Chapter - 1

Introduction

A Bubble column is a device in which a gas phase is bubbled through a column of liquid to promote a chemical or biochemical reaction in the presence or absence of a catalyst suspended in the liquid phase. Gas–liquid bubble columns are becoming popular and are widely used in industry as absorbers, strippers, reactors and fermenters due to the absence of any moving parts, simple construction, good mixing and mass transfer capacity, temperature control, minimum maintenance, and low capital cost. Bubble coalescence, high pressure drop, considerable back mixing in both phases, short residence time of gas and complex hydrodynamics flow patterns are the main disadvantages of a bubble column. However, bubble columns are extensively used in biotechnology, food processing, pharmaceutical processes and waste water treatment. As reactors, bubble columns are used in chemical processes involving oxidation, chlorination, alkylation, polymerization and hydrogenation (Shah et al., 1982; Fan, 1989). Examples of such processes are the partial oxidation of ethylene to acetaldehyde, wet-air oxidation (Deckwer, 1992), oxidation of cumene to phenol and acetone (Deckwer, 1992), liquid phase methanol synthesis, and hydrogenation of maleic acid. Bubble column reactors are also employed in the processes of oxidation of acetaldehyde to acetic acid, oxidation of p-xylene to dimethylterephthalate, synthesis of hydrocarbons, hydrolysis of phosgene, oxychlorination of ethylene to 1,2-dichlooroethane, hydroformylation (Oxo) processes and Fischer-Tropsch (FT) synthesis (Wender, 1996). Krishna and Sie (2000) showed that a bubble column reactor may achieve a productivity of 2500 times higher that of the classical FT reactors used in the 40s such as the fixed bed reactor, multibed reactor, etc. Other processes that use bubble columns include hydrotreating and conversion of petroleum residues and direct and indirect liquefaction in the production of liquid fuels

from coal (Degaleesan et al., 2001). In biochemical industries, bubble columns are used for cultivation of bacteria, cultivation of mold fungi, production of single cell protein, animal cell culture (Lehman et al., 1978), and treatment of sewage (Diesterweg, 1978). In metallurgical industries, it can be used for the leaching of ores.

Bubble columns can be batch or continuous, single or multistage. They can be operated co-currently or counter-currently. Bubble columns are difficult to design because of the complexity of flow characteristics, and their unknown behaviour under different sets of design parameters such as height, diameter and distributor design. The proper design and scale-up of a bubble column requires a good mathematical model. Deckwer (1979) has outlined a design procedure for modeling a reactor. Application of this procedure requires an exact definition of the requirement, i.e., the required production level, the nature of the reaction system and the type of product structure. However, there are considerable reactor designs and scale-up problems associated with such energy conversion processes involving bubble columns. Therefore, numerous experimental and computational studies have been performed to investigate the flow behavior of bubble column reactors for proper design and scale-up (Shaikh and Al-Dahhan, 2013).

Various types of bubble columns and their modifications are described by Shah et al. (1982). Modified bubble columns include loop reactors (Hines, 1978), horizontal sparger bubble column (Joshi and Sharma, 1976), downflow bubble column (Herbrechtsmeier and Steiner, 1978), sectionalized bubble column (Schugerl et al., 1978), down flow bubble column with ejector as mixing device (Kundu et al., 1995 and Mandal et al., 2004), reciprocating bubble column (RamaRao and Baird, 1988), hybrid rotating and reciprocating perforated plate (Dhanasekaran and Karunanithi, 2012), tapered

columns (Scott and Hancher, 1976; Lee et al., 1979; Pitt et al., 1981; Huang, et al., 2000), etc., which are widely used in practice. The advantage of the tapered bubble column lies in the fact that the residence time of the bubble can be increased in comparison to the cylindrical or rectangular column, the flow is always developing in nature and bubbles coalesce to form bigger bubbles, structure of the bigger bubbles change continuously from circular to flat and rupture of the big bubbles to small bubbles (Sen, 2003; Mandal et al., 2003).

The performance of a bubble strongly depends upon the flow conditions. There occur at least two basic flow patterns, which mainly depends on the gas flow rate (Ruzicka et al., 2001). For low gas flow rates, homogeneous flow is observed which is characterized by uniform bubble rise in nearly straight lines and similar sized bubbles. With increasing gas flow rate, a transition to heterogeneous regime occurs which is characterized by a non-regular flow patterns. The hydrodynamic parameters like pressure drop, holdup and bubble size distribution are very important parameters and these parameters are strongly dependent on the operating conditions, the physico-chemical properties of the flow, the gas sparger type and the column geometry (Mouza et al., 2005).

During the past decades, scientific interest in bubble column has increased considerably (Deckwer, 1992; Kantarci et al., 2005). The research on bubble columns covers a wide range including gas holdup (Fair et al., 1962; Shah et al., 1982; Heijnen and Van't Riet, 1984; Kawase and Moo-young, 1987; Krishna et al., 1991; Saxena and Rao,1991; Ruzicka et al., 2001; Pradhan et al., 1993; Cents et al., 2005; Lakota, 2007; Youssef et al., 2009; Shah et al., 2012), bubble characteristics (Abuaf et al., 1978; Lin

and Fan,1999; Guet et al., 2003; Luther et al., 2004; Cents et al., 2005; Manera et al., 2009), interfacial area(Kataoka et al, 1986; Tan and Ishii, 1990; Revankar and Ishii, 1993; Delhaye and Bricard, 1994; Kiambi et al., 2001; Cents et al., 2005; Manera et al, 2009), flow regime (Shah et al., 1982; Shaikh and Al-Dahhan,2007), heat and mass transfer characteristics (Deckwer et al., 1974; Wang and Fan, 1978; Shah et al., 1982; Heijnen and Van't Riet,1984; Zehner, 1986; Verma, 1989; Saxena and Rao, 1991; Avdeev et al., 1992; Lin and Fan, 1999; Merchuk et al., 1994; Schluter et al., 1995; Dudley, 1995; Shah et al., 2012), back mixing (Ohki and Inoue, 1970; Deckwer et al., 1974; Hikita and Kikukawa, 1974; Joshi, 1980, 1982; Heijnen and Van't Riet, 1984; Kawase and Moo-Young, 1986; Zehner,1986; westerterp et al., 1987; Wachi and Nojima, 1990; Majumder, 2008) and pressure drop (Carleton et al., 1967; Gharat and joshi, 1992; Molga and Westerterp, 1997; Majumder et al., 2006; Jawad, 2009), etc.

The gas holdup is one of the most important parameters characterizing the hydrodynamics of bubble columns and it depends mainly on the gas velocity, physical properties of the liquid and type of gas sparger (Bouaifi et al., 2001). The gas holdup can be measured by different techniques such as the bed expansion technique (Akita and yoshida, 1973; Guy et al., 1986), measuring the static pressure at different points in the column (Hikita et al., 1980), Optical probes (Abuaf et al., 1978; Cartellier, 1990), resistivity probes (Herringe and Davis, 1976; Vince et al., 1981) and hot film anemometry (Wang et al., 1984; Iskandrani and Kojasoy, 2001).

Fair et al. (1962) studied the hydrodynamic characteristics in a bubble column with varying column diameter, liquid height and sparger designs. They observed that gas holdup varies directly with superficial gas velocity and is strongly affected by the flow

regime, bubble characteristics, system properties, column geometry, and sparger configuration.

Braulick et al. (1965) reported their experimental investigation on gas holdup using air-water and air-electrolyte solution having column diameters 0.076 - 0.152 m and 4-arm antenna sparger. They observed that the introduction of electrolyte resulted higher gas holdup than water in all bubble columns.

Yoshida and Akita (1965) reported the variation of holdup and volumetric mass transfer coefficient in four columns having diameters of 0.077 - 0.6 m using air-Newtonian liquids. They used single nozzle sparger and observed insignificant effect of orifice diameter on the overall gas holdup.

Hughumark (1967) reported gas holdup in terms of superficial gas velocity and liquid properties for systems such as air-water, kerosene, glycerin in aqueous solution of Na_2SO_4 in a 0.1 m diameter of column. They proposed the following correlation,

$$\varepsilon_g = \frac{1}{2+\left(\frac{0.35}{u_g}\right)\left(\frac{\rho_l \sigma_l}{72}\right)^{0.33}} \tag{1.1}$$

Akita and Yoshida (1973) studied gas holdup using gas-Newtonian liquid flow having column diameters 0.152 - 0.6 m using a single hole orifice of 5.0 mm in diameter. They developed an empirical correlation to predict the gas holdup as follows,

$$\frac{\varepsilon_g}{\left(1-\varepsilon_g\right)^4} = 0.20\left(\frac{gD_c^2\rho_l}{\sigma_l}\right)^{0.125}\left(\frac{gD_c^3}{\mu_l}\right)^{0.083}\left(\frac{u_g}{\sqrt{gD_c}}\right) \tag{1.2}$$

Hills (1974) reported gas holdup using air-tap water using column of diameter 0.138 m, height 1.37 m and different sieve plates for the air distribution system. He found radial variation in the gas holdup.

Deckwer et al. (1974) carried out an investigation on gas holdup using air-Newtonian solution with different column diameters. They observed significant effect of trace contaminants on the gas holdup.

Hikita and Kikukawa (1974) studied gas holdup using air-Newtonian solution and proposed the following correlation,

$$\varepsilon_g = 0.505 u_g^{0.47} \left(\frac{0.072}{\sigma_l}\right)^{0.67} \left(\frac{0.001}{\mu_l}\right)^{0.05} \tag{1.3}$$

Botton et al. (1978) carried out an investigation on gas holdup using air-Newtonian liquids having column diameters 0.02 - 0.48 m. They observed that gas holdup was dependent on the column diameter in bubble flow regime.

Deckwer et al. (1978) have studied gas holdup and bubble size distribution using gas-electrolyte solution in column of diameter 0.15 and 0.2 m. They noted that in short columns, gas holdup does not vary axially if both entrance and end effects are negligible. Gas holdup increases with column length for tall columns due to volume expansion caused by hydrostatic pressure.

Nakanoh and Yoshida (1980) have reported studies on gas holdup and bubble size distribution using air-water, sucrose, sodium carboxylmethyl cellulose (CMC) and sodium polyacrylate (PA) in bubble column of diameter 0.1455 m. They observed smaller bubbles of a few mm in size in air-water system, whereas large bubbles mingled with many bubbles in viscous solutions.

Hikita et al. (1980) have studied gas holdup using different gas and liquid systems with a column diameter of 0.1 m. They observed gas holdup depended on the nature of the gas. They proposed the following empirical correlation for gas holdup,

$$\varepsilon_g = 0.672\left(\frac{u_g\mu_l}{\sigma_l}\right)^{0.578}\left(\frac{\mu_l^4 g}{\rho_l\sigma_l}\right)^{-0.131}\left(\frac{\rho_g}{\rho_l}\right)^{0.062}\left(\frac{\mu_g}{\mu_l}\right)^{0.107} \quad (1.4)$$

Hammar et al. (1984) reported gas holdup and bubble size distribution using gas-Newtonian liquids in columns diameter of 0.106 and 0.2 m. They proposed the following gas holdup correlation,

$$\frac{\varepsilon_g}{1-\varepsilon_g} = 0.4\left(\frac{u_g\mu_l}{\sigma_l}\right)^{0.87}\left(\frac{\mu_l^4 g}{\rho_l\sigma_l}\right)^{-0.27}\left(\frac{\rho_g}{\rho_l}\right)^{0.17} \quad (1.5)$$

Idogawa et al. (1985) studied gas holdups and bubble sizes using air-water system in a column of diameter 0.05 m and proposed the following gas holdup correlation,

$$\frac{\varepsilon_g}{1-\varepsilon_g} = 1.44u_g^{0.58}\rho_g^{0.12}\sigma_l^{-0.16\exp(-p)} \quad (1.6)$$

Idogawa et al. (1986) reported the gas holdup and bubble size distribution using air-water system with a column diameter of 0.05 m and height of 0.83 m. They observed a narrower bubble size distribution at high pressure and no axial variation of bubble diameter at 0.163 m from distributor.

Reilly et al. (1986) studied the gas holdup using gas-Newtonian liquids with column diameter of 0.3 m and proposed gas holdup correlation as,

$$\varepsilon_g = 296u_g^{0.44}\rho_l^{-0.98}\rho_g^{0.19}\sigma_l^{-0.16} + 0.009 \quad (1.7)$$

Schumpe and Grund (1986) studied gas holdup and bubble characteristics using the air-water system with a column diameter of 0.3 m. They observed that for superficial velocities lower than 5 cm/s, homogeneous (bubbly) flow prevails.

Idogawa et al. (1987) studied the gas holdup and bubble size distribution with electrical resistivity probe method using gas-Newtonian liquids using a 0.05 m diameter

column. They observed that the bubble characteristics were independent of liquid viscosity (<3 MPa.s), but were affected by surface tension at pressure <5MPa. They proposed a gas holdup correlation as,

$$\frac{\varepsilon_g}{1-\varepsilon_g} = 0.059 u_g^{0.58} \rho_g^{0.17} \left(\frac{\sigma_l}{72}\right)^{-0.22\exp(-p)} \tag{1.8}$$

Ozturk et al. (1987) reported studies on the gas holdup and mass transfer coefficient using different gas-liquid systems comprising of pure and mixed organic liquids and various gases. They observed that the gas holdup and the volumetric mass transfer coefficient increased with gas density. They observed that in several mixed liquids and adjusted mixtures, the gas holdups were high as compared to pure liquids with similar surface tension, density and viscosity.

Bondyopadhyay et al. (1988) studied the gas holdup in a bubble column with immiscible liquid mixtures. A multiple nozzle sparger was used in their study. The liquid mixtures studied contained water and one of the following organic phases, kerosene or dibutylphthalate. The column was operated continuously with respect to the gas phase and batch wise with respect to the liquid phase. Organic liquid with both positive and negative spreading coefficient were used. They observed that the holdup attained a minimum at the phase inversion point for liquid mixtures having negative spreading coefficient while the reverse was true for systems with positive spreading coefficients. A power-law dependence of the holdup fraction on superficial gas velocity was observed.

Nicol and Davidson (1988) studied the gas holdup in circulating bubble column with the air-water system. They found churn-turbulent regime in up flow and a uniform homogeneous regime in down flow.

Oyevaar et al. (1989) have reported studies on gas holdup using gas-distilled water, aq. DEA solution with column diameter of 0.0855 m. The gas holdup in the bubble column increases with increasing pressure. They observed that the transition from bubbly flow to churn-turbulent regime was delayed under a high pressure operating condition.

Wilkinson and Dierendonck (1990) investigated the gas holdup different gases ($He/N_2/Ar/CO_2$) in Newtonian liquids in a column diameter 0.16 m, height 1.5 and 2.0 m. They observed an influence of pressure and gas molecular weight on the gas holdup. They also noted that the gas holdup increases as the bubble size decreases with increasing gas density at a constant superficial gas velocity.

Wachi and Jones (1991) studied the flow dynamics in a draught-tube bubble column using various liquids like water, ethanol, glycerol, CMC.

Kojima et al. (1991) studied the gas holdup using compressed air-tap water, in a column of diameter 0.045 m. They observed that the gas holdup increased with an increase in gas velocity and decrease in orifice diameter.

Pino et al. (1992) studied gas holdup using air-kerosene in 29 cm and 10 cm diameter columns. They observed no appreciable differences in gas holdup between columns of 10 cm and 29 cm in diameters in the semi batch mode of operation. It was also reported that the effect of column height was insignificant for height to diameter ratios between 3 and 12. They observed that at high gas velocities foaming occurred for both columns and diameter had no effect on gas holdup.

Ityokumbul et al. (1994) studied gas holdup using the air-water system in a column of diameter 0.06 m. They found an insignificant effect of liquid velocity on the

gas holdup and liquid dispersion coefficient. The liquid dispersion coefficient in bubbly flow regime showed no dependence on gas velocity.

Sotelo et al. (1994) have reported studies on gas holdup using gas-water, ethanol, saccharose and glycerin with column diameters 0.04 and 0.08 m. They proposed the gas holdup depended on the ratio of the sparger pore diameter to the column diameter.

Krishna et al. (1994) studied the gas holdup, transition gas velocity and bubble rise velocities using water-air, helium, argon and sulfur hexafluoride with 5 and 10 cm diameter columns, with a sintered plate distributor. They investigated the influence of gas density on regime transition. They proposed that regime transition velocity increased with increasing gas density.

Jiang et al. (1995) measured gas holdup and bubble size distribution using gas-Newtonian liquid with a column of diameter 0.0508 m and height 0.8 m. They observed that an increase in pressure led to a decrease in bubble size and a narrower bubble size distribution.

Kundu et al. (1995) described the liquid holdup and pressure drop in a co-current gas-liquid downflow bubble column and developed correlations to predict pressure drop and gas holdup as a function of different physical and dynamic variables of the systems.

Deshpande and Joshi (1997) have reported studies on gas holdup using the air-water system with a rectangular bubble column. They developed a technique for simultaneous measurement of gas and liquid velocities along with gas holdup. Also, they reported that as the superficial gas velocity increased, the holdup also increased.

Li and Prakash (1997) studied the gas holdup using the air-water in a 0.28 m diameter column bubble column. They observed that the gas holdup decreases due to the higher rise velocity for the large bubbles.

Hyndman et al. (1997) have reported studies on gas holdup and bubble characteristics using air-water and air+argon-water with a 20 cm diameter column. They reported that three types of flow regimes are commonly observed in bubble columns which are the homogeneous (bubbly flow) regime, the heterogeneous (churn-turbulent) regime and slug flow regime. They observed that the below 4 cm/s superficial gas velocity, a bubbly flow regime prevails.

Krishna et al. (1997) studied gas holdup and bubble characteristics using air-parafinic oil in 10 - 38 cm diameter columns with a perforated plate distributor. They reported the effect of column diameter on the gas holdup.

Kojima et al. (1997) studied the gas holdup using air-water, aq. buffered solution, and aqueous enzyme solution system with a column of diameter 0.045 m. They reported the effect of orifice diameter on gas holdup and also observed that the gas holdup increases with increases of pressure. They proposed the following correlation for gas holdup.

$$\varepsilon_g = 1.18 u_g^{0.679} \left(\frac{\sigma_l}{\sigma_{l,0}} \right)^{-0.546} \exp\left\{ 1.27 \times 10^{-4} \left(\frac{\rho_l Q_g^2}{D_n^3 \sigma_l} \right) \left(\frac{P}{P_o} \right) \right\} \qquad (1.9)$$

Letzel et al. (1997) reported the experimental studies on gas holdup using the air-demineralized water system with a 0.15 m column diameter at high pressure. They reported that the pressure affected the transition velocity for homogeneous to

heterogeneous flow regime. They developed empirical correlation for their gas holdup data.

Li and Prakash (2000) carried out an investigation on gas holdup and bubble characteristics using air-water with a 0.28 m column diameter. They found gas holdup decreases for larger bubbles size and increases for smaller bubbles size.

Prakash et al. (2001) studied gas holdup, bubble characteristics and heat transfer coefficient using air-water –yeast cells with a 0.28 m column diameter. They observed that the addition of yeast cells in water altered the hydrodynamic and heat transfer behavior of the suspension. The gas holdup due to small-bubbles fraction increased and their rise velocities decreased while gas holdup due to large-bubbles fraction decreased and their rise velocity increased. The gas holdup was observed to increase with solids concentration. During the operation of the column, it was observed that a foam layer was formed at the top of the dispersion, due to the presence of surface active agents like alcohols, proteins, etc. in the solutions used. Increasing the yeast concentration just increased the surfactant concentration which in turn increased the foam bed and resulted in higher gas holdup values.

Bouafi et al. (2001) studied the gas holdup, bubble sizes, mass transfer coefficient using air-water with 15 and 20 cm column diameters. They observed that gas holdup increased with the rotational speed which can be explained by increase in circulation of the liquid and decrease in bubble size. They also observed that the smaller the bubble, the greater the gas holdup values. Thus, they also concluded that with small orifice gas distributors, gas holdup values are higher.

Chen et al. (2001) have reported studies on gas holdup using the air-water system with column diameters of 0.2 - 0.8 mm. They observed that the large scale column showed an almost uniform radial holdup distribution as compared to the other columns.

Kemoun et al. (2001) studied the gas holdup using the air-water system with a column diameter of 0.162 m. They compared their gas holdup data with existing correlations from literature.

van Baten et al. (2003) proposed a scale-up methodology for the hydrodynamic behavior of 1 m diameter bubble column from their experimental data obtained with a 5.1 cm bubble column. They also developed CFD modeling using an Eulerian framework.

Verma and Rai (2003) studied the gas holdup and mass transfer coefficient using air-ferro-ferricyanide (electrolytic solution) with a 5.15 cm. column diameter. They observed that the average mass transfer coefficient increased with an increase in gas velocity.

Cents et al. (2005) reported the influence of small amounts of additives on gas holdup, gas-liquid interfacial area and bubble size. They attributed that addition of toluene to a non-coalescing air electrolyte system reduced the interfacial area to large extent and caused the formation of large bubbles, thus transforming it into a coalescing system. They also noted addition of solubility concentration of toluene transforming it into a coalescing air-water system. It increased interfacial area and the system changed into a non-coalescing system.

Majumder et al. (2006) investigated the pressure drop using an ejector induced gas-liquid down flow bubble column and proposed an empirical correlation to predict the pressure drop.

Zhang and Zhao (2006) proposed low temperature methanol synthesis in continuous slurry bubble column. They used three different 0.042 - 0.1 m diameter bubble column reactor and also a tapered bubble column reactor.

Kazakis et al. (2007) studied the gas holdup using Newtonian liquids in a 9.0 cm cylindrical bubble column. They observed gas holdup depended on the sparger diameter and physical properties of the liquid.

Jasim (2009) studied gas holdup and mass transfer coefficient using Newtonian and non-Newtonian liquids. They observed that gas holdup increased with increasing gas velocity and coalescence inhibition of liquid.

Youssef et al. (2009) studied the gas holdup using the air-water system with and without internals in a 8 inch diameter bubble column and measured specific interfacial area, bubble cord length and bubble velocity (upward and downward). They observed an increase in local gas holdup and gas-liquid interfacial area as the area covered by internals was increased.

Cachaza et al. (2011) studied gas holdup and flow regimes using positive (alcohols) and negative (electrolytes) surfactants. They observed both surfactants reduced coalescence and increased gas holdup.

Shah et al. (2012) studied on gas holdup, axial liquid dispersion and mass transfer in packed, trayed and empty bubble columns. They found that packed and trayed bubble columns improved gas holdup and mass transfer as compared to an empty bubble column. They also reported that gas holdup, axial dispersion and mass transfer depended more strongly on gas velocity as compared to the liquid velocity.

At present, gas velocity–holdup relationship are classified into two broad categories described as homogeneous (bubble flow) and heterogeneous (churn-turbulent flow). In the homogeneous regime, bubbles generated at the gas distributor are of uniform size and dispersed homogeneously throughout the liquid phase. In the heterogeneous regime, bubbles agglomerate within a few centimeters of the gas distributor to form large bubbles, these large bubbles move towards the center of the column and follow a sinuous trajectory as they rise. Bubbles undergo coalescence and dispersion and the resulting bubble size distribution is relatively wide.

Transition from homogeneous to heterogeneous flow occurs at a superficial gas velocity between 0.02 to 0.06 m/s (Sarrafi et al., 1999). However, no accurate general criterion is available for the prediction of the condition under which the transition between the homogeneous and heterogeneous regime occurs. The effects of operational and geometrical parameters on the transitional superficial gas velocity have been analyzed systematically by Sarrafi et al. (1999). Deckwer (1985) reported that the homogeneous flow would be preferred for gas-liquid mass transfer operation. In chemical industry, however, bubble columns are mostly operated under heterogeneous flow conditions. Details of the flow regime and its definition are shown in Table1.1.

The literature review attempted here is not in breadth or depth of coverage but is focused mainly on the application and hydrodynamic studies in the field of bubble column. It can be summarized at the end that the large number of studies have been reported in literature using Newtonian liquid systems, but not much work have been carried out with non-Newtonian liquid systems. With the development in polymer processing, food processing, biomedical engineering, biochemical engineering and

wastewater treatment the liquid often behaves as non-Newtonian in nature. Hence, there is an urgent need to study the hydrodynamics using non-Newtonian liquids in tapered bubble column. Thus in view of the importance of the bubble column using non-Newtonian liquids a research programme has been undertaken to investigation the following aspects,

i. Investigation on the hydrodynamics behavior of the two phases (liquid-gas) tapered bubble column using SCMC as a non-Newtonian pseudo plastic liquid;

ii. Development of empirical correlation for gas holdup and frictional pressure drop as a function of physical and dynamic variables of the system;

iii. The applicability of Artificial Neural Network modeling for the prediction of gas holdup and frictional pressure drop;

iv. Investigation on the hydrodynamics behavior of the two phases (liquid-gas) tapered bubble column using electrolyte solutions.

Table 1.1 Regimes of Bubble Column operation- Definitions
(Kumar et al., 1976)

Regime	Description
Dispersed regime	The dispersed gas move freely as discrete bubbles in the liquid continuous phase, fractional gas holdup < 0.1. This occurs at very low gas rates.
Fluidized regime	The gas is dispersed into swarms of bubbles moving up the column with a maximum holdup of fractional gas holdup ≈ 0.25 at higher gas rates, common in industrial applications.
Froth regime	The gas rates are kept so high that gas phase holdup is more than about 50% resulting in froth conditions for the dispersion.
Foam regime	At very high gas rates, the gas phase holdup reaches about 90% and the froth turns into foam due to a high rate of coalescence of gas bubbles supported by liquid film.