CHAPTER 2

VOID FRACTION IN CO-CURRENT BUBBLE COLUMN

2.1 Introduction

This chapter describes the phenomenon of void fraction based on the theory of hydrodynamics and mass transfer characteristics in the co-current bubble column and reviewed its industrial applications. It discusses the fundamental concepts of two-phase gas-liquid flows and its basic measurement parameters which are used in the physical analysis. It also covers the discussion on different experimental and empirical measurements of void fraction in bubble column. The flow patterns generated at different gas and liquid velocities in vertical co-current column and the corresponding flow regime map is also described later in this chapter.

2.2 Bubble Columns

The bubble columns are two-phase gas-liquid systems in which a gas is dispersed through a sparger in form of small bubbles into a continuous liquid phase in vertical cylindrical column as shown in Figure 2.1 [8]. They are very popular as multiphase reactors in chemical, petrochemical, biochemical and metallurgical industries [9]. They are used especially in chemical processes involving reactions like oxidation, chlorination, polymerization and hydrogenation, in the manufacture of synthetic fuels by gas conversion processes and in biochemical processes such as biological waste water treatment and fermentation [10].

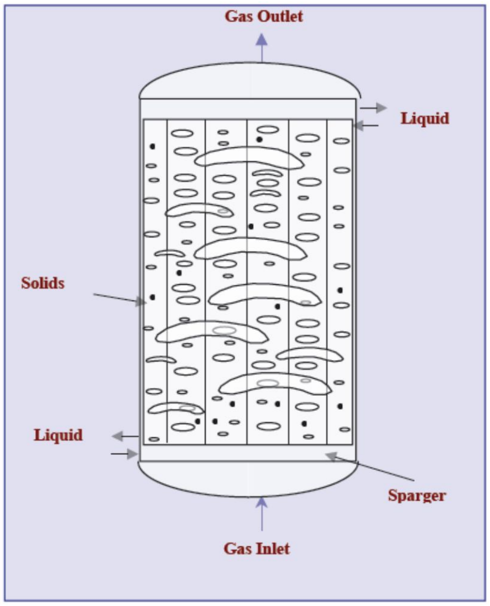

Figure 2.1: Schematic Diagram of Bubble Column [8].

The bubble columns offer many advantages over other kinds of multiphase reactors. They are simple in construction, no mechanically moving parts, good heat and mass transfer properties, reduced wear and tear, ease of operation, and low operating and maintenance costs [8]. They are classified into two types depending upon the flow direction in the vertical column. Depending upon this, the net liquid flow in a bubble column may be co-current or counter-current to the gas flow direction or may be zero as shown in Figure 2.2.

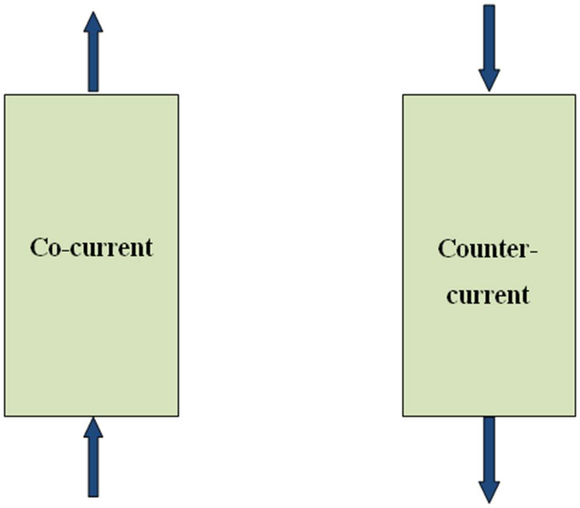

Figure 2.2: Direction of Flow in a Bubble Column.

2.2.1 Co-Current Bubble Column Pilot Plant

A co-current bubble column pilot plant is available in the Chemical Engineering Department of Universiti Teknologi PETRONAS (UTP). The next section will discuss its basic principle and construction.

2.2.1.1 Principle

The word "co-current" means that the air and liquid are in same phase/direction. The co-current bubble column pilot plant induced co-current in bubble columns (for up-flow and down-flow) which provides high interfacial area with larger mass transfer coefficients. This pilot plant is used to determine the optimum ejector geometry and to study and understand the hydrodynamics and mass transfer characteristics in the bubble columns. Figure 2.3 shows the current setup available in UTP for co-current pilot plant [11].

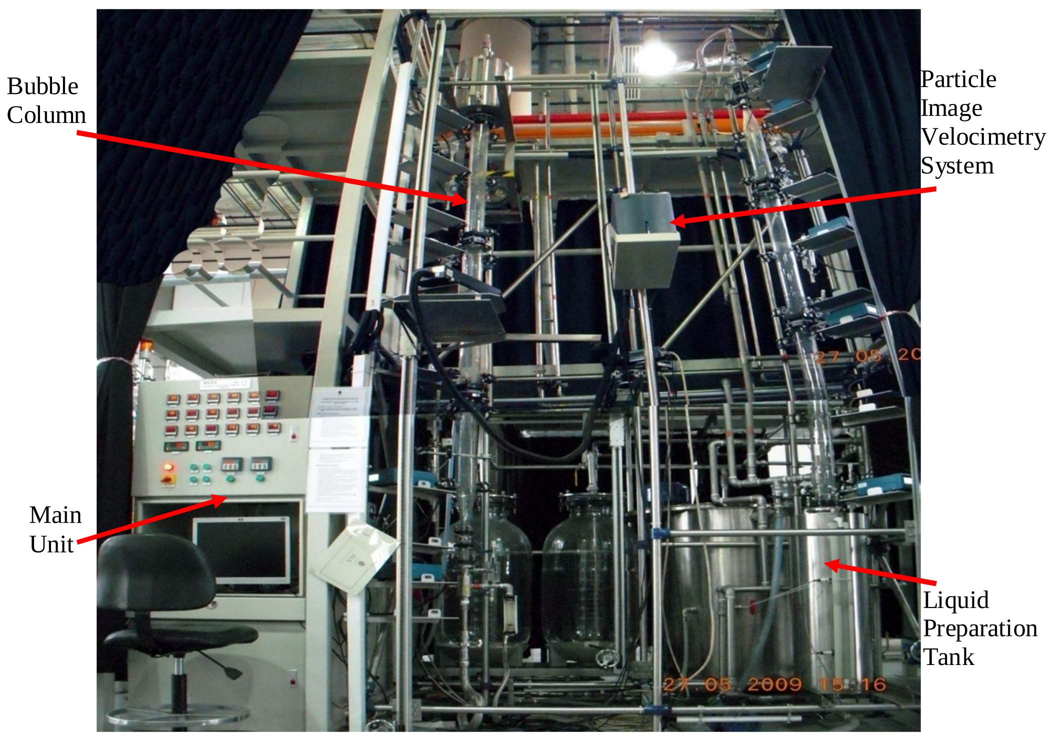

Figure 2.3: Co-Current Bubble Column Pilot Plant.

2.2.1.2 Construction

The existing bubble column pilot plant consists of three parts, namely the gas preparation unit, liquid preparation unit and the main unit which are discussed briefly [11]. The pilot plants are used to reduce the risk associated with construction of large process plants:

a) *Gas Preparation Unit*

   The gas preparation unit is used to control the flow of different gases and mix them at the desired composition before entering the main unit. It can accommodate up to 12 types of gases. The flow rate of each gas is measured and controlled using a thermal mass flow controller. The gas mixtures will pass through a static mixer before being introduced into the gas feed tank to smooth out any fluctuations in flow. A Coriolis flow meter downstream of the gas feed tank will measure the total gas flow rate into the system. There is also provision in the gas preparation unit to allow the gas mixtures to bypass the gas feed tank directly into the main unit [11].

b) *Liquid Preparation Unit*

   The liquid preparation unit contains six individual tanks with transfer pumps for storage and mixing of liquid solutions. The tanks are connected in such a way as to allow the liquid solutions in each tank to be mixed and transferred among each other tanks, besides being pumped into the liquid feed tank at the main unit. Liquid effluent collected in the receiver vessels at the main unit can also be transferred back to any of the six tanks at the liquid preparation unit [11].

c) *Main Unit*

   The main unit consists of vertical up-flow and down-flow co-current columns, liquid feed tank with pumps, receiver vessels and instrumentations along the column such as pressure indicators and conductivity sensors [11].

2.2.1.3 Application in Industry

They are used in following processes in industry:

i. Separation Process

ii. Absorption Process

2.3 Void Fraction in Co-Current Bubble Columns

Void fraction is one of the most important parameter to characterize the hydrodynamic behaviour of two-phase dispersion system in a bubble column. The behaviour of the void fraction has been attributed to many different factors, including geometry of the column; design of the gas distributor; physical properties of the gas and liquid phase; and the operating variables such as pressure, superficial gas and liquid velocity and temperature.

2.3.1 Definition

The void fraction is a dimensionless quantity and is often termed as "*holdup* or *fraction*" in two-phase flows. It is defined as the ratio of the volume of that phase to the total volume of the pipe [12] or can be defined as the fraction occupied by the gas phase in the total volume of a two- or three-phase mixture in a bubble column [7].

The earliest void fraction measurements dated back in 1940 and they still play the most important role in the study of two-phase flows. However, the term *'holdup'* can be defined as the fraction of the pipe volume occupied by a given phase, it is usually defined in place of liquid volume fraction while the term *'void fraction'* is used to represent the gas volume fraction (GVF). Both are used interchangeably in two-phase flow studies based on the requirement. The mathematical expressions for the two definitions are shown in equation (2-1) and (2-2) [12], [13]:

$$\lambda_g = \frac{A_g}{A} = \frac{V_g}{V_T} \tag{2-1}$$

$$\lambda_l = \frac{A_l}{A} = \frac{V_l}{V_T} = 1 - \lambda_g \tag{2-2}$$

where, λ_g is gas void fraction and λ_l is the liquid holdup. V_g, V_l and V_T are the volume of gas, liquid and total volume respectively. A is the total cross-sectional area of the pipe, while A_g and A_l are the area occupied by two phases respectively.

2.3.2 Hydrodynamic Parameter

The hydrodynamic parameters such as fluid flow rate, fluid properties, pipe diameter and pipe inclination vary with the flow regimes. These parameters have been utilized to identify the flow regimes. Typically, the global hydrodynamics have been quantified based on overall gas holdup.

2.3.2.1 Effect of Superficial Gas Velocity on λ_g

The past studies have mostly shown a positive effect of the superficial gas velocity on the gas void fraction [8], [14], [15]. The dependence of the void fraction on the superficial gas velocity can be defined by the following power-law expression [8]:

$$\lambda_g \sim U_{s,g}^n \tag{2-3}$$

where, n is dependent on the flow regime. Initially, the void fraction increases sharply and most linearly with the superficial gas velocity in the homogeneous flow regime where n in equation (2-3) is expected to be in the range of 0.8 to 1 [8]. Then it reaches a maximum value where the transition from homogeneous to heterogeneous flow regime occurs. The relationship between overall void fraction and superficial gas velocity varies over a range of velocities as shown in Figure 2.4.

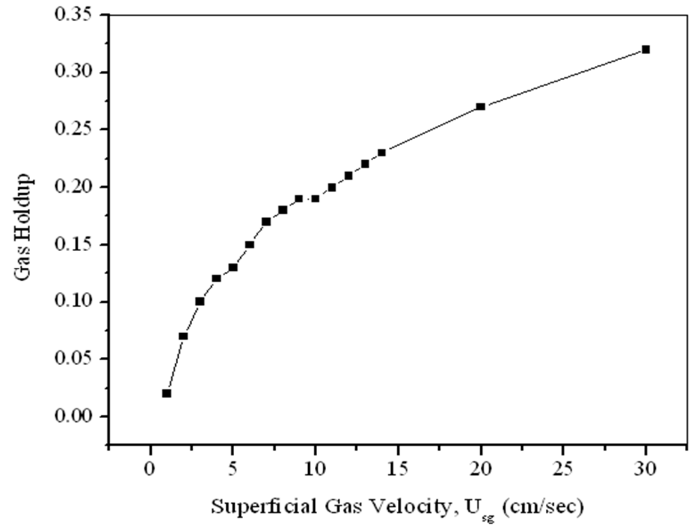

Figure 2.4: Overall Gas Holdup (*Reproduced from* Shaikh Al-Dahhan 2005) [16].

2.3.2.2 Effect of Water Quality on λ_g

The effect of using highly purified and deionised water against regular tap water also affect the void fraction distribution. According to Anderson and Quinn [17] and data published in the book [18], the magnitude of the void fraction with deionised water is lower than that obtained with regular tap water. So the bubble sizes observed in the column with deionised water much larger than regular tap water and therefore, the void fraction is lower for deionised water as will be more discussed in later chapters.

2.3.2.3 Effect of Gas Distributor on λ_g

The gas distributors are integral part of the design and scale-up of bubble columns. There are numerous types of gas distributor, which significantly differ in their size and number of orifices. Porous plates, perforated plates, multiple/single-orifice nozzle are the most commonly employed spargers in the bubble column. Spargers, like porous plates, generate uniform size bubbles and distribute the gas uniformly at the bottom of the liquid pool. Figure 2.5 illustrates some of these gas distributors. The characteristics of a gas distributor include, opening size, number of openings, sparger positioning, and nozzles position/orientation [19].

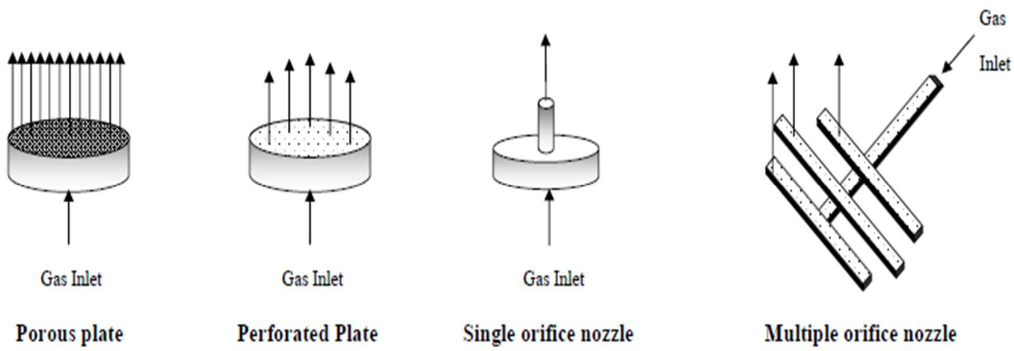

Figure 2.5: Different Types of Gas Distributors Employed in Bubble Column [19].

2.4 Measurement Methods for Void Fraction Calculation

The void fraction can be measured by numerous invasive and non-invasive techniques, which have been previously reviewed by several researchers. It includes, radiation attenuation (X- or γ-ray or neutron beams) for line or area averaged values, optical or electrical probes for local void fraction, impedance technique using capacitance sensors and direct volume measurement using quick-closing valves. To obtain accurate results from experiments, it is very important to select a suitable measurement technique. The use of different techniques depends on the applications and whether a volumetric average or local void fraction measurement is desired [20].

2.4.1 Experimental Measurements

2.4.1.1 Invasive Techniques

The main invasive methods for local measurements appeared in the early 1960's, before the development of experimental non-invasive hydrodynamic techniques, researchers involved in experimental work observed quite early the intense non-homogeneous and non-stationary characteristics of most gas-liquid flows.

2.4.1.2 Non-Invasive Techniques

There are numerous non-invasive techniques are also available to investigate the hydrodynamics of gas–liquid columns as shown in Figure 2.6 [21]. First, the global techniques has been presented, for example, the pressure drop measurements used to examine the gas and/or liquid hold up, the flow regime, the bubble size distribution and the mixing characteristics of the gas. Secondly, the techniques yielding local characteristics are the visualisation techniques such as Image and Photographic. Finally, the non-invasive Tomographic (i.e. capacitive and resistive) techniques are intensively used for bubble flow analysis [21].

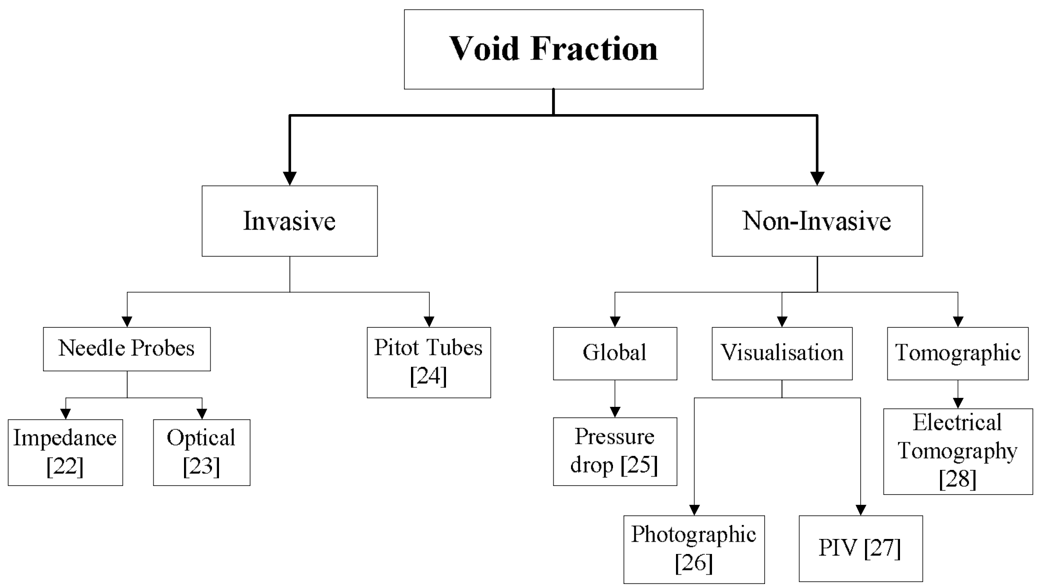

Figure 2.6: Different Invasive and Non-invasive Techniques to Measure Void Fraction.

2.4.2 Measurement by Empirical Correlation

An empirical correlation is a very useful engineering approach. Because, a large number of correlations appear in the literature and some of them are widely used in the process industry. The choice of the model depends on the application and also on the time and cost constraints.

A plethora of void fraction correlations are available in the literature. This would not be a concern, except for the fact that most of the correlations have some form or restrictions. The most common restriction is the flow pattern dependency. Another drawback is that many void fraction correlations have been validated with only experimental data that are limited to specific conditions, such as pipe orientation, flow pattern and gas-liquid combination.

In order to predict the void fraction in two-phase flow regardless of above mentioned restrictions, a general void fraction correlation has been developed. It was *Drift-Flux* model. Hibiki *et al*. (2003) define the basic concept of drift-flux model as, to consider the mixture as a whole, rather than as two separated phases [29]. It is a widely used model because of its applicability and simplicity in two-phase flows and can be applied to any pipe orientation. It has long been used to model vertical two-phase systems. It was developed principally by Zuber and Findlay in 1965 [30], although Wallis (1969) and Ishii (1977) in particular have added to its development.

The constitutive equations for the drift-flux model have been developed well for vertical upward two-phase flows in relatively small diameter pipe (25-50 mm) [32]. An expression for predicting the gas volume fraction and interpreting holdup data was developed by [30]. It correlates the actual gas velocity V_G and the mixture velocity $V_{M,}$ using two parameters C_0 and V_{gj}. It takes the following expression as mentioned in equation (2-4):

$$V_G = \frac{U_{sg}}{\alpha_{gas}} = C_0 V_M + V_{gj} \tag{2-4}$$

where, V_M is the mixture velocity which is the sum of superficial gas and liquid velocities, C_0 is referred to as a distribution parameter/coefficient. It accounts for considering the non-uniformity in the flow. V_{gj} called the drift velocity of gas, and accounts for local relative velocity between the gas and liquid phase [33]. With the two parameters and the superficial velocities, the gas volume fraction can be calculated. The accuracy of α_{gas} depends on the use of appropriate values for C_0 and V_{gj}. Table 2.1 indicates the different values for C_0 and V_{gj} used by different researchers in the literature for air-water bubbly flow in vertical orientation.

Table 2.1: Databases Used in this Study

No.	Type of Flow/ Pipe Orientation	Distribution Parameter, C_0 *and* Drift Velocity, V_{gj}	Limitations	Ref.
1	Bubbly flow/ Vertical	$C_0 = 1.2 - 0.2\sqrt{\rho_g / \rho_l}$ $V_{gj} = \sqrt{2}\left[\frac{g\sigma\Delta\rho}{\rho_l^2}\right]^{1/4}\left(1-\langle\alpha\rangle\right)^{1.75}$	Their study is also restricted to vertical oriented system and also using only the N_2-Water system.	[32]
2	Bubbly flow/ Vertical	$C_0 = 1.2, p_R < 0.5$ $V_{gj} = 1.4\left[\frac{g\sigma\Delta\rho}{\rho_l^2}\right]^{1/4}$	This model is restricted only for vertical oriented systems and for D < 5cm.	[34]

2.4.3 Measurement by Using Pixels

According to Zhiyao *et al*. (2003) the void fraction can also be calculated by using the number of pixels obtained from image reconstruction using ECT [35]. They proposed a new method for the void fraction measurement of two-phase flow by establishing a mathematical model of image reconstruction. The computer reconstructs the image of the cross-section of the pipe using the 66 capacitance measurements and thus, the void fraction can be obtained by using the gray level of the reconstructed image. After image reconstruction, the concentration 'c' of two-phase flow can be calculated by using equation (2-5) [35]:

$$c = \sum_{i=1}^{M} \frac{A_j}{A} \tag{2-5}$$

where, A is the total cross-sectional area of the pipe, $A_j = \frac{A}{P} \times K_j$ is the area of the j^{th} pixel, P is the number of pixels. Thus the void fraction (λ_g) of two-phase flow is [35]:

$$\lambda_g = (1 - c) \times 100\% \tag{2-6}$$

2.4.4 Estimation by Using Photographs

As defined earlier, the void fraction (λ_g) is an important parameter in bubble columns. It has always been a challenge to measure it due to highly non-symmetric nature of two-phase gas-liquid vertical flows, e.g. bubbles coalescence and break-up with the conduit wall makes the flow extremely unstable. The void fraction estimation by using the photographic technique is described in this section [36]. Figure 2.7 shows the distribution of phases for the estimation of volumetric void fraction. The space occupied by the solid particles, droplets, or bubbles in the mixture is defined as the volumetric void fraction of the dispersed phase as mentioned in equation (2-7). Equivalently, the volume fraction of the continuous (i.e. liquid) phase is defined in equation (2-8) [13]:

$$\alpha_d = \lim_{\delta V \to V^0} \frac{\delta V_d}{\delta V} \tag{2-7}$$

$$\alpha_c = \lim_{\delta V \to V^0} \frac{\delta V_c}{\delta V} \tag{2-8}$$

where; $\alpha_d + \alpha_c = 1$

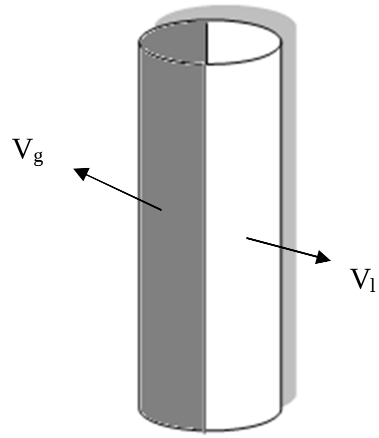

Figure 2.7: Volumetric Void Fraction [2].

2.5 Application of Void Fraction in Co-Current Bubble Column

The gas-liquid two-phase flow widely exists in many industrial applications, such as, chemical, petroleum and other process industries. The measurement of void fraction of two-phase flow is very important for safety, environmental protection, energy conservation and quality assurance in industry. Some of the technical applications of void fraction in co-current bubble column are as follows:

i. For process control in chemical production plants

ii. For transport of oil-gas mixture in pipelines

iii. Additionally, the prediction of void fraction in large pipes is significant for the analysis of accident scenarios, especially in reactors for the loss of coolant accidents [37].

2.6 Overview of Two-Phase Flow

The multiphase flow in general describes as the motion of two or more fluids in a medium and it is considered as a difficult phenomenon to understand, predict and model. The term *phase* refers to the gas, liquid or solid, and each may be a mixture of one or more components. There are several examples of multiphase flows in bubble columns which are generally observed in process industries. Among them the most frequent are [13]:

i. Solid-liquid flows found in suspensions or slurries

ii. Gas-liquid flows are most important in oil-well heads, boiling, condensation and in electricity generating plants

iii. Gas-solid flows occur in dense or lean phase pneumatic conveying

iv. Liquid-liquid flows are example of stratified flow or oil-water emulsion

Table 2.2 indicates the examples of single and multiple phases versus component of matter. The matter may change from one state / phase to another and these changes caused by the change in chemical reactions [38]. In order to describe the two-phase flow, the information on flow regime, void fraction and pressure drop is of vital importance. The interest in two-phase flow is due to its excessive importance in various industrial applications such as filtration, spray processes, fossil fuel plants, nuclear reactors and power generation systems. Gas – liquid flows that are typically constrained in pipelines or vessels possess several different configurations ranging from bubbly flow to annular flow [13].

The difficulty in the design of gas-liquid systems lies in the immediate existence of the two phases. The interface between the two phases can be divided into several configurations. This phenomenon is called flow pattern (or regime), which is one of the important feature of two-phase flows. In single-phase flow, the design parameters can be easily calculated and interpreted. However, the occurrence of the two different phases creates a challenge in the modelling of the flow system [39].

Table 2.2: Phase of Matter *vs.* Component of Matter [39]

Component	**Phase**	
	Single	Multiple
Single	Flow of water, oil, oxygen (single-phase, single component flow)	Flow of water and steam (two-phase, single component flow)
Multiple	Flow of air, liquid polymer mixture (single-phase multi-component flow)	Flow of air-water particles, e.g. bubble slurries (three-phase, multi-component flow)

2.7 Flow Pattern Classification in Co-Current Bubble Column

A particular type of geometric distribution of the components in co-current bubble column results in the formation of various *flow patterns* or *flow regimes.* In describing the configurations taken up by gas and liquid flowing together, researchers have used a variety of descriptions. Some are alternative names for the same flow pattern, while others are subdivisions of more major groups. Two-phase flow regimes are dependent upon numerous parameters. The most significant are as follows [40];

i. Flow rates of each phase

ii. Fluid properties of each phase (density, viscosity and surface tension)

iii. Pipe geometry (size and shape)

iv. Pipe orientation (horizontal, vertical and inclined)

v. Flow direction (i.e. upward, downward, co-current or counter-current)

The flow regimes in co-current bubble column reactors have been studied in various details and reported in many previous literatures [39], [40], [41]. However, this project is mainly concerned with the vertical co-current upward flow.

2.7.1 Flow Regimes in Co-Current Bubble Column

It is important to note that four main types of flow regimes have been studied by different researchers in vertical upward gas-liquid column of circular cross-section. Figure 2.8 illustrates them in order of increasing gas flow rate (from left to right). The application of bubble column can be categorised based on the flow regimes. The biochemical operations are mostly performed in bubble flow, such as cultivation of bacteria, treatment of sewage and etc. The churn-turbulent flow regime is responsible for highly exothermic processes.

i. Discrete Bubble flow: also referred to as homogeneous flow regime generally occurs at low superficial gas and liquid velocities. It is characterised by uniformly sized bubbles in a liquid continuum.

ii. Dispersed flow: is also a type of bubble flow in which the gas occupies the major cross-sectional area and the liquid is in the form of small droplets dispersed in the gas.

iii. Slug flow: on increasing the gas flow rate, collision between bubbles increases and they coalesce, forming large bullet shaped bubbles called as Taylor bubbles.

iv. Churn flow: on further increase in gas flow rate, the Taylor bubbles have broken down to give oscillating churn regime. The gas now exists predominantly as large irregularly shaped bubbles with smaller bubbles entrained in the liquid phase.

v. Annular flow: when the gas flow rate is sufficiently large to support a liquid film at the surface of the pipe, the gas flows continuously through the centre of the pipe [38], [39].

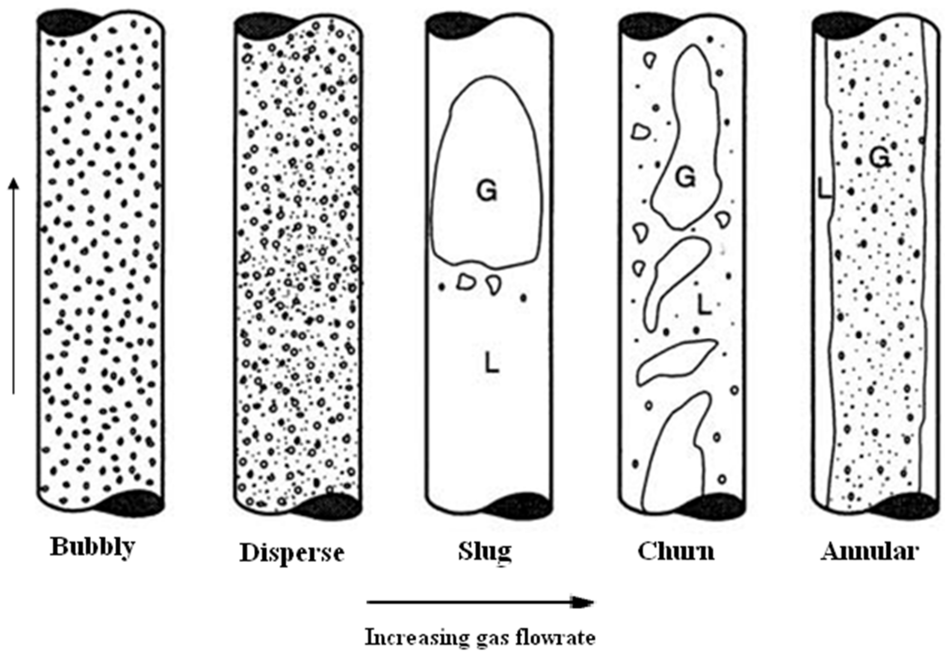

Figure 2.8: Flow Regimes in Vertical Co-Current Bubble Column [42].

2.7.2 Flow Regime Map of Co-Current Bubble Column

The different flow regimes can be envisaged by using a flow map which is mainly based on visual identification of phase distribution. A number of flow regime maps have been proposed by different researchers based on their observations. Flow regime data are often represented on a two dimensional diagram in terms of system variables. A wide variety of two-phase flow pattern maps exist in literature. The most commonly used variables are the gas and liquid superficial velocities as dimensional coordinates. However, there are some flow maps in literature that uses other parameters for dimensional coordinates than superficial velocities.

Hewitt and Roberts [43] plotted the data for gas momentum flux against liquid momentum flux for air-water system; Baker [44] also utilised the same approach for plotting the flow pattern map. For vertical upflow, flow pattern maps based on superficial velocities have been published since 1960's and are still being produced. Figure 2.9 is an example of it, for air-water system in an 82.6 mm inner diameter pipe, at ambient conditions due to Zhang *et al*. [45].

The superficial gas velocity increases in a vertical flow and the flow regime changes between all the phases, discrete, bubble-dispersed, bubble-slug-churn and annular. Note that for a particular superficial gas velocity, the multiphase flow is annular for all superficial liquid velocities.

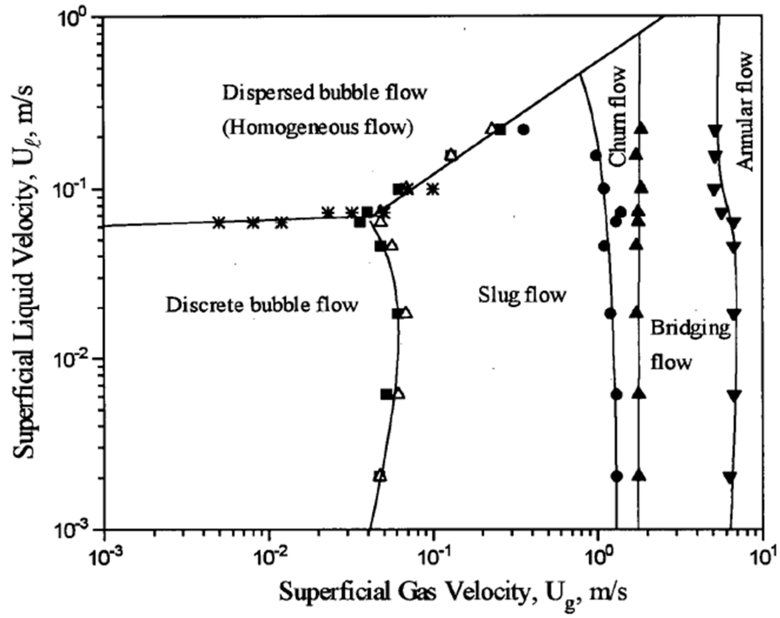

Figure 2.9: Bubble Column Flow Regime Map for Air-Water System [45].

Many researchers have discussed and studied the flow regimes experimentally and present their results by using a flow regime map. Some used the visual observations method and others determine the flow regime with the aid of instruments. Table 2.3 summarise some previous studies particularly for vertical gas-liquid flow that will be used to compare the experimental results obtained for this study in later chapter. In comparison with this study only limited researchers have used a gas distributor which can make the comparison difficult.

Table 2.3: Literature Survey Conducted on Air-Water Vertical Column

Investigator	Measurement method	Flow regime map	Experimental conditions			Limitations
			Gas-liquid	**Column diameter (mm)**	**Column height (m)**	
J.P.Zhang *et al*. (1997) [45]	Conductance probe	U_{sg} *vs.* U_{sl}	Air-water	82.6	2	All are restricted to a particular size of the column and its height.
Taitel *et al.* (1980) [46]	Visual observation	U_{sg} *vs.* U_{sl}	Air-water	25 and 51	-	
Chen *et al*. (1997) [47]	Empirical model	U_{sg} *vs.* U_{sl}	Air-water	25.4	-	
Weisman & Kang (1981) [48]	Visual observation	Q_g *vs.* Q_w	Air-water/ Air-glycerol	12, 25 and 51	6.1	
Fernandes *et al*. (1983) [49]	Visual observation	U_{sg} *vs.* U_{sl}	Air-water	50.7	11.1	

2.8 Methods for Flow Regime Detection

The measuring techniques in two-phase flows are quite different from those of single-phase flows: in fact, there exist peculiar quantities of this kind of flows, such as the void fraction and the interfacial area concentration, which require precise instrumentation. The experimental methods used for flow regime detection are broadly classified in the following categories [50]:

i. Visual observation

ii. Advanced measurement techniques.

2.8.1 Visual Observation

It is the simplest method to study the flow regime in bubble columns. The homogenous, vertically rising bubbles can be observed in the Figure 2.10 (a). However, in heterogeneous regime there is a concentrated interaction of bubbles and it is difficult to identify the velocity by visual observation as shown in Figure 2.10 (b). Moreover, this method can only be workable when the column is transparent.

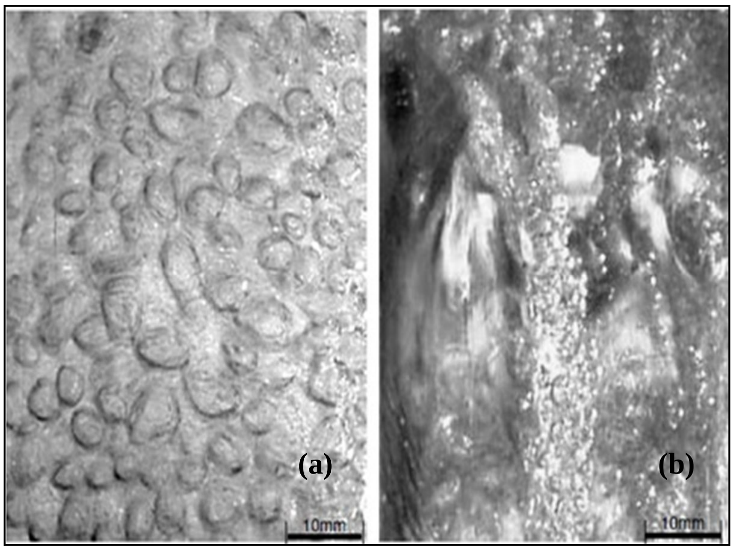

Figure 2.10: Photographs of (a) Homogeneous and (b) Churn-Turbulent Flow [51].

2.8.2 Advanced Measurement Technique

The regime transitions in a bubble column are still under investigation and several techniques have been proposed by different researchers. Based on the previous literature, following are the most commonly used methods that are being employed to determine the flow behaviour in the bubble column:

i. Electrical Capacitance Tomography (ECT)

   It is one of the modern progressive techniques for flow identification. The information is initially obtained by observing measurement data taken at the boundary of the sensing zone by placing a number of detectors.

Several projections are taken from the measurements that are reconstructed [14], [16]. The detailed discussions of this technique will be provided in next chapter.

ii. Electrical Resistance Tomography (ERT)

ERT has been proved to be an effective tool for mapping the concentration and velocity distributions for the second phase in two-phase flows, where electrical differences between the two-phase fluids exist. However, the application of such a two-phase flow device is limited because of the precision, speed and computational potential. Also, the conventional sensors would not be appropriate for the formation of large bubbles since the electrodes may lose contact with the conductive fluid [51].

iii. Particle Image Velocimetry (PIV)

Another classical optical technique for flow studies is the PIV. It is used for measuring instantaneous velocity fields in a wide range of applications. It is also non-intrusive but its application is limited to a flow with few bubbles and for relatively small void fraction values. This limitation is mainly due to the reflection and dispersion phenomenon which occurs on phase boundaries [27]. Also, the repetition rate of PIV systems is comparatively slow and it requires that small seeding particles are brought into the flow to trace the movement of the flowing medium. Optical access to the flow region is also necessary. Solid surfaces in the experimental setup can scatter light and disturb measurements.

2.9 Basic Flow Measurement Parameters

This section introduces a few definitions that are fundamental to multiphase flow measurement. There are various parameters that have been derived to support in the description of multiphase flow which includes, the volume fraction, superficial velocities, liquid holdup, void fraction, and slip and non-slip conditions.

2.9.1 Phase Volume Fraction

The phase volume fraction refers to the fraction by volume occupied by each phase in the mixture in a given pipe section at a given temperature and pressure condition [12].

2.9.1.1 Liquid Volume Fraction

It can be defined as a ratio of the liquid volume flowrate to the total fluid volume in the pipe segment at a given temperature and pressure. It can be expressed as [12]:

$$\alpha_{liquid} = \frac{Q_w}{Q_T} \tag{2-9}$$

where, α_{liquid} is the water volume fraction, Q_w is the water volumetric flowrate and Q_T is the total fluid volumetric flowrate.

2.9.1.2 Gas Volume Fraction

It is the ratio of a gas volume flowrate to the total fluid volume in the pipe segment at a given temperature and pressure. It can be expressed as [12]:

$$\alpha_{gas} = \frac{Q_g}{Q_T} \tag{2-10}$$

where, α_{gas} is the gas volume fraction (GVF), Q_g is the gas volumetric flowrate and Q_T is the total fluid volumetric flowrate.

2.9.2 Superficial Velocity

2.9.2.1 Superficial Liquid Velocity

Superficial liquid velocity (U_{sl}) is the liquid velocity flowing through a pipe cross-section without gases. It is therefore a ratio of liquid flow rate at an operating temperature and pressure condition divided by the total cross-sectional area of the pipe. Mathematically, it can be expressed as [12]:

$$U_{sl} = \frac{Q_w}{A} \tag{2-11}$$

where;

$$A = D_i^2 \frac{\pi}{4} \tag{2-12}$$

A is the cross-sectional area of pipe (m^2), Q_w is the water volumetric flowrate (m^3/s) and U_{sl} is the superficial liquid velocity (m/s).

2.9.2.2 Superficial Gas Velocity

Superficial gas velocity (U_{sg}) is the gas velocity flowing through a pipe without liquids. It has a similar equation as with the U_{sl} and is shown in the equation (2-13). The multiphase mixture velocity (V_M) can also be obtained by summing the superficial velocity of gas and liquid [12]:

$$U_{sg} = \frac{Q_g}{A} \tag{2-13}$$

where, Q_g is the gas volumetric flowrate (m^3/s), A is the cross-sectional area of pipe (m^2) and U_{sg} is the superficial gas velocity (m/s).

The multiphase mixture velocity can be obtained by summing the superficial velocity of gas and liquid, as shown in equation (2-14) [12]:

$$V_M = U_{sg} + U_{sl} \tag{2-14}$$

where, V_M is multiphase mixture velocity (m/sec).

2.9.3 Volumetric Flowrate, Holdup and Void Fraction

2.9.3.1 Phase Volumetric Flowrate

The phase volumetric flowrate can be obtained as a function of phase volume fraction and superficial velocity. The two expressions are shown below [12]:

$$Q_g = A\alpha_{gas}U_{sg} \tag{2-15}$$

$$Q_w = A\alpha_{liquid}U_{sl} \tag{2-16}$$

The summation of phase volumetric flowrate i.e. Q_w and Q_g gives the total volumetric flowrate, Q_T of multiphase fluid;

$$Q_T = Q_W + Q_g \tag{2-17}$$

2.9.3.2 Liquid Holdup

The liquid holdup (λ_l) is a ratio of cross-sectional area occupied by the liquid phase to the total cross-sectional area of the conduit [12].

$$\lambda_l = \frac{A_l}{A} \tag{2-18}$$

2.9.3.3 Gas Void Fraction

The ratio of the cross-sectional area in a conduit occupied by the gas phase and the cross-sectional area of the conduit is called as gas void fraction (λ_g) [12].

$$\lambda_g = \frac{A_g}{A} \tag{2-19}$$

where, A_g and A_l are the area occupied by two phases respectively and A is the total cross-sectional area of the pipe in m^2.

2.9.4 Slip and Non-Slip Conditions

A slip is a phenomenon that occurs in a multiphase flow (gas-liquid), in which the phases have varying velocities at a given cross-section of a pipe. This varying velocity can be caused by difference in fluid density. The lighter gas phase will normally move much faster than the liquid phase. The slip effect can be described by the relationship between the liquid holdup (λ_l), liquid volume fraction (α_{liquid}), gas void fraction (λ_g) and the gas volume fraction (α_{gas}). The above mentioned terms have already been discussed in section *2.9.1* and *2.9.3* [12].

Due to slip, the liquid holdup will be larger than the liquid volume fraction and the gas void fraction will be smaller than the gas volume fraction as shown in the expression (2-20) and (2-21):

$$\lambda_l \geq \alpha_{liquid} \tag{2-20}$$

$$\lambda_g \geq \alpha_{gas} \tag{2-21}$$

In no-slip conditions, the liquid holdup is equal to the liquid volume fraction and the gas void fraction is equal to the gas volume fraction. This can be explained in more detail by using the concept that if the gas superficial velocity will be equal to the liquid superficial velocity, the slip ratio would be one. If the slip ratio is zero, then the fluid will be free from gas and a single phase flow condition occurs [12].

2.9.5 Reynolds Number (Re)

It is a dimensionless number and can be defined as a ratio between the inertial forces and the viscous forces in a flowing stream. In a pipe, the flow is ‘laminar’ if Re is less than 2000 and if Re is greater than 4000 then the flow becomes ‘turbulent’. The superficial gas and liquid Reynolds number are shown in equation (2-22) and (2-23) [52]:

$$\mathrm{Re}_{sl} = \frac{\rho_l U_{sl} D_i}{\mu_l} \tag{2-22}$$

$$\mathrm{Re}_{sg} = \frac{\rho_g U_{sg} D_i}{\mu_g} \tag{2-23}$$

where, D_i is the inner diameter of the pipe (m), μ is dynamic viscosity (Ns/m^2) and ρ is density (kg/m^3)

2.10 Summary

The study of (multiphase) two-phase flow is a challenging field involving multidisciplinary knowledge. The reliable experimental techniques are fundamental tools in order to understand the phenomenon of multiphase flow particularly two-phase flow. Among the four different kinds of two-phase flows, gas-liquid flows are the most important and widely exist in chemical, petroleum, energy and power engineering applications. In this chapter the basic concepts of critical parameters in characterising the bubble column hydrodynamics were discussed. Besides other factors, it is noteworthy that void fraction is an important parameter of gas-liquid co-current bubble columns. The online void fraction measurement has the advantages of safety, environmental protection and energy saving in the industry. The measuring techniques for the investigation of void fraction in bubble columns were reviewed and briefly discussed as invasive and non-invasive techniques.

In the past few decades, much effort has been done for the development and application of online flow measurement techniques. The most notable are the ECT, ERT and PIV because of their non-invasive behaviour. Furthermore, gas-liquid two-phase flow regimes and their flow pattern maps were discussed and the basic flow parameters that used to describe the two-phase flow on which the flow regime depends were also considered.