MODELLING OF HYDRODYNAMICS IN HETEROGENEOUS BUBBLE COLUMN

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ABSTRACT

The applications of bubble columns are very important as multiphase contactors and reactors in process industry. They are wide and extensively used in chemical, petrochemical and biochemical industries. The advantages of bubble column are low maintenance and operating cost due to the compactness and no moving part. They also have an excellent mass and heat transfer characteristic or high heat and mass transfer coefficients, and high durability of catalyst or packing material. It is important to understand the nature of hydrodynamics and operational parameters to characterize their operation including pressure drop, gas superficial velocity, bubble rise velocity, etc., to do the design and scale-up process. Although experimental methods are available to elucidate the multiphase flow in bubble column by the means of advanced experimental methods i.e. X-ray tomography and laser doppler anemometry, the experimental setup is often expensive to develop. Alternatively, the computational fluid dynamics can be used to evaluate the performance of bubble column at lower cost compared to experimental setup. In this work commercial CFD software, FLUENT 6.3 was employed for modeling of gas-liquid flow in a bubble column. Multiphase simulations were performed using an Eulerian-Eulerian two-fluid model and the drag coefficient of spherical and distorted bubbles was modeled using the Tomiyama (1995) and Schiller-Naumann (1935) models. The effect of the void fractions on the drag coefficient was modeled using the correlation by Behzadi (2004). The CFD predictions were compared to the experimental measurement adopted from literature. The CFD predicts the turbulent kinetic energy, gas hold-up and the liquid axial velocity fairly well, although the results seem to suggest that further improvement on the interfacial exchange models and possibly further refinement on the two-fluid modeling approaches are necessary especially for the liquid axial velocity and turbulent kinetic energy. It is clear from the modeling exercise performed in this work that CFD is a great method for modeling the performance of bubble column. Furthermore, the CFD method is certainly less expensive than the experimental characterization studies.

ABSTRAK

Aplikasi medan gelembung sangat penting sebagai penemu pelbagai fasa dan reaktor dalam proses industri. Ia banyak digunakan dalam industri kimia, petrokimia dan biokimia. Kelebihan medan gelembung adalah kos baik pulih serta operasi yang murah kerana ianya utuh dan tiada bahagian yang bergerak. Ia juga mempunyai ciri-ciri perpindahan jisim dan haba yang sangat baik atau tinggi pekali perpindahan haba dan jisim, dan daya tahan mangkin yang tinggi. Adalah sangat penting untuk memahami sifat hidrodinamik dan parameter operasi untuk mengklasifikasikan operasi medan gelembung termasuk penurunan tekanan, kelajuan superfisial gas, kelajuan naik gelembung, dll, untuk membuat rekabentuk dan proses skala. Walaupun kaedah eksperimen yang sedia ada mampu untuk meramal aliran pelbagai fasa dalam medan gelembung dengan cara eksperimen yang canggih seperti tomographi X-ray dan anemometry laser doppler, tetapi ianya sangat mahal untuk dibangunkan. Walaubagaimanapun, pengkomputeran bendalir dinamik (CFD) boleh digunakan untuk menilai prestasi medan gelembung dengan kos lebih rendah berbanding dengan cara eksperimen. Dalam kajian ini, perisian CFD, FLUENT 6.3 telah diaplikasikan untuk simulasi aliran gas-cecair dalam ruangan gelembung. Pelbagai fasa simulasi dilakukan dengan menggunakan model dua-cecair Eulerian-Eulerian, pekali heretan gelembung sfera dengan keterheretan sfera dimodelkan menggunakan Tomiyama (1995) dan model Schiller-Naumann (1935). Pengaruh pecahan kekosongan pada pekali heretan dimodelkan menggunakan hubung kait oleh Behzadi (2004). CFD ramalan dibandingkan dengan hasil bacaan eksperimen yang diadaptasi dari artikel sastera. CFD dapat meramal tenaga kinetik turbulen, gas pegangan dan kelajuan cecair tengah dengan amat baik, walaupun hasilnya menyarankan penambahbaikan lebih lanjut tentang model pertukaran antara muka dan mungkin penambahbaikan pendekatan model dua bendalir terutama untuk kelajuan cecair tengah dan tenaga kinetik turbulen. Hal ini jelas seperti dalam dalam karya di mana CFD adalah kaedah yang bagus untuk pemodelan prestasi medan gelembung. Selain itu, kaedah CFD lebih murah daripada kajian eksperimen.

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NOMENCLATURE

C_D	-	drag coefficient
C_L	-	lift coefficient
C_m	-	virtual mass coefficient
$C_{\varepsilon 1}$	-	constant for eqs. 10
$C_{\varepsilon l}$	-	constant for eqs. 9
d_b	-	bubble size
$\vec{F}_{\mathrm{lg}}$	-	interaction force mainly due to drag
$\vec{F}_{lift}$	-	lift force
$\vec{F}_{vm}$	-	virtual mass force
g	-	gravity acceleration
G_k	-	turbulent production term
k	-	turbulent kinetic energy
P	-	pressure
v_{sg}	-	superficial gas velocity
Re_b	-	bubble Reynolds number
t	-	time
u, v	-	velocity components
u_t	-	turbulent viscosity

Greek

α	-	void fraction
ε	-	turbulent dissipation rate
ρ	-	density
σ_ε	-	constant for eqs. 9
σ_k	-	constant for eqs. 10

$\Pi_{k,l}$	-	characteristic turbulent kinetic energy for secondary phase
$\Pi_{\varepsilon,l}$	-	characteristic turbulent dissipation rate for secondary phase
$\bar{\bar{\tau}}_l$	-	liquid phase stress-strain tensor
μ_l	-	liquid viscosity

Subscripts

b	-	bubble
g	-	gas
l	-	liquid
m	-	mixture
i	-	mixture entity of *i* phase

CHAPTER 1

INTRODUCTION

1.1 Motivation

Bubble column are important process equipments as gas liquid contactor in multitude of processes industry. The significant industrial applications of bubble column remain undisputed mainly due to the advantages it offers. Bubble column are intensively utilized as multiphase contactors and reactors in chemical, petrochemical, biochemical and metallurgical industries (Degaleesan et al., 2001). 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. 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 costs are required due to lack of moving parts and compactness. The durability of the catalyst or other packing material is high. Due to their industrial importance and wide application area, the design and scale-up of bubble column reactors, investigation of important hydrodynamic and operational parameters characterizing their operation have gained considerable attention during the past years. Understanding on the hydrodynamics of bubble column are important to indicates the operation of bubble column because it is determined by many parameters such as high of the liquid inside the column, superficial gas velocity, gas sparger design and the diameter of bubble column. However, the variables that affect the performance of bubble column are the gas hold-up distribution, gas-liquid mass and heat transfer coefficients, the extent of mixing, bubble rise velocities and bubble size distributions.

The available experimental instrumentation techniques for prediction of hydrodynamics performance in bubble column such as phase/laser Doppler anemometry (PDA/LDA), particle image velocimetry (PIV), tomography, digital imaging (DI), computer automated radioactive particle tracking (CARPT), capillary suction probe (CSP) and particle image velocimetry laser-induced fluorescence (PIV-LIF) have been implemented during the last few decades. An overview of each measurements technique will be discussed more on Chapter 2. Nevertheless, these measurement techniques will require certain time to be able to handle the complexities in bubbly turbulent flows and require investing highly cost instruments and building a prototype plus, the experimental measurements are also possible to measure correctly those variables. Alternatively, recent advance in CFD modelling and availability of low cost and high speed computers have allowed performing three-dimensional simulation of complex multiphase flows in bubble column (Li et al., 2009). The proper use of CFD modelling can be very helpful in developing scale-up strategies and further understanding of the fluid dynamics inside bubble column. Computational fluid dynamics (CFD) is one of the branches of fluid mechanics that uses numerical methods and algorithms to solve and analyze problems that involve fluid flows. CFD simulation is applicable for a variety of gas-liquid dispersion problems including bubble column which offer a cheaper but with a faster solution compared with measuring using experimental instrumentation. Most of the time the Eulerian-Eulerian two-fluid model is employed to solve the two phase problem and the dispersed k-ε model is used for turbulence modeling.

1.2 Objective

The objective of this research is to study the turbulent kinetic energy, gas hold-up profile and axial liquid velocity behavior in bubble column by developing 3D Computational Fluid Dynamics (CFD) model and compared it prediction with the experimental data from previous author (Kulkarni et al., 2007). It is important to investigate and understanding the hydrodynamics nature of bubble column for design and scale-up propose and to prove CFD is capable to simulate those variable as same as experimental results.

1.3 Main Contribution

Understanding the operation and hydrodynamics are important for both design and scale-up purpose. To develop a prototype for experimental testing is require high cost and time consuming. This research has been carried out to give economical and faster solution. CFD simulation gives as same as experimental result or even better for multiphase flow depends on the selection of turbulence model for gas-liquid modelling besides contributing towards the developments of new and advanced technology.

1.4 Thesis Outline

This research presents full three-dimensional gas-liquid simulations in a cylindrical bubble column using Eulerian-Eulerian approach and was carried out by using Computational Fluid Dynamics (CFD). The following chapter (Chp. 2), give a brief overview about what has been done in the past (literature review) regarding on modelling of hydrodynamics in bubble column as well as a brief overview of the experimental instruments to predict the performance of bubble column. Chapter 3 presents methodology (modelling approach) used in this research where the mathematical modelling and numerical simulation were explained. Mathematical modelling which describe the fluid flow phenomena involved in a bubble column and the modelling strategy were presented in detail in chapter 3. Comprehensive comparison of the simulation results and the experimental data on gas hold-up profile, turbulent kinetic energy and axial liquid velocity with detailed discussion will be presented in the Chapter 4. Finally, some important conclusions drawn from present work and future work suggestions were given in Chapter 5.

CHAPTER 2

LITERATURE REVIEW

2.1 Overview

This chapter reviews the current development on CFD modelling of hydrodynamics bubble column. A crucial review on simulation approach that probably affects the performance of bubble column such as axial liquid velocity, gas hold-up profile and turbulent kinetic energy as the main interest in this study. Besides that, a brief summary about the experimental measurement technique to predict the hydrodynamics of bubble column was also discussed.

2.2 Introduction

Bubble columns are widely used for their simple construction and economically favorable operation. Gas is usually sparged upwards through a perforated plate or a series of nozzles into a continuous liquid phase. The hydrodynamics of the bubble column generally depends on the gas-liquid or gas-liquid-solid physical properties as well as column geometry and internal configuration. Bubble column have the advantages of being geometrically simple, easy operation and cost effective for two phase models. Modelling of hydrodynamics in bubble column has been carried out in this work for three important reason: firstly to study the turbulent kinetic energy, gas hold-up profile and axial liquid velocity behavior in bubble column; second, to evaluate the suitability of the modelling approach (turbulence and multiphase model) and third, to verify the modelling methods by comparing the simulation result with experimental data from previous studies. In this study, a cylindrical bubble column was simulated, filed with tap water; a multipoint sparger was placed at the bottom of the column and the superficial velocity assumed to be constant. The geometry of the bubble column studied here was similar to the one that has been studied experimentally and simulated numerically by Kulkarni et al. (2007). Bubble column simulation is fairly simple to perform and thus it will greatly reduce the overall development time of a new modelling approach.

2.3 Application of Bubble Column

Bubble columns are widely used especially in chemical processes involving reactions such as oxidation, chlorination, alkylation, polymerization and hydrogenation, in the manufacture of synthetic fuels by gas conversion processes and in biochemical processes such as fermentation and biological wastewater treatment (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 (Degaleesan et al., 2001).

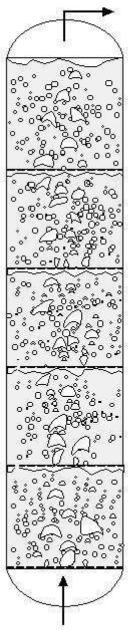

Figure 2.1: Bubble column reactor

2.3.1 Fischer-Tropsch Synthesis

The Fischer–Tropsch (FT) reaction that was discovered in Germany nearly three quarters of a century ago has recently become a subject of renewed interest, particularly in the context of the conversion of remote natural gas to liquid transportation fuels. The main incentives for this conversion are the increased availability of natural gas in remote locations, for which no nearby markets exist, and the growing demand for middle distillate transportation fuels gasoil and kerosine, especially in the Pacific and Asian regions. Natural gas can be converted to carbon monoxide and hydrogen synthesis gas via the existing or newly developed processes, such as steam reforming, carbon dioxide reforming, partial oxidation, and catalytic partial oxidation, followed by the FT synthesis reaction. For economic and logistic reasons, such energy conversions are best carried out in large scale projects and the capability of up scaling is therefore an important consideration in the selection of reactors for synthesis gas generation, as well as in FT synthesis. Another important issue in FT synthesis is the strong exothermicity: e.g., compared to the processes applied in the oil industry, the heat released per unit weight of feed or product is an order of magnitude higher, and corresponds with a theoretical adiabatic temperature rise of about 1600 K at complete conversion. Unless the product is so light that it is completely vaporized under reaction conditions, there action takes place in a three phase system: gas (carbon monoxide, hydrogen, steam, and gaseous hydrocarbon products), liquid product, and solid catalyst. The amounts of syngas and product molecules that have to be transferred between the phases are quite large: i.e., an order of magnitude larger than the amount of hydrogen molecules to be transferred in hydroprocessing of oils. Therefore, great demands are placed on the effectiveness of interfacial mass transfer in FT synthesis (Krishna & Sie, 2000).

2.4 Hydrodynamics and Operation of Bubble Column

2.4.1 Study of Gas Hold-Up Profile

Gas hold-up is one of the most important hydrodynamic parameters involved in the design, development, scale-up and troubleshooting of multiphase system. Gas hold-up is a dimensionless key parameter for design purposes that characterizes transport phenomena of bubble column systems. It is basically defined as the volume fraction of gas phase occupied by the gas bubbles. Many studies examine gas holdup because it plays an important role in design and analysis of bubble columns. As reported by Patel and Thorat (2008), the hydrodynamic performance obtained in the form of chordal gas hold-up was shown to be highly influenced as a result of the sparger design altercations. Superficial gas velocity seems to have large influence on radial hold-up profile especially at high concentration of foaming agent (Veera et al., 2004) and influence seems to be different for different sparger designs where for the multipoint sparger, the holdup profiles become parabolic as the distance increases from the sparger and for single point sparger, the holdup profile becomes flat as the distance increases from the spargers (Veera at al., 2001). The knowledge of gas hold-up in bubble column is important because has significant for the design and operation of transport systems and has a large application in industrial processes.

2.4.2 Study of Axial Liquid Velocity

The liquid flow and mixing behavior in bubble columns is partially described by means of global liquid recirculation velocity profile. Due to the complex character of the flow in bubble columns, the prediction of the axial liquid circulation is still a difficult task. Studies has been carried out about the liquid velocity and some of it have significant effects such as on the column dimension design, superficial gas velocity and flow pattern development. The measurement liquid and bubble velocities in a bubble column revealed that the bubble rise velocity is considerably larger than the terminal velocity of single bubbles (Lain et al., 1999). For instance, the axial liquid velocity becomes steeper with the increase in superficial gas velocity, and the correlation predicts the point of zero velocity well. The simulation can be used for prediction of the axial liquid velocity profile over arrange of conditions, which should help the process engineers assess convective liquid mixing in bubble column rapidly.

2.4.3 Study of Turbulent Kinetic Energy

In bubble column, the energy exchange from gas to liquid and vice versa. Because of liquid circulation in the column depends upon the overall energy balance it is important to understand the energy transfer from phase to phase as well as internal energy within the phase. During bubble formation at the orifice mouth, the pressure force acting on the bubble is the hydrostatic head and the pressure force through chamber. Once the bubble is detached, the pressure forces only the hydrostatic head where the pressure energy with the bubble is maximum. To balance the pressure inside the bubble and the hydrostatic head, it attains a shape close to a sphere. The balance is maintained such that as the pressure energy decreases, the potential energy increases. When the bubble reaches the top of the liquid, the potential energy is maximum for that bubble. Since the bubble rises at its constant slip velocity, the kinetic energy associated with it remains the same. During rise, the energy associated with a bubble decreases and the same amount is dissipated in friction (drag/inertia) between bubble and liquid. For large size bubbles, while the bubble rises it changes its shape to maintain the balance and its volume increases due to the reduction in the hydrostatic head. As a result of increase in bubble volume, rise velocity and the drag force increase causing higher amount of energy released to the liquid at each stage (Kulkarni et al., 2007).

2.5 Experimental Methods for Bubbly Flow

2.5.1 Laser Doppler Anemometry

LDA is a technique for measuring the direction and speed of fluids like air and water. It is a non-intrusive single point optical technique applicable for the simultaneous measurement of bubble size distributions and liquid velocities. In its simplest form, LDA crosses two beams of collimated, monochromatic, and coherent laser light in the flow of the fluid being measured. The two beams are usually obtained by splitting a single beam, thus ensuring coherency between the two. The two beams are made to intersect at their waists (the focal point of a laser beam), where they interfere and generate a set of straight fringes. The sensor is then aligned to the flow such that the fringes are perpendicular to the flow direction. As particles pass through the fringes, they reflect light (only from the regions of constructive interference) into a photodetector (typically an avalanche photodiode). By measuring the Doppler frequency-shift of the scattered light, one is able to calculate the velocity of the tracer particle and thus the flow velocity of the liquid (Kulkarni, 2008).

2.5.2 Phase Doppler Anemometry

A PDA system consists of a laser (typically a continuous wave Ar-Ion-laser), fiber optics, frequency shifter, transmitting and receiving optics, signal processor, traversing system and a computer to control the measurement and save the data. It is also a non-intrusive single point optical technique applicable for the simultaneous measurement of bubble size distributions and liquid velocities (Lain et al., 1999). The velocity of dispersed phase elements, i.e. particles, droplets or bubbles, is measured with the same principle as in LDA. The size measurement of the particles is based on another optical detector, which is working in the side-scatter mode. The laser beams from the transmitting optics cross at the focal point of the front lens. The receiving optics (for size measurements) is looking to the same focal point at certain angle. This angle is very critical since the scattered light intensity and polarization depend strongly on the viewing angle and the refractive indexes of the continuous and dispersed phase. The size measurement is based on the phase difference between the signals received by the two detectors.

2.5.3 Particle Image Velocimetry (PIV)

PIV is an optical method of fluid visualization. It is used to obtain instantaneous velocity measurements and related properties in fluids (Zhou et al., 2002). The fluid is seeded with tracer particles which, for the purposes of PIV, are generally assumed to faithfully follow the flow dynamics. It is the motion of these seeding particles that is used to calculate velocity information of the flow being studied. Other techniques used to measure flows are Laser Doppler velocimetry and Hot-wire anemometry. The main difference between PIV and those techniques is that PIV produces two dimensional vector fields, while the other techniques measure the velocity at a point. During PIV, the particle concentration is such that it is possible to identify individual particles in an image, but not with certainty to track it between images. When the particle concentration is so low that it is possible to follow an individual particle it is called Particle tracking velocimetry, while Laser speckle velocimetry is used for cases where the particle concentration is so high that it is difficult to observe individual particles in an image. Typical PIV apparatus consists of a camera (normally a digital camera with a CCD chip in modern systems), a high power laser which is an optical arrangement to convert the laser output light to a thin light sheet (normally using a cylindrical lens and a spherical lens), a synchronizer to act as an external trigger for control of the camera and laser, the seeding particles and the fluid under investigation. A fiber optic cable or liquid light guide often connects the laser to the lens setup.

2.5.4 Tomography

Tomography is imaging by sections or sectioning, through the use of waves of energy. A device used in tomography is called a tomograph, while the image produced is a tomogram. Tomography techniques have been applied to measure the gas hold-up in bubble column (Degaleesan et al., 2003) in recent years. There are several techniques related to tomography like electrical impedance tomography (EIT), electrical resistance tomography (ERT), electrical capacitance tomography (ECT), X-ray tomography (CT), gamma ray tomography (GRT). But not all tomography method are able to give a good result because some of it suffer a drawback like low spatial resolution and difficulty in the data field reconstruction.

2.5.5 Digital Imagine (DI)

A high speed imaging system can visualize and record bubbly flow phenomena that are too fast for human eyes because it is possible to visualize the event of bubble breakage and coalescence using a high speed camera. Application of high speed imaging is however limited to a small vessel and low void fraction as it requires a lot of well-directed light to freeze the motion and eliminate blur. Bubble images can overlap with each other at high void fraction and this make the identification of bubble size impossible. It might be also impossible to get a good image quality for a bigger tank die to limited direct light penetration. The main concern in the digital imaging technique is the method for bubble identification which determines the bubble size distributions. Such a task is difficult since the image quality varies with lighting condition and other factor like overlapping bubbles, blurriness of bubbles and the varying shapes of the bubbles.

2.5.6 Computer Automated Radioactive Particle Tracking (CARPT)

CARPT can be applied to measure the flow field, instantaneous and time averaged velocities, and turbulent parameters of high void fraction aeration system. It is based on the principle of tracking the motion of a single radioactive particle as a marker of a typical element of the fluid phase (usually the liquid phase) whose velocity field is to be mapped. The tracer particle representing a typical liquid element is tracked by an array of Nal(TI) scintillation detectors, placed at strategic positions around bubble column. If the liquid phase is to be tracked, the tracer particle must have a density which matches that of the liquid phase. Calibration for each detector in CARPT is necessary in order to determine the exact position of the tracer particle at each instant in time. Application of CARPT is not affected by opacity and void fraction, but it cannot be applied to measure the bubble size distributions and gas holdup (Degaleesan et al., 2003).

2.5.7 Particle Image Velocimetry Laser-Induced Fluorescence (PIV-LIF)

PIV-LIF method is a relatively new development in multiphase flow experimentation. This technique can provide whole-field velocity data in two phase water-bubble flows, with simulations separation and measurement of the different phase. In the LIF technique orange coloured light is scattered from fluorescence particles which are illuminated by green laser light. In combined PIV-LIV studies, the water phase or the flow field is seeded with tiny fluorescent particles. PIV-LIF recording system simultaneously separates and samples the two phase: the first camera with an orange filter detects the fluorescent water seeding and a second camera, with a filter corresponding to the laser wavelength, detects only the bubble phase where it collects the scattered light from the dispersed phase. The PIV-LIF can be used to measure the bubble rise velocities, mean liquid velocities and the velocities fluctuations in a bubble column.

2.6 CFD Modelling and Simulation of Bubble Column Operation

CFD has proven itself as a valuable tool for gaining insight in flow phenomena in general and complex multiphase flows arising in process equipment in particular (Dijkhuizen et al., 2010). Computational fluid dynamics (CFD) is one of the branches of fluid mechanics that uses numerical methods and algorithms to solve and analyze problems that involve fluid flows. CFD simulation is applicable for a variety of gas-liquid dispersion problems including bubble column (Ekambara et al., 2005) and (Kulkarni et al., 2007), which offer a cheaper but with a faster solution compared with measuring using experimental instrumentation. Most of the time the Eulerian-Eulerian two-fluid model is employed to solve the two phase problem and the dispersed *k-å* model is used for turbulence modeling. Many studied have been done related with bubble column modeling and the simulations have been carried out for the predictions of flow pattern in bubble column reactors using 1D, 2D and 3D models. All the models showed good agreement with the experimental data for axial liquid velocity and the fractional gas hold-up profiles (Ekambara et al., 2005). Kulkarni et al. (2007) for instance, reported the plots of axial mean liquid velocity at all measurement levels show the process of development of flow pattern in a bubble column and the same can also be seen from the fractional gas hold-up profile. The CFD predictions were seen to have an excellent match with the experimental results. CFD simulations were also employed to evaluate effects of the configuration of gas distributors on gas–liquid flow and mixing in a bubble column (Li et al., 2009; Dhotre and Joshi, 2007), modelling slurry reactor for Fischer Tropsch synthesis (Maretto & Krishna, 1999; Troshkoa and Zdravistch, 2009) and dynamic flow behavior (Pfleger and Becker, 2001; Zhang et al., 2006). Other related studies reported that the simulation (CFD) results indicate that the Eulerian formulation is a successful approach to predict the hydrodynamics of bubble column. CFD provides good engineering descriptions, and can be used reliably for predicting the flow and hold-up patterns in bubble columns (Mousavi et al., 2008) and (Dhotre et al., 2005), a stepwise procedure has been developed for the prediction of hold-up and liquid phase velocity profiles, a good agreement between the predicted and the experimental profiles of hold-up and axial velocity was observed. Recent study (Selma et al., 2010) were compared the predicted results with measured data available in the scientific literature; they show that the gas volume fraction, velocity profiles and local bubble size are in good agreements when an Eulerian–Eulerian approach with a standard *k-å* model of turbulence is used and the momentum exchange between the bubbles and the continuous phase is taken in to account with drag, lift and virtual mass forces. It is proven that CFD can give an excellent description of bubble column behavior in understanding the hydrodynamics performance. However, most of those or recently studies still cannot predict correctly the information regarding bubble column operation behavior as same as experimental results because there are many aspects need to be considered in the model, especially the multiphase fluid dynamics modelling and the interfacial exchange model. Therefore, the aim of this work is to develop a 3D CFD model to study the influence of turbulent kinetic energy, gas hold-up profile and the liquid axial velocity in bubble column. The CFD prediction was compared to the experimental data from Kulkarni et al. (2007).

Table 2.1: Summary of experimental and numerical study on bubble column

Author	Experiment			Modelling			Remarks
	Gas hold-up	Axial liquid velocity	Turbulent kinetic energy	Gas hold-up	Axial liquid velocity	Turbulent kinetic energy	
Baten & Krishna (2004)	No	No	No	CFD	CFD	CFD	The results demonstrate the strong increase of liquid circulations, and with increasing column diameter
Baten et al. (2003)	No	No	No	CFD	CFD	CFD	Turbulence in the slurry phase
Degaleesan et al. (2003)	CARPT	CT	No	CFD	CFD	No	CFD predict good trend in velocity and holdup profiles but agreement between predicted and measured holdup is poor
Dhotre et al. (2005)	No	No	No	CFD	CFD	No	Steady state heat transfer
Dhotre et al. (2007)	No	No	No	CFD	CFD	CFD	Variation of hold-up profiles with respect to the column height and the sparger design.
Ekambara & Dhotre (2010)	No	No	No	CFD	CFD	CFD	Assess different turbulence model (RNG, LES & RSM)
Gidaspow et al. (1997)	X-ray & GRT	CCD Camera	No	CFD	CFD	No	Slurry bubble column reactor for making of methanol from synthesis gas
Lain et al. (1999)	PDA	PDA	No	CFD	CFD	No	Measure the hydrodynamics interaction between bubbles

Magaud et al. (2001)	Dual optical probe	Hot film velocimetry	No	No	No	No	Decreasing the liquid velocity considerably amplifies the gas velocity effect
Mouza et al. (2004)	No	No	No	CFD	CFD	No	Axial liquid velocity and gas hold-up can be well predicted at the homogeneous regime for the air-water system
Olmos et al. (2001)	No	No	No	CFD	CFD	CFD	Euler–Euler simulations of gas–liquid flows in a bubble column have been coupled with a study of population balance
Popovic & Robinson (1987)	No	Light scattering	No	No	No	No	Specific interfacial area dependent on cross-sectional area ratio and the superficial gas velocity.
Ranade (1997)	No	No	No	CFD	CFD	CFD	Two models proposed to study the role of bubble wakes and column walls on bubble motion and momentum transport in bubble columns.
Schweitzer et al. (2001)	Fiber optic probes	No	Fiber optic probes	No	No	No	Investigate the local bubble flow structure in a slurry bubble column reactor and in a fluidized bed
Veera et al. (2001)	GRT	No	No	No	No	No	Gas hold-up profiles in foaming liquids in bubble columns