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Operational characteristics of a loop heat pipe with a flat evaporator and two primary biporous wicks

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ABSTRACT

Loop heat pipe (LHP) is an efficient heat transfer device with excellent performance. Its operation is based on the evaporation and condensation of the internal working fluid, and the compensation chamber temperature controls the loop operating temperature. Compared with cylindrical evaporator LHP, the flat evaporator LHP benefits from the flat thermo-contact surface, but suffers from more heat leak. In this paper, an LHP with a flat evaporator and two primary biporous wicks is studied for reducing the impact of heat leak on the compensation chamber. Liquid supply for the wick in the evaporator back is guaranteed by ensuring that the system is at a favorable elevation with slopes of 10° and 90° in the experiment. When the evaporator wall temperature is lower than 90 °C, the maximum operational heat load can reach 270 W with a slope of 90°, which corresponds to a heat flux of 26.5 W/cm^2. The maximum heat load is 210 W with the 10° slope. The system can start up steadily with a low heat load of 10 W, while a similar structure with single wick fails at this heat load. When heat loads are applied to both the evaporator wall and back simultaneously, the system has better operating performance for lower temperatures and thermal resistance. The wick in the evaporator back improves the performance at low heat load for the operation with only one side heat load, and plays a role in all operations with bifacial heat loads. As the heat load increases, the evaporating heat transfer coefficient increases to a maximum, and then settles maintaining a high value. The thermal resistance of the LHP with two primary wicks is lower for a larger slope. The minimum thermal resistance of the LHP is 0.218 °C/W at 270 W with a slope of 90°.

1. Introduction

In the normal operation of electronic devices, heat is accompanied as a byproduct. When a device exceeds specified temperature, its performance, life, and reliability are significantly reduced [1]. With the development of electronic technologies, the requirements for heat dissipation grow proportionally. Loop heat pipes (LHPs) are drawing a wide interest for their advantageous high heat transfer capabilities, flexible installation, and absence of moving parts. A LHP is an effective two-phase heat transfer device that utilizes the evaporation and condensation of the working fluid [2,3]. Different from the conventional heat pipe, the evaporator and the condenser are arranged separately, and connected by the vapor line and the liquid line using smooth pipes. For the existing LHP, the evaporators are either cylindrical or flat shapes. Compared with cylindrical evaporator LHP, the flat evaporator LHP benefits from the flat thermo-contact surface, but suffers from more heat leak problems.

Many researches have been carried out to study and improve the operating performance of LHP [4–7]. Maydanik et al. [8] presented a compact copper–water LHP to decrease the operating temperature with the retention of the high thermal performance of LHP. The compact LHP can operate in the heat load ranges from 5 W to 1200 W, at vapor temperatures from 26.5 °C to 103.4 °C, in the horizontal position. Li et al. [9] developed a copper–water compact LHP with a square flat evaporator, which can transfer heat loads of more than 600 W (with a heat flux in excess of 100 W/cm^2) with no occurrence of evaporator dry-out.

The compensation chamber temperature controls the loop operating temperature [10]. Numerous papers are devoted to the investigation of LHPs, but only a small percentage focus on the heat exchanges in the compensation chamber. Chernysheva et al. [11] developed a three-dimensional heat and mass transfer model of a flat evaporator LHP to investigate heat and mass in a compensation chamber filled with a liquid, and evaluated the average coefficients of internal heat exchange in the compensation chamber. Vlassov and Riehl [12] presented a mathematical model to predict the LHP behavior as a thermal control component of a satellite. Further, they found that the compensation chamber is very

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sensitive to active control using a thermal electric cooler (TEC), and a small power can shift the working point in LHP evaporator. Ku and Ottenstein [13] used the TEC instead of the electrical heater to maintain the compensation chamber at the desired set point temperature. Bai et al. [14] proposed a novel evaporator that features a small heat leak from the evaporator to the compensation chamber, aimed at improving the operating performance and reliability of LHP. In their paper, a mathematical model of the steady state operation was established, with the modeling results showing that the novel evaporator design can significantly reduce the heat leak from the evaporator to the compensation chamber.

In the application, some solutions are adopted to reduce the heat leak to the compensation chamber in the experiments. The modulated biporous wick evaporator (MBE) was fabricated, and a porous layer of absorbent wool with an ultra-low thermal conductivity was located between the wick and the compensation chamber in Xu's paper [15]. The MBE LHP significantly shortened the startup time and operated stably at the steady state with the maximum heat load of 200 W (heat flux of 40 W/cm^2) for the anti-gravity operation when the evaporator wall temperature is only 63 °C. Wang et al. [16] improved the evaporator structure from the O-ring type to the welding type. The experimental results showed that the operating heat load range expanded, and the maximum heat load increased from 140 W to 240 W because of the reduced heat leak to the compensation chamber. Joung et al. [17,18] proposed a thin planar bifacial evaporator with a bifacial wick structure for LHP's application to the closely packed heat sources such as fuel cells, and they examined the operating characteristics of the novel LHP for different fluid inventories and elevations. In their evaporator structure, the compensation chamber is not directly contacted with the evaporator wall, and less side-wall heat leak is transferred from the evaporator wall to the compensation chamber.

In order to improve the working conditions of the compensation chamber, a noval type of LHP with discolor-shaped evaporator with two primary biporous wicks is proposed, fabricated and tested in this work. The new design of evaporator aims to lower the temperature of the compensation chamber, which will improve the operating performance of the LHP. The main objective of the present paper is to comprehensively investigate the operational characteristics of the new type of LHP via experiments, including startup, heat load sharing of two sides of evaporator and unsteady operation et al.

2. Experimental setup

Two biporous wicks are adopted as the primary wicks in experimental LHP. The large pores in the biporous wicks can reduce the flowing resistance of the working fluid and enhance vapor escaping from the wicks. The small pores maintain sufficient capillary pumping force to supply liquid for the evaporating interface. Many experiments [19–22] have been carried out with biporous wicks and the experimental results show good performance.

The schematic of the flat evaporator LHP with two primary wicks and the structure of the evaporator are shown in Fig. 1. The two wicks are in contact with the two end surfaces of the flat disk-shaped evaporator. The circular stainless steel wire mesh is arranged between these two wicks, forming a close cylinder space as the compensation chamber.

According to the energy conservation, the equation of the liquid temperature in the compensation chamber is as below

$$m_{cc}c_p\frac{dT}{dt} = \dot{m}c_pT_{evap-in} + Q_{hl,wick} + Q_{hl,wall} \qquad (1)$$

where m_{cc} is the mass of the liquid in the compensation chamber, c_p is the special heat capacity of the liquid, $\dot{m}$ is the returning liquid flow rate into the compensation chamber, $T_{evap-in}$ is the temperature of returning liquid, $Q_{hl,wick}$ and $Q_{hl,wall}$ is the heat leak of backward conduction of the wick and side-wall conduction of the evaporator wall, respectively. The temperature of the compensation chamber is determined by the returning liquid flow rate, the heat leak, and the initial vapor–liquid ratio.

When heat load is applied to the evaporator wall, part of the heat load is transferred to the evaporator back due to the side-wall heat conduction. By inserting two wicks in the evaporator, the compensation chamber is not directly contacted with the evaporator wall, and so the heat leak of side-wall conduction has less influence on the compensation chamber. Moreover, there is larger evaporating area to produce more vapor, thus the new structure can improve the startup of LHP and reduce the temperature of the compensation chamber. The novel type of LHP has another advantage, that is, heat load can be applied to the evaporator wall and back simultaneously, which also extends the application of the system.

In this experiment, the operational characteristics of the LHP with different elevations were tested. Two elevations with gravity-assist ensured that the compensation chamber was filled with liquid working fluid, which corresponds to the LHP with slopes of 10° and 90°, respectively. All loops in the system were wrapped for thermal insulation. To reduce the operating temperature and remove the non-condensable gases, the system was evacuated to a pressure of 4.1×10^{-4} Pa before it was charged. The loop was made of copper, with sintered nickel powder as primary wicks, and methanol as the working fluid. And the volume filling ratio was 75% in this experiment, because a high filling ratio ensured that the liquid working fluid was supplied to the two wicks in the evaporator.

The heat source simulator was the copper cylindrical block with a diameter of 36 mm, and the heat input was the three inserted heating rods, monitored by a wattmeter with a relative error of 0.5%. A 10 mm thick adiabatic material with a thermal conductivity of 0.012 W/(mK) was wrapped outside the cylinder block surface. Temperatures were measured by T-type thermocouples with an accuracy of ±0.2 °C, and the thermocouples were fixed at the selected points in the system for monitoring the temperature as shown in Fig. 1(a). Four thermocouples were attached to the heated wall of the evaporator, and the average value was chosen to represent the temperature of the evaporator wall.

The heat sink temperature was set to 0 °C. The control accuracy of the cooling system was set to be 1 °C, meaning that the cooling system works when the temperature of the refrigerant in the cooling system deviates from the setting value by more than 1 °C. All the instruments were connected to the Keithley-2700 data acquisition system which helped to monitor and record test data from the LHP.

In this experiment, the primary heating surface at the bottom of the evaporator is named the evaporator wall, and the top is called the evaporator back. Two biporous wicks with high porosity are used as the primary wicks in the experiment. The uncertainty analyses of the porosity is estimated to be within ±0.42%. The main parameters of the present LHP are shown in Table 1.

3. Results and discussion

For the present experimental system, the performance of the LHP with one side heat load and bifacial heat load were tested. When the LHP operated with bifacial heat load, two cylinder blocks as heat resources were contacted with the evaporator wall and back, respectively. However, for testing of one side heat load operation, the cylinder block on the evaporator back was removed. Thus, in the two operations of the LHP, the heat capacities of the evaporator were different because of different heat resource arrangements.