International Journal of Heat and Mass Transfer 125 (2018) 959–971

Contents lists available at ScienceDirect

International Journal of Heat and Mass Transfer

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


International Journal of HEAT and MASS TRANSFER

Exploration of nanofluid pool boiling and deposition on a horizontal cylinder in Eulerian and Lagrangian frames

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ARTICLE INFO

Article history:
Received 3 March 2018
Received in revised form 27 April 2018
Accepted 28 April 2018

Keywords:
Pool boiling
Eulerian model
Discrete model
ANSYS-Fluent
Nanofluids
Nanoparticles

ABSTRACT

In spite of many advantages of using nanoparticles in convective heat transfer, there are still some hidden aspects of nanofluids regarding simulations. Pool boiling flows are complicated regarding analytical aspects, and the presence of particles can noticeably extend this complexity. One of the most important aspects of nanofluid pool boiling is concerned with the changes in nucleation site and bubble diameter due to particles deposition and surface roughness. To include these effects, new correlations are implemented as a user-defined function for nucleation site density and bubble departure diameter. On the other hand, the particles are introduced and tracked everywhere in the domain in the Lagrangian frame by using discrete model. As an application, a tube bundle with four tubes is considered with different orientation angles concerning each other and different pitch distances. Unsteady Eulerian two-fluid model in ANSYS-Fluent is employed to simulate the liquid and vapour flows in the computational domain. In this work, pool boiling nanofluid flow is numerically solved around a two-dimensional horizontal cylinder with 20 mm diameter and compared with experimental data. The nanofluid is consist of distilled water and aluminium oxide with a particle size of 38 nm. The good agreement is found, and further discussion regarding particles migration and deposition are presented. It is found that the percentage of deposition is dependent on heat flux and particle concentration. Also, heat transfer coefficient increases with expanding the horizontal distance between cylinders and then decreases to a fixed value.

1. Introduction

Mixing of liquids via ultrafine solid particles can result in heat transfer enhancement in heat exchangers and other industrial equipment. This enhancement connected to different mechanisms which the most important one is referred to improvement in thermal conductivity of the mixture [1–3]. On the other hand, since the increase in mixture viscosity is inevitable, improvement of final thermal efficiency is connected to the optimum range of the volume fraction of the nanoparticles [4–7] which can vary from a nanofluid to another. Due to the extensive area of applications, nanofluids can be used in flows with and without phase change. Laminar and turbulent forced convection in pipes and heat exchangers are some of the common examples with no phase change flows [8,9]. Using ultrafine particles in boiling flows has attracted great attention in recent years [10,11], with the particular application in pressurized and boiling nuclear reactors. Experimental observations show both enhancement and worsening of heat transfer coefficient using nanoparticles, depending on the type and size of the nanoparticles, type of the stabilizer, base fluid and flow regime, geometry and surface roughness [12,13]. Due to the complexity and many phenomena involved in pool boiling flows, especially with the presence of solid nanoparticles, the number of numerical work is limited, and most of the previous studies cover experimental measurements and visualization.

You and Kim [14] showed that heat transfer coefficient remained nearly unchanged for alumina nanofluids on a flat plate in pool boiling at saturation temperature 60 °C. However, critical heat flux was found abnormally increased up to 200%. Kim et al. [15] conducted pool boiling experiment on a wire heater for three different nanofluids of low volume fractions <0.1%. They reported a noticeable rise in critical heat flux, deposition of a porous layer of nanoparticles on the wire, wettability improvement on the heater and consequently drop in contact angle. The contact angle was found to vary between 71° to 80° for nanofluid on a clean surface. They stated that contact angle could be highly influenced by considering the deposited layer (after boiling test), dropping to less than 40°. Bang and Chang [16] observed deterioration in heat transfer coefficient of alumina nanofluid on a horizontal plate. The reduction in active nucleation sites in nucleate boiling was

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https://doi.org/10.1016/j.ijheatmasstransfer.2018.04.153
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Nomenclature

A_i	interfacial area [m^2]
A_p	particle projected area [m^2]
C_L	lift coefficient
C_w	wall lubrication coefficient
C_c	cunningham correction factor
C_D	drag coefficient
C_{ML}	rotational coefficient
C_ω	rotational drag coefficient
C_{qw}	bubble waiting time coefficient
c_p	specific heat (J/kg K)
d	diameter [m]
d_p	particle diameter [m]
d_w	bubble departure diameter [m]
D_T	thermophoresis diffusion coefficient [m^2/s]
h	heat transfer coefficient [W/m^2 K]
h_k	enthalpy [J/kg]
h_{lv}	latent heat of evaporation [J/kg]
I_p	moment of inertia [kg/m^2]
k	thermal conductivity [W/m K]
K_B	Boltzmann constant [m^2 kg/°K s^2]
m_p	particle mass [kg]
M_k	momentum induced by mass exchanged [kg/m^2 s^2]
N_w	nucleate site density
Nu	Nusselt number
n_w	wall normal vector
Pr	Prandtl number
q_k, q_k^t	laminar and turbulent heat flux [W/m^2]
Ra	surface roughness [m]
Re	Reynolds number
Re_p	particle Reynolds number
Re_{ω_p}	angular Reynolds number
Sc_b	Schmidt number
Δt_p	particle time step [s]
V, u	velocity [m/s]
u_i'	fluctuating velocity [m/s]

Greek letters

α	phase volume fraction
φ	particle volume fraction
Γ_k	exchanged mass [kg/m^3 s]
$\dot{\gamma}$	shear rate [1/s]
κ	turbulent kinetic energy [m^2/s^2]
μ	viscosity [Pa s]
μ_t	turbulent viscosity [Pa s]
ω_p	particle angular velocity [1/s]
Ω	relative particle-liquid angular velocity [1/s]
ρ	density [kg/m^3]
σ	surface tension [N/m]
θ	contact angle
$\Im_k$, $\Im_k^t$	laminar and turbulent shear stress [Pa]
ζ_i	Gaussian white noise random number
ξ	random number

Subscript

bf	base fluid
k	continues phase
l	liquid
m	mixture
nf	nanofluid
v	vapour
p	particle
sat	saturation
W, s	wall, surface

attributed to changes in surface roughness resulted by particles deposition. Zhu et al. [17] investigated nanofluid mixture properties and pool boiling on a heating wire. They stated that thermal conductivity and surface tension of the mixture played significant roles in heat transfer enhancement. The improvement in thermal conductivity and surface tension were measured 5% and 7%, respectively. They also reported the change in viscosity was negligible. On the other hand, they argued that the extreme increase in critical heat flux can be possibly concerned to the enhanced thermal conductivity, surface tension and the porous coating layer on the wire. Hu et al. [10] carried out nanofluids pool boiling experiment on a horizontal cylinder with ethylene glycol/water mixture as the base fluid. Particle size and volume fraction were presented as the contributing factors in rising and dropping of the heat transfer. Shoghl et al. [13] argued that any modification in heat transfer in nanofluid pool boiling is associated with the type and size of particles and also roughness of the surface caused by particles. Wang et al. [18] proposed a new correlation for the Nusselt number in pool boiling nanofluid based on the properties of the base fluid and the mixture.

On the theoretical aspect, Ham and Cho [19] studied the effects of various parameters on heat transfer, bubble departure frequency and diameter, waiting time ratio and nucleate site density. They used previous correlations from literature with considering the important impact of surface roughness induced by nanoparticles coating. Also, variation in contact angle was found as small as 10° up to the contact angle for pure water on a clean surface as 79°. Wang and Wu [20] employed a semi-implicit method for moving particles regarding the tracking of bubble growth in an alumina nanofluid. They introduced particle size and volume fraction at which the optimum heat transfer and bubble departure frequency were obtained. Li et al. [21] explained that bubble departure diameter, nucleate site density and other boiling parameters need to be substituted with new correlations based on the modified surface affected by nanoparticles. They also stressed on the adjustment of heat flux phenomena in the vicinity of the surface as a part of partitioning model. Shoghl et al. [22] performed both experimental and numerical study of nanofluids boiling over a horizontal cylinder. They used VOF multiphase approach in the simulations with no interactions between liquid and vapour. Only the mass exchange arising from evaporation was considered everywhere in the two-dimensional domain. Moreover, it was shown that contact angle highly depended on the type of the particles and varying from 40° to 110°. The same strategy was adopted by Liu et al. [23] in a two-dimensional model with cryogenic liquid.

Literature review shows that there are many phenomena involved in pool boiling with solid nanoparticles and further theoretical aspects are needed to be investigated regarding boiling characteristics, particle migration and deposition. Additionally, experimental observations have revealed that non-homogenous distribution of particles inside the medium seems unavoidable, and especially close to a wall [24]. Accordingly, using the discrete model to track the particles in the Lagrangian frame can provide higher accuracy in prediction. On the other hand, traditional correlations for nucleate site density and bubbles diameter used by many researchers cannot be sufficient to cover all the aspects of the presence of nanoparticles in pool boiling phenomena. Therefore, this study will attempt to implement new correlations to consider other important parameters in nanofluid pool boiling, such as surface roughness and particles size.