International Journal of Multiphase Flow 84 (2016) 292–314

Contents lists available at ScienceDirect

International Journal of Multiphase Flow

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

Experimental study on bubble dynamics and wall heat transfer arising from a single nucleation site at subcooled flow boiling conditions – Part 2: Data analysis on sliding bubble characteristics and associated wall heat transfer

Junsoo Yoo[a,*], Carlos E. Estrada-Perez[b], Yassin A. Hassan[b,c]

[a] Idaho National Laboratory, 2525 North Fremont Ave., P.O. Box 3860, Idaho Falls, ID 83415-3870, USA
[b] Department of Mechanical Engineering, Texas A&M University, 100 MEOB, College Station, TX 77843-3123, USA
[c] Department of Nuclear Engineering, Texas A&M University, 253 Bizzell West, College Station, TX 77843-3133, USA

ARTICLE INFO

Article history:
Received 24 December 2015
Revised 23 March 2016
Accepted 26 April 2016
Available online 28 April 2016

Keywords:
Subcooled flow boiling
Single nucleation site
Bubble sliding
Bubble coalescence
Sliding bubble velocity
Bubble size distribution
Boiling heat transfer

ABSTRACT

This second of two companion papers presents an analysis of sliding bubble and wall heat transfer parameters measured during subcooled boiling in a square, vertical, upward flow channel. Bubbles were generated only from a single nucleation site for better observation of both the sliding bubble characteristics and their impact on wall heat transfer through optical measurement techniques. Specific interests include: (i) bubbles departure and subsequent growth while sliding, (ii) bubbles release frequency, (iii) coalescence of sliding bubbles, (iv) sliding bubbles velocity, (v) bubbles size distribution and (vi) wall heat transfer influenced by sliding bubbles.

The results showed that sliding bubbles involve two distinct growth behaviors: (i) at low mass fluxes, sliding bubbles grew fast near the nucleation site, subsequently shrank, and then grew again, (ii) as mass flux increased, however, sliding bubbles grew more steadily. The bubbles originating from the single nucleation site coalesced frequently while sliding, which showed close relation with bubbles release frequency. The sliding bubble velocity near the nucleation site consistently decreased by increasing mass flux, while the observation often became reversed as the bubbles slid downstream due to the effect of interfacial drag. The sliding bubbles moved faster than the local liquid (*i.e.*, $u_r < 0$) at low mass flux conditions, but it became reversed as the mass flux increased. The size distribution of sliding bubbles followed Gaussian distribution well both near and far from the nucleation site. The standard deviation of bubble size varied insignificantly through sliding compared to the changes in mean bubble size.

Lastly, the sliding bubbles enhanced the wall heat transfer and the effect became more noticeable as inlet subcooling/mass flux decreased or wall heat flux increased. In particular, the sliding bubble characteristics such as bubble growth behavior observed near the nucleation site played a dominant role in determining the ultimate level of wall heat transfer enhancement within the test channel.

1. Introduction

The enhancement in wall heat transfer caused by boiling and its underlying mechanism has been a topic of great interest within heat transfer community over the last decades. In particular, forced convective boiling, the focus of this paper, is frequently encountered in various industrial applications such as cooling channels and evaporators of engineered systems. However, the mechanism of enhancing wall heat transfer due to the boiling bubbles is yet to be fully understood, and achieving accurate prediction of the process still remains a challenge due to the lack of knowledge about the basic principles.

Recently, advances in computing power and high-speed visualization techniques have made it possible to investigate more detailed features of two-phase flow during boiling process. Consequently, experimental efforts have recently been made to observe fundamental features of boiling which could hardly be captured before. This has opened up the possibility of utilizing mechanistic models which are expected to have more generality in application than previous empirical correlations. Among others, Kurul and Podowski's (1990) model has been one of the most used until recently to mechanistically treat the wall nucleation process. This model basically employed the wall heat flux partitioning

* Corresponding author.
E-mail address: kaks2000@gmail.com (J. Yoo).

http://dx.doi.org/10.1016/j.ijmultiphaseflow.2016.04.019
0301-9322/

concept of Bowring (1962), in which three subcomponents are included to represent the total wall heat flux (q_w): single-phase convection ($q_{1\emptyset}$), quenching (or transient conduction, q_Q), and evaporation (q_e). Kurul and Podowski (1990) used q_Q as defined in Delvalle and Kenning (1985) while q_e is calculated by the relation given by Bowring (1962). In order for this mechanistic model to possess high confidence in its predictive ability, the fundamental bubble parameters (or wall nucleation parameters) used to calculate each subcomponent should be well-defined, and this is where experimental insight is required. In general, the bubble departure/lift-off diameter (Chu et al., 2011; Klausner et al., 1993; Situ et al., 2005), bubble departure frequency (Euh et al., 2010; Situ et al., 2008), and active nucleation site density (Hibiki and Ishii, 2003) are the parameters commonly used to determine the wall heat flux components q_e and q_Q. However, Kurul and Podowski's (1990) model covers only the boiling process at a nucleation site. To properly address the effect of vapor bubbles in forced convective boiling, the bubble and wall heat transfer characteristics beyond a nucleation site must be figured out and modeled as well.

Compared to the researches on bubble behaviors at a nucleation site (*e.g.*, nucleation, bubble growth and departure), bubble behavior after departure from a nucleation site such as bubble sliding have been relatively less explored in experimental studies of forced convective boiling to date. Nevertheless, several authors have reported that such bubble motion can substantially influence wall heat transfer characteristics in flow boiling system. Cornwell (1990) measured the wall heat transfer of the forced convective boiling of R-113 in a tube bundle. He supposed that the total heat transfer is determined by three mechanisms: liquid forced convection, nucleation, and sliding bubbles. The relative significance of each mechanism depended on heat flux conditions as well as locations within the tube. Cornwell (1990) argues that, in the presence of bubbly flow, the sliding bubbles downstream in the tube contributed significantly to the wall heat transfer. Thorncroft et al. (1998) observed a significant difference in bubble dynamics between the boiling experiments of vertical upward and downward flows. In upward flows, the bubbles departing from the nucleation site typically slid along the heater without lift-off; whereas, in downward flows, the bubbles lifted off directly from the nucleation site or lifted off after sliding. From the observation of larger heat transfer coefficients for upward flow compared to those for downward flow under identical experimental conditions, Thorncroft et al. (1998) deduced that such increases in wall heat transfer for the upward flow result from the bubble sliding behavior. Regarding this, further experimental evidence was provided by Thorncroft and Klausner (1999), in which the turbulence enhancement of the bulk liquid was considered the main mechanism for the increase in wall heat transfer caused by sliding bubbles. A similar observation was also made by Houston and Cornwell (1996); they argued that the effect of increasing turbulence caused by sliding bubbles is more significant within a narrow channel than in an ordinary sized channel.

The above mentioned studies revealed the significance of sliding bubble motion on wall heat transfer in a forced convective boiling system and have subsequently inspired further research employing high-speed visualization techniques. Okawa et al. (2005) observed the rise characteristics of bubbles after departure from a nucleation site in a vertical upward subcooled flow boiling tube. Three different bubble rise characteristics were observed, which included (i) bubbles sliding for a long distance, (ii) bubbles lifting-off from the heater surface after sliding a few millimeters, and (iii) bubbles lifting off but subsequently reattaching to the heater surface. Okawa et al. (2005) proposed that the bubble lift-off is mainly attributable to the bubble shape deformation. Yuan et al. (2011) studied the effects of pressure on bubble dynamics during a subcooled flow boiling experiment in a vertical rectangular narrow channel. The bubble behavior captured by a high-speed camera (HSC) showed that pressure had a significant effect on bubble growth, lift-off, and sliding. Under lower pressure, bubbles growing at the nucleation site lifted off directly from the heater wall and collapsed without sliding. In contrast, bubbles under higher pressure kept growing while sliding along the heater wall even after the bubbles left (or departed from) the nucleation site. They also found that sliding bubble velocity as well as sliding distance was significantly affected by the bubble growth rate while sliding. Xu et al. (2013) observed sliding bubble dynamics in the vertical upward flow of a narrow channel. Several sliding bubble parameters such as bubble shape, bubble growth, and bubble velocity after departing from the nucleation site, were investigated. They found that the contact angles of the bubbles hardly changed during the sliding motion, and the sliding bubble velocity showed a proportional relation to the bubble diameter and liquid flow rate. Similarly, Li et al. (2013) investigated the bubble sliding behavior in subcooled boiling flow in a vertical narrow channel. The parameters of main interest were the bubble number, bubble size, and sliding bubble velocity. In particular, they studied both the mean and the statistical distribution of such parameters under different experimental conditions. According to them, the bubble size distribution depended significantly on the inlet subcooling and was less affected by the wall heat flux. They also found that the distribution of the sliding bubble velocity followed the normal distribution and the mean velocity increased when the inlet subcooling decreased.

However, despite the above-mentioned efforts, the experimental insight into sliding bubble characteristics in subcooled boiling flow are still lacking, and the mechanism of enhancing wall heat transfer due to sliding bubbles is not understood well. In this respect, we investigated sliding bubbles behavior and their impact on wall heat transfer through subcooled flow boiling experiments. In particular, to better understand the underlying physics, bubbles behavior arising from a single nucleation site was observed with both micro- and macro-scopic views from high-speed cameras while the heater surface temperature was measured with an infrared (IR) camera. Also, the images were taken strategically to ensure reliable statistics of the measured data. Details of the experimental strategy, image acquisition/analysis, data quality achieved, and associated uncertainty are described in Part 1 paper.

This second of two companion papers presents an analysis of bubble and wall heat transfer parameters measurement during the present work. In most cases, bubbles departing from the single nucleation site slid along the heater surface until they exit the test section except for a moment of bouncing just after the departure. Also, the thermal data taken by IR camera revealed that such sliding bubbles originating from the single nucleation site caused a significant increase in wall heat transfer compared to the single-phase forced convection. For a deeper insight into the mechanism, we observed the sliding bubble characteristics in various aspects. In particular, the effects of liquid subcooling, mass flux and wall heat flux on such characteristics were extensively investigated, and then the experimental evidence associated with the enhanced wall heat transfer due to sliding vapor bubbles is discussed.

2. Experimental setup, test conditions, and research scope

2.1. Flow boiling loop, test section design and cameras arrangement

The present subcooled flow boiling experiment was performed in a vertical, square, upward flow channel at atmospheric pressure. As working fluid, HFE-301 (Novec^{TM} 7000, 3M Inc.) was used, the