

Investigation of Cascade Loop Heat Pipes

Nandy Putra, Atrialdipa Duanovsah, Kristofer Haliansyah

Abstract—The aim of this research is to design a LHP with low thermal resistance and low condenser temperature. A Self-designed cascade LHP was tested by using biomaterial, sintered copper powder, and aluminum screen mesh as the wick. Using pure water as the working fluid for the first level of the LHP and 96% alcohol as the working fluid for the second level of LHP, the experiments were run with 10W, 20W, and 30W heat input. Experimental result shows that the usage of biomaterial as wick could reduce more temperature at evaporator than by using sintered copper powder and screen mesh up to 22.63% and 37.41% respectively. The lowest thermal resistance occurred during the usage of biomaterial as wick of heat pipe, which is 2.06 °C/W. The usage of cascade system could be applied to LHP to reduce the temperature at condenser and reduced thermal resistance up to 17.6%

Keywords—Biomaterial, cascade loop heat pipe, screen mesh, sintered Cu.

I. INTRODUCTION

EVOLUTION of electronic technology leads to a more compact design, which provide higher performance with less dimensional size. Higher heat flux will be produced by this development, leading to a higher temperature of electronic components. By using heat pipes [1] and vapor chamber [2], Putra et al developed passive cooling device to maintain the temperature of electronic device with high heat flux production. Loop Heat Pipe (LHP) that has a high thermal conductivity [3] with separated liquid line and vapor line, which let the liquid and vapor not block each other. LHP was first introduced by Gerasimov and Maydanik and was developed for aerospace needs between 1960 until 1970 [4]. It can transfer heat between great distances with small dimensional size. Performance of LHP is indicated by its thermal resistance, which is a ratio of temperature difference between the evaporator and condenser to heat which is transferred. The performance is affected by type of working fluid, filling ratio, configuration of evaporator, compensation chamber, inclination angle, ambient temperature, non-condensable gas, pressure drop in pipe, and capillary structure called wick that works as pump to drive fluids against gravity.

Many researches were done with varied wick to enhance LHP thermal performance. Wick, that receives heat flux, manage evaporation, and pump fluid to evaporator [5], [6] is usually tested by three factors which are the quantity of pumped fluid, flowing time of the fluid, and capillary velocity.

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The performance of the wick is affected by capillarity and permeability force. In order to increase wick performance, capillarity and permeability must be enhanced [7] through compaction of metal powder to homogenize pore diameter [6], [8]. Smaller pore diameter provide smaller thermal resistance, therefore manufacturing process of the wick plays role of thermal performance of the heat pipe [9], [10]. Jiyuan Xu [11] examined the affection of the volumetric ratio of pore former and pressure load at biporous wick. The research showed that smaller pressure and larger volumetric ratio of pore former conduce better porosity. Previous work by Putra et al [12], [13] used collaria biomaterial as wick inside LHP; it is known that biomaterial has more capillary force than sintered copper powder.

Beside wick, selecting type of working fluid and filling ratio is critical in designing LHP. Selecting pure water as working fluid with copper as a material of the pipe to create heat pipe will fulfill the needs of cooling system in electronic device [14]. Through his research, Roger R. Riehl [15] concludes that acetone is better to be used as working fluid rather than ammonia for its boiling point is lower than ammonia. Wuckchul Joung [16] experienced in varying filling ratio between 19% to 60.05% and gained 1.27 °C/W as the lowest thermal resistance with 78W heat input, 60.05% filling ratio, and the temperature at evaporator reach 124.1 °C. Shuangfeng Wang [17] stated that at low heat flux, two phase flow inside heat pipe will not occur and the thermal resistance is surely high. Moreover, it is known that a thick wick will give a better start up characteristic. Gravity force created a different flow characteristic with different inclination angle of LHP. As the result, saturated temperature, temperature of evaporator, and thermal resistance will be varied [18]. The effect of gravitation decreases by using wick along the fluid line [19].

The aim of this research is to design a LHP with low thermal resistance and low condenser temperature to keep the ambient condition from heating. Therefore, a self-designed cascade LHP was manufactured and tested experimentally.

II. METHODOLOGY

Generally, LHP is divided into fluid line, vapor line, wick, compensation chamber, evaporator, and condenser. Cascade LHP was basically designed by combining two LHP into one. The condenser of first LHP is fused with the bottom of evaporator at the second LHP, thus the condenser of the first LHP is the evaporator of second LHP. The first LHP is called first level LHP, and the second LHP is called second level LHP. Fig. 1 shows the designed cascade loop heat pipe made of copper. Wick of the heat pipe was varied by using biomaterial, aluminum screen mesh, and sintered copper

powder. Each type of wicks was tested under three load conditions which are 10W, 20W, and 30W.

Heat input was provided by 60W cartridge heater and controlled by voltage regulator. Temperatures were recorded in 10 points by using type K thermocouple and NI LabView software. Measurement points are marked by position from the end of liquid line of the first level of LHP. Measurement point is listed below:

1. T_1 : Evaporator (10mm)
2. T_2 : Evaporator (30mm)
3. T_3 : Vapor Line level 1 (100mm)
4. T_4 : Condenser level 1/ Evaporator level 2 (170mm)
5. T_5 : Condenser level 1/ Evaporator level 2 (190mm)
6. T_6 : Liquid Line level 1 (260mm)
7. T_7 : Vapor Line level 2 (330mm)
8. T_8 : Condenser (330mm)
9. T_9 : Condenser (350mm)
10. T_{10} : Liquid Line level 2 (420mm)

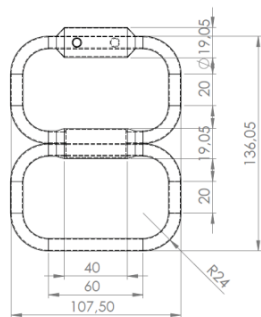


Fig. 1 Design of LHP

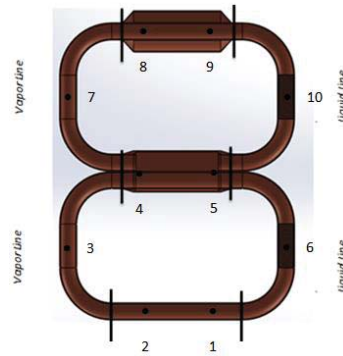


Fig. 2 Temperature Measurement Point of LHP

Fig. 2 shows the measurement point of the prototype. Insulation with *fiberglass wool* and *polyurethane box* was installed to minimize heat loss from the system. To remove the heat from heat pipe, fluid was circulated to the condenser of second level of heat pipe by CTB which maintained the fluid at 25 °C. Fig. 3 shows the experimental schematic diagram.

Collaria biomaterial with *Tabulate* type which its pore structure is homogenous enough was used. By using Scanning Electron Microscope (SEM), Fig. 4 shows that the average diameter of the pore is 42 μm . Not only has a good pore size, the surface roughness of biomaterial will create tracks for working fluid.

Production of sintered copper powder was begun with compaction process with 9.75 MPa. Furthermore, compacted 200 μm diameter powders are sintered at 900°C in 30 minutes. Fig. 5 visualizes SEM process of sintered copper powder. This type of wick has diameter size between 100 μm to 200 μm .

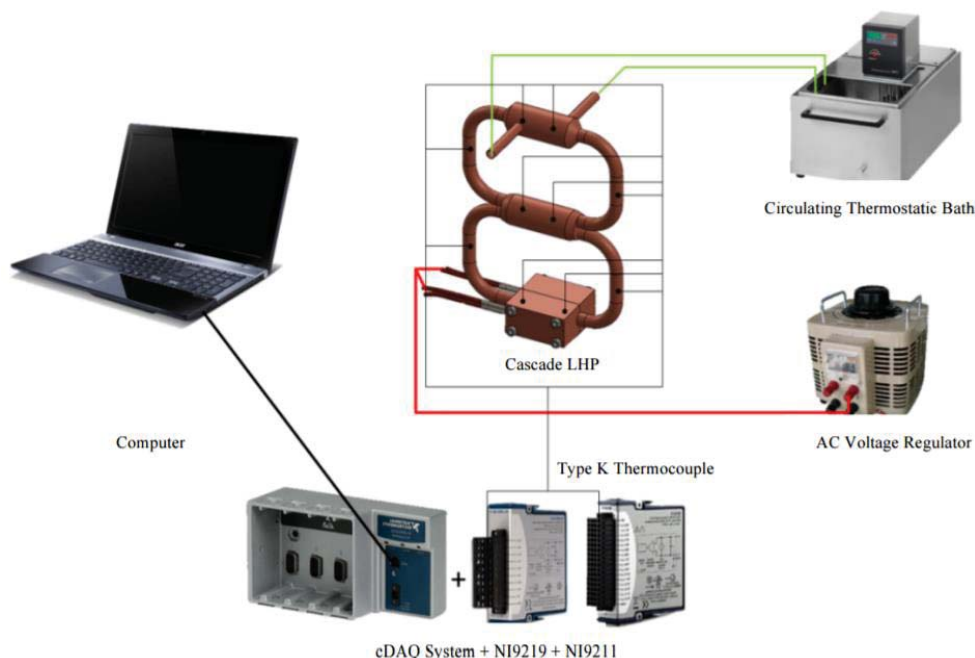


Fig. 3 Schematic Diagram of Experiment

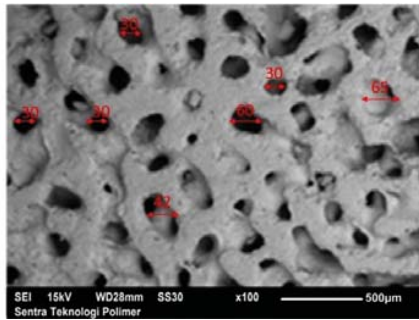


Fig. 4 SEM Visualization of Biomaterial

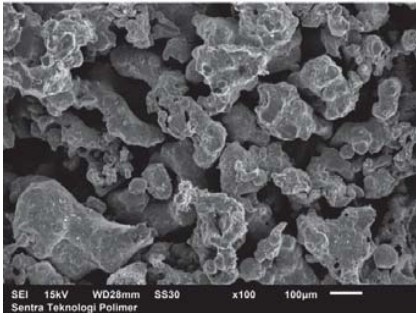


Fig. 5 SEM Visualization of Sintered Copper

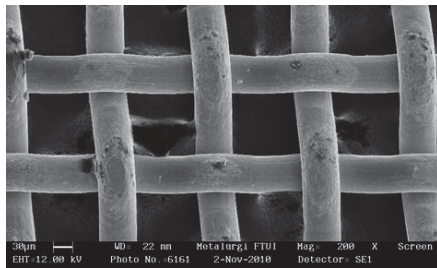


Fig. 6 SEM Visualization of Screen Mesh

Wick made of aluminum screen mesh with 200 mesh scale, 20 mm length and rolled with 7 mm diameter. Fig. 6 shows SEM process with 200 time's zoom of screen mesh which has 100µm length and width.

The first level of heat pipe will experienced a higher temperature at evaporator and condenser compared to the second level. As a consequence, using 1.5ml water as working fluid at the first level and 1.5ml 96% alcohol as working fluid at the second level is wise since the boiling temperature of water is higher than alcohol. The reduction of boiling temperature inside heat pipe is provided with -2.5 cmHg vacuum pressure inside the heat pipe.

III. RESULT AND DISCUSSION

The experiment was conducted until the system reach steady state that took time between 90 minutes until 120 minutes. Figs. 7, 8, and 9 show the experimental result for the experiment using biomaterial, sintered copper powder, and screen mesh as wick respectively. Similarity temperature profile was examined between each type of wick and heat load

where there are temperature drop from evaporator until vapor line and condenser at the first level. Temperatures begin to rise at the liquid line that caused by conduction from evaporator. Second level on the LHP has the same temperature profile characteristic with the first level, yet with the lower temperature difference between vapor line and liquid line. Boiling process at this experiment is proven since the temperature at vapor line is higher than at liquid line. Table I listed the temperature measurement at evaporator, condenser at the first level, and condenser at the second level. The reduction of temperature at evaporator by using biomaterial is 11.63%, 8.28%, and 2.87% compared to the usage of sintered copper powder at 10W, 20W, and 30W respectively. The reductions are very impactful when the usage of biomaterial with screen mesh is examined. The reductions are as much as 37.41%, 36.76%, and 34.28% at 10W, 20W, and 30W heat load. Moreover, the reductions by using sintered copper powder compared to screen mesh are 29.17%, 31.06%, and 32.34% at 10W, 20W, and 30W heat load.

Sintered copper powder is suitable for high thermal load. It is indicated when the temperature rise from 20W to 30W is much lower than 10W to 20W. Using aluminum screen mesh wire as wick at LHP is not wise. Despite the temperature profile still has similarity with other wick type; the temperature at the first level evaporator is much higher compared to the other type of the wick. This phenomenon caused by non-homogenous pore caused by rolling process to fit inside the copper pipe. Small temperature difference between vapor line and liquid line shows that conduction plays major at this variation.

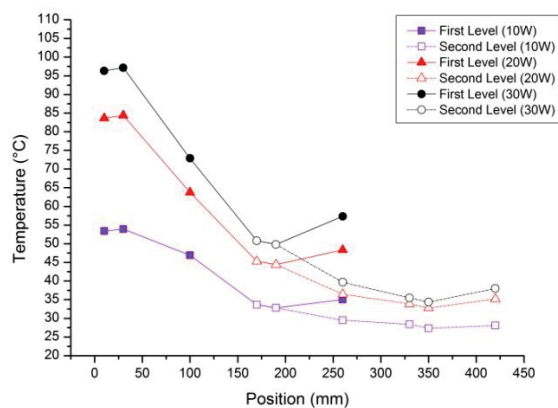


Fig. 7 Temperature Profile of Cascade LHP using Biomaterial

Joon Hong conclude that smaller pore size provides higher maximum thermal load and smaller thermal load [8]. It is known from Table II that biomaterial which pore size is the smallest, has the smallest thermal resistance for all heat load while screen mesh has the highest thermal resistance. Through the compacting and sintering process, sintered copper powder has homogenous pore size between 100 µm to 200 µm, creating low thermal resistance inside the LHP. Thermal resistance of sintered copper powder is not much higher than biomaterial. Non-homogenous pore caused by rolling process,

and large pore size of screen mesh lead into low capillary and permeability force which lead into high thermal resistance. This result is parallel from previous work [13] where collaria tabulate has transported more fluid by mass than sintered copper powder. It was predicted that by adding nano-particle to working fluid, the thermal performance will be increased.

Thermal resistance, which indicated thermal performance of LHP can be described with (1):

$$R = \frac{T_e - T_c}{q_{in}} \quad (1)$$

where T_e is temperature at evaporator, T_c is temperature at condenser, q_{in} is heat load that given to LHP. Through the calculation by using (1) and data that has been gathered, the thermal resistances of each variation are known. Table II informed the thermal resistance of each variation.

TABLE I
MEASURED TEMPERATURE OF VARIED LHP

Temperature at Measured Point	Biomaterial			Sintered Copper Powder			Screen Mesh Wire		
	10 W	20 W	30 W	10 W	20 W	30 W	10 W	20 W	30 W
Evaporator	53.4	83.66	96.3	60.43	91.21	99.15	85.32	132.3	146.54
Condensor (First Level)	33.63	45.28	50.82	32.04	43.71	48.09	45.53	66.36	80.74
Condensor (Second Level)	28.42	33.88	35.48	27.4	30.36	33.46	26.71	26.35	26.32

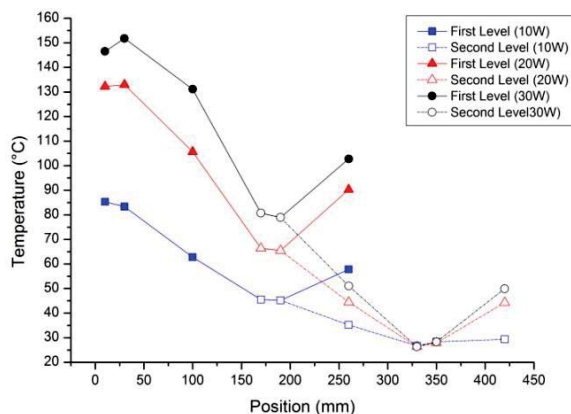


Fig. 9 Temperature Profile of Cascade LHP using Aluminum Screen Mesh

TABLE II
THERMAL RESISTANCE OF VARIED LHP

Heat load (W)	Thermal Resistance (°C/W)		
	Collaria Tabulate	Sintered copper	Screen mesh
10	2.58	3.38	5.68
20	2.53	3.09	4.61
30	2.06	2.22	3.80

Cascade design of LHP is promising enough to enhance thermal performance and predicted to reduce the temperature of condenser, especially at high heat input. It is proven by thermal resistance value of cascade LHP is much lower than normal LHP [13] by using condensed water at 30 W heat input. Thermal resistance of LHP decreased to up 17,6% by

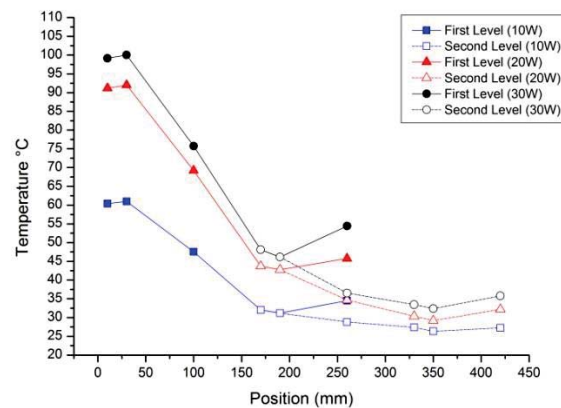


Fig. 8 Temperature Profile of Cascade LHP using Sintered Copper Powder

using cascade design with biomaterial wick and 30 W heat input.

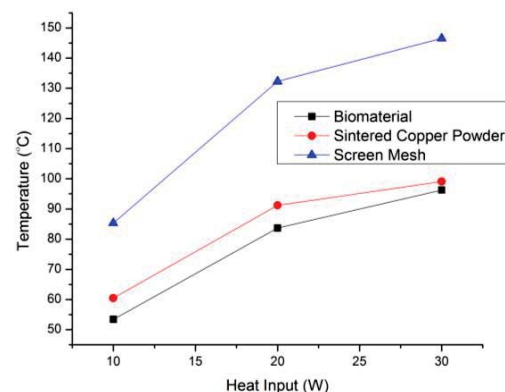


Fig. 10 Temperature at evaporator with varied wick structure and heat load

From Table II it is known that thermal resistance decreased as the heat load increased. This phenomenon explained by Chen et al. [20]. The thermal resistance of heat pipe decrease as the heat absorbed increase until the maximum heat input is reached. By the time the maximum heat input is reached, the thermal resistance will increase significantly as the heat input increase. Increasing thermal resistance after maximum heat input is caused by the dry out phenomenon. Study from this research describe that increasing temperature at evaporator linearly indicates insufficient amount of filled liquid. Fig. 10 shows increasing temperature at evaporator by addition of heat input. A nonlinear graph indicates sufficient filled liquid. Characteristic of the graphs are parallel to the characteristic

that has been found [20] by using flat plate heat pipe at low heat load.

IV. CONCLUSION

Research of cascade LHP was conducted with type of wick and heat load variation. Experimental result and further analysis shows that:

1. Cascade design of LHP reduces the temperature of condenser until range between 26-27 °C. Decreasing thermal resistance from previous work successfully proved that cascade design will provide heat transfer with better condenser temperature. Reduction of thermal resistance occurred up to 17.6% by using cascade design with biomaterial wick and 30 W heat input.
2. Collaria Tabulate is the best wick, which has high performance due to lowest thermal resistance and lowest temperature at evaporator for all heat load variation. Average temperature at evaporator while maximum heat load was applied was 96,8 °C, 99,8 °C, and 149,45 °C for biomaterial wick, sintered copper powder wick, and screen mesh wick respectively. Thermal resistance of LHP at maximum heat load condition was 2.06 °C/W, 2.22°C/W, and 3.8°C/W for biomaterial wick, sintered copper powder wick, and screen mesh wick respectively.

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