International Journal of Heat and Mass Transfer 83 (2015) 200–211

Contents lists available at ScienceDirect

International Journal of Heat and Mass Transfer

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

Observations of bubble shape and confinement in diabatic two-phase flow in a minichannel

Khaled E. Albahloul, D. Keith Hollingsworth *

University of Alabama in Huntsville, Huntsville, AL, USA

ARTICLE INFO

Article history:
Received 26 April 2014
Received in revised form 12 September 2014
Accepted 15 September 2014
Available online 17 December 2014

Keywords:
Two-phase
Sliding bubble
Bubble confinement
Heat transfer enhancement

ABSTRACT

Bubble images were acquired from within the channel for a bubbly gas/liquid flow in large-aspect-ratio minichannel with heat transfer. The purpose of these images is to document measurands that address bubble shape and confinement and to relate these measurands to the heat transfer enhancement. Data were collected under different operation conditions in a laminar flow of Novec 649 in a horizontal rectangular minichannel of 1.29–1.48 mm channel spacing. Air bubbles were injected at either a single point on the lower wall or through a sintered metal plug. Liquid crystal thermography was used to record time-averaged surface temperature data, and a borescope was used to acquire images from a point downstream of the on-coming bubbles. The smallest bubbles were approximately spherical, larger bubbles were asymmetric spheroids, and bubbles that spanned the channel were lozenge-shaped. A relationship between bubble height across the channel and diameter observed in the plane of the channel was demonstrated. Bubbles that spanned the channel had a diameter of at least 1.5 times the channel height. All three bubble shapes displayed an approximately fixed velocity ratio. The velocity scale for this ratio is the liquid velocity, corrected for vapor blockage, at the center of force of the bubble. The mechanisms for heat transfer enhancement in this air/liquid flow are mixing in the liquid phase in the bubble wakes and liquid acceleration due to vapor blockage. We hypothesize that these mechanisms are primarily responsible for the enhancement observed in highly confined vapor/liquid flows where nucleation and microlayer evaporation are present. This hypothesis was supported by a successful correlation that unites the present measurements and data from a flow of naturally nucleated vapor bubbles previously acquired in the same facility.

1. Introduction

The mechanisms by which highly confined bubbly flows enhance heat transfer in channels with dimensions at and below the millimeter scale have been the focus of several studies over the past 20 years. While micron-scale low-aspect-ratio microchannels have received the most attention, high-aspect-ratio millimeter-scale channels can exhibit a larger range of two-phase flow regimes. Perhaps the earliest work which sought to identify and predict the dominant source of the observed heat transfer enhancement in narrow channels was done by Ishibashi and Nishikawa [1] in 1969 and updated by Monde's group (Kusuda et al. [2], Monde et al. [3]). They identified a mixing process in the liquid driven by the passage of the bubble as the dominant heat transfer enhancement mechanism, and they offered a simple and elegant model that treated the process as transient conduction through a semi-infinite liquid phase. Work by our group [4–9] observed that, in a highly subcooled flow in a horizontal (~1.5 mm × 23 mm) channel with a uniform-energy-generation test surface, there were no active nucleation sites downstream of a boiling front formed by small a collection of active sites. This work concluded that bubbles issuing from the boiling front and sliding along the test surface increased the heat transfer far downstream of the front. The temperature of the uniform-generation surface was reduced and all potential nucleation sites downstream of the boiling front were extinguished or eliminated. A modification of the transient liquid-phase mixing mechanism proposed in [1–3] was used to correlate the measured enhancement in heat transfer. This modified model [6,8] introduced the concept of allowing the dimensionless depth of the assumed well-mixed region behind the bubble to be a parameter in the model. The results in [6,8] indicated the well-mixed depth to be a function of measured bubble diameter and bubble passage frequency. In these experiments, diameter was the only observed bubble length scale as bubble height across the channel cross-section could not be observed. Natesh [10], from

---

* Corresponding author.

http://dx.doi.org/10.1016/j.ijheatmasstransfer.2014.09.029
0017-9310/© 2014 Elsevier Ltd. All rights reserved.

Nomenclature

A	area, m^2
C_p	specific heat, J/(kg. °C)
D_h	channel hydraulic diameter, $\equiv 2HW/(H+W)$, mm
D_b	bubble diameter, *mm*
D_{he}	equivalent heated diameter, $\equiv 4H$, mm
F	force, *N*
F_o	fourier number $\equiv \alpha(D_b^2 f_b)$, based on bubble diameter, *dimensionless* $F_o \equiv \frac{\alpha}{D_b^2 f}$
F_o''	fourier number $\equiv \alpha/(D_b H_b F_b)$, based on bubble diameter and height, *dimensionless*
f_b	bubble frequency at the channel centerline, s^{-1}
f_{tot}	bubble frequency across the channel cross-section, s^{-1}
G	liquid mass velocity, kg/(m^2.s)
h	local heat transfer coefficient, *W*/(m^2. °C)
H	channel height, mm
H_b	bubble height, mm
H_b^*	dimensionless bubble height, $\equiv H_b/H$
k	thermal conductivity of liquid, W/(m. °C)
Nu	local Nusselt number, $\equiv h\ D_h/k$, *dimensionless* $Nu(x) \equiv h \cdot D_h/k_l$
Nu_0	theoretical single-phase Nusselt number, *dimensionless*
P_{in}	liquid pressure at the inlet, *atm*
P_{out}	liquid pressure at the outlet, *atm*
Pr	Prandtl number $\equiv \nu/\alpha$; *dimensionless*
Re	Reynolds number, $\equiv u_{l,ave} D_h/\nu$; *dimensionless*
$\dot{q}''_{gen}$	generated internal energy in the wall per unit wetted area, kW/m^2
$\dot{q}'_{loss,top}$	the heat loss per unit streamwise length through the glass, kW/m^2
$\dot{q}''_w$	heat flux from the test surface to the fluid, kW/m^2
T_m	local bulk mean temperature of liquid, °C
T_{in}	liquid inlet temperature, °C
T_{out}	liquid outlet temperature, °C
T_{sat}	local liquid saturation temperature, °C
T_w	local wall temperature, °C
$\Delta T_{sub,in}$	liquid subcooling at the inlet, °C
u_b	bubble velocity, mm/s
u_l	liquid velocity, mm/s
$u_{l,ave}$	average liquid velocity, mm/s
$u_{l,c}$	liquid velocity at channel centerline, mm/s
$u_{l,ave\text{-}corr.}$	average liquid velocity corrected to blockage, mm/s
$u_{l(Hb/2)}$	liquid velocity at the center of the bubble, mm/s
$u_{l(yc)}$	liquid velocity at the center of force, mm/s
$u_{l(yc)corr.}$	liquid velocity at the center of force corrected to blockage, mm/s
$\dot{V}_l$	liquid volume flow rate, (ml/s)
W	channel width, mm
x	coordinate in axial direction, mm
x^*	dimensionless axial position; $\equiv x/(D_h Re Pr)$
y	coordinate in vertical direction, mm
y_c	center of force position, mm
z	coordinate in spanwise direction, mm
Greek	
ρ	liquid density, kg/m^3
α	thermal diffusivity, m^2/s
ν	kinematic viscosity, m^2/s

this group, performed a laminar direct numerical simulation of a sliding gas bubble in the absence of phase change in a minichannel of the dimensions of [4–9] with channel height of 1.25 mm. He assumed a cylindrical bubble shape and forced a 90° contact angle at the upper and lower channel walls. He found a significant heat flux increase in a two-lobe-shaped structure directly behind the bubble and a long temperature depression trailing the bubble. The decay in heat flux with distance behind the bubble was consistent with the model developed in [6,8] when a well-mixed depth across the channel of 40% of the channel height was used in the model. This value is within the range of values (15–50%) found by Ozer [6,8] for naturally nucleated bubbles.

Some studies have addressed the issue of bubble shape in confining channels. Mishima et al. [11] focused their experimental study on two-phase flow in vertical rectangular channels that were 1–5 mm in height with a width of 40 mm. They measured pressure drop, slug bubble velocity, void fraction, and flow regime. Flow regimes were classified based upon bubbles shapes which were observed from the wider channel side, and they noted that bubble shape and behavior was affected by the channel height. No heat transfer measurements were reported. Ajaev and Homsy [12] reviewed the mathematical modeling of confined bubbles in square and rectangular cross section channels. This review focused on the shape and dynamics of bubbles which are comparable in size to the channel cross sections (characteristic diameter ~100 μm) that confine them. Lie and Lin [13] reported an experimental study of the effect of channel size on the heat transfer coefficient and associated bubble characteristics of a subcooled flow of R-134a. The channel was a horizontal narrow annular duct, with a gap dimension of 1 mm and 2 mm. They concluded that the heat transfer coefficient increases with decreasing channel gap and decreases with increasing the inlet subcooling. Bubble departure diameter and bubble frequency were correlated to the observables. Pan et al. [14] compared two-sided and one-sided heating in a narrow vertical channel (2 × 35 mm) based on observations of the onset of nucleate boiling and bubble behavior. Observation of bubbles showed that more and larger bubbles were produced in two-side case.

A number of studies reporting bubble shape have focused on the shape evolution prior to and just after detachment from a nucleation site. Duhar et al. [15] focused their experimental study on bubble growth rate and detachment in a 10 mm × 80 mm rectangular horizontal channel. Bubble radius evolution and bubble growth rate were observed through the 10 mm channel surface. These observations were used to supply data required by a theoretical analysis of the effective vertical forces acting on the bubble during the growth stage and after detachment. This analytical solution was used to predict the bubble diameter at detachment. They observed a spherical shape after detachment and a truncated-sphere shape during the growth stage. This study is limited to small bubbles; $D_b < 0.5$ mm and bubble diameter to channel height of <5%. Other similar studies have also focused on the bubble-formation phase in various forced flows [16–18].

Based on our review of the literature, there are no reported images *taken from within the channel* of bubbles that constitute a developed bubbly flow in large-aspect-ratio minichannels. The purpose of such images would be to observe and document those measurands (beyond the diameter observable in plan-form images) that address bubble shape. Such images and measurements should allow the importance of bubble shape on heat transfer enhancement to be discerned. The current work focuses on a simple experimental model, bubbly air/refrigerant flows without