

CFD SIMULATION OF THE DYNAMIC FLOW BEHAVIOR IN A BUBBLE
COLUMN REACTOR

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A project report submitted in partial
fulfillment of the requirement for the award of the
Degree of Master of Mechanical Engineering

Faculty of Mechanical and Manufacturing Engineering
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JULY 2015

ABSTRACT

In this project report an Eulerian two-phase Computational Fluid Dynamics (CFD) model for modelling bubble columns is presented. This model is able to predict the bubbly flow parameter such as gas holdup, contact surface area, air volume fraction, pressure drop, and velocity magnitude to understanding the hydrodynamic flow behaviors. Three types of gas distributor design are tested on the 1.5 m height and 0.15 m diameter bubble column cylinder. Five different velocities are used on the each gas distributor design in order to produces a variety flow pattern in the bubble column. The ANSYS Fluent Workbench 15.0 was used as the numerical solution to make the simulation analysis on the bubble column problems. In this simulation, gas (air) is dispersed through the gas distributor into liquid (water) in the bubble column to produces the bubbles rising along the cylinder. The graphically simulation result of gas holdup and velocity profile are compare to the previous simulation result similarly tendency in shape. Quite good agreement is obtained. It observed that by increasing the superficial gas velocity, gas holdup also increases and magnitude velocity will decreases when approached the wall. From the simulation result obtained, design “c” with larger holes diameter and open area ratio mostly given the highest value of gas holdup, contact surface area, air volume fraction and magnitude velocity compare to other design. The gas distributor holes sizing will be determined the size of bubble produces. The large bubble having more buoyancy force and rise velocity compare to small bubble.

ABSTRAK

Kaedah pemodelan *bubble column* menggunakan *Eulerian two-phase Computational Fluid Dynamics (CFD) model* yang di tunjukkan dalam laporan ini berupaya mengesan *bubbly flow* parameter seperti “*gas holdup*”, “*contact surface area*”, “*air volume fraction*”, “*pressure drop*”, dan “*velocity magnitude*” bagi memahami tingkah laku aliran hidrodinamik. Dalam simulasi ini, tiga jenis pembahagi gas di uji terhadap “*bubble column cylinder*” yang berketinggian 1.5 m dengan diameter 0.15 m. Untuk menghasilkan pelbagai corak aliran di dalam “*bubble column*”, lima halaju gas yang berbeza digunakan keatas setiap rekabentuk pembahagi gas. ANSYS Fluent Workbench 15.0 digunakan sebagai kaedah penyelesaian berangka bagi membuat analisis simulasi terhadap “*bubble column*”. Bagi menghasilkan gelembung udara yang naik di sepanjang silinder, gas (udara) di sesarkan melalui pembahagi gas kedalam cecair (air). Bagi mengesahkan keputusan yang diperolehi, satu perbandingan keputusan “*gas holdup*” dan “*velocity magnitude*” dalam bentuk graf telah dilakukan terhadap keputusan simulasi penyelidikan terdahulu dan persetujuan yang agak baik dicapai. Daripada pemerhatian didapati, dengan meningkatnya “*superficial gas velocity*”, “*gas holdup*” juga meningkat dan “*velocity magnitude*” akan berkurangan apabila menghampiri dinding silinder. Daripada keputusan yang diperolehi, didapati bahawa pembahagi gas rekabentuk “c” dengan diameter lubang dan nisbah kawasan terbuka paling besar selalunya memberikan nilai “*gas holdup*”, “*contact surface area*”, “*air volume fraction*”, dan “*velocity magnitude*” yang tinggi jika dibandingkan dengan design yang lain. Saiz lubang pembahagi gas akan menentukan saiz gelembung udara yang terhasil. Gelembung udara yang bersaiz besar mempunyai daya angkatan dan halaju kenaikan yang lebih jika dibandingkan dengan gelembung udara yang lebih kecil.

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LIST OF SYMBOLS AND ABBREVIATIONS

\emptyset	–	Diameter
3D	–	Three Dimensional
A	–	Open Area Ratio
CFD	–	Computational Fluid Dynamics
ϵ_G	–	Gas Hold up
ERT	–	Electrical Resistance Tomography
H/D	–	Height/Diameter k-epsilon
HFA	–	Hot Film Anemometer second
k- ϵ	–	K-epsilon
LDA	–	Laser Doppler Anemometer
PIV	–	Particle Image Velocimeter
U_{sg}	–	Superficial Gas Velocity
U_t	–	Transition Velocity
V	–	Velocity
V_G	–	Gas Velocity
VOF	–	Volume of Fluid

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CHAPTER 1

INTRODUCTION

Bubble column are important devices as gas liquid contactor in multiple industry processes. In the bubble columns, gases are representing in the form of bubbles, and come in contact with liquid. The purpose may be simply to mix the liquid phase and finally to produce fuel. A bubble column reactor is basically a cylindrical vessel with a gas distributor at the bottom. According to Kantarci et al., (2005) the gas is sparged in the form of bubbles into either a liquid phase or a liquid–solid suspension.

Bubble column reactors owe their wide application area to a number of advantages they provide both in design and operation as compared to other reactors (Shahimie, 2010). First, they have excellent heat and mass transfer characteristics, meaning high heat and mass transfer coefficients (Kantarci et al., 2005). Little maintenance and low operating cost because of the less parts moving and uncomplicated design. The durability of the component or other packing material is high.

1.1 Research Background

Understanding on the hydrodynamics of bubble column are very important part to indicates the operation of bubble column because it is determined by many variables such as high of the liquid inside the column, superficial gas velocity, gas sparger design and the diameter of bubble column. However, mostly the parameters that affect the performance of bubble column are the gas hold-up distribution, gas-liquid mass and heat transfer coefficients, while bubble rise velocities and bubble size distributions often will affect the mixing criteria.

Bubble column reactors are widely used in chemical, petrochemical and biochemical processes (Zhang et al., 2006 and Kantarci et al., 2005). It is also widely used for conducting gas-liquid reactions in a variety of practical applications in industry such as absorption, fermentations, bio-reactions, coal liquefaction and waste water treatment (Mouza et al., 2004).

Gas-liquid bubble columns can be operated in a number of different regimes. The flow regime encountered in the column depends on one hand on the superficial gas velocity and the physical properties of the phases, and on the other hand, on the aspect ratio of the column (Delnoij et al., 1997). Broadly, the regimes of operation in a bubble column are homogeneous, heterogeneous and the transition regime.

Bubble column reactor have a different behavior in homogeneous and heterogeneous regime, thus, the dependencies of rates of mass, heat and momentum transfer on the design and operating parameters (such as reactor geometry, gas and liquid flow rates and properties of the contacting phases) are also very different (Miguel et al., 2005).

Flow pattern in a bubble column reactor is a result of multitude of factors arising out of the motion of individual phases associated with pertinent viscous and the turbulent effects, which render it fully three dimensional at various levels of complexities in different directions. At low gas velocities, the rise velocity of bubbles and hence the downward flow of liquid is not very dominant to generate an appreciable flow pattern in the column (Kulkarni et al., 2007).

During the last 10 years, vigorous attempts have been made for experimental measurements of flow pattern using some of the advanced flow visualization techniques viz. laser Doppler anemometer (LDA), particle image velocimeter (PIV), hot film anemometer (HFA) and tomography.

The main focus of dissertation is to understand the hydrodynamic behavior of a concurrent gas-liquid up-flow bubble column with a different sparger design by using CFD analysis. One of the main reasons behind focusing on the hydrodynamics is its strong influence on the design and hence on the performance of a bubble column (Kulkarni et al., 2007). The air and water will be used as the function of gas and liquid in the bubble column reactor. The gas holdup, contact surface area, pressure drop, air volume fraction and velocity profile will be observers to understand the hydrodynamic behavior in the bubble column. There are currently strong efforts in industry to enable the use of computational fluid dynamics (CFD)

for the design, scale-up, and optimum operation of bubble column reactors. The simulation of bubbly flows is still not fully mastered mainly due to its complexity and the manifold interacting phenomena. The bubble column hydrodynamics are dominated by the movement of the bubble plume and the 3-D vortical flow structures in the liquid phase that continuously change sizes and positions.

It is generally accepted that only dynamic 3D flow models are able to simulate the essential features encountered in bubble columns to a reasonable extent. The results of CFD analysis are relevant engineering data used in conceptual studies of new designs, detailed product development, troubleshooting, and redesign and therefore CFD is gaining importance in general process applications (Anil et al., 2007).

The simulation method (CFD) will give more advantages compare to the others method. It is a very compelling, non-intrusive, virtual modeling technique with powerful visualization capabilities and can represent data in a various forms with chippers cost and time. Furthermore, CFD can predict a gas hold-up with different superficial gas velocity and a time-averaged flow structure. All the modelling in this study is done with the Eulerian-Eulerian approach, as this is considered as being the most suitable method for modelling the dynamic flow to understand the hydrodynamic behavior in a bubble column reactor.

1.2 Problem Statement

The hydrodynamic behaviour in the bubble column reactor is the most important part to ensure that the mixing capability of gas and liquid. Many factors are affected to the capability of these mixing. The gas volume fraction, gas hold-up and time-average flow structure, pressure drop is the some of them. These factors are depending on the parameter that will be used in the study such as superficial gas velocity and distributor design. The main problem is to determining the optimization of three design sparger by observation of hydrodynamic behaviour in the bubble column reactor with considering the factors.

1.3 Objective

1. To understand the hydrodynamic behaviour of a concurrent gas-liquid up-flow bubble column by CFD analysis.
2. To predict a gas hold-up and magnitude velocity with different sparger distributor geometry and superficial gas velocity.
3. To predict a surface contact area, pressure drop and volume fraction in order to describe bubble characteristic and dynamic behaviours.

1.4 Scope of the Study

These studies are conducted with the limitations below to ensure that, it's did not exceed the required purpose:-

1. The system used in the study is a cylindrical column of 15cm diameter and 1.5 m height.
2. A single gas distributors with different geometry are employed: a perforated plate (19 holes of $\phi 1$ mm, opening area: 0.084%), (19 holes of $\phi 2$ mm, opening area: 0.338%) and (19 holes of $\phi 3$ mm, opening area: 0.760%).
3. The plate sparger aerates the whole cross-section of the bubble column and three different gas distributors has a diameter of 1 mm, 2 mm and 3 mm and five different superficial gas velocities 1 m/s, 2.5 m/s, 5 m/s, 7 m/s and 9 m/s were use to produces fully turbulent flow in the sparger zone.
4. The eulerian-eulerian approach will be used for modeling the volume of fluid multiphase model flow.
5. The standard k- ϵ mixture turbulence, implicit model and transient time will be used to account the effect of turbulence.
6. Ansys Fluent software package will be used to simulate the system for various hydrodynamics parameters and results will be comparing to the previous simulation result as the validation process.

1.5 Significant of the Study

The significant of the study is with three different gas distributors design, time step, and various superficial gas velocities the variety of gas bubble hold up in a bubble column reactor can be obtained. The gas hold-up and the contact surface area predicted describe the hydrodynamic behaviour in the bubble column. Furthermore, the optimum design of sparger gas distributors can be obtained by the higher gas holdup and contact surface area produces in the result represented. After that, the optimum gas distributor was selected to present more parameter of hydrodynamic behaviour.



CHAPTER 2

LITERATURE REVIEW

The current development on CFD modelling of hydrodynamics bubble column is presented in this chapter. The CFD simulation on bubble column emphasis on parameters such as superficial gas velocity, gas hold-up profile contact surface area and air volume fraction that probably affects the hydrodynamic behavior of a concurrent gas-liquid up-flow bubble column is the main interest in this study. Besides that, a brief summary about the experimental measurement technique to predict the gas hold-up and the time-average flow structure was also discussed.

2.1 Introduction

A bubble column reactor is an apparatus that widely used in industry application for gas-liquid reactions. This apparatus are presented in most simple form basically in vertically square and cylindrical. A simple construction and lack of mechanical part are synonym with the reactor characteristic. Because of the reasonable cost and can be built in large size, a bubble column can be category as an adaptable reactor compare to the ability of the operationally.

In their operation, the gas normally are aerated through the sparger distributor locate at the bottom of column reactor. With the certain velocity, it wills dispersed by the distributor into bubble to the continuous liquid phase to produce the dynamic turbulent stream that cause the optimum gas exchange. Normally, the liquid flow rate is very low when it's passing through a bubble column. Otherwise, the gas hold up flow may vary widely according to the specified conversion level.

2.2 Application of Bubble Column

In the industrial application based on manufacture of synthetic fuels by gas conversion processes and in biochemical processes such as fermentation and biological wastewater treatment and in chemical processes involving reactions such as oxidation, chlorination, alkylation, polymerization and hydrogenation, normally bubble column is the most appropriate equipment used (Prakash et al., 2001). Some very well-known chemical applications are the famous Fischer-Tropsch process which is the indirect coal liquefaction process to produce transportation fuels, methanol synthesis, and manufacture of other synthetic fuels which are environmentally much more advantages over petroleum derived fuels (Mahajan, 2010). The most important industrial application of bubble column in biochemical is the utilization of microorganism to produce products such as enzymes, proteins, antibiotics, etc (Kantarci et al., 2005).

Table 2.1: Some of the typical application of bubble column (Mahajan, 2010).

Applications	Process Type	Researchers
Catalytic chlorination	Chemical	Lohse et al. (1983)
Production of thienamycin	Biochemical	Arcuri et al. (1986)
Manufacture of Acetic acid using <i>Acetobacter aceti</i>	Biochemical	Sun and Furusaki (1990)
Production of root cultures of <i>Hyoscyamus muticus</i>	Biochemical	Bordonaro and Curtis (2000)
Biological wastewater treatment	Biochemical	Prakash et al. (2001)
Fischer–Tropsch process to produce transportation fuels, methanol synthesis, and manufacture of other synthetic fuels	Chemical	Degaleesan et al. (2001)
Ethanol fermentation using <i>Saccharomyces cerevisiae</i>	Biochemical	Ogbonna et al. (2001)
Ferrous biological oxidation	Biochemical	Mousavi et al. (2008)

2.3 Hydrodynamics and Operation of Bubble Column

2.3.1 Gas Hold-Up (ϵ_g)

Gas hold-up plays an important role in the hydrodynamic parameters such as design, development, scale-up and troubleshooting of multiphase system. Gas hold-up is dimensionless key parameter for phenomena purposes of bubble column systems (Nader, 2008). Usually, it is known as the volume fraction of gas phase occupied by the gas bubbles (Shahimie, 2010). All studies examine gas holdup because it plays an important role in design and analysis of bubble columns. In the bubble column reactor, overall gas hold-up is used to characterize the hydrodynamics behaviour. It depends mainly on the gas velocity, physical properties of the liquid and type of gas sparger (Pirdashti & Kompany, 2009).

The variation in gas hold-up is the important thing in the gas-liquid phase, one of them is gas hold-up profile gives rise to pressure variation and thus liquid recirculation (Nader, 2008). Liquid recirculation is an important on mixing and heat and mass transfer predictions of radial gas hold up, it's would lead to better understanding of this phenomenon to scale-up the bubble column (Nader, 2008).

2.3.1.1 Effect of Superficial Gas Velocity to Gas Hold-up

Superficial gas velocity mainly affected the gas holdup in the bubble column. Superficial gas velocity is the average velocity of the gas that is sparged into the column which is simply expressed as the volumetric flow rate divided by the cross-sectional area of the column (Kantarci et al., 2005). According to Nader (2008), the slurry bed expands and holdup of each phase will be formed after the gas was injected into the slurry bubble column reactor. He found the different velocity and recirculation patterns of each phase presents. Superficial velocity is proportional to the gas holdup in the bubbly flow regime. With increasing the superficial gas velocity, the gas holdup also increase for both bubble columns and slurry bubble columns. However, the effect of superficial velocity on gas holdup is less obvious in the heterogeneous regime. As the superficial velocity increases, the overall holdup increases due to the large bubble holdup increase (Kantarci et al., 2005).

According to Moshtari et al., (2009), the homogeneous regime occurs at low gas flow, while the heterogeneous regime at high gas flows. Based on their experimental result, the bubble size is small and uniform and bubble travel upwards in a helical path without any major collision or coalescence at superficial velocity. At 9 cm/s superficial gas velocity, all the bubble will large. The transition from homogeneous to heterogeneous regime is observed at a superficial gas velocity between 0.09 to 0.11 m/s (Moshtari et al., 2009). The measurement result of gas hold up at different superficial gas velocity, with differential pressure method is shown in the figure 2.1.

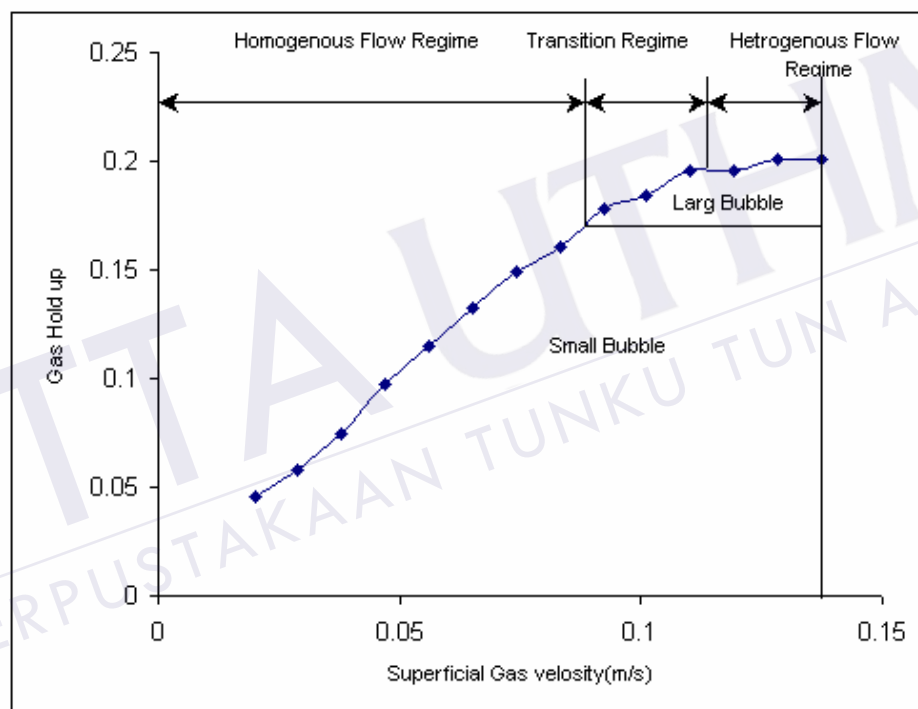


Figure 2.1: Effect of superficial gas velocity on gas holdup in air-water system (Moshtari et al., 2009)

Figure 2.2 show the result from analysis by (Pirdashti & Kompany, 2009). The result show the increasing of gas velocity will affect towards increasing of overall gas holdup. However, the increasing of gas holdup also depending on two regime called as homogeneous (bubbly flow) and heterogeneous (churn turbulent) regimes.

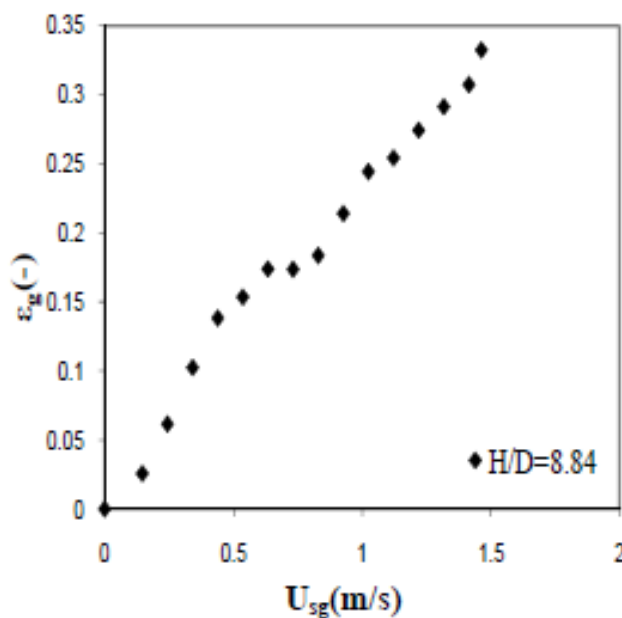


Figure 2.2: Overall gas holdup (ϵ_g) versus superficial gas velocity (U_{sg}) (Pirdashti & Kompany, 2009).

Figure 2.3 show the result of gas holdup increases study by (Mahajan, 2010). The result indicated the gas holdup increases monotonically by increases the gas (air) velocity.

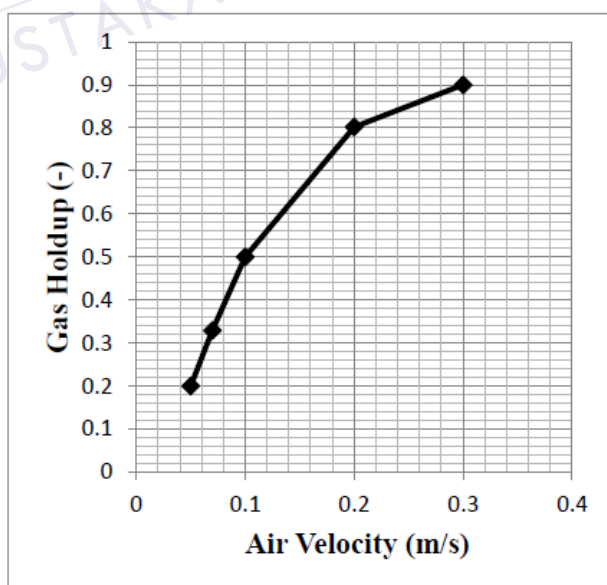


Figure 2.3: Gas Holdup versus air velocity for constant liquid velocity (Mahajan, 2010).

2.3.2 Axial Liquid Velocity

The liquid flow and mixing behavior in bubble columns is partially described by means of global liquid recirculation velocity profile (Shahimie, 2010). According to Kulkarni et al., (2007), in the near sparger region, the mean axial liquid velocity profiles for the positive maximum velocities are seen only in the region and away from centre, where the fractional gas hold-up was also higher as shown in the figure 2.4.

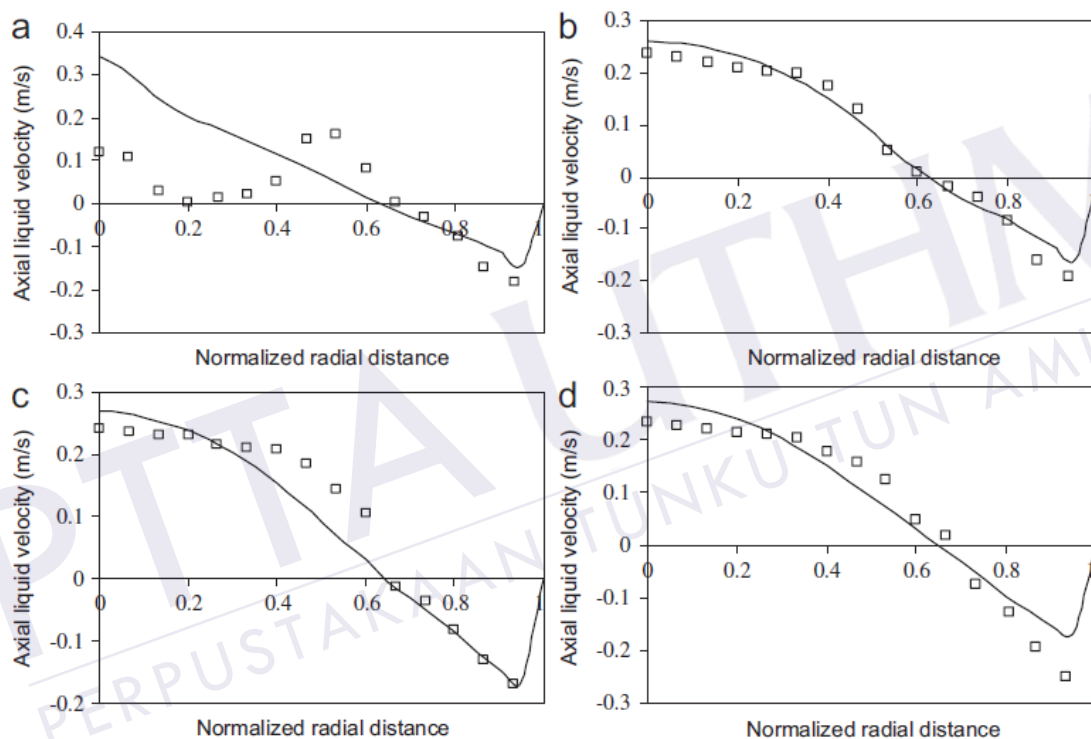


Figure 2.4: Comparison between the simulated and experimental profiles of axial liquid velocity at different axial positions in a 150mm i.d. bubble column with a single point sparger at $VG = 20$ mm/s: (a) $H/D = 0.5$; (b) $H/D = 2.5$; (c) $H/D = 3.4$; and (d) $H/D = 4.6$ (Kulkarni et al., 2007)

The prediction of the axial liquid circulation is still a difficult task due to the complex character of the flow in bubble columns. Some of the recent researcher study is about the liquid velocity and some of it has significant effects such as on the column dimension design, superficial gas velocity and flow pattern development. The bubble rise velocity is considerably larger than the terminal velocity of single

bubbles obtained by measurement liquid and bubble velocities in a bubble column (Shahimie, 2010). For the example, with increasing the superficial gas velocity, the axial liquid velocity becomes higher, and the correlation predicts the point of zero velocity well. To prediction the axial liquid velocity profile over arrange of conditions, the simulation technique can be used which help the process engineers should assess convective liquid mixing in bubble column rapidly.

2.3.3 Turbulent Kinetic Energy

The energy exchange in the bubble column can occur from gas to liquid or vice versa. Understanding the energy transfer from phase to phase as well as internal energy within the phase is very important because the liquid circulation in the column depends on the energy balance (Shahimie, 2010). The potential energy is maximum when the bubble reaches the top of the liquid. The kinetic energy remains the same when the bubble rises at its constant slip velocity. The energy associated with a bubble decreases and the same amount is dissipated in friction (drag/inertia) between bubble and liquid during the rising process (Shahimie, 2010). Velocity rise and drag force increase will causing higher amount of energy released to the liquid at each stage as a result of increase in bubble volume. Turbulent kinetic energy can be estimated from the velocity–time series data with measurement the average of eddy energy values (Kulkarni et al., 2007).

According to Kulkarni et al., (2007), they found that in the center region, the turbulent kinetic energy is almost constant value and decreased towards the wall and it is also increased away from the sparger. The predictions were different from the experiments with a finite k value are very close to the wall. All these can be observe in the figure 2.5.

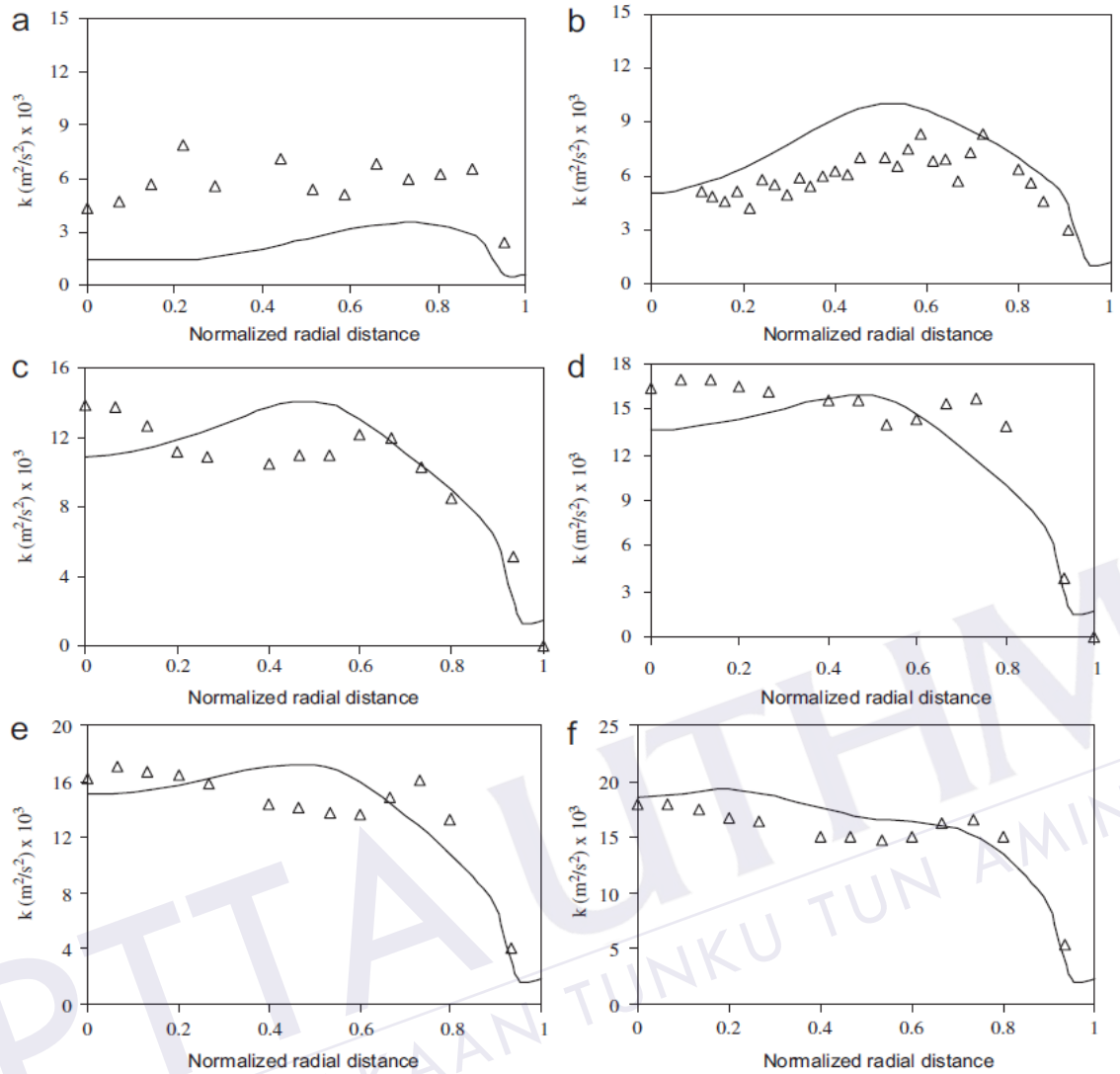


Figure 2.5: Comparison between the simulated and experimental profiles of turbulent kinetic energy at different axial positions in a 150mm i.d. bubble column with multi-point sparger at $VG = 20$ mm/s: (a) $H/D = 0.2$; (b) $H/D = 1.4$; (c) $H/D = 2.6$; (d) $H/D = 3.9$; (e) $H/D = 5.0$; and (f) $H/D = 6.2$ (Kulkarni et al., 2007).

2.4 Flow Pattern

The liquid flow structure in the bubble column varies in their pattern. It is depending on the hydrodynamic regime, gas hold-up, bubble column geometry and etc. In the bubble column operation, gases with certain velocity are dispersed by sparger distributor and carry liquid upwards with them in their wake and, at higher gas loading. Moreover, the liquid will flow down again, to produce liquid circulation patterns as show in figure 2.6.

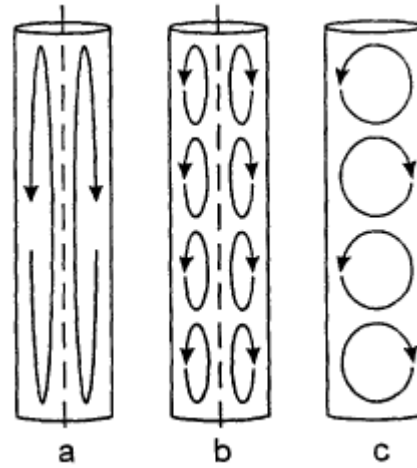


Figure 2.6: Liquid circulation patterns in bubble columns, a) large-scale overall circulation; b) donut-model of Joshi and Sharma (1979); c) circulation cells according to Zehner (1986).

2.5 Hydrodynamics Regime

Basically, there have three types of flow regimes in the bubble column which are the homogeneous (bubbly flow) regime; the heterogeneous (churn-turbulent) regime and slug flow regime (Kantarci et al., 2005). These regimes largely depend on the superficial velocity, physicochemical properties of the gas-liquid system, sparger design (mainly the hole diameter), column diameter and also the column inclination (Kulkarni et al., 2007). The homogeneous regime is characterized by a narrow bubble size distribution and radially uniform void fraction distribution. The bubbles interaction is minor and liquid recirculation takes place in between the bubbles. If the gas flow rate is increased, the void fraction increases and the flow become unstable. Instead, the bubble size distribution widens and the radial void fraction distribution is not homogeneous anymore. The void fraction near the center of the bubble column is larger than the average void fraction, and large vortical structures appear with a size comparable to the column diameter. These large scale structures contribute to the large scale circulation in the bubble column with up flow in the center and down flow near the wall.

When a liquid is sparged with gas, the bed of liquid begins to expand “homogeneously” and the bed height increases almost linearly with the superficial

gas velocity. This regime of operation in a bubble column is called the homogeneous bubbly flow regime. The regime of operating for superficial gas velocity exceeding $U_{\text{transition}}$ is commonly referred to as heterogeneous or churn turbulent regime (Moshtari et al., 2009). Homogeneous flow regime is obtained at low superficial gas velocities, approximately less than 5 cm/s in semi batch columns. This flow regime is characterized by bubbles of relatively uniform small sizes and rise velocities (Kantarci et al., 2005). The heterogeneous (churn-turbulent) regime exists for even higher gas throughput, when coalescence and breakup reach equilibrium. It is marked by a wide bubble size distribution. The bubble diameter can vary an order of magnitude. The degree of mixing in the flow is very strong (Harteveld, 2005). A slug flow regime has been only observed in small diameter laboratory columns at high gas flow rates. A slug flow means the formation of bubble slugs when larger bubbles are stabilized by the column wall (Kantarci et al., 2005). Figure 2.7 shows the three types of flow regime that has been observe by (Mahajan, 2010).

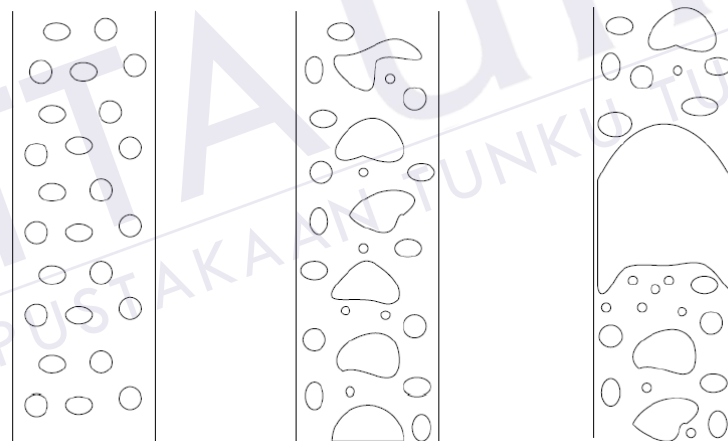


Figure 2.7: The flow regime observed in gas-liquid bubble column reactors: bubbly flow or homogeneous regime (left); heterogeneous regime (middle) and slug flow regime (right) (Mahajan, 2010).

According to the Figure 2.8, the homogeneous flow regime is obtained at low superficial gas velocities, approximately less than 0.05 m/s in semi batch columns. The churn-turbulent regime, also called the heterogeneous regime is maintained at higher superficial gas velocities (greater than 0.05 m/s in batch columns). At the small diameter (lower than 0.2 m) and at high gas flow rate, a slug flow regime can

be observed clearly. The slug regime is highly unstable. It can be found when the superficial gas velocity is increased further. Based on Figure 2.9, the study by (Naji, 2010) also stated that another regime occur called as transition regime where gas holdup may go through a maximums.

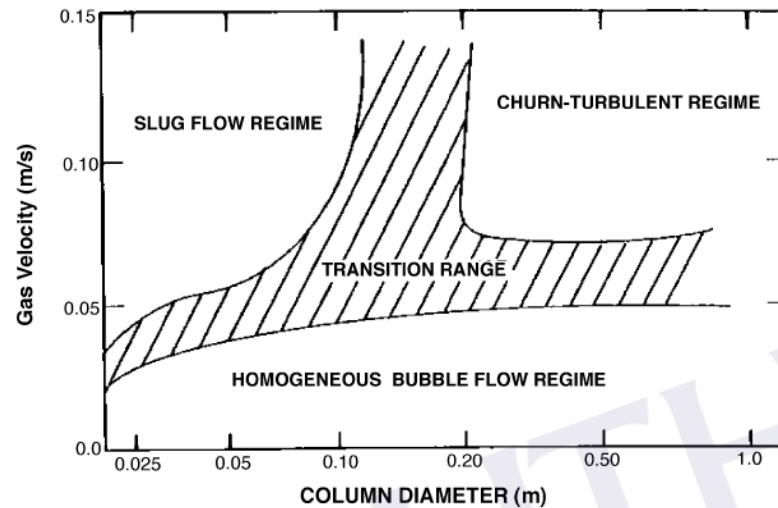


Figure 2.8: Flow regime map for bubble columns (Kantarci et al., 2005)

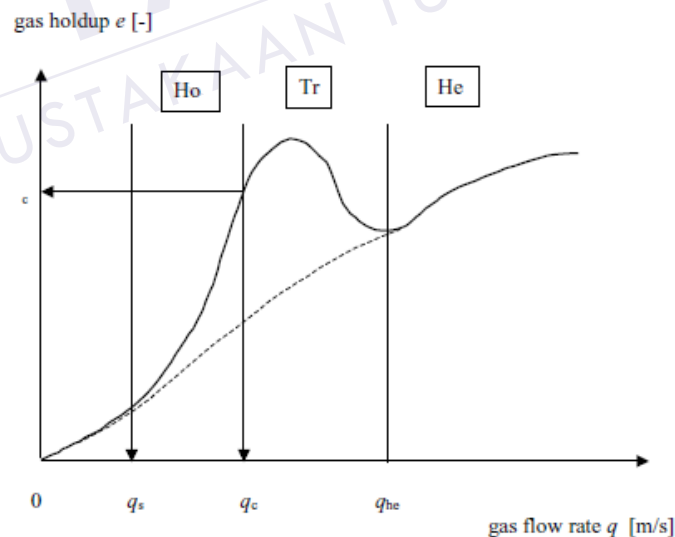


Figure 2.9: Definition sketch of flow regimes in bubble column. Full line: Ho-homogeneous regime; Tr-transition regime; He-heterogeneous regime; q_s -stable plate operation regime, beginning of homogeneous regime; q_c -critical point, end of homogeneous (Naji, 2010)

2.6 The Bubble Column Geometry and Parameter

The bubble columns geometry is important part that should not be careless in prediction of hydrodynamics and its influence on transport characteristics. In industrial applications, bubble columns usually designed with a length-to-diameter ratio (H/D) of at least 5. In biochemical applications this value usually varies between 2 and 5 (Kantarci et al., 2005). Even more, the use of large diameter reactors is desired because large gas throughputs are involved. Generally, the design and scale-up of bubble column reactors depend on the quantification of three main phenomena:

- i. Heat and mass transfer characteristics
- ii. Mixing characteristics
- iii. Chemical kinetics of the reacting system

(Zhang et al., 2006), in their study on numerical simulation of the dynamic flow behavior in a bubble column, a water and air was used as a continuous liquid phase and dispersed gas phase. The gas-liquid flow is assumed to be homogeneous bubbly flow. They propose the bubble column geometry as follows.

Table 2.2: The bubble column geometry and parameter propose by (Zhang et al., 2006)

Bubble Column Geometry	Value
Inlet area (A_{in})	0.0009 m ²
Inlet Gas Velocity (VG_{in})	0.1225 m/s
Superficial Gas Velocity	4.9 mm/s
Column Width	0.15 m
Column depth	0.15 m
Column height	0.45 m and 0.90 m

B. Moshtari, E. Babakhani & J. Moghaddas (2009), in their experimental set up, they also used water and air as a continuous liquid phase and dispersed gas phase. Table 2.3 shows the bubble column geometry that propose by (Moshtari et al., 2009).

Table 2.3: The bubble column geometry and parameter propose by (Moshtari et al., 2009)

Bubble Column Geometry	Value
Sparger Holes Diameter (A_{in})	0.001 m
Superficial Gas Velocity	0.11 – 0.9 m/s
Column Inner Diameter	0.15 m
Column height	2.8 m
Number of Sparger Holes	19

2.7 Sparger Design

Gas Sparger is important parameters to indicate the characteristic of bubble and indirectly affects gas hold up value. The sparger used to determines the bubble sizes observed in bubble columns. Basically, small orifices of diameter plate enable the formation of small bubble sizes. The common used gas sparger types in recent study are perforated plate, ring type, and porous plate. Regarding to the literature study by (Kantarci et al., 2005), stated that the smaller the bubbles, the greater of the gas hold up values. It can be concluded that with small gas distributors their gas hold up values were higher. Literature study of (Kantarci et al., 2005) also stated that gas holdup was found to be strongly affected by the type of gas distributor and another conclusion about the type of spargers was that the contributions of both small and large bubbles to gas velocity were lower with ring sparger as compared to the perforated plate.

The effect of perforated plate open area analysis by (Su & Heindel, 2005), show in figure has been studied. From the result, the gas hold up increasing with increasing open area ratio from $A=0.57\%$ and $A=0.99\%$. Based on figure, for both $A=0.57\%$ and 0.99% , gas holdup increases with increasing superficial gas velocity until a maximum gas holdup is reached, and then gas holdup decreases with increasing superficial gas velocity to a minimum value which indicates the end of the transitional flow regime. For $A=2.14\%$, no maximum gas holdup is observed, and the gas holdup continuously increases with superficial gas velocity. It means that the gas hold up will perform effectively if the perforated plates open area within certain range ($A \leq 1\%$). If the open area is beyond this range, it will decrease the effectiveness of gas hold up.

However, Su & Heindel (2005) also stated that further increasing open area beyond a critical value by increasing the number of holes with a constant hole diameter enhances bubble coalescence near the aeration plate because of a reduced hole spacing; this leads to a reduction in gas holdup.

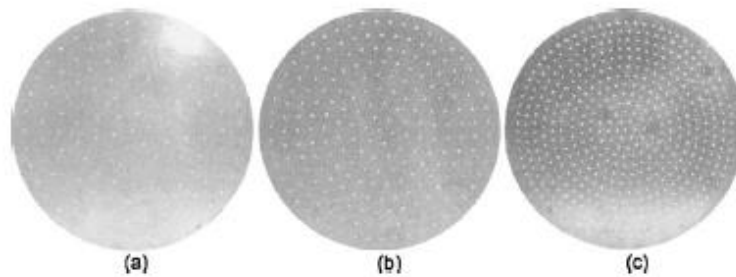


Figure 2.10: Gas distributor plates: (a) $A=0.57\%$, (b) $A=0.99\%$, and (c) $A=2.14\%$
(Su & Heindel, 2005)

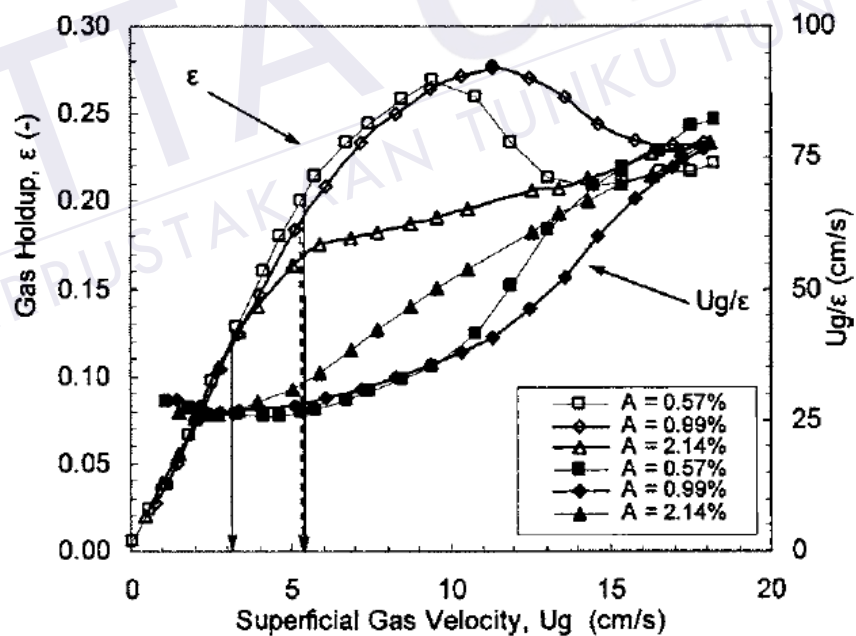


Figure 2.11: Gas holdup and flow regime transition using different aeration plates in an air-water system (Su & Heindel, 2005)

2.7.1 Effect of Sparger Geometry on the Distribution of Gas Holdup

The sparger geometry affects less the distribution of hold-ups when the superficial velocity rises (Haibo et al., 2006). According to (Su & Heindel, 2005) gas holdup increases with increasing plate open area or by increasing the number of holes. The ERT is a very powerful tool that used to diagnose the “inside” flow behavior, meanwhile in their study, the distribution of gas hold-up in the sparger region is mainly depend on the sparger design. Based on the previous study by (Su & Heindel, 2005), hole spacing play an important role at the inlet and directly influences the interfacial area and transport rate in bubble column reactor.

Figure 2.12 show the experimental equipment that has been setup by (JIN Haibo et al., 2006). They used the ERT sensors to diagnose the inside flow behavior. The sensors are place at 37 mm and 57 mm from air distributor.

Figure 2.13 shows the cross-sectional gas holdup of the water-air system under different superficial gas velocity for four types of air sparger arrangement. They observe that at 37 mm, the gas holdup distribution resembles closely the sparger configuration, while at the 57 mm, the gas holdup distribution shows the trend of the bubble diffusion in the lateral direction.



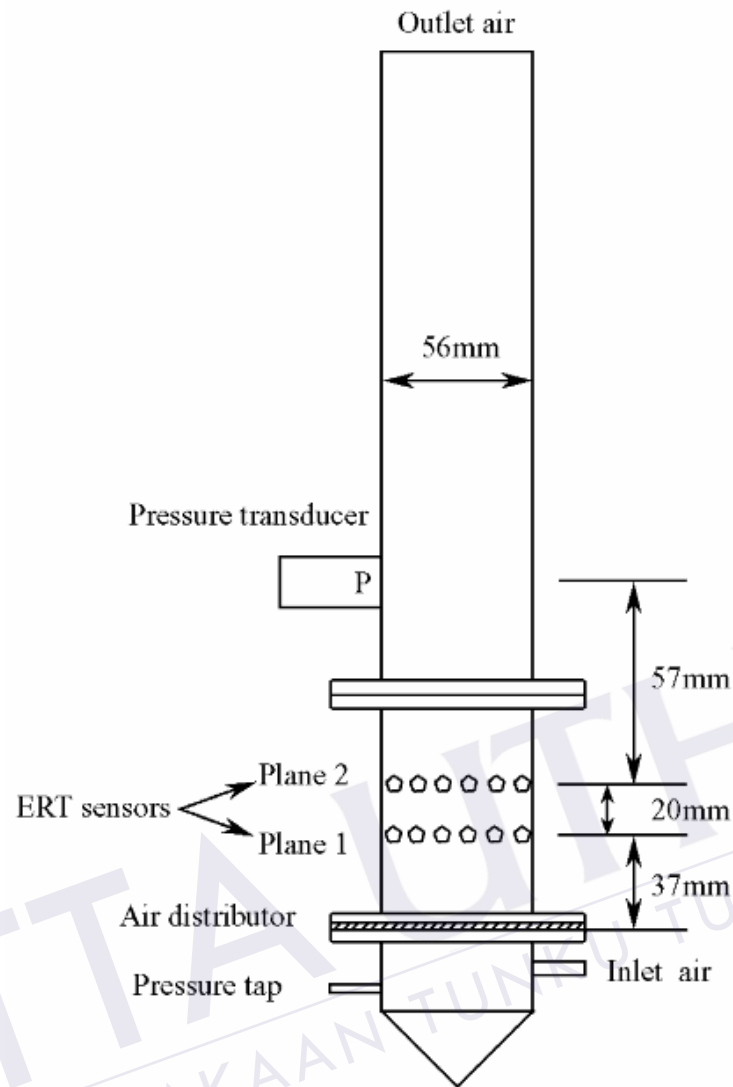
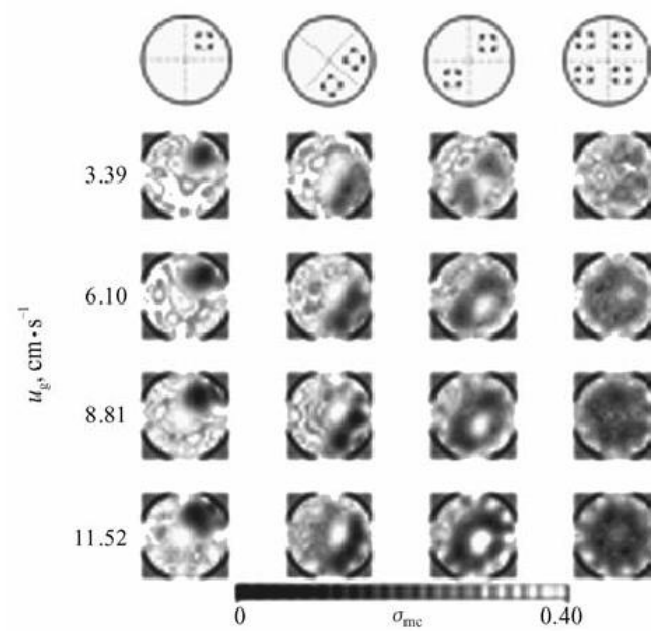
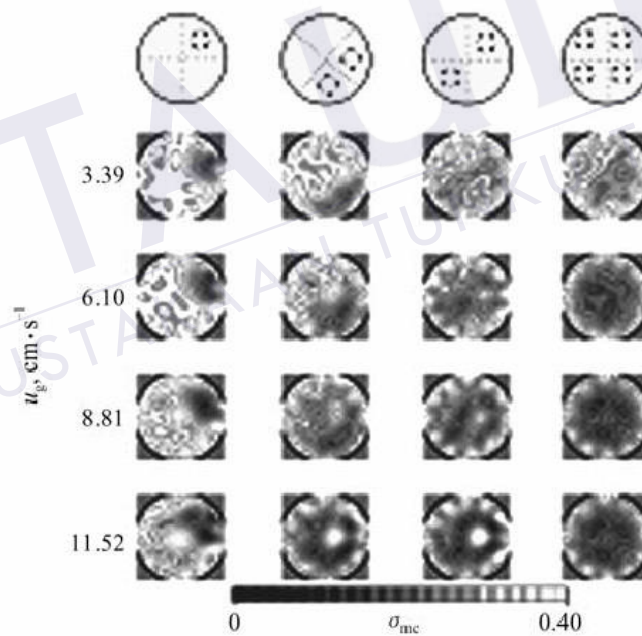


Figure 2.12: Experimental Setup by (JIN Haibo et al., 2006)



(a) 37 mm from air distributor



(b) 57 mm from air distributor

Figure 2.13: Effect of sparger geometry on the cross sectional image of gas hold-up
(JIN Haibo et al., 2006)

2.7.2 Effect of Sparger Type on Gas Hold-up.

According to B. Moshtari, E. Babakhani & J. Moghaddas (2009), in their experimental setup, they used perforated plate and porous plate with 0.1% porosity as shown in the figure 2.14.

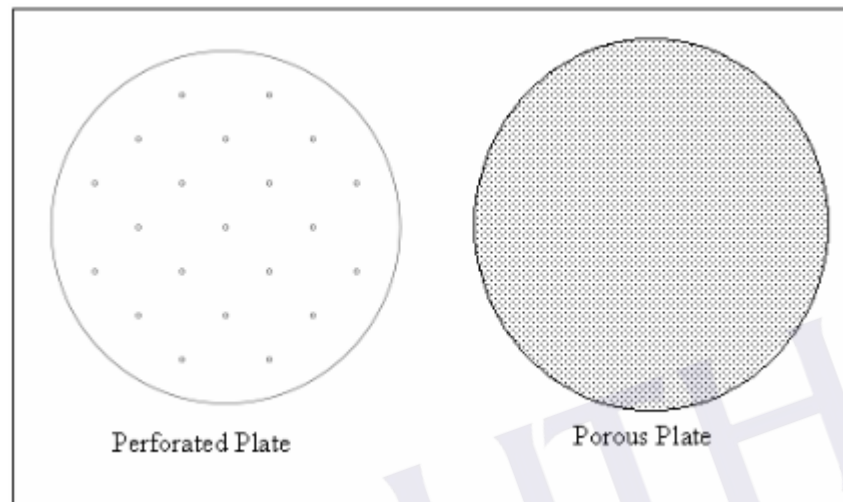


Figure 2.14: Two sparger type are used in the experimental setup (Moshtari et al., 2009)

Figure 2.15 shows the effect of sparger type on gas hold up in the bubble column that has been observed in the experimental setup by (Moshtari et al., 2009). Based on the experimental data, the break up and coalescence of the gas bubbles are affected the gas hold up in the column. Porous plate generates smaller gas bubble compare to perforated plate. Based on the figure, at the higher superficial gas velocity, the smaller size of pore will increased 40% the gas hold up compared to larger pore size.

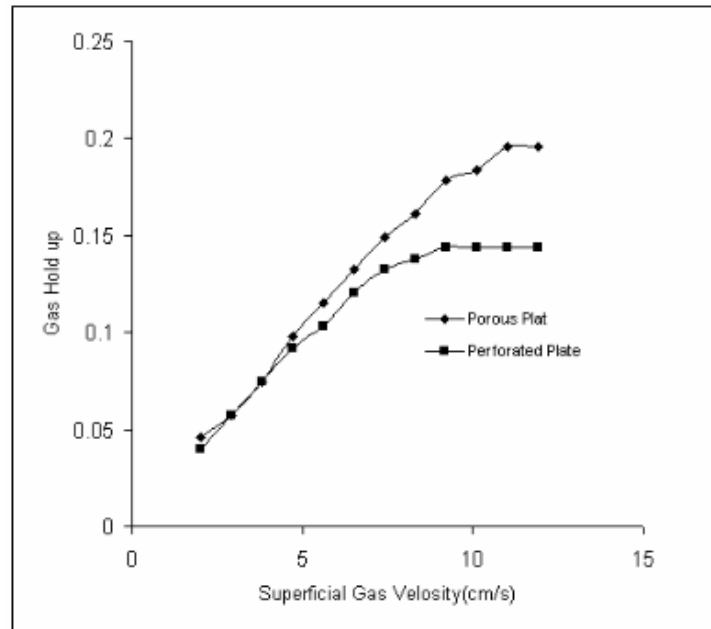


Figure 2.15: Effect of sparger types on gas hold up (Moshtari et al., 2009)

2.8 CFD Analysis

For the theoretical analysis, computational fluid dynamics has been widely used (Kulkarni et al., 2007). Therefore, the investigation and studied by experimentally and computationally of bubble column hydrodynamics characterization is become important and has been gained considerable attention during the past years. Recent research with bubble columns frequently focuses on the following topics: gas holdup studies, bubble characteristics, flow regime investigations and computational fluid dynamics studies, local and average heat transfer measurements and mass transfer studies (Kantarci et al., 2005). Understanding of hydrodynamics behavior in bubble column system is importantly because it is determined by parameters such as superficial gas velocity, liquid volume in the system, gas sparger design, and the ratio height-diameter of bubble column. Moreover, the variables that affect the performance of this system are gas-liquid mass and heat transfer coefficient, gas hold-up distribution (gas volume fraction), mixing rate, bubble size distributions and bubble rise velocities.

REFERENCES

- Anil, M., Agarwal, V. K., Siraj Alam, M., & Wasewar, K. L. (2007). CFD modeling of three-phase bubble column: 1. study of flow pattern. *Chemical and biochemical engineering quarterly*, 21(3), 197-205.
- Delnoij, E., Lammers, F. A., Kuipers, J. A. M., & Van Swaaij, W. P. M. (1997). Dynamic simulation of dispersed gas-liquid two-phase flow using a discrete bubble model. *Chemical Engineering Science*, 52(9), 1429-1458.
- Harteveld, W. (n.d.).(2005). Bubble columns-structures or stability, 90-64642-26-5
- Haibo, J. I. N., Wang, M., & Williams, R. A. (2006). The effect of sparger geometry on gas bubble flow behaviors using electrical resistance tomography. *Chinese Journal of Chemical Engineering*, 14(1), 127-131..
- Kantarci, N., Borak, F., & Ulgen, K. O. (2005). Bubble column reactors. *Process Biochemistry*, 40(7), 2263-2283..
- Kulkarni, A. A., Ekambara, K., & Joshi, J. B. (2007). On the development of flow pattern in a bubble column reactor: experiments and CFD. *Chemical engineering science*, 62(4), 1049-1072.
- Mena, P. M. P. N. C. (2005). Mass transfer and hydrodynamics in multiphase systems (Doctoral dissertation, Universidade do Porto).
- Shahimie, S. (2010). Modelling of hydrodynamics in heterogeneous. (Bachelor of chemical engineering, University Malaysia Pahang)
- Moshtari, B., Babakhani, E. G., & Moghaddas, J. S. (2009). Experimental study of gas hold-up and bubble behavior in gas-liquid bubble column. *Petroleum & Coal*, 51(1), 27-32.
- Nader, A. A. (2008). Simulation of Gas-to-Liquid (GTL) Process in Slurry Bubble Column Reactor (Master of science in chemical engineering, University of Technology)
- Naji, O. I. (2010). Heat Transfer in Bubble Columns Using Two Different Column Diameters (Doctoral dissertation, UNIVERSITY OF TECHNOLOGY).

- Pirdashti, M., & Kompany, R. (2009). Effects of Height to Diameter Ratio and Aeration rate on Liquid Mixing and Hydrodynamic Properties in a Bubble Column. *Iranian Journal of Chemical Engineering*, 6(3), 47.
- Su, X., & Heindel, T. J. (2005). Effect of perforated plate open area on gas holdup in rayon fiber suspensions. *Journal of fluids engineering*, 127(4), 816-823.
- Xue, J., Al-Dahhan, M., Dudukovic, M. P., & Mudde, R. F. (2008). Bubble velocity, size, and interfacial area measurements in a bubble column by four-point optical probe. *AIChE journal*, 54(2), 350-363.
- Yoshimura, H., Matsumura, H., Niwa, K., Nakamura, T., & Itoigawa, F. (2004). Study on Eco-Friendly Oil on Water Drop Metalworking Fluid (No. 2004-01-0789). *SAE Technical Paper*.
- Zhang, D., Deen, N. G., & Kuipers, J. A. M. (2006). Numerical simulation of the dynamic flow behavior in a bubble column: a study of closures for turbulence and interface forces. *Chemical Engineering Science*, 61(23), 7593-7608.
- Shaikh, A., & Al-Dahhan, M. H. (2007). A review on flow regime transition in bubble columns. *International Journal of Chemical Reactor Engineering*, 5(1).
- Mahajan, V. (2010). CFD analysis of hydrodynamics and mass transfer of a gas-liquid bubble column (Doctoral dissertation, NATIONAL INSTITUTE OF TECHNOLOGY, ROURKELA).
- Irani, M., & Khodaghali, M. A. (2011). Investigation of bubble column hydrodynamics using cfd simulation (2d and 3d) and experimental validation. *Petroleum & coal*, 53(2), 146-158.
- Kheradmandnia, S., Mousavi, S. M., Hashemi-Najafabadi, S., & Shojaosadati, S. A. (2014). Modelling and CFD Simulation of Hydrodynamics and Mass Transfer in a Miniature Bubble Column Bioreactor. *International Journal of Engineering and Technology*, 2(3), 223-242.