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Nucleate boiling of dilute nanofluids – Mechanism exploring and modeling

Xiangdong Li [a], Sherman Chi Pok Cheung [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

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ABSTRACT

Despite the overall merits of using nanofluids as heat transfer fluids are still under controversy in many fields, their application in nuclear reactor systems, especially the IVR system has been proved to be promising. However, the lack of fundamental understanding of the physical mechanisms has hindered the applications. For the purpose of developing a mechanistic model of nucleate boiling of nanofluids for nuclear applications, the common findings yielded from most experimental investigations available in the literature are analyzed in this study. It was demonstrated that the heater surface modification induced by nanoparticle deposition during the boiling process is the major cause of the dramatic boiling heat transfer performance of nanofluids. It was further suggested that the classic heat partitioning model is applicable to predicting nucleate boiling of nanofluids on condition that the surface modification and the nucleate boiling parameters (e.g. the active site density, the bubble departure diameter and frequency) are properly formulated.

1. Introduction

Nanofluids are dilute colloidal dispersions of nanoparticles in common base liquids. Due to their enhanced properties and behaviors associated with heat transfer, as well as many practical and potential applications, nanofluids have been attached a great importance and intensively investigated since 1995 when the novel concept "nanofluid" was firstly proposed by Choi [1,2]. Nowadays, nanofluids have been widely believed to be promising heat transfer fluids in many industrial fields such as microelectronics [3,4], nuclear engineering [5–8], heat pipes [9,10], refrigeration, air-conditioning and heat pump systems [11,12], just to name a few. The potential market for nanofluids for heat transfer applications is estimated to be over 2 billion dollars per year worldwide, with prospect of further growth in the next 5–10 years [13].

Due to its high efficiency in heat removal, nucleate boiling of nanofluids is preferred in many industry systems. Nowadays, although employing boiling nanofluids for the purpose of heat removal is still facing many challenges, a number of studies on nucleate boiling of low-concentration nanofluids (typically less than 0.1% vol.) and their applications in nuclear reactors [14–18] have brought out a promising prospect. Kim et al. [19] measured the properties of dilute water-based nanofluids and found that the saturation temperatures of these nanofluids were within ±1 °C of that of pure water while the surface tension, thermal conductivity and viscosity of the nanofluids were found to differ negligibly from those of pure water. Dramatically, these nanofluids achieved a critical heat flux (CHF) enhancement up to 200%. Furthermore, because of the base-liquid-alike properties of dilute nanofluids, many problems encountered in high- or medium-concentration nanofluids such as particle aggregation and sediment could be largely eliminated. These features have made dilute nanofluids ideal heat transfer fluids for nuclear applications.

However, as pointed by Siadur et al. [20], the absence of predictive model and the lack of theoretical understanding of the mechanisms responsible for the dramatic changes in heat transfer induced by the addition of nanoparticles in base liquids remains a major challenge hindering their applications in the aforementioned industry systems. Therefore, fundamental researchers are urgently needed to develop a mechanistic model capable of predicting heat transfer behaviors associated with nucleate boiling of nanofluids. Developing a predictive model not only leads to a thorough understanding of the mechanisms underlying the novel phenomena,

* 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).

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Nomenclature

A_c	surface area fraction at the heater surface controlled by convection (−)
A_q	surface area fraction at the heater surface controlled by quenching (−)
c_p	specific heat (W/kg/K)
D_p	average particle diameter (m)
d_{bW}	bubble departure diameter (m)
f	bubble departure frequency (Hz)
g	gravitational acceleration (m/s^2)
h_{fg}	liquid latent heat (J/kg)
n	active site density (sites/m^2)
P	system pressure (Pa)
Pr	the Prandtl number (−)
q	total heat flux at the heater surface (W/m^2)
q_c	heat flux due to convection (W/m^2)
q_e	heat flux due to evaporation (W/m^2)
q_q	heat flux due to quenching (W/m^2)
R_a	average roughness on a clean heater surface (m)
r_c	radius of active site (m)
St	the Stanton number (−)
T	temperature (K)
ΔT_{sup}	wall superheat, $\Delta T_{sup} = T_W - T_l$
t_w	bubble waiting time (s)
u_l	liquid velocity in the cell immediately next to the heater surface (m/s)

Greek letters

β	half cone angle (radian)
δ_m	thickness of liquid microlayer (m)
δ_n	thickness of the nano-layer (m)
δ_T	thickness of the thermal boundary layer (m)
ϕ	volume fraction of nanoparticles in the liquid (−)
λ	conductivity (W/m/K)
θ	liquid contact angle on clean heater surface (radian)
θ^*	liquid contact angle on nano-coated heater surface (radian)
ρ	density (kg/m^3)
σ	liquid surface tension (N/m)

Subscripts

W	the heater wall
sat	saturation
∞	bulk liquid
l	the liquid phase
v	the vapor phase
s	solid heater surface

but also is capable of providing ready-to-use information for CHF prediction.

In fact, efforts have been made to develop CFD predictive models for nanofluid single-phase and two-phase flows with heat and mass transfer. It is generally agreed that nanoparticles are mixed with the base liquid at near-molecular level [21], so that a nanofluid behaves hydrodynamically like a pure liquid and can be treated theoretically as a single-phase liquid despite it is actually composed of the base liquid and solid particles. This has allowed developing multi-dimensional mechanistic models for single-phase convective heat transfer of nanofluids based on computational fluid dynamics (CFD). Numerous studies have demonstrated that the single-phase CFD model is capable of describing the flow and heat transfer behaviors of nanofluids without phase change on condition that the physical properties are properly formulated [22]. Since nucleate boiling and two-phase flows have higher heat removal efficiency, there naturally comes out the question whether nucleate boiling and two-phase flows of nanofluids could be modeled using CFD.

In fact, nucleate boiling of pure liquid alone is an extremely complicated physical phenomenon whose mechanisms have not been thoroughly understood. The existence of nanoparticles in the base liquid further intensifies the complexity by presenting many novel phenomena such as surface modification [19,23] and flow modification [24,25]. Despite this, some important research outcomes have raised from the intensive studies in recent years, the mechanisms of nanofluid nucleate boiling underlying the novel phenomena are thought to be gradually revealed. In terms of the experimental observations available in the literature, the surface modification seems to be the major cause of the dramatic boiling heat transfer performance of nanofluids. Meanwhile, mechanistic CFD models for nucleate boiling of water, refrigerants and cryogenic liquids have been successfully developed by the authors [26–30] and many other investigators during the past years, based on the two-fluid [26] and the MUSIG model [28]. In these CFD models, the heat and mass transfer process on the heater surface was modeled using the heat flux partitioning model [31]. These mechanistic approaches have been shown to expedite a more thorough understanding of bubble nucleation on a heater surface and to further enhance the description of the bubble behaviors in liquid. These models are believed to have laid a substantial theoretical foundation on which a mechanistic CFD model could be readily developed for nucleate boiling of nanofluids. However, due to the specific characteristics presented in boiling of nanofluids, some closure correlations, especially those describing bubble nucleation, growth and departure on the heater surface have to be carefully formulated.

Therefore, by starting with analyzing the mechanisms of nucleate boiling, this paper focuses on the heat and mass transfer processes on a heater surface boiling in nanofluids and aims at summarizing the common findings observed in most experimental studies as well as clarifying their physical mechanisms. These common findings and mechanisms are expected to lead to a mechanistic heat flux partitioning model for nucleate boiling of nanofluids, which could be utilized in designing and assessing heat removal systems by nucleate boiling of nanofluids. Compared with other reviews of heat transfer using nanofluids, this paper puts more emphasis on mechanism exploring and the key issues when formulating a predictive model for nucleate boiling of nanofluids.

2. Mechanism of nucleate boiling

2.1. Effects of surface microstructure and liquid contact angle on bubble nucleation

The mechanism of nucleate boiling has been extensively studied during the past decades. It is generally agreed that the surface irregularities or microstructures (e.g. pits, cavities, scratches and grooves) capable of trapping a small amount of vapor serve as active nucleation sites when a heat flux is applied. Irregularity is an inherent characteristic of solid surface. The surface microstructures are observed to be distributed in a wide size range. However, not all the microstructures can develop into active sites, but only those in a certain size and geometric shape range can be activated.