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The effect of surfactant addition on the performance of a bubble column containing a non-Newtonian liquid

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ABSTRACT

The purpose of this work is to investigate how the addition of an organic surface active agent affects the characteristics of a bubble column equipped with a porous sparger and containing a non-Newtonian liquid. Water and an aqueous glycerin solution, both containing a minute amount of xanthan gum, were the non-Newtonian shear thinning liquids, while the gas phase was atmospheric air for all cases. Small amounts of the non-ionic surface active agent Triton X-100 was added to modify the surface tension of the non-Newtonian solutions. The results show that the diameter of the bubbles decreases and the transition point from the homogeneous to the heterogeneous is shifted to higher gas flow rates, when the surfactant is added. Appropriate correlations are also proposed, which take into account the liquid phase properties, the gas phase flow rate, as well as the column and sparger characteristics and predict with reasonable accuracy the transition point from the homogenous to the heterogeneous regime, the Sauter mean diameter of the bubbles and the average gas holdup.

1. Introduction

When it comes to gas–liquid contactors and reactors, bubble columns are of critical importance. Their use covers chemical, petrochemical, bioprocessing, bioremediation applications (Degaleesan et al., 2001; Moo-Young and Chisti, 1994) and the aerobic degradation of activated sludge (i.e. a non-Newtonian pseudoplastic liquid containing water, waste components and biomass) (Rosenberger et al., 2002). The absence of moving parts (resulting in lower energy consumption), the high heat and mass transfer rates, the ease of long-term sterile operation and most importantly the rapid mixing are their main advantages compared to other types of reactors (Kantarci et al., 2005). In addition, bubble columns are essential in the cultivation of shear sensitive cultures (e.g. microbial fermentations, fragile biocatalysts, and animal and plant cell cultures), due to the controllable shear rates that are applied inside the column leading to a uniform shearing environment (Chisti and Moo-Young, 1994; Moo-Young and Chisti, 1988).

The performance of bubble columns and especially the flow regimes and the hydrodynamic mechanisms encountered during their operation have been extensively studied in the past few decades. The main variables investigated are the gas holdup and the bubble characteristics along with the mass and heat transfer coefficients under the effect of certain parameters, such as the superficial gas velocity (U_{GS}), the liquid properties, the operating conditions (i.e. pressure and temperature) the type of sparger and the column and sparger diameters. A key parameter of a bubble column is the transition between the two major flow regimes, namely the homogeneous and the heterogeneous regime, depending on the gas flow rate, the column geometry and the physical

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Nomenclature

A	column cross section, (m^2)
Ar	Archimedes number, (dimensionless)
A_s	sparger cross section, (m^2)
C_S	Surfactant concentration, (% w/w)
d_B	bubble diameter, (m)
d_{32}	Sauter mean diameter, (m)
d_{Bi}	diameter of the bubbles of size class i, (m)
d_C	column diameter, (m)
d_P	pore diameter, (m)
d_S	sparger diameter, (m)
Eo	Eötvös number, (dimensionless)
f_B	number frequency of bubble size, (%)
Fr	Froude number, (dimensionless)
Fr_s	Froude number based on sparger diameter, (dimensionless)
Fr_{trans}	Froude number at transition point, (dimensionless)
g	acceleration of gravity, (m/s^2)
j	drift flux, (m/s)
k	minimum number of classes, (dimensionless)
n	number of classes used for the distributions, (dimensionless)
n_i	number of bubbles of size class i, (dimensionless)
Q_G	gas flow rate, (m^3/s)
Re	Reynolds number, (dimensionless)
S	sample size, (dimensionless)
U_{gs}	superficial gas velocity based on the sparger area, (m/s)
U_{GS}	superficial gas velocity based on the column cross section, (m/s)
$U_{GS,trans}$	superficial gas velocity based the column cross section at transition point, (m/s)
We	Weber number, (dimensionless)

Greek Letters

γ	shear rate, (s^{-1})
ε_g	average gas holdup, (dimensionless)
μ_L	liquid phase viscosity, (Pa s)
μ_{eff}	effective viscosity of a non-Newtonian fluid, (Pa s)
ρ_L	liquid density, (kg/m^3)
σ_L	surface tension, (N/m)

properties of both phases (Deckwer, 1992). In the *homogeneous* regime the bubbles generated are small, almost spherical and monodispersed, while the *heterogeneous* regime is characterized by a wide bubble size distribution. Anastasiou et al. (2013) and Kazakis et al. (2007) who studied bubble columns equipped with fine pore sparger, introduced the term *pseudo-homogeneous* regime to describe the regime in which discrete but not monodispersed bubbles are observed.

In previous works conducted in our Lab (Anastasiou et al., 2010; Kazakis et al., 2008, 2007; Mouza et al., 2005) we have experimentally studied bubble columns equipped with a fine pore sparger and containing various types of liquids. A fine pore sparger holds advantages over other types of gas distributors, since it produces numerous and smaller bubbles and thus offers a greater gas–liquid contact area. We have concluded that the various design parameters (i.e. the gas holdup, the transition point and the bubble size distributions) are influenced by the liquid phase properties and the bubble column geometrical characteristics. As a result, we have proposed appropriate correlations that are based on dimensionless groups and are able to satisfactorily predict the key design parameters. In a recent work (Anastasiou et al., 2013) we have studied bubble columns with fine pore sparger and non-Newtonian liquid phase. It is known that in bioreactors the fluids involved are usually non-Newtonian, while biosurfactants are commonly produced in biological processes. Consequently, there is still need to investigate the effect of surfactants on the operation of bubble columns that contain a non-Newtonian liquid.

It is known that the addition of small amounts of additives results in the extension of the homogeneous regime as it deters bubble coalescence (Camarasa et al., 1999). Similar findings are also reported by Ruzicka et al. (2008) who investigated the effect of salt additives (i.e. $CaCl_2$) on the homogeneous-heterogeneous regime transition in a water-air system. Anastasiou et al. (2010), who studied the addition of organic surface active agents (i.e. *SDS*, *CTAB*, *Triton X-100*) in a bubble column equipped with fine pore sparger and containing a Newtonian liquid, proposed a generalized correlation that can predict the gas holdup with reasonable accuracy (±10%).

García-Abuín et al. (2012) studied similar systems in a bubble column where the gas phase was distributed through five holes. To the authors' best knowledge there is still no work published considering the effect of surfactant addition to a non-Newtonian fluid on the performance of bubble columns equipped with a fine pore sparger.

Thus, the ***purpose*** of this work is to extend our previous studies concerning bubble columns, whose diameters are less than 15 cm and are equipped with a fine pore sparger, by investigating systems where the liquid phase is a ***shear-thinning*** liquid containing a small amount of a ***surfactant***. The gas phase is atmospheric air. The effect of liquid phase physical properties, gas phase flow rate as well as the column and the sparger geometrical characteristics on gas holdup and bubble size distribution will be experimentally investigated. Finally, the validity of previously proposed correlations (i.e. Kazakis et al., 2007; Anastasiou et al., 2010, 2013) for the prediction of gas holdup at the pseudo-homogeneous regime, the *Sauter* mean diameter of the bubbles and the transition point from the homogeneous to the heterogeneous regime, will be tested and adjusted to take into account the combined effect of the non-Newtonian behavior and the surfactant addition.

2. Experimental setup and procedure

The experimental setup (Fig. 1) consists of a vertical cylindrical *Plexiglass®* column of 9 cm i.d. and 150 cm height, filled with liquid up to 40 cm above the sparger. The gas phase enters the column through a fine pore sparger, namely a *316 L SS* porous disk (*Mott Corp.®*) with a nominal pore size of 40 μm, located at the center of the bottom plate. To investigate the effect of sparger to column diameter ratio, two sparger sizes were used, namely one with i.d. 4.5 cm and one with i.d. 9.0 cm that covers the whole bottom plate. Initially, i.e. when the smaller sparger was used, the gas was entering through a single nozzle (i.d. 1 cm) which was located 1 cm beneath the sparger. This setup has been used for all our previous experimental works