Dept. of Mech. Eng.
CUET

Published Online March 2019 (http://www.cuet.ac.bd/merj/index.html)

Mechanical Engineering Research Journal

Vol. 11, pp. 54–58, 2018

ISSN: 1990-5491

EXPERIMENTAL STUDY ON THE LOOP HEAT PIPE OPERATING UNDER HORIZONTAL ORIENTATION

P. H. Huynh[1], A. R. Tuhin[2], K. Z. Htoo[1], K. Kariya[3] and A. Miyara[3*]

[1]Graduate School of Science and Engineering, Saga University, Saga, 840-8502, Japan
[2]Exchange Student, Graduate School of Science and Engineering, Saga University, Saga, 840-8502, Japan
[3]Department of Mechanical Engineering, Saga University, Saga, 840-8502, Japan

Abstract: Nowadays, Loop heat pipe (LHP), a passive two-phase heat transfer device, has been paid more attention in the field of cooling the modern electronic devices such as processors, IGBT modules, LED luminaire, etc. In this study, the LHP with flat-rectangular evaporator was fabricated and investigated thermal performance under horizontal orientation in two different cases that vary in length of vapor, liquid, and condenser lines. Water was selected as working fluid while sintered stainless steel wick was the 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 dissipated from the heating block is at the power of 80 W (2.96 W/cm^2).

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

NOMENCLATURE

OD/ID = pipe outer, inner diameter, mm
k = copper thermal conductivity, W/m K
A = heating area, m^2
q = heat flux, W/m^2
Q = heating power, W
R_t = total thermal resistance, K/W
T_1, T_2, T_3 = Temperature inside the heating block, °C
T_4 = temperature at the base of evaporator, °C
T_{co} = temperature at the outlet of condenser, °C
T_{cci} = temperature at the inlet of compensation chamber, °C
T_{eo} = temperature at the outlet of evaporator, °C
T_{s1} = temperature at the top surface of the heating block, °C

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 elements per square of centimeter can reach 20 billion in 2020 [1]. It is sure that this tendency will offer 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 to the above challenges.

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

*Corresponding author: Email: miyara@me.saga-u.ac.jp; Tel: 0952-28-8623

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 researches on these LHPs has just begun to expand for ten years ago due to the complexity fabrication. For instance, in 2007 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 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 Wang *et al.* [4], Becker *et al.* [5], 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 10 mm; however, it requires complex fabrication procedure as well as easy to be deformed at high pressure operation.

In this study, the performance of LHP operating horizontally was investigated by experiment. The LHP has the flat-rectangular shape evaporator equipped with commercial stainless-steel sintered wick is fabricated. The working fluid in the LHP was water due to its advantage thermal properties. Fig. 1 displays the structure of the evaporator, and the internal shape of evaporator after fabricating was shown in Fig. 2. There are the crossing grooves on the evaporator's inner surface that acts as the paths for vapor flowing out the evaporator. Thermal performance of LHP is investigated when LHP works at different heat load in the two cases that connection lines such as vapor and liquid line, and condenser are different in length.

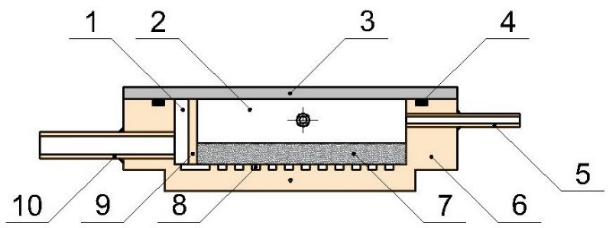

Fig. 1 The structure of the evaporator
1: vapor collector; 2: compensation chamber;
3: poly carbonate lid; 4: O-ring;
5: charging pipe; 6: copper evaporator body;
7: wick; 8: vapor grooves;
9: copper plate; 10: vapor pipe.

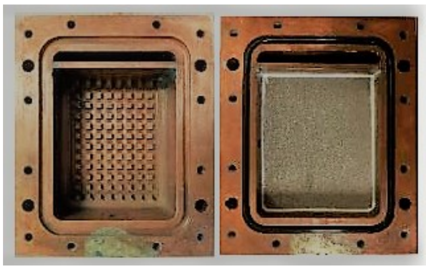

Fig. 2 Internal shape of evaporator with and without stainless-steel sintered wick.

2. EXPERIMENT DESCRIPTION

2.1 Experiment Setup

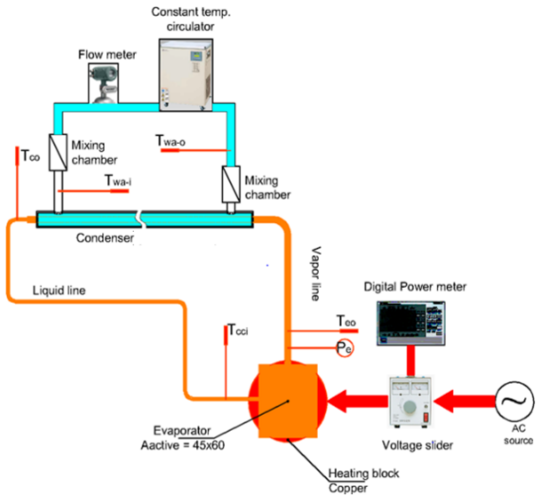

Fig. 3 The schematic diagram of experiment.

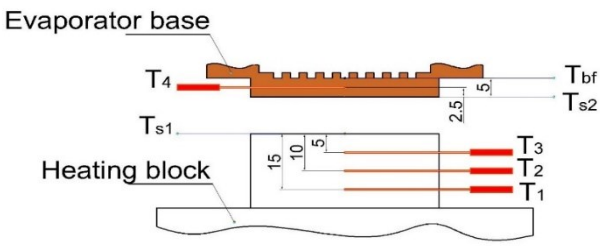

Fig. 4 Installation of thermocouples T_1, T_2, T_3 in the copper heating block and thermocouple T_4 at the evaporator base.

The schematic diagram of experiment is shown in Fig. 3. The LHP includes the evaporator, vapor line, condenser, and liquid line connecting respectively together. The heat dissipated from the electronics was illustrated by the four cartridge heaters inserted inside the copper heating block, and its magnitude was controlled and monitored by the YAMABISHI MVS520-Voltage slider and the YOKOGAWA WT230 digital power meter. A thin layer of thermal conductivity grease was filled between top surface of heating block and bottom surface of evaporator to eliminate the thermal contact resistance. However, to obtain the accurate value of heat load and heat flux flowing from the heating block to the evaporator of LHP, as shown in Fig. 4, three 0.5 mm K-type thermocouples were installed vertically to measure the temperature gradient. Besides, an 1 mm K-type thermocouples was inserted to the base of the evaporator to estimate the thermal contact resistance. To understand the circulation of working fluid inside the LHP, three K-type thermocouples T_{eo}, T_{co} and T_{cci} were inserted directly at different locations on the path of working fluid such as the outlet of evaporator, outlet of condenser as well as the inlet of compensation chamber. In this experiment, the condenser was cooled by water of which the inlet temperature and mass flow rate were maintained stably by the ADVANTEC LV-400-constant temperature circulator. The temperature difference of cooling water between the inlet and outlet of the condenser was measured by two K-type thermocouples $T_{wa\text{-}i}$, $T_{wa\text{-}o}$ while the MASSMAX MMM7150K mass flow meters was used to investigate the cooling water's mass flow rate. 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. The LHP performance was investigated under two cases that differ in length of vapor, condenser and liquid line.

Table 1 Main parameters of LHP

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 [7]	
Material	Stainless steel
Pore radius, µm	63
Porosity, %	36 – 48
Bulk volume, mm^3	50 x 41 x 5
Vapor line	
OD/ID, mm	6.35/4.35
Length, mm	700
	450
Condenser	
OD/ID, mm	6.35/4.35
Length, mm	600
	300
Liquid line	
OD/ID, mm	3.2/1.7
Length, mm	1300
	950
Working fluid	Water

2.2 Experimental Condition

During the experiment, the copper heating block, vapor tube and the condenser section were insulated carefully to reduce the heat loss and the influence of environment on the LHP performance. Room temperature were kept around 25°C. The mass flow rate and temperature of cooling water at the inlet of condenser were maintained at 30 kg/h and 28.5°C respectively. Because the evaporator lid is made from poly-carbonate, the heater should be turn of when T_4 reaches the value at 100°C.

Besides, to guarantee vacuum condition as well as proper amount of working fluid charged LHP, the charging system including liquid tank, glass level indicator and the stop valves as demonstrated in Fig. 5 was established, and the charging procedure was conducted carefully as following steps. Firstly, the whole volume of LHP and charging system was vacuumed by ULVAC GLD-051 pump. Then, charging water from the syringe to the liquid tank of the charging system while LHP and the charging system were disconnected by the stop valve. The charging system was vacuumed again to remove the non-condensable gases dissolved in the liquid. Finally, connecting the charging system and the LHP for water flowing into the LHP. The amount of charging water was determined from the change of liquid level observed at the glass level indicator.

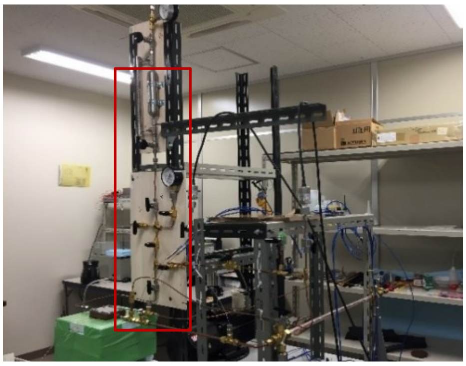

Fig. 5 The setup of LHP and charging system.

2.3 Data Reduction

From Fig. 4, heat load Q and heat flux q flowing from the heating surface to active area A (27 cm^2) of evaporator can be determined

$$\mathbf{q} = \frac{1}{3}\left(\mathbf{k}\frac{\mathbf{T_1 - T_2}}{\boldsymbol{\delta}} + \mathbf{k}\frac{\mathbf{T_2 - T_3}}{\boldsymbol{\delta}} + \mathbf{k}\frac{\mathbf{T_1 - T_3}}{\mathbf{2}\boldsymbol{\delta}}\right) \quad (1)$$

$$\mathbf{Q} = \mathbf{qA} \quad (2)$$

And temperature at the top surface of the heating block

$$\mathbf{T_{s1}} = \frac{1}{3}\left[\left(\mathbf{T_1} - 3\frac{\mathbf{q}\boldsymbol{\delta}}{\mathbf{k}}\right) + \left(\mathbf{T_2} - 2\frac{\mathbf{q}\boldsymbol{\delta}}{\mathbf{k}}\right) + \left(\mathbf{T_3} - \frac{\mathbf{q}\boldsymbol{\delta}}{\mathbf{k}}\right)\right] \quad (3)$$

Then, total thermal resistance of the LHP can be known

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

3. RESULTS AND DISCUSSION

3.1 Heat Transfer Capacity

From the experimental results, the 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 of evaporator, is lower than 100°C, the LHP with the shorter lines can work until heat load reaches 95 W while the longer one can transfer only 50 W from heating block 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 subcooled section existed inside the condenser, liquid line and wick structure. Opposite to conventional HP, in LHP the term 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 to happen and reduces heat transfer capacity of LHP.

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

3.2 Changing Of Temperature T_{s1} and Temperatures of Working Fluid at Different Positions inside the LHP with Heat Load Q

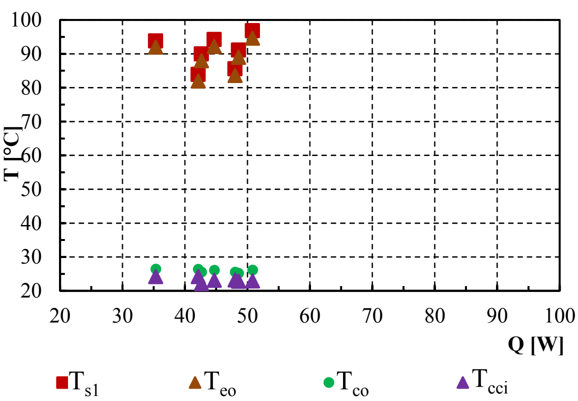

Fig. 6 Temperatures vs heat load in the case of long LHP.

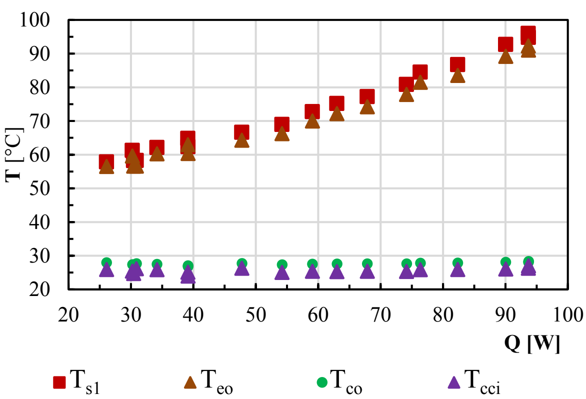

Fig. 7 Temperatures vs heat load in the case of short LHP.

Figs. 6 and 7 demonstrate the values of T_{s1} as well as T_{eo}, T_{co}, T_{cci} of the short and long 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 working fluid from compensation chamber to condenser that will cause the sudden increment of T_{cci}. If T_{s1} is assumed as operating temperature of electronics like processors, for the reliable and safety performance, it is often recommended that this temperature should not be higher than 85°C [8]. In the case of long LHP, values of T_{s1} are almost higher 85°C 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 85°C 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 becomes 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 changing of total thermal resistance R_t due to heat load are demonstrated in Fig. 8 and Fig. 9. 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 value of R_t at 0.7 K/W under heat load of 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 functioning at heat load higher than 50W, 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 because of the small evaporating rate and flooding condition of evaporator; as a result, evaporating vapor flows out vapor grooves to condenser difficultly, and supplying heat power has the trend towards transferring through the wick body more easily, cause value of R_t to become higher.

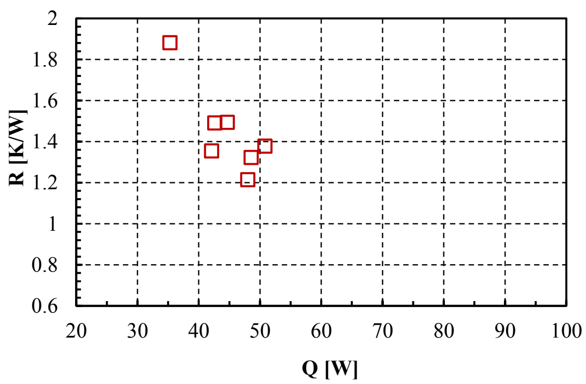

Fig. 8 R_t vs heat load in the case of long LHP.

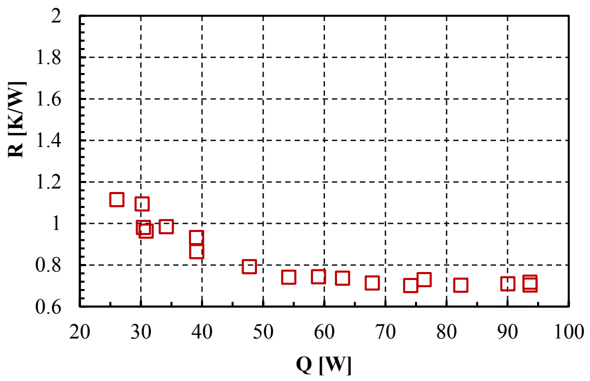

Fig. 9 R_t vs heat load in the case of short LHP.

4. CONCLUSIONS

In this study, the LHP with flat – rectangular evaporator was 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 top surface of heating block T_{s1} is higher than 85°C 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 100°C under horizontal condition. In addition, this LHP can keep T_{s1} below 85°C, 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.

REFERENCES

[1] S. M. Sohel Murshed and C. A. Nieto de Castro, "A critical review of traditional and emerging techniques and fluids for electronics cooling", Renew. Sustain. Energy Rev., Vol. 78, no. March 2016, pp. 821–833, 2017.

[2] R. Singh, A. Akbarzadeh, and M. Mochizuki, "Operational characteristics of a miniature loop heat pipe with flat evaporator", Int. J. Therm. Sci., Vol. 47, pp. 1504–1515, 2008.

[3] R. Singh, A. Akbarzadeh, and M. Mochizuki, "Effect of wick characteristics on the thermal performance of the miniature loop heat pipe", J. Heat Transfer, Vol. 131, no. 8, p. 082601, 2009.

[4] S. Wang, J. Huo, X. Zhang, and Z. Lin, "Experimental study on operating parameters of miniature loop heat pipe with flat evaporator", Appl. Therm. Eng., Vol. 40, pp. 318–325, 2012.

[5] S. Becker, S. Vershinin, V. Sartre, E. Laurien, J. Bonjour, and Y. F. Maydanik, "Steady state operation of a copper e water LHP with a flat-oval evaporator", Appl. Therm. Eng., Vol. 31, no. 5, pp. 686–695, 2011.

[6] Y. Maydanik, S. Vershinin, M. Chernysheva, and S. Yushakova, "Investigation of a compact copper e water loop heap pipe with a fl at evaporator", Appl. Therm. Eng., Vol. 31, no. 16, pp. 3533–3541, 2011.

[7] SMC Coporation, Sinter metal element (EB/ES Series), pp. 103–11 [cited 2017 Nov. 27th].

[8] K. Ebrahimi, G. F. Jones, and A. S. Fleischer, "A review of data center cooling technology, operating conditions and the corresponding low-grade waste heat recovery opportunities", Renew. Sustain. Energy Rev., Vol. 31, pp. 622–638, 2014.