International Journal of Chemical, Materials and Biomolecular Sciences
ISSN: 2415-6620
Vol:6, No:9, 2012

Hydrodynamics of Bubbly Flow in a Modified Reactor

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Abstract**—**This article reports on hydrodynamic, mass transfer performances of fine bubble in a modified reactor. The quality of mixing in the modified reactor is discussed in the paper. Mass transfer efficiency based on quality of mixing is enunciated. To interpret the gas phase volume fraction and the quality of mixing is the empirical models for the modified system are developed.

Keywords**—**Downflow, bubble, hydrodynamics, gas-liquid, mixing, mass transfer, gas holdup.

I. INTRODUCTION

THERE are many chemical processes like hydrogenation, fermentation, petroleum refining, separation by absorption, wastewater treatment etc., where the gas-liquid interfacial mass transfer controls the overall efficiency of the process. Gas-liquid reactors with fine bubble have some distinct advantages over other conventional devices. The reactors are the type of reactors, which not only provide a significant interfacial mass transfer area but is very simple in design and no mechanical agitator is required. Out of different types of gas-liquid contactor, the gas liquid reactor is modified as per industrial adaptation. Down flow gas-liquid column is now gaining importance due to its unique characteristics of higher residence time of the gas bubbles thus increasing the contacting efficiency. Some authors [1]-[7] worked on the ejector-induced plunging type reactor for generating fine bubbles and performing the mass transfer operation on the system. Down flow bubble column with ejector gas distribution exhibit some more favorable features as it functions both as a sparger and gas entrainment device. It can be operated in such a way that at a certain pressure, the finer fine bubble can be generated. However detailed hydrodynamic features viz. flow regime, size distribution, fractional gas holdup, pressure drop etc. are required for understanding, design and modeling of such type of reactors. The possibility of the gas separation in the downflow column is accountable due to more interfacial area compared to other gas liquid separation device.

II. EXPERIMENTAL SETUP AND PROCEDURE

A. Experimental Setup

The detail of experimental setup is shown in Fig. 1. It consists of a space assembly for gas supply; an extended pipeline contactor, a separator and other accessories are mentioned in the legend. The gas-liquid separator was sufficiently large to minimize the effect due to liquid going out of the separator or gas-liquid separation. When a steady-state condition of the system was attained, the total height of gas–liquid mixture in the column was noted after sudden close of operation. The overall gas holdups for the present system have been measured by flow isolating technique. When study state condition is attained in the system the total height of the gas-liquid mixture in the column was noted. Then switched off all the solenoid valves and pump simultaneously. This causes the immediate termination of flow of fluids. The gas-liquid mixture is then allowed to settle for some time until all the gas arrested in the column gets isolated and clear slurry liquid height observed in the column. The difference between the gas liquid mixing height and the corresponding clear liquid height gives the overall gas holdup in the column.

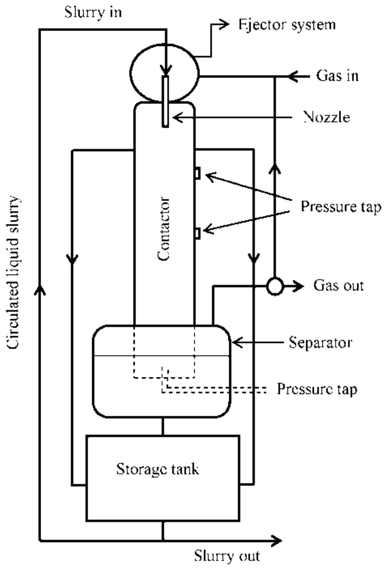

Fig. 1 Schematic diagram of experimental setup

B. Estimation of Gas Holdup

By phase isolating method, overall gas holdup was calculated as:

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$$\varepsilon_g = \frac{h_m - h_{sl}}{h_m} \tag{1}$$

In the absence of dynamic effect, the gas holdup can be estimated from the simple hydrostatic pressure considerations which yields

$$\varepsilon_g = 1 - \frac{\Delta P}{\rho_{sl} g h_m} \tag{2}$$

III. RESULTS AND DISCUSSIONS

A. Gas Holdup

To determine the efficiency of the reactor based on mass transfer, the knowledge of extend of gas holdup, mass transfer and quality of mixedness are required. Fig. 2 shows variation of overall gas holdup with gas flow rate at constant liquid flow rate.

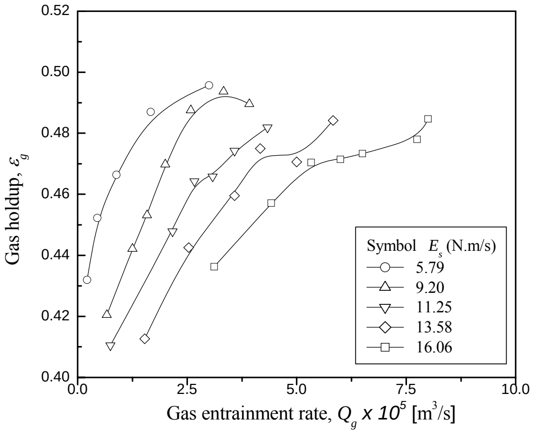

Fig. 2 Gas holdup profile

For the same liquid flow rate, gas holdup increases with increase in gas flow rate because of increased bubble population due to higher gas entrainment. Fig. 1 also shows that for same gas flow rate gas holdup decreases with increase in liquid flow rate due to increase in momentum imparted by liquid on the gas bubbles and results in lower residence time. The effect of all these parameters independently on gas entrainment is very complicated. Thus by dimensional analysis the correlation is made by fitting present experimental data with the help of multiple regression analysis which can be expressed by (3). The calculated values of gas entrainment rate fit satisfactory with the experimental values in a slurry system.

$$\frac{Q_g}{u_j d_n^2} = 6.56\times10^{-18}\left(\frac{\sigma_l}{u_j^2 d_n w}\right)^{-0.085}\left(\frac{\mu_{eff}}{u_j d_n \rho_{sl}}\right)^{-4.655}\left(\frac{g d_n}{u_j^2}\right)^{1.349} \tag{3}$$

with correlation coefficient (R^2) = 0.99 and standard error (SE) = 0.0974. w is the slurry concentration.

Lockhart–Martinelli [8] developed a correlation for predicting the holdup in concurrent flow of gas liquid mixture. They represented the correlations for the holdup in terms of the parameter, $X = \phi_g / \phi_l = \sqrt{\Delta P_{fsl} / \Delta P_{fsg}}$. The Lockhart-Martinelli correlation for the gas holdup is of the following form:

$$\varepsilon_g = \frac{1}{1 + f(X)} \tag{4}$$

where

$$f(X) = f\left(\frac{1-x}{x}, \frac{\rho_g}{\rho_l}, \frac{\mu_l}{\mu_g}\right) \tag{5}$$

In the present study, x is defined as a mass quality of gas in slurry liquid which is defined as:

$$x = (Q_g \rho_g)/(Q_l \rho_l) \tag{6}$$

Density and viscosity of the fluid are considered as a slurry density and slurry viscosity respectively. Based on the different developed correlations for various multiphase systems, the generic form of the correlations for gas holdup can be represented as follows:

$$\varepsilon_g = \left[1 + A\left(\frac{1-x}{x}\right)^p \left(\frac{\rho_G}{\rho_{sL}}\right)^q \left(\frac{\mu_{sL}}{\mu_G}\right)^r\right]^{-1} \tag{7}$$

where, A, p, q, r are coefficients. In the present study it is found that for different concentration of slurry in the range of present experiment (7) is satisfactorily fitted and found the equation as follows:

$$\varepsilon_g = \left[1 + 1.28\times10^9 \left(\frac{1-x}{x}\right)^{0.99} \left(\frac{\rho_g}{\rho_l}\right)^{4.034} \left(\frac{\mu_l}{\mu_g}\right)^{-0.126}\right]^{-1} \tag{8}$$

The correlation coefficient for the correlation of (8) is 0.99. The correlation coefficients infer that the experimental value for gas holdup satisfactorily fit well with the correlation.

B. Mixing Characteristics

Mixing is the most important factor affecting the performance of the column. Poor mixing results in low yield while good mixing gives high yield in a reaction. These are preferred for gas liquid processes that take place in the absorption regime with slow reaction. They may also be used for fast reactions, especially if they offer special features of good heat removal rates or simplicity of construction. The reactor is assumed to be operated co-currently downward with gas and liquid where gas is dispersed in a continuous liquid phase as a dispersed phase of fine bubbles. The theory on quality of mixing in the reactor has been modeled. Correlations have been developed to relate the quality of mixedness in the column by dimensional analysis. Based on information entropy theory the quality of mixing has been defined in the reactor. Based on the experimental data [9] and model proposed by Nedeltchev et al. [10] the quality of mixing has been calculated. Quality of mixing is a function of superficial gas and liquid velocities. The maximum quality of mixing can be achieved by increasing the superficial gas velocity [11]. The parity of quality of mixedness as a function of different dimensionless numbers obtained by regression analysis as follows:

$$1 - M(t) = 0.0123(Sh.M_i)^{-0.587} \tag{8}$$

According to penetration theory, the main process occurring inside the column is the mass transfer between bubble and liquid. This physical process is often the major criterion for design and scale up of the reactor. Intrinsic mass transfer number increases with increase in superficial liquid velocity and hence quality of mixedness (Fig. 3). As the superficial liquid velocity increases, the exchange of momentum increases for which the finer bubbles are formed due to breakup of bubbles. Consequently more interfacial area between gas and liquid are resulted. More interfacial area gives the more volumetric mass transfer coefficient. As a result the intrinsic mass transfer number increases with increase in superficial liquid velocity.

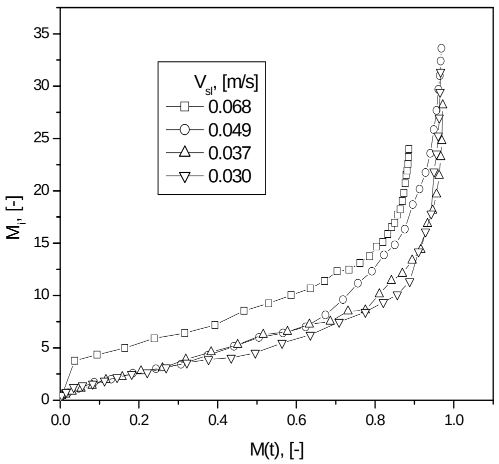

Fig. 3 Variation of mass transfer with intensity of mixing

C. *Energy Efficiency of Gas Entrainment*

The energy efficiency of the present system and other types of gas-liquid contactors has been summarized in Table I. The present system requires reasonable efficiency compared to that of other types of aeration systems. In the present system of gas-liquid-solid three phase flow, the experiments were carried out in the free suction regime, i.e., air was sucked through the secondary entrance of the ejector by the high-velocity liquid jet.

TABLE I
GAS-ENTRAINMENT PERFORMANCE OF GAS-LIQUID CONTACTORS BASED ON ENERGY SUPPLY

Authors	Type of contactor	$\dot{E}_s / Q_g$ [KW. s/m^3]
[12]	Tank-type gas entrainer	10^2 - 10^3
[13]	Aerated –stirred fermenter	80 - 140
[14]	Hollow impeller	300 - 700
[15]	Turbo aerator	60 - 800
[16]	Water jet aeration in pool system	15 – 30
Present Work	Ejector induced modified system	101 - 210

IV. CONCLUSIONS

In the present work hydrodynamic, mass transfer performances of fine bubble in a modified gas–liquid reactor. From the present study it was observed that gas entrainment rate is directly proportional to the jet velocity. In the present study the generalized correlations were proposed to predict the gas entrainment rate and gas holdup as a function of various dimensionless groups comprising of physical and system variables which are found to be fit well within the range of experimental study. The mixing characteristic in terms of mass transfer characteristics is enunciated and it is found that the maximum mixedness is inversely proportional to the intrinsic mass transfer number. The present study is describes the energy efficient gas entrainment and production of fine bubbles in an ejector induced gas-liquid dispersion reactor. The present study can be useful for understanding the gas entrainment, holdup characteristics, energy requirement and the models to predict the gas holdup for the development of multiphase phase reactor as well as further understanding of multiphase flow system.

NOMENCLATURE

h_m	Gas-liquid-solid mixing height, [m]
h_{sl}	Clear liquid-solid height, [m]
ρ_{sl}	Density of slurry, [kg/m^3]
ρ_g	Density of gas, [kg/m^3]
ΔP	Total pressure drop for three phase flow, [N/m^2]
g	Acceleration due to gravity, [m/s^2]
E_s	Energy supplied, [N.m/s]
Q_g	Volumetric flow rate of gas, [kg/m^3]
Q_{sl}	Volumetric flow rate of slurry, [kg/m^3]
u_j	Jet velocity, [m/s]
u_g	Gas velocity, [m/s]
ε_g	Gas hold up, [-]
X	Lockhart-Martinelli parameter, [-]
ϕ	Lockhart–Martinelli parameter, [-]
P_{fsl}	Pressure drop for single phase based on slurry, [N/m^2]
P_{fsg}	Pressure drop for single phase based on gas, [N/m^2]
x	Mass quality, [-]
μ_{sl}	Slurry Viscosity, [Ns/m^2]
μ_g	Gas Viscosity, [Ns/m^2]
Sh	Sherwood number, [-]
M_i	Intrinsic mass transfer number, [-]
M(t)	Quality of mixedness, [-]

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