Investigation of instability on loop heat pipe with flat evaporator

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Abstract. Loop heat pipes (LHPs) are heat transfer devices whose operating principle are based on the evaporation and condensation of a working fluid, using the capillary pumping forces to ensure the fluid circulation. A series of tests have been carried out with a loop heat pipe (LHP) with flat evaporator and a fin-and-tube type condenser. At some low heat loads, temperature oscillations were observed throughout the loop. Detailed study was conducted on the characteristics of temperature oscillation of the flat LHP at various heat loads. It is expected that the compensation chamber is the most critical component of the LHP; its hydrodynamic state dictates the extent and the characteristics of the temperature oscillations. The heat leakage from the evaporator to the compensation chamber, the heat loss to ambient and the subcooled liquid temperature dictate the vapor condition inside the compensation chamber, and the rate of vapor growth or dissipation dictated the nature of the temperature oscillation. The effects of different working fluid to the temperature oscillations were studied in detail.

Nomenclature

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
Q       heat load, W

Greek symbols

α  charging ratio of working fluid, %
θ  tilt angle

1. Introduction
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 pipe, such as operability against gravity, over large distance with minimal temperature loss and no moving parts for pumping the working fluid, etc. The first LHP was made by Ural Polytechnical of Russia in 1972, and detailed reviews 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 LHP with the cylindrical as well as flat evaporators have been developed and tested successfully. Compared with conventional cylindrical LHPs, the LHPs with flat evaporator have more advantages: firstly, it is more convenience 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 velocity grads and temperature gradient is smaller than that of LHPs with cylindrical evaporator, from the viewpoint of field synergy principle, the heat transfer efficiency of flat evaporator is better[3, 4]. So the capability of LHP with flat-plate evaporator for transferring high heat-flux achieve easily. The LHPs with flat evaporator can be considered as an optimum design for compact enclosures as it provide relatively more scope for design miniaturization [5].

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, working fluid, charging ratio, etc. The performance characteristics of LHPs are very complicated, the main objective of the current paper is to study temperature oscillation phenomenon of the flat evaporator miniature loop heat pipe with copper body and stainless mesh wick. The thermal oscillations are characterized by the continuous fluctuations in the temperature at different locations of LHP and thus inability of the evaporator to attain stable operating conditions. These oscillations are expected to result from the heat leakage of evaporator and hydrodynamic interaction between the compensation chamber, condenser and evaporator section [6-10].

2. Experimental prototype and test procedure

An experimental prototype of miniature LHP as shown in Figure 1 was constructed for carrying out the present investigation. The overall system was made up of evaporator with 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 40×30 mm and thickness of 13.5mm. There were 15 longitudinal and 18 latitudinal grooves machined on the inside of the evaporator active heated zone which were vapor removal channels. The evaporator was made by pure copper that provided superior thermal conductivity and minimal heat spreading resistance from the source to the porous wick surface. The Figure 2 illustrated the cross section of the evaporator assembly showing the location of the vapor channels, wick structure and compensation chamber. The wick of evaporator was 4mm thickness, which was made up of 82 layers 500 grids stainless steel mesh. The compensation chamber was 6mm thickness, which acted as a liquid reservoir and accommodates the extra liquid inventory displace from the other parts of the loop during start-up and transient operating conditions. There was 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 LHP were shown in Table 1.

| Table 1. Geometric characteristics of the experimental LHP. |
|-------------------------------------------------------------|
| **Evaporator**                                              | **Vapor Line**                  | **Liquid Line**                  | **Condenser**               |
| active heated zone                                         | diameter(O/I) (mm) 6/4          | length(mm) 320                    | diameter(O/I) (mm) 6/4      |
| thickness(mm)                                              | 1.5                             | length(mm)                        | length(mm) 810              |
| length/width (mm)                                          | 40/30                           |                                   | thickness(mm) 0.5           |
| groove thickness (mm)                                       | 1                               |                                   | length(mm) 0.05             |
| fin width (mm)                                              | 1×1                             |                                   | fin thickness (mm)           |
| fin number                                                 | 18×15                           |                                   | fin length/width (mm) 100/20|
| wall thickness(mm)                                         | 1.5                             |                                   | fan rotate speed(rpm) 3000  |
| steel sheet thickness (mm)                                  | 0.5                             |                                   |                               |
| compensation chamber                                       | length/width (mm) 34.5/30       |                                   |                               |
| height (mm)                                                 | 6                               |                                   |                               |
| porous wick                                                | length/width/height(mm) 36.5/30/4| material 316L                     | parameter of mesh 500#, 82 layers |

The LHP condenser was fin-and-tube type with the total tube length of 810mm and cross section of 100×20mm for each fin. A centrifugal fan was used to dissipate heat from the condenser to the ambient. The vapor line of the LHP was 320mm in length and 4mm internal diameter. For the return of the condensate to the evaporator, there was a liquid return line with the total length of 530mm and 4mm internal diameter. The transport lines and the condenser fin were overall made by pure copper.
The LHP was hermetically sealed by an O-ring seal between the evaporator flanges. For charging in working fluid, the LHP was firstly evacuated to $3.2 \times 10^{-4}$ Pa and then filled with the predetermined quantity of methanol (or acetone) whose purity is 99.5%. In order to test the thermal performance of the LHP, there was a heat load simulator in the form of copper block with two embedded cartridge heater and active area of $40 \times 30$ mm, which was uniform to the evaporator. For the purpose of minimizing heat losses to the ambient, the heat load simulator was thermally insulated using 10mm thickness nano-adiabatic material whose conductivity was just 0.012 W/(m.K).

A digital power meter with accuracy of $\pm 0.2$ W was used to measure and control the input power to the heat load simulator. Twelve T-type thermocouples with $\pm 0.2^\circ$ C accuracy were used to measure the temperature at different locations of the LHP and the ambient air. Figure 1 also showed the placement of the thermocouple points. All the instruments were connected to the Keyence Thermo Pro 2700 data acquisition system.

The current paper studied the temperature oscillation of LHP with flat evaporator at charging ratio ($\alpha$) 50vol.%, 60vol.%, 70vol.%, tilt angle ($\theta$) 10°, 50°, 90°, the working fluid methanol or acetone. The procedure of tests included measurements of temperatures at characteristic points of the LHP with a successive stepwise 12W increase and decrease of the heat load.

3. Experimental results and discussions

Temperature oscillation is a rather wide-spread phenomenon accompanying the LHP operation. The investigations conducted make it possible to differentiate three main types of the LHP operating temperature. The first of them is characterized by a low-amplitude (no more than 1°C) and a high-frequency; The second type is also characterized by a low-amplitude (no more than several centigrade) of temperature oscillation, but their period is several minutes; The third type is distinguished by high amplitude of temperature oscillation, which is tens of degrees, and a still longer period, which may be above ten minutes [11-13]. The temperature oscillation is relation to the heat load, tilt angle, the property and charging ratio of working fluid.
Figure 2. The start-up of LHP.

Figure 3. Performance tests of the LHP at power cycle. $\theta = 60^\circ$, $\alpha = 60\text{vol.}\%$ (acetone).
It is experimentally observed that the temperature oscillation of the LHP mostly occurred at some intermediate heat loads. The temperature oscillations of LHP with different operation condition and different working fluid were shown in Figure 2. It is observed from each plot that the frequency of occurrence for these oscillations was accordant at different locations but the amplitude was different. It was the fiercest of temperature oscillation at the inlet of condenser and evaporator, the amplitudes of evaporator and vapor line took second place, and the temperature oscillation was smallest at condenser and liquid line. The temperature oscillation was more obvious at the part near the interface of two-phase. Sometimes, the temperature oscillation was ruleless for the complicacy of two-phase flow in LHP.

The Figure 3 and Figure 4 showed the performance tests of the LHP at power cycle. It was obvious that the LHP could steadily run at low and high heat load, and temperature oscillations occurred at some intermediate heat loads. The reason was that the condenser need little roomage to condense the working fluid at low heat loads, and most liquid was in the condenser, the compensation chamber was full of two-phase which was made up of vapor and little liquid. There was enough roomage to satisfy the growth and dissipation in the compensation chamber, so the LHP could run steadily. With the increase of heat load, more vapor generated in the evaporator and pushed the liquid into the compensation chamber. With the increase of regurgitated liquid from condenser and the heat leakage from the evaporator, the growth and dissipation of bubbles inside the compensation chamber were fierce which dictates the characteristics of the temperature oscillation at every parts of LHP. At high heat loads, the compensation chamber was filled by the liquid, and the temperature oscillations of LHP disappeared. Besides the heat load, the tilt angle of system, the physical property and charging ratio of working fluid affected the temperature oscillation of LHP.

The Table 2 and Table 3 showed the temperature oscillations of the same LHP with methanol and acetone. Compared the two Tables, it was obvious that the temperature oscillation of LHP with flat evaporator was relation to the property of working fluid. The temperature oscillations of LHP with acetone as working fluid (LHP-acetone) mainly occurred at the heat load 24-36W and the amplitudes of LHP-acetone were almost less than 4°C. The temperature oscillation of LHP-methanol mainly occurred at heat load 12-60W, and some amplitudes were larger than 7°C (the largest was 12.54°C). Meanwhile, the periods of LHP-acetone were almost less than 120s, the LHP-methanol was longer than that of LHP-acetone, and the largest was 540s. So the temperature oscillation of LHP-methanol was fiercer than that of LHP-acetone. The reason is that the latent heat of acetone is about half of methanol. So at the same condition, the roomage of compensation chamber of LHP-acetone is less than that of LHP-methanol and the compensation chamber is filled by liquid quickly. So the compensation chamber is the most critical component of the LHP, and the bubble growth or
dissipation of working liquid inside the compensation chamber induces the nature of the temperature oscillation.

| Operation condition | Amplitude, °C | Periods, s | Operation condition | Amplitude, °C | Periods, s |
|---------------------|---------------|------------|---------------------|---------------|------------|
| 10°-50vol.%         | 36W 1.81      | 135        | 10°-60vol.%         | 24W 7.27      | 392        |
|                     | 48W 2.42      | 114        |                     | 36W 8.46      | 540        |
|                     | 60W 1.32      | 55         | 50°-60vol.%         | 24W 3.73      | 135        |
|                     | 36W 7.27      | 392        |                     | 36W 5.49      | 198        |
| 10°-70vol.%         | 12W 1.07      | 52         | 90°-60vol.%         | 24W 4.85      | 212        |
|                     | 24W 12.54     | 540        |                     | 36W 1.34      | 64         |
|                     | 12W 7.82      | 258        |                     | 24W 6.32      | 218        |
|                     | 24W 8.3       | 290        | 90°-70vol.%         | 36W 7.66      | 162        |
|                     | 36W 11.1      | 520        |                     | 36W 0.72      | 75         |
| 50°-70vol.%         | 12W 1.07      | 52         |                     | 36W 0.15      | 23         |

Table 3. Temperature oscillations of evap-wall in different operation conditions (acetone).

| Operation condition | Amplitude, °C | Periods, s | Operation condition | Amplitude, °C | Periods, s |
|---------------------|---------------|------------|---------------------|---------------|------------|
| 10°-60vol.%         | 36W 1.74      | 37         | 10°-70vol.%         | 24W 3.27      | 121        |
|                     | 24W 0.75      | 48         |                     | 36W 5.23      | 148        |
| 10°-50vol.%         | 24W 2.92      | 235        | 50°-70vol.%         | 24W 4.18      | 125        |
|                     | 36W 0.32      | 45         |                     | 36W 1.03      | 38         |
| 50°-60vol.%         | 24W 2.53      | 140        | 90°-70vol.%         | 24W 4.01      | 127        |
|                     | 36W 0.72      | 75         |                     | 36W 0.15      | 23         |

The experimental investigations showed that the temperature oscillations of LHP augment with the increase of charging ratio of working fluid. The tilt angle of LHP also affected the temperature oscillation, but the effect was not obvious. The effect of physical property of working fluid to temperature oscillation was obvious, it affected not only the intensity but also the zone of heat load that occurred temperature oscillation. So the temperature oscillation of LHP with flat evaporator was relation to the physical property and charging ratio of working fluid, tilt angle of system, the structure of LHP, and so on.

4. Conclusions

In this thesis, experimental investigations have been made to study the effect of different working fluid, different charging ratio and different tilt angle of system to the temperature oscillations on LHP with flat evaporator. The main outcomes of the study can be summarized as follows:

1) The LHP could run steadily at low and high heat load, the temperature oscillations only occurred at some intermediate heat loads.
2) It is observed from each plot that the frequency of occurrence for all temperature oscillations is accordant at different locations but the amplitude is different.
3) The temperature oscillation of LHP is relation to charging ratio and physical property of working fluid, tile angle of system.
4) Compared with LHP-acetone, the temperature oscillation of LHP-methanol is fiercer.

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