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Temperature Oscillation of mLHP with Flat Evaporator

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Loop heat pipes (LHPs) are heat transfer devices whose operating principle is based on evaporation and condensation of a working fluid, and which use the capillary pumping forces to ensure fluid circulation. Temperature oscillations are a rather wide-spread phenomenon accompanying the operation of miniature loop heat pipes (mLHP), which depends on the charging ratio of the working fluid, the device orientation in the gravity field, and the conditions of the condenser cooling, and so on. Intense oscillation, whose amplitude may exceed tens of centigrade degrees and the period may be equal to tens of minutes, arises from the lack of a working fluid in a mLHP when a hot condensate or vapor bubbles periodically penetrate into the compensation chamber and act on the vapor phase in it, thus increasing its temperature and volume. Changes in the external conditions, for instance, the LHP arrangement in an unfavorable orientation or applied heat load with respect to the conditions for which the filling volume is optimal, also contribute to initiation of intense temperature oscillation. All in all, the heat leak from the evaporator to the compensation chamber, the heat loss to the ambient, and the temperature and rate of subcooled liquid dictate the vapor bubble condition inside the compensation chamber, and the rate of the vapor bubble growth or dissipation inside the compensation chamber dictates the nature of temperature oscillation. The effects of different liquid charging ratios and the tilt angles to the temperature oscillation are studied in detail.

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Keywords: miniature loop heat pipe; flat evaporator; temperature oscillation; heat and mass transfer; experimental investigation

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INTRODUCTION

A loop heat pipe is a highly efficient heat-transfer device which does not require any additional regulating actions from the outside for ensuring its serviceability. Thus, LHPs offer many advantages over traditional heat pipes, such as operability against gravity and over a large distance with minimal temperature loss, no moving parts for pumping the working fluid, etc. A detailed review of the main characteristics of LHPs can be found in [1, 2]. LHPs have been successfully used in space engineering. With increasing power densities of electric devices, the LHP technology continues to be an important area of research. The mLHP with the cylindrical as well as flat evaporators have been developed and tested successfully. Compared with conventional cylindrical LHPs, the LHP with a flat evaporator has more advantages: firstly, it is more convenient for the flat-plate type evaporator to connect with the electronic devices which should be cooled, because most objects to be cooled have a flat thermal contact surface; secondly, the angle of the velocity gradient and temperature gradient is smaller than that of LHPs with a cylindrical evaporator, from the viewpoint of the field synergy principle, the heat transfer efficiency of the flat evaporator is better. So the capability of LHP with the flat-plate evaporator for transferring high heat flux is achieved easily. The LHPs with the flat evaporator can be considered as an optimum design for compact enclosures as it provides relatively more scope for design miniaturization.

LHPs provide a unique way for transporting heat using the phase change. The structure of LHPs can be various in terms of size, geometric shape, relative position, material, working fluid, charging ratio, etc. The performance characteristics of LHPs are very complicated, the main objective of the present study is to design and investigate the temperature oscillation phenomenon of the miniature loop heat pipe with a flat copper evaporator, stainless mesh wick, and methanol as working fluid. Thermal oscillations are characterized by continuous fluctuations in temperature at different locations of mLHP and thus inability of the evaporator to attain stable operating conditions. These oscillations are expected to result from the thermal and hydrodynamic interaction between the compensation chamber, condenser, and evaporator section [3, 4]. Copper–stainless steel–methanol combination is chosen for the present investigation due to the viability and acceptability of such a system for electronic cooling applications. The present research also endeavors to test the compatibility of the copper–stainless steel–methanol system for loop heat pipe applications.

1. EXPERIMENTAL PROTOTYPE

An experimental prototype of a miniature LHP as shown in Fig. 1 is constructed for carrying out the present investigation. The overall system consists of an evaporator with a porous wick, vapor line, fin-tube condenser, and liquid line. The evaporator was made in the shape of the flat rectangle with the active zone of size 40×30 mm and thickness of 13.5 mm. There are 15 longitudinal and 18 latitudinal grooves

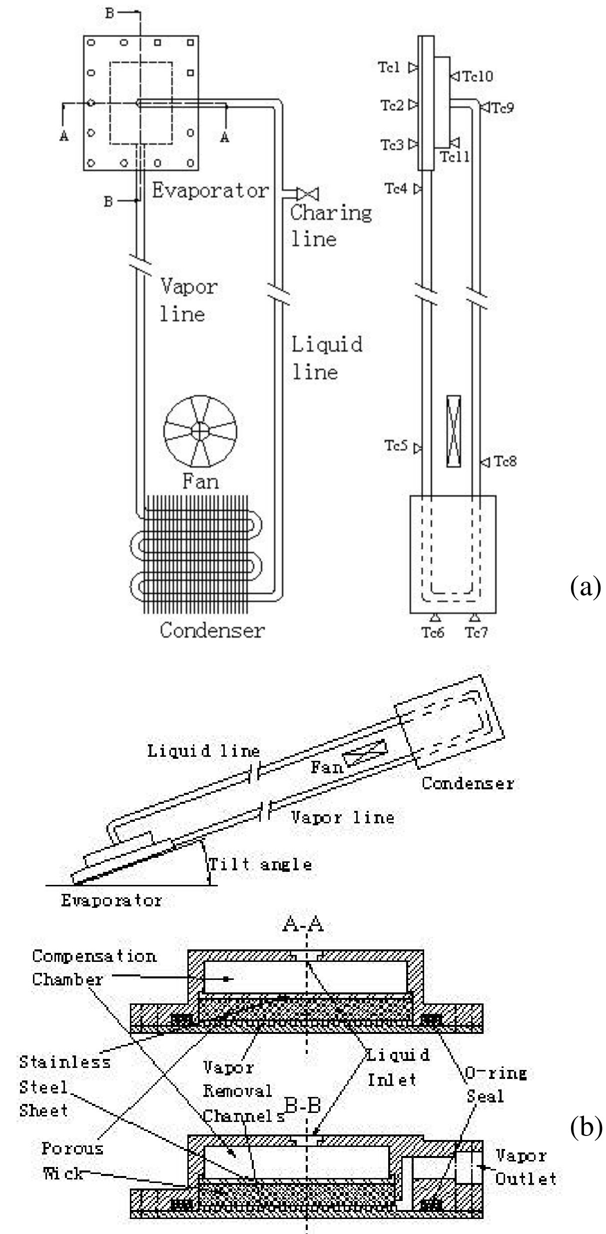

Fig. 1. Schematics of the mLHP: (a) top and side view of the mLHP and the placement of the thermocouple points; (b) cross section of the mLHP evaporator.

machined on the inside of the evaporator active heated zone which behave as vapor removal channels and also provide heat to the skeleton of the porous structure through conduction process. The evaporator is made from pure copper that provides superior thermal conductivity and minimal heat spreading resistance from the source to the porous wick surface. Figure 2 illustrates the cross section of the evaporator assembly showing the location of the vapor channels, wick structure, and compensation

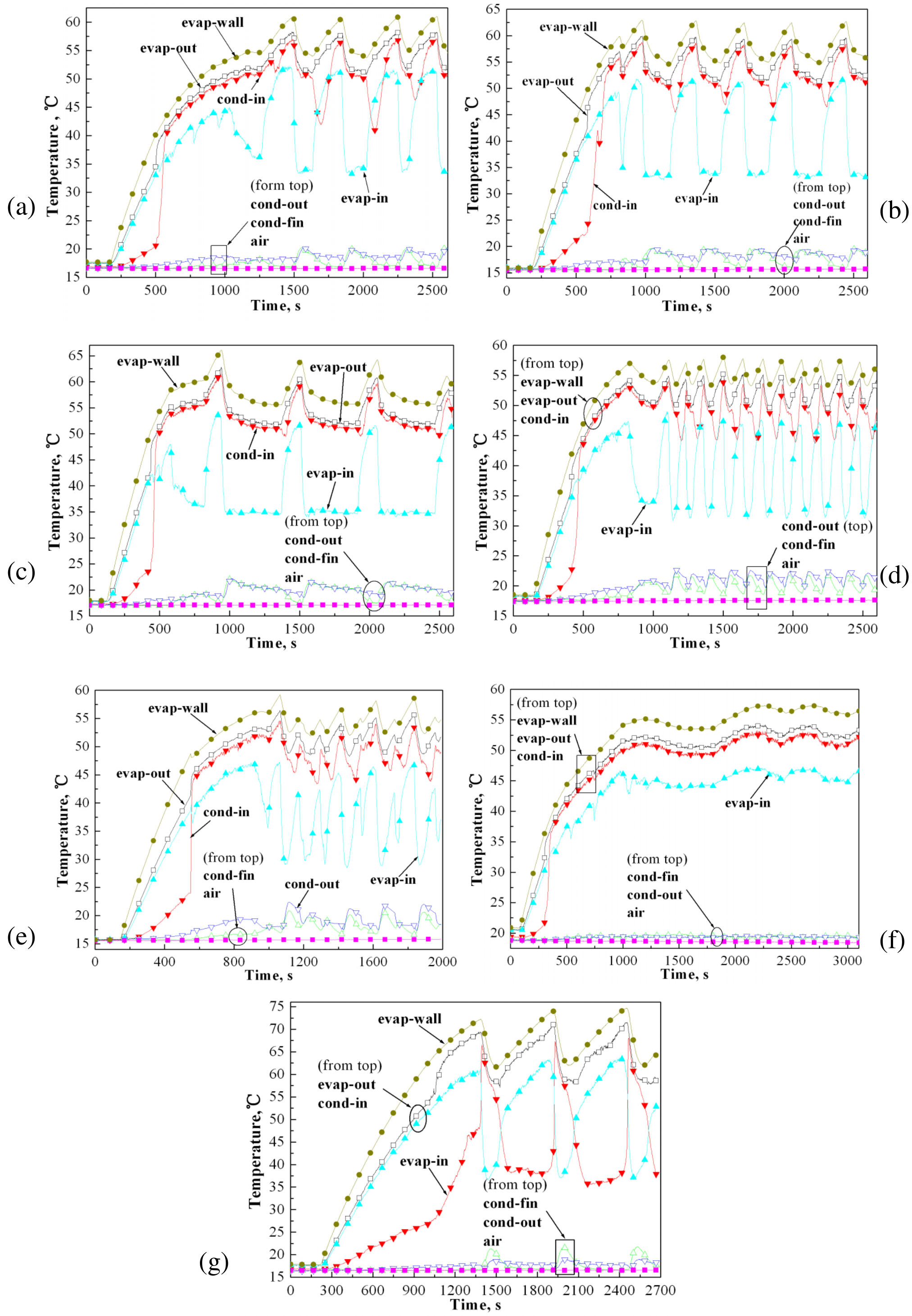

Fig. 2. Start-up of the mLHP: (a) θ = 10, 60 vol.%, Q = 24 W; (b) θ = 10, 60 vol.%, Q = 30 W; (c) θ = 10, 60 vol.%, Q = 36 W; (d) θ = 50, 60 vol.%, Q = 30 W; (e) θ = 90, 60 vol.%, Q = 30 W; (f) θ = 10, 50 vol.%, Q = 24 W; (g) θ = 10, 70 vol.%, Q = 24 W.

Table 1

Geometric characteristics of the experimental mLHP

<table>
<tr><td rowspan="11">Evapo-rator</td><td rowspan="5">active heated zone</td><td>thickness (mm)</td><td>1.5</td><td rowspan="2">Vapor line</td><td>diameter (O/I) (mm)</td><td>6/4</td></tr>
<tr><td>length/width (mm)</td><td>40/30</td><td>length (mm)</td><td>320</td></tr>
<tr><td>groove thickness (mm)</td><td>1</td><td rowspan="2">Liquid line</td><td>diameter (O/I) (mm)</td><td>6/4</td></tr>
<tr><td>fin width (mm)</td><td>1 × 1</td><td>length (mm)</td><td>530</td></tr>
<tr><td>fin number</td><td>18 × 15</td><td rowspan="5">Condenser</td><td>diameter (O/I) (mm)</td><td>6/4</td></tr>
<tr><td>wall</td><td>thickness (mm)</td><td>1.5</td><td>length (mm)</td><td>810</td></tr>
<tr><td>stainless steel sheet</td><td>thickness (mm)</td><td>0.5</td><td>fin thickness (mm)</td><td>0.05</td></tr>
<tr><td rowspan="2">compensation chamber</td><td>length/width (mm)</td><td>34.5/30</td><td>fin length/width (mm)</td><td>100/20</td></tr>
<tr><td>height (mm)</td><td>6</td><td>fan rotate speed (rpm)</td><td>3000</td></tr>
<tr><td rowspan="2">porous wick</td><td colspan="2">length/width/height (mm)</td><td colspan="3">36.5/30/4</td></tr>
<tr><td>material</td><td>316L</td><td>parameter of mesh</td><td colspan="2">500#, 82 layers</td></tr>
</table>

chamber. The 4-mm-thick wick of the evaporatoris made up of a stainless steel mesh (82 layers, 500 grids). The 6-mm-thick compensation chamber acts as a liquid reservoir and accommodates the extra liquid inventory displace from other parts of the loop during start-up and transient operating conditions. There is a stainless steel sheet with grooves between the porous wick and the compensation chamber to sustain the stainless steel wick. The geometric characteristics of the experimental mLHP are shown in Table 1.

The mLHP condenser is fin-and-tube type with the total tube length of 810 mm and cross section of 100 × 20 mm for each fin. A centrifugal fan is used to dissipate heat from the condenser to the ambient by means of forced convection of air with a temperature of 18 ± 2^{o}C. The vapor line of the mLHP is 320 mm in length and has a 4-mm internal diameter. For the return of the condensate to the evaporator, a liquid return line with the total length of 530 mm and 4-mm internal diameter is used. The transport lines and the condenser fin are entirely made from pure copper. The mLHP is hermetically sealed by an O-ring seal between the evaporator flanges. For charging, the loop is first evacuated to 3.2×10^{-4} Pa and then is filled with the predetermined quantity of methanol whose purity is 99.5%. In order to test thermal performance of the mLHP, a heat load simulator in the form of a copper block with two embedded cartridge heaters and an active area of 40 × 30 mm is used, which is uniform to the evaporator. For the purpose of minimizing heat losses to the ambient, the heat load simulator is thermally insulated using a 10-mm-thick nano-adiabatic material whose conductivity is just 0.012 W/m·K. According to Fourier's law of heat conduction, the quantity of heat loss is 0.28 W as the heat load attains the largest value of 120 W. So the head load simulator does not need to be equalized, and the absolute error of the heat load is less than 0.5%. Other parts of the mLHP are not heat preserving except for the heat load simulator and the active surface of the evaporator.

A digital power meter with an accuracy of 0.2 W was used to measure and control the input power to the heat load simulator. Twelve T-type thermocouples with 0.2^{o}C accuracy are used to measure the temperature at different locations of the mLHP and the ambient air. Figure 1 also shows the position of thermocouples. All the instruments are connected to the Keyence Thermo Pro 2700 data acquisition system that helps to monitor and record the test data from the mLHP prototype at a time interval of every 1.5 sec.

In this phase of experiments, the mLHP is operated at the tilt angle θ of 10^{o}, 50^{o}, and 90^{o}, and the charging ratio of 50 vol.%, 60 vol.%, and 70 vol.% in the cold mode. The procedure of tests included measurement of temperatures at characteristic points of the mLHP with a successive stepwise 12 W increase and decrease of the heat load and the start-up tests with the heat loads from 12 W (q = 1 W/cm^2) to 120 W (q = 10 W/cm^2). For the safety of tests the maximum heat load is limited by the value that the operating temperature of the evaporator wall reaches 75^{o}C.

2. TEMPERATURE OSCILLATION

Temperature oscillation is a rather wide-spread phenomenon accompanying the mLHP operation. The investigations conducted make it possible to differentiate three main types of the LHP operating temperature [6]. The first of them is characterized by a low amplitude (no more than 1^{o}C) and a high frequency. The second type is also characterized by a low amplitude (no more than several centigrade) of temperature oscillations, but their cycle is longer and reaches several minutes. The third type is distinguished by a high amplitude of temperature oscillations, which reaches tens of degrees, and a still longer period, which may be equal to tens of minutes.

2.1 Effect of Heat Load on Temperature Oscillation

In general, the mLHP temperature oscillation does not occur at low as well as high heat loads. It is experimentally observed that the temperature oscillation of the mLHP mostly occurs at heat loads from 18 W to 48 W. Shown in Fig. 2a–c are time scannings of experiments at a heat load of 24 W, 30 W, 36 W, 60 vol.% charging ratio, and 10^{o} tilt angle, respectively. It is observed from each plot that the frequency of occurrence for these oscillations is the same at different locations but the amplitude is different. In particular, the extent of the oscillations is very high at the evaporator inlet. At different heat loads, the frequency and amplitude of these oscillations are different. With the increase of heat load from 24 W to 36 W, it is noted that the frequency of the oscillations decreases while the amplitude increases. For low heat loads, the amount of liquid quantity inside the compensation chamber is small and the vapor fraction is huge. This reduces the heat capacity of the compensation chamber and thus increases the effects of heat leak from the evaporator to the compensation chamber and the heat loss from the compensation chamber to ambient air. As a result, the frequency of the oscillation increases while the amplitude of the oscillation decreases at low heat loads since the heat leak from the evaporator to the compensation chamber is less than that at high heat loads, thus the oscillation is lack of energy to increase the amplitude.

2.2 Effect of Tilt Angle on Temperature Oscillation

The effect of the tilt angle to the temperature oscillation is shown by Fig. 2b–e. It is noted that the temperature oscillation at 10^o and 50^o tilt angles pulsates with a fixed amplitude, but the amplitude decreases and the frequency increases with the increasing of the tilt angle from 10^o to 50^o. Sometimes the amplitude periodically varies as shown in Fig. 2e. As the tilt angle increases, the liquid quality in the compensation chamber increases and the distribution of liquid and vapor in the compensation chamber changes, which changes the heat capacity of the compensation chamber and the heat loss from the compensation chamber to ambient air, so the characteristics of temperature oscillation varied.

2.3 Effect of Charging Ratio on Temperature Oscillation

Experiments on the effect of the charging ratio on the behavior of temperature oscillation are presented in Fig. 2a,f,g. It is observed that with the increase of the charging ratio from 50 vol.% to 70 vol.%, the amplitude of temperature oscillation increases. At the condition of 24 W heat load and 10^o tilt angle, the frequency and amplitude are small at a charging ratio of 50 vol.%, and they are normal at a charging ratio of 60 vol.%, but the amplitude is huge (about 12^oC) at 70 vol.%. The reason for the intense temperature oscillation is, evidently, an overshoot of vapor or insufficiently cooled condensate into the compensation chamber. They cause an abrupt increase in the temperature and the bulk of the vapor phase there. In this case, pressure pulsations in the flow of the working fluid correspondent to increasing pulsations of the vapor temperature might cause a breakdown in the wick and the deterioration of the evaporation zone replenishment, which, as a result, caused a crisis in the mLHP operation.

2.4 The Mechanism of Temperature Oscillation

It is experimentally observed that the temperature oscillation is related to the applied heat load, tilt angle, and charging ratio. Shown in Table 2 are the amplitude and periods of temperature oscillations of $T_{\text{evap-wall}}$ under different operating conditions. It is observed that the temperature oscillation of the mLHP occurs in a zone of heat loads, and it reaches the largest amplitude at one heat load (Q_A) at the fixed operating condition. The temperature oscillation decreases until it disappears with the heat load away from Q_A. The present experiments show that the temperature oscillation is weakened and the upper and lower limits of heat loads at which temperature oscillation occurs synchronously rise with the tilt angle increase. For example, at the same charging ratio of 60 vol.%, temperature oscillation occurs in the mLHP at a heat load between 18 and 36 W at a tilt angle of 10^o; the lower and upper limits of

Table 2

Amplitude and periods of temperature oscillations of $T_{evap\text{-}wall}$ at different operating conditions

Operating conditions		Amplitude, °C	Periods, sec	Operating conditions		Amplitude, °C	Periods, sec
θ = 10°, 60 vol.%	18 W	4.05	320	θ = 10°, 50 vol.%	24 W	2.81	605
	24 W	7.27	392		36 W	2.42	114
	30 W	8.08	415		48 W	1.32	55
	36 W	8.46	540	θ = 50°, 90°, 50 vol.%		No obvious oscillation	
θ = 50°, 60 vol.%	24 W	3.73	135	θ = 10°, 70 vol.%	12 W	1.07	52
	30 W	4.93	148		24 W	12.54	540
	36 W	5.49	198	θ = 50°, 70 vol.%	12 W	7.82	258
θ = 90°, 60 vol.%	24 W	4.85	212		24 W	8.3	290
	30 W	6.03	210		36 W	11.1	520
	36 W	1.34	64	θ = 90°, 70 vol.%	24 W	6.32	218
	42 W	1.65	75		36 W	7.66	162

temperature oscillation occurrence zone at a tilt angle of 50° are 24 and 36 W; and the lower and upper limits of temperature oscillation occurrence zone at a tilt angle of 90° are 24 and 42 W. The reason is that at the same charging ratio and heat load, the working liquid inside the compensation chamber is at a smaller tilt angle, which reduces the thermal capacity of the compensation chamber. For the effect of the heat leak, the liquid-to-bubble ratio inside the compensation chamber will reach the zone of temperature oscillation occurrence at a low heat load. Contrarily, the liquid-to-bubble ratio inside the compensation chamber reaches the zone of temperature oscillation occurrence at a higher heat load with the tilt angle increasing which increases the thermal capacity of the compensation chamber. So the lower limit of the zone of temperature oscillation occurrence increases with the increase in the tilt angle. With the increasing of the heat load, the amount of liquid increases and the amount of bubbles decreases inside the compensation chamber. As the liquid occupies almost the entire compensation chamber, the mLHP temperature oscillation will not occur. Otherwise, the upper limit of the zone of temperature oscillation occurrence increases with the tilt angle increasing, too. The reason is that the operating temperature is higher at a bigger tilt angle, which increases the heat leak to the compensation chamber, and the heat leak will change the liquid-to-bubble ratio. Otherwise, the lower and upper limits of the zone of temperature oscillation occurrence are related to the distribution of the liquid and bubbles inside the compensation chamber.

As the charging ratio increases, the temperature oscillation is enhanced, otherwise, the upper and lower limits of heat loads at which temperature oscillation occurs decrease synchronously and the zone of heat loads at which temperature oscillation occurs becomes narrow. For example, at the same tilt angle of 10° the lower and upper limits of the zone of temperature oscillation occurrence at a charging ratio of 50 vol.% are 24 and 48 W; they are 18 and 36 W at a charging ratio of 60 vol.%, and they are 12 and 24 W at a charging ratio of 70 vol.%. The reason is that the liquid-to-bubble ratio inside the compensation chamber dictates the lower and upper limits of the temperature oscillation occurrence zone. At the same tilt angle and heat load, the liquid inside the compensation chamber increases with the increase in the charging ratio, so the liquid-to-bubble ratio will reach temperature oscillation occurrence at a low heat load. For the same reason, the liquid will occupy the entire compensation chamber at a low heat load and then the temperature oscillation disappears.

2.5 Effect of Power Cycle to Temperature Oscillation

Figure 3a,b shows temperature oscillation of mLHP in the power cycle. Comparing with the temperature oscillation when the heat load decreases from the high-heat-load steady zone III to the mid-heat-load oscillation zone II, the temperature oscillation is usually more intense when the heat load increases from the low-heat-load steady zone

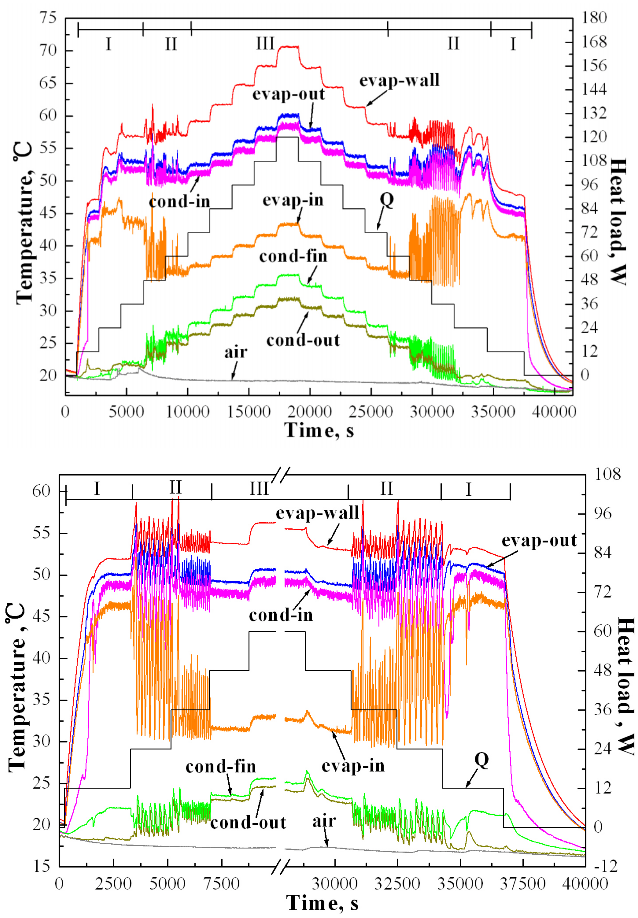

Fig. 3. Performance tests of the mLHP at power cycles: (a) $\theta = 10^{o}$, 50 vol.%; (b) $\theta = 90^{o}$, 60 vol.%.

I to the mid-heat-load oscillation zone. When the heat load increases from the I-zone to the II-zone, the liquid is charging into the compensation chamber, the cold liquid cools the vapor and the evaporator wall, the power of the vapor decreases quickly. And when the heat load decreases from the III-zone to the II-zone, with the decrease of the mass flow rate, the vapor generates in the compensation chamber and pushes the liquid out of the compensation chamber to the condenser, meanwhile, the evaporator wall releases heat which quickens the growth of velocity and increases the quantity of vapor. The rate of vapor growth or dissipation inside the compensation chamber dictates the characteristics of the temperature oscillation of mLHP. Otherwise, the former state will affect the latter operating condition, such as in Fig. 3a, 12 $\rightarrow$ 24 W, the mLHP could achieve a steady state, but as 36 $\rightarrow$ 24 W, the system achieved a temperature oscillation state. As shown in Fig. 3b, with the heat load 0 $\rightarrow$ 12 W, the mLHP achieved a steady state in short time, but with the heat load 24 $\rightarrow$ 12 W, the system achieved a steady state in long time. So there is large inertia of the hydrodynamic oscillation in the system.

CONCLUSIONS

In this paper, experimental investigation of the miniature loop heat pipe with the flat evaporator, air cooling fin-tube condenser, and copper–stainless steel–methanol configuration is conducted. The main outcomes of the study can be summarized as follows:

- Temperature oscillations are observed throughout the loop for applied heat load in the range of 18 to 48 W, and the temperature oscillation reaches the largest amplitude at different heat loads (Q_A) under different operating conditions. The temperature oscillation decreases until it disappears with the heat loads being away from Q_A. There is no temperature oscillation when the applied heat load is less than 18 W or larger than 48 W.
- The compensation chamber is the most critical component of the mLHP, and the rate of the bubble growth or dissipation inside the compensation chamber dictates the nature of temperature oscillation.
- Comparing with the temperature oscillation of the heat load decreasing from the high-heat-load steady zone to the mid-heat-load oscillation zone, the temperature oscillation is more intense when the heat load increases from the low-heat-load steady zone to the mid-heat-load oscillation zone under the same operating condition.
- With the increase of the charging ratio, the lower and upper limits of heat loads at which temperature oscillation occurs decrease and the temperature oscillation occurrence zone of heat load narrows, but the amplitude becomes larger, sometime over 10^{o}C.
- With the increase of the tilt angle, the amplitude increases and the frequency decreases, otherwise, the lower and upper limits of heat loads at which temperature oscillation occurs increase.

- There is large inertia of the hydrodynamic oscillation in the system, so the former state will affect the working state of the latter operating condition.

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NOMENCLATURE

A	area, m^2
b	thickness, m
q	heat flux, $W \cdot cm^{-2}$
Q	heat load, W
R	thermal resistance, $^oC \cdot W^{-1}$
T	temperature, ^oC

Greek symbols

λ	thermal conductivity, $W \cdot m^{-1} \cdot K^{-1}$
θ	tilt angle, deg

Subscripts

air	ambient air
cond	condenser
cond-fin	fin of condenser
cond-in	condenser inlet
cond-out	condenser outlet
evap	evaporator
evap-in	evaporator inlet
evap-out	evaporator outlet
evap-wall	active zone of evaporator.

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