Preliminary Assessments of Combined Effects of Surface Tension and Viscosity on Bubble Column Hydrodynamics

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The present contribute reports results of combined effects of liquid features on the hydrodynamics of a lab-scale bubble column. In particular, the combined effects of viscosity - Newtonian fluid – and surface tension were investigated. The experimental apparatus consisted of a 10 L bubble column: a 120 mm ID, 1.8 m high Plexiglas column equipped with 0.4 mm needles gas distributor, free area 0.13%. The unit was equipped with gas flow controller, humidifier, diagnostic instrumentation, and data acquisition unit. The unit was operated batchwise with respect to the liquid phase at temperature of 25°C. The liquids investigated were aqueous solutions of sodium alginate and sodium chloride. The concentration of sodium alginate was increased up to 0.5%$_W$, the sodium chloride up to 2 M. Solutions were characterized in terms of viscosity, surface tension, and conductivity. The viscosity ranged between 0.90 and 20 mPa•s, the surface tension between 68.4 and 71.9 mN/m, and conductivity between 0 and 5.34 S/m.
Results showed that the transition velocities between hydrodynamic regimes (homogenous regime – transition regime – heterogeneous/turbulent regime) strongly depends on investigated liquid features.

1. Introduction

Multiphase reacting systems are successfully adopted in several industrial fields, from the energy industries to biotechnology processes, from pharmaceutical production to chemical conversions. Typically, unit configurations depend on phase properties and application (Fan, 1989; Deckwer, 1992; Olivieri et al., 2010; Cozma and Gavrilescu, 2012). Although the undoubted success of these systems, their characterization to support optimized designing and conduction still ask for investigation.

Hydrodynamics of two phase gas-liquid vertical apparatus – bubble columns (BC), airlifts – is typically characterized by three regimes: homogeneous regime, vortical-spiral flow regime, and heterogeneous/turbulent regime (Chen et al., 1994). Flow structures and transport phenomena may drastically change with the hydrodynamic regime. Accordingly, the performances of two phase units change with the hydrodynamic regime. It has been highlighted that liquid properties, reactor design, and operating conditions strongly affect the stability interval of the hydrodynamic regimes (Zahradník et al., 1997; Ruzicka, 2013). In particular, viscosity (μ), surface tension (σ), and rheological behaviour of the liquid phase affect the two-phase flow structures and the stability of different regimes (Zahradník et al., 1997).

Liquid viscosity has a twofold effect on gas-liquid hydrodynamics: low viscosity stabilizes the homogenous regime, high viscosity destabilizes this regime (Ruzicka et al., 2003; Olivieri et al., 2011). Accordingly to the observed effects, Ruzicka et al. (2003) proposed that the role of the viscosity on hydrodynamics depends on the acting stresses. For viscosity of the order of magnitude of the water, the drag force is sufficient to reduce bubble rise velocity but it is not strong enough to promote bubble coalescence.

Therefore, an increase in gas hold-up is observed. At high viscosity, bubble-coalescence prevails over the drag reduction and flow uniformity is broken by large bubbles.

Electrolytes have a twofold effect on the hydrodynamics: the homogenous regime is stabilized at low electrolyte concentration (c_E), and it is destabilized at high electrolyte concentration (Ruzicka et al., 2008; Orvalho et al., 2009). The gas holdup changes with the surface tension and it is characterized by a maximum at a critical surface tension. Three phenomena contribute to the voidage increase. First, small bubbles form when the surface tension increases. Second, bubble coalescence is suppressed and small bubbles do not have the opportunity to grow. Third, boundary conditions at the bubble surface change from slip to no-slip flow and bubbles experience a higher drag. As a results of the three phenomena bubble up-rise velocity decreases and gas holdup increases. At high surface tension, the voidage saturation may be to the reduced capacity to both repressing bubble size increase and increasing rigidity of the bubble surface.

Plots of hydrodynamic features (e.g. gas flow rate or voidage) at the verge of the hydrodynamic regime stability vs. fluid features (viscosity, electrolyte concentration) are typically characterized by a maximum. The critical value of the fluid feature at the maximum marks the interval of stabilizing vs. destabilizing regions with respect to the hydrodynamic regime.

The literature is lacking of maps of regime stability regarding the simultaneous multi-features of the liquid phase. The present contribution reports on the combined effects of the liquid features on the hydrodynamics of lab-scale bubble column (BC). In particular, the combined effects of viscosity - Newtonian fluid – and surface tension were addressed. The hydrodynamics was characterized in terms of gas holdup and drift-flux as a function of the superficial gas velocity.

2. Experimental

2.1 Materials
The surface tension and the viscosity of the investigated solutions were modulated by fine tuning of the concentration of sodium chloride (electrolyte) and of sodium monoacid alginate (viscous agent). Ultra pure water obtained by a distillation system with a reversed osmoses filter was adopted as solvent.

The liquid kinematic viscosity was measured by CVO 120 High Resolution NF Rheometer of the BOHLIN INSTRUMENTS. The rheometer was equipped with a double cup system: the dimensions of the stainless steel double caps were 40/50 mm.

A Sigma 70 KSV INSTRUMENTS was adopted to measure the surface tension. It was equipped with a ring system: 9.545 mm radius platinum ring, wire diameter 0.185 mm.

The density (ρ) of solutions – datum fundamental for accurate measurement of the surface tension – was measured with the DMA 5000 (ANTON PAAR).

The conductivity (γ) of the solutions was measured by the Stratos device (Knick) with the conductivity probe IN PRO 7001. The equipment was calibrated using a 0.1M sodium chloride solution in bi-distilled water characterized by known conductivity.

Table 1 reports the composition and the properties of the investigated liquid solutions at 30°C.

2.2 Apparatus
The experimental apparatus consists of a bubble column (BC) (Figure 1). The BC was equipped with a gas flow controller, a humidifier, an internal heater, diagnostic instrumentations, and a data acquisition unit. The BC was a cylindrical column made of Plexiglas characterized by ID 0.12 m and height 2.0 m. The gas distributor consisted of a windbox and a needle plate. The wind-box chamber of 0.30 m height was filled with ceramic rings to uniform gas flow. The needle plate consisted of 128 needles of 0.4 mm orifice diameter, 20 mm long. Pressure taps were present along the BC. Further details can be found elsewhere (Olivieri et al., 2007, 2011).

Instrumentation consisted of broad-bandwidth relative pressure transducers, differential pressure transducers, and a fine thermoresistance.

Visual inspection of the apparatus enabled qualitative and quantitative characterization of the hydrodynamic regime. A rough assessment of the overall gas hold-up was evaluated by measuring the liquid free-surface level.

The pressure was measured along the unit by means of electronic broad-bandwidth relative pressure transducers. Electronic differential pressure transducers measured the pressure difference in the BC between different levels. Data were logged on a PC equipped with an acquisition-board. The acquisition frequency was set at 8 kHz and the acquisition time at 300 s. Local gas hold-up was assessed working out

Table 1: Liquid phase properties

NaAlg - %$_w$	NaCl - M	μ – mPa s	σ – mN/m	γ – S/m	ρ – kg/m^3
0	0	0.90	71.9	0	0.997
0.18	0.1	5.35	71.2	4.58	1.001
0.2	0.001	14.2	70.7	0.0715	0.998
0.2	0.5	5.45	69.2	2.93	1.018
0.2	0.7	5.10	69.7	3.73	1.025
0.2	2	5.35	72.6	5.34	1.071
0.4	0.05	18.1	68.4	0.6767	1.000
0.4	0.10	18.9	69.9	1.23	1.002
0.4	0.15	17.7	68.6	1.78	1.004
0.4	0.7	17.2	70.1	2.96	1.025
0.4	1	20.05	70.9	3.38	1.037

the time averaged value of the axial pressure drop. The overall gas holdup (ε_G) was assessed as the average of local values.

All the measurement are characterized by error < 5%. Liquid phase properties are characterized by error <1%

2.3 Operating conditions and Procedures

Tests were carried out at 25°C. The liquid volume in the BC was set at 10 L.

The plant was operated batchwise with respect to the liquid. Air was continuously fed to the column during operation at atmospheric pressure. The gas superficial velocity (U_G) was quasi-steadily increased from zero up to a maximum value that was limited by one of the following constraints: i) the maximum expansion of the two-phase system compatible with the present configuration of the units (column height = 2.0 m); ii) the maximum admissible over-pressure in the units upstream the gas sparger. Steadiness of operation was continuously monitored by recording the pressure along the unit.

The temperature of the system was finely controlled to prevent spurious effects due to change of liquid properties with the temperature.
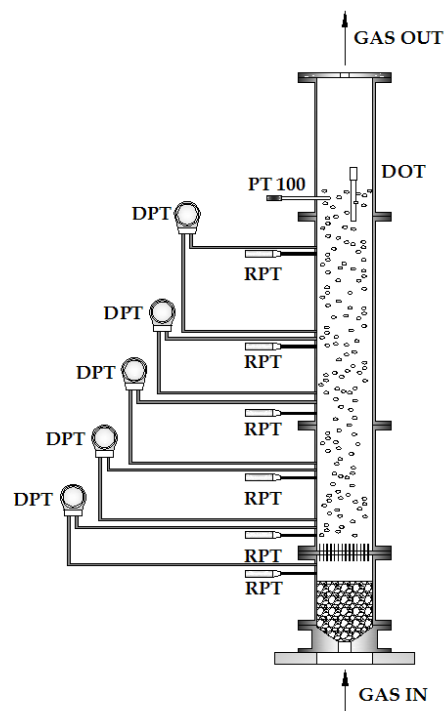

Figure 1: Bubble column apparatus. DPT) differential pressure transducer; RPT) relative pressure transducer; DOT) dissolved oxygen probe; Pt 100) thermoresistance.

3. Results and Discussion

3.1 Selection of the solutions

The preliminary characterization of the liquid solutions reported in table 1 pointed out that both the viscosity and the surface tension depended on the sodium chloride and the sodium alginate. In particular, the sensitivity of the surface tension to the NaCl concentration resulted quite low under the operating conditions tested. Nevertheless the low sensitivity the attention to the exact control of the surface tension was necessary. Indeed, Orvalho et al. (2009) reported that even small change in σ has strong effects on the BC hydrodynamics.

The fine tuning of the electrolyte effects on liquid features was carried out adopting the liquid phase conductivity as controlled feature. From one hand, the sensitive of γ with respect to NaCl concentration is higher than that of σ. From another hand, the relationship between γ and σ is quite reliable. Figure 2 reports the map of γ vs. μ for all the investigated solutions. The iso-concentration of both NaCl and NaAlg are also reported. It appears that NaCl=0.01 M marks solutions for which the sensitivity of viscosity/surface tension on the salts change: for NaCl>0.01 M, γ is quite constant with the NaCl concentration and μ depends mainly on the alginate concentration; for NaCl<0.01 M, both γ and μ are sensitive on NaCl and alginate concentration.

Tests aimed at investigating the effects on BS hydrodynamics behaviour of viscosity separately from those of the surface tension were carried out adopting three groups of solutions. Two groups were characterized by constant viscosity (group I – μ~5 mPa s; group II – μ~18 mPa s), one group was characterized by constant surface tension (group III – σ~71 mN/m).

3.2 BC hydrodynamics

Figure 3 reports the Wallis drift flux plot for tests carried out with the solutions belonging to the group I. According to the procedure reported by Olivieri et al. (2011), the transition between the homogenous regime and the vortical-spiral flow regime in BC was marked by the velocity (U_G^C) and the overall gas holdup (ε_G^C) at which the data depart from the theoretical curve (dashed lines). The critical values of U_G and ε_G were assessed for each solution of the group I, II, and III.

Figure 4 reports the values of U_G^C (4.A) and ε_G^C (4.B) for solutions characterized by constant viscosity: group I – μ~5 mPa s; group II – μ~18 mPa s. For solution of the group I, effects of σ on the stability of the homogenous regime was not monotonic: the superficial gas velocity and gas holdup at the onset on the vortical-spiral flow regime are characterized by a minimum at σ = 71.2 mN/m (0.18%w NaAlg, 0.1 M NaCl). The behaviour of solutions of the group II appears different from that observed for the solution of the group I. Under the operating conditions tested, U_G^C and ε_G^C appeared almost constant with the surface tension. It is interesting to note that the maximum gas holdup increases with the viscosity, even though the transition at the vortical-spiral flow regime is anticipated when the viscosity increases.
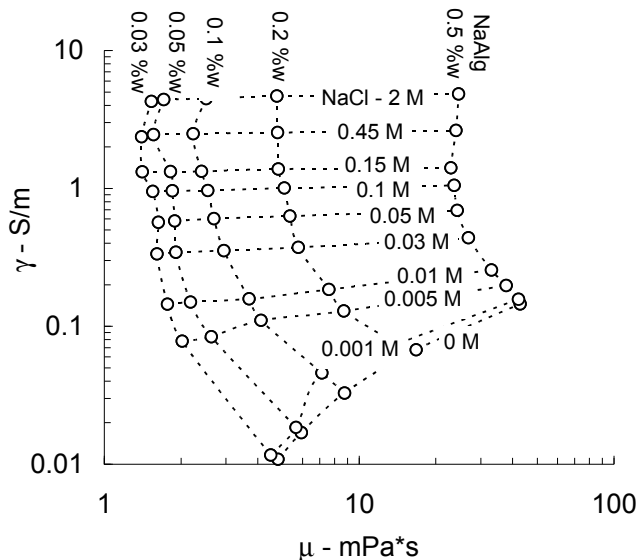

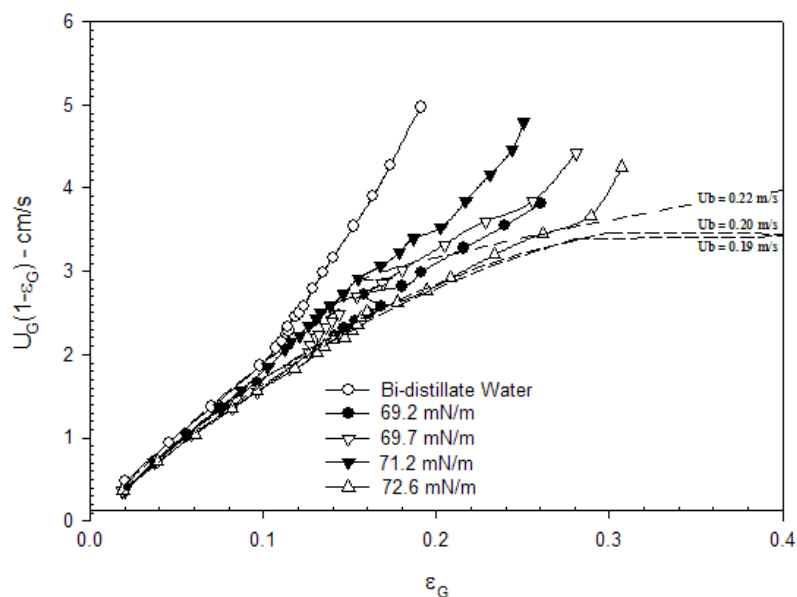Figure 2 – Map of γ vs. μ for different solutions at constant concentration of NaCl and NaAlg

Figure 2 – BC hydrodynamics. Drift flux vs. the overall gas holdup. Solutions of the group I, characterized by $\mu = 5$ mPa s.

Figure 5 reports U_G^C (5.A) and ε_G^C (5.B) assessed for solution of the group III characterized by constant σ (71 mN/m) and viscosity ranging between 1 mPa s and 15 mPa s. The homogeneous regime stability is characterized by a maximum in terms of both superficial gas velocity and of gas-holdup. At viscosity values lower than 5.4 mPa s the regime stability increases with μ, at value of viscosity larger than 5.4 mPa s the stability of the homogenous regime decreases The solution characterized by the largest interval of stability is made of 0.18%$_w$ sodium alginate and 0.1 M sodium chloride.

4. Final remarks

The hydrodynamics of a bubble column has been successfully investigated as regards the effects of the liquid viscosity and surface tension.
The conductivity was adopted to fine tuning of the solution with respect the electrolytes concentration. A map of the conductivity vs. viscosity was prepared for the investigated solutions.
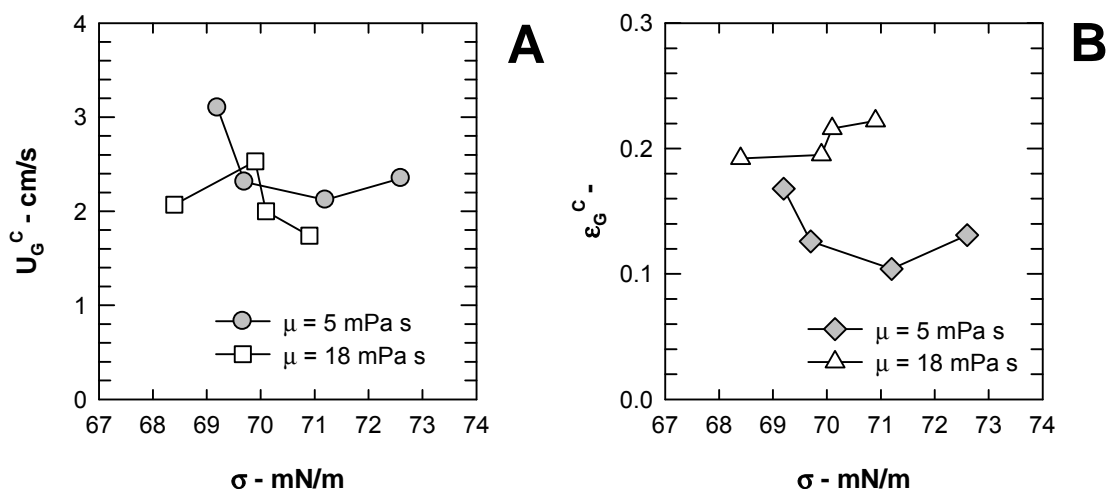

Figure 4 – BC hydrodynamics. Effects of the surface tension at constant viscosity on transition regime velocity (A) and transition gas holdup (B).
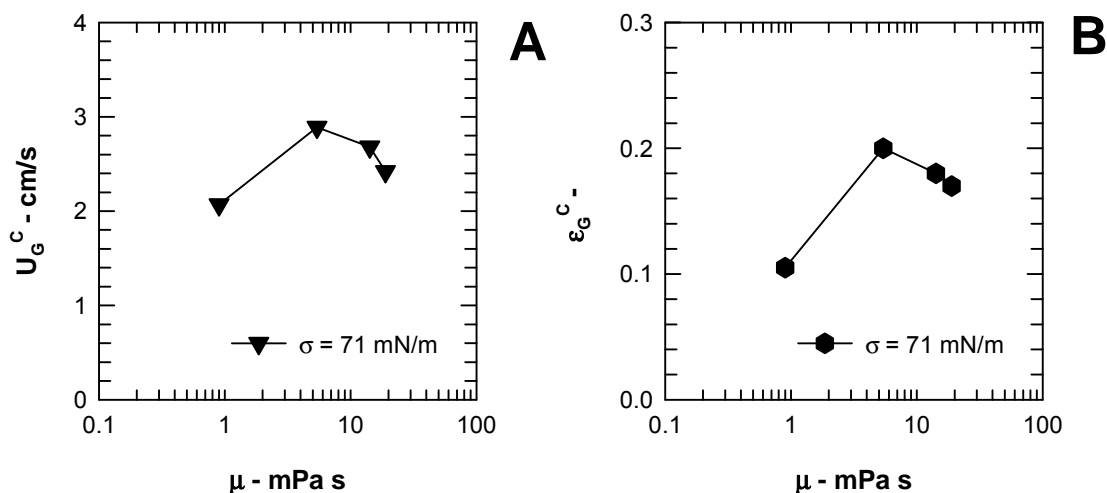
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Figure 5 – BC hydrodynamics. Effects of the viscosity at constant surface tension on transition regime velocity (A) and transition gas holdup (B).

The effects of the liquid features investigated on the hydrodynamics of the bubble column were non monotonic.

Acknowledgements

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