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Experimental research on the heat performance of a flat copper-water loop heat pipe with different inventories

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ABSTRACT

The heat performance of a flat copper-water LHP, including the start-up property, operation capacity and evaporator thermal resistance, with three inventories (charging ratio ranged from 40 to 60%) was experimentally investigated. In order to observe the flow in the compensation chamber and the evaporating zone, a flat evaporator with a transparent cover (56 mm in diameter and 30 mm in total thickness) was manufactured. The porosity of the sintered copper wick was 47.26%, and the averaged pore radius was 22.65 μm. Severe heat leak, namely bubbles attaching on the wick during the start-up and heat pipe effect during the operation at a high heat load of 120 W, was observed. In addition, intermittent backflow from the condenser, which resulted in strong temperature oscillations, was also shown at low heat loads. It was experimentally found that high inventory was an effective method to address heat leak in spite of strong temperature oscillations at low heat loads. The optimal inventory of the proposed LHP was 10.0 ml (charging ratio of 50%), it could start smoothly in no more than 250 s and operate steadily at least at a heat load of 120 W (heat flux of 16.97 W/cm^2) with the allowable evaporator wall temperature of 90 °C.

1. Introduction

Loop heat pipes (LHPs) are robust, compact and passive two-phase heat-transfer devices without pump and they are firstly proposed by Russian scientist Maydanik in 1972 [1]. After several decades of development, mainly two types of LHP evaporator, the cylinder evaporator [2–4] and the flat evaporator [5–7], have been intensively investigated. Since LHPs can transport heat at a level of higher orders of magnitude than using highly conductive solid materials over long distance, they have been one of the most promising candidates in heat pump water heating system [8,9], waste heat utilization [10] and thermal control of satellites and spacecraft [1] as well as in the field of cooling electronics [11].

However, it is really difficult to figure out the complex characteristics of heat transfer and hydrodynamics processes in LHPs. Visual investigations were introduced to obtain additional information and a comprehensive understanding of the operation in LHPs, because traditional temperature measurement at different points of the device was insufficient [12]. The Ref. [12] focused on visual investigation of the condensation process of LHPs. Besides that, Entremond et al. [13] put a borescope into the liquid core to observe the start-up process. John et al. [14] used neutron radiography to observe the process of partial drying of the wick during operation. Vapor formation, nucleate boiling and evaporation were observed by Junwoo et al. [15] with a transparent evaporator made of Pyrex glass.

The heat load imposed on the evaporator of a LHP can be divided into two parts: heat for evaporation and heat leak [16]. Generally, the heat that leaks through the thermal conduction of a wick will heat the working fluid in the compensation chamber, which results in a higher evaporator temperature and LHP performance degradation. Therefore, it is thought that a copper wick is not suitable for the LHP because of high thermal conductivity, and wicks made of low thermal conductivity materials, such as nickel [17], stainless steel [18] and titanium [19], are desirable. However, Maydanik et al. [20] proposed a LHP with a copper wick having a 1200 W heat transfer capacity, in that high thermal conductivity of the copper wick could promote efficient heat exchange in the evaporating zone. In order to alleviate heat leak resulted from a copper wick, Wang et al. [21] increased the thickness of copper wick to improve the start-up characteristics of the copper-water LHP at a low heat load. Zhang et al. [4] pointed out that heat leak due to the copper wick could also be restrained by high inventory of water because a saturated wick can avoid tremendous heat leak, meanwhile an extremely high charging ratio of 78.3% would cause strong temperature oscillations. Besides,

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Nomenclature

ΔP	pressure difference, Pa
Q	input power, W
R	thermal resistance, °C/W
T	temperature, °C
ΔT	temperature difference, °C
Greek symbols	
ε	porosity
Subscripts	
bw	bottom side of the wick
cc	compensation chamber
ci	inlet of the condenser
co	outlet of the condenser
cont	contact
eo	outlet of the evaporator
ev	evaporator
ew	evaporator wall
ez	evaporating zone
e,vap	(heat load imposed on) the evaporator to vaporize the working fluid
e,cc	(heat load imposed on) the evaporator to the compensation chamber
LHP	loop heat pipe
sat	saturation
uw	upper side of the wick

other literatures focused on the effect of inventory on the heat transfer performance of LHPs with polytetrafluoroethylene (PTFE) wicks and metal foam wicks. The effect of ethanol inventory on the thermal performance of a miniature LHP with the PTFE wick was investigated by Nishikawa et al. [22]. It was found that the evaporator temperature increased with increasing inventory because of the increase in the thermal resistance of the condenser. A wick made from a multi-layer metal foam was introduced into LHP by Zhou [23], and it was concluded that 40 ml of ethanol was the optimized inventory.

In this paper, the effect of inventories (charging ratio ranged from 40 to 60%) on a copper-water LHP is investigated, since heat leak resulted from a copper wick has always been a serious problem. Similar research has been carried out by Zhang et al. [4], but it is insufficient to figure out the complex characteristics of heat transfer and hydrodynamics processes in the cylindrical evaporator only in a traditional temperature measurement way. Thus, a flat evaporator with a transparent cover is manufactured, and a high-speed camera is applied to observe the flow in the compensation chamber and the evaporating zone. The temperature profiles at different heat loads will be analyzed together with the flow in record. Moreover, temperature difference between two surfaces of the wick is also measured and calculated to evaluate the heat leak under different inventories.

2. Experimental apparatus and procedures

2.1. Experimental set-up

The schematic diagram of the flat LHP and the detail of the temperature measurement points were presented in Fig. 1. It was composed of an evaporator, two separated transport lines for liquid and vapor flows, a cross-flow condenser with an axial DC fan and a nickel-chrome serpentine heater. T-type thermocouples were applied for temperature measurement. Two were sheathed thermocouples (1 mm in diameter, Omega) for measuring wall temperature of the evaporator (T_{ew1} and T_{ew2}), and the readings were averaged to consider as the evaporator wall temperature (T_{ew}). Another four were fine wire duplex insulated thermocouples (0.38 mm in diameter, Omega) and inserted into the LHP. Two of them were placed at the inlet and outlet of the condenser for flow inlet and outlet temperature measurement (T_{ci} and T_{co}), respectively. The other two were attached on the upper surface and the bottom surface of the capillary wick (T_{uw} and T_{bw}) to evaluate the heat leak during the experiments. The accuracies of all thermocouples in use were ±0.5 °C.

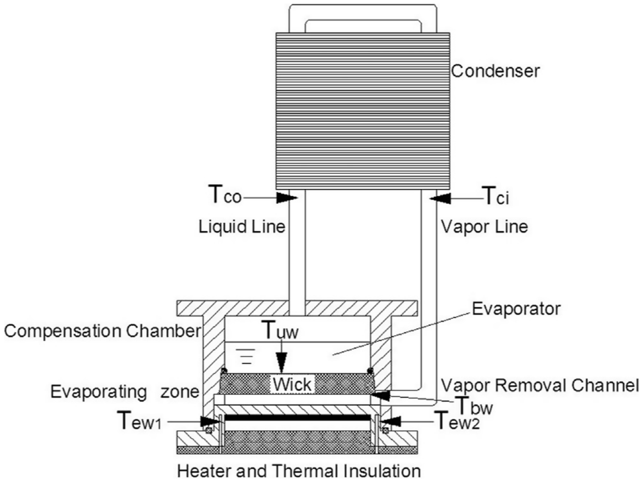

Fig. 1. Schematic diagram of the flat LHP and the detail of temperature measurement points.

As shown in Fig. 2(a), the evaporator consisted of an evaporator cover, a capillary wick, a brass plate and two O-rings. It was designed as a flat disk shape to fit the electronic equipment with 56 mm in diameter and 30 mm in total thickness. In order to observe the flow in the evaporator, a polycarbonate plastic rod was machined, sanded and polished to serve as a transparent evaporator cover whose maximum permissible temperature of long term operation was 130 °C. Due to the low thermal conductivity of polycarbonate plastic, the heat leak conducting from the evaporator wall could be neglected. Six longitudinal grooves with an individual cross section of 2 mm width × 3 mm depth was machined on the brass plate, served as vapor removal channels, and conducted heat from the nickel-chrome serpentine heater to the bottom face of the capillary wick. A capillary wick, which was 5 mm in thickness, was sandwiched between the evaporator cover and the brass plate. As presented as in Fig. 2(c), the space above the wick was 9 mm in thickness and acted as the compensation chamber (cc) to accommodate the excessive working fluid for keeping the wick wet. The space beneath the capillary wick was the evaporating zone (ez), where the evaporation was able to be observed from the transparent cover during experiments. An O-ring seal (36 mm in diameter) was positioned between the evaporator cover and the brass plate to prevent air infiltration from the ambient. Another small O-ring seal (28 mm in diameter) was also