Hydrodynamic Characteristics of Mixing in Three Phase System

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Abstract – The hydrodynamic behavior of bubble columnl has been studied for various non-Newtonian liquid (Carboxy Methyl Cellulose solution).

The critical gas velocity (V_{GC}) for complete suspension of the sand particles range (63-250)µm in low aspect ration (L/D=0.8-1.4) is obtained. The mixing time, the intensity of mixing have been measured in a cylindrical hemispherical bottom gas sparged vessel (diameter=0.46m, height=1m), for three air spargers (single ring, double ring, and 4-arms) with different numbers and size of holes (1mm, 2mm, and 3mm).

Electroresistivity probe was adopted in this work, contained two electrodes, one vertical above the other and separated by a known distance (0.85 cm), to measure the local gas hold-up, bubble frequency, bubble velocity, bubble size and number of bubbles by using the personal computer. The probe detects the difference in conductivity of gas and liquid.

Keywords: Three phase system, bubble characteristic, non-Newtonian liquid, critical gas velocity.

I. Introduction

Gas- liquid and three phase systems are widespread application in the catalytic slurry reactions, biological and petrochemical industries. Three phase systems describe a gas-liquid-solid flow system in which particles are in motion induced by gas and/or liquid phases [1]-[3].

In three phase fluidization, the particles are fluidized by the co-current flow of liquid and gas or immiscible liquid –liquid phases, the gas or immiscible liquid forms discrete bubble or droplet phase and a continues phase containing the solid particles. The fluidized bed technology has become a common method to increase heat and mass transfer in physical and chemical operation [4],[5].

There are many different ways to provide mixing action in vessels, e.g. mechanical agitation, gas sparging and liquid jetting. A major advantage of gas sparged column is the simplicity of construction and easy of operation and maintenance owing to the absence of any moving parts. Also, they represent economic advantages over mechanically stirred vessels, i.e., low investment and operating cost [6],[7].

In some application of three phase systems such as a catalytic hydrogenation of vegetable oils, slurry reactors, evaporative crystallization, and soon, the success and efficiency of the process is directly influenced by the extent of mixing between the three phase, despite its great industrial importance [8].

II. Apparatus and Experimental Techniques

Experiments were carried out in a cylindrical QVF glass hemispherical bottom 0.46m inside diameter and

Im total height. The experimental apparatus are shown schematically in Fig.1. Glass pressure tube 5mm diameter immersed into the liquid until the bottom of the vessel. This tube was connected to an inclined tube manometer to measure the hydrostatic pressure of the vessel content.



Fig. 1. The schematic diagram

The compressed air was fed to the vessel through two calibrated rotameters. The rotometers are $20m^3/hr$ capacity connected in parallel. A U-tube mercury manometer was connected to the line after the rotometers to measure thee pressure upstream of the air sparger. This pressure is used to correct the reading of the rotameters [9].

The air distributor (sparger) was placed above the bottom of the vessel at a distance 5cm. The air was distributed by means of three different shapes air sparger. The inside diameter of sparger tube was 1.27cm, and the sparger diameter-to-vessel diameter ratio was 0.5. The shape and dimensions are listed in Table(I).

The liquids used in this work are tap water and four different concentration (0.1,0.2, 0.3, and 0.4)wt% Carboxy Methyl Cellulose (CMC)solution. The physical properties of the liquids are listed in Table (II).

Sand with four different particle sizes (63-105), (105-150), (150-210), and (210-250) μ m were used with density ($\rho_s = 2600 \text{ kg/m}^3$).

The hydrostatic pressure measurement was used to determine the critical gas velocity for complete suspension. The sand particles of known quantity (0.5, 1, 1.5, and 2) kg were placed at the bottom of the vessel. The air flow rate was increased until all sand particles were suspended. The hydrostatic pressure of the suspension was measured by means of an inclined manometer. Then, the air flow rate was gradually decreased, the pressure that measured by inclined manometer was remained constant until a certain point at which the hydrostatic pressure decreased. This point represents the condition of complete suspension of solid. At this point the flow rate that measured by means of the rotameter is used.

TABLE I SPECIFICATION OF GAS SPARGERS

No.	Gas	Code	Sparger	Hole	No. of	Free
	Sparger		Diamete	Diamet	Holes	Hole
			r (m)	er		Area
				(mm)		(A_o/A)
						%
1	Single	SR1	0.23	1	136	0.064
	Ring					
2	Single	SR2	0.23	2	136	0.257
	Ring					
3	Single	Sr3	0.23	3	68	0.3
0	biligie	510	0120	5	00	0.0
	Ring					
4	Double	DR1	0.17,0.2	1	244	0.115
	Ring		3			
~	4 4 5 1 4		0.00	2	00	0.1.66
5	4-ARM	4-	0.23	2	88	0.166
		ARM-1				

TABLE II						
Liquid	Liquid Density ρ_L (kg/m ³)	Liquid Viscosity µ _L (mPa.s)	Surface Tension σ_L (N/m)			
Water +CMC	1004	2	0.0728			
0.1% wt						
Water +CMC	1005.3	2.5	0.0732			
0.2% wt						
Water +CMC	1005.5	3	0.0737			
0.3% wt						
Water +CMC	1005.6	5	0.0741			
0.4% wt						

A pulse technique was used to measure mixing time using an electrolyte solution of HCl of 20ml volume and 20% concentration.

The hydrodynamic parameters such as bubble characteristic (bubble diameter, bubble rise velocity, and bubble frequency) and gas hold-up were measured using electroconductivity prob.

III. RESULTS AND DISCUSSION

III.1. Bubble Diameter

Fig.2 and Fig.3 showed the distribution of bubble diameter at a given particle size $(250-210) \mu m$. It can be seen that the bubble diameter near the wall wear smaller than that at the center, this is attributed to large rising bubbles breakup at the surface and then they go down near the wall. These figures also indicated the relationship between bubble diameter and L/D which are 0.8, 1,1.2, and 1.4. Examining these figures it can be noticed that when L/D increased the critical gas velocity decreased, knowing that the relation between the critical gas velocity and bubble diameter acts as a proportional relation. These observation were coincide with Rigby, et al.[10] and Shollenberger, et al. [11].



Fig. 2. Bubble diameter versus probe position. L/D=0.8, dP=(250-210)µm, SR1,No. of holes=136, hole size=1mm, WS=2kg



Fig. 3. Bubble diameter versus probe position. L/D=1.4, dP=(250-210)µm, SR1,No. of holes=136, hole size=1mm, WS=2kg

The effect of particle size on the bubble diameter was shown in Fig.4. The bubble diameter would increase with increasing particle size because the relation between particle size and bubble diameter is a proportional relation and any increases in gas velocity should consequently leads to an increase in bubble diameter. The same behavior noticed by Abdel-Rahman [12].



Fig. 4. Bubble diameter versus probe position. L/D=1.2 dP=(210-150) $\mu m,$ SR1,No. of holes=136, hole size=1mm, WS=2kg

Fig.5 and Fig.6 showed the effect of liquid viscosity on bubble diameter. It was noticed that bubble diameter increased slightly by increasing liquid viscosity, this is due bubble breakup which decreased by increasing liquid viscosity.



Fig. 5.Bubble diameter versus probe position. L/D=0.8, dP=(250-210)µm, SR1,No. of holes=136, hole size=1mm, liquid viscosity=2×10 -3 pa.s.,WS=2kg

The bubble diameter for different types of air spargers were shown in Figs.7-10. These figures showed that the behavior of bubble diameter for single ring is the same as for 4-arms, and double ring respectively. In addition to that the bubble size increased by increasing the size of the holes.



Fig. (6): Bubble diameter versus probe position. L/D=0.8, dP=(210-150)µm, SR1,No. of holes=136, hole size=1mm, liquid viscosity=5×10 -3 pa.s.,WS=2kg



Fig. (7): Bubble diameter versus probe position. L/D=1.2 dP=(210-150) μ m, SR2,No. of holes=136, hole size=2mm, WS=2kg



Fig. (8): Bubble diameter versus probe position. L/D=1.2, dP=(210-150)µm, SR3 ,No. of holes=68, hole size=3mm, WS=2kg



Fig. (9): Bubble diameter versus probe position. L/D=1.2 dP=(210-150)µm, 4ARM-1,No. of holes=136, hole size=2mm, WS=2kg



Fig. (10): Bubble diameter versus probe position. L/D=1.2, dP=(210-150)μm, DR-1, No. of holes=244, hole size=1mm, WS=2kg

III.2. Bubble Rise Velocity

The effect of bubble rise velocity and probe position in the vessel for different particle size and L/D were shown in Figs.11-13. These effects indicated that the bubble rise velocity near the walls were less than that at the center due to the effect of both the forces balance and wall that being a reduction in their velocity. This behavior was the same as noticed by Kumar [13]. In addition to that the bubble rise velocity was increased by decreasing L/D and increasing the distance from the surface, this causes increase in bubble rise velocity due to the proportional relation between gas velocity and bubble rise velocity as it noticed by Kim, et al.[14].



Fig. (11): Bubble rise velocity versus probe position. L/D=0.8 dP=(210-150)µm, SR1, No. of holes=136, hole size=1mm, WS=2kg



Fig. (12): Bubble rise velocity versus probe position. L/D=1.4 dP=(250-210) μ m, SR1, No. of holes=136, hole size=1mm, WS=2kg

Figs.14-15 showed the effect of liquid viscosity on the bubble rise velocity. It was found that the bubble rise velocity decreased by increasing liquid viscosity because of the decreasing in bubble diameter, critical gas velocity and increasing the friction force as it mentioned by Fan,et al.[1] and Thamer, et al. [15].



Fig. (13): Bubble rise velocity versus probe position. L/D=1.2 dP=(210-150)μm, SR1, No. of holes=136, hole size=1mm, WS=2kg







Fig. (15): Bubble rise velocity versus probe position. L/D=1.2 dP=(210-150)µm, SR1, No. of holes=136, hole size=1mm, WS=2kg , liquid viscosity=5×10-3 pa.s.

The effect of different types of air spargers on the bubble rise velocity were plotted in Figs.16-19 that showed the behavior of bubble rise velocity for single ring is the same as for 4-arma and double ring respectively.



Fig. (16): Bubble rise velocity versus probe position. L/D=1.2 dP=(210-150)μm, SR2, No. of holes=136, hole size=2mm, WS=2kg.



Fig. (17): Bubble rise velocity versus probe position. L/D=1.2 dP=(210-150)µm, SR3, No. of holes=136, hole size=1mm, WS=2kg.



Fig. (18): Bubble rise velocity versus probe position. L/D=1.2 dP=(210-150)µm, 4ARM-1, No. of holes=88, hole size=2mm, WS=2kg .



Fig. (19): Bubble rise velocity versus probe position. L/D=1.2 dP=(210-150)µm, DR1, No. of holes=244, hole size=1mm, WS=2kg.

III.3. Bubble Frequency

The bubble frequency profiles as a function of probe position in the vessel at different L/D and particle size were shown in Fig.20-22. The general trends of these curves were somewhat similar to those obtained for bubble diameter and bubble rise velocity.



Fig. (20): Bubble frequency versus probe position. L/D=0.8 dP=(210-150) $\mu m,$ SR1, No. of holes=136, hole size=1mm, WS=2kg .



Fig. (21): Bubble frequency versus probe position. L/D=1.4 dP=(210-150) $\mu m,$ SR1, No. of holes=136, hole size=1mm, WS=2kg .



Fig. (22): Bubble frequency versus probe position. L/D=1.2 dP=(210-150) $\mu m,$ SR1, No. of holes=136, hole size=1mm, WS=2kg .

III.4. Gas Holdup

Plotting the gas hold-up at a given particle size (210-250)µm versus the probe position in the vessel were shown in Figs.23-25. The gas hold-up near the wall was less than that in the center due to the superficial gas velocity is maximum at the center that increase gas hold-up, this behavior is observed by Degaleesan, et al. [16].

The gas hold-up increased with increasing the vertical distance from the liquid surface and decreasing with L/D. Shah, et al., [6] and Jackson, et al. [17] found the same relationship which indicated that increasing gas hold up leads an increasing in the critical gas velocity.



Fig. (23): Gas hold-up versus probe position . L/D=1.4 dP=(210-150) μ m, SR1, No. of holes=136, hole size=1mm, WS=2kg .



Fig. (24): Gas hold-up versus probe position . L/D=1.4 dP=(210-150)µm, SR1, No. of holes=136, hole size=1mm, WS=2kg.



Fig. (25): Gas hold-up versus probe position $\,$. L/D=1.2 dP=(210-150)µm, SR1, No. of holes=136, hole size=1mm, WS=2kg .

The effect of liquid viscosity on gas hold-up is shown in Fig.26-27. Examining these figures it can be seen that the gas hold-up decreased by the liquid viscosity due to the reduction in the critical gas velocity for complete suspension of the solid particles by increasing liquid viscosity and corresponding reduction in gas hold-up as mentioned by Daharwadker, et al. [18] and Lin,et al. [19].



Fig. (26): Gas hold-up versus probe position . L/D=1.2 dP=(210-150)μm, SR1, No. of holes=136, hole size=1mm, WS=2kg , liquid viscosity=2×10-3pa.s.



Fig. (27): Gas hold-up versus probe position . L/D=1.2 dP=(210-150)μm, SR1, No. of holes=136, hole size=1mm, WS=2kg , liquid viscosity=5×10-3pa.s.

Fig.28 showed the plotting of mixing time versus critical gas velocity for water. It was found that the mixing time decreased with increasing gas velocity as it is observed by Haque, et al. [20].

The effect of liquid viscosity on mixing time was represented in Fig.29, it was noticed that the mixing time increased with increasing liquid viscosity, this observation was in agreement with Haque, et al. [20] and Abdel-Rahman [12].



Fig. (28): Mixing time versus critical gas velocity . L/D=(0.8-1.4) dP=(250-63) μ m, SR1, No. of holes=136, hole size=1mm, WS=2kg .



Fig. (29): Mixing time versus critical gas velocity . L/D=(1.2-1.4) dP=(250-63)µm, SR1, No. of holes=136, hole size=1mm, WS=2kg , liquid viscosity=(2×10-3-5×10-3)pa.s.

III.6. Intensity of Mixing

The intensity of mixing was estimated using the method used by Brodkey, et al. [21]. Table (III) showed the experimental results which indicated the intensity of mixing for a given particle diameter($(210-150)\mu$ m and L/D=1.2 was higher than the other, this is due to highly bubble distribution at the circulations.

III.7. Critical Gas Velocity for Complete Suspension III.7.1 Effect of Liquid- to-Vessel Diameter Ratio (L/D)

For liquid level-to-vessel diameter ratio were used, namely; 0.8, 1, 1.2 and 1.4.Fig.30 showed the effete of L/D on critical gas velocity for complete suspension. This figure indicated that critical gas velocity decreases

with increasing L/D ratio. Koid, et al. [22] suggested that for hemispherical end bottom, the critical gas velocity was decreased by increasing L/D.

Exp .No	Gas Sparger	(kg/m3)	αP (μm)	(m/s)	L/D	Time (s)	of Mixing (I)%
1	SR1	44.44	210-250	0.0277	0.8	15	67.47
2	SR1	33.33	210-250	0.0267	1	16	65.99
3	SR1	27.027	210-250	0.0259	1.2	17	64.69
4	SR1	27.727	210-250	0.0253	1.1	18	67.29
5	SR1	44.44	150-210	0.0264	0.8	14.5	63.75
6	SR1	33.33	150-210	0.0250	1	15	68.17
7	SR1	27.027	150-210	0.0242	1.2	15.5	72.64
8	SR1	27.727	150-210	0.0228	1.1	16	71.3
9	SR1	44.44	105-150	0.0258	0.8	16	65.8
10	SR1	33.33	105-150	0.0247	1	16.5	65.93
11	SR1	27.027	105-150	0.0236	1.2	17	70.36
12	SR1	27.727	105-150	0.0225	1.1	17.5	71.64
13	SR1	44.44	63-105	0.0253	0.8	15	68.63
14	SR1	33.33	63-105	0.0241	1	16	67.82
15	SR1	27.027	63-105	0.0231	1.2	16.5	67.12
16	SR1	27.727	63-105	0.0223	1.1	17	67.5

TABLE III. EXPERIMENTAL RESULTS



Fig. (30): Critical gas velocity versus liquid level to vessel diameter ratio (L/D), $dP=(250-63)\mu m$, SR1, No. of holes=136, hole size=1mm, WS=2kg.

III.7.2. Effect of Solid Concentation

The effect of solid concentration (C_W) on the critical gas velocity for complete suspension of solid particle is shown in Figs.31-32. It was noticed that the critical gas velocity increased by increasing solid concentration and particle size, this was due to the increase of settling velocity of solid particle. This phenomena was observed by Abdel-Rahman[12].

III.7.3. Effect of Liquid Viscosity

Four solutions of Carboxy methyl Cellulose (0.1, 0.2, 0.3 and 0.4)wt% were used having viscosities of 2,2.5,3 and 5 (mPa.s) respectively.

Figure (33) showed the effect of liquid viscosity on the critical gas velocity at different particle size of solid. The critical gas velocity decreased with increasing liquid viscosity. This behavior is attributed to the decreasing in the terminal velocity with increasing liquid viscosity.



Fig. (31): Critical gas velocity versus solid concentration. L/D=(0.8-1.4), dP=(250-63)µm, SR1, No. of holes=136, hole size=1mm, WS=2kg.



Fig. (32): Critical gas velocity versus solid concentration L/D=(1.2-1.4), dP=(250-63)µm, SR1, No. of holes=136, hole size=1mm, WS=(0.5-1.5)kg.



Fig. (33): Critical gas velocity versus liquid velocity L/D=(1.2-1.4), $dP=(250-63)\mu m$, SR1, No. of holes=136, hole size=1mm, WS=2kg .

III.8. Emperical Correlation

Critical gas velocity was correlated with CW, L, dP, VS, Δ , g and physical properties of liquid (ρ L, μ L, σ L) using Backinghams π -theorm method [8] as shown in the following equation with absolute error of 4.67% and variance 0.99.

$$\frac{V_{GC}}{V_S} = 0.291 (Fr)^{1.41} (\text{Re})^{0.50} (We)^{-0.32} \left(\frac{d_P}{L}\right)^{0.83} \left(\frac{C_W}{\rho_L}\right)^{0.12}$$
(1)

The above equation was obtained using Oausian-Newton method. A comparison between experimental values of VGC with that of the predicted values is shown in Fig.34.



Fig. (33): Comparison between the observed values of critical gas velocity and the predicted values.

IV. **Conclusions**

Abbreviation and acronyms should be defined the first time they appear in the text, even after the have already been defined in the abstract. Do not use abbreviations in the title unless they are unavoidable.

- The hydrodynamic parameters such as the bubble 1diameter, bubble rise velocity and gas hold-up were decreased with increasing liquid level -tovessel diameter. These values were smaller near the vessel wall compared with that at the center.
- 2-The critical gas velocity for complete suspension of solid particles increased with a decrease in the liquid level-to-vessel diameter and liquid viscosity, and it increase with the increasing of solid concentration and particle size.
- 3-Mixing time increased with the decreasing of critical gas velocity and increased with liquid viscosity.

Nomenclature

C_w: Solid concentration, wt of solid/wt of slurry.

- D : Vessel diameter (m)
- $d_{\rm P}$: Particle diameter (µm)
- Fr : Froud No. =($\sqrt{Lg/Vs}$).
- g : Acceleration gravity (m/s2)
- L; Clear liquid height (m)

Re : Reynolds No.=($\rho L L VGC$)/ μL

V_{GC} : Critical gas velocity (cm/s)

 V_{s} : Settling velocity of solid particle (m/s) Weber No.= $(\rho_L V_{GC}^2 L)/\sigma_L$

We ∵ ∆ρ

Greek symbols

- ρ_L : Liquid density (kg/m3)
- $\rho_{\rm S}$: Solid density (kg/m3)
- $\Delta \rho$: Density difference between solid and liquid (kg/m3)
- μ_{L} : Liquid Viscosity (mPa.s)
- $\sigma_{\rm L}$: Liquid surface tension (N/m)

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