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Effect of pin-fins on the onset of flow instability of water in silicon-based microgap

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ABSTRACT

This paper is focused on the effect of inner pin-fins on the onset of flow instability (OFI) in microgaps. An experiment is performed on the OFI of water through four types of microgaps with different shaped pin-fins and a plain microgap without pin-fins. The microgaps have a hydraulic diameter of 210 μm. It is found that the OFI is delayed in the pin-fin microgap with larger friction factor as compared to that with smaller one. A theoretical analysis for the effect of friction factor on OFI is further developed. It is shown that OFI moves to the direction of decreasing mass flux with the increasing friction factor, which well explains the experimental results. However unexpectedly, when the temperature and pressure oscillations occur due to the flow boiling instability after OFI, the oscillation amplitudes for the pin-fin microgap with the larger friction factor are larger than those with the smaller one. To account for this unexpected result, the flow patterns during the flow boiling instability just after OFI are presented. The effects of pin-fins and inlet restrictors on OFI are also compared. It is found that the pin-fin configurations delay the occurrence of OFI as compared to the plain microgap. However, when the flow boiling instability occurs after OFI, the former increase the oscillation amplitudes of temperature and pressure measurements, and the latter decrease them. The mechanism analysis of the different effects between pin-fins and inlet restrictors is also presented.

1. Introduction

As a promising microelectronic cooling technology, the boiling heat transfer in microchannels has been investigated extensively in the past decades [1–3]. A number of experimental studies shown that the flow boiling in microchannels was very susceptible to the flow boiling instability, which caused temperature, pressure, mass flow rate oscillations, and even premature transition to CHF condition [4–7]. Among various issues of the study on the flow boiling instability, the onset of flow instability (OFI), also termed as the critical point between steady and unsteady flow [8], is an important one. Normally, the OFI is identified as the minimum point on the demand curve of pressure drop versus mass flow rate. When the mass flow rate is lower than that of OFI, the flow boiling instability may occur. The OFI study is helpful to understand the mechanism of the flow boiling instability and further to develop efficient technologies for delaying or suppressing the occurrence of the flow boiling instability. Thus, it has attracted increasing attention in the last decades.

Roach et al. [9] carried out an experiment on the OFI of water flow in copper microtubes having diameters of 1.17 mm and 1.45 mm at low mass flux of 220–790 kg/m^{2}s. They found that at low mass flux, the measured heat flux at OFI cannot be predicted by the existing models or correlations of OFI for macrochannels. Xu et al. [10] performed an experiment to investigate the OFI of water and methanol in a copper heat sink consisting of 26 rectangular microchannels with a width of 300 μm and a depth of 800 μm. They found that the OFI occurred at a certain outlet fluid temperature which was several degrees lower than the saturated temperature corresponding to the outlet pressure. Wu et al. [11] performed an experiment to study the flow boiling instability of water in silicon microchannels with a hydraulic diameter of 72.7 μm. It was found that with the increasing heat flux, the difference in mass flux between the OFI and ONB (onset of nucleate boiling) decreased. Wang et al. [12] investigated the effect of inlet restrictors on the flow boiling instability of water in parallel microchannels with a hydraulic diameter of 186 μm. Their results showed that the inlet restrictors had a significant effect on the occurrence of OFI. When the boiling instability occurred, the amplitudes of temperature and pressure oscillations in the microchannels with inlet restrictors are much smaller than those without inlet restrictors. Kuo and Peles [13] investigated the effect of system pressure on the flow boiling instability for water flow in silicon

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Nomenclature

a, b	geometric parameters of pin-fin (m)
A	area of heated wall (m^2)
A_{fin}	cross-sectional area of pin-fin (m^2)
c_p	specific heat capacity (kJ/kg °C)
D	diameter (m)
f	friction factor
G	mass flux (kg/m^2s)
h	specific enthalpy (J/kg)
h_{fg}	latent heat of vaporization (J/kg)
H	height of pin-fins (m)
I	electric current to heater (A)
L	length of pin-fin microgaps (m)
M	total mass (kg)
ΔM	mass increment (kg)
P	pressure (bar)
ΔP	pressure drop (bar)
q	heat flux (W/m^2)
q'	heating power per unit length (W/m)
s	pin-fin spacing (m)
T	temperature (°C)
Δt	time interval (s)
v	specific volume (m^3/kg)
$\bar{v}$	average specific volume (m^3/kg)
V	electric voltage to heater (V)
W	width of pin-fin microgaps (m)
x	vapor quality

Greek symbol

ε	pin-fin density
φ	heat transfer ratio

Subscripts

A	acceleration
F	friction
in	inlet
l	liquid
out	outlet
OFI	onset of flow instability
sat	saturation
sp	single-phase
tp	two-phase
v	vapor
w	wall

microchannels with a hydraulic diameter of 223 μm. They found that the occurrence of OFI was delayed as the system pressure increased. Zhang et al. [14] performed an experimental and numerical study on the Ledinegg instability of water flow in three kinds of silicon microchannels with different hydraulic diameters. They found that the smaller microchannels were more susceptible to the flow boiling instability. The numerical results showed that the inlet restrictors increased the flow stability by decreasing the mass flux at OFI and reducing the slope of pressure drop - mass flux demand curve for mass flux lower than OFI. Recently, Fan and Hassan [15,16] investigated the effect of inlet orifices on the flow boiling instability in the stainless steel microtubes with a diameter of 889 μm. Experiments were performed using three different orifice configurations, with 20%, 35%, and 50% area ratio of orifice area to main microtube area. It was found that with the decreasing area ratio, the heat flux at OFI increased, i.e., the occurrence of OFI was delayed.

Although great advances have been made on the OFI in microchannels, they were focused on the plain microchannels. The OFI study in enhanced heat transfer microchannels is scarce. In macroscale heat transfer applications, pin-fins were used extensively to enhance heat transfer performance due to the increasing heat transfer surface area and the convective heat transfer coefficient. Tuckerman [17] first employed high aspect ratio (H_{fin}/D_{fin} = 8:1) pin-fins to enhance microchannel performance. Their study showed that the longer pin-fins were not desirable since the heat transfer efficiency of the fins decreased with the fin height. Recently, a number of researchers have applied the pin-fins with the small aspect ratio (H_{fin}/D_{fin} < 3:1) to microchannels. They studied the flow friction factor and convective heat transfer coefficient of fluid flow in microchannels with pin-fins entrenched inside [18–24]. Up till now, the studies on fluid flow and heat transfer in microchannels with pin-fins are still in preliminary stage, especially for the flow boiling instability [25]. As compared to the plain microchannels, the inner pin-fins in microchannels have important effects on bubble dynamics and flow patterns for the flow boiling instability in microchannels with pin-fins. The flow boiling instabilities in microchannels with and without pin-fins are very different. As for the effect of pin-fins

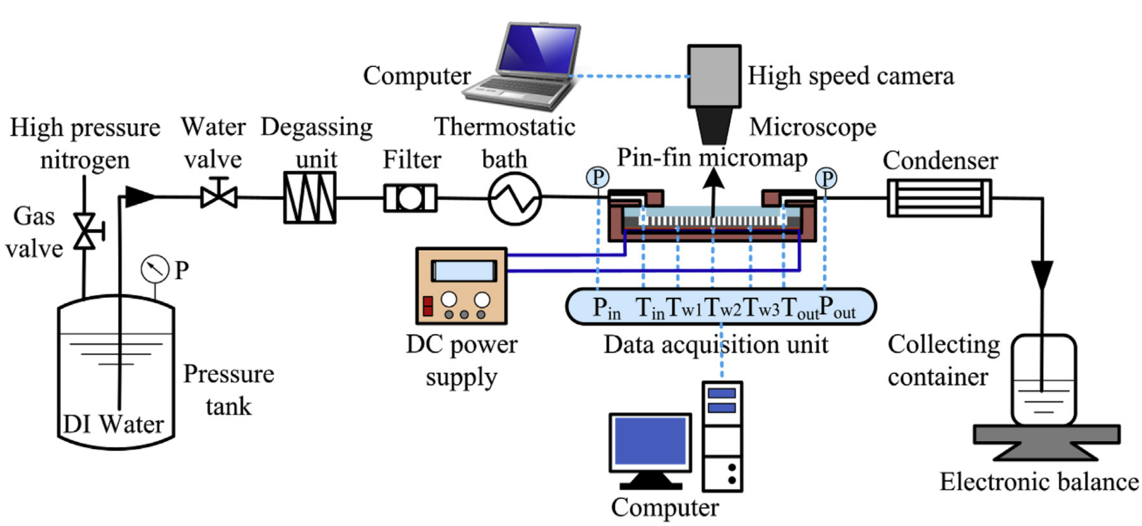

Fig. 1. Experimental setup.