International Journal of Heat and Mass Transfer 98 (2016) 114–123

Contents lists available at ScienceDirect

International Journal of Heat and Mass Transfer

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

Confined bubble growth and heat transfer characteristics during flow boiling in microchannel

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ARTICLE INFO

Article history:
Received 9 October 2015
Received in revised form 20 February 2016
Accepted 20 February 2016

Keywords:
Confined bubble
Bubble growth
Heat transfer
Flow boiling
Microchannel

ABSTRACT

Bubble behaviors are closely related to the heat transfer performance during flow boiling in microchannel, however, the effect of channel cross-section decreasing on the bubble growth is still not fully understood at present. In this work, an experimental investigation is conducted to investigate the bubble growth characteristics during flow boiling in a single microchannel with 0.5 mm × 1 mm rectangular cross-section, and the heat transfer performance of flow boiling and its influencing factors are studied. Experiments are conducted with subcooled deionized water and the bubble behaviors are visualized by a high speed CCD camera installed upon the test section. Depending on the heat flux, different growth features are observed in the bubble growth process. Two kinds of bubble growth model are identified: the power law model in initial growth period and the linear law model in later period. The confinement effect of the microchannel is deemed as the mechanism causing the alteration of bubble growth models during its growth process. The deformation features of confined bubble are discussed to illustrate the intensification of evaporation on the liquid–vapor (LV) interface at bubble root, which increases the growth rate of bubble in its confined growth period as well as the heat transfer capability of bubble. Therefore, the maximum local heat transfer coefficient along the channel is found in the region where confined bubble and/or short elongated bubble flow pattern are dominant. Moreover, the heat flux is found to have great influence on the overall heat transfer performance of flow boiling in microchannel, but the effect of mass flux is much less.

1. Introduction

In recent decades, with the extensive application of the MEMS processing technology and the rapid development of the electronic packaging technologies, the high/ultra-high power density generated in the electronic components and devices in various high-tech fields, such as in military, space, and automotive applications, is seriously threatening the safe and reliable operation of the equipment [1,2]. Flow boiling in mini/micro-channel provides the promising and effective method to dissipate high heat flux while maintaining the surface at a reasonable temperature [3,4], hence the researches on the topic of microscale boiling are currently attracting more attention throughout the world [5–7]. Significant effort has been made in understanding the bubble dynamics [8–10], flow pattern transition [11–13] and heat transfer mechanisms [14–16] during flow boiling in microchannel. However, the intrinsic connection between the bubble behaviors and the heat transfer characteristics during flow boiling in microchannel is still not well-understood, hindering their better application in practice. The reduction of the channel dimension will affect the bubble behaviors as well as the heat transfer characteristics during flow boiling.

Many authors have investigated the distinguished bubble behaviors in microchannel flow boiling [17–21]. In particular, Bogojevic et al. [22] studied the bubble dynamics during flow boiling in parallel rectangular microchannels using deionized water (DI water) as the working fluid, and results of the experimental investigation demonstrated that the bubble growth rate in microchannels is different from that in macroscale channels. Three stages of spherical bubble growth were observed and bubble growth was found to accelerate as the bubble reached the superheated liquid near channel walls.

In fact, the main representation of the unique bubble behaviors in microchannel is the appearance of the confined and elongated bubbles which is deemed as one of the main reasons for the outstanding heat transfer performance in microchannel flow boiling

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http://dx.doi.org/10.1016/j.ijheatmasstransfer.2016.02.063
0017-9310/

Nomenclature

A_p	projected area of bubble [m^2]
A_w	wetted area of microchannel [m^2]
C_{pl}	specific heat at constant pressure [J/kg K]
C_s	empirical constant
D	bubble diameter [m]
D_{eq}	bubble equivalent diameter [m]
G	mass flux [kg/m^2 s]
h_{ave}	average heat transfer coefficient [W/m^2 K]
h_l	specific enthalpy of liquid [J/kg]
h_{fg}	latent heat of vaporization [J/kg]
h_z	local heat transfer coefficient [W/m^2 K]
H_b	bubble height [m]
H_{ch}	channel height [m]
k	empirical constant
k_s	solid thermal conductivity [W/m K]
L_b	bubble length [m]
L_{ch}	channel length [m]
L_{sub}	length of subcooled region [m]
M	parameter for pin efficiency
N	empirical constant
q_w	wall heat flux [W/m^2]
Q_{eff}	effective heat [W]
Q_{input}	input power [W]
Q_{loss}	heat loss [W]
t	time [s]
T_{tci}	temperature by thermocouples [K]
T_f	fluid temperature [K]
T_{sat}	saturation temperature [K]
T_w	wall temperature [K]
W_{ch}	channel width [m]
x_e	thermodynamic equilibrium quality
Z	distance [m]

Greek letters

α	maximal local void fraction
β	bubble aspect ratio
η	fin efficiency

and correspondingly attracts extensive investigation recently. Mukherjee and Kandlikar [23] numerically analyzed the growth of a vapor bubble during flow boiling of water in a square cross-section microchannel, and the results showed that steady initial bubble growth followed by a rapid axial expansion after the bubble filled the channel with a thin liquid film around it. The bubble then rapidly turned into a plug and filled up the entire channel. A trapped liquid layer was observed between the elongated bubble and the channel as the elongated bubble grew. Gedupudi et al. [24] proposed a simple 1-D model for bubble growth in a single microchannel based on the experimental observations, and two stages of partially and fully confined bubble growth in the channel of rectangular cross-section were considered. The model was subsequently tested by performing the 3-D numerical simulation of bubble growth from nucleation to full confinement in Zu et al. [25] study. The predictions of the model were in satisfactory agreement with the experimental observation of the distorted profile of the bubble during partially and fully confined growth. Barber et al. [10,26] investigated the effect of channel confinement on bubble growth in a single microchannel geometry with refrigerant as working fluid. Three main stages of bubble growth were observed, namely unconfined bubble growth, partial bubble confinement, and full bubble confinement. The confined growth of vapor bubbles in the microchannel led to instances of channel vapor blockage and resulted in sharp pressure fluctuations at both the microchannel inlet and outlet, which was hence regarded to take main responsibility for the instability in microchannel flow boiling. Wang and Sefiane [27,28] conducted a series of experiments to investigate the confined bubble behaviors in microscale space. The evolution of bubble geometry during growth process was obtained with visualization method. The bubble equivalent radius was found to increase linearly till a critical time, beyond which the growth turned into exponential, and the critical time was affected by heat flux and mass flux conditions. More recently, Yin et al. [29,30] experimentally studied the bubble confinement behaviors in microchannel. Two bubble shape parameters, maximal local void fraction and bubble aspect ratio, were used to describe the bubble deformation features and to reveal the onset of channel confinement during bubble growth process. It was deemed that the bubble confined growth started before the bubble filled the entire cross-section of microchannel, and the periodically fluctuated change of bubble shape was observed during bubble confined growth.

The flow pattern in microchannel is the composite result of bubble behaviors during flow boiling, which directly determines the heat dissipation capability. Various heat transfer mechanisms were proposed based on the different flow patterns observed in microchannel [16,31–34]. With the minimization of channel cross-section, the effect of the gravity force decreases while the surface tension force becomes dominant. Combining with the confinement effect of the microchannel on the bubble growth, unique flow pattern features and heat transfer characteristics are enforced. Chen and Garimella [35] conducted a high-speed visualization and heat transfer measurement experiment on the flow boiling in a silicon microchannel heat sink using dielectric fluid, and four dominant flow patterns were observed with the heat flux increase, namely the bubbly flow, vapor slug flow, wispy-annular flow and churn flow. Correspondingly, the heat transfer coefficient varied with the transition of the dominant flow pattern. Huh and Kim [36] experimentally investigated the characteristics of flow boiling of water in a single horizontal rectangular microchannel. The experimental local boiling heat transfer coefficients was evaluated and studied with the simultaneous visualization of flow patterns. It was found that the boiling flow in the microchannel is characterized by the fast and long elongated slug bubbles grown from single bubbles, and most conventional correlations do not provide reliable heat transfer coefficient predictions. Harirchian and Garimella [11,37] conducted experiments with FC-77 to investigate the microchannel flow boiling regimes and the heat transfer characteristics in different test pieces of varying channel size. Five flow regimes (bubbly, slug, churn, wispy-annular, and annular flow), were generally identified, and the confinement effects in microchannels were found to be very important as they affected the heat transfer mechanisms in flow boiling. Kandlikar [38] claimed that the obviously reduced micro-layer contribution for heat transfer caused the heat dissipation capability to deteriorate due to the thicker films observed under elongated bubbles in flow boiling. Hence avoiding or delaying the formation of elongated bubble flow pattern would be the effective way to improve the heat transfer and CHF in microchannels. Choi et al. [39] experimentally studied water flow boiling respectively in hydrophilic and hydrophobic rectangular microchannels, and it was found that the boiling heat transfer coefficient in the hydrophobic rectangular microchannel was higher than that in the hydrophilic rectangular microchannel, which was caused by the different bubble behaviors and flow patterns in them.