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Drag of contaminated bubbles in power-law fluids

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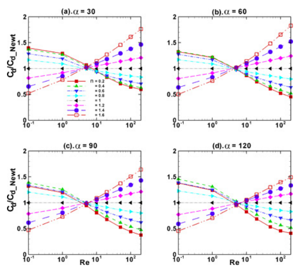
HIGHLIGHTS

- For Re > 20 and $\alpha \geq 60^\circ$, recirculation wake is formed for all values of n.
- Size of recirculation wake decreases with decreasing α and/or increasing n.
- C_d decreases with the decreasing α and/or with the increasing Re.
- C_d *vs.* Re results indicate crossover Reynolds number w.r.t. value of n.

GRAPHICAL ABSTRACT



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ABSTRACT

Flow and drag phenomena of spherical bubbles in contaminated power-law fluids are numerically investigated using the spherical stagnant cap model over the range of conditions as the Reynolds number (Re: 0.1–200), the power-law index (n: 0.2–1.6) and the degree of contamination (α: 0–180°). The conservation equations of mass and momentum are solved using the semi-implicit method for pressure-linked equations (SIMPLE) algorithm along with the quadratic upstream interpolation for convective kinematics (QUICK) scheme for momentum terms. The solver has been thoroughly validated with the existing literature results over wide range of pertinent conditions. The new results show that for Re > 20 and $\alpha \geq 60^\circ$, a recirculation wake behind the contaminated bubble is observed for all values of power-law index; and the size of the recirculation wake is found to decrease with the increasing power-law index. Furthermore, a crossover Reynolds number (at Re ≈ 5) exists for drag coefficient *vs.* Reynolds number behavior with respect to the power-law index; and it is found to be independent of the degree of contamination. Below this crossover Reynolds number, compared to Newtonian fluid results, the normalized drag coefficients are large for shear-thinning fluids (n < 1) and are smaller for shear-thickening fluids; and opposite trends are observed beyond the crossover Reynolds number.

1. Introduction

The presence of bubbles is almost ubiquitous in many chemical, biochemical, food and pharmaceutical industries. Some applications include bubble columns, production of polymeric alloys and ceramics, pulp and paper suspensions, paint and detergents, food processing and preservation, wastewater treatment, etc. The basic characteristic of clean bubbles that sets them apart from solid particles is their mobile surface. However, in many aforementioned applications, the surface mobility of dispersed bubbles can easily be affected by the presence of impurities (or contaminations) in the continuous phase. During the course of bubble rise in contaminated liquids, the insoluble surfactants can be adsorbed on the surface of the bubble and because of the surface advection the so-adsorbed surfactants move from the front stagnation point to the rear end. These surfactants further accumulate at the rear end to form a spherical stagnant cap which is immobile and do not allow the stresses to transmit to the interior of bubbles while the rest of the interface remains mobile [1–4]. This model is referred to as spherical stagnant cap model and is successfully extended to the case of droplets as well [5]. Subsequent research work has led

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Nomenclature

Ca	Capillary number (dimensionless)
C_d	total drag coefficient (dimensionless)
C_{df}	friction drag coefficient (dimensionless)
C_{dp}	pressure drag coefficient (dimensionless)
F_d	drag force (N)
I_2	second invariant of the rate of deformation tensor (s^{-2})
m	power-law consistency index (Pa s^n)
n	power-law behavior index (dimensionless)
P	pressure (Pa)
r	radial distance (m)
R	bubble radius (m)
Re	Reynolds number (dimensionless)
R_∞	domain radius (m)
U_o	Inlet velocity (m/s)
V	Velocity vector (m/s)

Greek symbols

α	stagnant cap angle (degree)
ε	rate of strain tensor (s^{-1})
η	dynamic viscosity of fluid (Pa s)
ρ	density of fluid (kg/m^3)
τ	extra stress (Pa)

to a coherent picture on the drag behavior of partially contaminated bubbles in Newtonian fluids [5–16]. The kinetics of stagnant cap formation depends on the adsorption/desorption kinetics of surfactants and convection over the bubble interface [17,18].

On the other hand, many polymeric liquids in chemical, biochemical and processing industries obey non-Newtonian viscosity including power-law viscosity [19]. Therefore, in our recent work [20], the effect of stagnant cap angle on the rise velocity of spherical bubbles in contaminated power-law fluids of moderate shear-thinning behavior ($n = 0.6, 0.8$) at Re = 10–200 has been numerically investigated using a finite difference method based SMAC algorithm implemented on a staggered grid in spherical coordinates. Unfortunately, our in-house code [20] faces convergence difficulty with the increasing non-linearity of governing equations as the power-law index deviates increasingly from unity; and this convergence difficulty magnifies with the decreasing Reynolds number (Re < 10). However, this kind of convergence difficulty in numerical studies on highly shear-thinning or highly shear-thickening fluids is not at all uncommon and many other researchers have also experienced such convergence problems [21–25]. Furthermore, in many real-life applications, often one encounter highly shear-thinning or highly shear-thickening type power-law fluids interacting with dispersed bubbles/droplets at small but finite Reynolds numbers. On the other hand, ANSYS Fluent is robust and reliable computational fluid dynamics based software for this kind of flow problems. Therefore, both from theoretical and engineering applications points of view, an extension of our previous work [20] to wider parametric range is necessary; and this work is aimed to fill this gap in the literature over the range of the power-law index, n: 0.2–1.6, Reynolds number, Re: 0.1–200; and stagnant cap angle, α: 0–180° using ANSYS Fluent.

2. Previous work

The literature pertaining to the rise of spherical bubbles in surfactant-laden Newtonian and power-law fluids are presented in our recent work [20] and elsewhere [26–28], respectively, and hence only small scores of them are presented herein. The spherical stagnant cap model, which was developed for the case of bubbles rise in contaminated Newtonian fluids [1], was then generalized by Sadhal and Johnson [2] for the case of spherical droplets in the creeping flow limit. They proposed an analytical expression for the drag force of contaminated bubbles and drops in the limit of Re → 0. He et al. [6] found that the results of Sadhal and Johnson [2] leads to under-prediction of cap angle and drag coefficient because their approach is limited to very small concentrations of contamination, and hence revisited the same problem by taking account of non-linear effects. Fdhila and Duineveld [7] carried out experiments and numerical simulations to obtain the rising velocity of small bubbles in quiescent contaminated solutions in the range of Reynolds numbers 50–200. Cuenot et al. [8] numerically investigated the effects of contamination (weakly soluble surfactants) on bubble rise velocity at higher Reynolds numbers. McLaughlin [9] numerically investigated the effect of surfactants on a deforming bubble rising in water at Reynolds numbers up to 600. These results [8,9] also provide the numerical support to the reliability of the stagnant cap model even at high Reynolds number. Takemura and Yabe [11] have experimentally and numerically investigated the rising velocity and the dissolution rate of carbon dioxide bubbles in slightly contaminated water. They found that their drag coefficients and Sherwood numbers obtained by stagnant cap model are in excellent agreement with their own experimental counterparts. Recently, Palaparthi et al. [14] conducted experiments and numerical simulations for glycerol–water system with a polyethylene–oxide surfactant under the assumption of spherical stagnant cap model. They also obtained a good agreement between experimental and numerical results. Wang et al. [15] numerically demonstrated that the mobility of the surfactant-retarded bubble interface can be increased by raising the bulk concentration of the surfactant. According to them, at high bulk concentrations of the surfactant, the interface can be saturated with the surfactant so that to act against the convective partitioning to decrease the surface surfactant gradient. In their subsequent work, Wang et al. [16] theoretically demonstrated that these surfactants can be used to control the formation, size and even disappearance of the recirculation wakes behind contaminated bubbles at order-one Reynolds numbers. Therefore, on the basis of experimental and numerical literature cited above, it is safe to conclude that a coherent picture has arrived on the flow and drag behavior of contaminated spherical bubbles in Newtonian liquids at least in the steady axisymmetric flow regime.

On the other hand, the literature on combined effects of non-Newtonian fluids and their contamination on the rise of spherical bubbles are very scarce. Rodrigue et al. [29] experimentally investigated the rising velocity of contaminated bubbles in Carreau model non-Newtonian fluids. Later Rodrigue et al. [26] employed perturbation technique to theoretically investigate the drag force of a contaminated bubble in Carreau model fluids in the limit of small Carreau number. Rodrigue et al. [30] further extended their study for power-law and Carreau model fluids using thermodynamic approach (which assumes linear difference in the surface tension from the equilibrium value) and a physical approximation (based on geometry and boundary conditions) in the limit of small Reynolds number. Tzounakos et al. [31] experimentally investigated the effect of surfactant concentration on the terminal velocity, shape and drag coefficient of bubbles in power-law liquids. They found that the bubble shape is independent of the surfactant concentration used in their study; however, the rise velocity and surface mobility of bubbles are strong functions of the concentration of the surfactants. In this work, using ANSYS Fluent, the flow and drag phenomena of contaminated bubbles in power-law liquids (both shear-thinning and shear-thickening) are numerically investigated over wider range of the conditions as the Reynolds number, Re: 0.1–200, the power-law index, n: 0.2–1.6, and stagnant cap angle, α = 0–180°.