A method of fast quality control inspection of loop heat pipe

Bin-Juine Huang1*, H H Huang1, T L Liang1, P E Yang1, S S Hu1
1Department of Mechanical Engineering, National Taiwan University, Taipei, Taiwan

Abstract. The dynamic behaviour of loop heat pipe (LHP) changes with heat load and physical properties of LHP such as fluid charging, wick material, and tolerance in manufacture. The start-up phenomena of a LHP can be classified into four modes, according to the heat load $Q_{in}$: failure mode, oscillating mode, overshoot mode, and normal mode. It is found that the operation mode is related to the rate of temperature rise in evaporator during initial transient performance using a step heating load. The abnormal high rate of temperature rise can be observed for LHP with failure, oscillating or overshoot mode performance. Based on this phenomenon, the normal-mode performance of LHP can be assured from a short transient test in about 80s using a step heat load, instead of using steady-state test (taking 1,800s). This transient test method has been applied in the quality inspection of commercial loop heat pipe in mass production. No LHP failure was found for more than 10 years for about 30,000 sets of street LED luminaires designed with LHP.

1. Introduction
Loop heat pipe (LHP) is a passive heat-transfer device that uses micro-scale wick technology to transfer a large amount of heat to a distant place through a connecting pipe. There is a startup condition for a LHP [1-3] that requires a temperature difference across the wick structure.

The phenomena of minimal start-up heat load and temperature overshoot was observed. Start-up of LHP is a behaviour of dynamic system that is very complex. The factors affecting the start-up of LHP include working fluid used, design of compensation chamber and evaporator, the initial state of working fluid in the evaporator, the charge volume of working fluid, LHP attitude, the initial state of LHP before heat load applied, etc. Two phenomena were observed very often during the start-up of LHP: (1) temperature overshoot; and (2) minimal heat load required to start up.

The quality inspection test of LHP may be carried out by measuring the steady-state performance. But it will take a long time for reaching a steady state, at least 1800s (30 min), and the cost is very high.

The transient behaviour of LHP can be used to distinguish the normal or abnormal operation of LHP in steady state. The present study tries to develop a fast transient test method for LHP. A fast inspection method in quality control of a mass production is then developed according to the transient behaviour of LHP.

2. System dynamics behaviour of LHP
The system dynamic behaviour of LHP can be studied by building a system dynamics model [4]. The start-up phenomena of a LHP can be classified into four modes, according to the heat load $Q_{in}$: (1) failure

* corresponding author: bjhuang@seed.net.tw
mode when $Q_{in} < Q_{\text{min}}$, (2) oscillating mode when $Q_{\text{min}} < Q_{in} < Q_{\text{crit}}$, (3) overshoot mode when $Q_{\text{crit}} < Q_{in} < Q_{s}$, and (4) normal mode when $Q_{s} < Q_{in}$.

The minimum heat load $Q_{\text{min}}$ is defined as the condition that a LHP can start up successfully. If the heat load $Q_{in}$ is lower than $Q_{\text{min}}$, start-up will fail (failure mode).

When the heat load $Q_{in}$ is lower than $Q_{\text{crit}}$, temperature oscillation occurs (oscillating mode). The vapor flow to the condenser is in oscillating or pulsating state. As the heat load $Q_{in}$ is higher than $Q_{\text{crit}}$, LHP enters the overshoot mode in start-up and an overshoot of temperature will be observed.

When the heat load $Q_{in}$ is higher than $Q_{s}$, a smooth start-up will occur. Table 1 shows the design specification of the LHP used in the present study (Figure 1).

![Figure 1. Design of the LHP for experiment.](image)

| Table 1. Specification of the LHP used in the study. |
|------------------------------------------------------|
| Evaporator: capillary force 50 cm-Hg |
| porosity 60% |
| pore size 5-10 μm |
| outer diameter 14 mm |
| total length 90 mm |
| Connecting Tube: material OFCU |
| outer diameter 4 mm |
| inner diameter 2.3 mm |
| Condenser Plate: material OFCU |
| dimension 200mmx 300mm x 0.5mm |
| Heating Block: material Aluminum alloy 6063 |
| dimension 45mm x 40mm x 20mm |
| Working Fluid: Acetone |

Experimental analysis of the LHP transient performance at different operating conditions was carried out to study the characteristic operating modes of LHP [4].

For $Q_{in} < 5W$ ($Q_{\text{min}}$), start-up failure is observed (Figure 2). For $20W(Q_{\text{crit}}) < Q_{in} < 40W(Q_{s})$, oscillation phenomenon is observed (Figure 3). For heat load $Q_{in} < 40W(Q_{s})$, overshoot phenomenon is observed (Figure 4). When the heat load $Q_{in} > 40W(Q_{s})$, a smooth start-up is observed (Figure 5).
smooth transient temperature rising curves are observed at condenser inlet. This is supposed to be the normal-mode operation of a LHP.

**Figure 2.** Failure mode performance ($Q_{in} = 2W$).

**Figure 3.** Oscillating mode performance ($Q_{in} = 20W$).
3. Fast inspection in quality control of LHP

The quality inspection test of LHP may be carried out by measuring the steady-state performance of each LHP. But it will take a long time for reaching a steady state, at least 30 minutes (1800s), and the cost is very high.

It can be seen from Figure 2 to Figure 5 that, the rate of the heating flock temperature rise at the start-up period is quite different at different heat load $Q_{in}$. It is observed that the temperature rise rate per heating load (K s$^{-1}$W$^{-1}$) is much higher if LHP does not operate normally. This dynamic or transient
behaviour of LHP can be used as the criterion for fast inspection of LHP in quality control during mass production.

The present study develops a transient test method to measure the temperature rise, $\Delta T_b = T_b(t) - T_{b,0}$, of the heating block right after employing a step heat load 100W where $T_{b,0}$ is the initial block temperature. The rate of temperature rise at a short time period may be used to identify the operation mode at steady state performance.

We select the conditions for the standard test as follows:

- Key parameter: temperature rise of heating block $\Delta T_{b,0} = T_b(t_o) - T_{b,0}$ at fixed time interval $t_o$
- Step heat load: 100W (fixed)
- Operation attitude: horizontal (0°)

We use 11 sets of identical LHPs randomly picked from a mass production line [5] for the study. Their thermal resistance may be different due to manufacturing process variation. The steady-state performance of these 11 LHPs are measured first and the LHP with start-up failure are identified as LHP02, LHP03, LHP07 and LHP09. Then, all the 11 LHPs are run step response test at heat load 100W.

The measured temperature response curve of the heating block is shown in Figure 6. It is found that temperature rise of the heating block $\Delta T_{b,0}$ at $t_o = 80$ s will exceed 30°C ($\Delta T_{crit}$) for LHP with start-up failure. According to the results of the steady-state test, LHP02, LHP03, LHP07 and LHP09 are the LHP with start-up failure and the others are passed. Using this fast test method for quality inspection, we can shorten the time of the test from 1,800 s (steady-state test) to 80 s. Figure 7 is the transient test equipment of LHPs developed for the transient test of six LHPs simultaneously.

This test method can be applied to any other LHP with different design or manufacturing process. The calibration test (steady-state test) must be carried out first using the samples taken randomly from a production line. The test results of sampled LHPs with start-up failure are used to compare with the transient temperature response curves of all the LHPs to identify GO or NO-GO of LHPs, from which the critical temperature rise at time $t_o$, $\Delta T_{crit}$, can be determined and used in transient test.

The LHPs have been in mass production and used in the heat dissipation of 100W LED street light. One thousand LED street lights (commercial product) were installed on the campus of National Taiwan University in 2008 (Figure 8). They are still running today without any failure of LHP. Only failure of LED power adaptors was found, about 2% per year.

The measurement uncertainty is ±0.5°C in temperature $T_b$ and ±10% in input heating power $Q_{in}$. This error has been taken into account in the selection of $\Delta T_{crit}$.

![Figure 6. Temperature response curves of 11 LHPs.](image-url)
4. Conclusions

The present study develops a transient test method for fast inspection in the commercial production of LHP. The rate of temperature rise ($T_b - T_{bi}$) of the LHP heating block right after employing a step heat load is used to determine the normal or abnormal performance of LHP. Using this fast test method, we can reduce the time of the test from 1,800 s (steady-state test) to 80 s. For the 100W LHP production, the LHP is identified as abnormal (NO-GO) if $\Delta T_{bo}$ is higher than $\Delta T_{crit}$ (chosen as 30°C) at $t_o=80$ s. This fast inspection method in quality control has been used in the mass production of LHP [5]. No LHP failure occur for about 30,000 sets installed in LED luminaires during the past 10 years.

This test method can be applied to any other LHP with different design or manufacturing process. The calibration test (steady-state test) must be carried out first. The steady-state test results of sampled LHPs with start-up failure are used to identify the conditions for LHPs with start-up failure, i.e. finding the critical temperature rise at time $t_o$, $\Delta T_{crit}$. By selecting a proper critical temperature rise at time $t_o$, $\Delta T_{crit}$, LHPs can be identified as GO or NO-GO in the transient test and the QC test can speed up.

5. References

[1] Maidanik Yu F  Loop Heat Pipe Technology, Institute of Thermal Physics, Ural Branch of the Russian Academy of Sciences, Ekaterinburg, Russia.
[2] Maidanik Yu F and Pastukhov V G 1999 Loop Heat Pipe-Recent Developments, Test Results and Applications, Institute of Thermophysics, Ural Division of Russian Academy of Sciences, SAE Technical Paper 1990-01-2530
[3] Maydanik Y 2005 Review of loop heat pipes, *Appl. Therm. Eng.* **25** (5&6) 635–657
[4] Huang B J, Huang H H, Lian T L 2009 System dynamics model and startup behavior of loop
heat pipe. *Appl. Therm. Eng.* **29** 2999-3005

[5] Huang B J, Chuang H Y, Yang P E 2017 Low-cost manufacturing of loop heat pipe for commercial applications. *Appl. Therm. Eng.* **126**, 1091-1097.

**Acknowledgement**

This study was supported by Advanced Thermal Devices (ATD) Inc (Taiwan) and Ministry of Science and Technology, Taiwan, through Grant: NSC93-2212-E-002-032.