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The effects of nanoparticles on the lift force and drag force on bubbles in nanofluids: A two-fluid model study

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

[a] School of 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

Bubbly flows of air-water and air-nanofluid were investigated numerically using the two-fluid model. Through comparing the predicted bubble velocity and void fraction profiles against the experimental data, the classic two-fluid model, which has been widely validated for two-phase flows of pure liquids, was found to be inapplicable to those of nanofluids because of the empirical nature of the interfacial force formulation. The roles of interfacial forces were believed to be significantly altered in nanofluids rather than in pure liquids due to the spontaneous phenomenon of nanoparticle adsorption at bubble interfaces. Because of the nanoparticle layer, bubbles submerged in nanofluids would partially behave like a rigid sphere and develop a rotation movement. A slanted wake could be induced behind the bubble, generating a lateral Magnus force pointing towards the pipe centre and consequently making the positive-to-negative reversion of lift force occur at a smaller bubble diameter. Meanwhile, the slanted wake would also make bubbles in the viscous regime experience a drag force similar to that in the distorted regime, which makes the viscous-to-distorted transition point occur at a smaller bubble Reynolds number. It was recommended that the most important task when modelling bubbly flows of nanofluids using the two-fluid model is to reformulate the interfacial forces accounting for the effects of nanoparticle adsorption.

1. Introduction

Heat transfer enhancement has long been a hot research topic because of the continuously increasing demands for heat removal in many industries. Thanks to the development of nano-technology, a new type of engineered colloidal dispersions of nanometre-sized particles in common base liquids, the so-called “nanofluid”, has been regarded as a revolutionary heat transfer medium in view of its significant heat transfer enhancement in nucleate boiling [1–3]. As the formation of a thin layer of deposited nanoparticles on the heater surface was widely observed in most nucleate boiling experiments using nanofluids, which does not exist in nucleate boiling of pure liquids, the heat transfer enhancement of nanofluids has been generally attributed to the surface modification induced by nanoparticle deposition during the boiling process [4]. It is believed that the deposited nanoparticles play a dominant role in altering the boiling heat transfer intensity through significantly changing the microstructures and properties of the heater surface, as well as the characteristics of bubble dynamics [5]. In the meantime, nanofluids for heat transfer applications are generally dilute with every low nanoparticles loads (less than 0.1 v%). Under such low nanoparticle concentrations, the liquid thermophysic properties are negligibly modified [6], which makes it safe to assume that dilute nanofluids behave hydrodynamically identical to their pure base liquids. Some numerical studies on boiling flows of nanofluids further assumed the two-phase behaviours of nanofluids are also identical to those of base liquids [7], and only focused on the effects of surface modifications induced by nanoparticle deposition.

However, emerging evidence in recent years revealed that nanoparticles have significant impact on the two-phase flow structures and dynamics. Using a high-speed visualization and image processing technology, Rana et al. [8] measured the void fraction in boiling flows of water and ZnO/water nanofluids (0.001–0.01 v%) in horizontal annulus. They found that with the

* Corresponding author. School of Engineering, RMIT University, PO Box 71, Bundoora, VIC 3083, Australia.
E-mail address: jiyuan.tu@rmit.edu.au (J. Tu).

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Nomenclature

$\boldsymbol{B}$	Body force, (N m^{-3})
C_D	Drag coefficient, (dimensionless)
C_L	Lift coefficient, (dimensionless)
C_{TD}	Turbulent dispersion coefficient,(dimensionless)
C_{W1}, C_{W2}	Lubrication coefficient,(dimensionless)
$c_{monolayer}$	Critical volume concentration, (dimensionless)
d_b	bubble diameter, (m)
d_{cr}	Critical bubble diameter, (m)
d_H	Maximum bubble horizontal dimension, (m)
Eo	Eötvös number, (dimensionless)
$Eo\prime$	Modified Eötvös number, (dimensionless)
$\boldsymbol{F}_D$	Drag force, (N m^{-3})
$\boldsymbol{F}_k$	Interfacial force, (N m^{-3})
$\boldsymbol{F}_L$	Lift force, (N m^{-3})
$\boldsymbol{F}_{TD}$	Turbulent dispersion force, (N m^{-3})
$\boldsymbol{F}_W$	Wall lubrication force, (N m^{-3})
g	Gravitational acceleration, (m s^{-2})
j	Superficial velocity, (m s^{-1})
k	Thermal conductivity, (W m^{-1} K^{-1})
k_B	Boltzmann constant, (J K^{-1})
k_s	Empirical constant in the drag coefficient calculation, (dimensionless)
$\boldsymbol{n}_W$	Outward vector normal to the wall surface
p	The system pressure, (Pa)
Re_b	Bubble Reynolds number, (dimensionless)
T	Temperature, (K)
$\boldsymbol{U}$	Velocity, (m s^{-1})
y_W	Adjacent point normal to the wall surface, (m)

Greek symbols

α	Void fraction, (dimensionless)
μ	Viscosity, (Pa s)
ρ	Density, (kg m^{-3})
σ	Surface tension, (N m^{-1})
ϕ_V	Nanoparticle volume concentration, (dimensionless)

Subscripts

f	Pure fluids
g	Gas phase
l	Liquid phase
nf	Nanofluids

increasing nanoparticle concentration, the void fraction in nanofluid decreased as much as 86% when compared to that in water, which indicates that ZnO nanoparticles in fluid act as void-fraction-suppressing agent. The hydrodynamic behaviours in the pool boiling of water and Al_2O_3/water nanofluids (0.001 and 0.002 v%) were also investigated by Dominguez-Ontiveros et al. [9]. Through comparing the velocity profiles obtained by Dynamic Particle Image Velocimetry (DPIV), the fluid velocity distributions were found to be generally less uniform and lower in magnitude for the nanofluid cases than for those of the pure water case. Recently, radial distributions of air-nanofluid (Al_2O_3/water 0.1v%) bubbly flow parameters in a vertical tube were measured by Park and Chang [10]. The measurements showed that the air-nanofluid bubbly flow had a more flattened void fraction distribution, lower bubble velocity, higher interfacial area concentration and smaller bubble size than those in the air-water flow.

Considering the profound inter-coupling of two-phase flow structures and the overall heat transfer performance [11], it is crucial to achieve an effective modelling of the two-phase flow dynamics in order to obtain comprehensive predictions of nanofluid boiling flows in the future. Beyond that, as nanoparticles are finding an increasing number of applications in various industries, multi-dispersed bubbly systems containing nanoparticles are commonly encountered. For example, nanoparticles are tested at the laboratory scale in bubble column reactors [12] to enhance chemical reactions and interfacial mass transfer, and they are also used as surfactants to stabilize emulsions [13] and foams [14]. An in-depth understanding of the effects of nanoparticles on bubble behaviours in liquids is obviously beneficial to many emerging and traditional industries.

Therefore, this study tries to reveal the mechanistic effects of nanoparticles on two-phase flow dynamics, with the aim to improve the two-fluid model for effective modelling of bubbly flows of nanofluids with and without heat and mass transfer.

2. Theoretical models

Numerous studies [15] have demonstrated that due to their small sizes, nanoparticles could be assumed to be mixed with the base fluid at a near-molecular level and thus a nanofluid can be numerically treated as a pseudo-homogeneous single-phase liquid. The framework of the two-fluid model [16], which has been regarded as the mechanistic macroscopic formulation of the thermal-hydraulic dynamics of two-phase flow system, is theoretically applicable to bubbly flows of nanofluids. In the model, two sets of conservation equations governing the balance of mass, momentum and heat of gas and liquid are solved. For an isothermal air-nanofluid flow, the two-fluid model takes the following form:

The continuity equation:

$$\frac{\partial}{\partial t}(\alpha_k \rho_k) + \nabla\cdot(\alpha_k \rho_k \boldsymbol{U}) = 0 \tag{1}$$

The momentum equation:

$$\frac{\partial}{\partial t}(\alpha_k \rho_k \boldsymbol{U}_k) + \nabla\cdot(\alpha_k(\rho_k \boldsymbol{U}_k \times \boldsymbol{U}_k - \mu_k(\nabla \boldsymbol{U}_k + (\nabla \boldsymbol{U}_k)^T))) = \alpha_k(\boldsymbol{B} - \nabla p_k) + \boldsymbol{F}_k \tag{2}$$

where the subscripts k is the phase denotation ($k = l$ for the liquid phase and $k = g$ for the gas phase); α, ρ, $\boldsymbol{B}$, $\boldsymbol{U}$ and $\boldsymbol{F}_k$ represent the volume fraction, density, body force, velocity and interphase forces, respectively.

For bubbles submerged in a continuous liquid, the interfacial force $\boldsymbol{F}_k$ generally includes the forces due to drag and the effects of lateral lift, wall lubrication and turbulent dispersion.

$$\boldsymbol{F}_k = \boldsymbol{F}_D + \boldsymbol{F}_L + \boldsymbol{F}_W + \boldsymbol{F}_{TD} \tag{3}$$

The drag force $\boldsymbol{F}_D$ is calculated by:

$$\boldsymbol{F}_D = 3C_D \alpha_g \rho_l |\boldsymbol{U}_g - \boldsymbol{U}_l|(\boldsymbol{U}_g - \boldsymbol{U}_l)/4d_b \tag{4}$$

The drag coefficient C_D is empirically correlated by Ishii and Zuber [17] to the bubble Reynolds number Re_b and Eötvös number Eo: