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Steady-state and transient performance of a miniature loop heat pipe ☆

Yuming Chen [a,*], Manfred Groll [a], Rainer Mertz [a], Yu F. Maydanik [b], S.V. Vershinin [b]

[a] *Institute of Nuclear Technology and Energy Systems (IKE), University of Stuttgart, Pfaffenwaldring 31, 70569 Stuttgart, Germany*
[b] *Institute of Thermal Physics, Ural Branch of the Russian Academy of Sciences, Pervomaiskaya St. 91, Ekaterinburg, 620219, Russia*

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Abstract

A series of tests have been carried out with a miniature loop heat pipe (mLHP), which has been developed for consumer electronics cooling, for horizontal and four vertical orientations under different sink temperatures. The mLHP has a cylindrical evaporator of 5 mm outer diameter and 29 mm length. The steady-state operating characteristics are similar for different orientations except for the orientation where the evaporator is above the compensation chamber. At an evaporator temperature of 75 °C, an evaporator heat load up to 70 W can be reached with thermal resistance of about 0.2 °C/W. The transient behavior of the mLHP is studied in detail. In general, the mLHP can be started up with very low power input (5 W). Big temperature oscillations in the liquid line were found in many cases, however, the temperature oscillations in the evaporator are minimum. The orientations greatly influence the operating characteristics of the mLHP. At least for the horizontal orientation, the overall performance of the tested mLHP is satisfying.

Keywords: Loop heat pipe; Heat transfer; Electronics cooling; Temperature oscillation; Transient behavior

1. Introduction

The main principles of the Loop heat pipes (LHPs) include the use of fine-pored wicks and transport lines without capillary structure and, organization of effective heat exchange in evaporator and condenser [1]. Thus, LHPs offer many advantages over traditional heat pipes, such as operability against gravity, maximum heat transport capacity, etc. LHPs have been successfully used in space engineering. They also offer a great potential for terrestrial applications, especially for consumer electronics cooling [1–3]. As electronic equipments are becoming smaller and more powerful, there is an urgent need to find a solution for dissipating increasingly higher power densities. Miniaturization of LHPs is thus at the forefront of an extensive research and development.

LHPs provide a unique way for transporting heat using phase change. The structure of LHPs can be various in terms of size, geometric shape, relative position, material, number of components, working fluid, charge rate, etc. The performance characteristics of LHPs are very complicated not just because of the great variety of LHP structures. Even for a given LHP, since all loop components are thermally and hydrodynamically interrelated, the operating characteristics can also be influenced by the pre-start conditions and operating history. In some cases, a steady-state operation cannot be achieved, rather, the loop operates in an indefinite thermal and hydraulic oscillation mode [2,4]. This is indicated by the oscillations of the measured temperatures. Some "peculiar" behavior was also observed, such as temperature hysteresis and temperature overshoot [5,6]. Under given conditions viz, the ambient temperature, sink temperature and elevation, the steady-state operating temperature of a LHP depends on the history of the applied heat load. When the applied heat at the evaporator is increased in predetermined steps and then after reaching a maximum value, if it is decreased in the same steps, then the steady-state temperatures for each step having the same value of applied heat were different [7,8]. This phenomenon is known as temperature hysteresis. It was suggested that this phenomenon may occur because of partial dry-out of the secondary wick due to rapid power decrease [9].

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* Corresponding author. Tel.: +49 711 6852479; fax: +49 711 6852010.
E-mail address: chen@ike.uni-stuttgart.de (Y. Chen).

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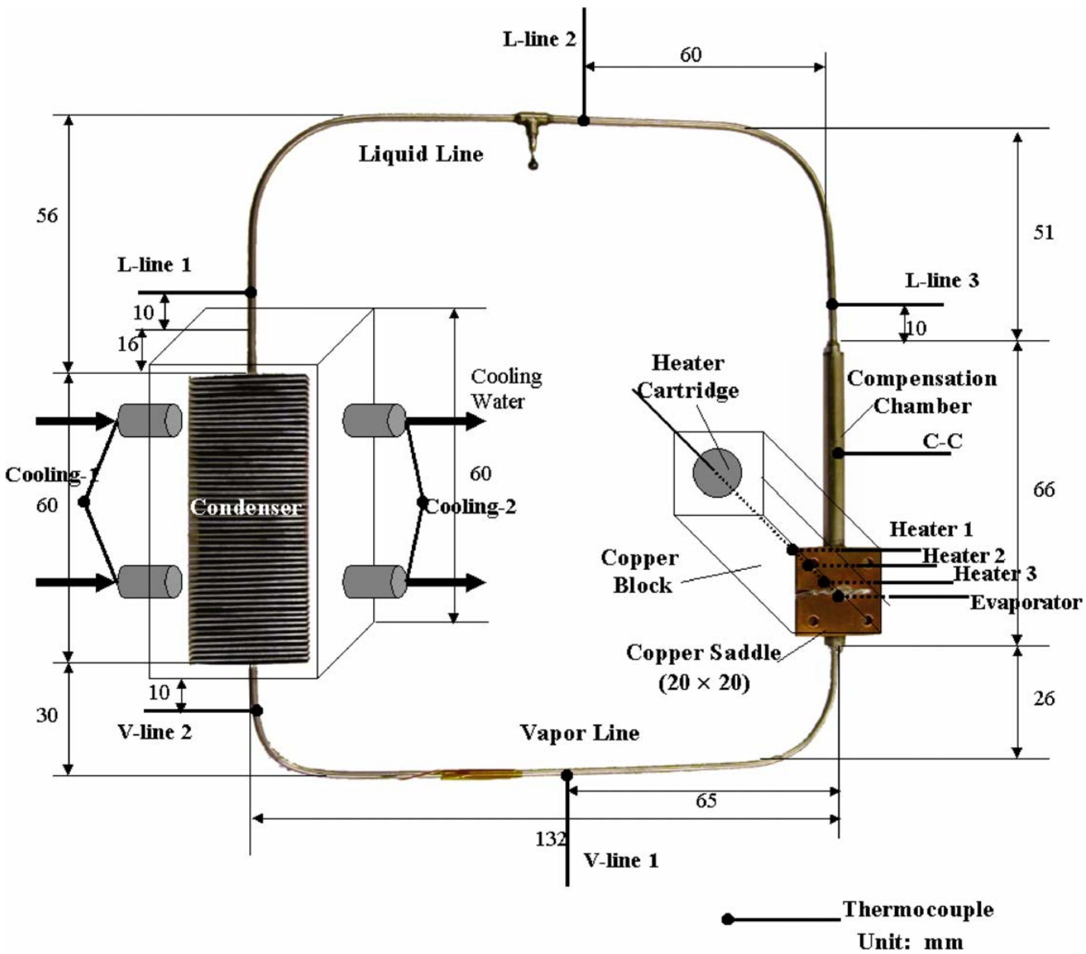

Fig. 1. Schematic of the test set-up.

The start-up characteristics of LHPs are also complicated. According to the pre-start states in the compensation chamber-evaporator assembly, four basic situations were categorized which result in different start-up behavior [5]. It was suggested that the condition when the evaporator core contains two-phase fluid and vapor channel contains liquid represents the most difficult pre-start condition for a stable start-up [5]. The orientation of a LHP also has a pronounced effect on the required superheat, maximum temperature at start-up and the time required for start-up [10].

This paper presents the results of a first test series for a miniature loop heat pipe (mLHP). The tested mLHP has been developed by Institute of Thermal Physics (ITP), Ural Branch of the Russian Academy of Science, Ekaterinburg. It was designed for cooling of CPUs of mobile personal computers. Therefore, the operating characteristics at horizontal position and ±10 degree would be of the main concern. This study compares the performance of the mLHP for horizontal and four vertical orientations. The tests for the small tilt angles are underway.

2. Experimental set-up

The tested mLHP is the world's first device with an evaporator 5 mm in diameter. The evaporator configuration has been determined by the conditions of location in a portable computer [3]. The mLHP with schematic of the test set-up is shown in Fig. 1. The mLHP was electrically heated via a cartridge heater and cooled by a water calorimeter. The electric heat input was measured as well as the thermal heat input (evaporator heat load) to the mLHP. The evaporator heat load was determined via the three heater thermometers (PT100). The loop temperature was measured by 7 thermocouples (type K) attached on the outer wall of the mLHP as indicated in Fig. 1. The thermocouple "Evaporator" is located between the heater block and the saddle. The readings of these thermocouples are directly used in the following sections to represent the temperatures at different locations. They are not the temperatures inside the loop structure. The uncertainty of the thermocouple readings is less than ±0.2 K. The whole loop including evaporator and compensation chamber was thermally insulated to a certain degree. However, the thermal insulation has to be improved in future test series. When determining the evaporator heat load, thermal losses or gains have not been considered.

The structures of the evaporator and condenser are shown schematically in Fig. 2. The evaporator and compensation chamber (CC) share the same cylindrical envelope with an outer diameter of 5 mm. The liquid line outlet is directly located inside the evaporator wick structure. No secondary wick is employed. A copper saddle is mounted on the evaporator wall.

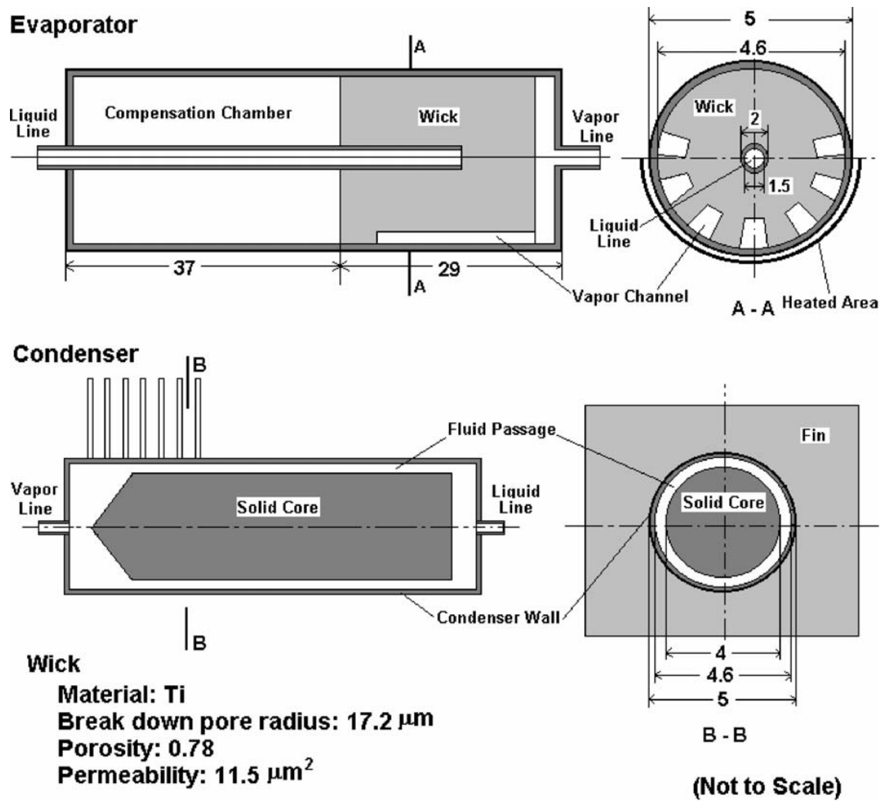

Fig. 2. Schematic of evaporator and condenser.

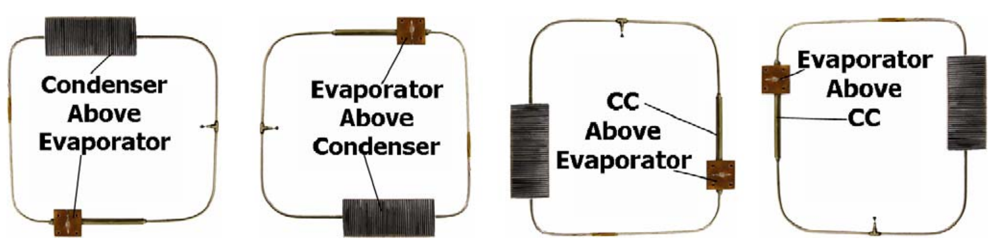

Fig. 3. Four vertical orientations.

There are 7 vapor channels in the heated side of the wick. The liquid line and vapor line have an outer diameter of 2 mm and an inner diameter of 1.5 mm. The condenser is composed of an annular flow passage and fins on the outside of the condenser wall. The material for the mLHP body is stainless steel, the working fluid is ammonia. Material and properties of the wick are indicated in Fig. 2.

The tests carried out so far comprised measurement of the various mLHP temperatures as a function of heat load, for different sink temperatures and mLHP orientations. The tests included start-up behavior and the transient behavior for, mostly, positive power steps. The maximum heat load is limited by the loop pressure for safety reason. The maximum evaporator temperature was set at 80 °C. Besides the horizontal orientation, there are four vertical orientations, viz. “condenser above evaporator”, “evaporator above condenser”, “CC above evaporator” and “evaporator above CC” (Fig. 3).

In practical applications, the structure of the condenser, the coolant and the cooling method can be different. This will greatly change the thermal resistance of the condenser. Therefore, here the thermal resistance of the mLHP, R, is defined as

$$R = \Delta T/Q \quad \text{with } \Delta T = T_{\text{ev}} - (T_{\text{V-line2}} + T_{\text{L-line1}})/2 \tag{1}$$

Here, the mean temperature of the condenser inlet and outlet is taken as the condenser temperature. Q is the evaporator heat load, T_{ev}, $T_{\text{V-line2}}$, $T_{\text{L-line1}}$ are the measured temperatures at the position of the evaporator, V-line2 and L-line1, respectively (refer Fig. 1).

3. Steady-state heat transfer performance

The typical performance curves of the mLHP operating in horizontal orientation are shown in Fig. 4(a) as evaporator temperature ($T_{\text{evap.}}$) against evaporator heat load (Q) for different sink temperatures (T_{sink}). When the condenser sink temperature is lower than the ambient temperature (about 26 °C), the operating temperature first decreases then increases with heat load, otherwise, the operating temperature increases almost linearly

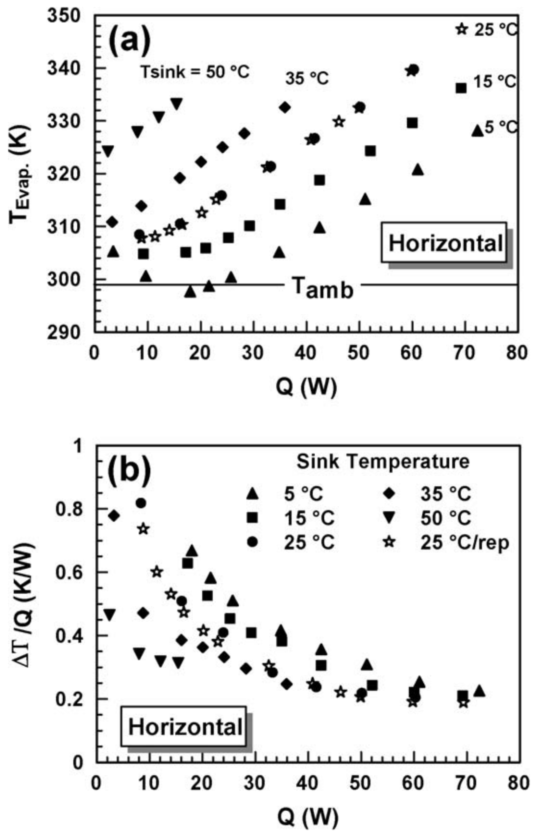

Fig. 4. Typical performance curves of mLHP in horizontal position: (a) evaporator temperature; (b) thermal resistance.

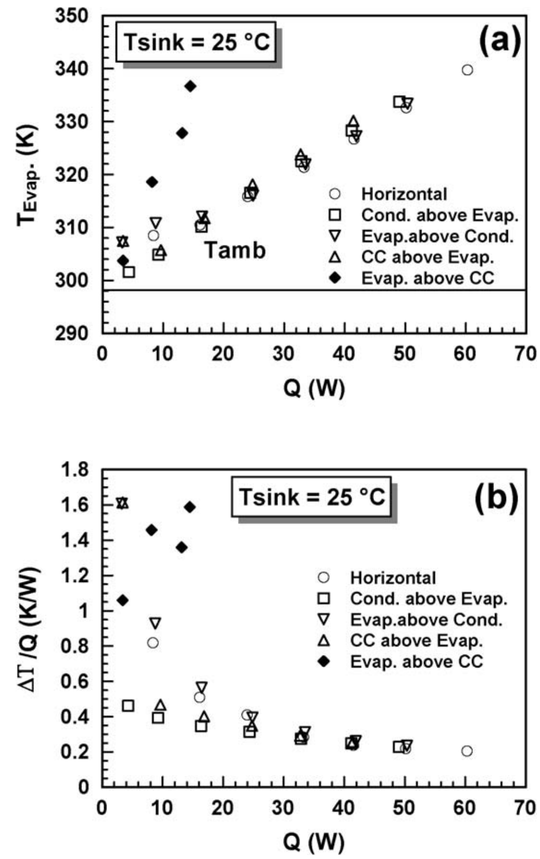

Fig. 5. Comparison of mLHP performance for different orientations at fixed sink temperature of 25 °C: (a) evaporator temperature; (b) thermal resistance.

with heat load. This is related to the heat exchange between the liquid line and the ambient and it is greatly influenced by the mass flow rate or heat load [6]. The thermal resistance of the mLHP (defined by Eq. (1)) is shown in Fig. 4(b). The thermal resistance decreases with increasing sink temperature. With increasing heat load, the thermal resistance decreases and approaches a minimum value of about 0.2 K/W.

Comparisons of mLHP performance for different orientations are shown in Fig. 5 (a) and (b) at a fixed sink temperature of 25 °C. Both the operating temperature (Fig. 5(a)) and the thermal resistance (Fig. 5(b)) are similar for different orientations, except for the case “evaporator above CC”. In fact, for this orientation, the mLHP does not work at all for $T_{sink} = 25\,°C$ and also for $T_{sink} = 5\,°C$ and 15 °C. This is related to the gravity and buoyancy forces: the supply of the liquid to the evaporator is difficult (liquid tends to stay in the compensation chamber), furthermore, when vapor comes out from the condenser and enters the liquid line, it may stop just below the condenser. Thus the liquid line temperature remains essentially constant with heat load (not shown). This indicates that there is no movement of liquid and vapor inside the loop and the mLHP does not work. This is the case for $T_{sink} \leqslant T_{amb}$. For $T_{sink} = 35\,°C$ and 50 °C, the mLHP works with similar thermal resistances as for the other orientations. Typically, for the given condenser and a sink temperature of 25 °C, the mLHP can dissipate heat of 70 W at an evaporator temperature of 75 °C. Overall, the steady-state data can be repeated quite well (see for example Fig. 4).

4. Start-up

In general, the mLHP can be started up with very low power input (5 W). In general, there is a small temperature overshoot during start-up, which can be attributed to the slow movement of cold liquid from the condenser [2].

Start-up difficulty is encountered for the orientations “condenser above evaporator” and “evaporator above condenser”. For the former case, there is a very high temperature overshoot for $T_{sink} = 15\,°C$ and 25 °C; for the other sink temperatures, the start-up is rather smooth. Fig. 6 shows the start-up of the mLHP for “condenser above evaporator” at $T_{sink} = 15\,°C$. Before the start-up, the loop temperatures, except for L-line1 (close to the condenser), keep rising. The temperatures of CC and V-line1 are close to that of the evaporator. The mLHP does not start up until the evaporator temperature reaches 318 K (at an electric power of 15 W). The start-up is indicated by the sudden rise of the condenser inlet temperature (V-line2, refer the enlarged figure, Fig. 6(b)). The cold liquid inside the condenser is pushed out into the liquid line, thus the liquid line temperature (L-line1, L-line2 and L-line3) decreases. The returning cold liquid lowers the compensation chamber and evaporator temperatures. Thus the evaporator heat load increases suddenly, and temporally exceeds the electric

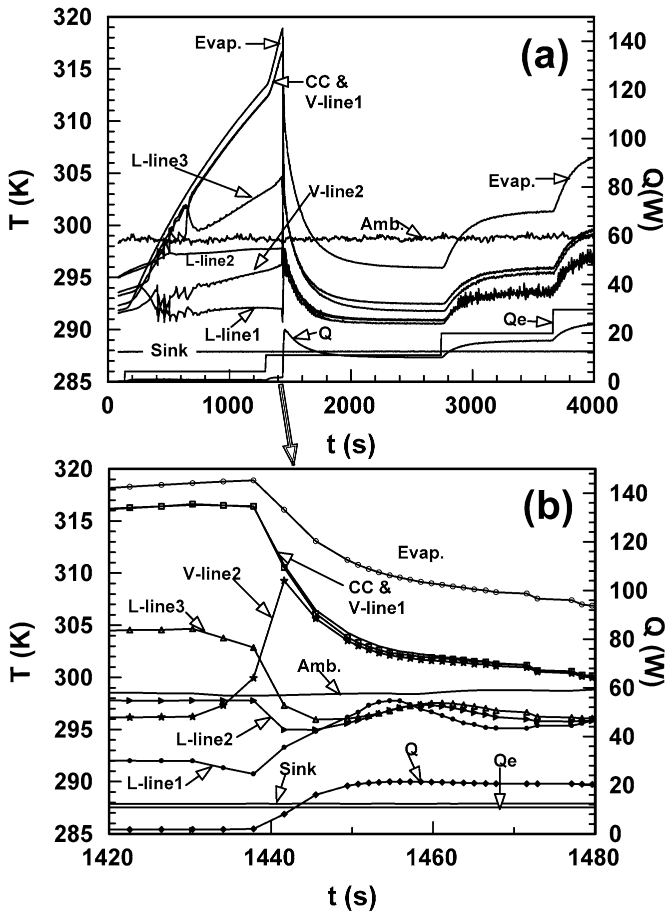

Fig. 6. Start-up of mLHP for "condenser above evaporator" at $T_{sink} = 15\,^{\circ}C$.

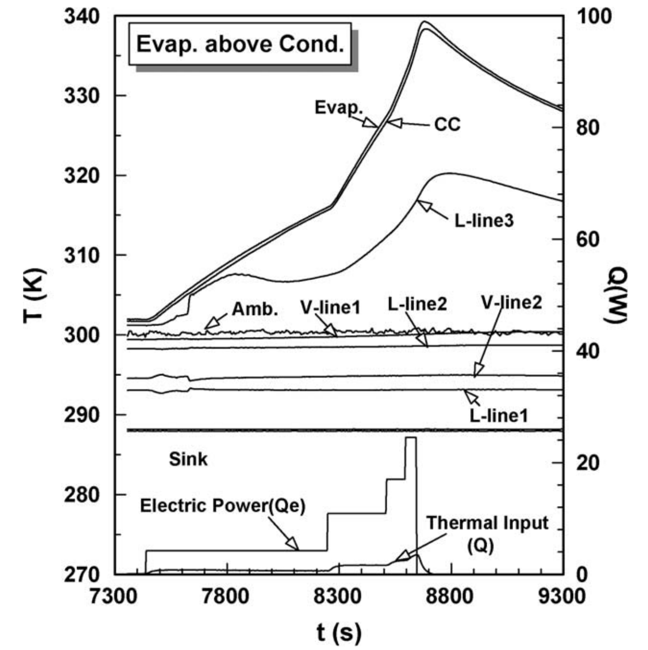

Fig. 7. Failed start-up for "evaporator above condenser" at sink temperature of 15 °C.

power input. After the start-up, the loop temperatures adjust themselves to a steady state or to a periodically oscillating state.

The reason for the high start-up temperature for "condenser above evaporator" may be that the lower part of the loop, including evaporator, CC and vapor channels, are initially filled with liquid. Due to boiling hysteresis, boiling initiation does not take place until the wall superheat reaches certain degree (can be as high as 10 K). After the initiation of boiling, the two-phase structure inside the loop, especially inside the evaporator wick, vapor channels and compensation chamber has to readjust itself until start-up can take place. The time delay for the cold liquid to reach the compensation chamber alone can not account for such a high temperature overshoot. Indeed, once the mLHP is started, the loop temperatures drop very quickly.

For "evaporator above condenser", evaporator and CC may be initially in a partially dry condition. For small start-up heat input, the mLHP does not start up for $T_{sink} = 5\,^{\circ}C$; it may start up or not for $T_{sink} = 15\,^{\circ}C$. For $T_{sink} = 25\,^{\circ}C$ and 35 °C, it starts up smoothly. For $T_{sink} = 50\,^{\circ}C$, it starts up, however, with a high temperature peak. Fig. 7 shows a failed start-up for "evaporator above condenser" at a sink temperature of 15 °C. In this case, the temperatures at the upper part of the loop (evaporator, CC and L-line3) keep rising, while the temperatures for the rest of the loop remain unchanged.

5. Temperature oscillations

For most operation conditions temperature oscillations were observed. From about 40 experiments with different sink temperatures and heat loads, the temperature oscillations are exclusively initiated by a sudden change of experimental conditions, e.g., by changing heat load or sink temperature. In other words, oscillation never started from a steady state operation.

Fig. 8 shows the loop temperatures for the orientation "evaporator above condenser" at $T_{sink} = 25\,^{\circ}C$. Slight temperature oscillations occur at $Q = 25$ W. With increasing heat load to 30 W, the temperature of L-line1 (condenser exit, refer the enlarged curves) increases suddenly. This is followed by an increase of the temperature of L-line2, L-line3, CC, Evaporator, V-line1 and V-line2, viz., the temperature wave travels along the flow direction and it is initiated at the condenser exit. Physically, as the heat load increases suddenly, the condenser is unable to condense all vapor, a vapor bubble or slug extends outside the condenser and enters the liquid line. This warm (not subcooled) fluid raises the CC and evaporator temperature, which causes the heat leak to increase and the temperature difference between the evaporator and the heater to decrease, thus the evaporator heat load decreases and less vapor is generated. The condenser can accommodate all received vapor. The vapor front then recedes inside the condenser; all vapor is condensed; the condensate gets subcooled and consequently the liquid line temperature decreases. The colder returning fluid lowers the CC and evaporator temperatures, and the heat load increases again. This process can go on indefinitely.

The frequencies of the oscillations at different positions along the loop are the same. The oscillations at the condenser exit and at the evaporator are 180 degree out of phase. The shift of the phase of oscillation mainly occurs in the liquid line. Al-

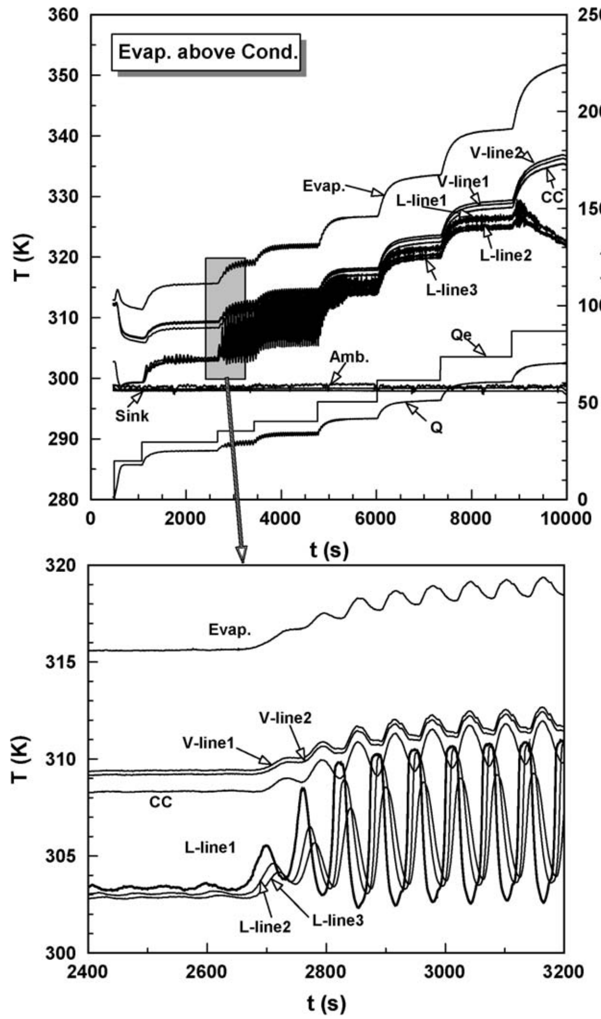

Fig. 8. Loop temperature oscillations for “evaporator above condenser” at $T_{\text{sink}} = 25\,^{\circ}\mathrm{C}$.

most no phase shift occurs from the evaporator to the condenser inlet, viz., the oscillations along this part of the loop have essentially the same phase. This indicates that the flow velocity inside the liquid line is much lower than that in the other part of the loop.

From Fig. 8, one can observe that, as heat load increases, the amplitudes of the oscillations decrease. This is, according to [4], due to the change of two-phase fluid distribution among the evaporator core, CC and condenser. However, if the large amplitude oscillations (at moderate heat loads) are caused by the periodic emergence of vapor bubbles or slugs in the liquid line, the vapor phase in the liquid line is unlikely to disappear with increasing heat load. Most likely, the bubbles will become smaller and more numerous as the flow rate increases. In this case, the amplitude of the oscillations will decrease and the frequency will increase.

Temperature oscillations greatly depend on the mLHP orientations. Big oscillations were found for the orientations “horizontal”, “evaporator above condenser” and “CC above evaporator”. Fig. 9 shows the heat load ranges under which the oscillations occur. Both the heat loads for the oscillations to start and to stop decrease with increasing sink temperature. In some

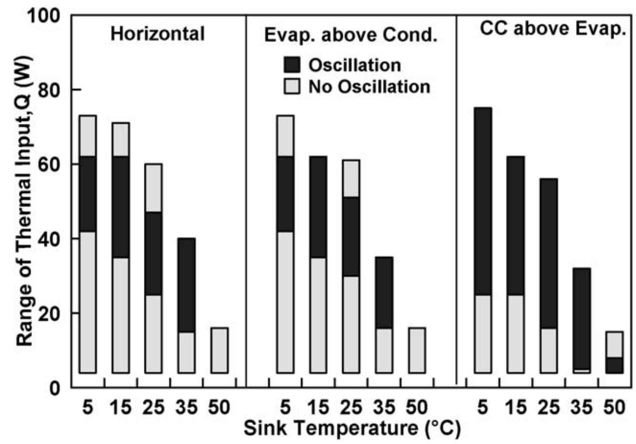

Fig. 9. Heat load ranges under which the oscillations occur.

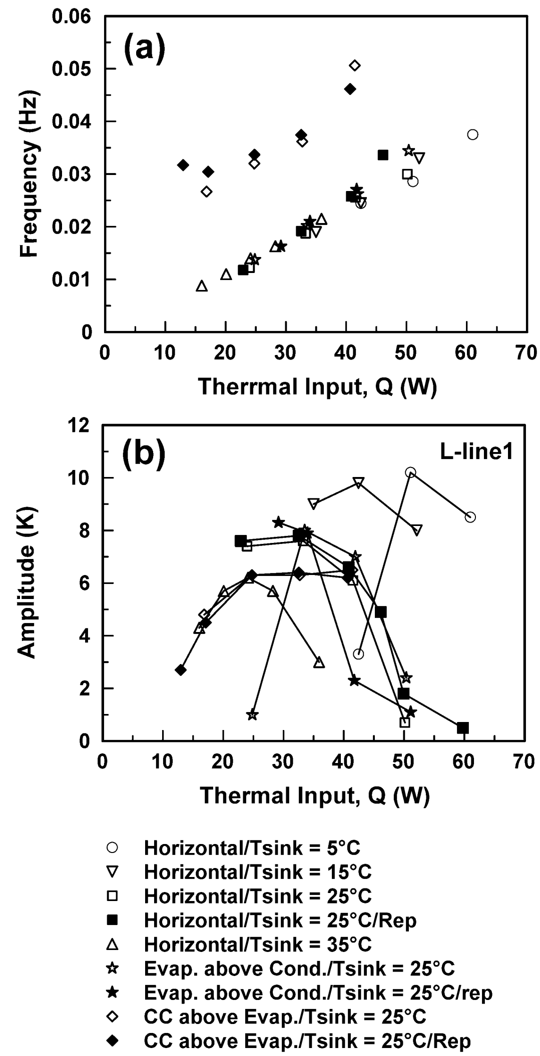

Fig. 10. (a) Frequency of temperature oscillations; (b) amplitude of the oscillation of L-line1.

cases, especially for “CC above evaporator”, the end of the oscillations was not observed within the experimental ranges. The heat load range under which the oscillations occur is also the biggest for the orientation “CC above evaporator”. This is re-

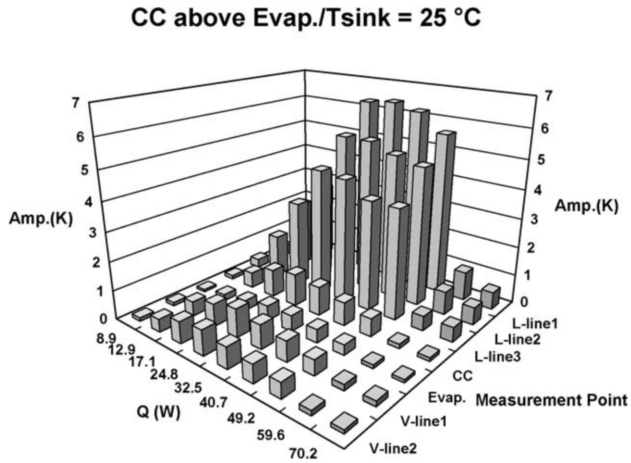

Fig. 11. Amplitudes of the temperature oscillations at various positions along the loop for different heat loads.

lated to the buoyancy force. Since, for "CC above evaporator" (refer Fig. 3), the vapor bubbles (slugs) are easy to travel outside the condenser with the assistance of the buoyancy force. In contrast, for "evaporator above CC" and "condenser above evaporator", the vapor bubbles are unable to travel downwards to the compensation chamber, thus no big temperature oscillations were found.

Figs. 10(a) and 10(b) show the frequency and amplitude of the oscillation of L-line1 for different orientations and sink temperatures. The frequency increases almost linearly with heat load (Fig. 10(a)). For "horizontal" and "evaporator above condenser", the frequencies are quite similar. The sink temperature shows little influence on the frequency. The frequency for "CC above evaporator" is much higher. This is also due to the effect of buoyancy force. The oscillations are initiated suddenly at certain heat loads with a relatively big amplitude and, with increasing heat load, the amplitude of oscillation generally passes through a maximum (Fig. 10(b)). At higher heat loads, the oscillations die down suddenly with rapid decrease of amplitudes with heat loads. The peak amplitude increases with decreasing sink temperature.

Also shown in Fig. 10 are the results of three repeated experiments for different orientations at $T_{\text{sink}} = 25\,^{\circ}\text{C}$. In general, the frequency and amplitude of the oscillations can be repeated within a difference of 10%. Relatively big discrepancy of the aptitudes is seen for "evaporator above condenser" during the die-down period. The reason for this discrepancy is unclear.

Though the amplitude of the temperature oscillations in the liquid line can be higher than 10 K, the amplitude in the evaporator is very small, of the order of 1 K or less. An example is shown in Fig. 11, where the amplitudes at different positions along the loop and the effect of the heat load are clearly demonstrated.

6. Conclusions

A miniature loop heat pipe was tested for horizontal and four vertical orientations under different sink temperatures. Following conclusions can be drawn from this study:

(1) The mLHP can work under all test conditions except for the orientation "evaporator above compensation chamber" at a sink temperature lower than ambient temperature.
(2) The thermal resistances of the mLHP are similar for different orientations at a given evaporator heat load and sink temperature, except for "evaporator above compensation chamber". Particularly, for a sink temperature of 25 °C and the maximum allowed evaporator temperature of 75 °C, an evaporator heat load of 70 W can be dissipated, the resulting thermal resistance is 0.2 K/W.
(3) In general, the mLHP can be started up smoothly or with a small temperature overshoot except for the orientations "condenser above evaporator" and "evaporator above condenser".
(4) Big temperature oscillations in the liquid line were found except for the cases "evaporator above CC" and "condenser above evaporator". However, the temperature oscillations in the evaporator are always minimum.
(5) The oscillations are supposed to be initiated by the appearance of vapor bubbles in the liquid line after changing the test conditions, e.g. heat load or sink temperature.
(6) With increasing heat load, the oscillation frequency increases continuously, while the amplitude passes through a maximum. The sink temperature shows little influence on the frequency.
(7) For the tested mLHP, which is targeted at consumer electronics cooling, the overall operating characteristics for horizontal orientation is proved to be satisfying.

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