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Effect of different charge ratios on transient performance of a flat type of the LHP with a shared compensation chamber

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ABSTRACT

In this paper, the loop heat pipe (LHP) with a shared compensation chamber (SCC) has been put forward, and the SCC must supply working fluid to two primary wicks in the opposite replenishment way. Thus, charge ratio of the working fluid would have a great influence on operating behaviors of this new LHP system. Through the calculation, the optimal charge ratio for this new system ranged from 0.69 to 0.77. In this investigation, transient performance of this system were analyzed at charge ratio of 60% (below the optimal value) and 75% (optimal value), respectively. With the evaporator temperature below (90 ± 2)°C, the experimental results showed that the LHP system could start up successfully at the given heat load range when one side was only heated or two sides were heated simultaneously. With Charge ratio fixed at 60% and the LHP system in the horizontal orientation, startup tests with two sides manifested reverse direction of fluid circulation because of heat leak from two heating sides. For the LHP system with 10^0 of tilt angle (the condenser above the evaporator), startup with one side could enter into steady state at the heat load ranging from 10 W to 140 W. However, with charge ratio increasing to 75% and the LHP system located at 10° of tilt angle, operating performance with two sides was greatly improved, and the total transferred maximum heat load reached up to 240 W. Especially at low heat load ranges, the LHP system stability was obviously improved. Otherwise, continuous operation with two sides was tested, and the total thermal resistances of two different cases were discussed based on parallel electrical resistance analysis.

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1. Introduction

The rapid advance in thermal packaging of electronic equipment leads to large amount of waste heat from electronic devices [1], various cooling technologies have been developed to address these thermal problems. Loop heat pipes (LHPs) are highly efficient two-phase heat-transfer device with a considerable potential for development and application in various fields [2]. In past decades, LHPs have been successfully tested and employed in aerospace engineering [3], and its applications gradually extend from spacecraft to terrestrial electronics [4]. The key component of the LHP is the evaporator structure, mainly affecting the heat transfer performance and the maximum transferred heat load. With the development of the LHP technology, the shape of LHP evaporators have been evolved into two types: the cylindrical and the flat, based on the purpose, the shape and dimensions of heat source, and also working fluid used [5]. Flat evaporators benefit from its flat surface without additional cylinder-plane reducer for thermal contact with flat heat source, but still suffering from high deformative nature of the flat surface, high heat leak from the active zone and temperature oscillations [6,7].

In order to implement LHPs inside limited space, numerous experiments and theoretical analysis have been carried out to improve the structure of the flat evaporator and test the operating characteristics of LHPs with flat evaporators. More efforts have been made to the design of the miniature loop heat pipes (m-LHP), which can be easily integrated inside the compact enclosure of electronic equipment [2,8,9]. Depending on the relative direction of the main liquid flow in the wick and heat flow to the evaporator wall, a clearly defined development of two main types of the flat evaporators are evaporators with opposite replenishment (EOR) and evaporators with longitudinal replenishment (ELR) [5], respectively. Liu et al. have combined the advantages of a capillary pumped loop and a flat type of the LHP [10], and have done lots of experiments to study the effect of various factors, including porous wicks, orientations, different working fluids and charge ratio, on

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the heat transfer performance of the LHP with EOR [11–16], making much contribution to the development of LHPs with EOR. For the LHPs with ELR, Randeep et al. presented results about the compensation chamber positioned on the side of the wick structure [17], and Wukchul et al. investigated a flat bifacial evaporator, transient response and steady state were discussed in detail [18,19]. However, concerning the LHP with EOR whose the compensation chamber is shared by two sides of the evaporator is still rarely published, the lack of data about this structure necessitates further investigation.

In this work, the structure of the evaporator with a SCC was introduced, and its startup performance and transient response were mainly discussed at two different charge ratios of 60% and 75%. In the last of this paper, thermal property was analyzed and compared under the condition of operation with two sides simultaneously heated.

2. Test setup

The test system was a miniature methanol-copper LHP which consisted of an evaporator with the integrated compensation chamber (CC), two nickel wicks, a secondary wick, liquid/vapor line transport lines, and a condenser, Table1 summarized the geometry parameters of the loop components, where O.D. and I.D. represented the outer and inner diameter, respectively. Main features of the LHP were that two sides of its evaporator could be utilized for heat dissipation. Fig. 1 presented the assembly diagram of the new evaporator structure.

Two capillary wicks and a secondary wick were inserted into the evaporator, and they encircled an annular cavity, working as the compensation chamber. The gap between side 1 and side 2 formed the vapor chamber for collecting vapor from vapor grooves. The evaporator and the condenser were joined together by vapor and liquid transport lines, developing a closed loop. The tube-in-tube condenser was used to cool the working fluid, whose temperature was controlled by a chiller. Heat source 1 and heat source 2 were made of copper block with three embedded cartridge heaters and had an active diameter of 35 mm. The supplied heat load was regulated by the wattmeter with relative accuracy of 0.5%, and both of two heat sources could work alone. For reducing the effect of the ambient temperature on the system, the whole loop and heat sources were wrapped by 10 mm thickness adiabatic material with conductivity of 0.012 W/m·K. 24 T-type thermocouples were attached to the LHP system to monitor the temperature of characteristic points, and the data was acquired by Keithley-2700 data acquisition system, Fig. 2 described the locations of the characteristic points and T-type thermocouples, Tc24 tested the ambient temperature.

The LHP system only can operate efficiently under the condition of a certain charge ratio of working fluid, the optimal charge ratio can be determined by the following equations:

Table 1
Summary of design parameters.

Components	Dimensions	value
The evaporator	O.D./height	43.30/16.65 (mm)
Capillary wick 1	Thickness/groove width/groove depth	4.26/2/1.59 (mm)
	porosity	75%
Capillary wick 2	Thickness/groove width/groove depth	4.21/2/1.59 (mm)
	porosity	78%
Secondary wick	O.D./I.D./thickness	37.6/27/6 (mm)
Vapor line	O.D./I.D./length	4/3/330 (mm)
Liquid line	O.D./I.D./length	4/3/490 (mm)
Condenser	O.D. for the working fluid	4 (mm)
	O.D. for the coolant	12 (mm)
	Length	802 (mm)

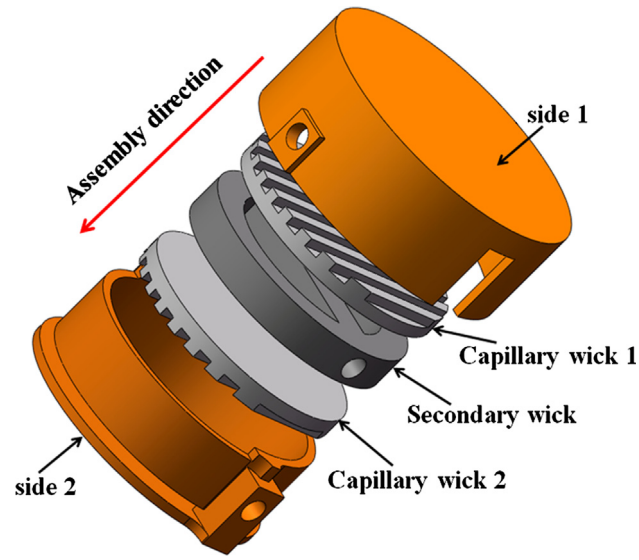

Fig. 1. The internal structure of the evaporator with a SCC.

$$\alpha V_{total} > V_{cond} + V_{ll} + V_{wick} + (1-\beta)V_{cc} \quad (1)$$

$$\alpha V_{total} < V_{cond} + V_{ll} + V_{wick} + V_{cc} \quad (2)$$

where α is the charge ratio, an experienced value for β is vapor share in the CC. V_{cond}, V_{ll}, V_{wick}, V_{cc}, and V_{total} represent the internal volume of the condenser, liquid line, porous wick (including primary wick and secondary wick), CC and the whole LHP system, respectively. For this system, β was taken to be equal to 0.5 and the optimal value α ranged from 69% to 77%. Investigation was conducted at charge ratio of 60% (below the optimal value) and 75% (optimal value). Before charging the working fluid, the LHP system was evaluated to 4.0×10^{-4} Pa and 4.1×10^{-4} Pa at 60% and 75%, respectively.

3. Results and discussion

A successful startup is the most important performance for the LHP, and is defined as that the LHP reaches steady state or operates with a certain amplitude and period. From the view of the working fluid circulation, it can flow from the evaporating surface to the CC or from the CC to the evaporating surface through the condenser. The former one is suitable for most of successful LHPs, accompanying with low operating temperature while the latter only occurs under certain conditions for minority of special LHPs, accompanying with high operating temperature.

After successful startup, subsequent steady operation is affected by many factors, including heat load, charge ratio, tilt angle, working fluid, system structure and materials. Aiming at this LHP with a SCC, this investigation was mainly focused on analysis of its transient performance, including startup performance and heat load cycle, at two different charge ratios of 75% (optimal value) and 60% (below the optimal value).

3.1. Startup tests with one side

Under the same conditions except for charge ratio, startup with one side was made a comparison. Heat source 2 worked alone, namely, heat load was only applied to side 2. Most of heat was conducted to capillary wick 2 for the liquid vaporization and part of heat was transferred to capillary wick 1 through the evaporator side wall. The operation with one side was similar to most of LHPs with EOR. Figs. 3 and 4 depicted two startup processes of 140 W.

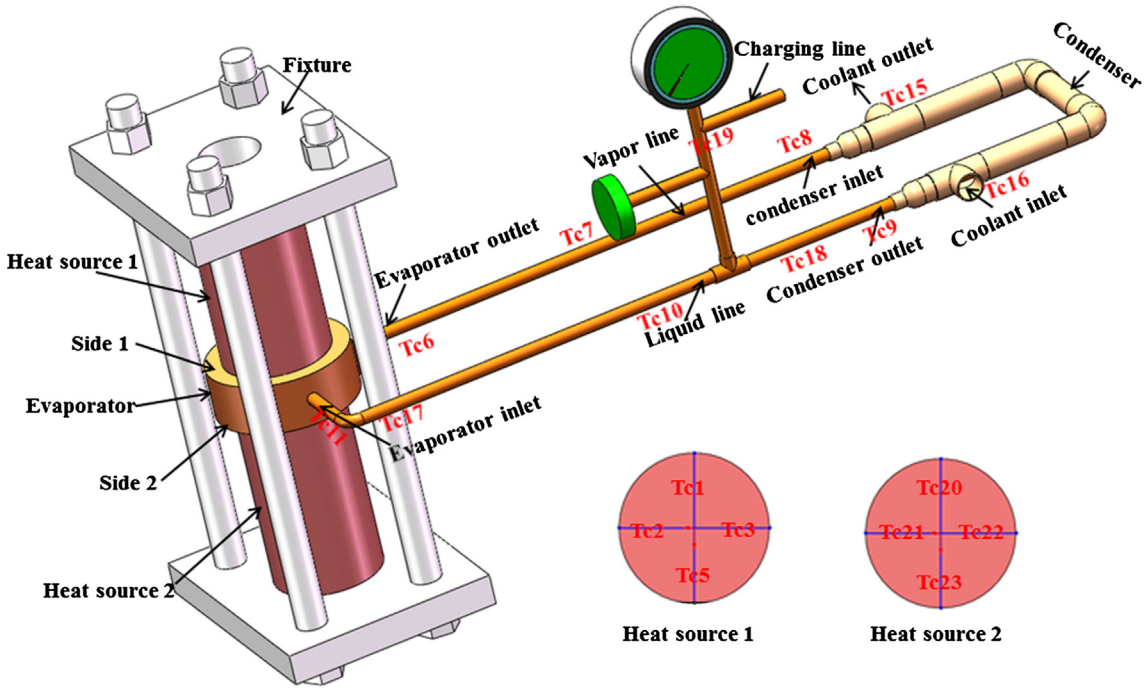

Fig. 2. The locations of characteristic points and T-type thermocouples fixed at the LHP system.

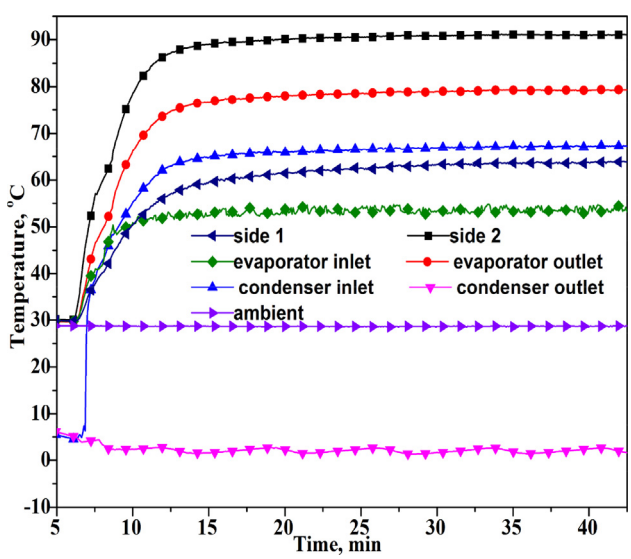

Fig. 3. Startup at 140 W-10°-60%

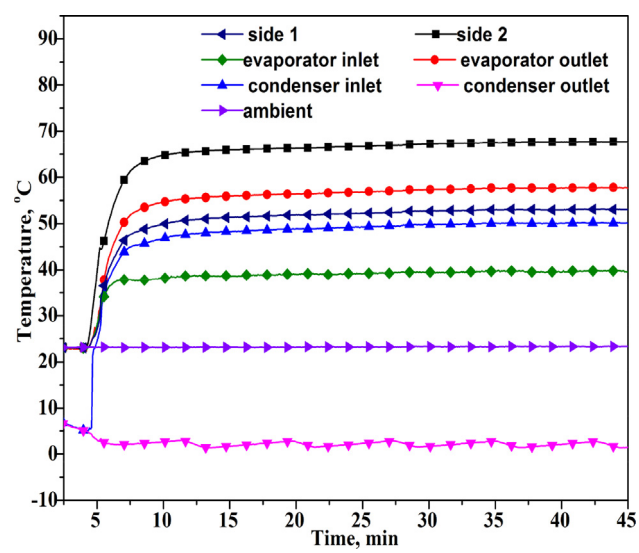

Fig. 4. Startup at 140 W-10°-75%

Similar behavior of two startup processes at 140 W was observed, the lower operating temperature was achieved at 75%. According to the second of serviceability [20], which is just suitable for LHPs, creating a sufficient temperature and pressure drop between the CC and the evaporating surface of the wick is very necessary for normal operation. The temperature difference between side 1 and side 2, which was closely related with the driving force of the working fluid circulation, was 24.3 °C and 14.5 °C at 60% and 75%, respectively. Two sides of the evaporator achieved smaller temperature difference at 75%, the greater pressure drop between the CC and the evaporating surface of the wick would be established. With charge ratio increased, there was less space reserved for phase change in the internal loop [22], and in turn the corresponding temperature drop decreased. Maintaining stable operation at 60% required lower pressure drop, but capillary wicks might quickly dry out because of liquid insufficient when heat load was beyond 140 W. Under the condition of the optimal charge ratio, when heat load was applied to one side of the evaporator, the SCC just needed to supply one primary wick. At the same time, heat leak from the active zone could be transferred to another wick. Thus, there existed two advantages for the evaporator with a SCC. On one hand, the liquid replenishment was enhanced with one side heated. On the other hand, heat leak was reduced because of liquid evaporation on another wick surface.

With the evaporator temperature below (90 ± 2) °C, the maximum transferred heat load was 210 W under the optimal charge ratio range while 140 W below the optimal value. With charge ratio increased from 60% to 75%, share of liquid in the CC also

became large, which made two nickel wicks fully saturated, the nickel wicks could get enough liquid from the CC. Startup process at 210 W was shown in Fig. 5, which was similar to 140 W.

3.2. Startup tests with two sides

Startup with two sides was tested in the horizontal orientation at 60%, Fig. 6 gave startup process with 20–20 W. The temperature of side 1, side 2, evaporator inlet and outlet rose together as two sides were provided with 20 W. However, based on the temperature of characteristic points, the condenser inlet temperature suddenly jumped above the ambient temperature, and subsequently decreased below the temperature of the condenser outlet. After this procedure, the working fluid circulation was established and the loop started to enter into the steady state, startup process appeared to be completed. However, the flow direction of the working fluid in the loop was entirely different from the normal fluid circulation occurred in the internal loop. The vapor first reached the condenser inlet and condensed into liquid and then returned to the CC through the liquid line with the help of capillary force. Startup process with 20–20 W at 60%, the working fluid circulation showed reverse direction, moving from the CC to the evaporating surfaces through the external loop, the temperature of evaporator outlet and condenser inlet was lower than that of evaporator inlet and condenser outlet. Under reverse circulation of the working fluid, the LHP system accompanied with high operating temperature.

With the external conditions unchanged, another test for 30 W firstly supplied to side 1 and 20 W later to side 2 was carried out. Fig. 7 gave the temperature change of the characteristic points, the condenser inlet and outlet temperature showed normal for side 1. Once 20 W was applied to side 2, it was observed that the condenser inlet and outlet temperature abruptly changed. The circulation of the working fluid started to flow in the opposite direction, but finally the loop reached the steady state. There were two reasons that could account for this phenomenon. Firstly, two nickel wicks participated in vaporization at the same time and more liquid was needed, one of two capillary nickel wicks might dry out because of insufficient liquid supply at charge ratio below the optimal value. Second, heat leak from two sides to the CC was very serious because of heat conduction through the evaporator sidewall, leading to liquid vaporization in the CC and formed the opposite pressure difference.

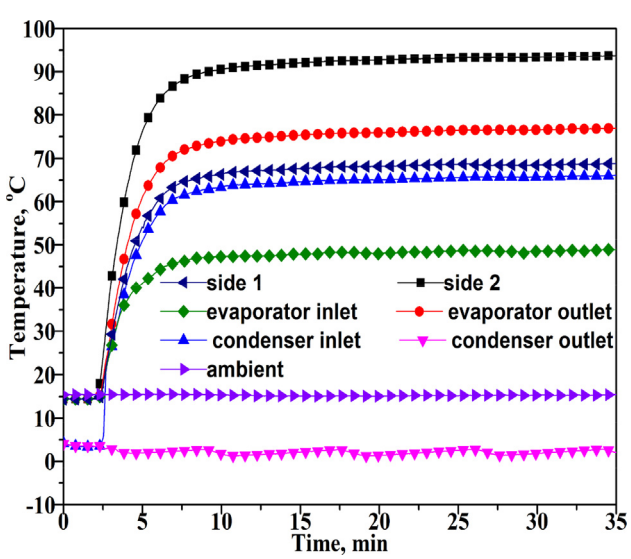

Fig. 5. Startup at 210 W-10°-75%

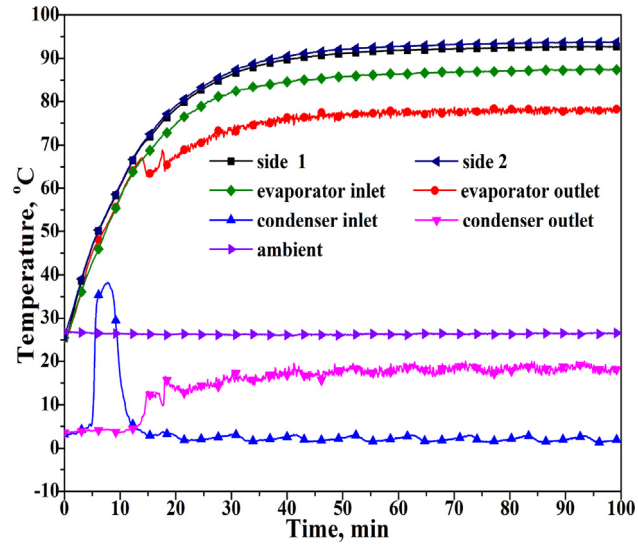

Fig. 6. Startup at 20 W-20 W-0°-60%

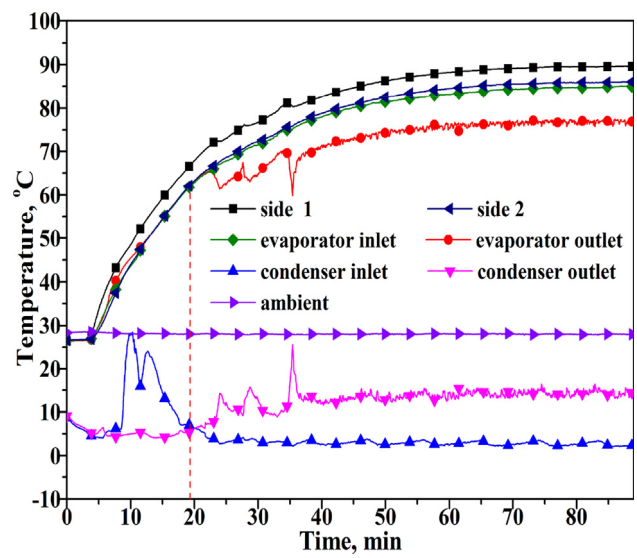

Fig. 7. Startup at 30 W (first)-20 W (later)-0°-60%

When charge ratio was fixed at 60% and the LHP system operating orientation was 10° of tilt angle (the condenser above the evaporator), the test for 40–20 W was described in Fig. 8, namely, side 1 successfully started up with 40 W firstly and then 20 W was loaded to side 2. Under this circumstance, successful operation with two sides was observed, just possessing high operating temperature.

Under the conditions of 75% of charge ratio and 0° of tilt angle, the test with 20–40 W was carried out to confirm the heat transfer capacity of the LHP with a SCC. Fig. 9 gave the operating curve of 20–40 W, it was obvious that the working fluid circulation couldn't be established, the condenser inlet and outlet temperature didn't changed much during the whole test. At 75%, the condenser was completely filled with liquid and the generated vapor couldn't enter into it in the horizontal orientation. No sub-cooling liquid returned to the CC, and heat leak wasn't compensated for, leading to startup failure.

Both high charge ratio and gravity-assisted elevation made sure that two capillary nickel wicks were saturated with liquid, avoiding the occurrence of wicks' dry-out. Under this circumstance, the working fluid circulation became normal, and startup behavior

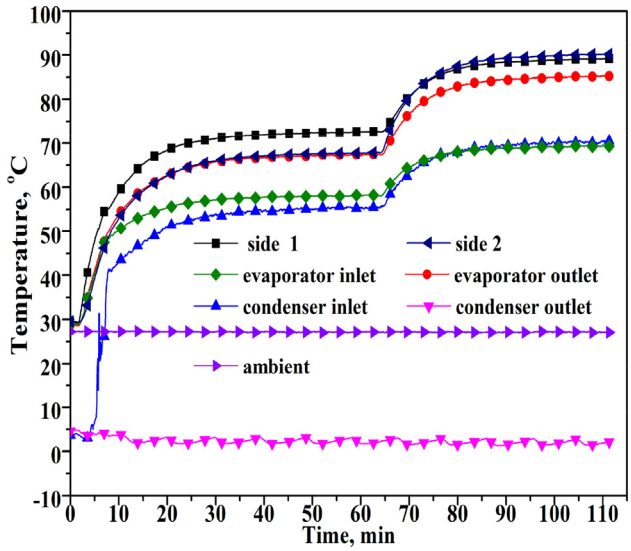

Fig. 8. Startup at 40 W (startup first)-20 W-10°-60%

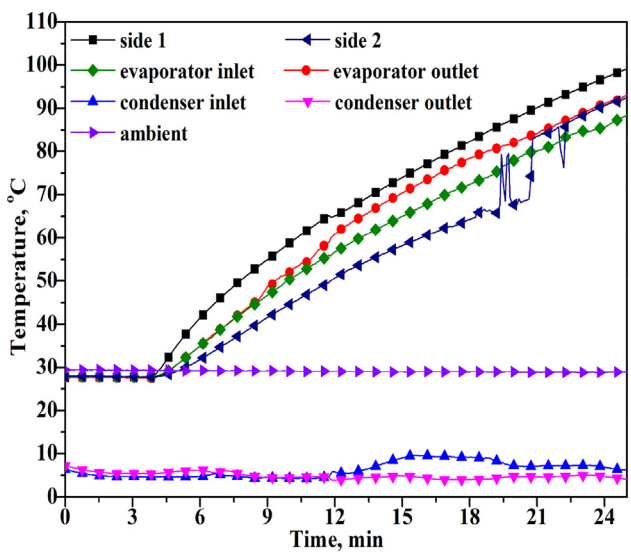

Fig. 9. Startup at 40 W-20 W-0°-75%

of two sides was almost identical. This system could transfer heat load range from 10–10 W to 120–120 W when two sides were simultaneously heated. Fig. 10 showed startup process of 20–20 W, the loop quickly entered into the steady state, and eventually operated at 28 °C. With charge ratio increased from 60% to 75% and the condenser located above the evaporator, operating performance with two sides was greatly enhanced, startup time was short and the LHP system stability was also improved. Higher charge ratio and gravity assistance could wet up two wicks inside the evaporator, inhibiting insufficient liquid supply and weakening the effect of heat leak from the active zone.

3.3. Response to variable heat load

Two heat sources worked simultaneously, and were separately attached to two sides of the evaporator. Two different cycles of heat load were conducted, and the tested results indicated that the LHP system could utilize two sides of the evaporator with a SCC to dissipate heat, and operate normally no matter how heat load was supplied under the conditions of 75% and 10° of tilt angle.

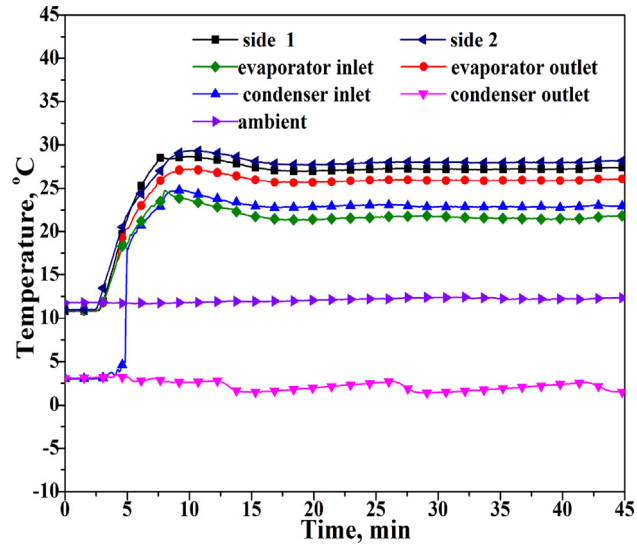

Fig. 10. Startup at 20 W-20 W-10°-75%

Fig. 11 described operating process with continuous heat load. Side 2 was fixed at 100 W and started up successfully, and then variable heat load with the increment of 10 W was applied to side 1. When 10 W was supplied to side 1, the established equilibrium state was abruptly broken, triggering liquid evaporation on the surface of capillary wick 1. The temperature of side 2 decreased slightly and the side 1 increased accordingly. Heat conduction from the evaporator sidewall laid a good foundation for startup process of side 1, the operation at 10 W quickly reached the steady state. Meanwhile, amount of the generated vapor increased, the co-evaporation of two capillary wicks reduced the temperature of side 2.

When heat load applied to side 1 was increased to 20 W, temperature overshoot of two sides was noticed, and a small rise of the evaporator inlet and outlet temperature was gained. With the whole loop entering into the steady state, the temperature of characteristic points except for condenser outlet and ambient slightly decreased. With heat load higher than 20 W, the temperature of two sides linearly increased with heat load, as shown in Fig. 12.

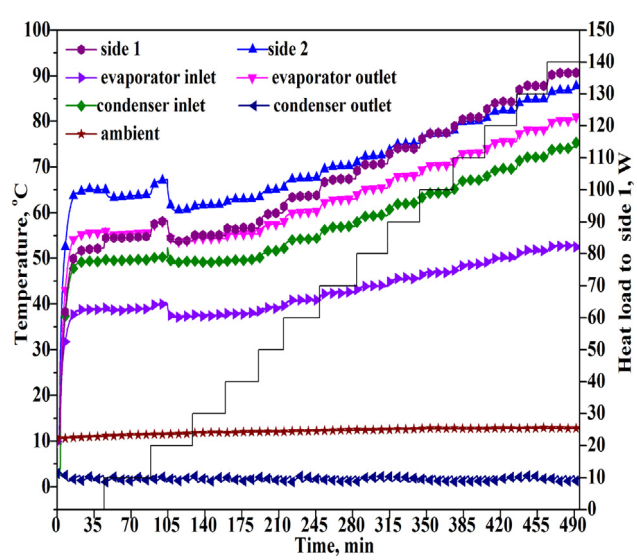

Fig. 11. continuous operation of side 2 fixed at 100 W and side 1 with the increment of 10 W (10°, 75%).

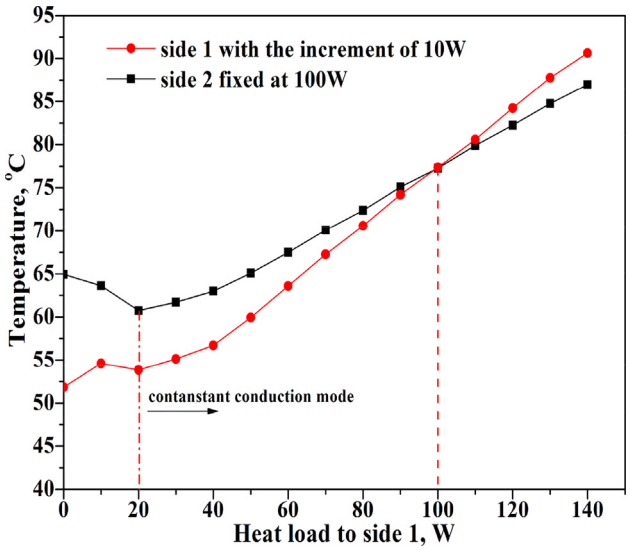

Fig. 12. Analysis of operating temperature of two sides.

The condition of 20–100 W operated at the transition point, which transferred from variable conduction mode to constant conduction mode.

With the testing procedure progressed, the condensed surface in the condenser was gradually opened up and the condenser was fully utilized. For the condensed liquid, it took a while to return from the condenser to the CC, resulting in the temperature increase in the CC owing to the effect of heat leak. The CC temperature dominated the loop operating temperature, and temperature overshoot was a response to it. When heat load ranged from 30 W to 140 W, the temperature of side 1 and side 2 varied with heat load increasing. Based on temperature difference between two sides, the whole operation process could be divided into three parts: (a) the evaporation of capillary wick 1 was gradually intensified with heat load smaller than 100 W; (b) the evaporating intension of two capillary wicks was equal when heat load applied to two sides had the same value; (c) the evaporation of side 1 was higher than that of side 2.

3.4. Comparisons with traditional LHPs

There existed numerous investigations about LHPs with a disk-shaped evaporator, but all of them possessed an active zone. Compared to traditional LHPs with methanol as the working fluid, the LHP with a shared compensation chamber was equipped with two capillary wicks and a secondary wick. Wang et al. [6] investigate the LHP with a disk-shaped evaporator, zigzag startup and overshoot startup occurred, accompanying with large temperature oscillation. Liu et al. studied methanol and acetone as the working fluid of the LHP system, the tested maximum heat load was 60 W [11], and temperature fluctuations were appeared in most of testing curves [11,12]. Joung et al. [21] found the sleeping mode operation at a heat load of 10 W during the tests. Therefore, temperature fluctuations, temperature overshoot and large startup threshold always appeared in traditional LHPs when methanol worked as the working fluid. Liquid evaporation could simultaneously occur on the surface of two capillary wicks for the disk-shaped evaporator with a SCC when heat load was applied to the evaporator active zone. Co-evaporation of two capillary wicks efficiently suppressed temperature fluctuations, and greatly improved the initial startup process at the optimal value of charge ratio.

3.5. Analysis of thermal property

Thermal resistance is always used to evaluate the operating performance of the LHP. For the existing LHPs, the loop thermal resistance is defined as the ratio of the difference between the evaporator wall temperature and the average temperature of the condenser inlet and outlet to the applied heat load, but unsuitable for the LHP with a SCC. The heat and mass transfer process for the LHP with a SCC is depicted in Fig. 13, the vapor firstly accumulates in the vapor chamber with two sides simultaneously heated, and then shared the external loop for fluid circulation. From the view of heat transfer, the evaporator with a SCC amounts to two parallel evaporators, only sharing the external loop. Similar to parallel electrical resistance calculation, the total thermal resistance for the evaporator with a SCC may be calculated as follows:

$$R = \frac{T_e - T_{cond}}{Q_{app}} \tag{3}$$

$$\frac{1}{R_{total}} = \frac{1}{R_1} + \frac{1}{R_2} \tag{4}$$

where T_e refers to T_1 and T_2, which stand for the temperature of side 1 and side 2, respectively. T_{cond} is the average temperature of the condenser inlet and outlet, Q_{app} corresponds to heat load applied to each side, R_1 and R_2 were the loop thermal resistance for side 1 and side 2, respectively. Based on Eqs. (3) and (4), the total thermal resistance for two sides was analyzed when heat load was applied to two sides of the evaporator. Two cases were considered. Case 1 was continuous equal heat load that appeared in Ref. [22], and case 2 was side 2 fixed at 100 W and side 1 with the increment of 10 W. Fig. 14 gave the total thermal resistance dependence of total heat load. From the calculated results, thermal resistance for case 1 varied from 1.145 °C/W to 0.216 °C/W, while ranging from 0.390 °C/W to 0.212 °C/W for case 2.

For case 2, the value of R_1 decreased with the increase in heat load applied to side 1. When heat load applied to side 1 was less than 20 W, side 2 was mainly utilized for heat dissipation, and the value of R_2 was relatively small. Under such condition, the value of R_1 contributed to the total thermal resistance for case 2.

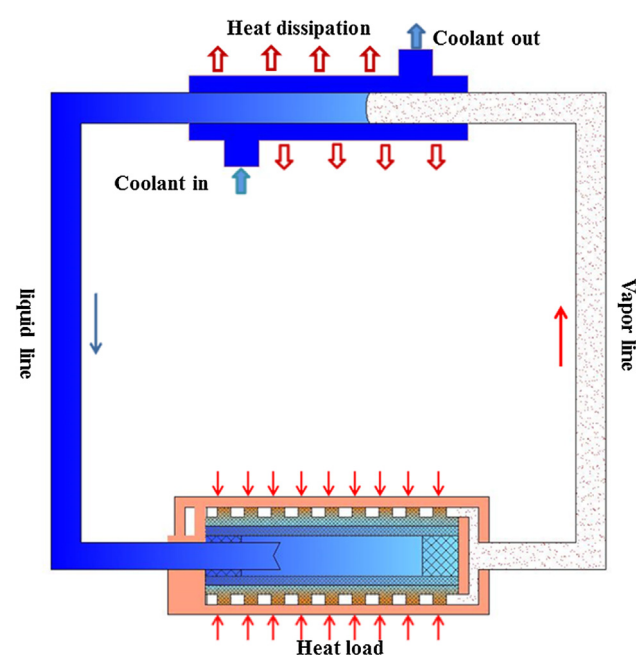

Fig. 13. The diagram of heat and mass transfer process of the LHP with a SCC.

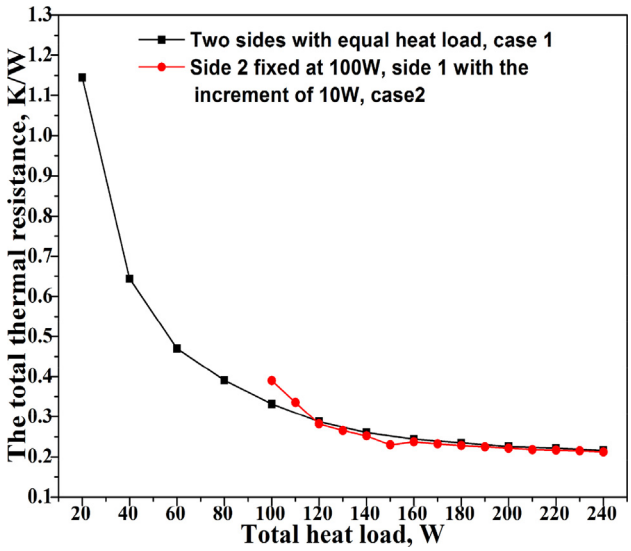

Fig. 14. Analysis of thermal resistance with two sides.

With total heat load higher than 120 W, thermal resistance for two different cases showed almost the same value. When heat load to each side was close, the evaporation on the surface of each wick was nearly equal, and the reciprocal effect became weaker. The total thermal resistance wasn't only influenced by the total heat load, but also affected by heat load distribution between two sides. According to the calculated method introduced in Refs. [23,24], the relative uncertainties of thermal resistance for side 1, side 2 and total thermal resistance were 1.54%, 3.1% and 3.5%, respectively.

4. Conclusions

Aiming at solving thermal management issues with narrow space, a new evaporator structure was introduced into the LHP. In the present paper, the LHP with a SCC was investigated at different charge ratios of 60% (below optimal value) and 75% (optimal value). It could be concluded from the experimental results:

(1) At 60%, two capillary wicks were difficult to be saturated with liquid. The flow direction of the working fluid in the loop showed abnormal for operation with two sides because of serious heat leak.
(2) With charge ratio increasing from 60% to 75% and the condenser above the evaporator, startup process with two sides quickly entered into steady state, and similar behavior of two sides was observed.
(3) The LHP system demonstrated a good response to different heat load cycles and the evaporation of two sides was intensified by each other when two heat sources worked at the same time.
(4) The total thermal resistance for operation with two sides was analyzed at different heat load cycles, and their value was determined by the transferred total heat load and the heat load distribution between two sides.

Conflict of interest

The authors claim that none of the material in the paper has been published or is under consideration for publication elsewhere.

Acknowledgement

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