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Experimental study on thermo-hydrodynamic behaviors in miniaturized two-phase thermosyphons

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ABSTRACT

In this paper, the thermo-hydrodynamic behaviors in miniaturized two-phase thermosyphons are experimentally investigated by a visualization system. The effects of heat load and channel dimension on the thermo-hydrodynamic behaviors are examined and further quantitatively recognized by a state diagram depending on the Weber number and Bond number. In addition, the vapor–liquid two-phase flow, heat transfer regimes and thermal performances are analyzed and discussed. The results indicate that, differing from the conventional two-phase thermosyphon, the state of working fluid in a miniaturized two-phase thermosyphon is no longer only in a fashion of pool and annular-flow states, but also in a fashion of oscillation state. The oscillation state is the characteristic two-phase flow regime of a miniaturized two-phase thermosyphon and possesses the feature of random formation and oscillatory motion of liquid plug in minichannels. The pool state occurs at small Weber number, the annular-flow state is observed at large Weber number, and the oscillation state takes place at medium Weber number when Bond number is approximately smaller than 0.7. The thermal performance of oscillation state is better than that of pool state but is less powerful than that of annular-flow state. The heat transfer regimes are the film evaporation and condensation combined with thermal conduction in the pool state, the forced evaporation and condensation in the oscillation state, and the film evaporation and condensation in the annular-flow state, respectively.

1. Introduction

Cooling of high-heat-flux electronics in a fixed system with strictly limited space are usually encountered in the real engineering applications [1,2], taking the computer closet in the Antarctic astronomical station, the solar collector and infrared imaging spectrometer as an example. In the context of this particular situation, the challenge consists in the design of a highly-effective, no-pump drive and compact heat transfer device. Although micro heat pipes have been found to be effective for the requirement of no-pump and compact structure in these applications [3,4], too small channel dimension results in the unsatisfactory heat transfer capability, and the temperature uniformity is also dissatisfied. With the aid of gravity, the two-phase thermosyphon shows superior thermal performance and may hence meet the above challenge [5,6]. Considering that the channel scale of conventional two-phase thermosyphon is typically larger than 3 mm [7], the two-phase thermosyphon is required to be miniaturized for the cooling applications in a strictly limited space. The miniaturization, although often not properly known, could highly affect the vapor–liquid two-phase flow and thermal performance of the two-phase thermosyphon. Therefore, it is crucial to understand the thermo-hydrodynamic behaviors in miniaturized two-phase thermosyphons.

The two-phase thermosyphon is a sealed container filled with vapor–liquid two-phase medium. It generally operates in the vertical mode with the evaporation section at the bottom and the condenser section at the upper part, in which the gravity plays an important role in the circulation of working fluid. As channel dimensions shrink, the relative importance of surface to volume forces increases, causing the heat and mass transfer regime to be significantly different from the conventional channels [8]. The vapor–liquid two-phase flow in a miniaturized two-phase thermosyphon involves the scale effect, interface evolution, flow instability and thermo-hydrodynamic coupling. The two-phase flow regime above the liquid pool that locates at the bottom of the evaporator section is no longer just the annular flow. Induced by the balance of gravitational force and surface tension force as

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Nomenclature

A	cross-sectional area of a single channel, m^2
Bo	Bond number
C_p	specific heat, J kg^{-1} °C^{-1}
D	hydraulic diameter of channel, mm
g	gravitational acceleration, m s^{-2}
h_{fg}	latent heat, J kg^{-1}
L	length of rectangular minichannel, mm
L_1	total length of metal plate, mm
L_{a}	length of the adiabatic section, mm
L_{c}	length of the condenser section, mm
L_{e}	length of the evaporator, mm
m	mass flow rate of circulating water, kg
N	number of channel
Q	heat load, W
Q	heat-transfer rate, W
R	thermal resistance, °CW^{-1}
t	time, s
Δt	time interval, s
T_{in}	inlet ater temperatures, °C
T_{out}	outlet water temperatures, °C
T_{a}	typical temperature points at the middle of the adiabatic section, °C
T_{c}	typical temperature points at the middle of the condenser section, °C
T_{e}	typical temperature points at the middle of the evaporator, °C
T_{sat}	saturation temperature, °C
$\overline{T}_c$	average temperatures of the condenser section at the steady state, °C
$\overline{T}_e$	average temperatures of the evaporator section at the steady state, °C
U	velocity of the gas phase, m s^{-1}
We	Weber number
W_1	total width of metal plate, mm
W_2	total width of channel area, mm

Greek symbols

μ_{l}	liquid dynamic viscosity, Pa s
ρ_{g}	densities of gas phase, kg m^{-3}
ρ_{l}	densities of liquid phase, kg m^{-3}
σ	surface tension, N m^{-1}

Subscripts

a	adiabatic
c	condenser
e	evaporator

characterized by the Bond number, the plugs are formed for the vapor–liquid two-phase flow in minichannels. The channel dimension may strongly affect the vapor–liquid flow and heat transfer inside the two-phase thermosyphon, especially at the scale with the appearance of capillary pumping action. In this context, an important question arises as to how the miniaturization affects the vapor–liquid two-phase flow and thermal performance in two-phase thermosyphons.

Despite great experimental and theoretical efforts have been devoted to exploring the thermo-hydrodynamic behaviors of both the conventional two-phase thermosyphon [9–11] and the micro/miniature heat pipes [12–14], few study has focused on the miniaturized two-phase thermosyphon. Riffat et al. [15] investigated the thermal performance of miniaturized two-phase thermosyphon that applied in the solar collector via an analytical model, and subsequently proposed a new structure by the introduction of artery (outside) to solve the problem of larger viscosity and entrainment effect [16]. Their investigation indicated that the miniaturized two-phase thermosyphons have higher heat transport limits than miniature heat pipe of the same cross-sectional area. However, up to now, the detailed information of vapor–liquid two-phase flow in the miniaturized two-phase thermosyphon is less available in the literature. In addition, it seems that the flow regimes in a two-phase thermosyphon are related with the combination among fluid properties, heat load and channel dimensions. A detailed understanding of vapor–liquid two-phase flow behavior requires a unified view of flow regimes in miniaturized two-phase thermosyphons.

To provide a further insight into the underlying physics of two-phase flow and heat transfer, an experimental study is conducted to investigate the thermo-hydrodynamic behaviors in miniaturized two-phase thermosyphons via a visualization system by using digital microscope. In the experiment, the effects of heat load and channel dimension on the thermo-hydrodynamic behaviors are examined. In addition, the vapor–liquid two-phase flow, heat transfer regimes and thermal performance of the observed three states of working fluid (i.e. flow regimes) are analyzed and discussed. Particularly, a state diagram is provided to quantitatively characterize the thermo-hydrodynamic behaviors, depending on the Weber number and Bond number.

2. Experimental setup and procedures

In the experiment, the miniaturized two-phase thermosyphon is composed of a series of parallel minichannel that operates in the vertical mode. A visualization experiment is performed to observe and measure the gas–liquid two-phase flow and thermal performance in a miniaturized two-phase thermosyphon. Fig. 1 (a) illustrates the overall experimental setup, which mainly consists of the two-phase thermosyphon, electric heating unit, refrigeration unit and digital microscope. The two-phase thermosyphon is made by an aluminum metal plate (thickness: 3 mm), which is covered by a glass window (thickness: 6 mm) for the visualization of the flow patterns inside grooves. The contact surfaces between the glass window and the metal plate is sealed with transparent thin film. The metal plate (L_1 = 68 mm, W_1 = 59 mm) and the glass window are tightened with bolts around the two-phase thermosyphon. The two-phase thermosyphon is evacuated by a vacuum pump (RVP-4, limit pressure: 0.4 Pa) and then filled with working fluid. In the experiment, the working fluids of ethanol and methanol are applied. Note that, without specification, the following experimental data is obtained by the working fluid of ethanol. The contact angle of ethanol on aluminum is 12.3° [see Fig. 1 (b)].

To analyze the role of channel dimension on thermo-hydrodynamic behaviors in two-phase thermosyphons, seven cross-sectional dimensions of channel are employed in the experiment, in which the width and depth of rectangular cross-section are $W \times \delta$ = 0.5 mm × 1 mm, 1 mm × 1 mm, 1.5 mm × 1 mm, 2 mm × 1 mm, 2.5 mm × 1 mm, 3 mm × 1 mm and 4 mm × 1 mm