International Journal of Heat and Mass Transfer 76 (2014) 568–584

Contents lists available at ScienceDirect

International Journal of Heat and Mass Transfer

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

A proper observation and characterization of wall nucleation phenomena in a forced convective boiling system

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ARTICLE INFO

Article history:
Received 18 February 2014
Received in revised form 24 April 2014
Accepted 25 April 2014
Available online 2 June 2014

Keywords:
Wall nucleation
Bubble departure diameter
Bubble departure frequency
Subcooled boiling flow

ABSTRACT

Experimental information regarding fundamental bubble parameters such as bubble departure diameter and bubble departure frequency is crucial for the development and validation of mechanistic models to treat the wall nucleation phenomena in a forced convective boiling system. However, a thorough review of the literature reveals that there are several unidentified issues in the previous experimental works, issues which have never been explicitly addressed despite their possibly critical impact on the experimental results. Also, the experimental efforts are still being made without properly addressing the impact of those issues. Thus, in an effort to reveal such issues and to verify the errors created by not addressing them, we performed a series of systematic experimental investigations to evaluate the impacts of these issues and to subsequently make recommendations.

The explored issues include (i) the effect of different measurement views on the observation of the nucleating bubbles; (ii) the effect of applying different visualization recording speeds; and (iii) the effect of the number of experimental observations (i.e., sample size) on the statistics of measured bubble parameters. Then, based on the findings, more appropriate ways of observing and characterizing the fundamental bubble parameters were discussed.

Additionally, an image analysis method was developed to efficiently and accurately extract the quantitative information of fundamental bubble parameters from the experimental images of boiling bubbles. The performance of this method was tested in subcooled boiling flow circumstances, and it seems promising as a means of analyzing the vast number of images required to satisfy the high statistical demands to characterize wall nucleation features. The experimental findings and discussions in the present study will provide valuable guidance towards the proper investigation of the wall nucleation phenomena in a subcooled flow boiling system or, more generally, in a forced convective boiling system.

1. Introduction

Much attention has been paid to the efficient heat transfer mode of forced convective boiling due to its promising future for engineering applications, such as the cooling systems of nuclear reactors, electronic and propulsion devices. However, the physical mechanism involved in boiling is yet to be fully understood because its inherent nature is quite complicated, while the advances in experimental and analytical techniques to investigate the specifics of it are relatively limited. Nevertheless, in recent decades, many efforts to combine the rapidly advancing experimental achievements and mathematical tools to analyze the complex flow behaviors have led to substantial progress in understanding the two-phase flow system. As an effort to analyze or predict the detailed two-phase flow behaviors, the two-fluid (time-averaged) model—which handles the transient behaviors of two different phases separately—has been widely used. However, since the actual behaviors of each phase are not independent of each other, the interaction terms, called the interfacial transfer terms, play an important role under this two-fluid model framework because those terms control the local mass, momentum, and energy transfer between phases. As a result, the performance of two-fluid model depends heavily on the validity of the interfacial transfer terms which need to be well defined based on experimental information. In particular, for subcooled and saturated boiling flow, bubble nucleation at the heated wall (i.e., wall nucleation) is one such important piece of information needed from experiments because it is the main mechanism of enhancing the local heat transfer through the increase of interfacial area, the large evaporative heat transfer, and interactions between the liquid and

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http://dx.doi.org/10.1016/j.ijheatmasstransfer.2014.04.063
0017-9310/

vapor phase [1,2]. The bubble nucleation parameters usually considered in mechanistic models are (i) bubble departure and lift-off diameter, (ii) bubble departure frequency, and (iii) active nucleation site density. Thus, detailed experimental data about these fundamental bubble parameters are crucial to accurately predict the wall nucleation phenomena, and many experimental works have been performed in this context.

Klausner et al. [3] measured the bubble departure diameter in a horizontal forced convective boiling facility using saturated R-113. They found that asymmetric bubble growth and surface tension force are important to hold the bubble at the nucleation site before departure. In particular, the bubble departure and lift-off were conceptually distinguished in their work: Bubble departure was defined as the moment when the bubble leaves the nucleation site, while bubble lift-off indicated the moment when bubble is detached from the heated wall. In their experiments, vapor bubbles typically left the nucleation sites by sliding a finite distance along the heater rather than directly lifting off the wall. Subsequently, Zeng et al. [4] obtained additional data sets for the bubble lift-off diameter using the same facility. Zeng et al. suggested a prediction model for bubble departure and bubble lift-off diameter in which the bubble inclination angle is estimated as part of the dynamic solution instead of being used as an empirical constant. Also, they argue that the prediction model can be applied to the vertical boiling flow with proper modifications. Nucleation site density was measured in the same experimental facility, revealing the strong dependence of nucleation site density on the vapor velocity, heat flux, system pressure, and cavity size [5]. Using FC-87, Thorncroft et al. [6] studied the bubble growth and detachment process for the vertical upflow and downflow boiling. The data were collected under slightly subcooled boiling conditions (ΔT_{sub} = 1–5 K), and significant differences in bubble behaviors were observed between the upflow and downflow tests. Prodanovic et al. [7] investigated the bubble size, bubble life time, bubble growth time, and bubble condensation time for the subcooled boiling flow of water in a vertical upward annulus channel. Based on the measured data, Proanovic et al. suggested semi-empirical correlations to predict variations in bubble size and life time. Situ et al. [8] measured the bubble lift-off diameter in a vertical upward annulus channel. They obtained the bubble lift-off diameter for 91 test conditions at atmospheric pressure. Based on the data collected, a non-dimensional prediction model for the bubble lift-off diameter was proposed; the proposed model fit their experimental data with a relative error of ±35.2%. Later, Situ et al. [9] measured the bubble departure frequency in the same facility. They compared the existing models and correlations to the existing experimental data in the literature as well as to their own data. Then, an empirical correlation that correlates the dimensionless bubble departure frequency and the non-dimensional nucleate boiling heat flux was derived; the average prediction error was revealed as ±113%. Using a test section geometry similar to Situ et al. [8,9], Euh et al. [10] measured the bubble departure frequency under various subcooled boiling conditions of water. They argued that mass flux, heat flux, subcooling, and pressure are the major parameters affecting the bubble departure frequency. Euh et al.'s experimental data were compared with the existing models, and they proposed a new prediction model by modifying Situ et al.'s model [9]. Chu et al. [11] observed the bubble lift-off diameter as well as the bubble nucleation frequency in a vertical annulus test section through which water flowed upward under various subcooled boiling conditions. They investigated the bubble lift-off diameter as well as bubble nucleation frequency depending on heat flux, mass flux, and subcooling degree. Note that in Chu et al.'s work, the mean values of bubble parameters measured were estimated by averaging the measured values over the several nucleation sites under each experimental condition. This was to avoid the biased result of bubble characteristics induced by the specific microstructure of individual nucleation sites. Recently, Brooks et al. [12] measured bubble departure frequency, departure diameter, and several bulk flow parameters, e.g., void fraction and interfacial area concentration, for the subcooled boiling conditions of water in a vertical annulus channel. The bubble parameters measured were compared with the existing models, and the modeling of wall nucleation source terms in the interfacial area transport equation [2] was discussed based on the result.

In addition to the experimental and modeling works described above, many efforts have been made by various researchers to better understand and predict the wall nucleation phenomena under various forced convective boiling conditions, and those efforts are still ongoing. However, considerable variation and inconsistency still exist among the experimental investigations, even under similar test conditions. These differences often hinder progress toward better insight into the underlying physics of wall nucleation phenomena. This is mainly due to the inherently chaotic nature of the boiling mechanism, indicating that the experimental results are quite sensitive to many variables such as heater wall surface condition and flow boundary condition. In addition, substantial errors and measurement uncertainties may occur due to limitations of the imaging techniques used to observe the nucleating bubbles. Specifically, optical distortions, limited resolution, and difficulty in the analysis of images crowded with bubbles at high heat flux conditions are important issues to be considered for the accurate measurement of fundamental bubble parameters. Also, the specific strategy of visualization by experimentalist and the obtained quality of bubble image can affect the measurement results. Moreover, due to the normally strong stochastic features of boiling process [3,4,13–15], a limited number of experimental observations may not represent the boiling characteristics and the parametric effect properly. For instance, when considering the significant differences in the number of experimental observations used by different researchers (Table 1), the question of whether or not the sample number used was truly representative of the measured parameter under the given experimental conditions arises. Undoubtedly, if the statistical average at each test condition is not reliable, the uncertainty will increase [16] and the resulting experimental information can be even misleading.

To the best of the authors' knowledge, no efforts have been made to treat the aforementioned issues explicitly, and experimental investigations are still being performed without addressing or quantifying the effects of those issues. However, as will be shown in the following sections, failure to consider those fundamental issues may significantly mislead experimental investigations and subsequently damage the quality of the physical models which are derived based on experimental results. In this context, we first discuss the possible issues existing in the visual measurement of fundamental bubble parameters based on the comparative analysis of experimental studies in the literature (Section 2). Then, in an effort to experimentally verify the individual issues, we performed subcooled flow boiling experiment (Section 3) in which various aspects of measurement issues on the bubble departure diameter and bubble departure and/or nucleation frequency were investigated (Section 4). Lastly, we suggest an image analysis method to more efficiently and accurately extract the quantitative information from the experimental images of boiling bubbles. The validity of this method of analysis is demonstrated in Section 5.

2. Comparative analysis of experimental studies in the literature

Ten different visual experimental studies were reviewed and compared based on items which are expected to have an impact