Experimental Thermal and Fluid Science 74 (2016) 247–256

Contents lists available at ScienceDirect

Experimental Thermal and Fluid Science

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

Confined characteristics of bubble during boiling in microchannel

Liaofei Yin, Li Jia *

Institute of Thermal Engineering, School of Mechanical, Electronic and Control Engineering, Beijing Jiaotong University, Beijing 100044, China
Beijing Key Laboratory of Flow and Heat Transfer of Phase Changing in Micro and Small Scale, Beijing 100044, China

ARTICLE INFO

Article history:
Received 2 September 2015
Received in revised form 20 December 2015
Accepted 22 December 2015
Available online 2 January 2016

Keywords:
Boiling
Microchannel
Confined characteristics
Bubble shape parameters
Contact angle

ABSTRACT

Bubble confined growth during boiling in micro-scale space is experimentally investigated. Degassed deionized water (DI water) is used to study the confined characteristics of growing bubble in microchannel. Mechanisms of bubble confinement in microscale space are discussed. Effects of heat flux and microchannel size on bubble confined growth are examined. The cross-sections of the tested rectangular microchannel are 0.5 mm × 1 mm and 1 mm × 1 mm respectively. The bubble growth process is observed and recorded by high speed CCD camera with 250 frames per second. The confined characteristics of bubble in microchannel are represented by the fluctuated variation of bubble root contact angle and other two bubble shape parameters, namely the maximal local void fraction of bubble and the bubble aspect ratio. The increased bubble growth force caused by miniaturization of space size is the chief mechanism for bubble confined characteristics in microchannel. Moreover, it is found that whether a growing bubble in microchannel will show confined characteristics is irrelevant to whether or not it will finally occupy the whole microchannel cross-section. The bubble confined characteristics are jointly controlled by the bubble growth rate and the size of microscale space. In some cases the bubble confined growth features are not displayed throughout the growth period even the bubble completely occupies the whole microchannel cross-section.

1. Introduction

Microscale boiling has attract more and more attention due to the outstanding heat dissipation capability [1]. The excellent cooling performance of microchannel boiling has great application potential in industry, military, aerospace and other fields, such as the cooling of electronic chip, electromagnetic weapons and aerospace avionics components. Moreover, the bubble generated in microscale is also regarded as a kind of efficient drive and control unit in micro-electronic-mechanical-systems (MEMS) [2], and microbubbles have been widely used in thermal inkjet atomizer, micromechanical actuators, microvalve and other MEMS devices. There are a growing number of experimental and numerical studies on two-phase flow and boiling heat transfer in microchannels [3–5].

The bubble behaviors greatly control the two-phase flow process and heat transfer performance in microchannel. Particularly, some unique bubble behaviors occur during flow boiling in microchannel due to the microscale effect caused by the channel size reduction, one of them is the bubble confinement and elongation in microchannel. The growing bubble will be confined by microchannel wall before its departure and then elongates along the axial direction of the channel, resulting in the confined bubbly flow and elongated bubble flow which induce the different heat transfer features from that in macrochannel. Some heat transfer models [6–8] were proposed based on the motion of confined and elongated bubble to predict the heat transfer coefficient in microchannel flow boiling.

The study on bubble behaviors is the key to fully understanding the boiling phenomena in microchannel. The bubble growth characteristics in microchannel are different from that in conventional channel due to the confinement effect of the miniaturized channel cross-section. Edel and Mukherjee [9] experimentally studied the vapor bubble growth during flow boiling in a single brass microchannel of 25 mm length, 201 μm width, and 266 μm depth using water as working fluid. Vapor bubble growth rate increased with increasing wall superheat, and an upstream progress of the Onset of Bubble Elongation (OBE) was observed that began at the channel exit and progressed upstream. Mukherjee et al. [10] studied the bubble growth during flow boiling in a microchannel using numerical method, and found that the liquid vapor surface tension value has little influence on bubble growth. Wang and Sefiane [11]

* Corresponding author at: Institute of Thermal Engineering, School of Mechanical, Electronic and Control Engineering, Beijing Jiaotong University, Beijing 100044, China. Tel.: +86 (10)51684321.
E-mail address: ljia@bjtu.edu.cn (L. Jia).

http://dx.doi.org/10.1016/j.expthermflusci.2015.12.016
0894-1777/

Nomenclature

A_p	projected area of sliding bubble (m^2)
Co	confinement number
C_s	empirical constant
D_{eq}	equivalent bubble diameter (m)
D_h	hydraulic diameter (m)
d_w	bubble contact diameter (m)
F_b	buoyancy force (N)
F_{cp}	contact pressure (N)
F_g	bubble growth force (N)
F_m	evaporation momentum force (N)
F_{qs}	quasi steady-drag force (N)
F_s	surface tension force (N)
H_b	bubble height (m)
L_b	bubble length (m)
R_b	bubble radius (m)
r_r	curvature radius at reference point (m)
q_w	heat flux (W/m^2)
t	time (s)
W_c	channel width (m)

Abbreviations

OCC	onset of channel confinement
FCC	fully confinement by channel cross section

Greek letters

α	maximal local void fraction
β	bubble aspect ratio
ε	heat loss ratio
θ_r	root contact angle (°)
θ_t	top contact angle (°)
ρ_l	liquid density (kg/m^3)
σ_{lv}	surface tension coefficient (N/m)

investigated the single vapor bubble growth and heat transfer mechanism during flow boiling in a high aspect ratio mini-channel. They found that bubble size grew linearly after nucleation, and then the bubble growth turned into exponential from a critical time. The critical time decreased with increasing heat flux and decreasing mass flux. Recently, Yin et al. [12] studied the bubble confined growth and elongation during flow boiling in a rectangular microchannel with 667 μm hydraulic diameter using DI water, and it was found that the bubble growth rate in free growth period was far less than that in confined growth period, and the bubble growth rate decreased with bubble size before confinement but increased with the elongated bubble length. Tibiriçá and Ribatski [13] conducted the flow boiling experiment in a 0.4 mm circular horizontal channel using R134a and R245fa refrigerants as working fluid and found that the bubble growth process had a square root time-dependence.

It is generally inevitable that a growing bubble during flow boiling in microchannel will be confined by channel cross-section. The bubble confinement and elongation are investigated by many researchers in recent years because of the significant role of bubble behaviors. Kenning et al. [14] studied the complete growth process of a vapor bubble in a capillary tube filled with uniformly superheated water, and two growth stages were distinguished, i.e. the unconfined growth stage and the confined growth stage. However, these two stages were differentiated only by whether or not the bubble occupied the tube cross-section, so the confined bubble in their study was actually the elongated bubble in fact. The elongation rate of bubble in tube axial direction was measured, and the gradual transition of bubble from unconfined to confined growth was not taken into account in their work. Barber et al. [15] investigated the effect of channel confinement on bubble growth during a refrigerant FC-72 flow boiling in a single microchannel. The free and confined growth of a vapor bubble in microchannel flow boiling were observed, and the periodic pressure fluctuations were caused by bubble dynamics and instances of vapor blockage during confined bubble growth in the microchannel. Wang et al. [11,16,17] conducted a series of experiments to investigate the confined bubble dynamics and the effects on pressure and heat transfer during flow boiling in a high-aspect ratio microchannel. The bubble growth and bubble geometry were captured and analyzed with the aid of a high speed camera. Due to the effect of confinement, the bubble aspect ratio first maintained at 1 and then dropped drastically when the bubble width was approaching the channel width. The evolution of bubble aspect ratio increased with applied heat flux and decreased with the mass flux. In addition, Wang and Sefiane [18] also experimentally studied the bubble confined in microscale space without liquid flow using degassed pentane and FC-72, and the microscale space was a gap between superheated parallel plates with spacing of 114 μm and 250 μm respectively. They found that bubble growth rate increased with higher plate superheating and wider plate gap.

The bubble dynamics have significant effects on the heat transfer performance in microchannel flow boiling, and the bubble confinement and elongation behaviors are the key aspects of bubble dynamics. From the above literature review, it can be noticed that many investigations have been made to study the growth characteristics of confined bubble and elongated bubble, but how the bubble gradually transforms from the unconfined growth state to confined growth state is not fully understood, and the confined characteristics of bubble in microscale remains elusive and indescribable. As Kenning et al. pointed out in [14], the process of bubble growth from nucleation to confinement requires more detailed study. Therefore, the confined characteristics of bubble growth during boiling in microchannel were studied in present work, and as a preliminary study the liquid in microchannel was not allowed to flow along the channel during bubble growth. The elimination of the effects of liquid flow on the bubble growth helps to understand the mechanisms of bubble confinement in microchannel and to obtain the most essential characteristics of bubble confined growth. Two bubble shape parameters, namely the maximal local void fraction of bubble and the bubble aspect ratio, as well as the bubble contact angle, were suggested and mainly concerned during bubble growth in microchannel. Moreover, the effects of heat flux and channel size on the bubble confined growth were studied.

2. Description of the experiment

2.1. Experimental flow loop

The flow loop consisted of a syringe pump, a 7-μm particle filter, a microchannel test section and a beaker (see Fig. 1). The degassed DI water was injected into the flow loop by a syringe pump at a constant flow rate. The particle filter was located after the syringe pump to remove any particles which may block the microchannel. A T-type thermocouple (TC) was placed before the