Thermal performance comparison of flat plate evaporator loop heat pipe operating between horizontal condition and gravity assisted condition

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Abstract. With huge developments of science and engineering especially information and communication technology, loop heat pipe (LHP), a passive two-phase cooling device, can be considered one of the promising heat transfer devices with effective thermal conductivity. In this study, a new evaporator structure is fabricated and experiments are carried out horizontal and gravity assisted operating condition. Water is selected as working fluid while sintered stainless steel wick is installed as capillary structure of LHP. The Results show that, gravity assisted LHP has higher performance compared to horizontal LHP and it can keep stable operating state at heat load 520 W without dry out phenomenon.

1. Introduction

Nowadays, conventional heat pipe (HP) is used widely and successfully in cooling electronic equipment. With their miniature and multinational tendency, heat flux generated from electronics increases day by day. For example, there is a survey that 50-1000 elements have been installed per chip in the 1960s but the prediction said that it will be about 20 billion per 1 cm² in 2020 (1). Therefore, it is necessary to study on new cooling methodologies with new challenges of heat transport capacity. Although both HP and LHP is a heat transfer device which operation principle based upon phase changing process and utilizes the capillary or gravity force to complete the circulation of working fluid, there is a difference between normal HP and LHP. To compare with other HP, the LHP has the higher capacity of heat transfer and flexible characteristics because of the absence of the wick structure in the connection lines as well as separation of vapor and liquid lines. It can eliminate the occurrence of entrainment or flooding limitation that restricts condensed liquid from returning evaporator. Moreover, the LHP comprises a two-phase working fluid reservoir which is known as compensation chamber. This compensation chamber plays an important role to determine the pressure and temperature of LHP. In addition, fine porous sintered wick is often selected to create
strong capillary force for operating under horizontal condition as well as favourable gravity assisted condition. Until now, LHP with cylindrical evaporator has been utilized successfully in cooling electronics of extra terrestrial applications. To compare with flat rectangular evaporator LHP, the main disadvantage of cylindrical evaporator LHP is having higher thermal resistance between evaporator and heat source. To reduce the thermal contact resistance, even if thermal resistance sheet is inserted between evaporator and heater source, it will little decrease the thermal resistance, but at the same time it will increase the weight of electronics device. Although both flat rectangular evaporator LHP and disk type evaporator LHP have the almost same performance and can reduce the thermal contact resistance, but most of the electronics device that require cooling have a flat surface. In summary, flat rectangular evaporator LHP can use the proper area of electronics device as well as reduce the thermal contact resistance. Therefore, with developing trend of electronics equipment especially CPU, data centre etc… LHP with flat rectangular evaporator are now again considered as potential solution.

From the previous points, there are many studies are going on to find an efficient, low cost and long term reliable electronics cooling solution with minimum maintenance demand. Zhou et al. (2) designed a mini LHP for cooling mobile electronics, which consists of a heating power of 11 W and an evaporator temperature of 97.2 0C. Ayaka Suzuki et al. (3) experimented on cooling performance of a JEST (Jet Explosion Stream Technology) type LHP. They confirmed that maximum heat transport rate was 780 W, when heat flux was 195 W/cm2 and obtained a total thermal contact resistance of 0.13 K/W. Cheiko Kondou et al. (4) carried out experiment on looped thermosyphon performance with volatile fluids such as R1234ze(Z) and R1234ze(E) as working fluids. In their study, they conclude that by using super-hydrophilic boiling surface, nuclear boiling heat transfer can be enhanced. Shioga and Mizuno (5) investigated a MLHP with water as working fluid for thermal management of smart phones.

In this study, a flat-rectangular evaporator copper LHP is fabricated and the experiment was conducted to measure the performance under horizontal condition which is also known as ‘no gravity’ condition and gravity assisted condition. Sintered stainless steel is used and water is selected as working fluid as water can operate in low pressure and has good compatibility with copper. As shown in Figure 1, a system of fins or crossing grooves is machined to confirm the heat transfer from heater to the wick and create the paths for vapor flow out sufficiently.

Figure 1. Evaporator with sintered stainless-steel wick

2. Experiment setup and condition

2.1. Experimental setup

Figure 2 demonstrates the schematic diagram of the experiment. Both horizontal and gravity assisted LHP are consisted as a loop that connected evaporator, vapor line, condenser and liquid line, respectively together. Evaporator, vapor line, condenser and liquid lines are placed in same elevation in case of horizontal LHP. On the other hand, when experiment was carried out in gravity assisted condition, vapor and liquid line was set up vertically and condenser was set up horizontally above evaporator and connected with vapor line and liquid line. Other experimental apparatus kept same orientation in both cases. Four cartridge heaters are inserted inside the copper heating block to heat the
evaporator section. To reduce the thermal contact resistance, a thin layer of thermal conductivity grease is filled between the upper surface of heating block and the lower surface of evaporator. AC source is converted into DC source by the YAMABISHI MVS – 520 Volt slider and heat load is adjusted while magnitude is monitored on the YOKOGAWA WT230 digital power meter. On the other hand, condenser is cooled by water which circulate between condenser and ADVANTEC LV – 400 constant temperature circulator. As shown in figure 3, three (0.5mm diameter) K type thermocouples are inserted into the heating block to calculate the heat flux and temperatures (T1, T2, T3) at the top surface of heating block Ts1. One (1mm diameter) K type thermocouple has been inserted to estimate the temperature (T4) at bottom surface of evaporator. Moreover, temperatures at evaporator outlet (Teo), condenser outlet (Tco) as well as compensation chamber inlet (Tcci) are determined by three K type thermocouples and inserted directly on the path of working fluid. The mass flow rate and the temperature difference of cooling water when flowing through the condenser are measured by the MASSMAX MMM7150K mass flow meters and two K type thermocouples Twa-i, Twa-o respectively. Another thermocouple Ta measures the surrounding air temperature. Except for Ta, thermocouples are calibrated to ensure 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 the LHP’s parameters in detail.

Figure 2. Schematic diagram of experiment

Figure 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 | 700 |
| OD/ID, mm | 6.35/4.35 |

| Condenser |  |
|---|---|
| Length, mm | 600 |
| OD/ID, mm | 6.35/4.35 |

| Liquid line |  |
|---|---|
| Length, mm | 1300 |
| OD/ID, mm | 3.2/1.7 |

**2.2. Experimental condition**

The insulation of the heating block, evaporator, vapor line and condenser section are done carefully to eliminate the heat loss from heater as well as influence of environment on the result. During experiment, room temperature is kept constant around 25°C. The constant temperature circulator maintains the inlet temperature T\(w_a\)-i and mass flow rate of cooling water are of 28.5°C, 30 kg/h respectively. The heat power input is increased until the temperature (T4) reaches 100°C. 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 Figure 4 was established, and the charging procedure was conducted carefully as following steps.
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, water is charged into LHP by opening the stop valve (connection between charging system and 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 the heat flow rate flowing through the heating surface to active area of evaporator

\[ q = k \frac{T_1 - T_2}{\delta} = k \frac{T_2 - T_1}{\delta} = k \frac{T_1 - T_3}{2\delta} \]  

(1)

\[ Q = qA \]  

(2)

Heater surface temperature \( T_{s1} \)

\[ T_{s1} = T_1 - 3 \frac{q\delta}{k} \]  

(3)

This temperature is considered as electronics temperature. With different electronic devices, the limits of this temperature are different. From (6), this value is often recommended to be at 85°C for reliable and effective operation of electronics such as microprocessors, processors etc.

Total thermal resistance \( R_t \)

\[ R_t = \frac{T_{s1} - T_{wa-i}}{Q} \]  

(4)

3. Results and Discussion

3.1. Heat transfer capacity

Experiments showed that operating condition has the significant effects on varying heat transfer capacity of LHP. Under horizontal condition, fluid circulation in an LHP only driven by the capillary force where gravity assisted condition, fluid circulation in an LHP driven by both capillary and gravitational forces. With the condition, temperature \( T_4 \) at the base body of the evaporator, is lower than 100 °C, the gravity assisted LHP can work until the heat load reaches 520 W. On the other hand, horizontal LHP can transfer only 50 W from heater to the heat sink. For the horizontal LHP, the capillary condition can describe in Eq (5). Vapor phase pressure drop such as vapor grooves, vapor line, and condenser line pressure drop is denoted by \( \Delta p_v \). On the other hand, pressure drop when liquid flows through liquid line and wick structure is denoted by \( \Delta p_l \). The length of the connection lines
contributes to the increment of total pressure drop, causes the capillary limitation happens and this explains why horizontal LHP reduces heat transfer capacity.

\[ \Delta p_c = \frac{2\sigma}{r} > \Delta p_v + \Delta p_l \]

### 3.2. Ts1 and temperatures at different positions inside LHP change with heat load \( Q \)

![Figure 5](image)

**Figure 5.** Temperatures vs heat load in the case of horizontal LHP

![Figure 6](image)

**Figure 6.** Temperature vs heat load in the case of gravity assisted LHP

The values of \( T_s1 \), \( T_e0 \), \( T_co \) and \( T_cci \) of the horizontal and gravity assisted LHPs are demonstrated on figure 5 and figure 6 when operating at different heat load conditions. Both cases, \( T_co \) is a little lower than \( T_s1 \) which confirms that circulation happens inside the LHP. Moreover, \( T_co \) and \( T_cci \) are nearly equal together. This result shows that there is no reverse flow from compensation chamber to condenser that will cause the sudden increment of \( T_cci \). In horizontal LHP, \( T_s1 \) is almost higher than 85 °C although heat load is lower than 55 W. Besides, changing tendency of this temperature is not regular with heat load. However, gravity assisted LHP can keep \( T_s1 \) lower than 85 °C until heat load reaches 350 W.
3.3. Total thermal resistance vs heat load

To understand more clearly performance of both horizontal and gravity assisted LHPs, the values of total thermal resistance $R_t$ according to heat load are demonstrated in Figure 7. In horizontal condition, $R_t$ is always higher than 1.2 K/W and it has the reducing trend with heat load range from 35 W to 55 W. On the other hand, gravity assisted condition, the minimum value of $R_t$ is 0.133 K/W and the operation characteristics can be divided into two types that are variable thermal resistance and constant thermal resistance. From this, it is observed that in case of gravity assisted condition (when working at high heat load), the relation between heater surface temperature ($T_{s1}$) and heat load ($Q$) is nearly linear. The higher values of $R_t$ under low heat load conditions can be explained on the basis of upon the small evaporating rate; as a result, it is difficult for evaporating vapor flows out vapor groove to condenser.

![Figure 7. Rt of gravity assisted (G) and horizontal (H) LHP with heat load](image)

4. Conclusions

In this study, a LHP with flat rectangular-shape evaporator is manufactured and compared the performance between horizontal condition and gravity assisted condition. It is confirmed that circulation happens in both horizontal and gravity assisted condition. However, heat transfer capacity of horizontal LHP is lower than gravity assisted LHP because of higher pressure loss. Temperature at the surface of heater $T_{s1}$ is higher than 85 °C and total thermal resistance is greater than 1.2 K/W.

The gravity assisted LHP can operate stably in the range of heat load from 50 W to 520 W when temperature at the base of evaporator is lower than 100°C. Besides, 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 350 W. The operation characteristics of LHP can be classified into two modes that are variable thermal resistance and constant thermal resistance.

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Nomenclature

| (a) Symbol | (b) Meaning | (c) Unit |
|-----------|-------------|----------|
| OD/ID     | Pipeouter, inner diameter | (m) |
| κ         | Copper thermal conductivity | (W/m·K) |
| A         | Heated area | (m²) |
| q         | Heat flux | (W/m²) |
| Q         | Heat load | (W) |
| R         | Total thermal resistance | (K/W) |
| δ         | Distance among thermocouples | (m) |
| σ         | Surface tension | (m) |
| r         | Pore radius | (N/m) |
| T₁, T₂, T₃ | Heater temperature | (°C) |
| T₄        | Evaporator base temperature | (°C) |
| T₅        | Room temperature | (°C) |
| T₆        | Temperature at condenser outlet | (°C) |
| T₇        | Temperature at compensation chamber inlet | (°C) |
| T₈        | Temperature at evaporator outlet | (°C) |
| Tₛ₁       | Temperature at heater surface | (°C) |