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Experimental study of the loop heat pipe with a flat disk-shaped evaporator

Dongdong Wang [a], Zhichun Liu [a,*], Jun Shen [a], Chi Jiang [a], Binbin Chen [a], Jinguo Yang [a], Zhengkai Tu [b], Wei Liu [a,*]

[a] School of Energy and Power Engineering, Huazhong University of Science and Technology, Wuhan 430074, China
[b] State Key Laboratory of Advanced Technology for Material Synthesis and Processing, Wuhan University of Technology, Wuhan 430070, China

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ABSTRACT

A miniature loop heat pipe (LHP) with a flat evaporator is a promising solution for dealing with cooling requirements for high-power electronic devices. The present paper discusses the operating performance and heat transfer characteristics of a miniature LHP with a flat disk-shaped evaporator. It had a heated disk diameter of 40 mm and height of 19 mm, and was designed with brass as the evaporator material with braze welding, 630 mesh stainless steel wire mesh as the wick and methanol as the working fluid. In this investigation, both start-up and variable heat load tests were conducted. Three start-up modes were experimentally observed in this investigation: (1) zigzag start-up, (2) overshoot start-up, and (3) stable start-up. When the evaporator's heated wall temperature was lower than 85 °C, with a variable heat load ranging from 20 W to 240 W corresponding to the heat flux of 1.6–19.1 W/cm^2, the LHP ran stably and showed good self-adjusting ability. Moreover, comparison of the impacts of sealing method for evaporator on operating performance of miniature LHP with flat-disk type evaporator was conducted. With the same structural parameters and operating conditions, the LHP with an O-ring sealing evaporator could only work stably with heat loads ranging from 30 W to 140 W, corresponding to the heat flux of 2.38–11.1 W/cm^2. This work was able to verify the importance of the sealing method in improving the performance of the miniature flat type LHPs.

1. Introduction

An loop heat pipe (LHP) is an efficient passive heat transfer device utilizing the phase change of the working fluid, and is used widely in spacecraft thermal control and the cooling of electronic devices with a high heat flux [1]. Differently from the traditional heat pipe, the LHP's evaporator and condenser are set up separately and connected by the vapor line and the liquid line, which is convenient to arrange the evaporator and the condenser according to actual need. And the porous wick is arranged only in the evaporator for reducing the flowing resistance. The capillary force resulting from the phase change interface in the wick in the evaporator promotes the cycle of the working fluid, and the wick pumps the working fluid to the evaporating interface, which also limits the expansion of the vapor layer to reduce thermal resistance.

LHP is known for its high pumping ability and robust operation [2]. Many experiments have been carried out to study and improve its performance. Li et al. [3] designed a copper–water compact LHP with a flat, square evaporator, which could transfer heat load of more than 600 W (with a heat flux in excess of 100 W/cm^2) with no occurrence of evaporator dry-out. They proposed two main modes, boiling trigger start-up and evaporation trigger start-up, to explain the varying start-up behavior for different heat loads. Nguyen et al. [4] reported an LHP with a circular flat evaporator and a copper power wick, improving insufficient subcooling of liquid in the compensation chamber. Many different orientations of the elevation and direction of the evaporator have been considered. The LHP operates a heat load in excess of 140 W (15.55 W/cm^2) with a total thermal resistance of 0.39 °C/W. Launay et al. [5] observed that the LHP's thermal resistance and maximum heat transfer capability were affected by the choice of the working fluid, the fill charge ratio, the porous wick geometry and thermal properties, the sink and ambient temperature levels, the design of the evaporator and compensation chamber, the elevation and title, the presence of non-condensable gases, and the pressure drops of the fluid along the loop, and the main objective they

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* Corresponding authors. Address: 415 Power Building, 1037 Luoyu Road, Hongshan District, Wuhan 430074, China. Tel.: +86 27 87542618; fax: +86 27 87540724.

E-mail addresses: zcliu@hust.edu.cn (Z. Liu), w_liu@hust.edu.cn (W. Liu).

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Nomenclature

A	area of the heater (m^2)
dt	time change (s)
dT	temperature change (°C)
h	evaporating heat transfer coefficient ($W\,m^{-2}\,°C^{-1}$)
m	mass (kg)
$\dot{m}$	mass flow rate (kg/s)
P	pressure (Pa)
ΔP	pressure drop (Pa)
Q_{app}	applied heat load (W)
Q_{leak}	heat leak (W)
r_{eff}	effective radius (m)
R	thermal resistance (°C/W)
T	temperature (°C)

Subscripts

cap	capillary
cc	compensation chamber
cond	condenser
evap	evaporation
g	gravity
l	liquid line
t	total
v	vapor line
w	wick

wanted was aiming at achieving the state of the art for future design and applications.

The evaporator is the core component of an LHP and it consists of the evaporation section and the integrated compensation chamber, which are hydraulically and thermally connected via the wick structure. Through a series of experiments, Wang et al. [6] found that with increasing thickness of the sintered capillary interlayer the performance of start-up in the LHP improved. Heat leak to the compensation chamber was reduced and the temperature difference between the compensation chamber and the evaporation room increased. When the compensation chamber had a heat sink installed, the temperature and pressure difference between the compensation chamber and evaporation room were augmented, which improved start-up performance. Xu et al. [7,8] designed a new connection between the evaporator envelope and the wick surface without the clearance, and LHPs with a cylindrical evaporator were fabricated with water as the working fluid and a 70% inventory. This experiment achieved a heat transfer capacity of 500 W under the allowable evaporator temperature of 85 °C, and a low thermal resistance of 0.070–0.165 °C/W.

Flat evaporators can fit the heat delivery surface well, but there are also some drawbacks, such as high back-heat conduction through the evaporator wall and temperature oscillation, which limit the application of the flat-type LHP [9–13]. In order to improve LHP operation performance, Liu et al. [9–11] developed an LHP with a biporous wick, and experimental results showed that LHP operation capability can be improved. They [12] also conducted an investigation into the impact of working fluid on the operating characteristics of LHP. Singh et al. [14] examined the effect of wick characteristics on the thermal performance of the miniature loop heat pipe. In the present paper, an LHP with a flat disk-shaped evaporator using the braze welding method was first designed, fabricated and tested. Then a comparison with an LHP with the almost same evaporator but using the O-ring sealing method was carried out. The main objectives of this paper are to study the operating performance of the flat disk-shaped LHP, and to obtain an effective approach for improving operating capability.

2. Operation principle and experimental system

The flat LHP consists of five parts: the evaporator, the condenser, the vapor line, the liquid line, and the compensation chamber as shown in Fig. 1. According to the operating principle of LHP [1], the capillary force developed at the menisci of the evaporating liquid–vapor interface in the wick should be equal to or greater than the total loop pressure drop, to drive the circulation of the working fluid without the use of an external pump.

The capillary force is provided by the menisci in the evaporator wick,

$$P_{cap} = \frac{2\sigma}{r_{eff}} \tag{1}$$

where σ is the surface tension of the working fluid and r_{eff} is the effective radius of the menisci in the wick. And the total loop pressure drop is expressed as

$$\Delta P_t = \Delta P_{groove} + \Delta P_v + \Delta P_{cond} + \Delta P_l + \Delta P_w + \Delta P_g \tag{2}$$

where the terms on the right hand are the pressure drops of the groove, vapor line, condenser, liquid line, wick, and gravity, respectively.

When a heat load is applied to the bottom of the evaporator, the liquid in the wick is evaporated and the formed menisci develop capillary forces to pump the liquid from the compensation chamber. The generated vapor flows into the condenser and condenses into the sub-cooled liquid. The liquid returns to the compensation chamber through the liquid line, to restrain the temperature rise of the evaporator.

According to the energy conservation, the equation of the liquid temperature in the compensation chamber in the unsteady state:

$$m_{cc}c_p\frac{dT}{dt} = \dot{m}c_pT_{in} + Q_{leak} \tag{3}$$

where m_{cc} is the mass of the liquid in the compensation chamber, c_p is the specific heat of the liquid, $\frac{dT}{dt}$ is the liquid temperature change in the compensation chamber, $\dot{m}$ is the liquid flow rate into the compensation chamber, T_{in} is the liquid temperature flowing into the compensation chamber, and Q_{leak} is the heat leak to the compensation chamber through the evaporator wall and the wick. It can be found from Eq. (3) that, the liquid flow rate, the heat leak, and the initial vapor–liquid distribution together determine the liquid temperature in the compensation chamber, leading to different operating characteristics under different heat loads.

Most of the heat load is supplied for the vaporization of the liquid, and small amount is transferred to the compensation chamber, which increases the liquid temperature in the compensation chamber. The operating resistance of the system increases and the system performance decreases. It is very important to control the heat leak to the compensation chamber in enhancing the heat transfer capacity of the LHP, and the optimization of the evaporator structure can be an effective way to reduce the heat leak.

The evaporator's structures are shown in Fig. 2. The structure of the two types of evaporators are almost same, excepting the O-ring type needs a larger fringe for installing the O-ring to seal the evaporator. But for the welding type, the welding is adopted to seal the evaporator, as a result, the larger fringe is unnecessary for it. It can be seen that the O-ring sealing extends the bottom surface area of the evaporator, which exacerbates the evaporator's side-wall heat

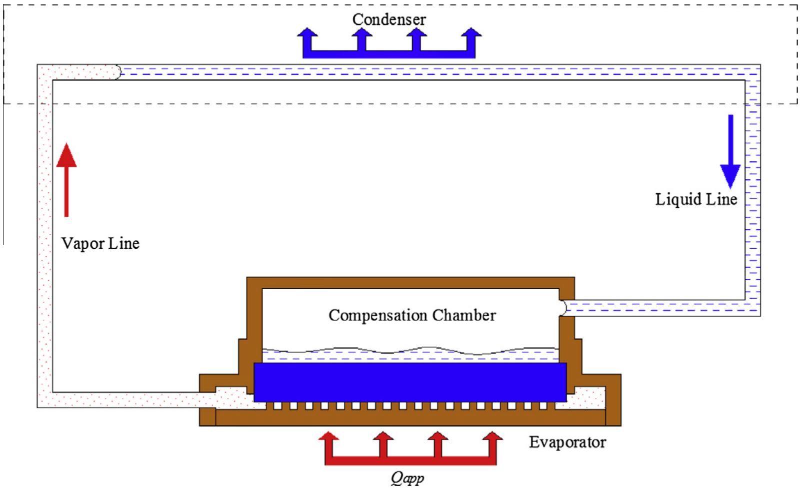
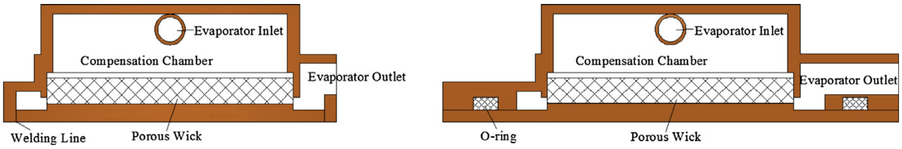


Fig. 1. Schematic of LHP with flat evaporator.



(a) Welding type (b) O-ring type

Fig. 2. Structure of the evaporator of an LHP.

leak to the compensation chamber and is not conducive to the effective operation of the LHP.

Table 1 shows the geometric and materials characteristic of the experimental LHP with a welding evaporator. In this experimental system, the evaporator was made of brass material and methanol (with purity of 99.5%) was used as the working fluid. The porous wick was composed of 630 mesh pressed stainless steel wire mesh with porosity of 60.2%. The heat source simulator was a copper cylinder block with a diameter of 40 mm and the heat input was controlled by a wattmeter with a relative error of 0.5%. A 10 mm thick nano-adiabatic material was wrapped outside the cylinder block surface. Temperature were measured by T-type thermocouples with accuracy of ±0.2 °C, and the thermocouples were fixed at the selected point on the system for monitoring temperature, as shown in Table 2. Four thermocouples were attached to the heated wall of the evaporator, and the average value (TC1 or T1) was chosen to represent the average temperature of the evaporator wall. The LHP was tested in the horizontal orientation where the evaporator and the condenser were on the same level.

In order to reduce the influence of non-condensable gas, the system needed to be vacuumed as much as possible before being charged. The boiling temperature of methanol is 64.6 °C under atmospheric pressure, so in order to reduce the operating temperature of the system, lower internal pressure in the system was required. Comparing these two systems in almost the same conditions, we found that the welding type could be pumped to a low internal pressure of 2.6×10^{-4} Pa and the O-ring type to 1.7×10^{-3} Pa.

3. Experimental results and discussion

3.1. Start-up performance

The start-up performance is an important performance indicator for LHP. In this experiment, the start-up curve can be divided into three categories: (1) zigzag start-up, (2) overshoot start-up, and (3) stable start-up [15].

3.1.1. Zigzag start-up

Fig. 3 shows the LHP start-up processes under a heat load of 20 W with different heat sink temperatures. It can be observed from the figures that the start-up curves with the heat load of 20 W exhibit a zigzag shape under different heat sink temperatures.

Table 1
Geometric material characteristics of the experimental LHP.

Evaporator	Heated diameter (mm)	40	Vapor line	Diameter (mm) I/O		4/5
	Height (mm)	19		Length (mm)		320
	Material	Brass		Material		Copper
Compensation chamber	Diameter (mm)	38	Liquid line	Diameter (mm) I/O		4/5
	Height (mm)	9.5		Length (mm)		405
	Material	Brass		Material		Copper
Porous wick	Diameter (mm)	40	Double tube condenser	Inner tube for working fluid	Diameter (mm) I/O	4/5
	Height (mm)	4		Outer tube for coolant	Diameter (mm) I/O	12/14
	Porosity (%)	60.2		Length (mm)		610
	Material	Stainless steel		Material		Copper

Table 2
Locations of thermocouples.

Location	Welding type	O-ring type
Evaporator wall	TC(2,3,4,5)	T(2,3,4,5)
Evaporator outlet	TC8	T8
Evaporator inlet	TC9	T9
Condenser inlet	TC11	T11
Condenser outlet	TC13	T13
Compensation chamber	TC14	T14
Ambient	TC19	T19

When the heat sink temperature is 0 °C, the fluctuation cycle and amplitude of the evaporator wall temperature are about 810 s and 17 °C, respectively. With a heat sink temperature of −15 °C, they are about 460 s and 9 °C, respectively. It is found that at the same heat load, the temperature fluctuation cycle is shorter and the amplitude is smaller in LHP with lower heat sink temperature. Because the lower heat sink temperature corresponds to the lower operating temperature and the lower internal pressure, the working fluid can flow more easily in the system with the lower heat sink temperature.

In this mode, the inlet temperature of the condenser is very unstable and easily drops to the temperature of the heat sink. When the LHP start-up at low heat load, the quality and rate of the generated vapor are relatively small, and the vapor expanding to the condenser rapidly condenses into the liquid. Before the start-up process is completed, the liquid in the compensation chamber is pumped to evaporate in the evaporating interface in the wick, and then the generated vapor condenses and stays in the condenser. The working fluid does not circulate in the system, so the temperature of the evaporator continues to rise. And the pressure of the vapor rises up to the total loop pressure drop to activate the circulation of the working fluid. At this moment, the working fluid distributes mainly in the condenser, and marginally in the compensation chamber. Once the working fluid flows in the system, the sub-cooled liquid flows into the compensation chamber and greatly reduces the temperature of the evaporator, and the working fluid evaporation decreases and the pressure reduces to less than the total loop pressure drop. The circulation of the working fluid cannot be sustained, and the inlet temperature of the condenser drops to the temperature of the heat sink. And another accumulation of vapor will be needed to maintain the cycle.

3.1.2. Overshoot start-up

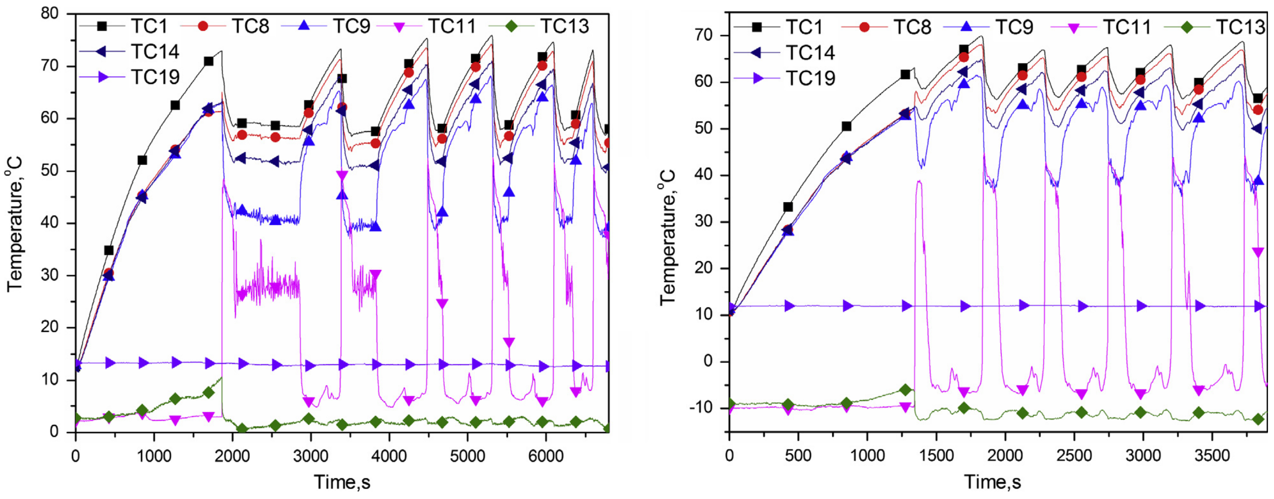
Fig. 4 shows that the overshoot start-up curves at 30 W are similar under different heat sink temperatures. These two start-up times are about 750 s. The evaporator wall temperature is 53.9 °C with heat sink temperature of 0 °C, and 53 °C with heat sink temperature of −15 °C. However, under variable heat load continue operation, it is 58 °C with heat sink temperature of 0 °C at 30 W. The start-up is different from the variable heat load continuous operating condition. Because the initial vapor–liquid distribution has a great impact on the operating temperature [16,17], the influence of the heat sink temperature is not obvious in the start-up process. Increasing the heat load, the overshoot start-ups are still found at heat load of 70 W and 100 W (Fig. 5), but then the LHP can operate in steady state.

The range of the overshoot occurring in this experiment is large, both at low heat load (30 W, Fig. 4) and at high heat loads (70 W and 100 W, Fig. 5). When the heat load is greater than 70 W, however, once the LHP starts up successfully, it can run steadily without temperature fluctuation (as shown in Fig. 5). Furthermore, once the LHP starts up successfully under any heat load, no overshoot phenomenon is found in the variable heat load continuous operating condition. This is because of the permanent circulation of the working fluid in LHP under this operating condition. The compensation chamber is supplied continuously by the sub-cooled liquid so that the temperature of the liquid in the compensation chamber does not drop to any significant extent.

In the overshoot start-up process of LHP, the overshoot phenomenon of the temperature is caused by the hysteresis of the returning liquid. After the heat load is applied to the evaporator wall, the vapor needs some time to be generated and accumulated to drive the flow of the working fluid. Once the working fluid flows up, a large amount of the sub-cooled working fluid flows into the compensation chamber, and the sub-cooled quantity is greater than the heat leak. The temperature of the evaporator reduces, but the circulation of the working fluid can be sustained for high heat load inputting, and the LHP adopts a relatively stable operation. Different from the zigzag start-up, there is still a vapor flowing into the condenser, and the inlet temperature of the condenser is greater than the ambient temperature.

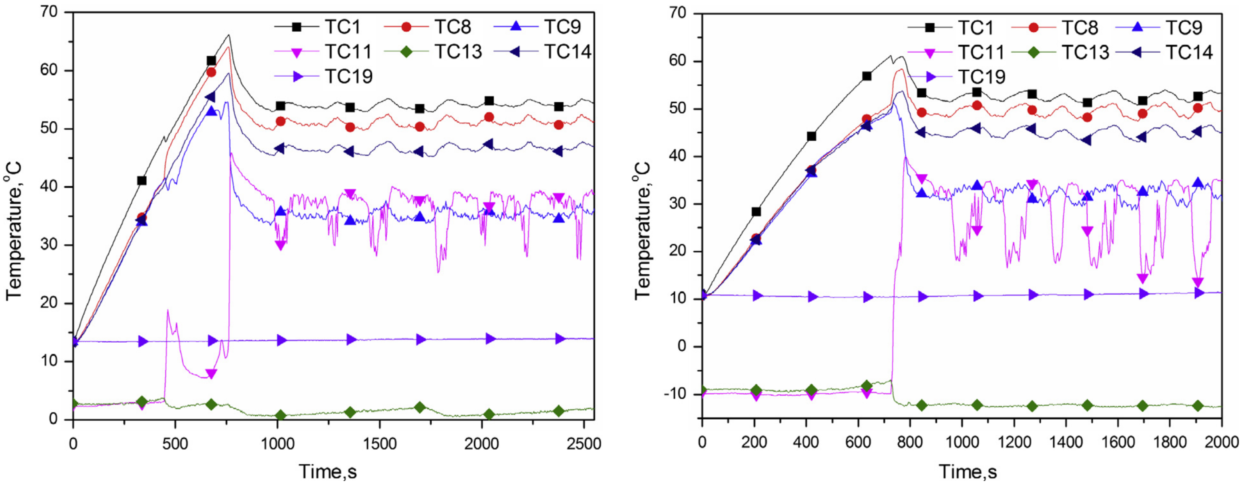
3.1.3. Stable start-up

Fig. 6 shows the start-up process at a heat load of 70 W with a heat sink temperature of 0 °C. The whole process is relatively



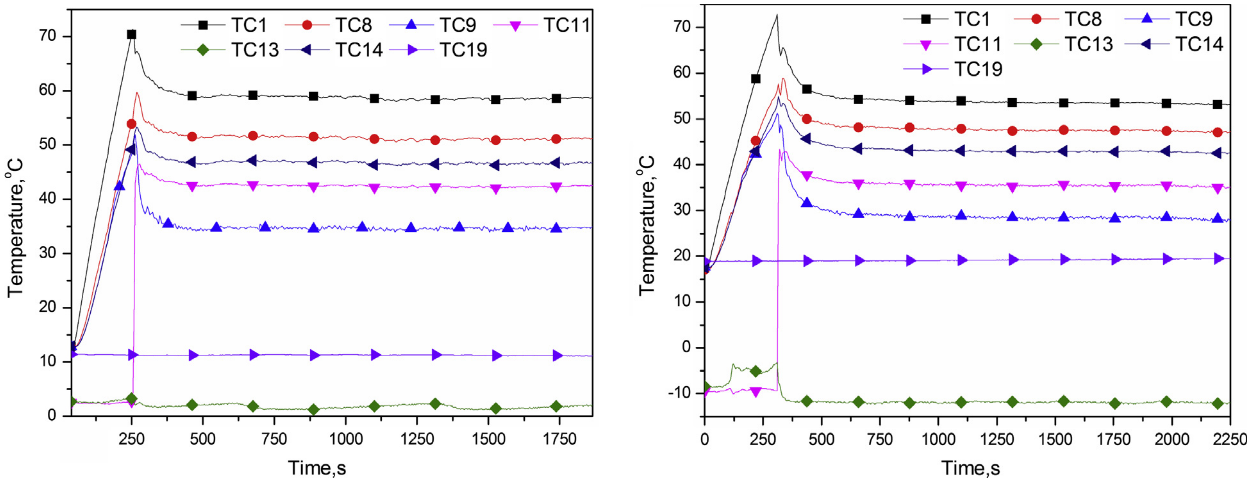
(a) Heat sink temperature: 0°C (b) Heat sink temperature: -15°C

Fig. 3. Zigzag start-up process at 20 W.



(a) Heat sink temperature: 0°C (b) Heat sink temperature: -15°C

Fig. 4. Overshoot start-up process at 30 W.



(a) 100W and 0°C (b) 70W and -15°C

Fig. 5. Overshoot start-up process at different heat loads and heat sink temperatures.

smooth without obvious temperature overshoot and fluctuation. The sub-cooled liquid returns into the compensation chamber and does not lower the temperature of the evaporator. So the evaporation in the porous wick is stable, and the LHP gradually achieve stable operation.

The overshoot start-up, however, occurs at the same heat load of 70 W with a heat sink temperature of −15 °C, as shown in Fig. 5(b). Because the temperature of the fluid returning to the compensation chamber is lower than that of the heat sink temperature of 0 °C, and the sub-cooled quantity is greater than heat leak. The returning fluid absorbs the heat leak and also reduces the temperature of the liquid in the compensation chamber.

Increasing the heat load, the leak heat transferring from the evaporator wall and the wick to the compensation chamber increases. The compensation chamber is almost full of the working fluid. The sub-cooled liquid sent back to the compensation chamber cannot completely absorb the heat leak, but the temperature rise of the compensation chamber slows down, and then the evaporator wall temperature keeps rising and finally reaches steady state.

3.1.4. Compared with start-up process of O-ring type LHP

In order to investigate the effects of the sealing method on LHP operation performance, a comparison with an LHP with an O-ring sealed evaporator was conducted. All the parameters were the same with braze welding-type evaporator except a larger fringe was used to install the O-ring.

Fig. 7 shows the start-up processes of O-ring type LHP with heat sink temperature of −15 °C under different heat loads. The O-ring type LHP can start up successfully at the heat load of 30 W and operate in the zigzag start-up mode. Increasing the heat load to 40 W, the O-ring type LHP turns into the overshoot start-up mode. And at the heat loads of 70 W and 100 W, the LHP operates in the stable start-up mode. There are temperature fluctuations in the start-up process of 70 W with maximum temperature fluctuation in the evaporator inlet. However, after an overshoot start-up process, it can run steadily without temperature fluctuation in the welding type LHP at 70 W.

It can be found that the welding type LHP has a significant advantage on the operating temperature during start-up process, and has lower start-up heat load than the O-ring type LHP. But

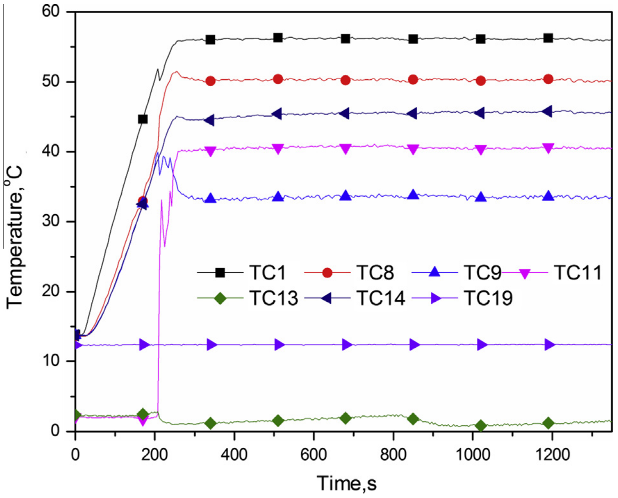


Fig. 6. Stable start-up process at 70 W with heat sink temperature of 0 °C.

the overshoot start-up occurs more easily in the welding type LHP. This may be due to the internal structure deformation during the welding process of the evaporator, which increases the flowing resistance of the working fluid in the LHP and suppresses the activation of the start-up.

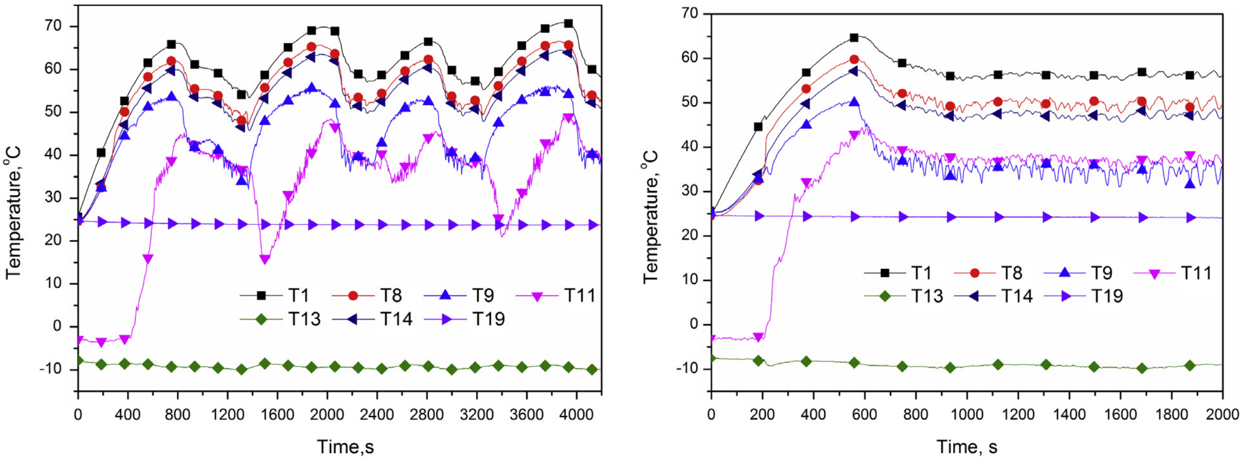
3.2. Variable heat load operation

The variable heat load operation is very important to verify the performances of the LHP under transient heat loads. Fig. 8 shows the operating process of the experimental LHP under variable heat loads with a heat sink temperature of 0 °C. When it reached the steady state, the operation of LHP in the case of increasing or decreasing heat load was tested. It can be observed that the LHP can operate stably under variable heat loads and each measuring point temperature remains relatively stable under different heat loads. The variable heat load operation of the LHP verified a good performance of adjusting to the heat load change. At the same heat load, the operating temperature of the LHP while decreasing heat load is lower than that of the LHP while increasing heat load.

In the operating process, the condenser outlet temperatures are almost the same. This is because the condenser length is sufficient, so that the working fluid in the condenser outlet is in the subcooled state with the approximate temperature of the heat sink. The temperature oscillation in the condenser outlet is caused by the intermittent operation of the refrigeration unit under a certain temperature control precision.

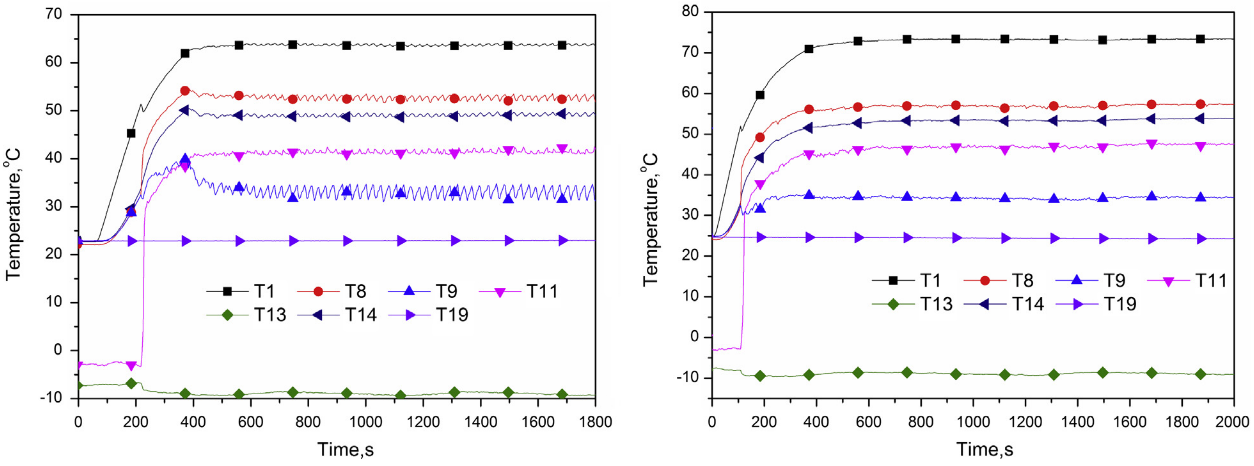
3.3. Temperature distribution

Fig. 9 shows the operating temperature of the two LHPs. Comparing the operating characteristics of the two different LHPs,



(a) Zigzag start-up process at 30W

(b) Overshoot start-up process at 40W



(c) Stable start-up process at 70W

(d) Stable start-up process at 100W

Fig. 7. Start-up process of O-ring type LHP with heat sink temperature of −15 °C.

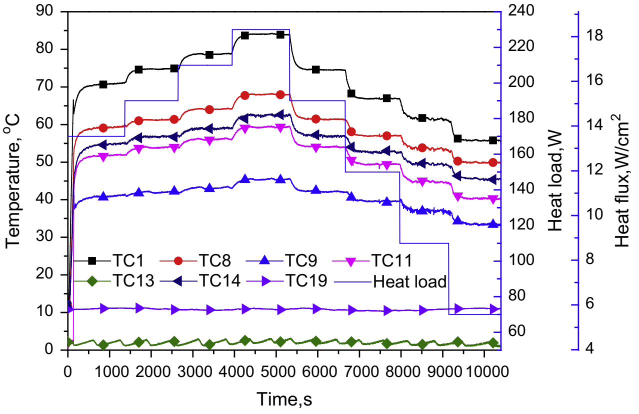


Fig. 8. Variable heat load continuous operation with heat sink temperature of 0 °C.

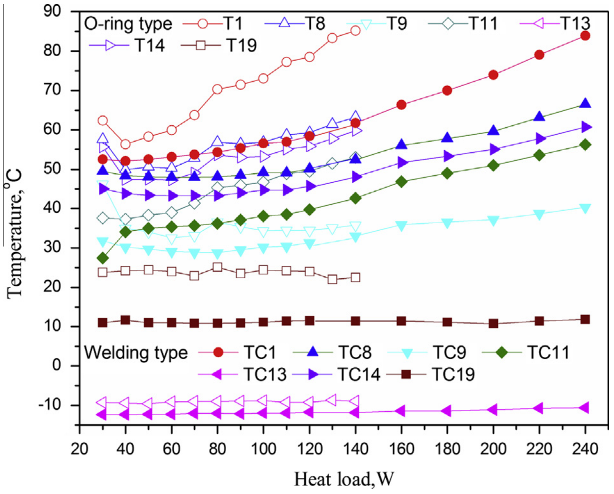


Fig. 9. Operating temperature of the two LHPs.

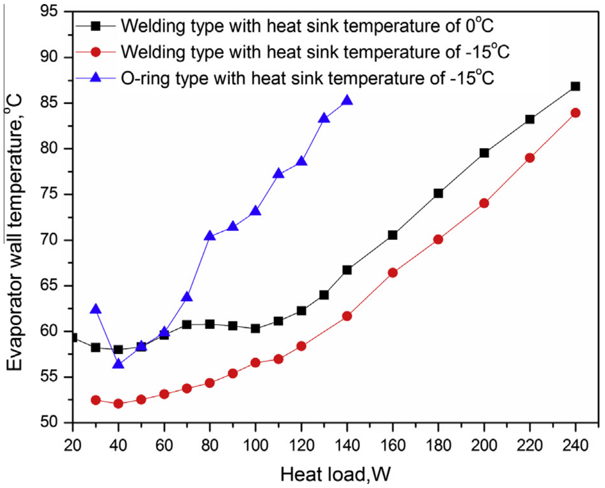


Fig. 10. Evaporator wall temperature of different LHPs.

it is found that the temperature of all measuring points of the welding type was lower than that of the O-ring type at the same heat load. The temperature curve of the O-ring type had a turning-point at the heat load of 80 W, and the welding type had an inconspicuous turning-point at 100 W, which corresponding to the point that LHP operates changing from the variable conductance mode to the constant conductance mode [9].

It is also found from Fig. 9 that the compensation chamber temperature of the O-ring type is higher than that of the welding type with the same evaporator inlet temperature, which is caused by the larger side-wall heat leak. When the compensation chamber temperature is the same, the evaporator wall temperature of the O-ring type is higher than that of the welding type, which reflects performance improvement after the vacuum degree of the LHP increases.

As can be seen from Fig. 10, with different sealing modes the LHP operating performances were obviously different. And the evaporator wall temperature is lower with lower heat sink temperature. At the heat sink temperature of −15 °C, when the evaporator wall temperature did not exceed 64.6 °C, the maximum heat load of the O-ring type LHP was 70 W, and that of the welding-type LHP could reach 140 W. When the evaporator heated wall temperature did not exceed 85 °C, the highest heat load of welding-type LHP could reach 240 W, which corresponded to a heat flux of 19.1 W/cm^2, and that of the O-ring type LHP only reached 140 W, corresponding to heat flux of 11.1 W/cm^2. In the previous papers with methanol as the working fluid in LHP, the heat load is 100 W (heat flux of 10.4 W/cm^2) when the evaporator wall temperature is less than 75 °C in Ref. [11] and the heat load is 160 W (heat flux of 16.8 W/cm^2) with the evaporator wall temperature below 85 °C in Ref. [10]. It can be found that this welding type LHP has an obvious improvement on the operating performance in this paper.

Comparison of the two sealing mode systems showed that most structures were identical, except that the welding-type LHP no longer needed the extra fringe surface used for sealing and fixing the O-ring. Moreover, when the LHP was vacuumed, it achieved a higher vacuum degree for the braze welding-type LHP. Thus, it can be deduced that the experimental performance improvement was mainly caused by two factors: first, the fringe area of the evaporator was reduced, weakening the influence of the side-wall heat leak to the compensation chamber, and, second, the vacuum degree inside the LHP improved, so the evaporating temperature of the working fluid decreased.

3.4. Thermal resistance

Thermal resistance is calculated to reflect the thermal performance of LHP. The total thermal resistance of LHP in this experiment is defined as:

$$R_{LHP} = (TC1 - T_{cond})/Q_{app} \tag{4}$$

and

$$T_{cond} = (TC11 + TC13)/2 \tag{5}$$

where Q_{app} is the input heat load, and T_{cond} is the average temperature of the condenser. The evaporating thermal resistance and evaporating heat transfer coefficient are used to reflect the performance of the porous wick in the evaporator. The evaporating thermal resistance is defined as:

$$R_{evap} = (TC1 - TC8)/Q_{app} \tag{6}$$

Thus, the evaporating heat transfer coefficient is

$$h = Q_{app}/A(TC1 - TC8) \tag{7}$$

where A is the area of the heater.

Fig. 11 shows the thermal resistance and the evaporating heat transfer coefficient. It can be observed that, with the increase of heat load, the total thermal resistance decreases, and the evaporating thermal resistance decreases and then increases in the welding type LHP, which corresponds to an opposite tendency on the part

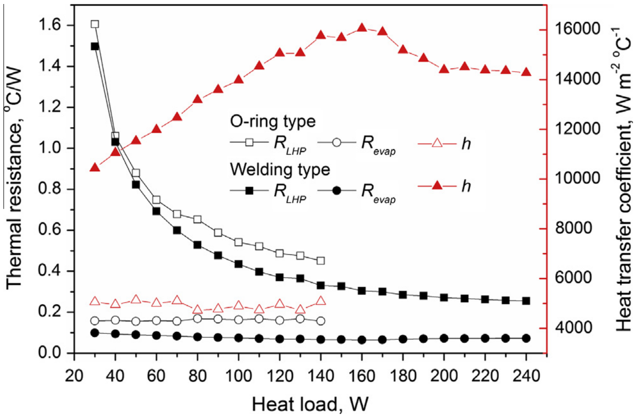


Fig. 11. Thermal resistance and evaporating heat transfer coefficient.

of the evaporating heat transfer coefficient. Within the changed range of heat load from 30 W to 240 W, the total thermal resistance changes in the range of 1.50–0.26 °C/W, and the evaporating thermal resistance is 0.065–0.100 °C/W. The maximum evaporating heat transfer coefficient is 16,057 W m^{-2} °C^{-1}, which occurs at a heat load of 160 W.

At low heat load, only small quantity of liquid can evaporate, and so the heat transfer coefficient is not high. When heat load increases, the evaporating of liquid is intensified and, as a result, the heat transfer coefficient increases, just as illustrated in Refs. [18,19]. Also, the thickness of the vapor layer contacting with the evaporator's heated internal surface increases. When the heat load reaches a certain value, the effect of the thickness of the vapor layer is greater than that of the increase of the evaporation, the evaporating thermal resistance increases and the evaporating heat transfer coefficient decreases.

4. Conclusions

Start-up and variable heat load operating experiments of an LHP with a flat disk-shaped evaporator using the braze welding method were carried out, and three start-up processes were studied. Temperature oscillations take place with low heat load during the zigzag start-up process. The overshoot start-up occurs more possibly with the lower heat sink temperature, and stable start-up is more favorite. The welding-type LHP is an obvious improvement on the O-ring type LHP. When the evaporator wall temperature does not exceed 85 °C, the maximum heat load can reach 240 W, which corresponds to heat flux of 19.1 W/cm^2, but the maximum heat load for the O-ring type LHP is only 140 W, corresponding to heat flux of 11.1 W/cm^2. It can be deduced from the results that in order to improve the performance of LHPs, it is necessary to design the evaporator to reduce the heat leak to the compensation chamber.

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References

[1] Y.F. Maydanik, Review loop heat pipes, Appl. Therm. Eng. 25 (2005) 635–657.
[2] J. Ku, Operating characteristics of loop heat pipes, in: 29th International Conference on Environmental System, Denver, Colorado, July 12–15, 1999.
[3] J. Li, D.M. Wang, G.P. Peterson, Experimental studies on a high performance compact loop heat pipe with a square flat evaporator, Appl. Therm. Eng. 30 (2010) 741–752.
[4] X.H. Nguyen, B.H. Sung, J. Choi, S.R. Ryoo, H.S. Ko, C. Kim, Study on heat transfer performance for loop heat pipe with circular flat evaporator, Int. J. Heat Mass Transfer 55 (2012) 1304–1315.
[5] S. Launay, V. Sartre, J. Bonjour, Parametric analysis of loop heat pipe operation: a literature review, Int. J. Therm. Sci. 46 (2007) 621–636.
[6] S.F. Wang, W.B. Zhang, X.F. Zhang, J.J. Chen, Study on start-up characteristics of loop heat pipe under low-power, Int. J. Heat Mass Transfer 54 (2011) 1002–1007.
[7] J.Y. Xu, L. Zhang, H. Xu, Performance of LHPs with a novel design evaporator, Int. J. Heat Mass Transfer 55 (2012) 7005–7014.
[8] L. Zhang, J.Y. Xu, H. Xu, Effect of inventory on the heat performance of copper–water loop heat pipe, Exp. Thermal Fluid Sci. 44 (2013) 875–882.
[9] B.B. Chen, Z.C. Liu, W. Liu, J.G. Yang, H. Li, D.D. Wang, Operational characteristics of two biporous wicks used in loop heat pipe with flat evaporator, Int. J. Heat Mass Transfer 55 (2012) 2204–2207.
[10] Z.C. Liu, H. Li, B.B. Chen, J.G. Yang, W. Liu, Operational characteristics of flat type loop heat pipe with biporous wicks, Int. J. Thermal Sci. 58 (2012) 180–185.
[11] H. Li, Z.C. Liu, B.B. Chen, W. Liu, C. Li, J.G. Yang, Development of biporous wicks for flat-plate loop heat pipe, Exp. Thermal Fluid Sci. 37 (2012) 91–97.
[12] Z.C. Liu, D.X. Gai, H. Li, W. Liu, J.G. Yang, M.M. Liu, Investigation of impact of different working fluids on the operational characteristics of miniature LHP with flat evaporator, Appl. Therm. Eng. 31 (2011) 3387–3392.
[13] S. Becker, S. Vershinin, V. Sartre, E. Laurien, J. Bonjour, Y.F. Maydanik, Steady state operation of a copper–water LHP with a flat-oval evaporator, Appl. Therm. Eng. 31 (2011) 686–695.
[14] R. Singh, A. Akbarzadeh, M. Mochizuki, Effect of wick characteristics on the thermal performance of the miniature loop heat pipe, J. Heat Transfer 131 (2009) 082601.
[15] B.J. Huang, H.H. Huang, T.L. Liang, System dynamics model and startup behavior of loop heat pipe, Appl. Therm. Eng. 29 (2009) 2999–3005.
[16] X.F. Zhang, J.P. Huo, S.F. Wang, Experimental investigation on temperature oscillation in a miniature loop heat pipe with flat evaporator, Exp. Thermal Fluid Sci. 37 (2012) 29–36.
[17] G.P. Celata, M. Cumo, M. Furrer, Experimental tests of a stainless steel loop heat pipe with flat evaporator, Exp. Thermal Fluid Sci. 34 (2010) 866–878.
[18] Q. Liao, T.S. Zhao, Evaporative heat transfer in a capillary structure heated by a grooved block, AIAA J. Thermophys. Heat Transfer 13 (1999) 126–133.
[19] Q. Liao, T.S. Zhao, A visual study of phase-change heat transfer in a two-dimensional porous structure with a partial heating boundary, Int. J. Heat Mass Transfer 43 (2000) 1089–1102.