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The effects of liquid phase rheology on the hydrodynamics of a gas–liquid bubble column reactor

Amin Esmaeili, Christophe Guy, Jamal Chaouki*

Department of Chemical Engineering, École Polytechnique de Montréal, P.O. Box 6079, St. C.V., Montreal, Que., Canada H3C 3A7

HIGHLIGHTS

- The effect of liquid rheology on hydrodynamics of a bubble column reactor is studied.
- A new approach based on the dynamic moduli is proposed to interpret the rheological effects.
- Coalescing effects of highly viscous liquids can be suppressed in the presence of elasticity.
- The elastic effects of non-Newtonian liquids increase the gas holdup.
- Bubble chord length decreases when the elasticity of liquid dominates.

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ABSTRACT

In this study, the effects of liquid phase rheology on the hydrodynamics of a pilot scale bubble column reactor is extensively investigated by applying various types of test liquids with different rheological characteristics as the operating fluids. Two fiber optic probes and several pressure transducers are used and different time-domain and frequency-domain analyses are applied to perform a comprehensive interpretation of the pressure signals and measure the hydrodynamic parameters of the gas phase. A new approach is proposed based on the dynamic moduli of viscoelastic solutions to better understand the simultaneous viscous and elastic effects. It was observed that the elasticity of the operating liquid reduced the average bubble chord length and increased the total gas holdup. The obtained results reveal that although the viscosity is more favorable for coalescence, the elasticity of the operating liquid can prevent bubble coalescence by showing a solid-like behavior at the interface of two bubbles.

1. Introduction

Bubble column reactors have a wide range of applications in processes based on the contact between gas and liquid phases, such as the Fischer–Tropsch (FT) synthesis, the liquid phase methanol synthesis (LPMeOH) and the hydroconversion of heavy oils and petroleum residues (Shaikh and Al-Dahhan, 2007; Sheikhi et al., 2013; Wang et al., 2007). These reactors have received a great deal of attention from both academia and industry over the last few decades since they offer excellent heat and mass transfer performance, low operating and maintenance costs because of the absence of moving parts, and are easy to operate (Gandhi et al., 1999; Kantarci et al., 2005; Shah et al., 1982).

With the dramatic increase in the world energy demand and the appearance of a new generation of feedstocks, gas–liquid contactors and in particular bubble column reactors have become increasingly important. Although many liquids in industrial processes are low molecular weight and Newtonian-like fluids, an increasing number of high molecular weight solutions with complex internal structure and non-Newtonian behavior are being used in the fields of enhanced oil recovery, wastewater treatment, polymerization processes, and the production of foods and pharmaceuticals. Bubble behavior as the key hydrodynamic factor in bubble column reactors can drastically change in the presence of non-Newtonian fluids. While research on bubble columns is mainly focused on Newtonian fluids, it is of fundamental importance to understand the non-Newtonian effects on the behavior of bubbles and hydrodynamics.

Generally, increasing the liquid phase viscosity has been shown to decrease the total gas holdup and hinder the formation and stability of a homogeneous bubble bed. This negative effect is mainly ascribed to the existence of drag forces enhancing bubble coalescence in the gas sparger zone (Ruzicka et al., 2003; Urseanu et al., 2003; Zahradnik et al., 1997). Schafer et al. (2002) pointed out that the turbulence in the liquid phase diminishes by increasing the viscosity and consequently, the liquid eddies obtain less

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* Corresponding author.
E-mail address: jamal.chaouki@polymtl.ca (J. Chaouki).

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energy and bubble breakage decreases, which results in an increase in bubble size. Larger bubbles with wider bubble size distribution in a highly viscous medium cause the heterogeneous flow regime to appear at lower superficial gas velocities (Clarke and Correia, 2008; Gupta et al., 2009; Su et al., 2008). The negative effects of viscosity on the interfacial area have also been reported in several studies (Clarke and Correia, 2008).

The hydrodynamics of bubbles in non-Newtonian fluids is quite different from that in Newtonian fluids. Previous studies mostly considered Newtonian and non-Newtonian media with simple internal structure and rheological behavior. However, the non-Newtonian characteristics are responsible for a number of particular phenomena that are not observed in Newtonian fluids (Kawase et al., 1992; Kemiha et al., 2006). Gomez-Diaz et al. (2009) showed that the gas–liquid interfacial area decreases as the viscosity of pseudoplastic k-carrageenan solutions increases. Majumder et al. (2007) have reported a significant contribution of viscous forces to the bubble–liquid interfacial shear stress and a higher pressure drop in non-Newtonian solutions. Miura et al. (2012) have indicated that increasing the non-Newtonian properties of Carboxymethyl Cellulose (CMC) and Xanthan gum solutions reduce the gas holdup.

Moo-Young and Kawase (1987) showed that the bubble coalescence rate is higher in the shear-thinning CMC solutions compared to the viscoelastic Polyacrylamide (PAA) solutions. This has been attributed to the resistance effect of the viscoelastic fluid squeezed out between a pair of bubbles, resulting in a decrease of the coalescence rate and the formation of numerous fine bubbles with a long retention time in the PAA solution. On the other hand, it has also been reported that the solid-like properties of elastic liquids can diminish the bubble breakup rate and increase the average bubble size (Suh et al., 1991). Olivieri et al. (2011) have investigated the effects of liquid properties on the hydrodynamics of a lab-scale bubble column reactor. Their results showed that the homogeneous flow regime is stabilized in non-Newtonian liquids having elastic properties and the regime transition velocity increases with liquid elasticity.

Due to the inherently complex nature of elasticity, the literature on the effects of elastic properties on the hydrodynamics of bubble columns is scarce and conflicting results have been reported. Therefore, there is still strong motivation to gain a better understanding of the detailed influence of fluid elasticity on hydrodynamics. The effects of increasing viscosity and elasticity on hydrodynamic parameters have been summarized in Table 1.

Several processing techniques have been developed and utilized to characterize the hydrodynamics of bubble column reactors, including particle image velocimetry, electrical resistance tomography, laser Doppler anemometry, bed vibration signature, optical fiber signals and pressure fluctuations (Cartellier, 1992; Shaikh and Al-Dahhan, 2007; Sheikhi et al., 2013; Wild et al., 2003). Drahos et al. (1991) characterized three basic flow patterns in the bubble column using statistical analysis of pressure fluctuations in both time and frequency domains. They showed that the power spectrum of pressure fluctuations is a useful tool to identify different sources of the pressure fluctuations in the bubble column reactors. Al-Masry et al. (2007) and Gourich et al. (2006) identified the flow regime transition point by statistical and spectral analysis of the differential pressure signals. Barghi et al. (2004) applied the statistical analysis of pressure fluctuation signals combined with gas holdup analysis to study the flow regime transition in a slurry bubble column. Recently, Sheikhi et al. (2013) studied the hydrodynamic state of a bubble column by analyzing the pressure fluctuations in both time and frequency domains. Moreover, Chilekar et al. (2005) estimated the average large bubble size in slurry bubble columns using spectral analysis of pressure fluctuation signals. Xu et al. (2005) and Schweitzer et al. (2001) applied fiber optic probes to evaluate bubble flow characteristics in a bubble column reactor by performing the measurements at several radial and axial positions. Chaumat et al. (2007) established a new methodology for the double optic fiber probe to derive gas holdup, bubble velocity and the mean Sauter diameter in a pilot bubble column operated under high gas flow rate. Chen et al. (2003) investigated the effect of column scales on the local gas holdup, bubble frequency, bubble size, bubble velocity and flow structure by means of a single-tip optical fiber probe.

Table 1
Summary of the effects of increasing viscosity and elasticity on different hydrodynamic parameters.

Parameter	ε_g	$U_{g,tran.}$	**Bubble coalescence**	d_b	a
↑ **Viscosity**	↓	↓	↑	↑	↓
↑ **Elasticity**	?	↑	↓	?	?

↑: Increasing; ↓: Decreasing; ?: No trend reported.

The viscosity and also the elasticity of the liquid phase may have strong effects on the bubble and liquid dynamics in bubble columns operating with non-Newtonian liquids. However, these phenomena are not well understood at this stage. Due to the complex rheology of non-Newtonian liquids, studies on the hydrodynamics of bubble columns operating with these types of liquids are still scarce and experimental work in this area is mainly limited to the study of single bubbles moving in stagnant liquids. On the other hand, it is very difficult to separate the viscosity and elasticity effects if they are studied together. Therefore, the main objective of this work is to conduct an extensive experimental study on the simultaneous effects of viscosity and elasticity of non-Newtonian liquids on the most important hydrodynamic parameters of bubble columns such as gas holdup, bubble size, and bubble related parameters. A complete set of non-Newtonian solutions has been strategically chosen to discriminate between the elastic and viscous effects. In order to gain comprehensive insight into the hydrodynamics and bubble properties, the pressure fluctuations are sampled by a series of pressure transducers along the column height and several data analysis approaches and techniques are applied to measure the hydrodynamic parameters and characterize the flow dynamics inside the column. Furthermore, the local measurements are conducted by using two fiber optic probes to evaluate the gas holdup radial distribution and mean bubble chord length.

2. Experimental details

2.1. Bubble column setup

The experiments described in this study are carried out in a 2.7 m high Plexiglas column with an inside diameter of 0.292 m. Oil-free compressed air is used as the gas phase and injected into the column through a perforated plate distributor with 94 holes that are 1 mm in diameter providing uniform distribution of the gas phase. The air flow rate is adjusted by two rotameters and the superficial gas velocity varies from very low gas velocities up to 0.22 m/s covering both homogeneous and heterogeneous flow regimes. The liquid phase is fed into the column through a conical box located at the bottom of the column. Since the liquid phase is operated in a batch mode, the unaerated liquid height is set to 1.1 m at the beginning of all experiments. The bubble column setup is schematically shown in Fig. 1.

2.2. Pressure time series and fiber optic probe measurements

Several fast response pressure transducers (response time ~1 ms) flush-mounted on the column wall are used to record