CHEMICAL ENGINEERING RESEARCH AND DESIGN XXX (2013) XXX–XXX

Contents lists available at ScienceDirect

Chemical Engineering Research and Design

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

Effect of contamination on rise velocity of bubble swarms at moderate Reynolds numbers

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ABSTRACT

In this work, hydrodynamics of contaminated bubble swarms is numerically investigated using the free surface cell model combined with the spherical stagnant cap model. The governing field equations are solved numerically to elucidate the effect of Reynolds number, gas holdup and degree of contamination on the hydrodynamic behavior of bubble swarms. New extensive results are reported over the range of conditions as follows: Reynolds number, *Re*: 1–200, bubble holdup, Φ: 0.1–0.5, and stagnant cap angle, α: 0–180°. Finally, the effects of these parameters on streamlines and vorticity contours, surface pressure and vorticity distributions and on drag coefficients are discussed in detail. Briefly, the drag coefficients decrease with the decreasing stagnant cap angle and/or the decreasing bubble hold up and/or the increasing Reynolds number; whereas the ratio of the pressure and friction drag coefficients exhibits mixed trends with respect to these parameters.

Keywords: Contaminated bubbles; Stagnant cap; Hydrodynamics; Bubble holdup; Reynolds number; Drag

1. Introduction

The presence of bubbles is ubiquitous in process streams in many chemical and biochemical applications. However, it is difficult to maintain clean conditions and the presence of surfactants in multiphase flows is inevitable. The effect of surface contamination on the hydrodynamics of bubbles can effectively be handled by the use of the so-called spherical stagnant cap model. According to this model, the insoluble and non-diffusing surfactants get adsorbed on the surface of a bubble and move toward the rear end of the bubble because of surface advection caused by the main flow. Further these surfactants accumulate at the rear end of the bubble forming an immobile stagnant cap while the rest of the bubble surface remains mobile. As the concentration of surfactants gradually increases, the surface of the bubble is increasingly covered by surfactants and ultimately in the limit of the fully covered by surfactants the bubble behaves as a solid particle. The angle of surface contamination is a measure of the fraction of the bubble surface covered by the surfactants and is referred to as the stagnant cap angle (α). In our recent paper (Kishore et al., 2013), this model has been used to predict the drag behavior of a single spherical bubble in surfactant-laden power-law fluids, along with a thorough review of the pertinent literature and hence it is not repeated here. It is readily recognized that most real life applications entail swarms of bubbles rather than single bubbles. Notwithstanding the valuable physical insights gained from the study of single bubble dynamics, the presence of the neighboring bubbles modifies the flow field around each bubble which, in turn, impinges on the resulting momentum, heat and mass transfer rates in such systems. From a theoretical standpoint, a mathematical framework is needed to describe the inter-bubble interactions which can then be combined with the momentum equations to obtain the velocity field for bubble swarms rising in surfactant-laden fluids. Thus, the combination of spherical stagnant cap model and spherical cell approach can be advantageous. The spherical cell model, which is somewhat less rigorous, the inter-particle interactions are approximated by postulating the each spherical particle to be surrounded by a hypothetical concentric envelope of continuous phase. The size of the envelope is chosen such that the volume

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Received 7 May 2013; Received in revised form 13 September 2013; Accepted 7 October 2013
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http://dx.doi.org/10.1016/j.cherd.2013.10.006

Nomenclature

C_d	total drag coefficient
C_{df}	friction drag coefficient
C_{dp}	pressure drag coefficient
F_d	drag force (N)
p	pressure
r	radial distance
R	bubble radius (m)
Re	Reynolds number
R_∞	cell boundary
U_o	free stream velocity (m/s)
v_r	r-component of velocity
v_θ	θ-component of velocity
v_ϕ	ϕ-component of velocity

Greek Symbols

α	stagnant cap angle (degree)
ε	rate of strain tensor (s^{-1})
θ	streamwise direction (degree)
Π_ε	second invariant of the rate of strain tensor
ϕ	azimuthal direction (degree)
Φ	bubble holdup
μ	dynamic viscosity of fluid (Pa s)
ρ	density of fluid (kg/m^3)
$\tau_{r\theta}$	shear stress (Pa)

Subscripts

r	r-component
θ	θ-component
ϕ	ϕ-component

fraction of the dispersed phase of the cell is equal to the overall mean volume fraction of the system. Thus, the radius of the hypothetical envelope is related to the size of an individual sphere via the mean volume fraction of the dispersed phase. Further, in the spherical cell approach, all particles are assumed to be spherical and mono-size. Furthermore, over the years, many boundary conditions on the hypothetical envelope have been proposed (Chhabra, 2006; Zholkovskiy et al., 2007a,b); however, Happel (1958) and Kuwabara (1959) conditions are extensively used in hydrodynamic studies of bubbles, drops and particles in Newtonian and non-Newtonian continuous fluids (Chhabra, 2006). Though, both models prescribe free stream velocity for normal component of the velocity; however, the second boundary condition along the hypothetical envelope is different. In the free surface cell model, Happel (1958) proposed zero shear stress thereby emphasizing the non-interacting nature of cells. On the other hand, Kuwabara (1959) suggested the use of zero vorticity on the envelope. Because of the extra energy dissipation in the zero vorticity cell model, the resulting values of drag are larger than those obtained by the free surface cell model. While it is difficult to theoretically justify either of these conditions, both have been used to treat scores of situations involving flow of Newtonian and non-Newtonian fluids through multiple bubbles, drops and particles over wide range of Reynolds numbers (Chhabra, 2006). Furthermore, recently, Zholkovskiy et al. (2007a,b) have extensively reviewed the literature on the use of spherical cell approach for pure multiparticle-fluid hydrodynamics to electrokinetic phenomena in concentrated dispersed systems; and provided comparative information on the merits and demerits of different boundary conditions used along the spherical cell boundary. However, in regard to multiparticle-fluid interactions (such as in the case of flow through packed and fluidized beds, etc.), the superiority of free surface cell model over other cell models has been demonstrated in Chhabra (2006). Therefore, the aim of this work is to numerically investigate the hydrodynamics of contaminated bubble swarms rising in Newtonian liquids by solving governing continuity and momentum equations within the framework of the spherical stagnant cap model combined with the free surface cell model.

2. Previous work

Since the existing literature on the effects of surface-active agents (or contamination) on the rise velocity of single bubbles in Newtonian and non-Newtonian fluids is reviewed elsewhere (Rodrigue et al., 1996, 1997, 1999; Rodrigue and De Kee, 2002; Kishore et al., 2013), hence it is not repeated here. The reliability and accuracy of the spherical stagnant cap model are presented in our previous work (Kishore et al., 2013); however, some key findings on the effects of surfactants on bubble rise velocity other than stagnant cap model are presented herein. Rodrigue et al. (1996, 1997, 1999) and Rodrigue and De Kee (2002) have presented an excellent review on effects of surface-active agents on sudden change in the bubble rise velocity in Newtonian and non-Newtonian fluids. Zana and Leal (1978) proposed film and surfactant models to account for the effects of interface contamination on the bubble rise velocity. In the film model, they advocated that the adsorbed surfactant layer at the interface forms an elastic membrane film. In the surfactant model, the polymer molecules act as surface-active agents which modify the surface tension. Other possible explanations for the jump in bubble rise velocity due to the presence of surface-active agents is based on migration of polymer molecules in solution and on theory of mixing; and is thoroughly reviewed by Larson (1992) and Agarwal et al. (1994). According to this model, the polymer solutions can become nonhomogeneous because of molecule migration from higher to lower stress regions. Thus, a layer free from polymer can develop near the surface of the bubble. However, this model can explain a transition but not an abrupt change in bubble rise velocity, because this phenomenon is very slow and is dominated by molecular dynamics (Rodrigue and De Kee, 2002). Liu et al. (1995) attributed the sudden change in bubble rise velocity to the change in the shape of the bubble and the formation of cusp in the rear of the bubble. Finally, it is worthwhile to mention here that though several models are available to account for the effects of contamination on bubble rise velocity, from an engineering point of view, the stagnant cap model has gained wide acceptance in explaining the experimental results both on drag and heat/mass transfer coefficients (McLaughlin, 1996; Liao and McLaughlin, 2000; Liao et al., 2004; Ponoth and McLaughlin, 2000; Takemura and Matsumoto, 2000; Takemura and Yabe, 1999; Tzounakos et al., 2004; Zhang and Finch, 2001).

Furthermore, since the literature on the swarms of contaminated bubbles in Newtonian fluids is virtually non-existent even in the creeping flow regime, let alone for intermediate to large Reynolds numbers, it is instructive to briefly review the previous work for two extreme cases of the stagnant cap angles, i.e., $\alpha = 0$ (clean bubbles) and $\alpha = 180^\circ$ (fully contaminated bubbles or solid spheres). Within the framework of the free surface cell model adequate information is now available

Please cite this article in press as: Nalajala, V.S., et al., Effect of contamination on rise velocity of bubble swarms at moderate Reynolds numbers. Chem. Eng. Res. Des. (2013), http://dx.doi.org/10.1016/j.cherd.2013.10.006