International Journal of Thermal Sciences 98 (2015) 42–50

Contents lists available at ScienceDirect

International Journal of Thermal Sciences

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

A parametric study of the heat flux partitioning model for nucleate boiling of nanofluids

Xiangdong Li [a], Yang Yuan [a], Jiyuan Tu [a, b, *]

[a] School of Aerospace, Mechanical and Manufacturing Engineering, RMIT University, PO Box 71, Bundoora, VIC, 3083, Australia
[b] Key Laboratory of Ministry of Education for Advanced Reactor Engineering and Safety, Institute of Nuclear and New Energy Technology, Tsinghua University, PO Box 1021, Beijing, 100086, China

ARTICLE INFO

Article history:
Received 5 November 2014
Received in revised form
26 May 2015
Accepted 29 June 2015
Available online 26 July 2015

Keywords:
Nanofluids
Nucleate boiling
Heat flux partitioning
Nanoparticle deposition
Surface modifications

ABSTRACT

The dramatic boiling heat transfer performances of nanofluids have been widely attributed to the nanoparticle deposition during the boiling process. The deposited nanoparticles significantly change the microstructures and properties of the heater surface, and hence alter the characteristics of bubble nucleation and departure. Therefore, it is crucial to take into account the effects of nanoparticle deposition when modeling nucleate boiling of nanofluids using the heat flux partitioning (HFP) model (Kurul N., Podowski M.Z., 1990) [1]. In this study, new closure correlations were incorporated for the nucleate boiling parameters including the active site density, the bubble departure diameter and frequency. Parametric studies were performed through 2-D computations to analyze the effects of surface wettability enhancement, the nanoparticle material and size, respectively. The results demonstrated that through appropriate considering the modifications induced by nanoparticle deposition, the HFP model achieved a satisfactory agreement with the experimental data available in the literature, and provided a more feasible and mechanistic approach than the classic Rohsenow correlation for predicting nucleate pool boiling of nanofluids.

1. Introduction

As a new type of engineered fluids, nanofluids have gained an increasing attention due to their enhanced properties associated with heat transfer [2]. Since 2003 when Das et al. [3] and You et al. [4] pioneered the studies on boiling of nanofluids, an exponentially increasing number of analogous investigations have been conducted with the aim to reveal the mechanisms underlying the dramatic heat transfer performances and novel phenomena observed in boiling nanofluids.

With a view to the practical feasibility, dilute nanofluids, typically with a nanoparticle concentration lower than 0.1% by volume, are generally preferred due to their improved colloidal stability and negligibly altered physical properties from those of their pure base liquids. Kim et al. [5] measured the properties of several dilute aqueous nanofluids (water-Al_2O_3, water-ZrO and water-SiO_2 with concentrations of 0.001%v, 0.01%v and 0.1%v) and compared them with those of pure water. The results demonstrated that the saturation temperature of these nanofluids was within ±1 °C of that of pure water while their surface tension, thermal conductivity and viscosity were negligibly changed. However, significant critical heat flux (CHF) enhancement up to 60% was detected in these nanofluids. These specific features of dilute nanofluids allow the minimum modification of existing heat removal systems and have made them ideal working fluids for heat transfer enhancement in many industrial equipments including nuclear reactors [6] and high-power electronic devices [7].

For the purpose of system design and performance assessment, a robust model capable of predicting heat transfer by boiling nanofluids is in great demand. Due to the near-molecular mixing [8] between the nanoparticles and the base liquid, a dilute nanofluid behaves hydro-dynamically like its pure base liquid and can be numerically treated as a single liquid phase despite the existence of two phases. This has allowed in the literature developing thermal-fluid dynamic models [9] for nanofluids based on computational fluid dynamics (CFD). For vapor–liquid two-phase flows of nanofluids with heat and mass transfer, our recent study [10] demonstrated that the two-fluid model [11] is still applicable. However, due to the specific phenomena observed in boiling nanofluids such as surface modifications [12] and flow modifications [13] which are

* Corresponding author. School of Aerospace, Mechanical and Manufacturing Engineering, RMIT University, PO Box 71, Bundoora, VIC, 3083, Australia. Tel.: +61 3 9925 6191; fax: +61 3 9925 6108.
E-mail address: jiyuan.tu@rmit.edu.au (J. Tu).

http://dx.doi.org/10.1016/j.ijthermalsci.2015.06.020
1290-0729/

not presented in nucleate boiling of pure liquids, the closure correlations/models of the two-fluid model have to be properly reformulated to account for the specific features induced by the existence of nanoparticles.

A comprehensive literature survey [14] revealed that the forming of a porous layer of deposited nanoparticles on the heater surface, which is believed to be caused by evaporation of the liquid microlayer, is one of the common findings of most experimental studies on nucleate boiling of nanofluids. This porous layer not only changes the surface morphology and properties, but also alters the characteristics of bubble nucleation and departure, and is widely believed to be the essential cause of the dramatic boiling heat transfer performance of nanofluids. Therefore, as proven in our recent study [10], the key issue when formulating a theoretical model for nucleate boiling of dilute nanofluids is to characterize the surface modifications and the altered bubble nucleation behaviors.

Therefore in this study, new closure correlations were incorporated into the heat flux partitioning (HFP) model by Kurul and Podowski [1] in order to capture the characteristics of heat and mass transfer on nanoparticle-deposited heater surfaces. Parametric studies were performed to analyze the effects of the improved surface wettability and altered surface roughness on bubble nucleation and departure. The HFP model was then incorporated as a boundary condition into the fully validated two-fluid model for boiling flows [15,16] and 2-D numerical computations were conducted using the commercial CFD code CFX 4.4. The numerical results were compared against both the experimental data available in the literature and the classic Rohsenow pool boiling correlation.

2. The heat flux partition (HFP) model

Although the morphology and properties of the heater surface have been significantly changed by the deposited nanoparticles, the boiling heat transfer mechanisms involved on a nano-coated surface are believed to keep unchanged as those on a clean surface. Therefore, the HFP model proposed by Kurul and Podowski [1] is still mechanistically applicable to nucleate boiling of nanofluids. According to the HFP model, the heat flux from a heater surface is transferred into the fluids through three mechanisms, namely the evaporation, quenching and convection mechanisms by

$$q = q_e + q_q + q_c \tag{1}$$

where, q_e, q_q and q_c represent the heat flux components transferred by evaporation, quenching and convection, respectively.

$$q_e = \frac{\pi}{6} d_{bW}^3 \rho_w f n h_{fg} \tag{2}$$

$$q_q = \frac{2}{\sqrt{\pi}} f A_q \sqrt{t_W \lambda_l \rho_l c_{p,l}} (T_W - T_l) \tag{3}$$

$$q_c = A_c S t \rho_l c_{p,l} u_l (T_W - T_l) \tag{4}$$

where, d_{bW}, f, n, t_w, A_c and A_q are the bubble departure diameter, bubble departure frequency, active site density, bubble waiting time, the area fractions of the heater surface subjected to convection and quenching, respectively. Due to the inherent complexity of bubble nucleation and departure, these parameters are generally formulated empirically or semi-empirically. Although a number of correlations are available in the literature and some of them have been fully validated for boiling of pure liquids, however, their applicability to nanofluids is still open to question. For the purpose of effective modeling, the nucleate boiling parameters have to be carefully formulated.

2.1. The active site density

According to the classic Bankoff bubble nucleation mechanism, the availability of cavities on a heater surface for bubble nucleation is strongly affected by the surface microstructures and wettability. Based on this mechanism and a cone cavity assumption, Yang and Kim [17] correlated the active site density to the surface microstructures and liquid contact

$$n = N \int_0^{\theta/2} f(\beta) d\beta \times \int_{r_{c,\min}}^{r_{c,\max}} f(r_c) dr_c \tag{5}$$

where, N is the total number of possible nucleation sites available on a unit heater surface area, $f(\beta)$ and $f(r_c)$ are the probability density functions for the cone angle (β) and cavity mouth size (r_c), respectively. The key issue when applying the Yang–Kim correlation is to provide statistical parameters for the surface microstructures ($f(\beta)$ and $f(r_c)$), which depend on the heater material and surface polishing and have to be determined experimentally. Unfortunately, due to the diversity and inherent complexity of realistic heater surfaces, it's anything but an easy job to formulate a universal active site density correlation based on Eq. (5).

As a simplification, the active site density has been widely correlated to the wall superheat and some other parameters such as the liquid contact angle and the surface roughness. Among them, the correlations proposed by Benjamin and Balakrishnan [18], Wang and Dhir [19] and Basu et al. [20] are highly regarded in terms of accuracy for nucleate boiling of water [21]. However, a recent comparison [10] of these correlations against the experimental data of aqueous nanofluids proved that they are actually not applicable to nanofluids. This is perhaps due to the fact that they are empirical and limited to pure liquids. For nanofluids, the active density needs to be reformulated so that the effects impacted by the nanoparticles could be taken into account.

It is widely believed that the deposited nanoparticles affect bubble nucleation through two ways [5]. Firstly, they alter the total number of sites available for bubble nucleation by changing the microstructures of the heater surface. Secondly, the deposited nanoparticles largely improve the wettability of the heater surface, which causes a part of the nucleation sites being flooded by the liquid and cannot be activated. Therefore, it is crucial to take both the morphology and property modifications into account when modeling the active site density in nanofluids.

In order to describe the effects of nanoparticle deposition on bubble nucleation, Ganapathy and Sajith [22] proposed a semi-analytic correlation for the active site density based on the Benjamin–Balakrishnan correlation [18], in which both the wettability enhancement and the nanoparticle size relative to the surface roughness were considered.

$$n = 218.8 \frac{1}{\gamma} \mathrm{Pr}_l^{1.63} \left(\left(14.5 - 4.5 \left(\frac{R_a P}{\sigma} \right) + 0.4 \left(\frac{R_a P}{\sigma} \right)^2 \right) \beta^{-3} \left(\frac{R_a}{d_p} \right)^{-0.5} \right)^{-0.4} \Delta T_{sup}^3 \tag{6}$$