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Operational characteristics of flat type loop heat pipe with biporous wick

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ABSTRACT

Loop heat pipes (LHPs) are two-phase heat transfer devices that utilize the evaporation and condensation of working liquid to transfer heat. In present paper, experimental researches are conducted for a new type of flat type LHP, in which biporous porous media and stainless steel mesh are adopted as primary wick and secondary wick respectively, and this innovative structure can support the primary wick and assist it pumping working liquid. The loop is made of copper with sintered nickel powder as primary wick and methanol as the working fluid. Both start-up test and performance test are conducted to validate the reliability and performance of the loop. From the test results, it is found that, in the horizontal position, the loop is able to start-up with a heat load rang between 20 W and 160 W(heat flux of 16.8 W/cm^2) with evaporator wall temperature below 85 °C. At heat load between 30 W and 80 W, temperature oscillations are observed throughout the loop, however, the effect of this oscillation on the performance of the loop is not significant. During a random loading test, the loop can stand a load jump as high as 100 W without an operation failure. The thermal resistance of the LHP lies between 0.46 °C/W to 2.28 °C/W.

1. Introduction

Loop heat pipes (LHPs) are capillary force driven heat control devices developed by former Soviet Union in 1970s. Its original purpose is to provide a cooling method in the high gravity field. The first LHP is invented by scientists Gerasimov and Maydanik [1], with a length of 1.2 m and a heat transfer capacity of about 1 kW.

Like the conventional heat pipe, the LHP employs two-phase working fluid to dissipate the heat, but separated the evaporator and condenser by long, often flexible pipe line. Wolf et al. [2] pointed out that LHPs combine the advantage of both conventional heat pipes and capillary pumped loop. Moreover, LHP possesses the following advantages: self-priming, require no power input; no moving part, passive heat transport system, high reliability; ability to operate against gravity. Due to these advantages, LHPs are applied extensively in space craft, electronic device cooling, and solar thermal systems [3], and many experiments and theoretical analysis are carried out to improve its performance [4–6].

Unlike the cylindrical evaporators, flat evaporators are easy to attach to the heat source without need of cylinder-to-plane reducer materials at the interface which will increase the total thermal resistance and mass of a LHP. Due to above advantages, especially for electronic cooling, the flat type LHP has been extensively investigated both theoretically and experimentally, yet most of the investigation on evaporator only with one type of wick [13–15].

In the high heat flux condition, the vapor and liquid flow rate are equally high in the evaporator. Due to the small radius and permeability, monoporous wicks will produce considerably high resistance, leading to the operation failure, especially in the high heat flux condition. Therefore, some scholars proposed biporous wick [7,8] to improve the high heat flux capability for LHP. As shown in Fig. 1, the two different size pores can allow the wick to achieve a better performance through the separation of liquid and vapor: the large pore can reduce liquid flow resistance effectively, moreover, large pore also provide extra area for liquid film to evaporate, and the small pore can maintain the system with sufficient capillary force.

While affecting the performance of LHP fundamentally, the wick is the most important yet most difficult component to fabricate in the LHP. Many scientists have done lots of work to improve the performance of porous wick, Xin et al. [9] fabricate wicks by sintering the mixture of nickel powders and copper powders, and the best wicks can reach the porosity of 70%, the permeability of 10^{-13} m^2, and mean pore radius of 0.54 μm; Semenic et al. [10] test the performance of both monoporous wicks and biporous wicks, and find that best biporous wick has critical heat flux at 990 W/cm^2; the bidispersed wicks used in the experiment are manufactured by Advanced Cooling Technology. Cao et al. [11] fabricate biporous wicks with copper powder, and large/small pore-diameter

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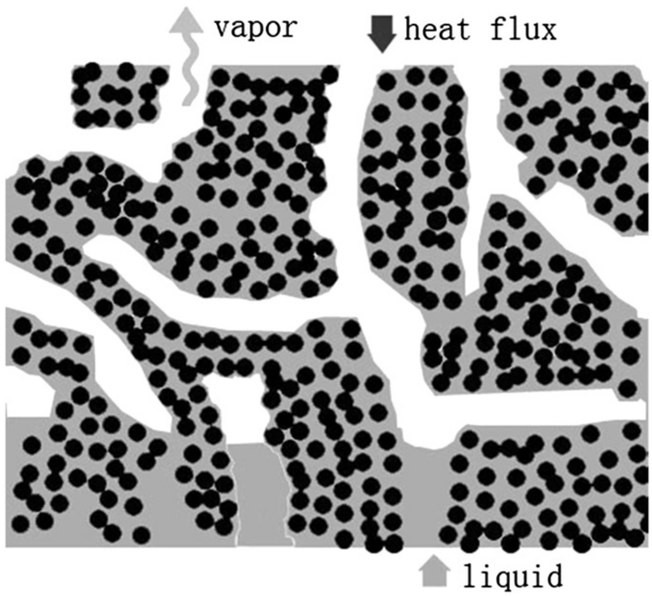

Fig. 1. Schematic of biporous wick.

ratios are 200/80 μm, 400/80 μm, 800/80 μm, they also investigate heat and mass transfer in the wicks. Yeh et al. [12] add pore former into filamentary nickel powder to manufacture biporous wick, study the effect of sintering temperature, particle size of pore former, and the pore former content on heat transfer performance of wicks, and find that particle size and pore former and the pore former content are the significant factors. In this paper, the flat type LHP with biporous wick was designed, fabricated and tested, and the main objective is to investigate the start-up and transient performance for the LHP.

2. Experimental prototype

In this paper, the primary wick was made by cold-pressing sintering method as shown in Fig. 2 and Fig. 3. Due to the pore former mixed into the nickel power, this wick has two kinds of pore size: small pore formed by the gap between nickel powders and large pore developed by the pore former. As shown in Fig. 1, when the LHP operates in the high heat flux condition, the vapor will selectively occupy the large pore, forming vapor channel. The meniscus in the wicks includes two parts: the one in the large pore, and the other one in the small pore. Actually, the vapor channels in the large pores provide extra area for film evaporation. Moreover, the existence of large pore makes it easier for vapor to secede from the wick. And the gap between nickel powders and pore generated by numbers of nickel powder agglomeration were relatively small, they can provide the system with high capillary force and enough liquid. Meanwhile, duo to the pore former, the inner connectivity was improved, which was very essential for the wick. The fabrication of the wick is discussed with details in another paper [18].

As shown in Fig. 4, an experimental prototype is designed for the investigation; the parameters of the prototype are given at Table 1. Typically, the flat type LHP has only one wick in the evaporator [13–15]. In this paper, like many cylindrical LHPs, a secondary wick is inserted into the evaporator, assisting the primary wick pumping working fluid. The secondary wick is made by several hundred layers of stainless steel mesh. Its elasticity can make the primary nickel wick attach the evaporator wall tightly no matter how the

Fig. 2. Image of biporous wicks.

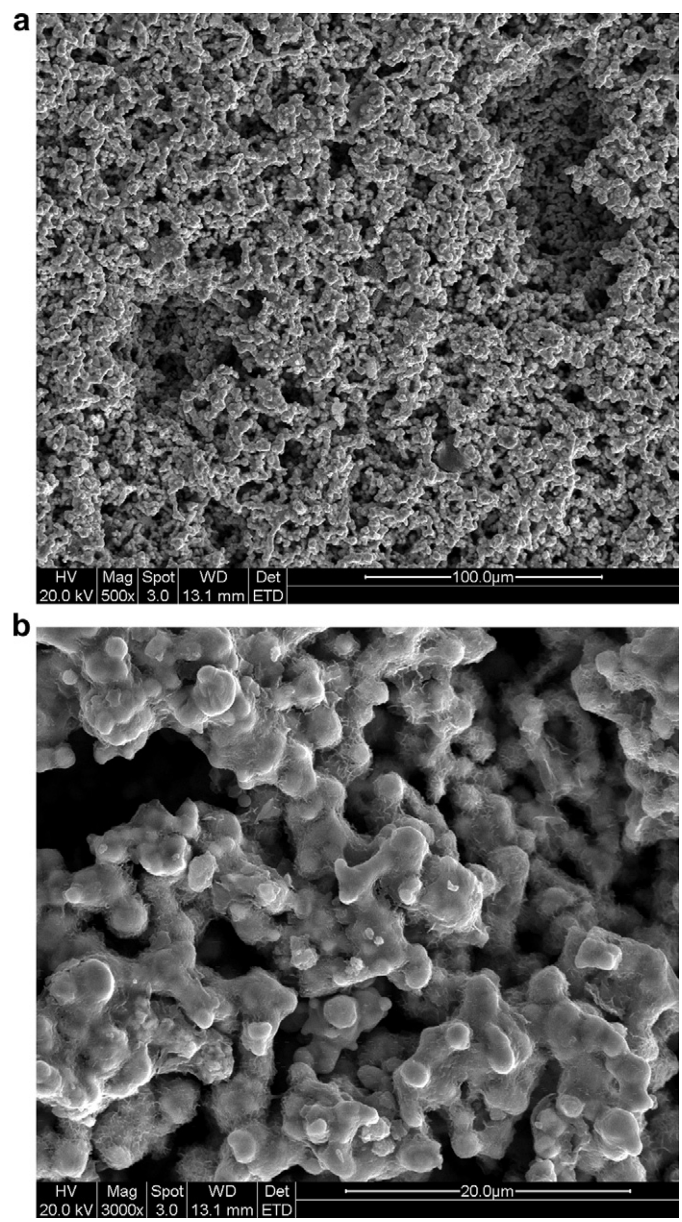

Fig. 3. SEM image of biporous wick in the experiment. (a) 500x; (b) 3000x.

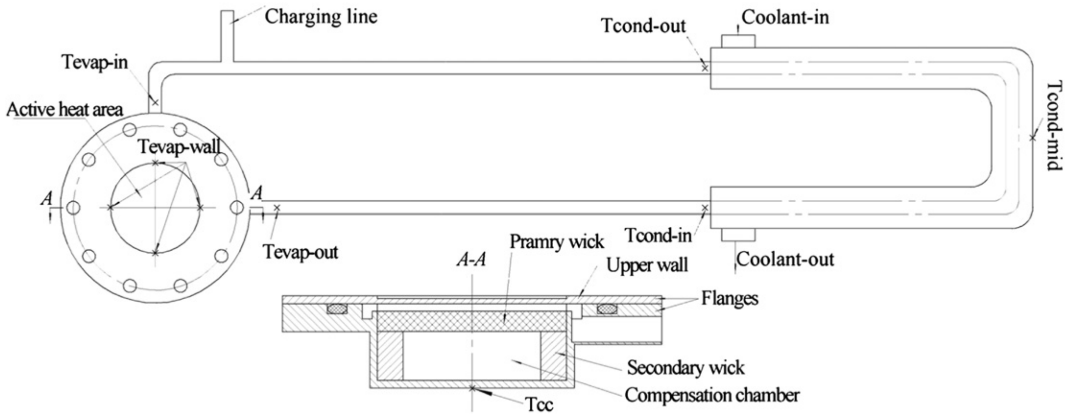

Fig. 4. Schematic of LHP and the temperature measuring point.

working condition varies. The evaporator is made of brass and the vapor/liquid line is pure copper. The condenser is tube-in-tube heat exchanger, and it is connected with water chiller; the coolants are mixture of water and ethylene glycol working at temperature of -10 ± 1 °C.

The LHP is hermetically sealed by an O-ring seal between the evaporator flanges. To test its air tightness, charge the loop with 0.2 MPa Nitrogen, keep it for 48 h, and check its pressure drop. For charging, the loop is firstly evacuated to 6.40×10^{-4} Pa by oil diffusion pumps and then filled with the predetermined quantity of methanol with purity of 99.5%.

In order to test the performance of LHP, a heat load simulator in form of copper cylinder with three embedded cartridge heater and diameter of Φ35 mm is used. In order to minimize heat loss to the ambient, the heat load simulator is thermally insulated using 10 mm thickness nano-adiabatic material (Aspen, thermal conductivity 0.012 W/m·K). According to the calculation, the heat loss is less than 0.3% of total power applied to the simulator.

A digital power meter with accuracy of ±0.2 W was used to measure and control the input power to the heat load simulator. Eleven T-type thermocouples with ±0.2 °C accuracy are used to measure the temperature at different locations of the LHP and the ambient air. Fig. 4 also shows the placement of the thermocouple points. All the instruments are connected to the Keithley 2700 data acquisition system which helps to monitor and record the test data from the LHP prototype at a time interval of every 3 s.

Table 1
Main design parameters of LHP.

Evaporator	Upper wall	Thickness(mm)	1.5
		Rib width(mm)	1
		Groove width(mm)	1
		Number of ribs	19
	Compensation chamber	Diameter O/I(mm)	74/36.9
		Height(mm)	15
		Thickness(mm)	1.5
	Primary wick(nickel)	Diameter/Height(mm)	36.9/3.94
		Porosity	69.4%
	Secondary wick(stainless steel mesh)	Diameter O/I(mm)	36.9/26.9
		Height(mm)	8.06
Condenser		Diameter (O/I)(mm)	16/15
		Length(mm)	620
Vapor line		Diameter O/I(mm)	5/4
		Length(mm)	300
Liquid line		Diameter O/I(mm)	5/4
		Length(mm)	360

3. Results and discussion

3.1. Start-up test

The start-up characteristics are critical in evaluating the reliability of LHP for cooling electronic device. Figs. 5–8 is the temperature of LHP at heat load of 10 W, 20 W, 50 W and 100 W respectively. From the comparison of the start-up profiles, the start-up procedure of LHP contains three main processes [15]: (1) clearing off the liquid from evaporator grooves, vapor line and part of condenser; (2) generating enough pressure difference across the porous wick that is necessary to drive the working fluid around the loop; and (3) the LHP system achieve steady state or temperature oscillation state. Start-up represents the most complex transient phenomenon in the loop operation. The secondary wick located between the compensation chamber and the evaporator ensures that the primary wick is always full of working liquid and LHP can be started by applying the heat load to the evaporator without the need of a time-consuming preconditioning process like the capillary pump loop. Such a self-start ability is one of the attracting advantages of LHP, however, self-start does not necessarily guarantee an instant or quick start. Start-up of an LHP is a function of compensation chamber and evaporator construction, initial condition [17].

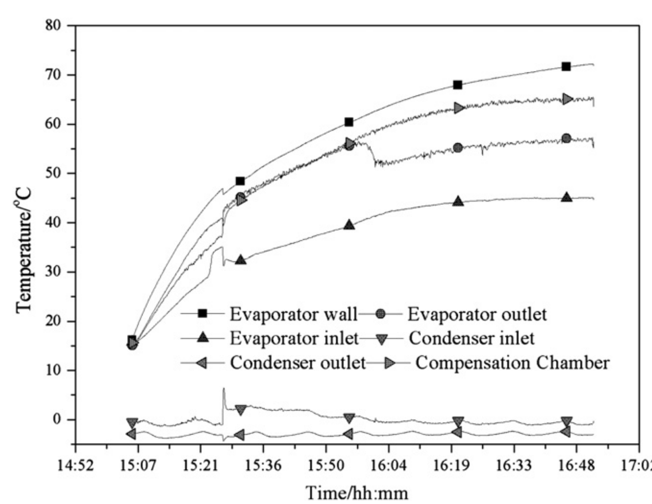

Fig. 5. Start-up of LHP at heat load of 10 W.

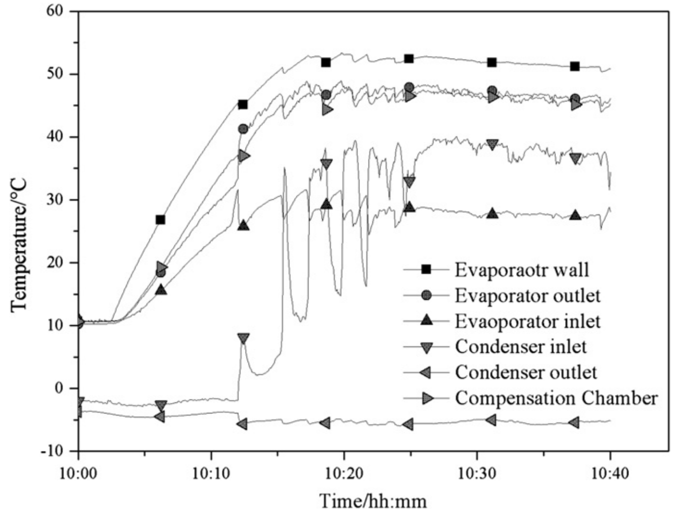

Fig. 6. Start-up of LHP at heat load of 20 W.

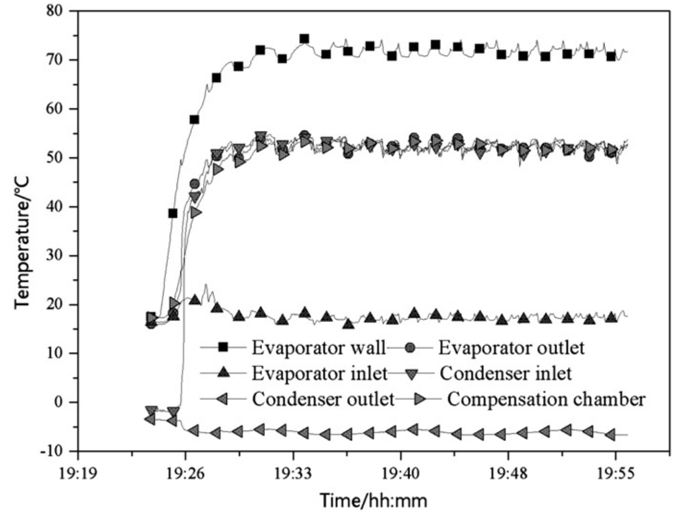

Fig. 8. Start-up of LHP at heat load of 100 W.

At heat load of 10 W, after 15 min, the temperature of evaporator inlet rises faster than the temperature of evaporator outlet, which means that the back conduction in flat evaporator is significant. Five minutes later, the temperature of evaporator outlet and condenser inlet rises up, and the temperature of evaporator inlet drops, which means that the working fluid is circulated and the system start-up. However, 30 min later, the temperature of evaporator outlet drops, the vapor–liquid two-phase cycle fails to be established, and in the rest of 60 min, the temperatures of loop keep rising, and the temperature of evaporator wall exceeds 70 °C, the loop fails to start-up. The reason for low heat load fail to operate is that, the mass flow of the cold returning fluid is too lower to compensate the heat leak from the heat wall to compensation chamber of the flat evaporator.

At heat load of 20 W, the loop successfully starts up. The temperature oscillation can be observed under this heat load. The temperature oscillation is caused by thermal and hydrodynamic interactions between the evaporator, the compensation chamber and the condenser [16]. As in low heat load, the flow rate of vapor is relatively small, capacity of condenser is much higher than the heat load, therefore at the inlet of condenser, the interface of vapor and liquid keep moving front and back, leading the oscillation of

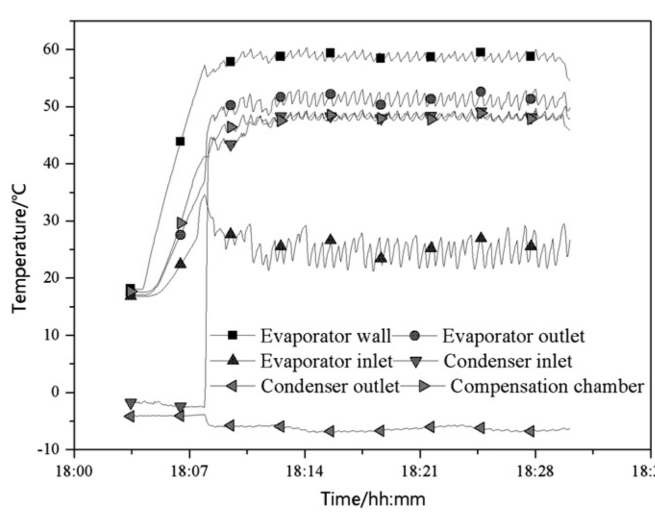

Fig. 7. Start-up of LHP at heat load of 50 W.

temperature in the whole loop. It is noted in Figs. 6,7 that even large temperature oscillation at condenser inlet, the magnitude at evaporator is much smaller. Like heat load of 10 W, the temperature of evaporator inlet rose up before the temperature of outlet. It takes the loop 17 min to start-up.

Duo to the structure of the flat evaporator, compared with cylinder LHP, the heat leak from evaporator to compensation chamber is relatively higher, enlarging the possibility that the vapor generate in the compensation chamber. When the volume of vapor generated in compensation chamber accumulate to a certain amount, vapor rushes into the liquid line, leading the $T_{evap-inlet}$ rises, which is undesirable for LHP's operation, because the existence of vapor in liquid line increase the flow resistance for subcooled liquid returning back and make it difficult for the loop to establish the cycle. At low heat load, such as 10 W, the generation rate of vapor in evaporator is low, and due to the back conduction, $T_{evap-inlet}$ keeps rising, which means the subcooled liquid is not enough, leading the primary wick in the evaporator running out of liquid, and the loop finally fails to start-up. While at high heat load, the large amount of vapor generated in the wick quickly rushes into the vapor line, and is cooled in condenser, and then returns to evaporator, meanwhile the back conduction can be compensated by the returning fluid, and as a result, the cycle is quickly established.

3.2. Performance test

The LHP is operated under different heat load cycles to validate its reliability and transient response to the changing heat load. In these tests, the heat load is either varied in fixed steps (10 W as an interval) from 20 W to 160 W as shown in Fig. 9, or it is changed in random loading as shown in Fig. 10. It can be seen from the figures that LHP performs very reliably and presents very fast response to the changes of heat load.

In the fixed steps mode as shown in Fig. 9, the temperature oscillations mainly occurs at heat load in the range of 30 W to 80 W. For heat load less than 120 W, the increase in the evaporator wall temperature for each step increment in heat load is relatively small, normally 2 °C, somewhere even less than 1 °C. Any increase in heat loads beyond 120 W produces a more linear and steep rise in evaporator wall temperature. At low heat load, the flow rate of vapor is small, so most of the condenser, liquid line and compensation chamber are occupied with working liquid. With the

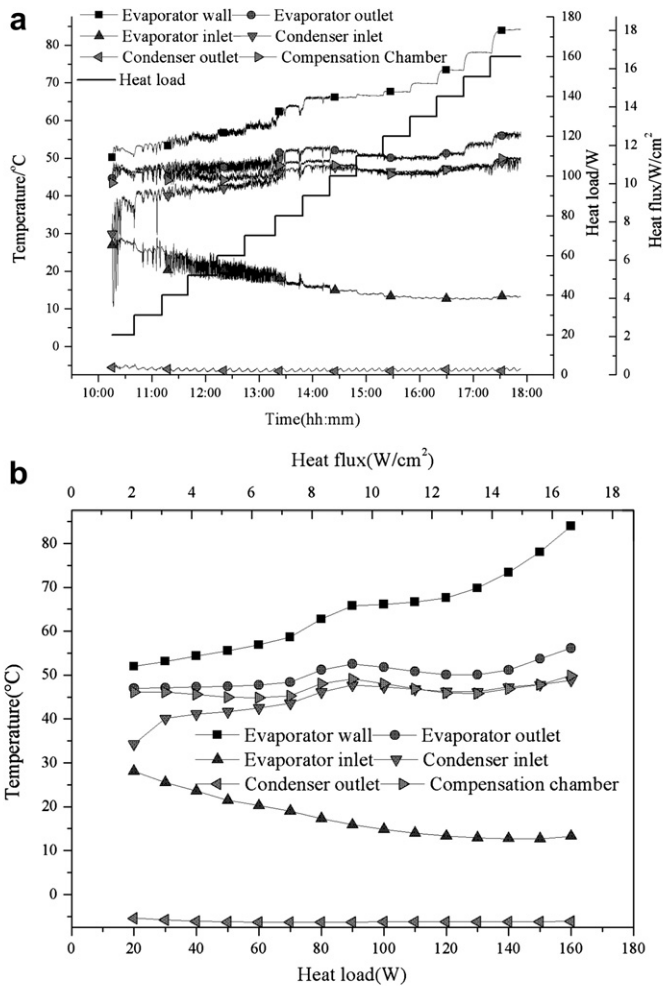

Fig. 9. Temperature of LHP under step heat load (a) Temperature of LHP versus time (b)Temperature of LHP versus heat load.

increase of heat load, the generate rate of vapor increases and needs more area in the condenser to condensation. In order to clear the liquid from the condenser, the vapor pushes the liquid out from condenser to compensation chamber. The increasing amount of liquid in compensation chamber helps to enlarge the heat capacity

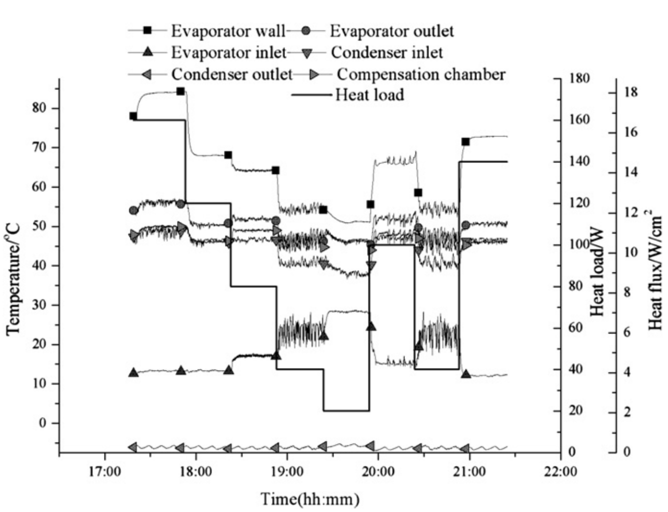

Fig. 10. Temperature of LHP under random heat load.

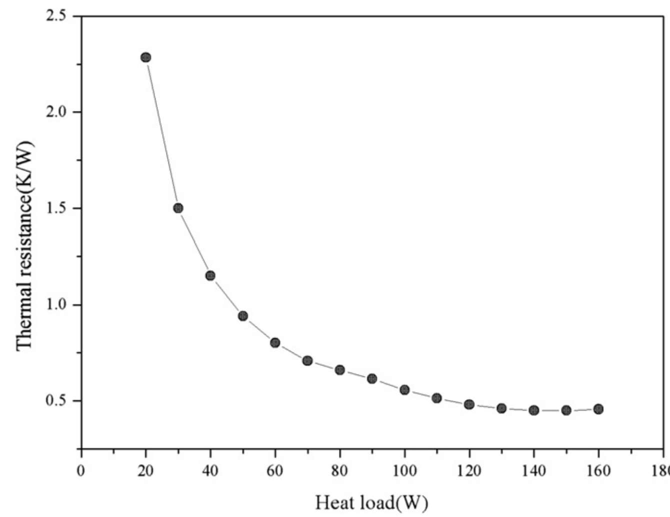

Fig. 11. Thermal resistance of LHP.

of compensation chamber and offset the effect of heat leak from evaporator to compensation chamber. The temperature of compensation chamber determines the whole loop's operation temperature [17]. Therefore, the temperature of evaporator wall does not show a linear progression relationship with heat load. It seems that the condenser is completely occupied with vapor when the heat load is beyond 120 W, with further increase of heat load, the LHP at this time behaves in a constant conductance mode like a conventional heat pipe and presents a linear monotonic temperature trend, 4–5 °C increase for each 10 W increase of heat load.

In the random loading mode, large heat load jumps or slumps are applied to the LHP to validate its reliability. It can be seen from the Fig. 10, that LHP can stand the jump as high as 100 W (from 40 W to 140 W) and the response time is short.

The LHP is able to transfer a maximum heat load of 160 W while keeping the temperature of evaporator wall below 85 °C.

According to the heat pipe theory, the thermal resistance of LHP can be defined as:

$$R_{\mathrm{LHP}} = \left(T_{\mathrm{evap-wall}} - T_{\mathrm{cond}}\right) \Big/ Q$$

Where, $T_{\mathrm{evap-wall}}$ is the average temperature of active heated wall, T_{cond} is the average temperature of condenser, $T_{\mathrm{cond}}=(T_{\mathrm{cond-in}} + T_{\mathrm{cond-out}}-10)/3$, where -10 means the temperature of coolant is -10 °C. Q is the heat load.

For heat load in range of 20 W to 160 W, R_{LHP} lies between 0.46 °C/W to 2.28 °C/W as shown in Fig. 11. The minimum value of 0.46 °C/W for R_{LHP} is achieved at heat load of 160 W.

4. Conclusions

The experimental investigation for the working capability for flat type LHP with biporous wick was carried out, and the main result of the study can be concluded as follows:

1. The LHP is able to start-up at heat load as low as 20 W, the start-up time of LHP decrease with the increase of heat load applied to the evaporator.
2. In the horizontal position, the LHP can dissipate a heat load of 160 W with temperature of evaporator wall below 85 °C.
3. In the random loading mode, the LHP is able to stand a 100 W heat load jump without an operation failure, and the response time is short.

4. The thermal resistance of LHP decreases with the increase of heat load. For heat load in range of 20 W to 160 W, R_{LHP} lies between 0.46 °C/W to 2.28 °C/W. The minimum value of 0.46 °C/W for R_{LHP} is achieved at heat load of 160 W.
5. For heat load from 20 W to 120 W, the increase in the evaporator wall temperature for each step increment in heat load is relatively small, normally 2 °C, somewhere even less than 1 °C. While when the heat load is beyond 120 W, LHP presents a monotonic temperature trend, 4–5 °C increase for each 10 W increase of heat load.

Acknowledgments

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Nomenclature

$T_{evap\text{-}wall}$: average temperature of evaporator wall, °C
$T_{evap\text{-}in}$: temperature of evaporator inlet, °C
$T_{evap\text{-}out}$: temperature of evaporator outlet, °C
$T_{cond\text{-}in}$: temperature of condenser inlet, °C
$T_{cond\text{-}out}$: temperature of condenser outlet, °C
T_{cc}: temperature of compensation chamber, °C
R_{LHP}: thermal resistance of loop heat pipe, °C/W
Q: heat load, W
α: charging ratio, %