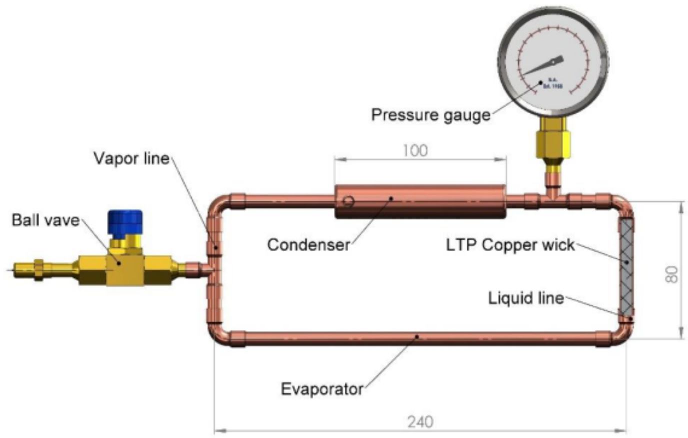

Figure 3. Loop heat pipe with LTP Copper wick

The LHP was made of 10 mm OD copper tubes with a length of 240 mm and height of 80 mm. The condenser section had a length of 100 mm and was equipped with a 25 mm OD cooling water jacket. The evaporator section was clamped between two grooved copper plates. Thermal paste was filled into gaps between the grooves and the evaporator surface to reduce the thermal contact resistance. The LHP with the holder plates was inserted between two battery simulators made of aluminum alloy measuring 48 mm x 82 mm x 138 mm. The battery simulator dimension was determined based on the dimension of a 12 V – 20 Ah Lithium-Ion battery. Each battery simulator was equipped with a 200 W cartridge heater for simulating the heat generation inside the battery. An AC voltage regulator was used to vary the heat generation. K-type thermocouples with 0.3 mm in diameter are connected to a data acquisition system to measure the surface temperature of the battery. A thermocouple is mounted on each surface of the upright wall of the battery simulator, including the inner surface, i.e., surfaces in contact with the heat pipe holder plate. A thermostatic bath is used to supply the condenser cooling water with a constant temperature of 28°C. For electric power measurement, a digital power meter which was connected to the computer was applied.

Figure 4 shows the experimental setup. The experiments were carried out in a room where the air was conditioned at 28°C. The battery simulator was placed on a flat surface so that its base surface is not exposed to the surrounding air. The heat transfer to the surrounding air occurred from the side and top planes by natural convection. All parts of the LHP exposed by the surrounding air are isolated using Rockwool, and the outer surface is covered with aluminum foil as shown in figure 5. Thus the heat absorbed by the evaporator can be approximated as the heat released by the condenser. The first experiment was done without heat pipe, and the second was done using the LHP. In each experiment, the heat generation of 20 W, 30 W, and 40 W were applied. The applied values correspond to the high heat generation of a Lithium-Ion battery. Changes in heat generation values are made after the steady state was reached. For the experiment using heat pipe, the volumetric flow rate of the cooling fluid was kept at 180 ml/minute. The volumetric flow rate was measured by using a measuring glass and a stopwatch.

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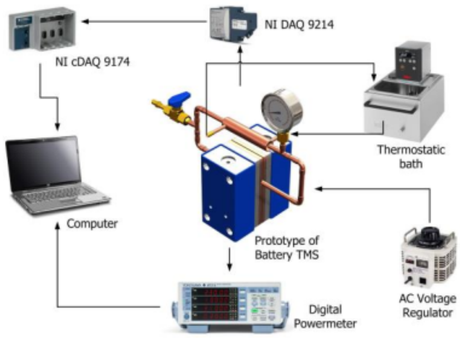

Figure 4. Experimental setup

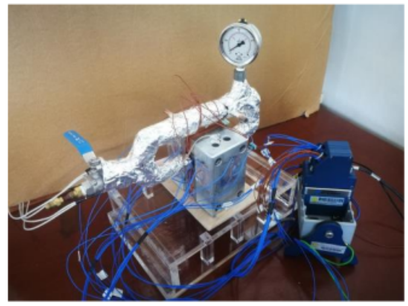

Figure 5. Prototype of battery thermal management system

3. Results and Discussion

Figure 6 shows the results of temperature and heating power measurements of the experiment without heat pipe. It appears that the surface temperature of the battery simulator is almost uniform. The ambient air temperature is slightly fluctuating but can be considered constant. The battery heat generation is simulated by the electric heating power can be kept constant at low voltage but tends to fluctuate at the higher voltage. It is due to the fluctuation of the electric voltage of the PLN, which cannot be overcome by the use of a voltage regulator. Fluctuations in heating power increase sharply with the increase of heating power since it is directly proportional to the square of the electric voltage.

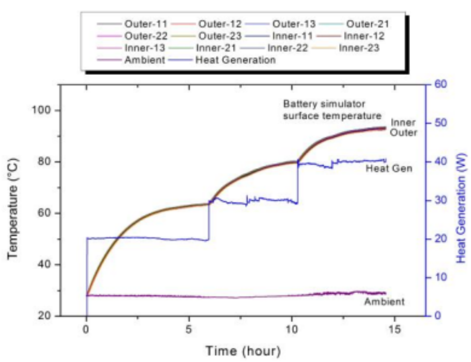

Figure 6. Results of temperature and heat generation measurement without heat pipe

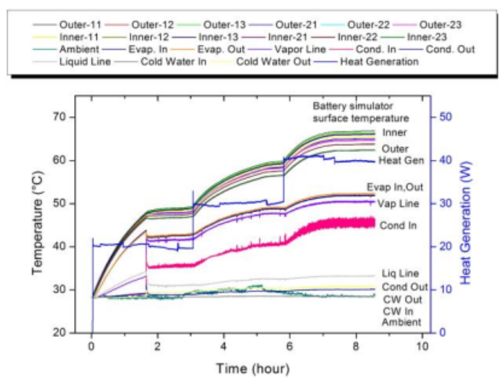

Figure 7. Results of temperature and heat generation measurement with heat pipe

Figure 7 shows the results of temperature and heating power measurements of the experiment with the heat pipe. At 1.65 hour, the temperature of the condenser wall on the inlet side increased sharply indicating the LHP successfully start-up. At the same time, the slope of the surface temperature curve of the battery simulator suddenly turns flatter. The ambient temperature and the heating power is similar to that of the previous experiment. The use of LHP causes some of the generated heat to flow to it. The low thermal resistance of LHP caused the battery simulator temperature at a position close to it to be lower than elsewhere. Thus, the battery temperature of the battery is not as uniform as in the first experiment.

Figure 8 shows the average surface temperatures of the battery simulators, both those without LHP and those using LHP for every heating power. At the heat generation of 20 W, the temperature of the battery simulator can be kept below 50 °C. At the 40 W heat generation, the battery simulator surface temperature can be lowered from 93°C to 65°C, or a decrease by 28°C. It appears that the LHP with LTP Copper wick was capable of providing a significant temperature reduction. These results indicated that the LHP was able to transfer heat effectively from the surfaces between the battery simulator through the evaporator toward the condenser. To know how much heat is transferred through LHP, an energy balance analysis is done as follows.

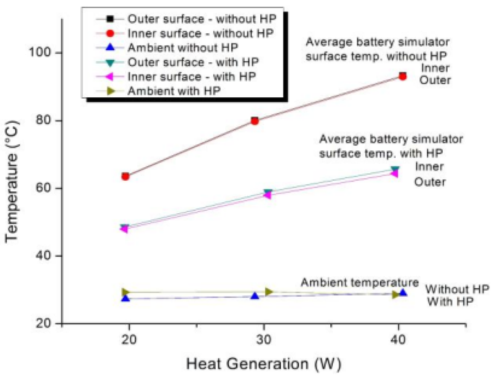

Figure 8. Effect of heat pipe utilization on battery simulator surface temperature

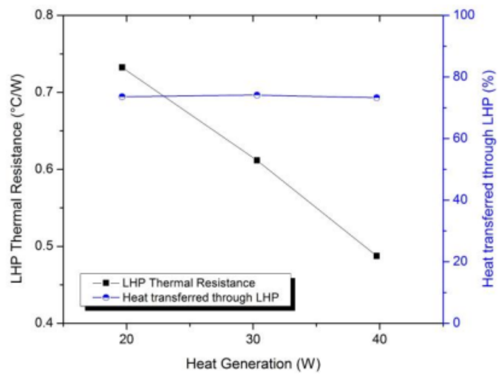

Figure 9. LHP performance

With ignoring the heat loss to the surrounding air, the heat transfer through the LHP was obtained using heat balance at the condenser section according to Eq. 1. The percentage of heat transfer is obtained by dividing the heat transfer through the LHP by the heat generation. Figure 9 shows the calculations results of the heat transfer through the LHP. It appears that for all heat generation, the percentage of heat transferred is always constant about 75%. The LHP thermal resistance can be obtained from equation 2. From figure 9 it appears that the thermal resistance tends to descend further at a higher heat load. It suggests that the LHP is still able to handle any higher heat load.

$$Q = \rho \dot{V} c_p (T_{co} - T_{ci}) \quad (1)$$

$$R = \frac{(T_e - T_c)}{Q} \quad (2)$$

Q : Heat transfer through the LHP (W)
R : Thermal resistance of LHP (°C/W)
ρ : Specific mass of cooling fluid (W)
$\dot{V}$: Volumetric flow rate of cooling fluid (m^3/s)
T_{co}, T_{ci} : Outlet and inlet temperature of cooling fluid (°C)
T_e, T_c : Average temperature of evaporator and condenser (°C)

4. Conclusion

The experiments to determine the performance of battery thermal management system using loop heat pipe with LTP Copper capillary wick have been successfully performed. The loop heat pipe with LTP Copper capillary wick was capable of significantly decreasing battery simulator temperature. At the heat generation of 20 W, the temperature of the battery simulator can be kept below 50 °C. At the heat generation of 40 W, the battery simulator temperature can be lowered from 93 °C to 55 °C, or a decrease by 38 °C. The loop heat pipe with LTP Copper capillary wick was able to effectively remove the heat from the battery simulator as much as 75% of the heat generated by the heater.

5. Acknowledgments

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