HYDRODYNAMICS IN A BUBBLE COLUMN AT ELEVATED PRESSURES AND TURBULENCE ENERGY DISTRIBUTION IN BUBBLING GAS-LIQUID AND GAS-LIQUID-SOLID FLOW SYSTEMS

DISSERTATION

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By

Zhe Cui, M.S. Ch.E.

The Ohio State University
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Dissertation Committee:
Professor Liang-Shih Fan, Adviser
Professor Kurt W. Koelling
Professor James Lee

Approved by

Adviser
Graduate program in Chemical Engineering
Multiphase flow systems (bubble column systems, three-phase fluidized bed systems) are widely used in various industrial processes. Bubble columns commonly refer to gas-liquid systems without the presence of particles. Three-phase fluidized beds normally refer to gas-liquid-solid systems with large particles (particle size in the magnitude of mm). In these multiphase systems, gas is dispersed into bubbles using a sparger and bubbles rise through the liquid or liquid-solid medium. In both gas-liquid and gas-liquid-solid systems, large axial dispersion of phases and high flow patterns can be achieved by the excellent macromixing characteristics. Bubble columns also provide excellent heat- and mass-transfer without the aid of external mechanisms and relatively easy operation. Despite the advantages of operation with the two and three phase systems, the transport behavior in these systems is very complex and a comprehensive knowledge of the transport phenomena, including hydrodynamics and turbulence properties are required for successful application of these systems.

In this study, the hydrodynamics in a high pressure bubble column is experimentally investigated. The liquid vertical and horizontal velocities are measured using an LDV (Laser Doppler velocimetry) technique. The Reynolds shear and normal stresses are obtained. The effect of the pressure on the transition of the flow regime, flow
field and the Reynolds stresses are discussed. Furthermore, the effects of the liquid properties on the hydrodynamics of the bubble column are also investigated.

The turbulence energy distributions in the gas-liquid bubble column system and the effect of solids on the turbulence are investigated using the LDV and the PIV (particle image velocimetry). The superficial gas velocity employed ranges from 0.025 to 7.5 cm/s, covering such bubble flow conditions as single-bubble chain, bubbly flow and churn-turbulent flow. Turbulence induced by rising bubbles through bubble wakes is also examined. The energy containing ranges for the bubble-induced turbulence and the shear-induced turbulence are determined from the liquid phase power spectra. Experimental results indicate that the bubble-induced turbulence dominates over the liquid shear-induced turbulence under the operating conditions of this study. The development of the flow field and the turbulence energy of the liquid phase in the nozzle region are probed. Furthermore, a self-similarity phenomenon is observed in a two-phase flow system. The analysis of power spectra indicates that the bubble-induced turbulence includes the turbulence from eddies in the bubble wake and that from the drift velocity change due to rising bubbles. The interaction between two turbulence fields is studied with a two-orifice gas distributor. The interaction can only be observed when the turbulence in both fields is strong and the interaction tends to enhance the turbulence in both fields. Furthermore, the effect of the solid particles on the liquid phase turbulence is studied. The presence of solids reduces the transition frequency from the energy containing range to the inertial range. The effect of the solids on the liquid-phase turbulence is complex. It depends on solids properties and flow field around particles. The liquid phase turbulence is enhanced in the presence of particles at high superficial gas velocities while it is
attenuated under low superficial gas velocity conditions. A criterion based on the variation of a parameter defined by $U_g(\tau)/u_{mf}$ is proposed to account for the effect of the solids on the liquid phase turbulence. The prediction based on this criterion matches well with the experimental results.

The behavior of a 6 mm mesobubble in an acoustic standing wave field is examined both experimentally and numerically. The acoustic standing waves at 16 kHz and 20 kHz are generated using two Nickel magnetostrictive transducers located at the top and bottom of the column. Experimental studies of the rise velocity of a mesobubble in the acoustic field indicate an axial wavy rising pattern of the bubble synchronized with that of the standing wave. The bubble rise velocity is significantly lower than that in the absence of an acoustic field. The behavior of bubble volume contraction and expansion can be accounted for by a 3-D direct numerical simulation of the bubble dynamics and flow field based on the compressible N-S equations coupled with the level-set method.
Dedicated to my parents, wife and daughter for their love and support
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VITA

February, 1975 .......................... Born - Heilongjiang Province, P. R. China

September 1991 – July 1996................. B.S. Chemical Engineering
Tsinghua University
Beijing, P. R. China

September 1996 – July 1999................. Graduate Research Assistant
Department of Chemical Engineering
Tsinghua University
Beijing, P. R. China

September 1999 – present..................... Graduate Research Associate
Chemical Engineering
The Ohio State University
Columbus, OH, USA

PUBLICATIONS


3. “Synthesis of Linear Alkylbenzene Catalyzed by Hβ Zeolite”, *Applied Catalysis*


FIELDS OF STUDY

Major Field: Chemical Engineering
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<td>$a$</td>
<td>acceleration of bubble, m/s$^2$</td>
</tr>
<tr>
<td>$a$</td>
<td>interfacial area per unit volume, m$^2$/m$^3$</td>
</tr>
<tr>
<td>$A$</td>
<td>cross area, m$^2$</td>
</tr>
<tr>
<td>$c$</td>
<td>sound speed, m/s</td>
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<tr>
<td>$C_D$</td>
<td>drag coefficient</td>
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<tr>
<td>$C_g$</td>
<td>oxygen concentration in the gas phase</td>
</tr>
<tr>
<td>$C_f$</td>
<td>skin friction coefficient with microbubbles</td>
</tr>
<tr>
<td>$C_{f0}$</td>
<td>skin friction coefficient without microbubbles</td>
</tr>
<tr>
<td>$C_l$</td>
<td>oxygen concentration in the liquid phase</td>
</tr>
<tr>
<td>$C_p$</td>
<td>pressure drag coefficient</td>
</tr>
<tr>
<td>$C_V$</td>
<td>specific heat at constant volume, J/(mol·K)</td>
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<tr>
<td>$D$</td>
<td>bubble column diameter, cm</td>
</tr>
<tr>
<td>$d$</td>
<td>nozzle diameter, mm</td>
</tr>
<tr>
<td>$d$</td>
<td>diameter of dropping particle, m</td>
</tr>
<tr>
<td>$D$</td>
<td>column diameter, m</td>
</tr>
<tr>
<td>$d_b$</td>
<td>bubble diameter, mm</td>
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$d_b$  diameter of microbubble, m

$d_e$  equivalent bubble diameter, mm

$d_p$  particle diameter, mm

$d^*$  microbubble length scale

$e$  internal energy, J

$e_H$  Hugoniot energy, J

$E$  total turbulent kinetic energy, cm$^2$/s$^2$

$F_D$  buoyancy force, N

$f$  bubble formation frequency, Hz

$F_B$  Bjerknes force, N

$F_s$  surface tension, N

$g$  gravitational acceleration, m/s$^2$

$h$  axial height from nozzle, mm

$I$  Laser beam intensity with bubble

$I$  turbulence intensity

$I_0$  Laser beam intensity without bubble

$k$  wave number

$K(\phi)$  curvature

$l$  distance of measuring point from the wall, cm

$L$  length scale of bubble column, cm

$m$  mass, kg

$N$  total amount of samples in LDV measurement
\( p \) \quad \text{pressure, Pa}

\( P \) \quad \text{surface pressure, Pa}

\( P_H \) \quad \text{Hugoniot pressure, Pa}

\( p_n^* \) \quad \text{interface pressure, Pa}

\( P_\infty \) \quad \text{pressure in the bulk flow, Pa}

\( \Delta P \) \quad \text{pressure drop between two measurement points with microbubbles, Pa}

\( \Delta P_0 \) \quad \text{pressure drop between two measurement points without microbubbles, Pa}

\( R \) \quad \text{bubble column radius, cm}

\( R \) \quad \text{specific gas constant, J/(mol} \cdot \text{K)}

\( R_{oa} \) \quad \text{amplitude of radial oscillation at the pressure antinode, m}

\( R_{res} \) \quad \text{resonance bubble diameter, m}

\( r \) \quad \text{distance from center, cm}

\( r_{1/2} \) \quad \text{jet’s half-width}

\( s \) \quad \text{constant entropy, J}

\( T \) \quad \text{temperature, K}

\( t_b \) \quad \text{time for bubble pass through measurement volume}

\( u \) \quad \text{liquid axial velocity, cm/s}

\( U \) \quad \text{terminal velocity, m/s}

\( u^* \) \quad \text{friction velocity, m/s}

\( U' \) \quad \text{fluctuating velocity, cm/s}

\( u_0 \) \quad \text{liquid axial velocity at center, cm/s}

\( u_b \) \quad \text{bubble rising velocity, cm/s}
$u_n^*$ interface normal velocity, cm/s
$u_{mf}$ minimum fluidization velocity, cm/s
$u_t$ terminal velocity, cm/s
$u'(i)$ axial fluctuating component, cm/s
$U_g$ superficial gas velocity, cm/s
$U_g(\ r\ )$ local gas velocity, cm/s
$\langle u \rangle$ average axial velocity, cm/s
$\langle u'u' \rangle$ liquid axial normal Reynolds’ stress, cm$^2$/s$^2$
$\langle u'v' \rangle$ liquid shear Reynolds’ stress, cm$^2$/s$^2$
$V$ bubble volume, m$^3$
$V_l$ liquid flow rate, l/s
$V_g$ gas flow rate, l/s
$v$ liquid radial velocity, cm/s
$v'(i)$ radial fluctuating component, cm/s
$\langle v \rangle$ average radial velocity, cm/s
$\langle v'v' \rangle$ liquid radial normal Reynolds’ stress, cm$^2$/s$^2$
$\langle w'w' \rangle$ liquid normal Reynolds’ stress in $z$ direction, cm$^2$/s$^2$
$x$ position vector
$y$ normal coordinate from the wall, cm
$y^+$ inner distance variable

$\Delta$ grid size, m
\( \gamma \) ratio of specific heat

\( \varepsilon_g \) gas holdup, dimensionless

\( \varepsilon_g(r) \) local gas holdup, dimensionless

\( \theta \) angle, degree

\( \lambda \) wavelength, m

\( \mu_l \) liquid viscosity, Pa\cdot s

\( \nu \) kinetic viscosity, m\(^2\)/s

\( \rho \) liquid density, kg/m\(^3\)

\( \rho_g \) gas density, kg/m\(^3\)

\( \rho_l \) liquid density, kg/m\(^3\)

\( \rho_s \) solid density, kg/m\(^3\)

\( \sigma_l \) surface tension, N/m

\( \tau \) viscous stress tensor

\( \tau \) artificial time

\( \phi(x, t) \) level-set function

\( \omega \) angular frequency
CHAPTER 1

INTRODUCTION

Bubble columns and fluidized beds have wide applications in physical, chemical, petrochemical, electrochemical and biochemical processing (Fan, 1989). In these multiphase systems, gas is dispersed into bubbles using a sparger and bubbles rise through the liquid or slurry medium. Hence, momentum is transferred from the faster, upward moving gas phase to the slower liquid phase. Depending on the gas and liquid flow rates and the physical properties of the system, bubble columns can be operated in either homogeneous bubbling flow, heterogeneous bubbling flow or slugging flow regimes. Bubble column and gas-liquid-solid fluidized bed reactors have gained considerable attention over the past few decades due to the various advantages they offer such as easy particle removal and replacement, excellent heat and mass transfer, and efficient temperature control. Since bubble columns are simple to construct and do not involve any mechanically moving parts, they are very suitable for high-pressure
operating conditions when the leakage around rotating shafts is a concern. High pressure and temperature operating conditions are common in industrial reactors. Table 1.1 lists several industrial applications of bubble column reactors along with their operating conditions. These are only some of the many applications where bubble columns are used for processing chemicals. Specifically, the residuum hydrotreating technology has grown in importance mainly because of three reasons: heavier crude supply, more stringent environmental regulations, and the shift in market demands from fuel oil to light products (Dautzenberg and de Deken, 1984). Bubble columns have been used as reactors in all the newly developed residuum hydrotreating processes, such as M-Coke, CANMET (Dautzenberg and de Deken, 1984), and T-Star (Clausen et al., 1992). Other applications such as Fisher-Tropsch and coal hydrogenation technologies will one day become important parts of the chemical processing industry, given the enormous potential and supply of the primary raw material (coal). Further, bubble columns are also used in biotechnological areas (Schugerl et al., 1977) such as antibiotic fermentation (Fregapane et al., 1999), single cell protein production and animal cell culture (Chisti, 1989). Other applications include wastewater treatment (Beltran et al., 1995; Boyes et al., 1995) and dehydration of ortho-boric acid (Kang et al., 1995).

In spite of the importance of high pressure bubble columns, hydrodynamics and transport phenomena under high pressure conditions are not fully understood. Most studies in the literature concerning bubble columns were conducted under ambient conditions, only a limited number of studies covered the high pressure and high temperature conditions which are of greatest importance and relevance to industrial
operation of bubble column reactors. For better design, optimization, and scale-up of high-pressure bubble column reactors, a comprehensive study on the hydrodynamics, bubble characteristics and transport phenomena under high pressure conditions is needed. The objective of this study is to obtain more information about the hydrodynamics, including the liquid flow field and the turbulence properties of a high pressure bubble column. Furthermore, the turbulence properties, especially the distribution of the liquid phase turbulence and the factors governing the liquid phase turbulence in bubbly flows are studied systematically. The source of the liquid phase turbulent energy relative to the location of bubbling is probed. The effect of the solid phase on the liquid phase turbulence is discussed. Furthermore, the bubble behavior in an acoustic bubble column is studied both experimentally and numerically. The modulation of a mesobubble in the presence of an acoustic standing wave is investigated.

In this study, a high-pressure and high-temperature three-phase fluidization and visualization system developed at The Ohio State University is employed. The details are introduced in Chapter 3. The system can be operated at pressures up to 21 MPa and temperatures up to 250°C. Three pairs of quartz windows installed on the front and rear sides of columns allow the direct flow visualization to be carried out under actual operating conditions. Some measurement techniques used in this study are also introduced in Chapter 2, such as the LDV (laser Doppler velocimetry) technique and the PIV (particle image velocimetry) technique. The acoustic gas-liquid-solid multiphase system and the technique for gas-liquid mass transfer measurements are introduced in Chapters 6.
Studies in the literature have indicated significant effects of pressure on some hydrodynamic variables in bubble columns and slurry bubble columns. For example, elevated pressures lead to an increased gas holdup in the system, and this increase is mainly attributed to the small bubble size at high pressures. The bubble size in multiphase fluidization systems is dictated by three processes: initial bubble formation, bubble coalescence, and bubble breakup. The increased gas momentum in the bubble-formation process has been suggested as one factor behind the bubble size reduction at high pressures, especially at low gas velocities. To fully understand the hydrodynamics in high pressure systems, it is necessary to quantify the liquid velocity and the Reynolds stresses (turbulence properties) under high-pressure conditions. Chapter 3 presents the hydrodynamics results including flow field and Reynolds stresses investigated using a LDV in a high pressure bubble column. The axial liquid velocity profiles at different gas velocities and different pressures for the air-water system are measured. The regime transition is identified based on the liquid velocity measurement, and the transition superficial gas velocity is obtained as about 4-6 cm/s in the air-water system. Reynolds normal and shear stresses are calculated under different conditions for pressures up to 1.5 MPa. Reynolds normal stress is about an order of magnitude higher than the Reynolds shear stress, and it decreases with increasing pressure. The development of liquid velocity profiles along the axial direction is examined by the measurements of liquid velocity profiles at different axial positions above the distributor. The flow structure is fully developed when the axial position is about 220mm above the distributor corresponding to a height-to diameter ratio of 4.4 in this work. Furthermore, the effect of
the liquid properties and the pressure on the flow field and the turbulence properties in a high pressure bubble column is discussed.

In gas-liquid and gas-liquid-solid flow systems, turbulence plays an important role in multiphase mass-transfer, heat-transfer and mixing processes. Turbulence is a multi-scale phenomenon, in which the large-scale motion of the fluid is inherently intertwined with the small-scale motion of the fluid through complex, chaotic processes involving vortex stretching. A comprehensive understanding of the variation of the broad spectrum of spatial and temporal scales on turbulence is thus necessary in order to properly simulate or control the turbulent flow in reactor systems. In Chapters 4 and 5, liquid phase turbulence and the effects of gas and solid phases on the liquid phase turbulence are studied systematically. Chapter 4 focuses on the source of the liquid phase turbulence in a bubbly flow. The bubble induced turbulence and the shear induced turbulence are separated in the liquid phase turbulence energy spectrum. Compare to the liquid shear-induced turbulence, the bubble-induced turbulence is found to be the dominant factor in the liquid phase turbulence generation under the operating conditions of this study. The anisotropic properties of the bubble-induced turbulence are also examined through the re-orientation of the direction of the LDV measurement. The bubble-induced turbulence includes the turbulence in the eddies of the bubble wake as well as that induced by the drift velocity due to rising bubbles. The interaction between the two turbulence fields is discussed in Chapter 4. Chapter 5 focuses on the effect of the solid phase on the liquid phase turbulence in a bubble column. The effect of solid particles on the liquid-phase turbulence is complex and depends on the solid properties as well as the gas velocity. The liquid phase turbulence is enhanced in the presence of
particles at a high gas velocity while it is impeded in the presence of particles at a low
gas velocity. A criterion based on the parameter, $U_g( r )/u_{mf}$, can be used to account for
the effect of solid particles on the turbulence in the liquid phase of a three-phase fluidized
bed. Predictions based on this criterion matches well with the experimental results.
Furthermore, the energy spectra in gas, liquid and solid phases are reported and
discussed.

In bubble column and fluidized bed systems, the gas rises in the form of bubbles
through a continuous liquid phase. By inducing liquid agitation or providing gaseous
reactants to the liquid medium, bubbles play an important role in gas-liquid or gas-liquid-
solid systems. As the characteristics of bubble motion and bubble interfacial dynamics
govern the performance of the bubbling systems, the understanding, and hence the ability
of controlling the bubble motion and interfacial dynamics in bubble column reactors are
important to effective operation of these systems. In Chapter 6, a gas bubble with a
diameter of 6 mm is injected into a acoustic bubble column. The effect of the acoustic
standing wave field on the bubble behavior is studied. Due to the Bjerkness force, the
bubble rise velocity is reduced, yielding a longer residence time in the bubble column
system. The bubble behavior in the acoustic standing wave field is simulated using a 3-D
direct numerical simulation based on the compressible N-S equations coupled with the
level-set method. The experiments and simulation reveal a consistent value of 20-25% for
the ratio of the Bjerknes force to the buoyancy force for a single mesobubble rising in the
acoustic field.
Finally, recommendations for future research on bubble column and three phase fluidization systems are discussed in Chapter 7.
## Table 1.1. Industrial applications of slurry bubble column reactors.

<table>
<thead>
<tr>
<th>PROCESS</th>
<th>T (°C)</th>
<th>P (MPa)</th>
<th>REFERENCE</th>
</tr>
</thead>
<tbody>
<tr>
<td>Partial oxidation of ethylene to acetaldehyde</td>
<td>130</td>
<td>0.3</td>
<td>Deckwer, 1992</td>
</tr>
<tr>
<td>Wet-air oxidation of sewage sludge</td>
<td>200–300</td>
<td>4–12</td>
<td>Deckwer, 1992</td>
</tr>
<tr>
<td>Oxidation of cumene to phenol</td>
<td>80–125</td>
<td>0.5–0.8</td>
<td>Deckwer, 1992</td>
</tr>
<tr>
<td>Hydrociline formation by hydrogenation</td>
<td>50–60</td>
<td>2.5–3</td>
<td>Deckwer, 1992</td>
</tr>
<tr>
<td>Methanol synthesis</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>(1) BASF</td>
<td>350–400</td>
<td>25–35</td>
<td>Wender, 1996</td>
</tr>
<tr>
<td>(2) Eastman Chemicals, Air-Product, DOE</td>
<td>220–250</td>
<td>5–10</td>
<td>Peng et al., 1998</td>
</tr>
<tr>
<td>Fischer-Tropsch synthesis</td>
<td>220–270</td>
<td>0.1–4</td>
<td>Fox, 1990</td>
</tr>
<tr>
<td>Hydroformylation processes</td>
<td>160–200</td>
<td>5–10</td>
<td>Wender, 1996</td>
</tr>
<tr>
<td>Residuum hydrotreating</td>
<td>300–425</td>
<td>5.5–21</td>
<td>Dautzenberg and de Deken, 1984</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>Clausen et al., 1992</td>
</tr>
<tr>
<td>Benzene hydrogenation</td>
<td>180</td>
<td>5.0</td>
<td>Deckwer, 1992</td>
</tr>
<tr>
<td>Methanation</td>
<td>350</td>
<td>6.8</td>
<td>Blum and Toman, 1977</td>
</tr>
<tr>
<td>Coal gasification</td>
<td>980</td>
<td>3.0</td>
<td>Yosim and Barclay, 1981</td>
</tr>
</tbody>
</table>
The principles and some sample results of a laser Doppler velocimetry (LDV) and a high-framing rate and high-capacity particle image velocimetry (PIV) techniques for use in multiphase flow systems are presented. Both laser Doppler velocimetry and particle image velocimetry techniques are non-invasive optical techniques which can be used to conduct in situ measurements without disturbing the flow field in the measured systems. The LDV technique can be used to measure the velocity in the flow, with high spatial resolution, and fast dynamic response. The PIV technique provides accurate instantaneous and full-field flow information for a given plane in the multiphase flow system to determine the time/volume-averaged flow information for each phases, including velocity and dispersed phase holdup distributions. This mode of PIV operation is commonly referred to as particle tracking velocimetry (PTV). The PIV developed for
multiphase systems has the unique ability to discriminate between the different phases. In this chapter, a basic theory of the LDV techniques for measuring velocities, including the Doppler model and the fringe model will be discussed. Details of PIV technique used in multiphase flow systems are introduced.
2.1 LASER DOPPLER VELOCIMETRY (LDV)

2.1.1 Introduction

Bubble columns and gas-liquid-solid fluidization systems are multiphase contactors to which a gas or a mixture of gases is introduced and rises in a form of bubbles through a continuous liquid phase. Because of their good heat and mass transfer characteristics, bubble columns and gas-liquid-solid fluidization systems are widely used in industry for chemical, biochemical and petrochemical processing (Fan, 1989). The hydrodynamics of gas-liquid and gas-liquid-solid systems have been extensively studied over the past few decades (Chen et al., 1999). However, there is a lack of detailed physical understanding and predictive tools for design and optimization of such systems. Recently, the use of the computational fluid dynamics (CFD) has contributed to the understanding of such complicated hydrodynamic behaviors. However, the application of CFD is restrained due to the lack of a fundamental understanding of flow behavior and gas-liquid interactions in multiphase flow systems. Due to the difficulties encountered in performing the necessary measurements and the limitation of the measurement methods, data on the flow behavior in these multiphase flow systems are scarce in the literature. Therefore, finding appropriate techniques for measuring the hydrodynamic characteristics is essential to the development of an optimum design and the scale-up of the process.

The LDV technique is a non-intrusive method, which causes no disturbance to the measured flow fields. The LDV technique can also be used to capture the flow characteristic with fast dynamic response, high-spatial resolution, and measure a wide
range of velocities. Because of all these advantages, the LDV technique has become one of the most powerful measurement methods for experimental studies of multiphase flow systems.

2.1.2 Principle of the LDV Technique

The Laser Doppler Anemometer, or LDA, is a widely accepted tool for fluid dynamic investigations in gases and liquids. It has been used as such for more than four decades since it was invented by Yeh and Cummins in 1964. It is a well-established technique that gives information about flow velocity. Its non-intrusive principle and directional sensitivity make it very suitable for applications with reversing flow, chemically reacting or high-temperature media and rotating machinery, where physical sensors are difficult or impossible to use. It requires tracer particles in the flow. The method’s particular advantages are: non-intrusive measurement, high spatial and temporal resolution, no need for calibration and the ability to measure in reversing flows.

Compare to other measurement methods, the LDV techniques has many special features: 1. it is a non-intrusive method; 2. no calibration is required in the measurement; 3. the velocity ranges from 0 up to supersonic; 4. one, two or three velocity components can be measured simultaneously; 5. the measurement distance ranges from centimeters to meters; 6. it can be used to measure flow reversals; 7. the spatial and temporal resolutions are high; 8. both instantaneous and averaged velocities can be measured.

The basic configuration of an LDA consists of a continuous wave laser, transmitting optics (including a beam splitter and a focusing lens), receiving optics (comprising a focusing lens, an interference filter and a photodetector), a signal
conditioner and a signal processor. A general system configuration is shown in Fig. 2.1.
The laser beam generated from the laser system is divided into two laser beams. Two laser beams are forced to intersect at the measurement volume by the focusing lens. The photo detector receives light scattered from tracer particles moving through the measurement volume and convert light intensity into an electrical current. The scattered light contains a Doppler shift, which is proportional to the velocity component perpendicular to the bisector of the two laser beams. The noise from the signal is removed in the signal conditioner and signal processing. Then the conversion factor between the Doppler frequency and the velocity can be calculated with a known wavelength of the laser light, a known angle between the intersecting beams.

In all scatter modes, back scatter mode is used most often. It is because that it allows integration of the transmitting and receiving optics in a single head. This is much simpler to align than two heads.

Liquids often contain sufficient natural seeding, whereas gases must be seeded in most cases. Ideally, the particles should be small enough to follow the flow, yet large enough to scatter sufficient light to obtain a good signal-to-noise ratio at the photo-detector output. Typically the size range of particles is between 1 µm and 10 µm. The particle material can be solid (powder) or liquid (droplets).

Doppler Effect

The velocity measurements are made based on the Doppler effects. The velocity and the frequency of the incident light are $c$ and $f_i$, respectively. When the light is scattered by the tracer particles, due to the particle movement, the frequency of the
scattered light received by the receiver is \( f_s \). From the Doppler theory, the frequency of the scattered light received by the receiver can be calculated as

\[
    f_s = f_i \frac{1 - e_i \left( \frac{U}{c} \right)}{1 - e_s \left( \frac{U}{c} \right)}
\]

(2.1)

where \( e_i \) and \( e_s \) are the direction of incident and scattered light, \( U \) is the particle velocity. Since \( U/c \) is much less than 1, Eq. (2.1) can be linearized to:

\[
    f_s \approx f_i \left[ 1 + \frac{U}{c} (e_s - e_i) \right] = f_i + \frac{f_i}{c} U (e_s - e_i) = f_i + \Delta f
\]

(2.2)

When two waves of slightly different frequency are superimposed, because of the two waves intermittently inferring with each other constructively and destructively, the phenomenon is called a beat frequency. The beat frequency is calculated by

\[
    f_D = f_{s2} - f_{s1}.
\]

(2.3)

Then,

\[
    f_D = \frac{2 \sin \theta / 2}{\lambda} u_x
\]

(2.4)

can be obtained by substituting Eq. (2.1) into Eq. (2.3). Where \( \theta \) is the angle between the two incoming laser beams and \( u_x \) is the particle velocity component in the measured direction.

The beat frequency, \( f_D \), is much lower than the frequency of the incident and the scattered light. It can be measured as fluctuations in the intensity of the light reflected from the seeding particles. The Doppler frequency is directly proportional to the \( x-\)}
component of the particle velocity, and the velocity can thus be calculated directly from
\( f_D \).

The Fringe Model

When two coherent laser beams intersect, they will interfere with each other and
form the measurement volume. Consequently, parallel planes of light and darkness is
produced by the interferences as shown in Fig. 2.2. The interference planes are fringes,
and the distance \( \delta_f \) between the fringes is depend only on the wavelength \( \lambda \) and the
angle \( \theta \) between the incident beams as

\[
\delta_f = \frac{\lambda}{2 \sin(\theta/2)}.
\]  

(2.5)

The fringes are oriented normal to the x-axis. Therefore, the intensity of the
scattered light from a tracer particle moving through the measurement volume varies with
a frequency proportional to the x-component of the particle velocity, \( u_x \). The beat
frequency, \( f_D \) is then obtained by

\[
f_D = \frac{u_x}{\delta_f} = \frac{2 \sin(\theta/2)}{\lambda} u_x
\]  

(2.6)

which is identical to the result in Eq. (2.4).

Measurement Volume

The measurement volume is formed when two coherent laser beams from the
transmitting system intersect. The measurements take place in the measurement volume.
Furthermore, due to the Gaussian intensity distribution in the beams, the measurement
volume is an ellipsoid. The dimensions/diameters of the measurement volume, \( d_x, d_y \) and \( d_z \) are given by the \( 1/e^2 \) intensity points. With the beam diameter of the focused laser beams, \( d_f \), and the angle \( \theta \) between the two beams, the size of the measurement volume can be calculated by

\[
\begin{align*}
  d_x &= \frac{d_f}{\cos(\theta/2)} \\
  d_y &= d_f \\
  d_z &= \frac{d_f}{\sin(\theta/2)}
\end{align*}
\]  

where \( d_x, d_y \) and \( d_z \) are the height, width and length of the measurement volume.

From the height \( d_x \) of the measurement volume and the fringe spacing, \( \delta_f \), the total number of fringes in the measurement volume can be calculated by:

\[
N_f = \frac{d_x}{\delta_f} = \frac{2d_f}{\lambda}\tan(\theta/2).
\]  

**Frequency Shift**

In the LDV measurements, the basic configuration gives the same output for opposite velocities of the same magnitude. The direction of the particle velocity cannot be determined. To distinguish between positive and negative flow direction, frequency shift is employed. The Bragg cell adds a fixed frequency shift, \( f_0 \), to the diffracted beam. As long as the particle velocity does not introduce a negative frequency shift numerically larger than \( f_0 \), the Bragg cell will thus ensure a positive Doppler frequency. The resulting
output frequency is then the Doppler frequency plus the frequency shift. The frequency shift $f_0$ allows measurement of velocities down to

$$u_x > -\frac{\lambda f_0}{2\sin(\theta/2)}$$

(2.11)

without any directional ambiguity.

2.1.3 Applications of the LDV Technique

Due to the advantages shown as above, the LDV technique has been employed in multiphase flows for more than 30 years. First attempts to carry out LDV measurements in particulate two-phase flow were undertaken by Lading (1971) and Davies (1973) in bubble flows. Davies (1973) showed that the bubble velocity can be determined independently of the liquid velocity if the bubble size exceeds the size of the natural contaminants in the water. Boerner et al. (1984) compared laser-Doppler and hot-film measurement techniques in studies of bubbly two-phase flow. It is found that when the optical method (LDA) is applicable, both measurement techniques yield comparable results. The finding is consistent with observations in single-phase flow.

In this study, a Dantec two-dimensional ($x$- and $y$- components) laser Doppler velocimetry system is used in the backscatter mode. A 300-mw air-cooled argon-ion laser and a beam separator are used to generate two pairs of beams of wavelengths of 514.5 nm and 480 nm. The light is transmitted through a fiber optic cable and a probe with 25 cm focal-length lens. The configuration yields 48 fringes with fringe spaces of 3.40 and 3.22 $\mu$m and measurement volumes of $0.164 \times 0.164 \times 2.162$ mm and $0.156 \times 0.156 \times 2.05$ mm for 514.5 and 480 nm wavelength, respectively. The scattered light is collected
through the same probe (backscatter mode) and is processed by a Dantec 58N70 signal processor.
2.2 PARTICLE IMAGE VELOCIMETRY (PIV)

2.2.1 Introduction

In a multiphase flow system, the ability to simultaneously measure the velocity fields and the phase distributions of all phases is an important but challenging issue. With the continuing advancement in multiphase modeling and simulations, the simultaneous measurement of velocity fields and the phase distributions of all phases in a multiphase system can provide a better understanding of the coupling effects between phases and presents the opportunity to provide data useful for the verification of models in multiphase computational fluid dynamics. The ability to simultaneously measure the flow properties of all phases, may also lead to a better phenomenological approach, or an even more desirable fundamental approach of modeling the fluid dynamics and particle mechanics of the system. This improved fluid or particle mechanics based modeling of multiphase systems coupled with knowledge of the other transport phenomena, such as the heat and mass transfer, and reaction parameters, in the case of a reacting system, will lead to better design and facilitate scale-up of multiphase systems.

Another important requirement in the measurement of multiphase systems is the ability to obtain the full-field macro-and microscopic scale instantaneous fluid dynamic information of the flow. The full-field flow properties are necessary if the coupling effects of the different phases are to be understood. In multiphase systems, such as bubble columns and gas-liquid-solid fluidized beds, it has become recognized that the transient behavior is of utmost importance in dictating the performance of such multiphase flow systems, especially reacting systems. The demonstrated measurement
technique, which has the capability to provide the transient and full-field behavior of a fluid flow system without obstructing the flow, is particle image velocimetry (PIV).

Particle image velocimetry has been used in the measurements of single-phase flows in many different operational modes. The two modes of operation, which have become the most common, are the high image density mode and low image density modes. In the high image density mode of operation, images of the flow field are obtained through a double or multiple exposed photographs. The flow field is illuminated by a thin sheet of laser light that is generated by a pulsed laser to provide the double or multiple exposures. The image is divided into many small interrogation grids. The size of the interrogation grid depends on the accuracy of the required measurement and on the time available for processing. With a smaller interrogation grid size, the higher accuracy and more detailed information can be obtained. On the other hand, it requires a longer processing time because of a higher number of grids.

Keane and Adrian (1990) provide several guidelines for the determination of the interrogation grid size. The displacement of the group of particles within the interrogation grid is then determined using correlation methods or by measuring the Young’s fringe pattern of the particle images. The displacement together with the time interval between consecutive exposures provides the velocity at each interrogation spot. The primary difference between PIV techniques of various investigators is in the algorithm for the auto- or cross-correlation technique. Okamoto et al. (1995) provided a review of studies conducted with modified cross-correlation techniques.

A PIV technique that operates in the low image density limit is characterized by a particle-tracking algorithm to track individual particles rather than groups of particles.
The individual particles are traced over several time intervals to obtain Lagrangian-type fluid dynamic information. The full-field image of the illuminated flow field is digitized directly from the actual flow field through the use of a high-resolution CCD camera, from a video recording of the flow field, or from a multiple exposed photograph of the flow field. The procedures to locate the digitized particle images and compute the displacements between image pairs to determine the velocity are logical computer operations.

2.2.2 PIV Technique for Multiphase Flows in This Study

To be employed in multiphase flow systems, the PIV technique should have the ability to discriminate between the different phases and provide the instantaneous, full-field flow properties of each phase. The PIV technique consists of illumination of the flow field (e.g., through laser sheeting), recording of the illuminated flow field with a charge-coupled device (CCD) camera, and the image processing of the recorded data. A brief description of the principle of the PIV system is given below. The laser sheeting technique, the recording apparatus will also be discussed.

_Laser Sheetin_g

A Lexel 3500, 4-watt argon-ion laser system is operated in a continuous mode in the PIV system employed in this study. The time interval between consecutive images is based on the digital processing of video frames; hence, a pulsed laser system is not required. A cylindrical lens attached to the end of a fiber optic cable is used to generate a sheet of laser light of varying width of 2 to 10 mm.
High-Framing Rate CCD Camera and High-Capacity Frame Grabber

In this study, a high-framing rate and high-resolution CCD camera equipped with a variable electronic shutter ranging from 1/60 to 1/10000 second is used to record the image of the flow field. The highest framing rate is 480 fields/second. A CCD image picked up on the high-framing rate camera features 512 pixels by 246 lines. A frame grabber equipped with 40 MHz pixel clock to support the high-framing rate and high-resolution simultaneously digitizes the CCD image from the camera. The high-framing rate allows the accurate measurements of the velocity fields. Furthermore, the frame grabber is equipped with 256 Mbytes on-board image memory that can store up to 2184 fields of 512 by 245 pixels. This high-capacity image memory allows digitizing consecutive images for a long time. The high-framing rate camera is also connected to the high-speed video recorder to store the images for further studies.

Image Processing

The image processing occurs in five steps: (1) image acquisition, (2) image enhancement, (3) particle or gas bubble identification and calculation of the centroids, (4) discrimination of the bubble images between the two phases, and (5) matching of the bubbles in three consecutive video fields and calculation of the velocity. The PIV technique utilizes a particle-tracking algorithm to determine the velocity of rising bubbles.

The instantaneous flow properties of each phase for a particular plane in the flow field, including velocity vectors and phase distributions, can be obtained. The ability to
independently evaluate the flow properties of each phase through the discrimination
algorithm renders the image processing of the PIV technique for multiphase systems
unique. The general flow chart of the PIV system is shown in Fig. 2.3.

In the first step, the background and electronic noise is first removed from the
digitized images through the use of grey level filtering in an effort to improve the image
quality. The enhancement filtering process includes high- and low- pass threshold
filtering and a local gradient filtering. The identification of the particle images then
begins by the execution of scanning subroutine, which locates a pixel with non-zero grey
value and an image boundary search is performed in a clockwise manner to locate the
entire boundary of the particle image. The search is completed when the initially
detecting pixel is encountered. Integration along each axis is performed inside the
identified boundary of the particle image. The centroids and the volume equivalent
spherical diameters of the particle images are then computed. Using this diameter of the
particle image and a pre-calibrated scale factor based on the size of the flow field being
investigated, the actual particle diameter can be determined. The scanning and boundary
searching subroutines continue until all the particle images of the entire field are
processed.

After the identification of the particle images, the discrimination of particles
images of different phases is processed based on a prior knowledge of the size
distribution of each phase in the multiphase system. Each field of the sequentially
recorded frames is split and stored into three sub-fields based on the discrimination of the
phases. The processed image data of each sequentially recorded sub-field is stored in
specific buffer addresses of the PC RAM in order to overcome any direction ambiguity.
problems. After the discrimination of phases, each phase is processed independently to determine the velocity vectors and phase distributions.

With the discrimination of phases completed, the calculation of the velocities of the particle images is conducted via a particle tracking algorithm by computing the displacements of the found centroids from consecutive sub-fields under the assumption of linear and constant flow during the short time interval (1/30 to 1/480 s) between subfields. The starting sub-field and the number of sub-fields (minimum of three) used for determining the velocity vectors can be specified. The procedure to find the instantaneous particle displacement vectors consists of a displacement scanning subroutine, which requires an estimation of the maximum particle displacement and the maximum tolerance of displacement vectors including magnitude and direction. The subroutine scans for identified centroids, upon locating a centroid the subroutine searches the next adjacent sub-field for possible centroids located around the position of the identified centroid. The radius of the searching circle is based on the input of the maximum particle displacement. Upon locating the displacement between two centroids of adjacent cub-fields, a search for particle centroids of the third adjacent sub-field begins. If a particle with the allowed displacement and direction tolerance is found in the third sub-field, the subroutine with either continue the search to the next adjacent sub-field or identify the three as being a matched sequence. The minimum requirement for the matched sequence to be a velocity vector is the matching in three adjacent sub-fields. However, if no such particle is found in the third sub-field, the subroutine will move to the next possible displacement obtained by searching the first and second sub-fields within the region of maximum setting radius. The same procedure is followed when more
than three sub-fields are specified. The procedure is continued until all the particle images of the first sub-field are scanned.

The PIV technique has the capability of providing the Lagrangian acceleration. The Lagrangian acceleration of an identified particle is obtained from the velocity vectors calculated from consecutive frames. The PIV technique also has the ability to volume average the data in a single frame or multiple frames, so that the mean velocity, velocity fluctuations and holdup fluctuations can be calculated. This ability when applied to all phases allows for the calculation of slip velocities at any of the locations where more than one phase may exist in the flow field.
Figure 2.1 System configuration of an LDV system

Forward scatter and side scatter (off-axis):
- Difficult to align
- Vibration sensitive

Back scatter:
- Easy to align
- Use friendly
Figure 2.2 Fringes form two coherent laser beams
Figure 2.3 Flow chart for the particle image velocimetry for multiphase flow

Image acquisition
(Framing rate, field of view, resolution, etc.)

Image enhancement
(Threshold / gray level gradient discrimination, etc.)

Identification of object boundary

Phase discrimination

Time-averaged &
Time/volume-averaged quantities;
Time series

Instantaneous velocity vectors

Instantaneous phase distributions
CHAPTER 3

EXPERIMENTAL STUDY OF HYDRODYNAMICS IN HIGH PRESSURE BUBBLE COLUMN SYSTEMS

SUMMARY: The hydrodynamics of a gas-liquid flow is investigated in a high-pressure multiphase bubble column system. The liquid vertical and horizontal velocities are measured using LDV technique. The Reynolds shear and normal stresses are obtained. The effects of the pressure on the transition of the flow regime, flow field and the Reynolds stresses are discussed. Furthermore, the effects of the liquid properties on the hydrodynamics of the bubble column are also investigated.
3.1 INTRODUCTION

Bubble columns and slurry bubble columns are some of the most commonly used industrial processes. Considerable interests have been recognized in the field of physical, chemical, petrochemical, electrochemical, and biochemical operations (Fan, 1989). Processes like waste water treatment and biochemical fermentation are carried out in gas-liquid systems while resid hydrotreating, Fischer-Tropsch Synthesis, coal hydrogenation, and antibiotic fermentation processes are carried out in gas-liquid-solid three-phase fluidized beds. Despite the advantages of operation with the two and three phase systems, the transport behavior in these systems is very complex and a comprehensive knowledge of the transport phenomena, including hydrodynamics and turbulence properties, is required for successful application of these systems.

Many applications of slurry bubble column reactors such as methanol and Fisher-Tropsch syntheses are typically operated at elevated pressures (1.0~8.0 MPa) and at high superficial gas velocities (~30 cm/s). The design and scale-up of these reactors require comprehensive knowledge of the hydrodynamics under these operating conditions. The fundamentals of the transport phenomena have been extensively studied over the past decades and comprehensive literature reviews are available (Shah et al., 1982; Fan, 1989; Deckwer, 1992; Saxena and Chen, 1994). However, most studies were conducted under ambient pressure conditions, and relatively little is known regarding the hydrodynamics at high pressures with relevance to industrial processes.

Two main flow regimes are commonly identified for three-phase fluidization systems based on the bubble flow behavior: the dispersed bubble (homogeneous) regime
and the coalesced bubble (churn-turbulent) regime. It is necessary to have the knowledge of the transition from the homogeneous bubble flow to the churn-turbulent flow regimes for the design and operation of industrial reactors. The transition velocity depends on a number of factors such as gas distributor design, physical properties of the phases, and column size. The flow regime transition has been studied extensively under ambient conditions over the last three decades (Wallis, 1969; Joshi and Lali, 1984; Shnip et al., 1992; Tsuchiya and Nakanishi, 1992).

The pressure effect on the regime transition has been examined by many researchers in gas-liquid systems (Tarmy et al., 1984; Clark, 1990; Krishna et al., 1991, 1994; Wilkinson et al., 1992; Hoefsloot and Krishna, 1993; Reilly et al., 1994; Letzel et al., 1997; Lin et al., 1999). The flow regime transition is normally identified based on instability theory, analysis of fluctuation signals, and the drift flux model. Letzel et al. (1997) identified the pressure effect on the stability of bubbly flows in a nitrogen-water system based on the stability theory of Batchelor (1988) and Lammers and Biesheuvel (1996). Higher gas density is found to have a stabilizing effect on the flow and that the gas fraction at the instability point (i.e., transition point) increases with gas density, while the gas velocity at the instability point only slightly increases with gas density. Using the standard deviation of the pressure fluctuation and the drift flux model, the flow transition from the homogeneous bubble flow regime to the churn-turbulent flow regime in a nitrogen-Paratherm NF heat transfer fluid system was investigated over a wide range of operating conditions (e.g., pressures up to 15.2 MPa and temperatures up to 78°C) (Lin et
The transition velocity is higher at higher system pressures and/or temperatures.

The pressure effect on the flow regime transition is mainly due to the change in bubble characteristics, such as bubble size and bubble size distribution. Under high pressure conditions, bubble coalescence is suppressed and bubble breakup is enhanced. Also, the distributor tends to generate smaller bubbles. All these factors contribute to small bubble sizes and narrow bubble size distributions and, consequently, delay the flow regime transition at high pressures. Based on the drift flux of gas, Luo et al., (1997a) identified the transition velocity in a three-phase fluidized bed system. The drift flux of gas increases with the gas holdup in the dispersed regime; in the coalesced bubble regime, the rate of increase is much larger. As the pressure increases, the transition gas velocity and the gas holdup at the transition point increase. The pressure effect on the regime transition is significant at low pressures, but the effect levels off at a pressure around 6 MPa. The transition velocity increases with liquid velocity and slightly increases with particle size, similar to the regime transition behavior at ambient conditions. The addition of fine particles to the liquid phase promotes bubble coalescence, and thus accelerates the transition to the churn-turbulent regime (Clark, 1990).

As shown in above, although plenty of efforts have been in the last several decades, little is known about the hydrodynamics in the high pressure bubble column systems. This is due to the limitation of the measurement methods. In this study, the hydrodynamics, including the liquid flow field, the turbulence properties in the liquid
phase are studied in a high pressure bubble column. Furthermore, the transient velocity is also investigated.
3.2 EXPERIMENTAL

The hydrodynamics of a high pressure bubble columns are investigated using a high-pressure and high-temperature multiphase flow and visualization system developed at the Ohio State University. The schematic of the high pressure and high temperature multiphase flow and visualization system is shown in Fig. 3.1. The system has two test columns of different scales. One of the columns has an inner diameter of 50.8 mm and a height of 1.0 m; the inner diameter and height of the other one are 101.6 mm and 1.37 m, respectively. Figure 3.2 shows a photograph of the 101.6 mm column. This system is comprised of 7 main components: the high-pressure column, a liquid supply tank, a liquid piston pump, a liquid pulsation damper, high-pressure gas cylinders, a gas-liquid separation tank, and pressure and temperature control systems.

The liquid in the supply tank and the gas from cylinders are preheated to a desired operating temperature before they are introduced in the column. The gas entering at the bottom of the column via a sparger mixes with the liquid in the plenum section. Then, the mixture is introduced into the bed through a distributor. A perforated plate with 120 square pitched holes of diameter 1.5mm diameter is used as the distributor. The cylindrical stainless steel column is 1.38m in height and 0.102m in ID, consisting of three sections, i.e., the plenum (0.18m), test (0.9m) and disengagement (0.3m) sections. The expansion section has a larger inner diameter (152.4 mm) to minimize the entrainment of the liquid by the gas streams. The height of this section is sufficient to ensure complete separation of solids from the gas-liquid mixture. For the same purpose, the gas-liquid stream passes through a copper screen with various opening sizes, depending on the particle size, prior
to entering the gas-liquid outlet. Another feature of this section is a port for particle feeding and access to the bed. The fairly large diameter of the port allows for both the feeding of particles and the insertion of probes for various kinds of measurement.

Three pairs of quartz windows are installed on both the front and rear sides of the column allowing the direct visualization to be carried out. Each window is 12.7 mm wide and 92 mm long. In addition, seven pressure ports are drilled in the column wall for pressure and temperature measurements as well as the insertion of probes.

The system can be operated at a pressure up to 21 MPa and a temperature up to 250°C. The inlet gas pressure is regulated by a two-stage regulator, and the flow rate is controlled by a flow control valve and measured by a mass flow meter. The system pressure is controlled by a back pressure regulator located at the outlet of the column. At the top of the column, a copper screen is installed to prevent particle entrainment.

In this study, instantaneous and averaged velocity (vertical and horizontal), and the Reynolds stresses (normal and shear) are obtained using the LDV technique.
3.3 RESULTS AND DISCUSSION

Figure 3.3 shows the experimental results of liquid velocities obtained from both the 1-D and 2-D measurement modes under ambient condition. It is found that the flow structure in bubble columns is axisymmetric. The repeatability of measurements is also shown in Fig. 3.3 and the results are reproducible.

Figure 3.4 shows the comparison of LDV measurement with literature data reported by Chen et al. (1999). It is found that the results from the LDV measurement agree well with those obtained using different measurement techniques.

3.3.1 Effect of Gas Velocity on Liquid Axial Velocity

Figure 3.5 shows liquid axial velocity profiles measured under ambient conditions at different gas velocities. It is shown that the liquid axial velocity increases with increasing superficial gas velocity in the central region of the bubble column. The velocity profile becomes steeper at higher gas velocities. There is gross liquid circulation in the column, and the reverse of liquid flow occurs at the point where \( r/R = 0.7 \), which matches with other literature studies.

3.3.2 Transition of Flow Regime

Figure 3.6 shows the effect of gas velocity on the axial liquid velocity at the column center. The axial liquid velocity at the center point increases with an increase in the superficial gas velocity, however, the increase rate varies with gas velocity. At low gas velocities, the central liquid velocity increases quickly with superficial gas velocity. When the gas velocity exceeds a certain value (i.e., about 4.8 cm/s in this study), the
The increase rate of center liquid velocity with gas velocity becomes smaller. The point that the increase rate suddenly changes can be defined as the flow regime transition point.

In order to further verify the transition point identified based on the liquid velocity measurement, the gas holdup is also measured using a pressure transducer, and the drift-flux method is used to identify the regime transition.

Figure 3.7 shows the gas holdup data in the 2-inch column under ambient conditions and Fig. 3.8 shows the relation between the drift-flux and the gas holdup. The transition velocity obtained based on the drift-flux method is about 5.8 cm/s as shown in Fig. 3.7, which agrees with the results obtained from our LDV measurements and the findings in most literature studies in the range of 4.0 ~ 6.0 cm/s (Yamashita and Inoue, 1975; Drahos et al., 1992; Hyndman and Guy, 1995; Bakshi et al., 1995).

3.3.3 Effect of Pressure on Axial Velocity

Figures 3.9 and 3.10 show the comparison of liquid axial velocity profiles measured under ambient condition and 1.5 MPa condition. The superficial gas velocities is 3.2 cm/s and 7.6 cm/s respectively. It is shown that the liquid axial velocity decreases with increasing pressure in the central region of the bubble column. This occurs because the bubble size and bubble rise velocity decrease with an increase in pressure (Luo et al., 1999). Therefore, the liquid axial velocity decreases with the increase of the operating pressure.

3.3.4 Transition of Flow Regime under High Pressure Condition

Axial liquid velocities at the column center at different gas velocities are also
measured under 1.5 MPa condition for the identification of the transition of flow regime.
The results are shown in Fig. 3.11. It is shown that the axial liquid velocity at the center point increases with an increase in the superficial gas velocity, however, the increase rate varies with gas velocity. Unlike the ambient case, the center liquid velocity increases slowly with increasing gas velocity at low gas velocities. When the gas velocity exceeds a certain value (i.e., about 8.2 cm/s in this study), the increase rate of center liquid velocity with gas velocity becomes larger. It is due to the fact that at lower superficial gas velocities, the bubble column is in bubbling regime, bubble size is smaller and more uniform, and the gas holdup is more uniform, so the increase of superficial gas velocity will not affect the liquid axial velocity too much. While at higher superficial gas velocities, the bubble column is in bubble coalescence region, bubble sizes are much larger and bubble size distribution are wide, also the gas holdup at the center region is much larger than that at the wall region, so there are internal circulation in the bubble column, and the effect of superficial gas velocity on the liquid axial velocity is greater.

Compared with the transition point under ambient condition (about 4.6 cm/s), the transition superficial gas velocity is much higher under 1.5 MPa condition. It is because that the pressure reduces the size of bubbles at the same superficial gas velocity then delay the occurrence of flow regime transition.

3.3.5 Reynolds Stresses

Figure 3.12 shows the profile of normal stresses and shear stress under ambient condition. As shown in the figure, the Reynolds normal stresses are an order of magnitude larger than the Reynolds shear stress.
The radial variation of the normal stresses can be explained by considering the swirling motion of the central bubble stream. In the bubble column system, with different gas velocities, there are three different flow regimes: dispersed bubble flow regime, the vortical-spiral flow regime and turbulent flow regime (Chen and Fan, 1992). When the bubble column is operated in vortical-spiral flow regime, there are four flow regions as shown in Fig. 3.13. The four flow regions of the macroscopic flow structure are the descending flow region, the vortical-spiral flow region, the fast bubble flow region and the central plume region (Chen et al., 1994). The fast bubble flow region was referred as the central bubble stream and it is characterized by significant coalescence and breakup of bubbles that move upward in a spiral manner at a high interstitial velocity. So, with the effect of rising bubbles, in the center of the column, the flow is more frequently upward, whereas in the vortical region, the flow dynamically changes from upward to downward depending on the location of the central bubble stream. The flow in this region, therefore, experiences large fluctuations in the axial component of the liquid velocity, leading $\langle v'v' \rangle$ to peak closer to the center of vortical structures rather than in the center where the motion is primarily directed upward. The swirling motion of the central bubble stream also leads to the peak in $\langle u'u' \rangle$ in the central region of the column, since the horizontal velocity attains its highest magnitude in the center while the rather uniform downflow or upflow closer to the wall regions does not contribute as significantly to the radial fluctuations.
3.3.6 Effect of the Gas Velocity

Figure 3.14 shows the effect of gas velocity on the Reynolds axial normal stress under ambient condition. The Reynolds axial normal stress increases with increasing gas velocity because an increase in gas velocity enhances the swirling motion of the central bubble stream, and thus the Reynolds normal stress.

3.3.7 Effect of Pressure on the Axial Normal Stress

Figure 3.15 shows the effect of pressure on the axial normal stress. The pressure effect is significant and the stress decreases as the pressure increases. Bubble size plays an important role in determining the fluctuations of the liquid phase. The mean bubble size becomes smaller and the bubble size distribution as well as the velocity distribution becomes narrower at higher pressures, therefore, the fluctuations of the liquid phase induced by rising bubbles are reduced.

3.3.8 Liquid Velocity Profiles at Different Axial Positions

Liquid velocity profiles are measured at different axial positions at an elevated pressure (1.5 MPa). The axial positions for the measurements are 40 mm, 120 mm, 220 mm, 280 mm and 420 mm above the distributor. The height of the liquid is 650 mm. The results are shown in Fig. 3.16.

As shown in Fig. 3.16, in the entrance region (e.g., 40 mm above the gas distributor), the liquid axial velocity is low and the profile is flat. In the region near the distributor, the liquid has not been fully accelerated by the rising bubbles. The bubble size is small and the bubble size distribution is uniform in this region. With the increase
in the axial height, small bubbles coalesce to form larger bubbles, and the acceleration of liquid by rising bubbles is pronounced. The flow structure is developing. In this developing region (about 120 mm above the distributor), the liquid velocity profiles are steeper and the internal circulation of the liquid is observed. When the flow structure is developed (220 mm above the distributor), the processes of bubble coalescence and break-up reach equilibrium state, and the liquid velocity profiles are stable in this region. In this work, the flow structure is fully developed when the axial position is about 220 mm above the distributor corresponding to a height-to-diameter ratio of 4.4.

3.3.9 Flow Fields in Churn-turbulent Regime

The profiles of axial liquid velocity are also measured in the churn-turbulent flow regime. Figure 3.17 shows the axial liquid velocity profiles at superficial gas velocities of 14.7 cm/s and 20.2 cm/s. Much stronger internal circulation can be seen in the churn-turbulent flow regime (e.g., \( U_g = 14.7 \) cm/s), compared to the homogeneous bubbling regime and the transition regime. When the gas velocity is further increased, the laser beams cannot penetrate to the column center, and the data rate is not high enough to obtain accurate values of liquid velocity in the central region. Therefore, only the liquid velocities in the wall region are presented in Fig. 3.17 for high gas velocity conditions (e.g., \( U_g = 20.2 \) cm/s).

Figure 3.18 shows the axial and tangential Reynolds normal stresses at a superficial gas velocity of 14.7 cm/s. In the churn-turbulent flow regime, the turbulent fluctuation is much stronger than that in the homogeneous bubbling and transition regimes.
3.3.10 Effect of Liquid Properties on the Flow Structure

To study the effect of liquid properties on the flow structure in a bubble column, Norpar 15 is used as the liquid phase in this work. Some important physical properties of Norpar 15 are listed in Table 3.1. Norpar 15 is an inviscid liquid like water but a little lighter, and the surface tension between air-water is much higher than that between air-Norpar 15.

Figure 3.19 shows the comparison of liquid velocity profiles of air-Norpar 15 and air-water systems under 0.1 MPa and 1.5 MPa, the gas velocity, \( U_g \), is 3.2 cm/s. In both pressure conditions, the velocity profile of air-Norpar 15 system is flatter than that of air-water system. The liquid axial velocity at the center of the column in the air-water system is about 20 % greater than that in the air-Norpar 15 system. Compared with air-water system, the surface tension between the air-Norpar 15 is much lower, so the bubble size in the air-Norpar 15 system is smaller than that in air-water system under the same pressure and gas velocity conditions. Bubble rising velocities are also lower and the large-scale liquid internal circulation is not as strong as in air-water system. The velocity profiles are steeper with the increase of surface tension between gas-liquid interfaces.

Figure 3.20(a) shows the axial Reynolds normal stresses calculated from LDV measurements at 1.5 MPa, while the gas velocities were at 2.3, 4.0 and 7.6 cm/s, respectively. Compared with the increase in air-water system shown in Fig. 3.20(b) (the Reynolds stress increases 100 % when the gas velocity increases from 2.3 cm/s to 7.6 cm/s), the increase in Reynolds stress in air-Norpar 15 system under the same condition is only about 50 %. It is because of that in the air-water case, the bubble column is
operated in the transition regime when gas velocity is 7.6 cm/s. Larger rising bubbles induce stronger fluctuations of the liquid phase. In air-Norpar 15 system, the increase of the bubble size while varying the gas velocity from 2.3 cm/s to 7.6 cm/s is less significant (both in bubbly flow regime), so the increase in the Reynolds stress in the liquid phase is also not as significant as in air-water system.

The comparison of the Reynolds normal stress profiles between air-water and air-Norpar 15 systems is shown in Fig. 3.21. The pressure is 1.5 MPa and $U_g = 7.6$ cm/s. It is shown that at the same condition, the turbulence intensity in air-water system is about 30 % greater than that in air-Norpar 15 system. It is because the surface tension in air-Norpar 15 system is smaller than that in air-water system. As a result, the bubble size in air-Norpar 15 system is smaller and this leads to weaker turbulence in the liquid phase.
3.4 CONCLUDING REMARKS

Hydrodynamics including flow field and Reynolds stresses is investigated using an LDV in a bubble column. The axial liquid velocity profiles at different gas velocities under ambient conditions for the air-water system are measured. A transition between the regimes is identified based on the liquid velocity measurements, and the transition superficial gas velocity is obtained as about 4~6 cm/s in the air-water system. The axial liquid velocity profiles at different gas velocities and pressures for the air-water system are probed. The Reynolds normal and shear stresses are calculated under different conditions for pressures up to 1.5 MPa. Reynolds normal stress is about an order of magnitude higher than the Reynolds shear stress, and it decreases with increasing pressure. The development of liquid velocity profiles along the axial direction is examined by the measurements of liquid velocity profiles at different axial positions above the distributor. The flow structure is fully developed when the axial position is about 220mm above the distributor corresponding to a height-to diameter ratio of 4.4. Liquid velocities in the wall region at high gas velocities are reported, the superficial gas velocity is up to 20.2 cm/s. Norpar 15 is also used as liquid phase and the effects of the change in the liquid properties on the flow structure are examined. The stable bubble size, which is determined by the surface tension in a bubble column has significant effect on the flow structure.
Table 3.1. Comparison of physical properties between Norpar 15 and water

<table>
<thead>
<tr>
<th></th>
<th>Norpar 15</th>
<th>Water</th>
</tr>
</thead>
<tbody>
<tr>
<td>Density, kg/m³</td>
<td>773</td>
<td>999</td>
</tr>
<tr>
<td>Viscosity, cp (25°C)</td>
<td>2.53</td>
<td>0.862</td>
</tr>
<tr>
<td>Surface tension, mN/m</td>
<td>28.9</td>
<td>72.75</td>
</tr>
</tbody>
</table>
Figure 3.1 Schematic of the high-pressure and high-temperature multiphase flow and visualization system.
Figure 3.2 Photograph of the 101.6 mm bubble column
Figure 3.3 Comparison of the liquid velocities measured by the 1-D and 2-D measurement modes (P=0.1 MPa, Dc=5.1 cm, U_g=2.5 cm/s).
Figure 3.4 Comparison of LDV measurement with literature data (P=0.1 MPa, \( U_g = 1.9 \) cm/s).
Figure 3.5 Axial liquid velocity profiles under ambient conditions in the 2-inch bubble column.
Figure 3.6 Effect of gas velocity on the axial liquid velocity at column center.
Figure 3.7 Effect of superficial gas velocity on the gas hold-up in the 2-inch bubble column ($U_{g,\text{tran}} = 5.8$ cm/s).
Figure 3.8 Identification of flow regime transition based on drift-flux method
Figure 3.9 Comparison of Liquid Velocity Profiles, $U_g = 3.2$ cm/s.
Figure 3.10 Comparison of Liquid Velocity Profiles, $U_g = 7.6$ cm/s.
Figure 3.11 Effect of superficial gas velocity on the liquid axial velocity at the center of the 2-inch bubble column (P = 1.5 MPa and U_{g,tran} = 8.2 cm/s).
Figure 3.12 Reynolds stresses profiles, (Ambient pressure, \( U_g = 2.3 \text{ cm/s} \)).
Figure 3.13 Macroscopic flow structure of the vortical-spiral flow condition in a three-dimensional gas-liquid-solid system.
Figure 3.14 The effect of superficial velocity on Reynolds normal stress at ambient pressure.
Figure 3.15 Effect of pressure on the Reynolds normal stress, \((U_g = 2.3 \text{ cm/s})\).
Figure 3.16 Liquid velocity profiles at different axial positions (P = 1.5 MPa, $U_g = 3.2$ cm/s).
Figure 3.17 Liquid velocity profiles at high gas velocities ($P = 1.5$ MPa, $H/D = 8.4$).

Liquid Velocity, cm/s

- $U_g = 14.7$ cm/s
- $U_g = 20.2$ cm/s

$r/R$
Figure 3.18 Reynolds normal stresses at high gas velocities ($P = 1.5$ MPa, $U_g = 14.7$ cm/s).
Figure 3.19 Liquid axial velocity profiles, $U_g = 3.2$ cm/s.
(a) Reynolds stress profiles in air-Norpar system

(b) Reynolds stress profiles in air-water system

Figure 3.20 Reynolds stress profiles, P = 1.5 MPa.
Figure 3.21 Reynolds normal stress profiles, \( P = 1.5 \) MPa, \( U_g = 7.6 \) cm/s.
CHAPTER 4

TURBULENCE ENERGY DISTRIBUTION IN BUBBLING GAS-LIQUID FLOW SYSTEMS

SUMMARY: The turbulence energy distributions in the gas-liquid bubble column system are investigated using the LDV and the PIV. The superficial gas velocity employed ranges from 0.025 to 7.5 cm/s, covering such bubble flow conditions as single-bubble chain, bubbly flow and churn-turbulent flow. Turbulence induced by rising bubbles through bubble wakes is also examined. The energy containing ranges for the bubble-induced turbulence and the shear-induced turbulence are determined from the liquid phase power spectra. Experimental results indicate that the bubble-induced turbulence dominates over the liquid shear-induced turbulence in turbulence generation under the operating conditions of this study. The development of the flow field and the turbulence
energy of the liquid phase in the nozzle region are probed. Furthermore, a self-similarity phenomenon is observed in a two-phase flow system. The analysis of power spectra indicates that the bubble-induced turbulence includes the turbulence from eddies in the bubble wake and that from the drift velocity change due to rising bubbles. The interaction between two turbulence fields is studied with a two-orifice gas distributor. The interaction can only be observed when the turbulence in both fields is strong and the interaction tends to enhance the turbulence in both fields.
4.1 INTRODUCTION

Bubble columns and gas-liquid-solid fluidization systems are multiphase contactors to which a gas or a mixture of gases is introduced and rises in a form of bubbles through a continuous liquid phase. Because of their good heat and mass transfer characteristics, bubble columns and gas-liquid-solid fluidization systems are widely used in industry for chemical, biochemical and petrochemical processing (Fan, 1989). The hydrodynamics of gas-liquid and gas-liquid-solid systems have been extensively studied over the past few decades (Chen et al., 1999). However, there is a lack of detailed physical understanding and predictive tools for design and optimization of such systems. In recent years, the computational fluid dynamics (CFD) have become a viable technique for process simulation. Further understanding of the hydrodynamic phenomena, especially turbulence properties in these systems are necessary in order to establish a better closure relationship for CFD models. With advances in measurement techniques, local and global flow properties, such as phase hold-up, velocity field of phases and flow structures can now be quantified. These techniques include computer automated radioactive particle tracking (CARPT) (Devanathan et al., 1990; Chen et al., 1999), hot-film anemometry (HFA) (Franz et al., 1984; Boerner et al., 1984), particle image velocimetry (PIV) (Chen and Fan, 1992; Reese et al., 1993; Chen et al., 1994), laser doppler velocimetry (LDV) (Franz et al., 1984; Boerner et al., 1984; Lance and Bataille, 1991; Mudde et al., 1997b; Lee et al., 2001) and electrical capacitance tomography (ECT) (Warsito and Fan, 2001a, 2001b).
In gas-liquid and gas-liquid-solid flow systems, turbulence plays an important role in multiphase mass transfer, heat transfer and mixing. Turbulence is a multi-scale phenomenon, in which the large-scale motion of the fluid is inherently intertwined with the small-scale motion of the fluid through complex, chaotic processes involving vortex stretching. A comprehensive understanding of the variation of the broad spectrum of spatial and temporal scales on turbulence is thus necessary in order to properly simulate or control the turbulent flow. Rising bubbles induce liquid turbulence. The studies of the turbulence properties due to the rising bubble, its wakes, and the presence of solids are of importance to the fundamental characterization of the transport behavior of bubble columns and fluidized bed systems.

Turbulence can be characterized by its fluctuating properties. Sato et al. (1981a, 1981b) subdivided the eddy diffusivity of the liquid phase into two components to express the turbulent structure in a bubbly flow. One component is the inherent liquid turbulence (shear-induced turbulence) independent of relative motion of bubbles and the other is the additional turbulence caused by bubble agitation (bubble-induced turbulence). A theoretical model based on the subdivision was used to predict the momentum and heat transfer process in a channel flow. Chen et al. (1994) studied the instantaneous flow structure of a three-dimensional gas-liquid-solid fluidized bed using the PIV technique. Lance and Bataille (1991) investigated bubble-induced turbulence and shear-induced turbulence in an air-water flow with a very low void fraction (0~5 %) using hot-film and LDA techniques. The turbulence induced by bubbles and generated with a grid in a 1.2 m/s liquid flow was compared. Their results suggested that the turbulent fluctuations produced by the wakes of the bubbles contribute only a small part
of the overall fluctuating kinetic energy in their system. Mudde et al. (1997) studied the hydrodynamics of a two-dimensional bubble column in various flow regimes using the PIV technique. The time series of the flow field was studied. It demonstrated that the flow could be split into a low-frequency contribution due to the vortical structures and a high-frequency fluctuating part. Furthermore, the shear stress in the smaller columns could be related to the averaged vertical velocity profile according to a Boussinesq approximation. Mudde et al. (1997b, 1998) and Groen et al. (1999) used the LDV technique for a bubble column with the gas hold-up ranges up to 25%. The backscatter mode is used in their work with a reasonable data rate obtained. The power spectrum in the liquid phase is also analyzed, and shows a $-5/3$ law for the higher frequencies.

Turbulence properties were studied in a high-pressure bubble column using the LDV technique (2001). The Reynolds shear and normal stresses are analyzed and discussed in relation to large-scale structures present in the bubbly flow. The Reynolds normal stresses are an order of magnitude larger than the Reynolds shear stress in the liquid phase based on their experimental results.

The results of prior studies indicate that bubble-induced turbulence and shear-induced turbulence are two sources of liquid phase turbulence in bubble columns. However, the dominating mechanism of the liquid phase turbulence is still not clear in such bubbly flows. In this study, the PIV and LDV techniques are utilized to obtain the turbulence properties in the liquid phase in a bubble column. The factors governing the liquid phase turbulence in bubbly flows are studied systematically. The source of the liquid phase turbulent energy relative to the location of bubbling is probed.
4.2 EXPERIMENTAL

4.2.1 Measurement Conditions

The experiments are conducted using air and tap water in a 10.2 × 10.2 cm Plexiglas® square column as shown in Fig. 4.1. The height of the column is 150 cm. The liquid phase is operated under a batch condition with the static liquid height of 82.5 cm. A 6 mm I.D. single nozzle is used as the gas distributor. The superficial gas velocities of 0.025, 0.75, 2.25, 4.5, 6.0 and 7.5 cm/s are used, which cover both the bubbly flow and the turbulent flow regimes. The LDV (Laser Doppler Velocimetry) and PIV (Particle Image Velocimetry) are employed for measurement of the velocity field and turbulence energy in the flow system. To study the effect of distributors on the turbulent energy distribution in the distributor region, six gas nozzle/orifice distributors are used in this study. Details of the gas distributors are given in Table 4.3.

4.2.2 Laser Doppler Velocimetry System

A two-dimensional laser Doppler velocimetry system is used in backscatter mode. A 300 mW air-cooled Argon-ion laser and a beam separator are used to generate two pairs of laser beams of wavelengths of 514.5 nm and 480 nm. The light is transmitted through a fiber optic cable and a probe with 25 cm focal-length lens. The configuration yields 48 fringes with fringe spaces of 3.40 and 3.22 μm and measurement volumes of 0.164 × 0.164 × 2.162 mm and 0.156 × 0.156 × 2.05 mm for 514.5 and 480 nm.
wavelength, respectively. The scattered light is collected through the same probe (backscatter mode) and is processed by a signal processor.

Due to the presence of the dispersed phase (particles and gas bubbles), the application of the LDV technique in multiphase flows is limited to a low gas hold-up and a low solids loading condition. Mudde et al. (1998) showed that in backscatter mode with proper seeding, the liquid velocity can be measured in a bubble column system. In this study, experiments are carried out with the gas hold-up up to 20%.

Neutrally buoyant Phiolite particles of 1.02 g/cm$^3$ in density with a size range of 10 ~ 20 $\mu$m are used as liquid tracers. All measurements in this study are sampled between 600 and 2400 seconds. Only the coincident signals of axial and radial components are validated.

The sampling rate is a strong function of the distance between the measurement point and the wall due to the light scattering caused by bubbles. Ohba et al. (1976) showed the ratio between the received intensity with bubbles $I$ and without bubbles $I_0$ in a bubbly flow, as

$$
\frac{I}{I_0} = \exp \left( -\frac{3}{2} \frac{l}{d_b} \varepsilon_g \right)
$$

(4.1)

where $l$ is the distance between wall and measurement point; $d_b$ is bubble diameter; and $\varepsilon_g$ is the gas hold-up.

4.2.3 Particle Image Velocimetry System
The PIV system developed by Chen and Fan (1992) is used to measure the bubble rise velocity in this study. A high-resolution (512 × 480 pixels) and high-framing rate (240 fields per second) CCD (charge-coupled device) equipped with a variable electronic shutter ranging from 1/60 to 1/20000 s is used to record the image from the flow field, and the flow field is illuminated by laser sheeting technique. A 4 W Argon ion laser system is used as the laser source, which is operated in a continuous mode, and a laser sheet of 3 ~ 5 mm thickness is created through the use of a cylindrical lens. A high-capacity (256 MB on-board memory) frame grabber with 40 MHz pixel clock is used to digitize the analog output from the high-resolution/high-framing rate CCD array. The high-framing rate camera is also connected to the high-speed video recorder to store the images.

The image processing occurs in five steps: (1) image acquisition, (2) image enhancement, (3) particle or gas bubble identification and calculation of the centroids, (4) discrimination of the bubble images between the two phases, and (5) matching of the bubbles in three consecutive video fields and calculation of the velocity. The PIV technique utilizes a particle-tracking algorithm to determine the velocity of rising bubbles. Further information regarding the PIV technique is given in Chen et al. (1994).
4.3 RESULTS AND DISCUSSION

4.3.1 Averaged Velocity and Reynolds Stresses

The results from the LDV measurements are time series of instantaneous velocities in the measured phase as shown in Fig. 4.2. The averaged axial and radial velocities are obtained directly from the LDV measurements by ensemble averaging as given by

\[ <u> = \frac{1}{N} \sum_{i=1}^{N} u(i) \]  \hspace{1cm} (4.2)

\[ <v> = \frac{1}{N} \sum_{i=1}^{N} v(i) \]  \hspace{1cm} (4.3)

where \( u \) and \( v \) represent the axial and radial velocities, respectively, and \( N \) is the total number of samples. The averaged properties are denoted by \(<\>\).

The fluctuating components are calculated by Reynolds decomposition as given by

\[ u'(i) = u(i) - <u> \]  \hspace{1cm} (4.4)

\[ v'(i) = v(i) - <v> \]  \hspace{1cm} (4.5)

The Reynolds axial and radial normal stresses and shear stresses are used to quantify the turbulence energy in the liquid phase, and are obtained by

\[ <u'u'> = \frac{1}{N} \sum_{i=1}^{N} [u(i) - <u>]^2 \]  \hspace{1cm} (4.6)

\[ <v'v'> = \frac{1}{N} \sum_{i=1}^{N} [v(i) - <v>]^2 \]  \hspace{1cm} (4.7)
\[ <u'v'> = \frac{1}{N} \sum_{i=1}^{N} \{u(i) - <u>\} \{v(i) - <v>\} \]  

Figure 4.3 shows a radial profile of the averaged axial liquid velocities. The profile shows that the flow is symmetrical and the measurement method has full repeatability.

In the PIV measurements, the bubble rise velocities are calculated by

\[ <u(j)> = \frac{1}{n(j)} \sum_{(x,y) \in \text{strip}(j)} u(x,y) \]  

\[ <v(j)> = \frac{1}{n(j)} \sum_{(x,y) \in \text{strip}(j)} v(x,y) \]

where \{u(x,y), v(x,y)\} is the vector attributed to a particular strip \((x,y)\) when the centroid of the bubble is located in that strip; \(u\) and \(v\) are the axial and radial components of the velocity.

4.3.2 Power Spectra

With the LDV results, the power spectra in both liquid and solid phases are obtained using the FFT (Fast Fourier Transform) technique. Since the arrival times of the velocity samples are statistically random, the sample-and-hold technique is used to obtain the power spectra. The sampled and held signal is an accurate representation of the true velocity when the data density is sufficiently high (Adrian and Yao, 1987). A typical power spectrum in the liquid phase is shown in Fig. 4.4. Similar to that for the single-phase flow, the energy containing range and inertial range can be identified in the power.
spectrum, and the Kolmogorov -5/3 law is obeyed in the inertial range at high frequencies.

4.3.3 Bubble-Induced Turbulence

Bubble-induced turbulence in the bubble wake after the passage of rising bubbles is studied in the bubble column under single bubble chain flow conditions. The superficial gas velocity $U_g$ is 0.025 cm/s, and the bubble formation frequency is 10 Hz. Under this flow condition, rising bubbles pass through the measurement volume that is located at the center of the bubble column, 10 cm above the gas nozzle. The diagram of a rising bubble, bubble wake and the measurement volume is given in Fig. 4.5. The LDV technique is used to obtain the turbulence energy in the bubble wake and main flow while the PIV technique is used to obtain the bubble rise velocity and bubble size.

When a rising bubble passes through the measurement volume, a gap appears in the time series signal in the LDV measurement as shown in Fig. 4.6. The size of bubble can be calculated with $t_b$, the time for a bubble passing through the measurement volume and $u_b$, bubble rise velocity. After the bubble passing, the bubble wake, which rises at the same averaged velocity as the bubble will also pass through the measurement volume. The axial and radial velocities of the liquid in the bubble wakes can be measured. The wake size is determined by $<u_w> = u_b$, where $u_b$ is obtained from the PIV measurements. With the combination of the LDV and PIV results, the averaged wake size can be estimated. The turbulence energy in the bubble wake, in the main flow, and the overall turbulence energy in the liquid phase can also be calculated.

In the analysis of the LDV and PIV results, the following assumptions are made:
1. $\langle u_b \rangle = u_b$.

2. Horizontal movement of bubble wakes can be neglected during the bubble wake passing through the measurement volume due to $\langle u_b \rangle \gg \langle v_b \rangle$.

3. Rising bubbles are of identical properties, i.e., have same bubble rise velocities and same bubble size.

4. Wakes are round or in elliptic shape.

Under the operating condition, bubble rising velocity, $u_b$, is 27.4 cm/s, bubble size is 5.52 mm (from the PIV measurements), 5.34 mm (from the LDV measurements). Liquid velocity in the axial direction is 23.9 cm/s that is much larger than that in the radial direction, 0.6 cm/s. The averaged size of the bubble wake is 6.5 mm, which is of the same magnitude as the rising bubble.

The property for the turbulence energy in single bubble chain conditions is given in Table 4.1. It is seen that the turbulence in the bubble wake is much stronger (more than 200%) than that in the main flow. The ratio of radial to axial turbulence energy ($\langle v'v' \rangle/\langle u'u' \rangle$) is approximately 1, which is much higher than that in the main flow, i.e., 0.54, implying a stronger mixing in bubble wakes than that in the main flow. For the present bubbling flow, the bubble-induced turbulence is dominant compared to the liquid shear-induced turbulence.

With the bubble wake region identified, the liquid phase turbulent energy is calculated for the bubble wake as well as for the main flow. Figure 4.7 shows the turbulent energy in the bubble wake and the overall turbulent energy in the main flow for different bubble sizes. The equivalent bubble diameter, $d_e$, ranges from 3.6 mm to 9 mm corresponding to the bubble Reynolds number for 720 to 1800. It is found that with an
increase in the bubble diameter, both the bubble wake turbulent energy and the overall turbulent energy in the main flow increase. Furthermore, the turbulent energy in the bubble wake is much higher (about 200% at \(d_e = 3.6\ mm\)) than that in the main flow. With an increase in the diameter of a rising bubble, the size of the wake induced by the bubble increases; the turbulent energy in the wake is thus stronger. When the bubble size is sufficiently large (e.g., \(9\ mm\) in the present study), the turbulent energy in the bubble wake becomes equal to that in the main flow. This is due to the fact that when the bubble size in a single bubble chain is sufficiently large, the main flow becomes occupied by the bubble wake region induced by rising bubbles. In a bubble column operated under the turbulent regime, the gas holdup is higher than 20%. Rising bubbles and their wakes occupy a major portion of the bubble column. Therefore, the turbulence in the bubble column operated under the turbulent regime is much higher than that under the bubbly flow regime.

The total turbulence energy profile under single bubble chain conditions is shown in Fig. 4.8, where the total turbulent kinetic energy \(E\) is calculated by

\[
E = \frac{1}{2} \langle U' \cdot U' \rangle = \frac{\langle u' u' \rangle + \langle v' v' \rangle + \langle w' w' \rangle}{2}
\]

where \(U'\) is the fluctuating velocity.

Since the LDV technique used in this study can only measure the velocity in \(x\) and \(y\) directions as shown in Fig. 4.9, the turbulence energy \(\langle w' w' \rangle(x_0, y_0, z_0)\) is taken as \(\langle v' v' \rangle(x_0, z_0, y_0)\), and \(r = (y_0^2 + z_0^2)^{1/2}\), is the distance between the measured point and the axis. Because the flow in the bubble column is axial-symmetric, \(\langle w' w' \rangle(x_0, y_0, z_0) = \langle v' v' \rangle(x_0, z_0, y_0)\).
In Fig. 4.8, the peak of the turbulence energy appears in the central region of the bubble column, where rising bubbles and bubble wakes pass through. The turbulence energy in the wall region is only 10% of that in the central region. Also, the total turbulence energy is only a function of the distance from the axis, \( r \), implying that the wall effect is negligible especially in the central region of the square bubble column.

4.3.4 Bubble Induced Turbulence and Shear Induced Turbulence

To determine the frequency of the bubble-induced and the liquid shear-induced turbulence, power spectra are obtained and analyzed in the central and wall region in a bubble column. To minimize the presence of rising bubbles in the wall region, single bubble chain conditions are employed. The superficial gas velocity is 0.025 cm/s with the measurement point location at 10 cm above the gas nozzle. The diameter of the nozzle is 6 mm. Figure 4.10 shows the power spectra in the central and wall regions in the bubble column. The energy containing range and the inertial range are indicated in the power spectrum plots. The power spectra in the wall region comprise those induced by the liquid shear and by the bubbles as indicated by two marked lines, each with a slope of \(-5/3\). The first slope (to the left hand side of the figure) represents the inertial range of the shear induced turbulence spectra that begin at the frequency of 0.2 Hz. At the frequency lower than 0.2 Hz, it represents the energy containing range of the shear induced turbulence spectra. The shear-induced turbulence is due to the internal liquid circulation. The second slope represents the inertial range of the bubble induced turbulence spectra that begin at the frequency of 10 Hz. At the frequency lower than 10 Hz, it represents the energy containing range of the bubble induced turbulence spectra. In the central region,
only one slope is observed. Its physical implication corresponds to that for the second slope in the wall region spectra described above with the generation of the liquid phase turbulence dominated by bubble flows. It indicates that the shear-induced turbulence has a lower frequency (<0.2 Hz) while the bubble-induced turbulence has a higher frequency (0.2 ~ 10 Hz).

To investigate the contribution of the bubble-induced turbulence and the shear-induced turbulence to the liquid phase turbulent energy, power spectra and turbulent energy are compared as shown in Fig. 4.11 and Table 4.2. The turbulent energy and power spectra are obtained in the bubble column with a two-orifice gas distributor. The operating conditions are given in Table 4.2.

As shown in Fig. 4.11, for case 1 ($U_g = 0.75$ cm/s, $<u'u'>$) and case 2 ($U_g = 0.75$ cm/s, $<v'v'>$), the power spectrum in the high frequency range (> 0.2 Hz) is similar. It indicates that the bubble-induced turbulence in both cases 1 and 2 is similar due to the absence of rising bubbles in the measured region at a lower superficial gas velocity. The difference between two power spectra is found in the low frequency range (< 0.2 Hz), which corresponds to the energy containing range of the shear-induced turbulence. In case 2 and case 3 ($U_g = 6.0$ cm/s, $<v'v'>$), similar power spectra are found in a low frequency range that represents the shear-induced turbulence. In a high frequency range (> 0.2 Hz), a significant difference is observed in the power spectra as shown in Fig. 4.11. It reveals that the bubble-induced turbulence for case 3 is much stronger than that for case 2 due to the presence of rising bubbles in the measured region. The difference of the turbulent energy between case 1 and case 2 is 50 cm$^2$/s$^2$; while the difference in the turbulent energy between case 2 and case 3 is 350 cm$^2$/s$^2$. It indicates that the turbulent
energy at least in an amount of 350 cm$^2$/s$^2$ is induced by rising bubbles, representing more than 65% of the total turbulent energy, for case 3. The liquid phase turbulent energy is dominated by the bubble-induced turbulence in the region with rising bubbles.

To study the anisotropic property details of the bubble-induced turbulence, the Reynolds normal stress is investigated through the re-orientation of the directions the LDV measurement in the bubbly flow. The direction studied varies from horizontal to vertical direction. The Reynolds normal stresses for four different directions are examined as shown in Fig. 4.12. Figure 4.12 shows the liquid phase power spectra obtained with different directions at the same measurement point. The superficial gas velocity is 2.25 cm/s, which is in the bubbly flow regime. It is seen that the power spectra of the turbulent energy increase with the change in the measurement orientation from the horizontal to the vertical direction in both the shear-induced frequency range and the bubble-induced frequency range. Since the Reynolds normal stresses in eddies after the rising bubbles are identical in all directions, the increase of the Reynolds normal stresses in the bubble-induced frequency range indicates that the bubble-induced turbulence includes another component beyond that in eddies of the bubble wake. Specifically, rising bubbles induce turbulence through the drift effect as well as bubble wakes. Since the liquid drift velocity induced by rising bubbles is affected by the direction of the bubble motion, the power spectra of the Reynolds normal stresses or turbulent energy in the bubble-induced frequency range vary with the measurement direction. Further, from the power spectra shown in Fig. 4.12, it is found that the bubble-induced turbulence due to the drift velocity has the same magnitude as that due to eddies in the bubble wake.
To investigate the bubble-induced and the shear-induced turbulence in the non-homogenous regime, power spectra are compared for two superficial gas velocity conditions at two measurement points. The superficial gas velocities are 4.5 and 6.0 cm/s; the measurement points are at the center of the bubble column (50 mm from the wall) and 5 cm above the orifice (25 mm from the wall). A two-orifice gas distributor is used in this measurement.

The power spectra at two measurement points with two superficial gas velocities are shown in Fig. 4.13. At each measurement point, the power spectra in the shear-induced turbulence frequency range are similar under different superficial gas velocities. The difference can only be found in the bubble-induced turbulence frequency range. Because the concentration of rising bubbles is high at a higher superficial gas velocity, the bubble-induced turbulence is also higher at a higher superficial gas velocity. At the point above the orifice, the gas hold-up is higher than that at the center point, and thus the bubble-induced turbulence is also higher. The liquid phase turbulence is dominated by the bubble-induced turbulence in the present operating conditions. Thus, the extent of local gas hold-up is closely associated with the liquid phase turbulence.

4.3.5 Effect of gas distributors on the turbulence field

The effects of the distributor on the initial bubble formation and size, and hence on the hydrodynamics in the column such as gas holdup, flow behavior and regime transition are significant. Studies of the distributor effects in a bubble column have been reported in the literature (Tsuchiya and Naknishi, 1992). However, little is known regarding the effects of distributors on the turbulence properties of the bubble column. To
examine the effect of the gas distributor on the turbulence distribution in the distributor region, different single nozzle and multi-orifice distributors are employed in this study as given in Table 4.3.

The effect of the nozzle diameter on the turbulence properties and the velocity profile in the liquid phase are shown in Fig. 4.14. Two single nozzles with diameter of 6.0 mm and 4.2 mm are used in the measurements. For the larger single nozzle (6.0 mm), it is seen that both the velocity and the turbulent energy are lower in the liquid phase under the identical superficial gas velocity. This is due to the fact that with a larger nozzle, the gas linear velocity at the outlet of the nozzle is smaller for a given gas flow rate. The kinetic energy contained in the gas phase is thus, smaller than that with a smaller nozzle. The energy transfer and the momentum transfer from the gas phase to the liquid phase are also smaller with a larger nozzle, yielding a lower velocity and turbulent energy in the liquid phase. It is also found that with a larger nozzle, the turbulent energy is smaller and the profile is wider. It indicates that a larger nozzle impacts wider in area on the liquid phase, leading to a more uniform velocity distribution and turbulent energy distribution in the distributor region.

To study the effect of the location of the nozzle on the liquid phase turbulence, one or two orifices are used in a two-orifice gas distributor of the study. Liquid velocity profiles and the turbulent energy profiles are obtained with one of the two orifices blocked. When the gas is introduced to both orifices, the gas flow-rate for each orifice is the same as that when only one orifice is used, thus the flow-rate is two times of that with only one orifice used. The liquid velocity profiles and the turbulent energy profiles are
measured. The interaction of turbulence fields generated by the gas from two orifices is probed.

Figure 4.15 shows the velocity profiles and the turbulent energy profiles with one (orifice 1 as shown in Fig. 4.15(a)) or two orifices (orifices 1 and 2 as shown in Fig. 4.15(a)) of a two-orifice gas distributor. The gas volume flow rate for each orifice is 37.5 cm$^3$/s ($U_g = 0.375$ cm/s). When only orifice 1 is used, a large liquid internal circulation in the distributor region is observed as shown in Fig. 4.15 (a). When the second orifice (orifice 2) is introduced, another large liquid internal circulation is observed as shown in Fig. 4.15(a). The liquid flows up in the region above the orifices then flows down in the wall region and the central region. The location of the bubbling has a significant effect on the flow field in the distributor region. The turbulent energy profiles at $h = 3$ cm are shown in Fig. 4.15 (b). When only orifice 1 is used, the turbulent energy shows a symmetric profile in the region above the orifice; there is little effect on the turbulent energy distribution over the other side of the column. When both orifices 1 and 2 are used, a symmetric turbulent energy profile is observed in the column as shown in Fig. 4.15 (b). However, there is little effect of the turbulence field due to gas from orifice 2 on the turbulence field induced by the gas from orifice 1. It indicates that at a low gas flow rate i.e., 37.5 cm$^3$ for each orifice, the interaction between the two turbulence fields is negligible.

The velocity profiles and the turbulent energy profiles with one or two orifices of the two-orifice gas distributor are shown in Fig. 4.16. The gas flow rate for each orifice is 112.5 cm$^3$/s. It is seen that the turbulence in the distributor region is much stronger than that with a lower gas flow rate i.e., 37.5 cm$^3$/s for each orifice, as shown in Fig. 4.15.
Although the distance between two turbulence fields are the same, the interaction between two turbulence fields is distinct. The introduction of the second orifice (orifice 1 as shown in Fig. 4.16(a)) into the system enhanced the turbulent energy in the turbulence field induced by the gas from the first orifice (orifice 2 as shown in Fig. 4.16(a)). For a certain distance, two turbulence fields can interact between each other only when the turbulent energy in the turbulence fields is sufficiently strong. The interaction between the two turbulence fields enhances the turbulent energy in both turbulence fields in bubble column systems. The turbulent energy induced by the rising bubble and the liquid shear in the first turbulence field diffuses and dissipates in the liquid phase. When both orifices are used, the overall turbulent energy in the bulk liquid phase increases compared to that with only one orifice being used. The diffusion and dissipation rate of the turbulence in the turbulence field induced by gas from orifice 2 decreases, and hence the turbulent energy in the turbulence field due to gas from orifice 2 is enhanced due to the balance between the turbulent energy generated and dissipated in the turbulence field. When operated under lower gas flow rate, the decrease in the diffusion and dissipation rate due to the increase in turbulence induced by gas from orifice 1 can be negligible, and hence the interaction between two turbulence fields is not observed.

To study the effect of the distributor on the turbulent energy distribution in the distributor region, the horizontal and vertical Reynolds normal stresses profiles are obtained for different gas distributors as shown in Fig. 4.17. In the distributor region ($h = 10$ cm as shown in Fig. 4.17 (a)), the distributor effect is significant. The Reynolds stresses profiles show a peak in the central region just above the nozzle when the single nozzle distributor is used while the peak is shown between wall and central region just
above the orifice when two-orifice distributor is used. The Reynolds stresses profiles are more uniform for the distributor with more orifices. There is little difference observed between the profiles with multi-orifices and porous plate distributors. The bubble-induced turbulence is dominating in the liquid phase turbulence, so the gas hold-up distribution is the governing factor for the turbulence distribution. Using more orifices, the gas hold-up distribution is more uniform, yielding a more uniform turbulence profile. Also, Fig. 4.17 shows that the vertical Reynolds normal stress is about 2 times higher than the horizontal Reynolds normal stress, indicating that the fluctuation in the vertical direction is dominating compared to that in the horizontal direction in the liquid phase in the bubble column systems. Figure 4.17 (b) shows the Reynolds stresses profiles at \( h = 40 \) cm with the same gas distributors used as the prior measurements. However, no significant difference is observed in both the horizontal and the vertical Reynolds stress profiles for different distributors. The flow field is fully developed and the gas hold-up distributions are more uniform and similar with each other in this region, yielding more similar profiles. The bubble-induced turbulence is uniform in this region due to a uniform gas hold-up. As a result, the maximum turbulent energy appears in the shear layer between up- and down- flows, as shown in Fig. 4.17 (b).

4.3.6 Turbulence Development in Bubble Column

The development of the turbulence energy and flow field of the liquid phase in the nozzle region \((h/d < 10\), where \( h \) is the distance from the nozzle, \( d \) is the diameter of the nozzle) is studied at different operating conditions. The values for \( U_g \) are 0.75, 2.25, 6.0 and 7.5 cm/s, which cover the bubbly flow regime and the churn-turbulent flow
regime. In this region, the liquid phase is accelerated by the gas phase flow. Also, the momentum transfer between two phases occurs in this region.

The radial profiles of the liquid axial velocity and turbulence energy in the nozzle region are shown in Fig. 4.18 and Fig. 4.19, respectively. It is seen that in the nozzle region, both the liquid axial velocity and turbulence energy profiles become flatter with the increase in the distance from the nozzle. The maximum liquid axial velocity and turbulence energy are found at the lowest measured position (1 cm from the nozzle). It implies that the liquid phase is accelerated in a very low region. With the development of the flow, the gas hold-up becomes more uniform.

At a lower superficial gas velocity (0.75 cm/s), both the liquid axial velocity and the turbulence energy at the central region decrease in the lower region (1 ~ 3 cm from the nozzle) and increase in the higher region (3 ~ 5 cm from the nozzle). At a high superficial gas velocity (7.5 cm/s), however, no such phenomenon is found in the nozzle region. The liquid axial velocity and the turbulence energy decrease due to the momentum transfer and energy dissipation in the liquid phase. At a lower superficial gas velocity (0.75 cm/s), liquid is accelerated by rising bubbles in the higher region, and the turbulence energy in the liquid phase is also increased by the wake induced by rising bubbles. While at a higher superficial gas velocity (7.5 cm/s), the loss of the energy in the liquid phase (both the kinetic and the turbulence energy) due to the dissipation cannot be compensated by the bubble wake induced turbulence.

Although the flow field in the nozzle region in a two-phase flow is much more complicated than that in a single-phase flow, a similar phenomenon is observed for these
flows. The self-similarity in the nozzle region in gas-liquid flow is shown in Fig. 4.20. In the figure, \( <u_0> \) is the liquid axial velocity at the center of the bubble column, and \( r_{1/2} \) is the jet’s half-width of the jet, which is defined as (Pope, 2000)

\[
<u(r_{1/2})> = \frac{<u_0>}{2}
\]  

(4.12)

The power spectra in the liquid phase are shown in Fig. 4.21. The superficial gas velocity is 6.0 cm/s, which is in the transition regime. The power spectra in the central region and the near-wall region (3 mm from the wall) are analyzed in a developing gas-liquid flow (10 cm above the nozzle). Similar to that in the single bubble chain condition, energy containing range and inertial range are found in the power spectra. Also, the Kolmogorov –5/3 law is obeyed in the inertial range. Compared with the power spectra in single bubble chain condition, the transition from the energy containing range to the inertial range occurs at a lower frequency (8 Hz) in the central region. The transition frequency is the frequency of the smallest eddies induced by a rising bubble. The decrease of the transition frequency at a higher superficial gas velocity implies the increase of the smallest bubble size. Another transition from the energy containing range to the inertial range is found in the power spectrum of the near-wall region at 10 Hz because smaller bubbles (compared with smallest bubbles in the central region) can induce smaller eddies in the near-wall region.

The effect of the superficial gas velocity on the internal circulation frequency is shown in Fig. 4.22. It is seen that with the increase in the superficial gas velocity, the frequency of the largest eddy (internal liquid circulation) also increases. The length-scale of the largest eddy, \( L \), is equal to the dimension of the bubble column. The increase in the
frequency is due to an increase in the characteristic velocity with an increase in the superficial gas velocity.
4.4 CONCLUDING REMARKS

The LDV and PIV techniques are used to obtain turbulence properties in gas-liquid flow systems. The experiments cover a wide range of the superficial gas velocities varying from the bubbly flow regime to the turbulent flow regime. Bubble-induced turbulence in the liquid phase is studied. Comparing the bubble-induced turbulence and liquid shear-induced turbulence, the bubble-induced turbulence is found to be the dominating factor in the liquid phase turbulence generation under the operating conditions of this study. The Kolmogorov $-5/3$ law is obeyed in the inertial range for the liquid phase. The anisotropic properties of the bubble-induced turbulence are also examined through the re-orientation of the direction of the LDV measurement. The bubble-induced turbulence includes the turbulence in the eddies of the bubble wake as well as the turbulence induced by the drift velocity due to rising bubbles. The interactive behavior between two turbulence fields is also studied. At a given separation distance of the two turbulence fields, the interaction is only observed when the turbulence in each of the fields is sufficiently strong. Furthermore, the interaction between two turbulence fields can enhance the turbulence in both fields.
Table 4.1. Turbulence energy in a single bubble chain for $U_g = 0.025$ cm/s and $h = 100$ mm.

<table>
<thead>
<tr>
<th></th>
<th>In wake</th>
<th>In main flow</th>
<th>Overall</th>
</tr>
</thead>
<tbody>
<tr>
<td>$&lt;u&gt;$, cm/s</td>
<td>31.2</td>
<td>22.2</td>
<td>25.5</td>
</tr>
<tr>
<td>$&lt;u'u'&gt;$, cm$^2$/s$^2$</td>
<td>149.8</td>
<td>66.0</td>
<td>134.4</td>
</tr>
<tr>
<td>$&lt;v'v'&gt;$, cm$^2$/s$^2$</td>
<td>136.9</td>
<td>37.1</td>
<td>93.3</td>
</tr>
<tr>
<td>Case #</td>
<td>$U_g$, cm/s</td>
<td>Energy measured</td>
<td>Turbulent energy, cm$^2$/s$^2$</td>
</tr>
<tr>
<td>-------</td>
<td>------------</td>
<td>----------------</td>
<td>--------------------------</td>
</tr>
<tr>
<td>1</td>
<td>0.75</td>
<td>$&lt;u'u'&gt;$</td>
<td>238.19</td>
</tr>
<tr>
<td>2</td>
<td>0.75</td>
<td>$&lt;v'v'&gt;$</td>
<td>188.48</td>
</tr>
<tr>
<td>3</td>
<td>6.0</td>
<td>$&lt;v'v'&gt;$</td>
<td>541.93</td>
</tr>
</tbody>
</table>

Table 4.2. Operating conditions and turbulent energy of power spectra shown in Fig. 4.11
<table>
<thead>
<tr>
<th></th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>Single nozzle</td>
<td>With nozzle diameters of 6 mm and 4.2 mm</td>
</tr>
<tr>
<td>2-Orifices</td>
<td>With 1 or 2 orifices used, with orifice diameter of 4.2 mm/orifice</td>
</tr>
<tr>
<td>4-Orifices</td>
<td>With 4 orifices used, with orifice diameter of 3 mm/orifice</td>
</tr>
<tr>
<td>Multi-Orifices</td>
<td>With 144 orifices used, with orifice diameter of 0.5 mm/orifice</td>
</tr>
<tr>
<td>Porous plate</td>
<td>With averaged pore diameter of 45 µm</td>
</tr>
</tbody>
</table>

Table 4.3. Gas nozzle/orifice distributor employed in this work.
Figure 4.1 Schematic of experimental setup for the measurement of turbulence in the liquid phase.
Figure 4.2 Typical time series of the liquid velocity measured with the LDV technique.
Figure 4.3 Symmetric liquid flow field and repeatability of LDV measurements for $U_g = 0.75 \text{ cm/s}$ and $h = 100 \text{ mm}$.
Figure 4.4 Typical power spectrum of turbulence in the liquid phase for \( U_g = 0.025 \text{ cm/s} \) and \( h = 20 \text{ mm} \).
Figure 4.5 Diagram of bubble wake measurement in a bubble column.
Figure 4.6 Time series of the liquid velocity in a single bubble chain for $U_g = 0.025$ cm/s and $h = 100$ mm.
Figure 4.7 Bubble induced turbulent energy in single bubble chain at $h = 5$ cm.
Figure 4.8 Total turbulence energy profile under the single bubble chain condition for $U_g = 0.025$ cm/s and $h = 10$ cm.
Figure 4.9 Coordinates for 3-D turbulence energy measurements.
Figure 4.10 Power spectra in the liquid phase in the central and wall regions in a bubble column
Figure 4.11 Contribution of bubble-induced turbulence and shear-induced turbulence in gas-liquid system.
Figure 4.12 Liquid phase turbulence power spectra with different directions.

\[ U_g = 2.25 \, \text{cm/s}, \, h = 5 \, \text{cm}, \, \text{single nozzle used.} \]
Figure 4.13 Comparison of bubble and shear induced turbulent energy in the transitional regime. h = 5 cm, two-orifice distributor.
Figure 4.14 Effects of single nozzle diameters on the flow field. 
(a) velocity profile and (b) turbulent energy profiles at $h = 5$ cm, $U_g = 2.25$ cm/s.
Figure 4.15 Liquid velocity and turbulence profiles with 1 and 2 orifices used.
(a) velocity profiles, (b) turbulence profiles at h = 3 cm, $V_g = 37.5$ cm$^3$/s for each orifice.
Figure 4.16 Liquid velocity and turbulence profiles with 1 and 2 orifices used.  
(a) velocity profiles, (b) turbulence profiles at $h = 3$ cm, $V_g = 112.5$ cm$^3$/s for each orifice.
Figure 4.17 Distributor effects on the liquid phase turbulence.
$U_g = 2.25$ cm/s, (a) $h = 10$ cm and (b) $h = 40$ cm.
Figure 4.18 Axial liquid velocity around the nozzle region for
(a) $U_g = 0.75$ cm/s; (b) $U_g = 7.5$ cm/s.
Figure 4.19 Turbulence energy around the nozzle region for
(a) $U_g = 0.75$ cm/s and (b) $U_g = 7.5$ cm/s.
Figure 4.20 Self-similarity of flow field in the nozzle region for $U_g = 6.0$ cm/s.
Figure 4.21 Power spectra in the liquid phase in the developing region for $U_g = 6.0$ cm/s and $h = 100$ mm.
Figure 4.22 Effect of the superficial gas velocity on the internal liquid circulation.
SUMMARY: The turbulence energy distributions in the gas-liquid bubble column system and the effect of solids on the turbulence are investigated using the LDV and the PIV. The superficial gas velocity employed ranges from 0.025 to 7.5 cm/s, covering such bubble flow conditions as single-bubble chain, bubbly flow and churn-turbulent flow. The analysis of the power spectra in gas, liquid and solid phases indicates that the Kolmogorov $-5/3$ law is obeyed in the inertial range. The presence of solids reduces the transition frequency from the energy containing range to the inertial range. The effect of the solids on the liquid-phase turbulence is complex. It depends on solids properties and flow field around particles. The liquid phase turbulence is enhanced in the presence of particles at high superficial gas velocities while it is attenuated under low superficial gas velocity conditions. A criterion based on the variation of a parameter defined by $U_g( r$
$j/u_{mf}$ is proposed to account for the effect of the solids on the liquid phase turbulence. The prediction based on this criterion matches well with the experimental results.
5.1 INTRODUCTION

Multiphase flow reactor systems, such as bubble column reactors, slurry bubble columns and three-phase fluidized bed reactors, are commonly employed in biochemical, chemical and petrochemical industries (Fan, 1989). These reactor systems provide excellent heat transfer and mixing characteristics and mass transfer rate. Successful applications of these multiphase-flow reactor systems lie in the comprehensive understanding of their complex transport phenomena mechanisms. Major research efforts have been put forth to characterize these mechanisms for the last few decades using various measurement techniques. These techniques include hot-film anemometry (HFA) (Boerner et al., 1984; Franz et al., 1984), particle image velocimetry (PIV) (Chen and Fan, 1992; Chen et al., 1994; Reese et al., 1993), computer automated radioactive particle tracking (CARPT) (Devanathan et al., 1990; Chen et al., 1999), laser doppler velocimetry (LDV) (Boerner et al., 1984; Lance and Bataille, 1991; Mudde et al., 1997; Lee et al., 2001) and electrical capacitance tomography (ECT) (Warsito and Fan, 2001a, 2001b). In recent years, the computational fluid dynamics (CFD) have become a viable means for process simulation of multiphase flow systems. Further understanding of the hydrodynamic phenomena, including turbulence characteristics, is necessary so that a better closure relationship for turbulence can be developed for CFD modeling (Boyer et al., 2002).

The effect of the solid phase on the turbulence in the continuous phase is studied for the two-phase flow, especially for the gas-solid flows. Hetsroni (1989) used particle Reynolds number as a criterion to determine the particle effect on turbulence
suppression. They found that the presence of particles with a low particle Reynolds number tends to suppress the turbulence of the carrier fluid motion, while particles with high particle Reynolds number, larger than about 400, tends to enhance the turbulence of the fluid motion. Gore and Crowe (1989) used a different approach involving the ratio of particle diameter to a turbulent length scale, $d_p/l_e$, as a critical parameter to estimate whether the relative turbulent intensity of carrier phase would increase or decrease with the addition of the second phase when particle-fluid interactions are dominant. Yuan and Michaelides (1992) developed a simplified theory for modification of turbulence intensity due to the existence of particles in dilute gas-solid flows. Energy dissipation due to the acceleration of a particle and flow disturbance resulting from the motion of the particle are compared. The combination of the two effects is used as a criterion for total turbulence modification in their theory.

In summary, although work has been conducted to study the effect of the solid phase on the turbulence characteristics in the continuous phase, most of the studies are confined to two-phase (solid-liquid or gas-solid) systems. To date, little is known regarding the turbulence behavior in the three-phase systems. In this study, the LDV and PIV techniques are utilized to obtain the turbulence properties in the gas, liquid and solid phases. The power spectra in the gas, liquid and solid phases are examined along with the multi-scale turbulence energy distributions and energy transfer from the large scale motion to the small scale motion. The modulation of turbulence due to solid particles in bubbling gas-liquid systems is also discussed.
5.2 EXPERIMENTAL

The experiments are conducted using air and tap water in a 10.2 × 10.2 cm Plexiglas® square column as shown in Fig. 5.1. The height of the column is 150 cm. The liquid phase is operated under a batch condition with the static liquid height of 82.5 cm. Particles used are Acetate particles of 2 mm and 500 µm in diameter and glass beads of 120 µm in diameter. The densities of acetate particles and glass beads are 1250 and 2500 kg/m³, respectively. A 6 mm I.D. single nozzle is used as the gas distributor. The superficial gas velocities of 0.025, 0.75, 2.25, 4.5, 6.0 and 7.5 cm/s are used, which cover both the bubbly flow and the turbulent flow regimes. The LDV (Laser Doppler Velocimetry) and PIV (Particle Image Velocimetry) are employed for measurement of the velocity field and turbulence energy in the flow system.

A Dantec® two-dimensional laser Doppler velocimetry system is used to measure the liquid vertical and horizontal velocities in backscatter mode. The laser system includes a 300 mW air-cooled Argon-ion laser producer and a beam separator that can generate two pairs of laser beams of wavelengths of 514.5 nm and 480 nm. The light is transmitted through a fiber optic cable and an optical probe with 25 cm focal-length lens. The configuration yields 48 fringes with fringe spaces of 3.40 and 3.22 µm. The measurement volumes are 0.164 × 0.164 × 2.162 mm and 0.156 × 0.156 × 2.05 mm for 514.5 and 480 nm wavelength beams, respectively. The scattered light and reflect signal are collected through the same optical probe (backscatter mode) and are processed by a Dantec® 58N70 signal processor. Time series of the liquid phase velocities are obtained.
The employment of the LDV technique in multiphase systems is limited to a lower gas hold-up due to the light scattering effect in the presence of the dispersed phase (Boyer et al., 2002). Mudde et al. (1998) showed that in backscatter mode with proper seeding, the liquid velocity could be measured in a bubble column system with sufficient confidence for gas hold-up up to 25%. In this study, all experiments are carried out with the solids loading of 4 % by volume, and the gas hold-up is up to 20% to ensure the validity of the LDV results and the analysis.

Neutrally buoyant Phiolite particles of 1.02 g/cm$^3$ in density with a size range of 10 ~ 20 µm are used as liquid tracers. All measurements in this study are sampled at a 600 to 2400 second period with different sampling rates. In the measurements, only the coincident signals of the vertical and horizontal components are validated.

The LDV technique is also used to measure the solid phase velocity in a three-phase system without any liquid tracers. The data rate from solid particles varies from 80 to 120 Hz. When liquid tracers are added, the overall data rate (from liquid tracers and solid particles) varies from 800 to 1200 Hz. Due to the order of magnitude difference between two data rates, the overall results are taken as those from the liquid phase.

The sampling rate is a strong function of the distance between the measurement point and the wall. Ohba et al. (1976) showed the ratio between the received intensity with bubbles ($I$) and without bubbles ($I_0$) in a bubbly flow, as

$$\frac{I}{I_0} = \exp\left(-\frac{3}{2} \frac{l}{d_b} \varepsilon_g\right)$$

(5.1)

where $l$ is the distance between wall and measurement point; $d_b$ is bubble diameter; and $\varepsilon_g$ is the gas hold-up in the bubble column. In this work, measurement points are 5 cm
from the wall. The sampling rates in two-phase measurements are up to 1200 Hz and they are up to 800 Hz in three-phase measurements.

The PIV system developed by Chen and Fan (1992) is used to measure the bubble rise velocity and determine the equivalent bubble diameter in this study. A high-resolution (512 × 480 pixels) and high-framing rate (240 fields per second) CCD (charge-coupled device) equipped with a variable electronic shutter ranging from 1/60 to 1/20000 s is used to record the image from the flow field, and the flow field is illuminated by a laser sheeting technique. A 4 W Argon ion laser system is used as the laser source, which is operated in a continuous mode, and a laser sheet of 3 ~ 5 mm thickness is created through the use of a cylindrical lens. A high-capacity (256 MB on-board memory) frame grabber with 40 MHz pixel clock is used to digitize the analog output from the high-resolution/high-framing rate CCD array. The high-framing rate camera is also connected to the high-speed video recorder to store the images.

The image processing occurs in five steps: (1) image acquisition, (2) image enhancement, (3) particle or gas bubble identification and calculation of the centroids, (4) discrimination of the bubble images between the two phases, and (5) matching of the bubbles in three consecutive video fields and calculation of the velocity. The PIV technique utilizes a particle-tracking algorithm to determine the velocity of rising bubbles. Further information regarding the PIV technique is given in Chen et al. (1994).
5.3 RESULTS AND DISCUSSION

Effects of solids on the turbulence in the continuous phase have been reported in the literature for gas-solid and liquid-solid flows (Hetsroni, 1989; Gore and Crowe, 1989; Yuan and Michaelides, 1992). The effect of solids on the turbulence in the continuous phase is complex and depends on the continuous phase properties as well as the solid phase properties. In three-phase fluidized beds, there are gas-liquid, gas-solid and solid-liquid interactions. The effect of particles on the turbulence in the liquid phase depends not only on the particle properties, but also on the superficial gas velocity and the flow field around particles. To study the turbulence modulation in gas-liquid-solid fluidized beds, three different particles with different size are used in this study. Measurements are conducted in the nozzle region and the fully developed region.

The effect of solids on the liquid axial velocity and the turbulence energy in the liquid phase in the nozzle region is shown in Figs. 5.2 and 5.3, respectively. Acetate particles of 500 µm in diameter are used as the solid phase. The superficial gas velocities used are 0.75 cm/s and 7.5 cm/s, with the solid loading of 4% by volume.

At a lower superficial gas velocity (0.75 cm/s in Figs. 5.2 and 5.3), the introduction of particles increases the liquid axial velocity but attenuates the turbulence energy in the liquid phase in the central region. At a higher superficial gas velocity (7.5 cm/s), conversely, the presence of particles decreases the liquid axial velocity but increases the turbulence energy in the liquid phase in the central region.
At lower superficial gas velocities, the gas hold-up in the nozzle region is low. The liquid hold-up is higher at a lower superficial gas velocity compared to a higher $U_g$ condition. Liquid and solid phases cannot be fully agitated by the gas-jet in the nozzle region. The axial velocity of particles is lower than that of the liquid phase (as shown in Fig. 5.2). When the low velocity particles are in contact with liquid, part of the eddy energy is imparted to the particle through the drag. Thus, at a lower $U_g$, the presence of the particles attenuates the turbulence in the liquid phase.

In the nozzle region, the gas-jet is the only energy source for all three phases. At a higher $U_g$, particles can be agitated and accelerated by the gas phase directly due to the high gas hold-up near the nozzle. The particle axial velocity is higher than the liquid axial velocity in this region as shown in Fig. 5.2. When fully accelerated particles disperse in the liquid phase, the liquid phase turbulence is enhanced.

When a two-orifice gas distributor is used in the bubble column, a similar effect is observed in the liquid phase turbulence as shown in Fig. 5.4. Furthermore, the horizontal Reynolds normal stresses increase significantly in the region between two turbulence fields with the presence of solid particles, even at a lower superficial gas velocity condition, indicating a stronger turbulence in this region. This is because at a low superficial gas velocity condition, solid particles cannot be fully agitated. In the central region between the two turbulence fields, the liquid phase velocity is low. Solid particles have a higher horizontal velocity than the liquid phase in this region. When the solid particles disperse in the region, liquid phase turbulence is enhanced. The enhancement in the liquid phase turbulence due to the presence of the solid particles can also enhance the mass transfer and the liquid mixing.
The spectra in the measured phases are useful to the understanding of the turbulence properties in the phase. In order to examine the effect of particles on the liquid phase turbulence, the power spectra are obtained for the gas-liquid system and the gas-liquid-solid system using 500 µm acetate particle and 120 µm glass beads, respectively.

The power spectra in the liquid phase under different operating conditions, in the solid and gas phases are shown in Fig. 5.5. The superficial gas velocity is 7.5 cm/s. The measured point is 5 cm above the nozzle. In the liquid phase power spectrum of the gas-liquid system, the transition from the energy containing range to the inertial range occurs at 7 Hz that is the characteristic frequency of eddies induced by the smallest rising bubbles. In the inertial range at a higher frequency, the Kolmogorov –5/3 law is obeyed. Although bubbles can induce turbulence through bubble wakes, these wakes do not affect the cascade process of turbulence at high frequencies. When large particles (500 µm) are introduced into the system, the turbulence in the liquid phase is enhanced due to the vortex shedding (Hetsroni, 1989) and corresponds to an increase in the energy containing range of the power spectrum.

The low solids loading does not affect bubble size and bubble wake size significantly. The length-scale of eddies induced by the smallest bubble is the same for two-phase and three-phase systems. Entrainment of particles in the eddy decelerates the eddy characteristic velocity. The frequency of bubble-induced eddy is also reduced. Thus, the transition from the energy containing range to the inertial range occurs at a lower frequency (around 1 Hz in the three-phase system) compared to that in the two-phase system.
When smaller particles (120 µm) are used, turbulence in the liquid phase is attenuated in the same manner as that reported by other researchers (Hetsroni, 1989; Gore and Crowe, 1989). A similar phenomenon is observed in the power spectrum. The power is reduced in the energy containing range compared to that for two-phase flows. Again, the decrease of characteristic frequency of transition to the inertial range is observed due to the entrainment of particles in the bubble wakes.

The fluctuation power spectrum for solid particles is also shown in Fig. 5.5. There is no significant difference between the solids power spectrum and the liquid power spectrum under the same operating conditions. Since the gas-jet is the only energy source in the three-phase system, both the turbulence in the liquid phase and the fluctuation in the solid phase have the same turbulence properties.

The turbulence modulation in bubbling gas-liquid-solid flow is studied in the developing region (150 mm above the nozzle) and fully developed region (400 mm above the nozzle). Two different particles, 500 µm and 2 mm acetate particles are used. The superficial gas velocity ranges from 0.75 cm/s to 6.0 cm/s. The effect of solids on the turbulence in the liquid phase in both regions is shown in Figs. 5.6 and 5.7, respectively. In both regions, the presence of 500 µm particles enhances the turbulence in the liquid phase. However, when 2 mm particles are used as the solid phase, liquid phase turbulence is enhanced only at a high superficial gas velocity (6.0 cm/s). Under other operating conditions ($U_g$: 0.75 cm/s ~ 4.5 cm/s), the presence of the solid phase attenuates turbulence in the liquid phase. Differing from that in a two-phase flow, the modulation of
the liquid phase turbulence in a three-phase system is more complicated; it depends on particle properties as well as flow field around particles.

In the three-phase system examined in this work, although gas is the only source of energy, solid particles are fluidized by both the gas and the liquid. To be fluidized, the solid particles must be dragged by the upward flow of the gas and liquid. That is, gas and liquid dissipate energy to the solid phase. When 2 mm particles are used as the solid phase, solids cannot be fluidized solely by the gas phase due to the low superficial gas velocity (0.75 cm/s to 4.5 cm/s). Thus, additional energy is required from the liquid phase for particle fluidization. The turbulence in the liquid phase is thus attenuated.

If the solid phase can be fluidized solely by the gas phase (500 µm particles in all cases or 2 mm particles at high superficial gas velocity condition), no additional energy is required from the liquid. The vortex induced by particles can enhance the turbulence in the liquid phase.

Based on the condition stated above, a criterion is proposed to estimate the turbulence modulation in three-phase systems as given below:

In the gas-solid system, $u_{mf}$ (minimum fluidization velocity) is used to estimate the lowest superficial gas velocity for fluidization. The criterion based on the parameters defined by the ratio of the local gas velocity to the minimum fluidization velocity, $U_g(r)/u_{mf}$ is used to account for the effect of particles on the turbulence in the liquid phase of the three-phase system. If $U_g(r)/u_{mf} < 1$, additional energy is required from the liquid phase to fluidize particles, hence, the turbulence in the liquid phase will be attenuated.
The effect of local gas velocity on the change of liquid-phase turbulence is shown in Fig. 5.8. The local gas hold-up distribution is estimated using Ueyama and Miyauchi’s correlation (Ueyama and Miyauchi, 1979)

\[ \varepsilon_g(r) = \varepsilon > (1 + 2/n)(1 - (r/R)^n) \]  

(5.2)

where \( \varepsilon_g(r) \) is the local gas hold-up, \( \varepsilon \) is the averaged gas hold-up which is obtained through the bed expansion method. \( n \) is a parameter which is obtained by

\[ n = 2188 \Re^{-0.598} \Fr_{g}^{0.146} \Mo_{L}^{-0.004} \]  

(5.3)

where

\[ \Re = \frac{DU_g(\rho_i - \rho_g)}{\mu}, \quad \Fr = \frac{U_g^2}{gD}, \quad \Mo = \frac{g\mu_i^4}{(\rho_i - \rho_g)\sigma_l^3}, \quad \mu \quad \text{and} \quad \sigma_l \quad \text{are viscosity and surface tension of water, respectively.} \]

The local gas velocity is

\[ U_g(r) = \frac{U_g}{\varepsilon_g(r)/\varepsilon} \]  

(5.4)

The minimum fluidization velocity is estimated by Equations (5.5) and (5.6) (Kunii and Levenspiel, 1991)

\[ u_i/u_{mf} = 9.2 \]  

(5.5)

\[ u_i = \sqrt{\frac{4d_p(\rho_i - \rho_g)g}{3\rho_g C_D}} \]  

(5.6)

where \( u_i \) is terminal velocity for particles and \( C_D \) is drag coefficient.

When the local gas velocity is higher than the minimum fluidization velocity of the particle, \( U_g(r)/u_{mf} > 1 \), the turbulence in the liquid phase is enhanced, i.e.,
When the local gas velocity is lower than the minimum fluidization velocity, the turbulence in the liquid phase is dampened by particles. As shown in Fig. 5.8, the critical \( U_g(r)/u_{mf} \) ratio identifies the increasing or decrease in turbulence, but does not provide the extent of the change. The criterion matched well with the experimental results.
5.4 CONCLUDING REMARKS

The LDV and PIV techniques are used to obtain turbulence properties in gas-liquid and gas-liquid-solid flow systems. The experiments cover a wide range of the superficial gas velocities varying from the bubbly flow regime to the turbulent flow regime. The power spectra in the gas, liquid and solid phase are measured. The Kolmogorov –5/3 law is obeyed in the inertial range for the liquid phase. The effect of solid particles on the liquid-phase turbulence is complex and depends on solid properties as well as gas velocity. The liquid phase turbulence is enhanced in the presence of particles at a high gas velocity while it is impeded in the presence of particles at a low gas velocity. A criterion based on the parameter, defined as $U_g(r)/u_{mf}$, can be used to account for the effect of particles on the turbulence in the liquid phase of a three-phase fluidized bed. The prediction based on this criterion matches well with the experimental results.
Figure 5.1. Schematic of experimental setup for the measurement of turbulence in the liquid phase.
Figure 5.2. Effect of solids on the liquid axial velocity in the nozzle region for (a) $U_g = 0.75 \, \text{cm/s}$ and (b) $U_g = 7.5 \, \text{cm/s}$. 
Figure 5.3 Effect of solids on the turbulence energy in the liquid phase in the nozzle region for (a) $U_g = 0.75$ cm/s and (b) $U_g = 7.5$ cm/s.
Figure 5.4 Effect of solids on the liquid phase turbulence with 2-orifice distributor used with $d_p = 500\mu m$, $h = 3cm$, 4% by volume. (a) $U_g = 0.75 \text{ cm/s}$ and (b) $U_g = 6.0 \text{ cm/s}$. 
Figure 5.5 Power spectra in the gas, liquid and solid phases for $U_g = 7.5 \text{ cm/s}$ and $h = 5\text{cm}$. 
Figure 5.6 Effect of solids on the turbulence energy in the liquid phase at \( h = 150 \text{ mm} \) for (a) \( d_p = 500 \mu \text{m} \) and (b) \( d_p = 2 \text{ mm} \).

(Open symbols for \( U_g \) in 3-phase, solid symbols for \( U_g \) in 2-phase)
Figure 5.7 Effect of solids on the turbulence energy in the liquid phase at $h = 400$ mm for (a) $d_p = 500 \mu m$ and (b) $d_p = 2$ mm.
(Open symbols for $U_g$ in 3-phase, solid symbols for $U_g$ in 2-phase)
Figure 5.8 Effect of the local gas velocity on the change of the turbulence energy in the liquid phase.

$\langle u'u' \rangle (s)$: turbulence energy in the liquid phase of a gas-liquid-solid system.
SUMMARY: The behavior of a 6 mm mesobubble in an acoustic standing wave field is examined both experimentally and numerically in this study. The acoustic standing waves at 16 kHz and 20 kHz are generated using two Nickel magnetostrictive transducers located at the top and bottom of the column. Experimental studies of the rise velocity of a mesobubble in the acoustic field indicate an axial wavy rising pattern of the bubble synchronized with that of the standing wave. The bubble rise velocity is significantly lower than that in the absence of an acoustic field. The behavior of bubble volume contraction and expansion can be accounted for by a 3-D direct numerical simulation of the bubble dynamics and flow field based on the compressible N-S equations coupled with the level-set method. The experiments and simulation reveal a consistent value of the ratio of the Bjerknes force to the buoyancy force for a single mesobubble rising in the acoustic field to be at 20-25%.
6.1. INTRODUCTION

In gas-liquid bubble columns and gas-liquid-solid fluidization systems, the gas rises in a form of bubbles through a continuous liquid phase. Due to their favorable heat and mass transfer properties, bubble columns and fluidized bed systems are widely used as reactors for chemical, biochemical and petrochemical operation (Fan, 1989). By inducing liquid agitation or providing gaseous reactants to the liquid medium, bubbles play an important role in gas-liquid or gas-liquid-solid systems. As the characteristics of bubble motion and bubble interfacial dynamics govern the performance of the bubbling systems, the understanding and hence the ability of controlling the bubble motion and interfacial dynamics are important to effective operation of these systems.

Studies have been conducted to control bubbling behavior in a bubble column or a fluidized bed using external force fields. For example, Kwauk et al. (1992) applied a magnetic field to a gas-liquid-solid fluidized bed of ferromagnetic particles and found a longer gas residence time and higher gas-liquid interfacial area. Ellenberger and Krishna (2002), and Krishna and Ellenberger (2002) applied mechanical vibration excitement at low frequencies to a gas-liquid bubble column and observed significantly smaller bubbles generated at the gas nozzle and appreciably higher gas holdup and mass transfer coefficient (up to 400%) in the column. Utilizing the electromagnetic generation of acoustic standing waves at high frequencies in a bubble column, Fan and Cui (2004) identified the increased liquid turbulence and bubble interfacial oscillation as major factors for enhanced gas-liquid mass transfer in the acoustic field aside from increased gas holdups. Effects of ultrasound on small (less than 2mm), spherical bubbles as manifested in bubble trapping and bubble rising and radial oscillations have been
extensively studied experimentally and numerically (e.g., Crum and Eller, 1970; Leighton et al., 1990; Doinikov, 2002; Lohse and Prosperetti, 2003). For example, Yosioka et al. (1955) carried out an experimental study on the bubble motion in a sound field and observed that the bubbles rise in a zigzag pattern. Crum (1975) studied the translational forces on pulsating air bubbles in a stationary sound field. Lauterborn (1976) studied numerically the radial oscillations of a sphere gas bubble in an incompressible viscous liquid in a standing wave field. Watanabe and Kukita (1993) numerically simulated the simultaneous behavior of translational and radial motions of a bubble in an acoustic standing field. Their work was extended by Doinikov (2002) by including the liquid compressibility. The analyses in most of the prior studies were based on Rayleigh-Plesset or Keller equations, which do not consider the bubble shape deformation and the liquid flow effect induced by the standing wave. Recently, Servant et al. (2001) employed the multi-fluid model to compute the spatial-temporal evolution of bubbles in the acoustic field. Nomura and Nishida (2003) used the discrete model to simulate a single bubble rising in an ultrasonic standing wave field. However, the compressible nature of the bubble and liquid phases are not considered in their studies. Clearly, much, remains to be explored with respect to the effect of the acoustic field on the fluid dynamic characteristics of larger bubbles (more than 2mm) with non-spherical shapes in a compressible standing wave medium.

Most acoustic applications for chemical reaction systems are in the ultrasonic frequency range (Ince et al., 2001). Under the high frequency range (5 – 10 MHz), acoustic fields are used for diagnostic purposes. Under the medium frequency range (300 kHz – 2 MHz), acoustic fields are used to yield sonochemical effects in which chemical
reactions are catalyzed via free radical generation under extreme temperatures and pressures through the formation, growth, and collapse of microbubbles formed by cavitation. Under the low frequency range (20 – 100 kHz), ultrasonic fields are used for power ultrasound applications such as cutting and welding.

When a bubble is present in an acoustic standing wave field with pressure variation represented by \( p = P_e \cos kx \sin \omega t \) (Wang and Lee, 1998), the pressure gradient oscillates, leading to bubble volume oscillation. Thus, the bubble oscillation is a forced oscillation due to the pressure gradient oscillation. For a bubble of sizes smaller than the resonant size, the bubble would oscillate in-phase with the acoustic pressure field, while for a bubble of sizes larger than the resonant size, it would oscillate out-of-phase with the acoustic pressure field (Leighton, 1994). The acoustic radiation force, Bjerknes force, on a bubble, \( F_B \), can be obtained by \( F_B = - \nabla \langle V \rho \rangle \) where \( V \) is the volume of the bubble. In the acoustic standing wave field, bubbles smaller than the resonant size, \( R_{res} \), can be trapped at a pressure antinode; while bubbles larger than the resonant size would travel towards pressure nodes (Watanabe and Kukita, 1993; Abe et al., 2002).

To simulate the wave propagation and the bubble motion concurrently, the compressible properties of the liquid and gas phase need to be considered. In treating the interface of a compressible object, Fedkiw et al. (1999) employed the ghost fluid method (GFM) for two-phase compressible flows. In this method, the entropy values of the real fluid in each phase are extrapolated to ghost cells located in the other phase, while the pressure and velocity values of the real fluid are preserved. Thus, each phase in the
multiphase system can be treated by using standard one-phase solvers. Abgrall and Karni (2001) presented a similar simple single fluid method (SFM) for which the state values of the ghost cells are directly obtained by copying the pressure, normal velocity and density from the real cells. Hu and Khoo (2004) proposed an interface interaction method to compute compressible multifluid problem. These methods are coupled with the Euler equations in the simulation.

In this study, the behavior of a mesobubble in an acoustic standing wave field is studied both experimentally and numerically. A 3-D numerical simulation based on the level-set method is conducted to account for the Bjerknes force and the behavior of the volume contraction and expansion of a rising bubble in acoustic standing waves. The interface interaction method is used to determine the interface movement in compressible multi-fluids. The standing wave propagation characteristics are also studied.
6.2. EXPERIMENTAL

The experiments are conducted in a cast acrylic acoustic assisted bubble column as shown in Fig. 6.1. The total height of the bubble column is 80 cm, with an inside diameter of 10.26 cm. The acoustic transducer is mounted at the bottom and/or placed at the top. Gas bubbles are introduced from a 1mm ID nozzle placed at 2 cm above the bottom of the column for single bubble flow conditions and from a porous plate for free bubbling conditions.

The acoustic transducers are made of nickel magnetostrictive oscillator that generates acoustic waves at 16 kHz and 20 kHz. The transducer is silver-brazed to a stainless steel plate of 3.2 mm in thickness and 10 cm in diameter, which vibrates like a diaphragm and transmits the acoustic wave when the transducer is powered. The power ranges up to 600W. While the magnitude of these vibrations is small, i.e., only one or two thousandths of an inch, strong accelerating forces are induced which compress and rarefy the liquid. The pressure fluctuation in the liquid phase due to the acoustic standing wave is measured using a B&K 8103 hydrophone. The sensitivity of the hydrophone is 25.4 \(\mu V/Pa\).

When the acoustic wave is applied to the bubble column system, the system temperature would increase due to acoustic heating. Thus, the present experiments are performed under temperature-controlled conditions as shown in Fig. 6.1. In the temperature-controlled experiments, water cooling coils are jacketed around the column. The effect of the water jacketing on the temperature uniformity in the column can be
assured by monitoring the temperature at various axial and radial locations of the column. For the temperature-controlled experiments, the measured temperature is constant at all locations near and away from the transducers all over the bubble column. Thus, the convective flow induced by the heat effect can be neglected in the measurements. The effect of the acoustic field on the behavior of bubbles is monitored by visualization using a CCD camera with a recording speed of 240 frames/sec.
6.3. BASIC EQUATIONS AND SIMULATION METHODS

6.3.1 Conservation Equations

In the numerical simulation, gas and liquid phases are treated as compressible fluids, the flow is governed by the compressible Navier-Stokes equations given by

$$\frac{\partial \rho}{\partial t} + \nabla \cdot (\rho \mathbf{u}) = 0, \quad (6.1)$$

$$\frac{\partial (\rho \mathbf{u})}{\partial t} + \nabla \cdot (\rho \mathbf{u} \mathbf{u}) = -\nabla p + \nabla \cdot \mathbf{\tau} + \rho g + F_{st}, \quad (6.2)$$

where $\rho$, $\mathbf{u}$, and $p$ denote the density of the fluid, the velocity vector and the pressure, respectively. The viscous stress tensor $\mathbf{\tau}$ is given by

$$\mathbf{\tau} = \mu [\nabla \mathbf{u} + (\nabla \mathbf{u})^T - \frac{2}{3} I \nabla \cdot \mathbf{u}], \quad (6.3)$$

The last term $F_{st}$ on the right side of Eq.(6.2) represents the surface tension. It is calculated as a volume force by the Continuum Surface Model (CSF) (Brackbill et al., 1992):

$$F_{st} = \sigma \kappa(\phi) \delta(\phi) \nabla \phi, \quad (6.4)$$

in which $\sigma$, $\kappa$, $\delta$ and $\phi$ are, the surface tension coefficient, the curvature, a smooth $\delta$ function and the level set function, respectively. The curvature $K(\phi)$ can be estimated as $\nabla \cdot (\nabla \phi / |\nabla \phi|)$.

The fluid densities on the both sides of the interface need to be determined:

$$\rho = \begin{cases} 
\rho_w(p, e), & \phi > 0 \\
\rho_s(p, e), & \phi < 0 
\end{cases} \quad (6.5)$$
where $\rho_w(p, e)$ and $\rho_a(p, e)$ are the equations of state for water and air, respectively.

6.3.2 Equation of State (EOS)

For compressible flows, the fluid density is a function of the pressure and the internal energy. In this study, the following equations of state for gas and liquid phase are employed.

*Gamma Law for Gas*

For bubble, an ideal gas law can be used as EOS:

$$p = \rho RT = (\gamma - 1)\rho e = (\gamma - 1)\rho C_v T,$$

where $R$ is the specific gas constant, $T$ is temperature, and $e$ is the internal energy, $\gamma$ is the ratio of specific heat, and $C_v$ is the specific heat at constant volume.

*HOM Equation of State for Water*

The water phase is modeled with the HOM equation of state (Mader, 1979). The pressure is given by

$$P = \frac{\gamma C_v (T - T_H)}{V} + P_H,$$

and the specific internal energy is given by

$$e = C_v (T - T_H) + e_H,$$

where $P_H$ is the Hugoniot pressure, given by

$$P_H = \frac{C}{V_0 - S(V_0 - V)^2(V_0 - V)},$$

where $S$ is the slope of the Hugoniot curve.
and $e_H$ is the Hugoniot energy, given by

$$e_H = 0.5 \times P_H (V_0 - V).$$  \hfill (6.10)

In these expressions, $V$ is the specific volume ($V = 1/\rho$) and $V_0$ is the initial specific volume ($V_0 = 1/\rho_0$). $C$ and $S$ are constants obtained from the relationship between shock speed and particle speed behind the shock. In this study, the values used are: $C = 1483 \text{ m/s}$, and $S = 2$.

The sound speed, for all equations of state, is expressed by

$$C_s = \sqrt{\left(\frac{\partial P}{\partial \rho}\right)_V + \frac{P}{\rho^2} \left(\frac{\partial P}{\partial e}\right)_\rho}$$  \hfill (6.11)

### 6.3.3 Level-Set Equation

To accurately identify the interface location, the level set method is used to track the gas-liquid interface on the Eulerian grid. The value of the level-set function is defined as negative in the gas region and positive in the liquid region, while the interface $\Gamma$ is simply described as the zero level set of the level-set function $\phi$, i.e.,

$$\Gamma = \{x \mid \phi(x, t) = 0\},$$  \hfill (6.12)

where $x$ represents position vector and $t$ the time. The level-set function has the following form:

$$
\phi(x, t) = \begin{cases} < 0, & x \in \text{gas bubble} \\ 0, & x \in \Gamma \\ > 0, & x \in \text{liquid} \end{cases}
$$  \hfill (6.13)

The motion of interface is represented by the convection of $\phi$:

$$\frac{\partial \phi}{\partial t} + \vec{V} \cdot \nabla \phi = 0$$  \hfill (6.14)
where $\vec{V}$ is the velocity of fluid.

In general the level-set function is initialized as the signed distance to the interface, with the positive distance in water and negative in air. But the level set function $\phi$ may not remain as a distance function at $t > 0$ after being adverted by solving Eq.(6.14) at each time step. Thus, a re-initialization technique is used to keep the level set function approximately remaining as a distance function. This is achieved by solving the steady state solution of the equation (Sussman et al., 1994):

$$\frac{\partial \phi}{\partial \tau} = \text{sign}(\phi)(1 - |\nabla \phi|),$$

(6.15)

where $\tau$ is an artificial time that has the unit of distance, $\Delta$ is the grid size and the sign function is defined as:

$$\text{sign}(\phi) = \begin{cases} 
-1, & \phi < 0 \\
0, & \phi = 0 \\
1, & \phi > 0 
\end{cases}$$

(6.16)

Equation (6.14) needs to be integrated for 3-5 time steps using a time step $\Delta \tau = 0.5 \Delta$. Detailed procedures are given in Chen and Fan (2004).

7.3.4 Treatment of Interface

On the interface interaction method proposed by Hu and Khoo (2004), it is assumed that there is no entropy exchange between the two fluids across the interface. This assumption is applicable to the condition in which the bubble interacts with the standing wave.
Assuming that there are two different fluids at the both sides of the interface in a 3-D problem, the interface interaction in the normal direction to the interface should be considered. For fluid at node L at the gas side near the interface, its state is assumed to be \( L(\rho_l, u_l, p_l) \), as shown in Fig. 6.2. Then, node R at the other side of the interface whose state is given by \( R(\rho_r, u_r, p_r) \) can be found following the same normal direction. With the method of characteristics, the relations between interface normal velocity \( u_{n*} \) and interface pressure \( p^* \) can be obtained as (Hu and Khoo, 2004):

\[
\begin{align*}
    u_{n*} &= u_{l,n}^* - \int_{\rho_l}^{p^*} \frac{dp}{\rho_l c_l}, \\
    u_{n*} &= u_{r,n}^* - \int_{\rho_r}^{p^*} \frac{dp}{\rho_r c_r}, \\
    P^* &= P_l(\rho_{l,j}, s_l) \\
    P^* &= P_r(\rho_{r,j}, s_r)
\end{align*}
\]

(6.17)

where \( c_l, s_l \) and \( c_r, s_r \) are the sound speeds and constant entropies on both sides of the interface, \( \rho_{l,l} \) and \( \rho_{l,r} \) are the densities of the two fluids on both sides of the interface.

For air-water flows with limited change of pressure and velocity across the interface, the integral equations above can be linearized to (Hu and Khoo, 2004)

\[
\begin{align*}
    u_{n*} &= u_{l,n}^* - \frac{P^* - P_l}{\rho_l C_l}, \\
    u_{n*} &= u_{r,n}^* - \frac{P^* - P_r}{\rho_r C_r}.
\end{align*}
\]

(6.18)

Then, the interface normal velocity \( u_{n*} \) and interface pressure \( p^* \) can be calculated directly as
\[ u^* = \frac{\rho_r C_r u_{i,n} + \rho_r C_r u_{r,n} + P_r - P_r}{\rho_r C_r + \rho_r C_r}, \]

(6.19)

\[ p^* = \frac{\rho_r C_r P_r + \rho_r C_r P_r + \rho_r C_r \rho_r C_r (u_{i,n} - u_{r,n})}{\rho_r C_r + \rho_r C_r} \]

Now that with the interface normal velocity and its location known, a correction is then performed by a simple interpolation between the interface and neighboring node (RR node as shown Fig. 6.2) as given by

\[ u_{i,n} = \frac{d_{LL} - d_L (u^*_{n} - u_{i,n}) + u_{i,n}}{d_{LL}}, \]

(6.20)

where \( d_{LL}, d_L \) are the distance from point LL and L to the interface.

At the same time the density \( \rho_L \) at the node L can be obtained by the isentropic EOS, \( \rho_L = \rho_i (p^*, s_i) \). The similar treatment can also be applied to node R.
6.4. RESULT AND DISCUSSION

6.4.1 Experimental Results

To establish an acoustic standing wave in the bubble column, acoustic waves are introduced from the top and the bottom of the column through acoustic transducers. The distance between two transducers is 56.4 cm which is 6 times of the acoustic wavelength \( \lambda = 9.4 \text{ cm at 16 kHz} \). The instantaneous pressure fluctuation and the amplitude of the pressure fluctuation along the axial direction are obtained using a B&K 8103 hydrophone as shown in Fig. 6.3. With an acoustic standing wave frequency of 16 kHz, a sinusoidal pressure signal measured at a given location is given in Fig. 6.3(a). From the instantaneous pressure fluctuation measurement, the pressure fluctuation amplitude can be obtained for a given column location as shown in Fig. 6.3(b). The figure exhibits an acoustic standing wave with the distance between two acoustic nodes of around 4.7 cm, matching well with the half of the standing wavelength for the given acoustic frequency used.

The effect of the superficial gas velocity on the pressure fluctuation in the bubble column is shown in Fig. 6.4. With an increase in the superficial gas velocity, the sound reflection by the increasingly concentrated bubbles increases. As a result, sinusoidal pressure signals are distorted and the amplitudes of the fluctuation reduce. However, the frequency of the fluctuation is still clearly identified to be at 16 kHz.

To study the effect of the acoustic standing wave on the rise characteristics of a single mesobubble of a diameter 6 mm, a single nozzle is used for bubble injection.
Bubble rise velocities under the acoustic field with a pressure amplitude of 15 kPa, 30 kPa are obtained using a high speed CCD camera. The results are compared with the bubble rise velocity in the absence of the acoustic field as shown in Fig. 6.5. The comparison clearly shows a wavy velocity pattern of the rise velocity and a decreased averaged rise velocity with an increase in the amplitude of the standing wave. The effect of the acoustic Bjerknes force is also evidenced which is further elaborated as given below.

In the acoustic bubble column system, a simple force balance can be obtained on a single rising bubble:

\[ ma = F_{\text{Buoyancy}} + F_{\text{Drag}} + F_{\text{Bjerknes}} + F_{\text{Added Mass}}, \quad (6.21) \]

where \( a \) is the acceleration of the bubble, \( u \) is the instantaneous rise velocity of the bubble and forces are obtained by

\[ F_{\text{Buoyancy}} = (\rho_l - \rho_g)gV, \quad (6.22) \]

\[ F_{\text{Drag}} = \frac{1}{2} C_D \rho_l A u^2, \quad (6.23) \]

\[ a = \frac{du}{dt}, \quad (6.24) \]

and \( F_{\text{Added Mass}} = -\frac{1}{2} \rho V \frac{du}{dt}. \quad (6.25) \]

With the assumption of a spherical bubble, \( C_D \) can be taken as \(~1.3\) (Fan and Tsuchiya, 1990). The time averaged Bjerknes force can then be estimated from the bubble rise velocity data obtained experimentally as well as the model equations (Eqs.
The averaged Bjerknes force for \( P_A = 30 \text{ kPa} \) obtained in this manner has the magnitude of 21% of the buoyancy force.

### 6.4.2 Numerical Results

**Standing Wave in Water**

In order to study the behavior of a single bubble in an acoustic standing wave, the characteristics of the standing wave field need to be ascertained first. Therefore the 3-D simulation of an acoustic standing wave between two plane transducers in water is carried out.

Figure 6.6 illustrates the geometric arrangement of the computational domain of the square column. The acoustic field is generated by two transducers located at the bottom and top of the column, respectively. The distance between the transducers is 13.875 cm, 3 times of a half-wavelength. The sound field can be described by the governing equations, Eqs. (6.1)-(6.3), and the equations of state, Eqs. (6.7)-(6.11). Note that the surface tension term is deleted in Eq. (6.2) in this case. The acoustic field is generated under the transducer boundary condition:

\[
 u_0(t) = U_0 \sin(\omega t), \tag{6.26}
\]

where \( \omega \) is the angular frequency and \( U_0 \) is the maximum transducer face velocity. The density and viscosity of water in simulation are 0.998 g/cm\(^3\) and 0.001 Pa·s, respectively.

Figure 6.7 illustrates the simulation results of the velocity and pressure distributions on the center plan of the column for \( U_0 = 2.5 \text{ cm/s} \). It can clearly be seen that a standing wave is formed. There exists a spatial phase shift of \( \lambda/4 \) between the velocity
and pressure. Due to the nonlinear behavior of the resonant wave, there is a temporal shift at pressure nodes such that the pressure node is not always at a fixed point. These results are validated by experiments as shown in Fig. 6.3(b).

The pressure contours on the central cross-section at several moments within one period are shown in Fig. 6.8. The pink color presents the pressure wave compression and the cyan color corresponds to pressure wave rarefaction. Clearly, it is seen that when the pressure at anti-node changes from wave rarefaction to wave compression within one cycle, the pressure at node doesn’t change.

*Spherical Bubble Rising in Standing Wave*

The simulation for a spherical bubble rising in a standing wave is performed in the column as shown in Fig. 6.9. The distance between the two transducers is half wavelength. In computation, at first, an acoustic standing wave field is computed. A spherical air bubble with a diameter of 0.555 cm is then placed at 3.25 cm above the bottom of column. The initial density and viscosity of air bubble are 0.001 g/cm³ and 1.78×10⁻⁵ Pa·s, respectively. The surface tension coefficient is 0.0728 N/m. The transducer velocity amplitude is $U_0=2.0$ cm/s. The other physical properties are the same as those used in the simulation of standing waves in water. A uniform grid size of 0.0231 cm and time step of $5×10^{-8}$ s are used in this simulation.

Figure 6.10 shows a series of the 3-D pressure field at different instances in time during the bubble rise. Comparing to the flow field without bubble at $t = 0.05$ ms, there is a distinct difference in the pressure field between the two. It is noticed that, with an acoustic field, the pressure is distorted in the vicinity of the bubble. Specifically, in the
presence of the bubble, the uniform pressure field is replaced by an axially symmetric pressure distribution, marked by concentric patterns on the cross section area. The formation of these patterns may attribute to the interference between the secondary wave and the primary standing wave. At the instant when the pressure gradient reduces to a small value, it appears that the interactions of the primary and secondary waves with the pressure field induced by bubble flow may prevail yielding a radially varied pressure field given in the figure. Figure 6.11 shows simulation results of pressure fluctuation at two locations axially right above and below the bubble. Due to secondary wave effects on the pressure oscillation, it is seen that there is a slight phase shift between these two locations while the oscillation frequency maintains the same.

A spherical gas bubble subject to pressure field oscillations undergoes volume contraction and expansion due to gas compressibility. This phenomenon is simulated in Fig. 6.12. It is seen that, $R_{\text{dia}}$, the amplitude of radial oscillation at the pressure antinode based on the simulation results is about $2.1 \times 10^{-6}$ m, which is of a value close to $R_{\text{dia}} = 2.5 \times 10^{-6}$ m estimated from Leighton (1994):

$$R_{\text{dia}} = \frac{2P_i}{R_0 \rho} \frac{1}{\sqrt{(\omega^2 - \omega_0^2)^2 + (2\beta_\text{tot} \omega)^2}}. \quad (6.27)$$

As the above equation does not consider the stress effect induced by the liquid flow, the closeness of these two values indicating that such effect is not significant on the bubble volume oscillation in this simulation condition.

The force exerted on the bubble due to pressure gradient in an acoustic field, or the Bjerknes force expressed by $-V(t)\nabla p$ can be calculated from the simulated
magnitudes of the instantaneous bubble radial oscillation and the pressure gradient across the bubble. The calculated instantaneous acoustic force acted on the bubble is shown in Fig. 6.13. Note that this acoustic force illustrated in Fig. 6.13 has been expressed in a ratio to the buoyancy force. The time-averaged Bjerknes force on the bubble can be calculated by:

\[ F_{Bjerknes} = \frac{\int_{t}^{t+\Delta t} (-\nabla p) dt}{t}. \]  

The simulation value based on Eq. (6.28) for the Bjerknes force is of a magnitude of 20-25% of the buoyancy force. This value compares reasonably close to the value obtained experimentally, i.e., 21% of the buoyancy force.
6.5. CONCLUDING REMARKS

The effect of the acoustic standing wave field on the behavior of a 6 mm mesobubble is examined both experimentally and numerically in this study. The acoustic standing waves at 16 kHz and 20 kHz are generated using two Nickel magnetostrictive transducers located at the top and bottom of the column. Experimental studies of the rise velocity of a mesobubble in the acoustic field indicate a wavy pattern of the velocity synchronized with that of the standing wave and the rise velocity is significantly lower than that in the absence of an acoustic field. With the compressibility of the gas and liquid phases, and gas-bubble interface oscillatory behavior properly considered, the standing wave propagation, and bubble volume contraction and expansion can be well accounted for through a 3-D direct numerical simulation based on the compressible N-S equations coupled with the level-set method. The experiments and simulation reveal a consistent value for the ratio of the Bjerknes force to the buoyancy force for a single mesobubble rising in the acoustic field to be at 20-25%. The bubble volume is calculated to oscillate at a magnitude of the volume fraction of 0.05% in the acoustic field of a frequency of 16 kHz and amplitude of 30 kPa. A slight phase change on the pressure oscillation below and above the bubble is observed. At the instant when the pressure gradient reduces to a small value, it appears that the interactions of the primary and the secondary waves with the pressure field induced by bubble flow may prevail yielding a radially varied pressure field.
Figure 6.1. Schematic diagram of the vertical acoustic gas-liquid column
Figure 6.2. Schematic for the numerical treatment of the interface
Figure 6.3. (a) Typical pressure fluctuation signals at a given location, and (b) typical pressure variation at a given time along the column in the acoustic bubble column system (E = 100W)
Figure 6.4. Effect of the superficial gas velocity on the pressure fluctuation in the bubble column
Figure 6.5. Effect of the acoustic standing wave on the bubble rise velocity ($d_b = 6$ mm)
Figure 6.6. Geometric configuration of the column in the simulation
Figure 6.7. Simulation results on the (a) axial velocity distribution, and (b) axial pressure distribution.
Figure 6.8. Pressure contour on the vertical cross-section at several time increments within one period (x10^4 Pa)
Case 1

Water

3.25 cm

4.625 cm

1.4 cm

Figure 6.9. Initial condition of the bubble in the standing wave field in the numerical simulation
Figure 6.10. 3-D pressure contour in the 16 kHz acoustic standing wave field ($10^4$Pa)
Figure 6.11 Simulation result of pressure fluctuation at the locations above and below the bubble in the 16 kHz acoustic standing wave field ($P_A = 30$ kPa)
Figure 6.12. Simulation result of bubble radial oscillation in the 16 kHz acoustic standing wave field ($P_A = 30$ kPa)
Figure 6.13 Simulation result of the acoustic force oscillation in 16 kHz acoustic standing wave field ($P_A = 30$ kPa)
CHAPTER 7

CONCLUSIONS AND RECOMMENDATIONS

A high-pressure and high-temperature three-phase fluidization and visualization system developed at The Ohio State University is employed to investigate hydrodynamics in the high pressure bubble column system. The distribution of the turbulent energy in liquid and solid phases is studied using an LDV system under the ambient conditions. The dominant mechanism of the liquid phase turbulence is discussed systematically. The effect of the solid phase on the liquid phase turbulence is also investigated. Furthermore, the effects of the acoustic standing wave on the bubble behavior in an acoustic gas-liquid bubble column are also studied. In the following, conclusions and recommendations for turbulence properties and liquid flow fields are discussed.

7.1 HYDRODYNAMICS IN HIGH PRESSURE BUBBLE COLUMN

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A further understanding of the hydrodynamics in the high pressure bubble column systems is of importance for designing and the scale-up of the high pressure bubble column reactors in the industry. Therefore, the effect of the pressure on the flow field, the Reynolds stresses and the effect of the liquid properties on the flow structure are studied.

Hydrodynamics including flow field and Reynolds stresses are investigated using an LDV in a high pressure bubble column. The axial liquid velocity profiles at different gas velocities under ambient conditions for the air-water system are measured. The regime transition is identified based on the liquid velocity measurement, and a transition superficial gas velocity at about 4~6 cm/s is found for the air-water system. The axial liquid velocity profiles at different gas velocities and pressures for the air-water system are probed. The regime transition is identified based on the liquid velocity measurement. Reynolds normal and shear stresses are calculated under different conditions for pressures up to 1.5 MPa. Reynolds normal stress is about an order of magnitude higher than the Reynolds shear stress, and it decreases with increasing pressure. The development of liquid velocity profiles along the axial direction is examined by the measurements of liquid velocity profiles at different axial positions above the distributor. The flow structure is fully developed when the axial position is about 220mm above the distributor corresponding to a height-to diameter ratio of 4.4 in this work. Liquid velocities in the wall region at high gas velocities are reported, the superficial gas velocity is up to 20.2 cm/s. Norpar 15 is used as liquid phase and the effect of liquid properties on the flow structure is examined. The stable bubble size, which is determined by the surface tension in the bubble columns, has significant effect on the flow structure.
7.2 LIQUID PHASE TURBULENCE

In gas-liquid and gas-liquid-solid flow systems, turbulence plays an important role in multiphase mass transfer, heat transfer and mixing. A comprehensive understanding of the variation of the broad spectrum of spatial and temporal scales on turbulence is thus necessary in order to properly simulate or control the turbulent flow. The studies of the turbulence properties due to the rising bubble, its wakes, and the presence of solids are of importance to the fundamental characterization of the transport behavior of bubble columns and fluidized bed systems.

The LDV and PIV techniques are used to obtain turbulence properties in gas-liquid flow systems. The experiments cover a wide range of superficial gas velocities, ranging from the bubbly flow regime to the turbulent flow regime. Bubble-induced turbulence in the liquid phase is studied. Comparing the bubble-induced turbulence and liquid shear-induced turbulence, the bubble-induced turbulence is found to be the dominant factor in the liquid phase turbulence generation under the operating conditions of this study. The Kolmogorov $-5/3$ law is obeyed in the inertial range for the liquid phase. The anisotropic properties of the bubble-induced turbulence are also examined through the re-orientation of the direction of the LDV measurement. The bubble-induced turbulence includes the turbulence in the eddies of the bubble wake as well as the turbulence induced by the drift velocity due to rising bubbles. The interactive behavior between two turbulence fields is also studied. At a given separation distance of the two turbulence fields, the interaction is only observed when the turbulence in each of the fields is sufficiently strong. Furthermore, the interaction between two turbulence fields can enhance the turbulence in both fields.
The power spectra in the gas, liquid and solid phase are measured. The Kolmogorov $-5/3$ law is obeyed in the inertial range for the liquid phase. The effect of solid particles on the liquid-phase turbulence is complex and depends on solid properties as well as gas velocity. The liquid phase turbulence is enhanced in the presence of particles at a high gas velocity while it is impeded in the presence of particles at a low gas velocity. A criterion based on the ratio, $U_g( r )/u_{mf}$, can be used to account for the effect of particles on the turbulence in the liquid phase of a three-phase fluidized bed. The prediction based on this criterion matches well with the experimental results.

7.3 ACOUSTIC BUBBLE COLUMN SYSTEMS

The effect of the acoustic standing wave field on the behavior of a 6 mm mesobubble is examined both experimentally and numerically in this study. The acoustic standing waves at 16 kHz and 20 kHz are generated using two Nickel magnetostrictive transducers located at the top and bottom of the column. Experimental studies of the rise velocity of a mesobubble in the acoustic field indicate a wavy pattern of the velocity synchronized with that of the standing wave. The rise velocity is significantly lower than that in the absence of an acoustic field. With the compressibility of the gas and liquid phases, and gas-bubble interface oscillatory behavior properly considered, the standing wave propagation, and bubble volume contraction and expansion can be well accounted for through a 3-D direct numerical simulation based on the compressible N-S equations coupled with the level-set method. The experiments and simulation reveal a consistent value for the ratio of the Bjerknes force to the buoyancy force for a single mesobubble.
rising in the acoustic field to be at 20-25%. The bubble volume is calculated to oscillate at a magnitude of the volume fraction of 0.05% in the acoustic field of a frequency of 16 kHz and amplitude of 30 kPa. A slight phase change on the pressure oscillation below and above the bubble is observed. At the instant when the pressure gradient reduces to a small value, it appears that the interactions of the primary and the secondary waves with the pressure field induced by bubble flow may prevail yielding a radially varied pressure field.

7.4 RECOMMENDATIONS

To date, most high-pressure studies are limited to point measurements or overall behavior study, because it is impossible to move the probes in the radial or axial positions for intrusive measurement techniques when the column is operating at high pressures. It has become apparent that further study is required to quantify the dynamic and overall flow structure in the column. Some non-intrusive techniques such as ECT (Electrical capacitance tomography) have shown their advantages in this aspect. The ECT technique is able to provide the complete profiles of some hydrodynamic variables such as phase holdup and bubble rise velocity in real time or over a short time period. By analyzing these results, the flow structure in the column can be identified and the effect of pressure on the overall flow structure can be examined. Moreover, by analyzing transient signals as well as the LDV results, further turbulence information and dynamic flow behavior can also be obtained.

Another interesting area is in the gas-liquid interface. So far, in the study of the turbulence properties in the bubble columns, rising bubbles are treated as spherical.
However, in the reality, rising bubbles with a diameter larger than 5 mm are always not spherical. Bubbles oscillate with a certain frequency during the rising period. The effect of the movement of the gas-liquid interface should play an important role in the gas-liquid mass transfer and momentum transfer, which induce turbulence in the liquid phase. Experimental approach itself may not provide enough information on these phenomena; however, the combination of the experimental and computational approaches is capable of providing more insight information on these phenomena.

Furthermore, most studies in the bubble column systems are based on air-water system. However, in the real application, some of the fluids used in the reactor are non-Newtonian. The hydrodynamics in gas-liquid systems with different rheological properties will be of importance and interest for designing such chemical reactors especially under the high pressure conditions. The application of the theories and correlations to such non-Newtonian systems will also need to be studied.


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