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Investigating bubble dynamics in a bubble column containing shear thinning liquid using a dual-tip probe

Niloufar Jamshidi, Navid Mostoufi*

Multiphase Systems Research Lab., School of Chemical Engineering, College of Engineering, University of Tehran, P.O. Box11155/4563, Tehran, Iran

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ABSTRACT

Bubble dynamics was characterized experimentally in non-Newtonian shear thinning fluids with different viscosities by a dual-tip resistivity probe. The experiments were carried out in a 9 cm diameter column while the superficial gas velocity varied between 0.5 and 7 cm/s. Air, injected through a diffuser, was the dispersed phase and various solutions of carboxy-methyl cellulose were used as the continuous liquid phase. An algorithm was developed to detect each individual contact of bubbles with the probe needles. It was shown that increasing the viscosity produces larger bubbles which make the homogeneous flow regime instable at liquid viscosities greater than 7 cP. It was found that the axial profiles of bubble chord length and velocity are affected by both shear thinning behavior of the solutions and the viscosity of the solution. The shear thinning behavior causes a descending trend of axial distribution of bubble rise velocity. Moreover, gas holdup reaches a maximum in the middle of the column in solutions studied. The probability distribution of bubble chord length was well fitted by a log-normal distribution. However, the bubble rise velocity distribution is Gaussian in the homogeneous regime at low gas flow rates. Correlations are given for evaluating bubble chord length and bubble rise velocity.

1. Introduction

Bubble columns are extensively used in a wide range of industrial processes, including industrial waste treatment [1,2], Fischer-Tropsch synthesis [3,4], enhanced oil recovery [5], evaporation [6] and fermentation [7,8], in which the continuous phase is often a non-Newtonian liquid [9,10]. These columns have many advantages as reactors which have promoted their uses in industry. For instance, large difference between densities of gas and liquid causes phases to mix well. Also, in catalytic reactions, the age of the solid catalyst particles would be prolonged, since the reaction heat is easily released to liquid from the particles because of high heat transfer coefficient of the surrounding liquid. Simple construction of bubble columns easifies the operation and it also reduces the relative operational costs [11]. However, the complex hydrodynamics of bubble column makes the design and scale-up of these reactors challenging. Therefore, further research on various hydrodynamic parameters as well as bubble dynamics in bubble columns is needed. The bubble characteristics is a key factor affecting the hydrodynamics of bubble columns and their scale-up [12–14]. The bubble velocity dictates the gas phase residence time in liquid. Thus, it affects the conversion in a reactor [12]. Therefore, it is important to investigate the bubble dynamics in more details in non-Newtonian viscous liquids which are widely used in industrial reactors.

Various measurement techniques have been employed to investigate the behavior of bubbles in bubble columns. Bubble frequency is an important parameter which directly affects the gas holdup [15]. Also, bubble chord length is directly related to the bubble size [16]. These two parameters are important because based on them interfacial mass transfer area in a bubble column reactor can be estimated. The bubble rise velocity and bubble chord length can be calculated by both single-tip and dual-tip probes. The way of estimation of rise time of bubbles differs in signal processing for single-tip [17–19] and dual-tip probes [20–24]. The resistivity or conductivity probes and fiber optic probes are the most applied methods of probing measurement techniques [17,18,23,25–27]. Although, the bubble rise velocity can be determined using a single-tip probe, a dual-tip probe can do the same with more accuracy. Measuring the bubble rise velocity by a single-tip probe contains two stages, (i) selecting two thresholds in the voltage signal (at rise of the voltage when the bubble is piercing the tip) and (ii) evaluating the rise time from rise of the voltage considering the chosen thresholds and estimating the bubble rise velocity by multiplying the rise time by a coefficient of proportionality obtained from the probe calibration [19,26]. Assessing the rise time from the voltage signal is affected by the level of thresholds as well as the liquid film drainage time of the probe tip [28–30]. Furthermore, an accurate and specific calibration procedure is needed to perform measurements, taking into

* Corresponding author.
E-mail address: mostoufi@ut.ac.ir (N. Mostoufi).

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Nomenclature

d_c	column diameter, (mm)
F	bubble frequency, (Hz)
$F_{s1,s2}$	cross correlation of S_1 and S_2
H	column height, (m)
h	height of the probe position, (m)
$h_{falling}$	height in which the probe was released, (m)
d_b	bubble diameter, (mm)
d_b'	bubble chord length, (mm)
K	consistency index, (Pa.s^n)
n	flow index
N_p	number of peaks in signal
v_{th}	threshold level voltage, (V)
T	test time, (s)
t	time, (s)
t_i	peak width, (s)
S_1	response signal of the downstream needle, (V)
S_2	response signal of the upstream needle, (V)
v_g	mean gas voltage, (m/s)
v_l	mean liquid voltage, (m/s)
V	voltage amplitude, (V)
v	impact velocity, (m/s)
u_{gs}	superficial gas velocity, (m/s)

Greek letters

γ	shear rate, (s^{-1})
ε_g	gas holdup
μ_{app}	apparent viscosity, (Pa s)
ν	dynamic viscosity, ($m^2 s^{-1}$)
σ	surface tension, ($N m^{-1}$)
ρ_l	liquid density, ($kg m^{-3}$)
$\Phi_g(t_i)$	phase density function
Ω	electrical resistance, (Ω)

account both single-tip probe design and liquid-gas system [29,31]. In the dual-tip probing, the bubble rise time is the lag time between the corresponding peaks appearing in response signals of the first and the second tips. It is reported that despite proper calibration of single-tip probe, still its measurements are associated with uncertainties [26]. Therefore, the rise time can be estimated directly by a dual-tip probe which is more accurate compared to a single-tip probe. In the present work, the dual-tip resistivity probe was utilized to measure bubble dynamics.

Magaud et al. [32] considered four probable arrangements for bubble crossing a dual-tip probe and accepted one of these layouts by a simple statistical analysis. Several researchers have considered the temporal distance between two successive peaks in the signals of downstream and the upstream wired mesh sensors to be the shortest bubble rise time in each event [23,33,34]. Other methods, such as cross-correlation and multichannel methods, also can be employed to calculate the mean bubble rise velocity [35]. A major drawback of these methods is that it is not easy to detect the distribution of bubble rise velocity and chord length. In the presented study, bubble rise time distribution was obtained by implementing cross-correlation method applied to small segments of two pulsed signal pairs simultaneously for detecting individual bubble.

Many researchers have studied the effect of liquid viscosity on the hydrodynamic parameters of bubble column, mainly gas holdup. However, a few researches have reported the effect of liquid viscosity on bubble dynamic parameters, like bubble size and bubble velocity. The effect of liquid viscosity on the column hydrodynamics also has been widely studied [21,22,36–42]. In most of these works, velocity and the size of bubbles and the corresponding distributions were not investigated. Some researchers studied the bubbly flow in non-Newtonian solutions [21,43–46] and investigated the effect of viscosity on gas holdup without focusing on bubble dynamics. Most of these researchers reported the negative effect of liquid viscosity on the gas holdup. Nevertheless, there are researches reporting an initially slight increase and a subsequent decrease of the gas holdup with increasing the liquid viscosity [22,40,47]. More recently, researchers have investigated the effect of liquid rheology on gas holdup and bubble size [18]. though; the bubble rise velocity and relative distributions are not studied. In major of the studies, it is confirmed that as the liquid viscosity increases, large bubble fractions and relative distribution width increases as gas holdup decreases [21,22,41,48]. Though, for bubble rise velocity which is less investigated, diverse results are reported. Wu et al. [22] proposed that for CMC solutions with viscosities less than 10.39 cP, bubble rise velocity increases as the viscosity increases and then remains constant for viscosities above 10.39 cP. Although, in another study with CMC solutions the increasing trend of bubble rise velocity with viscosity is confirmed up to 23 cP [21]. Therefore, the systematically investigating methods for direct measuring of the bubble dynamics, especially bubble rise velocity and its distribution need to be provided.

In this work, a non-Newtonian shear thinning liquid (aqueous solutions of carboxy methyl cellulose or CMC) was used for investigating the effect of viscosity on the bubble dynamics in a bubble column. Bubble velocity, bubble chord length, gas holdup, and bubble frequencies were measured by a dual-tip resistivity probe. The effects of CMC concentration, axial position of the probe and superficial gas velocity on the bubble dynamics were investigated. Also, the impact of the shear thinning behavior of liquid on bubble dynamics along the column was discussed. An algorithm was also developed to detect individual bubbles not deviated after touching the first needle.

2. Experiments

2.1. Experimental setup and materials

A cylindrical lab-scale bubble column made of Plexiglas was used to conduct experiments. The schematic of the experimental setup is sketched in Fig. 1. A perforated distributor was employed with about 0.3% open area. The column was initially filled with liquid, roughly up to $L/D = 13$. The gas flow rate was controlled using a mass flow controller (Alicat – MC series 50 SLPM). Details of the experimental setup are provided in Table 1.

Solutions of CMC in tap water with different concentrations (0.05, 0.1, 0.2, 0.6%wt, with corresponding viscosities of 1.4, 4.1, 7 and 21 cP, respectively) were used in the experiments. The solutions were prepared by gradual dissolving of small amounts of CMC powder to a stirred tank containing tap water. Physical properties of these liquids are given in Table 2. Surface tension of each solution was measured with a Krüss K6 tensiometer by the platinum ring detachment method with a precision of 1 mN/m. The simple shear study was also carried out using modular compact rheometer (MCR300 SN621205, Anton Paar) in the range of 1–1000 s^{-1}. The solutions exhibited a stronger shear thinning behavior as the CMC concentration was increased. The shear thinning behavior of CMC solutions is also reported in other investigations [21,49]. The power-law parameters evaluated based on the experimental data are reported in Table 2. Note that the values reported in this table are representative for the apparent viscosity at $u_{gs} = 0.05$ cm/s. The apparent viscosity in this table was estimated from [12]: