SUMMARY AND CONCLUSION

Introduction

Most of the processes in chemical process industry involve the flow and contact of multiple phases. Fine dispersion of one phase into another phase is desirable to promote intense mixing between immiscible phases, to increase interfacial area of contact and to create high turbulence in the continuous phase in order to achieve increased mass, momentum and energy transfer. Various types of contacting devices have been developed for achieving effective gas-liquid mixing. These may be broadly classified as co-current, counter-current and cross current systems. Among these, increased interests on co-current contacting systems have been shown because of their ability to handle high fluid flowrate without flooding, low pressure drop, higher interfacial area and mixing efficiency.

Significant works have been reported in co-current upflow system [Gharat and Joshi (1992) and Havelka et al (1997)]. However, studies on two-phase co-current downflow system have gained considerable importance in recent years, in view of its inherent advantages, viz. finer and uniform bubble size, negligible coalescence of bubbles, homogenization of the phases, higher residence time of the gas bubbles and efficient dispersion of dispersed phase in a continuous phase.

Literature review reveals that studies on the dispersion of gas in two-phase downflow have been carried out either with plunging jet or with sparger type system. In sparger type system, the gas sparger is fixed at the top of the column. Liquid with high velocity is forced through the column and as it moves it shears the gas from the sparger in the form of bubbles [Shah et al. (1983) and Kulkarni and Shah (1984)]. The concept of plunging jet in a downflow column comes from the studies of gas entrainment and dispersion by an impinging liquid jet into a pool of liquid [Van De Sande and Smith (1973) and McKeogh and Ervine (1981)]. However, this offers poor gas-liquid contact due to lower residence time of the gas bubbles. Therefore, studies have been concentrated on attempts to increase the gas-liquid contacting time. Higher gas-liquid contact can be obtained by increasing bubble penetration, but it requires enough downward liquid flow to overcome the buoyant force of the bubbles produced by liquid jet. In other way, a higher residence time of the entrained bubbles can be obtained by plunging a vertical liquid jet in a vertical column [Ohkawa et al. (1986), Bando et al. (1988) and Yamagiwa et al. (1990)]. In plunging jet system having a downcomer, the liquid jet coming out through the nozzle directly impinges into the liquid inside the downflow contactor and forms an intense mixing zone, where the entrained gas breaks into fine bubbles by shearing forces of the jet. The gas and liquid then flow cocurrently down the column where they are discharged at the bottom. As the gas bubbles are forced to move downward against their upward buoyant force, the bubbles spend more time in the column compared to upflow system.

A review of literature on design and development of fluid-fluid cocurrent contacting equipment shows that use of liquid jet ejectors as a gas-liquid distributor in downflow bubble column is gaining in importance as it functions both as a sparger and gas entrainment device. Ejectors are devices that utilize the kinetic energy of a high velocity liquid jet in order to entrain and disperse the gas phase. The bubble column with ejector system is very simple in design and no extra energy is required for gas dispersion as the gas phase is sucked and dispersed by the high velocity liquid jet. Thus, cocurrent down flow bubble column with ejector type gas distributor possesses the following distinct advantages over other conventional devices, such as (i) lower power consumption (ii) almost complete gas utilization [Yamagiwa et al. (1990)] (iii) higher gas holdup (iv) low pressure drop and (v) higher mixing efficiency.

Considerable works have been reported by different authors on efficient dispersion of gas by liquid jet in gas-liquid two-phase cocurrent contactor with ejector type gas distributor. Ohkawa et al. (1985) studied the flow characteristics of downflow bubble columns with gas entrainment by a liquid jet and established a correlation for gas holdup and gas entrainment rate. Okhawa et al. (1986) studied on flow behaviours and performance of a vertical liquid jet system having downcomers in an air-water system. They investigated the effect of operating variables such as the nozzle diameter, the jet velocity, the downcomer diameter and height etc. on the flow characteristics such as the bubble penetration depth, gas entrainment rate, gas holdup, etc. Bando et al. (1988) reported that with simultaneous gas-liquid injection nozzle in down flow bubble column, a spouting and a calm section appeared and gas holdup and interfacial area were higher in spouting section than in calm section. Yamagiwa et al. (1990) experimentally studied the flow behaviour of the cocurrent downflow bubble column with gas entrainment by a liquid jet operating at high liquid feed rate. They have evaluated the gas entraining capacity of their apparatus in terms of energy efficiency. Kundu et al. (1997) reported the performance of ejector for dispersion of gas into liquid in a co-current gas-liquid downflow bubble column. Evans et al. (2001) described the performance of confined plunging liquid jet bubble column as a gas-liquid reactor. Mandal et al. (2004) investigated the mass transfer characteristics in a co-current gas-liquid downflow bubble column.

From the above discussion, it may be expected that a cocurrent bubble contactor utilizing a jet ejector for improved gas-liquid mixing, would be highly suitable for many industrial processes like absorption, desorption and scrubbing, gas-liquid reactions, aerobic fermentations, waste treatment etc. However the studies regarding the hydrodynamics, mixing characteristics, bubble size distribution and interfacial area are scanty. Therefore, a precise knowledge of the hydrodynamics, mixing characteristics and bubble size distribution in a modified bubble column with downflow, forming a part of an ejector system, would be of considerable interest.

Research Program Undertaken

In view of wide applicability of downflow bubble column in both chemical and bio-chemical industries and the advantages accessible by an ejector system, the present work has been undertaken for systematic hydrodynamic study of gas-liquid two-phase flow in an ejector-induced modified downflow bubble column in the following aspects.

i) Entrainment and holdup characteristics

ii) Pressure drop Characteristics.

iii) Mixing characteristics of liquid phase.

iv) Bubble size distribution and interfacial area phenomena

The thesis is organized in seven chapters which are briefly described below.

In the first Chapter of the thesis, a comprehensive literature review on gas -liquid flow in vertical column with different gas distributors has been reported. The importance and the scope of the present investigation have also been discussed.

Chapter II deals with the details of the experimental setup and techniques applied for the present investigation. The apparatus basically consists of an ejector assembly, a vertical column and a gas-liquid separator along with other accessories. The ejector assembly was fitted at the top of the column with perfect alignment to obtain an axially symmetric jet. The lower end of the column is projected inside a rectangular gas-liquid separator. The nozzle in the ejector was fixed at the optimum position at a distance of one throat diameter from the entry of the throat, which was decided from earlier experiments [Mukherjee et al. (1988)]. Four different nozzles and two vertical columns have been used for the present study.

In experiment, a high velocity liquid jet was produced through the nozzle, which travelled straight through the ejector and vertical column and then directly hit the bottom of the gas-liquid separator. Under such situation, it was found that there was no aspiration of secondary air in the ejector. However, as soon as the liquid height in the separator touched the bottom part of the column the secondary air got entrained due to arresting of jet inside the column. The column was then filled with gas-liquid mixture by proper adjustment of pressure and liquid level inside the separator. Two distinct zones were observed in the column at this stage: an intense mixing zone at the top followed by a zone of two-phase bubbly flow. A number of manometers were connected at different positions of the ejector and column to measure the pressure readings. Gas holdup was obtained by taking the two-phase gas-liquid mixing height and the corresponding clear liquid height in the column. The experiments were carried out only in the bubbly flow regime. Water was used as liquid while, air was used as gas phase for the present system. The liquid flowrate and gas entrainment rate for the present system was varied from 0.68×10^{-4} to 3.27×10^{-4} m^3/s and 0.33×10^{-5} to 2.67×10^{-5} m^3/s respectively. Experimental data were collected at steady state of the system and reproducibility of the data were checked by repeating the experiments.

In Chapter III, entrainment characteristics of secondary air by liquid jet ejector in the downflow bubble column have been discussed. Several mechanisms of gas entrainment by liquid jet proposed by different authors have been presented. The rate of entrainment is primarily dependent on the jet velocity and the resistance of the liquid in the column. Besides, the energy dissipations in the ejector and in the intense mixing zone have some effect on gas entrainment. Hence, it is very difficult to predict theoretically the secondary gas entrainment. Thus, experimental data has been analyzed by expressing entrainment rate as dimensionless air entrainment ratio, Q_r. A dimensional analysis of the system has been done to predict the gas entrainment ratio in terms of some dimensionless groups formed by physical, geometric and dynamic variables of the system. Multiple regression analysis of the experimental data gives the following generalized correlation for both Newtonian and non-Newtonian liquid with correlation coefficient and standard deviation 0.965 and 0.02 respectively;

$$Q_r = 1.52 \times 10^{-4} D_R^{-0.534} H_R^{0.642} \mathrm{Re}_j^{0.268} We_j^{0.295} Fr_j^{-0.130} \tag{1}$$

Chapter III also deals with the gas holdup characteristics in the downflow column. A review of different models and empirical correlations proposed by various authors to analyze the gas holdup in two-phase gas-liquid flow has been presented. However, it has been found that the experimental data of the present system deviate from Lockhart-Martinelli (1949) correlation along with the modified forms suggested by Davis (1963) and Eisenberg and Weinberger (1979) models. This is due to enhanced gas dispersion in the present system with ejector type gas-liquid distributor in vertical downflow column [Mandal (2004)]. Therefore an attempt has been made to analyze the experimental gas holdup data of the present system by Slip-velocity model proposed by Behringer (1936) and drift flux model proposed by Zuber and Findlay (1965) models and correlations. The slip velocity of bubbles relative to surrounding liquid is defined as;

$$V_S = \pm[V_g - V_l] = \pm\left[\frac{V_{sg}}{\varepsilon_g} - \frac{V_{sl}}{1-\varepsilon_g}\right] \tag{2}$$

where negative sign has been incorporated to consider the downflow system. The experimental data of the present system was analyzed by fitting the model equations for