International Journal of Heat and Mass Transfer 112 (2017) 1081–1089

Contents lists available at ScienceDirect

International Journal of Heat and Mass Transfer

journal homepage: www.elsevier.com/locate/ijhmt

Subcooled flow boiling of water in a large aspect ratio microchannel

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ARTICLE INFO

Article history:
Received 11 December 2016
Received in revised form 8 May 2017
Accepted 8 May 2017
Available online xxxx

Keywords:
Flow boiling
Large aspect ratio
Microchannel
Flow patterns
Heat transfer

ABSTRACT

Water flow boiling in large aspect ratio microchannels was experimentally investigated in a rectangular microchannel 300 μm deep and 6 mm wide; hence, the hydraulic diameter was 571 μm and the aspect ratio was 20. The tests used mass fluxes of $G = 261–961\ kg/(m^2\ s)$ and heat fluxes of $q'' = 631–987\ kW/m^2$ with the combined effects on the flow boiling phenomena characterized by the Boiling number at an inlet temperature of 65 °C. The results show the flow patterns and the heat transfer and pressure drop characteristics during flow boiling in the large aspect ratio microchannel. Sweeping flow with relatively high heat transfer rates was observed while the strengthening effect of the bubble confinement on the heat transfer did not occur during the subcooled flow boiling in the large aspect ratio microchannel. Nucleate boiling dominated the heat transfer with the regular pressure drop fluctuations detected during the sweeping flow and the churn flow.

1. Introduction

Microchannel heat sinks have attracted much attention since the pioneering work of Tuckerman and Pease [1] in 1981 because of the large heat exchange surface areas per unit fluid flow volume and the corresponding high heat transfer rates. The flow boiling provides efficient heat dissipation as the coolant latent heat transports the heat, which reduces the coolant flow rate and the pumping power, while maintaining a relatively uniform wall temperature. Microchannel flow boiling combines the advantages of both the high heat transfer rate due to the microchannel size and the flow boiling so it is attracting much attention in heat transfer community. It has many applications in electronics, reactors, aerospace, and military fields [2]. Therefore, there have been numerous studies to understand the flow boiling behavior in microchannels. Most microchannels studied in the literature have the cross section of rectangles, triangles, trapezoids, or closed microtubes [3–6]. Due to the relative ease of fabricating rectangular microchannels, the vast majority of studies and practical applications of microchannel flow boiling have involved low and moderate aspect ratio rectangular cross-section microchannels [7].

Huh and Kim [8] experimentally investigated flow boiling in asymmetrically heated rectangular microchannels with aspect ratios of 0.93 and 2 with the bubbly flow and elongated bubble flow patterns as the dominant flow pattern in the middle of the test channels, while the very long elongated bubble flow, behaving like an annular flow, was mainly observed especially near the test section exit. In addition, the periodic pressure drop oscillations have often been observed, especially at higher mass fluxes and heat fluxes. The two-phase flow patterns and heat transfer characteristics of R134a refrigerant during flow boiling in a single rectangular micro-channel with an aspect ratio of 1.4 were experimentally studied by Keepaiboon and Wongwises [9] with their results showing six different flow patterns of bubbly flow, bubbly-slug flow, slug flow, throat-annular flow, churn flow, and annular flow. The flow patterns were found to strongly impact the heat transfer coefficients. Recently, Yin et al. [10,11] experimentally studied water flow boiling in a single microchannel with an aspect ratio of 0.5, the bubbly flow, the confined/elongated bubble flow and the annular flow were mainly observed and they were found to be greatly related to the heat transfer coefficient.

The microchannel aspect ratio significantly affects the flow boiling, as has been noted by many researchers. Soupremanien et al. [12] experimentally studied the influence of the aspect ratio on flow boiling in rectangular minichannels using Forane 365 HX as the working fluid in two minichannels with same hydraulic diameter of about 1.4 mm and different aspect ratios ($AR_1 = 7$ and $AR_2 = 2.3$). Their results showed higher heat transfer coefficients in the larger aspect ratio channel at low heat fluxes but lower heat transfer coefficients at higher heat fluxes, which shows that the flow boiling heat transfer in minichannels was influenced not only by the hydraulic diameter but also by the channel aspect ratio. Markal and Aydin [13] experimentally studied the saturated flow

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http://dx.doi.org/10.1016/j.ijheatmasstransfer.2017.05.028
0017-9310/

Nomenclature

A_{ch}	heated area of the microchannel (m^2)
AR	aspect ratio
Bo	Boiling number
Co	Confinement number
C_{pl}	specific heat of the liquid (J/kg K)
D_h	hydraulic diameter (m)
G	mass flux (kg/m^2 s)
g	acceleration of gravity (m/s^2)
H_{ch}	microchannel depth (m)
h_e	exit fluid enthalpy (J/kg)
h_{fg}	latent heat of the liquid (J/kg)
$h_{l,sat}$	saturated liquid enthalpy (J/kg)
h_{local}	local heat transfer coefficient (W/m^2 K)
I	current (A)
i	thermocouple row number
j	thermocouple column number
L_{ch}	microchannel length (m)
M	mass flow rate (kg/s)
Q_{input}	input power (W)
Q_{loss}	heat loss (W)
q''	heat flux (W/m^2)
T_f	fluid temperature (K)
$T_{l,in}$	liquid inlet temperature (K)
$T_{l,out}$	liquid outlet temperature (K)
T_{sat}	saturated temperature (K)
T_w	wall temperature (K)
W_{ch}	microchannel width (m)
x_e	thermodynamic vapor quality (–)
z	distance from inlet (m)

Greek letters

ρ_l	liquid density (kg/m^3)
ρ_v	vapor density (kg/m^3)
σ	surface tension coefficient (N/m)

boiling characteristics of deionized water in parallel rectangular microchannels with various aspect ratios (AR = 0.37, 0.82, 1.22, 2.71, 3.54 and 5.00) but with the same hydraulic diameter of 100 μm. The heat transfer coefficient increased with increasing aspect ratio up to AR = 3.54 and then decreased, while the total pressure drop did not correlate with the aspect ratio.

Large aspect ratio microchannels can be used in many industrial applications, because they have a large surface area to cross-sectional area ratio which reduces the working fluid flow rate while providing a large cooling area and with lower vapor side pressure drops and higher vapor side heat transfer rates [14,15]. Therefore, flow boiling in large aspect ratio microchannels is of interest [16,17], but there is little work in the literature focusing on flow boiling in large aspect ratio microchannels.

Wang et al. [15,18] experimentally investigated flow boiling and bubble confinement in microchannels with large aspect ratios of AR = 10 and AR = 20 using FC-72 and ethanol. The flows showed bubble nucleation and confined bubbly flow that rapidly turned into slug-annular flow followed by annular flow and wispy-annular flow with an evaporating film. In addition, they concluded that the channel aspect ratio affected the flow boiling heat transfer in large aspect ratio microchannels. Alam et al. [19] experimentally studied the local flow boiling heat transfer and pressure drop characteristics in microgap channels with aspect ratios of 33–66 using deionized water. Their results showed that the flow boiling heat transfer coefficient was dependent on the aspect ratio, with larger aspect ratios giving higher heat transfer coefficients. The dominant flow regimes in the microgap channels after the onset of nucleate boiling were confined slug and annular boiling.

Although flow boiling phenomena in large aspect ratio microchannels has been studied by some researchers, the available results still do not provide a good understanding of the heat transfer mechanisms and other characteristics. Besides, it is noted that the silicon-based microchannels were used in these few studies [15,18,19], but the metal-based microchannel may have more potential for application due to the relatively easier fabrication and lower cost. The present work experimentally investigated the flow boiling of water in a single copper-based microchannel with large aspect ratio. Flow pattern transition characteristics, the heat transfer characteristics and the pressure drop fluctuations during flow boiling in the large-aspect ratio microchannel were analyzed.

2. Experimental setup

2.1. Test loop configuration

The experimental system is illustrated in Fig. 1. The deionized water (DI water) was boiled violently for about half an hour and was then stored in the sealed liquid tank. A magnetic micro gear pump drove the fully degassed DI water into the flow loop with a 15 μm filter placed before the pump to remove any possible particles. A preheater was installed upstream of the test section to heat the liquid to the desired subcooling with a condenser downstream of the test section to cool the working fluid before it flowed back into the liquid tank. A 2 μm filter was used before the test section to prevent solid particles from entering the microchannel. The mass flow rate was measured using a Coriolis mass flow meter (DMF-1-1-B). The working fluid pressures and temperatures at the test section inlet and outlet were measured by two pressure transducers (Yokogawa EJA530E) and two K-type thermocouples (Omega). The flow patterns during flow boiling in the microchannel were visualized and recorded by a high speed CCD camera (BASLER A504k) above the test section. All the temperature and pressure data was collected by a data acquisition system (AMETEK EX1048A).

2.2. Test section

The microchannel test section with the large aspect ratio channels consisted of 6 parts as shown in Fig. 2. The microchannel between the upper surface of the Cu heating block and the polycarbonate cover was 300 μm high and 6 mm wide. The microchannel aspect ratio was defined as the ratio of the channel width to channel depth, so the channel aspect ratio in the present study was 20 which was quite large compared with the microchannels used in other studies. The channel was 40 mm long with a hydraulic diameter of 571 μm, so the channel confinement number ($Co = \sqrt{\sigma/g(\rho_l - \rho_v)D_h^2}$) was 4.38. Thus, the channel can be classified as a microchannel according to the criterion proposed by Kew and Cornwell (Co > 0.5) [20]. The roughness of the heated bottom wall of the microchannel was 0.3 μm. The Cu block was heated by a ceramic heater below the copper block with the whole setup held together by the PTFE housing and the epoxy resin board. The