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Modelling and critical analysis of bubbly flows of dilute nanofluids in a vertical tube

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HIGHLIGHTS

- The classic two-fluid model needs improvement for nanofluid bubbly flows.
- The nanoparticle self-assembly changes the interfacial behaviours of bubbles.
- Key job is to reformulate the interfacial transfer terms.

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ABSTRACT

The bubbly flows of air–nanofluid and air–water in a vertical tube were numerically simulated using the two-fluid model. Comparison of the numerical results against the experimental data of Park and Chang (2011) demonstrated that the classic two-fluid model, although agreed well with the air–water data, was not applicable to the air–nanofluid bubbly flow. It was suggested that in a bubbly flow system, the existence of interfaces allows the spontaneous formation of a thin layer of nanoparticle assembly at the interfaces, which significantly changes the interfacial behaviours of the air bubbles and the roles of the interfacial forces. As the conservation equations of the classic two-fluid model are still applicable to nanofluids, the mechanisms underlying the modified interfacial behaviours need to be carefully taken into account when modelling air–nanofluid bubbly flows. Thus, one of the key tasks when modelling bubbly flows of air–nanofluid using the two-fluid model is to reformulate the interfacial transfer terms according to the interfacial behaviour modifications induced by nanoparticles.

1. Introduction

As a new type of engineered liquids for enhancing heat transfer, nanofluids have been attracting an increasing attention since the novel concept "nanofluid" was firstly proposed by Choi and Eastman (1995). Nanofluids were initially investigated because of their improved thermal conductivity brought out by the nanoparticles. During the past years, numerous studies have been conducted on the convective transport phenomena in nanofluids (Buongiorno, 2006). Up to today, agreements have been reached on the mechanisms of heat transfer in single-phase nanofluids (Chandrasekar et al., 2012; Yu et al., 2012). It is generally accepted that due to their small sizes, nanoparticles are mixed with the base liquid at near-molecular levels. A dilute nanofluid behaves hydro-dynamically like its pure base liquid and could be treated theoretically as a single-phase liquid. This has allowed developing predictive models for single-phase flows of nanofluids based on the Navier–Stokes equations (Kamyar et al., 2012). Existing studies (Akbari et al., 2011; Moraveji and Ardehali, 2013) have proven that the single-phase computational fluid dynamics (CFD) model is capable of describing the flow and heat transfer behaviours in nanofluids on condition that the thermodynamic properties are properly formulated.

In recent years, the great potential of enhancing heat transfer using two-phase flows of nanofluids, especially by nucleate boiling, has been gradually recognized (Cheng et al., 2008). However, due to the relative novelty and inherent complexity, agreements are far to be reached in this area and many opinions are still in controversy (Barber et al., 2011). Nanofluids come with various concentrations, however, dilute nanofluids with very low nanoparticle loads (typically less than 0.1 v%) are generally preferred for

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Nomenclature

C	coefficient (–)
d	diameter (m)
Eo^*	the modified Eötvös number (–)
$\vec{F}$	interfacial force (N)
g	the gravitational acceleration ($m\,s^{-2}$)
k	turbulent kinetic energy ($m^2\,s^{-2}$)
P	pressure (Pa)
Re	the Reynolds number (–)
S	source term
$\vec{U}$	velocity (m/s)

Greek letters

α	volume fraction (–)
φ	nanoparticle concentration by volume (–)
μ	viscosity (Pa s)
ρ	density ($kg\,m^{-3}$)
σ	surface tension coefficient ($N\,m^{-1}$)

Subscripts

b	bubbles
D	the drag force
g	the gaseous phase
i, j	phase denotations
L	the lift force
l	the liquid phase
nf	nanofluid
TD	the turbulent dispersion force
W	the lubrication force

boiling applications (Buongiorno et al., 2009) when one considers the practical feasibility. For nanofluids with such low concentrations, a number of experimental measurements demonstrated that their physical properties (e.g. the thermal conductivity, density, viscosity, specific heat and latent heat) are negligibly different from those of their pure base liquids (Kim et al., 2007; Kwark, 2009). The dramatically changed boiling heat transfer performances have been attributed to the surface modifications induced by nanoparticle deposition during the boiling process (Vafaei and Borca-Tasciuc, 2014; Wen et al., 2011). In recent years, CFD modellings of nucleate boiling of nanofluids have been conducted (Li et al., 2014a,b, 2015) based on the two-fluid model of Ishii (Ishii, 1975). In these studies, the effects of nanoparticle deposition on bubble nucleation on the heater surface were properly considered. The model applicability and accuracy, although still not satisfactory, have been largely improved. However, an important fact may have been ignored – the nanoparticles suspended in the base liquid not only modify the heat surface, but also change the two-phase flow structures and hydrodynamic features.

Nayak et al. (2011) studied experimentally the transient and stability behaviours of boiling two-phase natural circulation loop with water and water–Al_2O_3 nanofluid (1.0 w%, approx. 0.25 v%), respectively. They found that the natural circulation flow behaviours of nanofluid were very close to that of water in single-phase conditions. However, the buoyancy induced flow rates in boiling conditions were relatively higher with nanofluid than with water. Dominguez-Ontiveros et al. (2010) observed the pool boiling of water–Al_2O_3 nanofluids (0.001 and 0.002 v%) using dynamic particle image velocimetry (DPIV). They found that the hydrodynamic behaviours of bubbles were significantly changed when nanoparticles are introduced into water. Recently, Rana et al. (2014) measured the void fraction in boiling flows of water–ZnO nanofluids (0.001–0.01 v%). The results revealed that the void fraction decreased down to 86% with the use of nanofluid in place of water.

In addition, the modifications of two-phase flow characteristics by nanoparticles were also observed in isothermal flows. Wang and Bao (2009) investigated the transition of two-phase flow regimes in a vertical capillary tube, using nitrogen as the gaseous phase and water–CuO nanofluid (0.5 w%, approx. 0.08 v%) and pure water as the liquid phase, respectively. They found that the bubbly-slug flow regime transition occurred at a lower liquid superficial velocity or a higher gas superficial velocity in the nanofluid than in water. This indicated that nanofluids could maintain a bubbly flow pattern with a higher void fraction than pure water, which is undoubtedly of great importance to enhancing two-phase heat and mass transfers, thanks to the larger interfacial area created by the higher void fraction in nanofluids. Wang and Bao (2009) suggested that the changed flow-regime transition characteristics were mainly due to the changed liquid surface tension. Park and Chang (2011) measured the local distributions of air–liquid bubbly flow parameters in a vertical tube using a conductivity double-sensor probe. Both pure water and water–Al_2O_3 nanofluid (0.1 v%) were used as the working liquids. The results showed that when the operational conditions were exactly the same, the air–nanofluid bubbly flow had a more flattened void fraction distribution, lower bubble velocity, higher interfacial area concentration and small bubble size than those in the air–water flow. They attributed these changes to the altered interfacial drag and lift forces.

Although the physical mechanisms underlying the flow modifications are yet to be discovered, it is evident that the existence of nanoparticles in the liquid has a significant effect on the two-phase flow structures and features, even with extremely low nanoparticle concentrations. As two-phase flows are coupled systems, an effective CFD simulation of two-phase flows requires accurate description of the inter-phase transport processes of mass, momentum and energy in the whole flow field. Therefore, in order to achieve an effective modelling of two-phase flows of nanofluids using the two-fluid model, the closure correlations, which are generally empirical or semi-empirical and thus not universal, have to be carefully reformulated or selected in order to account for the specific features induced by nanoparticles.

In order to identify the individual factors affecting the hydrodynamic behaviours of nanofluid two-phase flows, isothermal bubbly flow of air–nanofluid in a vertical tube was modelled in this study using the classic two-fluid model incorporated with various inter-phase transfer terms. Two-phase flow parameters including the air velocity and void fraction were predicted and compared against the experimental data of Park and Chang (2011). Bubbly flow of air–water was also simulated for the purpose of comparison. The results demonstrated that the classic two-fluid model had a satisfactory accuracy for the air–water bubbly flow, but was inapplicable to the air–nanofluid flow. Further analyses demonstrated that the suspended nanoparticles in the liquid tend spontaneously to assembly at the interfaces, which significantly changes the liquid–bubble interfacial behaviours and makes the existing empirical closure correlation invalid to the air bubbles submerged in nanofluids. Suggestions were given for future studies.

2. Modelling of bubbly flow in a vertical tube

2.1. The two-fluid model

The experimental data of Park and Chang (2011) were employed in this study for model validation and comparison. In their experiments, dilute water–Al_2O_3 nanofluid with a concentration of 0.1 v% was synthesized by dispersing γ-Al_2O_3 nanoparticles (mean diameter 25 nm) into distilled water. Then, the nanofluid was supplied