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Research Paper

Microscale infrared observation of liquid–vapor interface behavior on the surface of porous media for loop heat pipes

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HIGHLIGHTS

- The thermo-fluid behavior on the surface of a wick was visualized.
- Observations were conducted with a microscopic infrared camera and a microscope.
- There are three modes of liquid-vapor interface behavior in the wick.
- The effect of the groove width on the heat transfer performance were investigated.
- As the groove width reduced, a higher heat transfer capacity was observed.

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ABSTRACT

This paper reports on a visualization study investigating the characteristics of the liquid–vapor interface behavior on the surface of a wick in the capillary evaporator of loop heat pipes. Observations were conducted with a microscopic infrared camera and a microscope. Nine different samples simulate a part of a wick were made by two different materials: polytetrafluoroethylene (PTFE); and stainless steel (SS). First, three types of liquid–vapor interface behavior are reported. They are (a) evaporation at the menisci that formed at the boundary line between the heating plate, wick, and groove, (b) evaporation at the surface of small liquid bridges through nucleate boiling at the contact surface between the heating plate and wick, and (c) evaporation at the menisci in the wick. Secondly, the effect of the groove width on the maximum heat flux and the depth of a vapor pocket in the wick are reported. It was found that, as the groove width reduced, a higher heat transfer capacity was observed in both of the materials, except in the wick that had the smallest groove width. Additionally, it was found that the wick with the smallest fin width had the greatest potential for preventing vapor pockets formation in the wick.

1. Introduction

Loop heat pipes (LHP) have recently garnered a lot of interest as an advanced heat transportation technology due to their ability to cool electronic components with high heat flux. LHP is a two-phase heat transport device that utilizes the evaporation and condensation of a working fluid, and it uses a capillary action in a microscale porous structure that is called a wick inserted in the evaporator. LHP is used as a thermal control device in spacecraft [1] and terrestrial systems [2–5] because of its high heat transportation capability and its capacity for transporting heat over long distances with no electrical power needed.

An LHP consists of an evaporator, a vapor line, a condenser, a liquid line, and a compensation chamber (CC), and a schematic of it is shown in Fig. 1(a). The evaporator is composed of an evaporator case, a wick, grooves, and a liquid core, as shown in Fig. 1(b). The performance of an LHP is governed by the thermal hydraulics in the evaporator because it strongly depends on the performance of its wick. In order to enhance an LHP performance, an understanding of the thermo-fluid behavior in the wick is required. Previous studies have analyzed the heat and mass transfer in the wick [6–8]. In our group, Nishikawara et al. conducted a three dimensional numerical analysis of the two-phase thermal hydraulics of a capillary evaporator with a pore network model [9].

A number of visualization studies into the behavior of the liquid–vapor interface have also been conducted. Liao et al. conducted one such study on phase-change heat transfer in a

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Nomenclature

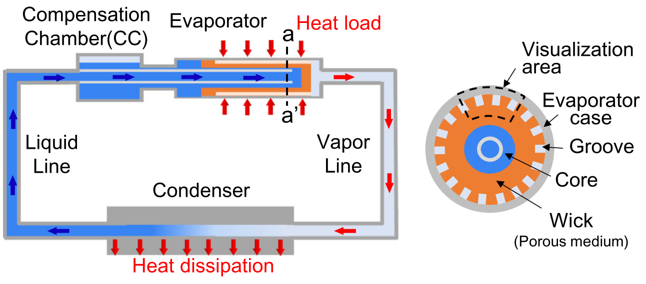
A_h	heat input area (m^2)
A_{wick}	wick cross sectional area (m^2)
A_{cnt}	contact area between heating plate and wick (m^2)
c_p	specific heat at a constant pressure (J/kg/K)
h_{ev}	heat transfer coefficient between heating plate and vapor (W/m^2/K)
h_{cnt}	heat transfer coefficient between heating plate and the wick contact surface (W/m^2/K)
K	permeability (m^2)
k	thermal conductivity (W/m/K)
L	length (m)
$\dot{m}$	mass flow rate (kg/s)
P	pressure (Pa)
q_{apply}	applied heat flux (W/cm^2)
Q_{apply}	applied heat (W)
Q_{ev}	heat of vaporization (W)
Q_{leak}	heat leak from the heating surface to liquid reservoir (W)
Q_{loss}	heat loss (W)
Q_{sens}	sensible heat (W)
R_{cnt}	thermal resistance between the heating plate and the wick (K/W)
T	temperature (°C)

Greek

λ	latent heat (J/kg)
μ	viscosity (Pa s)
ρ	density (kg/m^3)

Abbreviations

amb	ambient
cnt	contact
eff	effective
ev	evaporation
h	heated
r	reservoir
v	vapor



(a) (b)

Fig. 1. (a) Schematic of an LHP, (b) cross section of an evaporator.

vertical two dimensional porous media by using a high speed video imaging system [10]. Mottet et al. conducted a numerical analysis and visualized the wick being invaded by vapor through the use of a high definition camera [11]. However, the pore sizes in these studies were between one and two orders of magnitude greater than those present in the wicks of the LHP evaporators. A visual study of the thermal hydraulics in a porous media whose pore diameter is smaller than a few dozen microns is therefore required. In our previous work, the visualizations using the microscale infrared camera were carried out [12]. The wicks were made out of two different materials, polytetrafluoroethylene (PTFE) and stainless steel (SS), which had pore radii of 1.2 μm and 22.5 μm, respectively. It was found that there was difference of the heat transfer process caused by the difference of the thermal conductivity and the pore size. However, the microscale visible observations are required in order to investigate more detailed liquid-vapor interface behavior.

Some studies on optimizing the configuration of the wick have been conducted. Zhang et al. investigated the effect of structural parameters of vapor groove in the evaporator based on a three-dimensional model [13]. V.M. Kiseev et al. investigated the optimal ratio of the vapor groove surface area to the heat input area experimentally [14]. Wu et al. investigated experimentally the effect that increasing the number of grooves has on the performance of an LHP [15]. In our group, Nishikawara et al. conducted a study on optimizing the wick shape of by using a three-phase contact line (TPCL) based on numerical analysis [16]. As mentioned above, several studies on the optimization of the wick shape have been conducted. However, in order to reveal further physical phenomena such as the influence of the vapor groove width on the formation of vapor region at the contact surface and enhance the LHP performance, the evaluation with the visualization in the infrared and visible range is required.

This paper reports on the observation results of liquid–vapor interface behavior, which were carried out using a microscale infrared camera and a microscope. The characteristics of the thermal hydraulics of the PTFE and SS wicks, whose pore radii were 1.2 μm and 1.0 μm, respectively, are presented. Then the effect of the vapor groove width on the heat transfer performance are presented.

2. Experimental apparatus and condition

2.1. Experimental apparatus

Fig. 2(a) illustrates a schematic of the experimental apparatus. It simulates a part of the cross section of the evaporator, as shown in Fig. 1(b). It is composed of an imaging system, XY-stage, liquid reservoir, sample, heating plate, heater, and heat insulator. Fig. 2(b) shows the picture of the experimental apparatus and imaging area. The observation surface of the wick and the heating plate were in an open state under atmospheric environment. Ethanol, whose boiling point is 78.3 °C under atmospheric conditions, is used as a working fluid. The thermographs are taken by a microscopic infrared thermograph (Advanced Thermo TVS-500EX and TVM-7025U) that has a spatial resolution of 18 μm and measurement wavelength of 8–14 μm. Its detecting element is an uncooled micro-bolometer. The measurement accuracies are ± 2 °C when the measured temperature is less than 100 °C and ±2% when over 100 °C. Microscopic images were taken with a microscope (Keyence VHX-5000) whose spatial resolution is 1.02 μm.

2.2. Experimental condition

The samples are made up of two different porous materials: polytetrafluoroethylene (PTFE); and stainless steel (SS). The properties of the porous media are shown in Table 1. The pore radius and permeability were measured by the extended bubble point method and by the gas flow method in our laboratory [17].

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