International Journal of Heat and Mass Transfer 94 (2016) 174–179

Contents lists available at ScienceDirect

International Journal of Heat and Mass Transfer

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

A mechanistic model for predicting the maximum diameter of vapor bubbles in a subcooled boiling flow

Nhan Hien Hoang [a,b], In-Cheol Chu [b], Dong-Jin Euh [a,b], Chul-Hwa Song [a,b,*]

[a] University of Science and Technology, 217 Gajungro, Yuseong-gu, Daejeon, Republic of Korea
[b] Korea Atomic Energy Research Institute, Daedeok-daero 989-111, Yuseong-gu, Daejeon, Republic of Korea

ARTICLE INFO

Article history:
Received 4 August 2015
Received in revised form 17 November 2015
Accepted 17 November 2015
Available online 7 December 2015

Keywords:
Maximum bubble diameter
Subcooled flow boiling
Mechanistic model
Relaxation microlayer

ABSTRACT

Vapor bubbles attached to the heated surface in a subcooled boiling flow usually reach their maximum size during the latter phase of the bubble growth period when the liquid microlayer trapped under them is almost depleted. The heat transfer at the bubble during this phase involves only the transient heat conduction through a so-called relaxation microlayer surrounding the lower bubble surface and the condensation at the bubble dome. On this physical base, a new mechanistic model for predicting the maximum diameter of attached vapor bubbles in a subcooled boiling flow is proposed in this study. The new model is derived from the lumped energy balance for the bubbles. It is then validated using published experimental databases on the maximum bubble diameter measured for subcooled boiling flows of water under a wide range of flow conditions. A good agreement between the predicted maximum bubble diameter and the experimental one is obtained. The average relative error is less than about 35.5%. This model is expectedly worthy of being used in the analysis of subcooled boiling flows.

1. Introduction

Subcooled flow boiling is of great importance to many industrial applications, e.g., nuclear reactors and fossil boilers, in which a large heat transfer rate is required. It directly concerns the performance and safety of the relevant systems. Consequently, the modeling of the subcooled flow boiling is very essential to the design optimization and safe operation of the systems. Nevertheless, attempts to predict the subcooled flow boiling have had limited success, due in large part to the lack of satisfactory models and/or correlations for predicting the phase change heat transfer in the vicinity of the heated surface [1]. In a common mechanistic approach, the near-wall boiling heat transfer is described by a heat flux partitioning model in which models or correlations of the nucleation site density, bubble departure diameter and bubble release frequency are required [2]. However, such a combination of existing models and correlations of this type, according to a thorough assessment conducted by Cheung et al. [3], was unable to provide satisfactory predictions for a wide range of flow conditions. This is due to the complexity of the sub-processes, i.e., heat transfer mechanism, bubble dynamics, bubble nucleation and thermal response of the heated surface, involved in the near-wall boiling heat transfer. Deep knowledge on these sub-processes is, therefore, anticipated to overcome the difficulty encountered.

On the aspect of the bubble dynamics, a characteristic size of vapor bubbles generated on a heated surface needs to be identified for the analysis of the subcooled flow boiling and also the critical heat flux (CHF). To the best of our knowledge, three different types of bubble diameter have been used frequently as the characteristic bubble size. Firstly, the bubble diameter at the departure point where the bubble starts to leave its nucleation site as modeled by Fritz [4], Chang [5], Levy [6], Kocamustagaofullary [7] have been employed broadly in the calculation of void fraction, heat transfer, CHF, or merely to characterize the bubble growth. However, Klausner et al. [8], Situ et al. [9], and Chu et al. [10] later argued that the bubble diameter at the lift-off point where the bubble detaches from the heated surface is more appropriate for the calculation of heat and mass transfer near the heated surface considering the bubble sliding effect. Yun et al. [11] obtained a good CFD prediction for DEBORA experiments using Klausner's model of the bubble lift-off diameter. On the other hand, Ünal [12] claimed that the maximum diameter of the bubbles on the heated surface is closely related to the void fraction and heat transfer rate. Tu and Yeoh [13] also obtained a good CFD prediction for low-pressure subcooled boiling flows using Ünal's model of the maximum bubble diameter. In addition, the maximum bubble diameter as correlated

---

* Corresponding author at: Korea Atomic Energy Research Institute, Daedeok-daero 989-111, Yuseong-gu, Daejeon, Republic of Korea. Tel.: +82 42 868 8876.

E-mail address: chsong@kaeri.re.kr (C.-H. Song).

http://dx.doi.org/10.1016/j.ijheatmasstransfer.2015.11.051
0017-9310/© 2015 Elsevier Ltd. All rights reserved.

Nomenclature

c_p	specific heat capacity
D	diameter
g	gravity accelerator
h	heat transfer coefficient
h_{fg}	latent heat
k	thermal conductivity
m	condensation region dimension
Pr	Prandtl number
p	pressure
q''	heat flux
Re	Reynolds number
T	temperature
t	time
u	velocity

Greek symbols

α	thermal diffusivity
μ	viscosity
ρ	density
ΔT	temperature gradient

Subscripts

b	subcooled
c	condensation
f	fluid
g	gas
h	hydrodynamic
s	saturation
y	location from the surface
w	wall

by Zuber [14], Prodanovic et al. [15], etc., can be used to characterize the growth and collapse of both detaching and sliding bubbles.

Despite intensive studies on the modeling of these bubble diameters, a model or correlation of broad generality has not been obtained yet. In general, three different approaches have been employed to formulate these bubble diameters. The most common approach is to model the bubble departure or lift-off diameter based on an elaborate analysis of forces acting to move a bubble on a heated surface. Such a force analysis is usually rather complicated and difficult to handle owing to the lack of understanding on the role of force elements and criteria by which the bubble will depart or lift off, and to containing many unknown parameters [4–9,16,17]. Another approach is to correlate empirically the bubble departure, lift-off, or maximum diameter with determinable parameters, such as the pressure, superheat, subcooling, and/or heat flux. Such correlations often give a good prediction for their own experimental data, which covers a limited range of flow conditions. Moreover, the effect of some relevant parameters is not clear from a physical aspect [7,10,15]. The other approach is to employ a heat balance analysis to derive the maximum bubble diameter as done by Zuber [14], Ünal [12], and Han and Griffth [18]. The maximum bubble diameter models developed by this approach can characterize both the hydrodynamic and heat transfer aspects of the bubbles [12]. However, a detailed bubble heat transfer structure has not been clearly understood yet.

In conjunction with the energy balance approach, several different bubble heat transfer structures have been proposed. Firstly, Zuber [14] and Chi-Yeh and Griffth [18] supposed that the heat added through a thin superheated liquid layer surrounding the bubble surface, called the relaxation microlayer, is the sole heat source for the bubble growth. Later, Ünal [12] claimed that the heat contribution of the relaxation microlayer is negligible in comparison with that of the conventional (or evaporation) microlayer under the bubble. However, both these microlayer concepts were actually ambiguous because of the lack of experimental evidences. Sernas and Hooper [19] defined five configurations of the microlayer, but without details about the dimensions. According to their analysis, only a “thick microlayer” whose thickness is sufficient to delay the arrival of the temperature wave at the microlayer liquid–heated surface interface until a time later than 500 µs closely matched the measured bubble growth rate. A more reasonable bubble growth model that consists of both the evaporation and relaxation microlayers was suggested by Van Stralen et al. [20].

Recently, the debate on the bubble heat transfer structure can be answered based on the sophisticated experimental investigations of the boiling phenomenon obtained with the aid of advanced techniques, such as a micro-heater array and infrared thermometry [21,22]. According to the intensive review carried out by Kim [21], most of the energy required for bubble growth came from the superheated liquid layer surrounding the lower bubble surface, or the relaxation microlayer. The evaporation microlayer just accounts for less than 25% of the overall heat transfer from the heated surface. The contribution of this microlayer is much smaller, and even negligible, when it becomes depleted during the later phase of the bubble growth. In other words, only the relaxation microlayer covering the lower bubble surface and the subcooled liquid layer surrounding the bubble dome are involved in the bubble heat transfer during this phase. In this study, we adopted this physical base to derive a mechanistic model for the maximum bubble diameter.

2. Modeling of the maximum bubble diameter

To model the maximum bubble diameter, Ünal’s approach [12] was adopted together with the following assumptions.

- Vapor bubbles are approximately spherical when reaching their maximum size, as illustrated in Fig. 1. This is consistent with the experimental observations of the bubble shape presented by Situ et al. [9], Chu et al. [10], Prodanovic et al. [15] and

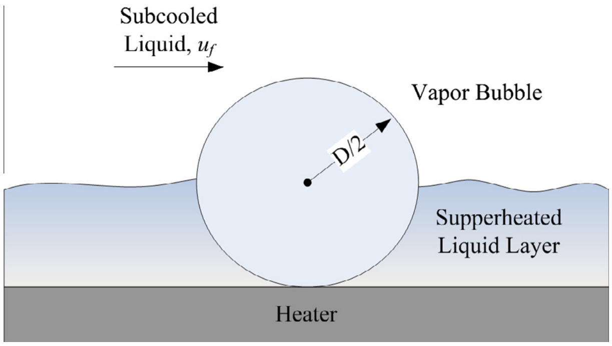

Fig. 1. Bubble heat transfer structure.