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Two-phase flow characteristics of a high performance loop heat pipe with flat evaporator under gravity

Guohui Zhou [a], Ji Li [b,*]

[a] School of Engineering Science, University of Chinese Academy of Sciences, 19A Yu-quan-lu Road, Shijingshan District, Beijing 100049, China
[b] Laboratory of Advanced Thermal Management Technologies, School of Engineering Science, University of Chinese Academy of Sciences, 19A Yu-quan-lu Road, Shijingshan District, Beijing 100049, China

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ABSTRACT

Aiming to fully investigate the two-phase flow characteristics inside a loop heat pipe (LHP), a visualization study for a compact copper-water loop heat pipe with flat evaporator was carried out under gravity favorable mode in this work. Under forced water cooling condition with the cooling water temperature of 25 °C, the results indicated that the compact LHP could efficiently dissipate a maximum heat load of 550 W with the evaporator temperature of 91.2 °C. A minimum LHP thermal resistance was 0.068 °C/W, which was obtained at 500 W. In addition, the evaporator temperatures at boiling incipience under different heat loads were evaluated, which showed slight dependence on the input heat load. Finally, the flow patterns during the startup stage and the steady stage associating with different heating loads were recorded and analyzed to investigate the internal operation mechanism of the LHP. As a result, various two-phase flow patterns were found to be related to the heat load, and the occurrence of partial dry-out was observed in the evaporator at the maximum heat load of 550 W, corresponding to a heat flux of 88 W/cm^2.

1. Introduction

Waste heat removal is a common demand when an electronic device runs. If the waste heat could not be efficiently removed, an excessively high temperature would lead to overheating, inevitably resulting in the performance and reliability deterioration of electronic devices. When the conventional thermal management methods cannot meet the demand of electronics cooling, more efficient cooling technologies are expected in order to ensure the reliability of the electronic devices with high power densities [1].

Loop heat pipes (LHPs) are highly efficient two-phase heat transfer apparatus, which passively operate through cyclically evaporating and condensing fluid pumped by wick to transmit heat from a heat source to a heat sink [2]. Since its first appearance in 1972 [2,3], LHPs have been extensively used in space applications [4,5], and cooling electronics [6,7] owing to its unique features, such as high heat transport capability, long-distance heat transfer, and flexibility in installing, becoming a promising means for electronics cooling [8]. Over the past decades, many types of LHPs have been presented and investigated, i.e., LHPs with cylinder evaporators [9,10] and flat evaporators [11–14], LHPs with various porous wick structures [15,16], wick materials [17–21] as well as working fluids [22,23], and so on. However, the majority of these studies investigate the heat transfer characteristics only by measuring the surface temperatures of LHPs, and there are no physical images to interpret the internal two-phase flow characteristics and the operation mechanism of LHPs. Hence, although LHPs have been studied extensively, there is insufficient knowledge to figure out the internal phase-change behaviors inside the evaporator and the condenser, and an essential LHP visualization makes it possible to attain the additional information to deeply understand the operation mechanism of LHPs.

In recent decades, only few visualization studies of LHPs have been carried out to observe two-phase flow characteristics, the processes of evaporation and condensation, and the distribution of working liquid inside the compensation chamber. Cimbala et al. [24] developed a method of neutron radiography for visualization of an LHP, which made it possible to observe two-phase flow in various components of an LHP and partial wick dry-out phenomena. Wang and Nikanpour [25] developed an LHP to observe the fluid flow and phase change phenomena in the compensation chamber, vapor line, liquid line, and the condenser, except the cylindrical evaporator. Bartuli et al. [26] conducted visual investigations of condensation and the redistribution of the working fluid in an LHP. The results showed that a stratified

* Corresponding author.
E-mail address: jili@ucas.ac.cn (J. Li).

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Nomenclature

A	cross-section area of condenser tube
D_h	hydraulic diameter of condenser tube
H	height, m
ID	inner diameter, m
L	length, m
OD	outer diameter, m
Q	heat load, W
R	thermal resistance, °C/W
T	temperature, °C
WT	wall thickness, m

Greek symbol

α	heat transfer coefficient, W/(m^2 K)
Γ	periphery of condenser tube

Subscripts

c	condenser
ci	condenser inlet
co	condenser outlet
e	evaporator
ei	evaporator inlet
eo	evaporator outlet
ll	liquid line
v	vapor
vl	vapor line

two-phase flow and film condensation were observed during all operating models under different condenser cooling temperatures. Xu et al. [27] proposed LHPs with two-layer composite wicks, which had a flat disk shape evaporator with a transparent polycarbonate plastic cover for visual investigations. In this study, the evaporation and the flow motion in the evaporators with a two-layer Cu-Ni composite wick and a copper wick were observed and compared. Wang and Wei [28] carried out a visual investigation of evaporation/boiling process within the evaporator and pool boiling during the startup process.

The literature review indicates that although limited researches have been carried out to observe the internal two-phase flow and phase-change behaviors in LHPs, there are no works till now to fully observe the two-phase flow characteristics both inside the evaporator including the compensation chamber and the condenser simultaneously. In order to completely investigate the two-phase flow characteristics and operation mechanism of LHPs, in this work, an LHP with flat transparent evaporator and condenser was presented for visualization study, in which two-phase flow characteristics inside the evaporator and the condenser under gravity were investigated carefully under forced water cooling condition. In addition, the startup temperatures of the LHP under different heat loads were identified, and the two-phase flow patterns during the startup stage and the steady state stage were also figured out.

2. Experimental apparatus and testing procedure

2.1. Experimental apparatus

The scheme of the experimental device for visualization is presented in Fig. 1. The LHP was mainly comprised of a flat evaporator, a vapor line, a liquid line, a condenser, and a charging line. The flat evaporator, whose inner active space was 60 mm × 35 mm × 3 mm (L × W×H), was a multi-layer transparent configuration, and the detailed scheme is shown in Fig. 2. As illustrated in Fig. 2, the evaporator was sealed by an O-ring seal between the transparent polycarbonate plastic plate and the evaporator substrate. The evaporator substrate, the transparent polycarbonate plastic plate, and the stainless steel cover were fixed together tightly with 12 stainless steel screws.

A capillary wick, as shown in Fig. 3(a), was integrated onto the evaporator substrate through a standard sintering process. The capillary wicking structure was 3 mm thick, which was fabricated of 400 mesh staggered cooper wire mesh with a porosity of 67.6%, and its SEM photograph is shown in Fig. 3(b). There were 18 rectangular strips, each 1 mm in width, which were machined by wire-electrode cutting at 1 mm interval. Two transport lines were fabricated from 6 mm (OD) × 0.45 mm (WT) copper tubing, which were uniformly flattened to an external height of 3 mm by using a flattening mill, and the lengths were 374 mm for vapor line and 376 mm for the liquid line, respectively. The condenser had a similar design with the evaporator, which was also sealed by using an O-ring seal between the transparent polycarbonate plastic plate and the condenser copper substrate. There were also 12 screws to fix the stainless steel cover, the polycarbonate plastic plate, and the condenser substrate together. A cooling passage line was embedded in the condenser substrate, and the present LHP was cooled by running thermostatic water through the cooling line. Deionized water was filled into the proposed LHP as the working fluid, and the filling ratio was calculated to be 38% (here the filling ratio is defined as the volume percentage of the total inner space of the LHP including the porosity of the capillary wick shared by the working fluid). The main geometrical parameters are summarized in Table 1.

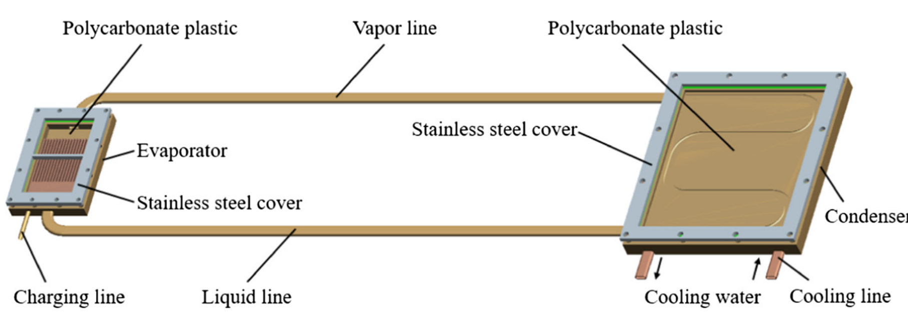

Fig. 1. Schematic diagram of the experimental LHP.