International Journal of Heat and Mass Transfer 116 (2018) 458–470

Contents lists available at ScienceDirect

International Journal of Heat and Mass Transfer

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

Transient film thickness and microscale heat transfer during flow boiling in microchannels

Yanhong Sun [a,b], Chaohong Guo [a,*], Yuyan Jiang [a,*], Tao Wang [a], Lei Zhang [a,b]

[a] Institute of Engineering Thermophysics, Chinese Academy of Sciences, No. 11, Beisihuanxi Road, Beijing 100190, People's Republic of China
[b] University of Chinese Academy of Sciences, Beijing 100049, People's Republic of China

ARTICLE INFO

Article history:
Received 15 May 2017
Received in revised form 8 September 2017
Accepted 9 September 2017

Keywords:
Microchannel
Liquid film thickness
Heat transfer
Flow boiling

ABSTRACT

The underlying mechanism of heat transfer for several sub-processes that control a bubble growth cycle during flow boiling in microchannels is studied in this article by means of high frequency measurements of liquid film thickness and temperature accompanying synchronous visualization. The test section is made up of glass tube having an internal diameter of 0.94 mm with the Indium Tin Oxide (ITO) electrically conductive layer as heaters. The initial liquid film thickness formed by a boiling bubble slug agreed well with Taylor's law. For most cases of the liquid film thickness evolution, the thinning of the liquid film was found to be much quicker than the prediction when considering evaporation effect alone. A new model for predicting the liquid film thickness evolution under flow boiling condition was developed by inclusion of the combination effect of evaporation and shear stress. It was found that the sub-processes of a bubble growth cycle were dependent on heat flux. The cyclical fluctuation of the temperature was due to the different heat transfer capability of the sub-processes. The time ratio and relative importance of the different heat transfer mechanisms were quantitatively estimated by linking the transient temperature fluctuations with the liquid film thickness variations.

1. Introduction

Flow boiling in microchannels has been utilized for many applications including micro-heat exchangers, miniature thermal control systems, and electronics cooling, etc. [1,2]. It offers specific advantages in enhancement of heat and mass transfer, high surface-to-volume ratios, and it also has the potential to minimize temperature variations over the device, and to increase the overall energy efficiency of large-scale cooling systems [3,4]. In view of these strengths, researchers have conducted many studies on flow boiling in microchannels, including overall trends in heat transfer coefficient, pressure drop, flow pattern, flow instability, critical heat flux as a function of influence parameters (i.e. geometry, heat flux, mass flux, vapor quality, etc.). In spite of the numerous studies on the flow boiling in microchannels, the physical understanding of the processes is still ambiguous [5,6]. For example, there is lack of unified conclusion of the governing heat transfer mechanisms [7,8]. Some researchers have suggested that the nucleate boiling is dominant because the experiment results show that the heat-transfer coefficient only depends on heat flux. While others believe that convection boiling also play a major role as the heat transfer coefficient also depends on mass flux or quality. Most of the descriptions are based on the time averaged or cumulative effect of different sub-processes without detail information of local, transient of temperature or liquid film thickness.

In view of the cyclic passages of liquid slug, elongated bubble and vapor slug during flow boiling in microchannels, it is important to implement transient measurements at a microscale and temporal resolution to look insight into the effect of individual sub-processes within a flow regime [9]. Jagirdar and Lee performed a flow visualization together with local, transient temperature measurement synchronously on a single microchannel [10]. Detailed insights into the effect of various events such as passage of vapor slug, 3-phase contact line, partial-dry-out and liquid slug on transient heat transfer coefficient was analyzed. They concluded that the thin film evaporation is the dominant heat transfer mechanism. Bigham and Moghaddam [8] examined the microscale physics of heat transfer events in flow boiling of FC-72 in a microchannel through a high spatial resolution (40–65 μm) and temporal resolution (50 μs) measurement tools. Flow visualization was conducted simultaneously with temperature and heat flux analysis. Four mechanisms of heat transfer including (1) micro-layer evaporation, (2) interline evaporation, (3) transient conduction, and (4) micro-convection were discussed. Rao and Peles studied the local wall temperature in a flow boiling configuration

* Corresponding authors.
E-mail addresses: guochaohong@iet.cn (C. Guo), yyjiang@iet.cn (Y. Jiang).

http://dx.doi.org/10.1016/j.ijheatmasstransfer.2017.09.027
0017-9310/

Nomenclature

A_B	acceleration (m/s^2)
Bo_a	bond number
C	empirical constant
Ca	capillary number
c_p	specific heat capacity (J/(kg K))
D	diameter (mm)
G	mass flux (kg/m^2 s)
h	heat transfer coefficient (W/m^2 K)
h_{lv}	vaporization latent heat (kJ/kg)
I	electric current (A)
k	thermal conductivity (W/(m K))
L	tube length (m)
P_v	vapor pressure (Pa)
q	effective heat flux (W/m^2)
q_{total}	total heat flux (W/m^2)
R	radius (mm)
Re	Reynolds number
t	time (ms)
T	temperature (K)
t_w	tube wall thickness (μm)
U	velocity (m/s)
V	voltage (V)
We	Weber number
z	axial location (m)

Greek symbols

μ	dynamic viscosity (Pa s)
ρ	density (kg/m^3)
σ	surface tension (N/m)
δ	liquid film thickness (μm)
δ_0	initial liquid film thickness (μm)
κ	curvature
τ	shear stress

Subscripts

B	bubble
l	liquid
i	interface
s	saturation
v	vapor
sub	sub-cooled
sat	saturation
w	wall
in	inner
out	outer
men	mean
f	fluid
Δ	super

by using thin-film thermistors [9]. They measured the surface temperature with high spatial resolution and a temporal resolution in the kHz range with synchronized flow visualization. Transient temperature evolution as a function of different flow patterns, such as bubbly flow, elongated bubble flow, partial wall dryout and critical heat flux were studied.

Insights gained from those above transient studies offer a much strongly substantiated knowledge of various heat transfer mechanisms, they also manifest the importance of thin film evaporation mechanism in heat transfer during flow boiling in microchannel. Thin liquid films play a primary role in heat transfer during flow boiling in microchannel [11,12]. Numerous experimental studies on liquid film thickness measurement in capillary tubes have been performed over the past decades [13]. However, most of them were performed under the isothermal condition when evaporation does not occur [14]. For example, Fairbrother and Stubbs [15] observed that the liquid film deposited on the wall when a wetting viscous liquid is displaced by a gas bubble, they noted that the bubble moved faster than the liquid. Taylor measured the liquid film thickness by comparing the difference between the bubble and mean flow velocity [16]. Bretherton [17] studied the drainage of a capillary at a low velocity both experimentally and theoretically, by using the lubrication approximation and the method of surface deformation of the bubble, he found that $\delta/R = 0.643(3Ca)^{2/3}$. Aussillous and Quere [18] later made a significant contribution to Bretherton's analysis by replacing the bubble nose curvature $\kappa = 1/R$ with $\kappa = 1/(R - \delta_0)$ and the obtained relation for dimensionless liquid film thickness is valid over a wide range of Capillary numbers ($Ca < 1.4$) and commonly referred to as Taylor's Law. He also noted that the Taylor's Law under evaluated the liquid film thickness in the visco-inertial regime. The author introduced the Weber number ($We = \rho_l U_{men}^2 (R - \delta)/\sigma$) to take the inertial effects into account in the viso-inertial regime. Han and Shikazono [19] improved the correlation for prediction of liquid film thickness considering both the visco-inertia and confinement flow regimes. They incorporate Reynolds number, Capillary number and Weber number into the prediction relationship:

$$\frac{\delta}{R} = \frac{1.34Ca^{2/3}}{1 + 3.13Ca^{2/3} + 0.54Ca^{0.672}Re^{0.589} - 0.352We^{0.629}} \tag{1}$$

This correlation extends the capillary number to 0.4 and the Reynolds numbers inferior to 2000. Han and Shikazono [20] also studied the effect of bubble acceleration on the liquid film thickness in micro tubes in order to simulate the effect of evaporation, the correlation will be described below.

In spite of the numerous studies on the liquid film thickness under isothermal conditions [21], very limited information is available for the evaporation condition [22,23]. Han et al. [23] conducted LFDM measurements of flow boiling film but the bubble was seeded by N_2 gas which is somewhat different from the situation in applications. In fact, the physics of bubble nucleation and bubble flush growth that resulting in the liquid film thickness variation are quite complex, and hence calls for detailed investigation. Furthermore, transient liquid film thickness measurement along with the temporal temperature, pressure and flow visualization measurement would further improve our understanding of flow boiling in microchannels. Those detecting techniques could provide the detailed information about the individual sub-processes development for one cycle of flow pattern transition. Therefore, the present study is focused on the synchronous measurement of transient liquid film thickness, temperature, pressure and flow visualization with high frequency during flow boiling of water in microchannels. The purpose of this study is to probe into the mechanism of flow boiling heat transfer and instability in microchannels and to improve the formulation of mechanical heat transfer models.

2. Experiment

2.1. Experimental system

The schematic diagram of the test apparatus is shown in Fig. 1. The experimental apparatus consisted of three major subsystems: a working fluid loop, a flow visualization system, and a data acqui-