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EXPERIMENTAL STUDY ON THE LOOP HEAT PIPE OPERATING UNDER HORIZONTAL ORIENTATION

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Abstract – *Nowadays, Loop heat pipe (LHP), a passive two-phase heat transfer device, has been paid more attention for applying in the modern cooling electronics system. In this study, a LHP with flat-rectangular evaporator is fabricated and investigated thermal performance under horizontal orientation in two different cases that vary in length of vapor, liquid, and condenser lines. Water is selected as working fluid while sintered stainless steel wick is capillary structure of the LHP. The results show that the LHP with shorter lines operates better than the longer one and can keep the heater surface temperature smaller than 85°C when the heat load is at 80 W.*

Keywords: Loop heat pipe, Electronics cooling, Capillary force, Phase change.

1. INTRODUCTION

Heat pipe (HP) has been applying successfully and become the state of commercialization in the electronics cooling field. However, during the past decades, the electronics such as the processors, microprocessors changed enormously with the miniaturized tendency. For instance, it is predicted that the number of element per 1 cm^2 can reach 20 billion in 2020 [1]. It is sure that this tendency will offers the new challenges such as heat transport capacity, operation heat flux to the present HP cooling systems. At this moment, LHP, a novel catalogue of HP, can be considered as one of promising solutions that can face with the above challenge.

Although both LHP and HP operates base upon phase changing processes and utilizes the capillary or gravity force to maintain the circulation of working fluid, there are some different points between normal HP and LHP. Firstly, in LHP evaporating vapor and condensed liquid flows in two separated pipes, so it can avoid the occurrence of entrainment or flooding limitation that prevents condensed liquid from returning evaporator. Another point is the location of the wick. While the wick body covers almost the length of normal HP, it exists only inside LHP's evaporator with the thickness smaller than 1cm. Obviously, the pressure drop through the wick can be reduced, so LHP can transport heat through the further distance than conventional HP. In addition, fine pore wick such as sintered wick is often selected in the LHP to create higher capillary force for operating under various orientations such as horizontal, adverse as well as favorable gravity condition. In summary, comparing to normal HP, LHP has more flexible characteristics, higher heat transport capacity and further heat transfer distance ability.

Even though there are numerous studies on LHP, but almost all of them focused on the cylindrical LHP which is suitable for extraterrestrial applications. On the contrary, in the electronics cooling field on the earth, the flat-shaped evaporator possesses more benefits such as lighter weight, simple assembly, smaller thermal contact resistance due to the absence of thermal adapter between the HP and electronic devices. Despite the above advantages, the number of research on these LHPs has just begun to expand for ten years ago due to the complexity fabrication. For instance, in 2007 Randeep Singh et al [2] conducted a research on investigating the performance of miniature LHP with flat disk shape evaporator. Under the horizontal condition, their LHP can keep evaporator temperature below 100±5°C when working in the 5 W to 70 W range of heat load. Besides, they also conducted another study for investigating the effect of wick characteristics on the LHP's performance [3]. Evaporator with copper wick performs better than one with nickel wick; however, it also causes the larger heat leak from evaporator to compensation chambers. Moreover, for reducing the thickness of LHP, there are some research groups such as S. Wang et al [4], S. Becker et al [5], Yu. Maydanik et al [6], etc…who conducted study on LHP with flat-oval evaporator. This group of LHP is classified into the ELR (Evaporator with Longitudinal Replenishment) branches which compensation chamber is located aside active zone. Almost ELR LHP is thinner than 10mm; however, it requires complex fabrication procedure as well as easy to be deformed at high pressure operation.

In this study, a LHP with flat – rectangular evaporator is fabricated and investigated heat transfer characteristic under horizontal condition. Sintered stainless steel wick is used in this experiment. Water is selected as working fluid due to low pressure operation and good compatibility characteristics with copper. As shown in Fig. 1, a system of fins or crossing grooves is fabricated on the evaporator surface to sure not only heat transfer from heater to the wick but also creating the paths for vapor flow out sufficiently. Thermal performance of LHP is investigated when LHP works at different heat load in the two cases which connection lines, which include vapor and liquid line, and condenser are different in length.

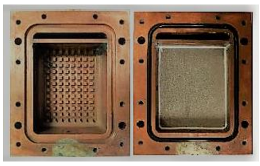

Fig.1: Evaporator with sintered stainless-steel wick

2. EXPERIMENT DESCRIPTION

2.1 Experimental setup and apparatuses

Figure.2 demonstrates the experimental schematic diagram. The LHP is profiled as a loop that includes evaporator, vapor line, condenser, and liquid line connecting respectively together. The evaporator is heated by the copper heating block which four cartridge heaters are inserted inside. To cut down thermal contact resistance, a thin layer of thermal conductivity grease is filled between top surface of heating block and bottom surface of evaporator. The YAMABISHI MVS – 520 Volt slider is used for converting the AC into DC source and adjusting amount of heat power input while magnitude is monitored on the YOKOGAWA WT230 digital power meter. In this experiment, condenser is cooled by water which circulate between condenser and ADVANTEC LV – 400 constant temperature circulator. As shown in Fig. 3, three 0.5mm – diameter K type T_1, T_2, T_3 are installed into the heating block to calculate the heat flux and temperature at the top surface of heating block T_{s1}. On the other hand, temperature from 1mm – diameter K type thermocouple T_4 can be used to estimate the temperature at bottom surface of evaporator. In addition, temperatures at evaporator outlet, condenser outlet as well as compensation chamber inlet are measured by three K type thermocouples T_{eo}, T_{co} and T_{cci} inserted directly on the path of working fluid. The mass flow rate and the temperature difference of cooling water when flowing through condenser are measured by the MASSMAX MMM7150K mass flow meters and two K type thermocouples $T_{wa\text{-}i}$, $T_{wa\text{-}o}$ respectively. Another thermocouple T_a measures the surrounding air temperature. Except for T_a, thermocouples are calibrated to sure that error is smaller than ±0.05°C. All measuring data is collected automatically by using Keithley 2071 Data Acquisition System which interfaces with PC by Exelink software. Table 1 shows LHP's parameters in detail.

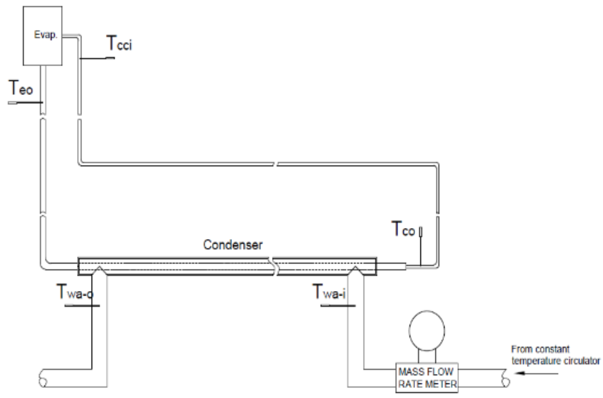

Fig.2: Schematic diagram of experiment

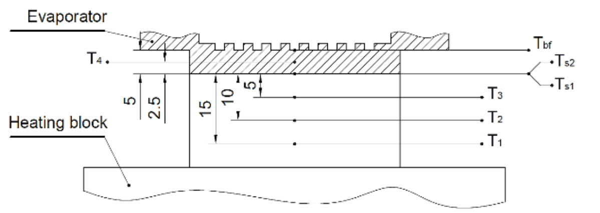

Fig.3: Positions of thermocouples inside heating block and base body of evaporator

Table 1: Main parameters of LHP in experiment

Evaporator		
Material	Copper	
Length, mm	80	
Width, mm	70	
Height, mm	25	
Active area, mm^2	60 x 45	
Fin geometry		
Cross area, mm^2	2 x 2	
Height, mm	1.5	
Fin pitch, mm	4	
Wick Structure		
Material	Stainless steel	
Pore radius, μm	63	
Porosity, %	36 – 48	
Bulk volume, mm^3	50 x 41 x 5	
Vapor line		
Length, mm OD/ID, mm	700 6.35/4.35	450 6.35/4.35
Condenser		
Length, mm OD/ID, mm	600 6.35/4.35	300 6.35/4.35
Liquid line		
Length, mm OD/ID, mm	1300 3.2/1.7	950 3.2/1.7
Working fluid	Water	

2.2 Experimental condition

The insulation of the heating block, evaporator, vapor line and condenser section are conducted carefully to eliminate the heat loss from heater as well as influence of environment on the result. During experiment period, room temperature is kept stably around 25ºC. The constant temperature circulator maintains the inlet temperature T_{wa-i} and mass flow rate of cooling water at value of 28.5ºC, 30 kg/h respectively. The heat power input is increased until the T_4 reaches 100ºC. Besides, to guarantee vacuum condition as well as proper amount of working fluid charged in LHP, the charging system consisting liquid tank, glass level indicator and stop valve as shown in Fig.4 was established, and the charging procedure was conducted carefully as following steps.

Fig.4: Connection between charging system (red rectangular) and LHP

Firstly, both of LHP and charging system was vacuumed to remove all non-condensing gases. Then, water was charged into charging system while LHP was disconnected by the stop valve. During this process, vacuum condition of charging system was lost; hence, it is necessary to vacuum the charging system again. Finally, the open the stop valve connecting between charging system and the LHP for water flowing into the LHP. The amount of charging water was determined from glass level indicator. Moreover, before charged into charging system, the purified water was also boiled to reduce the concentration of dissolve gases inside its volume.

2.3 Data reduction

Heat flux and heat flow rate flowing through the heating surface to active area of evaporator

$$q = k\frac{T_1 - T_2}{\delta} = k\frac{T_2 - T_1}{\delta} = k\frac{T_1 - T_3}{2\delta} \quad (1)$$

$$Q = qA \quad (2)$$

Heater surface temperature T_{s1}

$$T_{s1} = T_1 - 3\frac{q\delta}{k} \quad (3)$$

This temperature is considered as electronics temperature. With different electronic devices, the limits of this temperature are different. From [7], this value is often recommended to be at 85ºC for reliable and effective operation of electronics such as microprocessors, processers.

Total thermal resistance R_t

$$R_t = \frac{T_{s1} - T_{wa-i}}{Q} \quad (4)$$

3. RESULT AND DISCUSSION

3.1 Heat transfer capacity

From the experimental results, difference in length of connection lines and condenser varies the heat transfer capacity of LHP. With the condition that T_4, temperature at the base body of evaporator, is lower than 100ºC, the LHP with the shorter lines can work until heat load reaches 95 W while the longer one can transfer only 50 W from heater to the heat sink. The LHP can operate if the capillary condition described in Eq (5) is satisfied. The component Δp_v is the pressure drop relating to vapor phase that happens in vapor grooves, vapor line, and condenser. The Δp_l is the pressure drop when liquid flows through liquid line and wick structure. Opposite to conventional HP, in LHP the Δp_v is more dominated than the Δp_l. This explains why the vapor line and condenser become longer, despite the better cooling condition at condenser, it also contributes to the increment of total pressure drop, causes the capillary limitation happens and reduces heat transfer capacity of LHP.

$$\Delta p_c = \frac{2\sigma}{r} > \Delta p_v + \Delta p_l \quad (5)$$

3.2 T_{s1} and temperatures at different positions inside LHP change with heat load Q

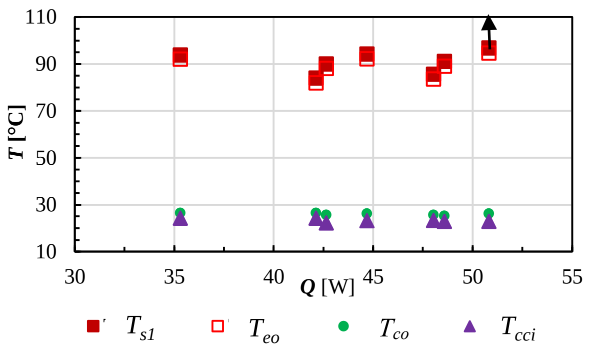

Fig.5: Temperatures vs heat load in the case of long LHP

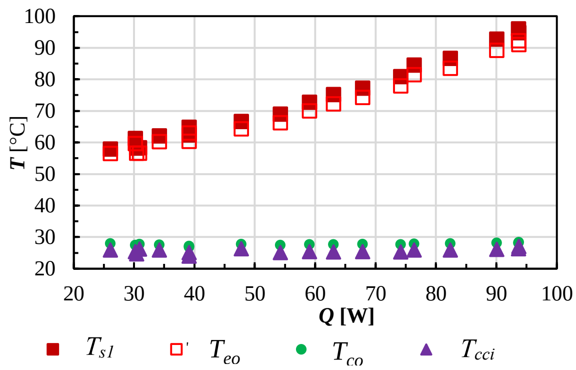

Fig.6: Temperature vs heat load in the case of short LHP

Figure. 5 and Fig. 6 demonstrate value of T_{s1} as well as T_{eo}, T_{co}, T_{cci} of the long and short LHPs when working at different heat load conditions. Both of long and short LHPs, T_{eo} is a little lower than T_{s1} while T_{co} and T_{cci} are nearly equal together. This result shows that the circulation exists in both cases, or there is no reverse flow of vapor from compensation chamber to condenser that will cause the sudden increment of T_{cci}. In the case of long LHP, values of T_{s1} are almost higher 85ºC although heat load is lower than 55 W. Besides, the changing tendency of this temperature is not regular with heat load. On the other hand, the short LHP can keep T_{s1} lower than 85ºC when heat load is at around 80 W. Besides, in the range of heat load that is larger than 50 W, the relation between T_{s1} and heat load become nearly proportional together which is similar to the constant conduction heat transfer mechanism.

3.3 Total thermal resistance vs heat load

For understanding more clearly performance of both long and short LHPs, the values of total thermal resistance R_t dependence of heat loads are demonstrated in Fig. 7. In this experiment, the R_t of long LHP are higher than 1.2 K/W while the short LHP can operate with the smallest R_t at 0.7 K/W with heat load at 75 W. For the long LHP, within the range of heat load from 35 W to 55 W, R_t has the reducing trend with heat load while for the short LHP, operation characteristics can be divided into two modes that are variable thermal resistance and constant thermal resistance. This explains why in the case of short LHP, when working at heat load higher than 50 W, the relation between T_{s1} and heat load is nearly linear. The higher values of R_t under low heat load conditions can be explained basing upon the small evaporating rate and flooding condition of evaporator; as a result, evaporating vapor flows out vapor groove to condenser difficultly, and supplying heat power has the trend that transfer through the wick body more easily, cause value of R_t to become higher.

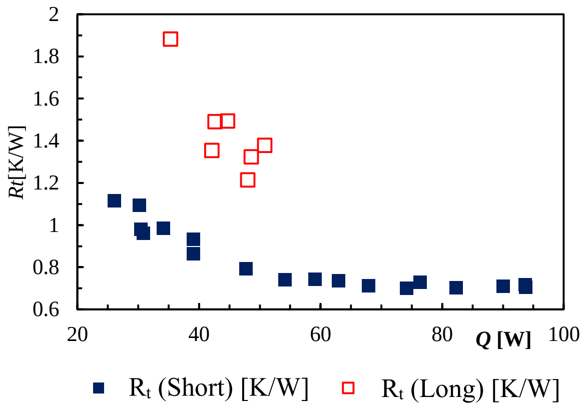

Fig.7: R_t of long and short LHP with heat load

4. CONCLUSION

In this study, the LHP with flat – rectangular evaporator is fabricated and investigated thermal performance under horizontal orientation when changing the length of connection lines and condenser.

Temperature distribution inside the LHP demonstrates that circulation happens in both of long and short LHP. However, longer connection and condenser line causes the heat transfer capacity of long LHP lower than short LHP because of increasing of pressure loss though cooling capacity of longer condenser is higher. Temperature at the surface of heater T_{s1} is higher than 85ºC and total thermal resistance are almost more than 1.2 K/W.

The short LHP can operate stably in the range of heat load from 25 W to 95 W when temperature at the base of evaporator is lower than 100ºC under horizontal condition. In addition, this LHP can keep T_{s1} below 85ºC, which can be regarded as limitation temperature for the reliable and effective operation of electronics, when operating at heat load around 80 W. The operation characteristics of LHP can be classified into two modes that are variable thermal resistance and constant thermal resistance.

5. REFERENCES

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6. NOMENCLATURE

Symbol	Meaning	Unit
OD/ID	Pipe outer, inner diameter	(m)
k	Copper thermal conductivity	(W/m·K)

A	Heated area	(m^2)
q	Heat flux	(W/m^2)
Q	Heat load	(W)
R_t	Total thermal resistance	(K/W)
δ	Distance among thermocouples	(m)
σ	Surface tension	(N/m)
r	Pore radius	(m)
T_1, T_2, T_3	Heater temperature	(ºC)
T_4	Evaporator base temperature	(ºC)
T_a	Room temperature	(ºC)
T_{co}	Temperature at condenser outlet	(ºC)
T_{cci}	Temperature at compensation chamber inlet	(ºC)
T_{eo}	Temperature at evaporator outlet	(ºC)
T_{s1}	Temperature at heater surface	(ºC)