STUDY OF AIR BUBBLE INJECTION INTO LAMINAR AND TURBULENT WATER FLOW THROUGH AN ANNULAR TEST SECTION

Debrata Das
CUNY City College

How does access to this work benefit you? Let us know!
Follow this and additional works at: http://academicworks.cuny.edu/cc_etds_theses
Part of the Chemical Engineering Commons

Recommended Citation
Das, Debrata, "STUDY OF AIR BUBBLE INJECTION INTO LAMINAR AND TURBULENT WATER FLOW THROUGH AN ANNULAR TEST SECTION" (2012). CUNY Academic Works.
http://academicworks.cuny.edu/cc_etds_theses/85

This Thesis is brought to you for free and open access by the City College of New York at CUNY Academic Works. It has been accepted for inclusion in Master's Theses by an authorized administrator of CUNY Academic Works. For more information, please contact AcademicWorks@cuny.edu.
STUDY OF AIR BUBBLE INJECTION INTO LAMINAR AND TURBULENT WATER FLOW THROUGH AN ANNULAR TEST SECTION

THESIS

Submitted in partial fulfillment of the requirement for the degree

Master of Engineering (Mechanical)

at

The City College of New York
of the

City University of New York

by

Debbrata Das

May, 2012

Approved:

________________________
Professor Masahiro Kawaji, Thesis Advisor

________________________
Professor Feridun Delale, Chairman
Department of Mechanical Engineering
Abstract

Injection of bubbles into a vertical upward flow of water in an annular flow channel was studied experimentally under laminar and turbulent conditions. In order to measure the size and shape of the bubbles, a flow visualization system was set up in a vertical test section with a high speed video camera. A PIV measurement technique was also used to determine laminar and turbulent velocity profiles in the liquid stream. In this study, an efficient image processing methodology was used to obtain the velocity profiles, bubble size, shapes and trajectory at different Reynolds numbers. The measured velocity profiles matched theoretical profiles for single-phase laminar and turbulent flows in an annular channel. The experimental results indicate that air bubble injection from an inner tube into the liquid stream causes large increase in the streamwise and spanwise velocity fluctuations near the inner tube wall for both laminar and turbulent liquid flows. The bubble size, shape, and trajectory data were also obtained for both laminar and turbulent flows. For laminar flow, bubble coalescence was observed to occur. The ensemble-average bubbles trajectory data showed that the bubble follow a similar trajectory in the annular flow channel following their departure from the injection hole.
Acknowledgement

At first I would like to express my appreciation to my advisor Professor Masahiro Kawaji of Mechanical Engineering, at City College of New York who has supported me throughout my thesis research with patience and knowledge and has allowed me the room to work in my own way. I would also like to thank Professor Kazuhiro Itoh, University of Hyogo, Japan, who helped me to understand the basic concept of the experiment. Special thanks go to Randy Samaroo who helped me do experiments and data processing. I would also like to thank Jorge Pulido who helped me to solve some of the experimental setup problems. Finally I would like to thank my school teacher Ardendhu Shakar Das, in Bangladesh, who encouraged me to reach my goal.
# Table of Contents

<table>
<thead>
<tr>
<th>Section</th>
<th>Page no</th>
</tr>
</thead>
<tbody>
<tr>
<td>Abstract</td>
<td>ii</td>
</tr>
<tr>
<td>Acknowledgement</td>
<td>iii</td>
</tr>
<tr>
<td>Table of Contents</td>
<td>iv</td>
</tr>
<tr>
<td>List of Figures</td>
<td>vi</td>
</tr>
<tr>
<td>Nomenclature</td>
<td>viii</td>
</tr>
<tr>
<td>1. Introduction</td>
<td>1</td>
</tr>
<tr>
<td>2. Experimental Set-Up and Procedure</td>
<td>3</td>
</tr>
<tr>
<td>2.1. Basic Experimental Set Up</td>
<td>3</td>
</tr>
<tr>
<td>2.2. Particle Image Velocimetry (PIV)</td>
<td>5</td>
</tr>
<tr>
<td>2.3 PIV System components</td>
<td>6</td>
</tr>
<tr>
<td>2.3.1. High Speed Camera System</td>
<td>7</td>
</tr>
<tr>
<td>2.3.2. Laser System</td>
<td>8</td>
</tr>
<tr>
<td>2.3.3. Seeding Particles</td>
<td>8</td>
</tr>
<tr>
<td>2.3.4. Lavision DaVis Ver 8.0.8</td>
<td>10</td>
</tr>
<tr>
<td>2.4 Measuring Technique</td>
<td>10</td>
</tr>
<tr>
<td>2.4.1 Experiment with laser sheet</td>
<td>10</td>
</tr>
<tr>
<td>2.4.2 Experiment without laser</td>
<td>12</td>
</tr>
<tr>
<td>2.5. PIV Evaluation</td>
<td>12</td>
</tr>
<tr>
<td>2.5.1 Cross correlation of images</td>
<td>14</td>
</tr>
<tr>
<td>3. Result and discussion</td>
<td>16</td>
</tr>
<tr>
<td>3.1 Laminar Flow</td>
<td>17</td>
</tr>
<tr>
<td>3.2 Turbulent Flow</td>
<td>23</td>
</tr>
</tbody>
</table>
3.3 Data comparison with theoretical result........................................30

4. Uncertainty Analysis.................................................................33

4.1 Uncertainty calculation.........................................................34

5. Conclusion.................................................................................35

References......................................................................................36
List of Figures

Figure 1. Schematic diagram of experimental set up

Figure 2. A bubble injection experiment facility

Figure 3. Sketch of a typical setup for PIV measurements

Figure 4. Double image capturing using a high speed camera

Figure 5. Double pulse Nd: YAG Laser system

Figure 6. Images with seed particle in frame 0 and frame 2

Figure 7. Images for water flow rate of 0.58 GPM(left) and 2.3GPM(right) with PIV

Figure 8. Images for water flow rate of 0.58 GPM(left) and 2.3GPM(right) without PIV

Figure 9. Image with digital geometric mask

Figure 10. Reference Points in PIV image

Figure 11. Cross Correlation of a pair of images

Figure 12. Velocity distributions of air bubble and surrounding water

Figure 13. Mean velocity profiles without air injection at y = -1.01mm

Figure 14. Mean velocity profiles without air injection at y = 3.98mm

Figure 15. Mean velocity profiles with air bubble injection at y = 0.15mm

Figure 16. Mean velocity profiles with air bubble injection at y = 3.98mm
Figure 17. Movement of the single bubble centroid with time

Figure 18. Change in major and minor axes of a single bubble

Figure 19. Aspect ratios of a single bubble with time

Figure 20. Mean velocity profiles without air bubble injection (y = 4.01mm)

Figure 21. Mean velocity profiles without air bubble injection (y = -1.07mm)

Figure 22. Mean velocity profiles with air bubble injection (y = 0.19mm)

Figure 23. Mean velocity profiles with air bubble injection (y = 4.01mm)

Figure 24. Trajectory of a single bubble centroid with time

Figure 25. Variation of major and minor axes of a single bubble

Figure 26. Ensemble average of bubble trajectory data over 10 bubbles

Figure 27. Ensemble average of major and minor axes and aspect ratio over 10 bubbles

Figure 28. Comparison of measured and theoretical velocity profiles in laminar flow (y = 8.73mm and y = 3.98 mm)

Figure 29. Comparison of measured and theoretical velocity profiles in laminar flow (y = 0.15mm and y = 3.98 mm)
Nomenclature

\[ a = \text{minor axis} \]

\[ b = \text{major axis} \]

\[ \Delta t = \text{time interval} \]

\[ D = \text{diameter of air injection hole} \]

\[ \text{I.D} = \text{inner diameter} \]

\[ \text{O.D} = \text{outer diameter} \]

\[ \text{PVT} = \text{particle tracking velocimetry} \]

\[ \text{PIV} = \text{particle Image Velocimetry} \]

\[ x = \text{displacement} \]

\[ d_p = \text{particle diameter} \]

\[ \rho_p = \text{particle density} \]

\[ \rho = \text{liquid density} \]

\[ \mu = \text{dynamic viscosity of liquid} \]

\[ U = \text{velocity of the particle} \]

\[ \text{Re} = \text{Reynolds number} \]
Chapter 1

Introduction:

The capability to determine two-phase flow dynamics is very important for safety analyze of nuclear reactors under transient and accident conditions. A number of mathematical and experimental investigations have been focused on different parameters, such as pressure drop, void fraction, profile of void fraction, bubble departing frequency, etc. Bubble nucleation, growth and departure in liquid under flow boiling conditions undergo various phenomena still too complex for mathematical model formulation and numerical simulation. Complicated interactions like collision and coalescence between adjacent bubbles, interactions between bubbles and the pipe wall, and transfiguration of bubbles affect the local conditions of the flow field, causing fluctuations in static pressure, velocity, and turbulent motions of liquid. Some of the most significant and important parameters measured in this study are bubble size, shape and velocity, and liquid velocity profile and its fluctuations.

Serizawa et al. (1975a,b) used a hot-film probe (CTA) method to measure liquid velocity profiles in bubbly two-phase flow in which two or three hot film probes are located perpendicular to each other to measure two-dimensional instantaneous velocity components and void fraction. They determined the liquid velocity, bubble diameter, local void fraction, and bubble frequency. They introduced air through a sintered tube with roughly 70μm pores into a mixing chamber to mix air with de-ionized water to realize a vertical upward two-phase bubbly flow. The superficial velocity range for water was from 0.45 to 0.77 m/s and 0.17 to 0.35 m/s for air. Nogueria et al. (2003) used a PIV and pulse shadow technique to determine velocity profiles in slug flow. The experiment was performed in a transparent acrylic column of 6-m height and
0.032m internal diameter. When the bubble successively cross the two light beams, the two signals obtained from two photocells were used to determine the velocity of the bubble.

Lindken and Merzkirch (1999) used two high speed video cameras positioned at 30° angle, one for PIV measurement and other for shadowgraphy measurement to measure 2D velocity of bubbles with 3D PVT. With this experimental set up they were able to determine the position of a bubble. Lindken and Merzkirch (2002) explained a novel method to determine the liquid velocity, bubble velocity, distribution of velocity fluctuation and bubble diameter. A double-pulsed high-power light emitting diode (LED) array emitting light at 675nm illuminated the multiphase flow for recording of air bubbles. With this set-up, light at a wavelength of 532 nm does not reach the detector. The light with a wavelength of 532nm is reflected from the tracer particles, and light reflection from air bubbles as considered w as a noise and removed by an optical filter. Finally only filtered signals from the tracer trace particles and bubbles were recorded.
Chapter 2

Experimental Set Up and Procedure:

2.1 Basic Experimental Set Up:

A schematic diagram of the experimental facilities for bubble injection into annular flow channel is shown in figure 1. The vertical test section consists of a 1.45m long polycarbonate pipe (I.D=19.05 mm and O.D=22.23mm) in which a 1.25m long inconel tube (I.D=7.62mm and O.D=9.75mm) is placed coaxially. The gap between the inner tube and outer pipe is 4.65mm. A small hole (D=0.4mm) drilled into the inconel tube at 0.90m above the bottom end of the inconel tube was used to inject air bubbles into the liquid flow.

Figure 1: Schematic diagram of experimental set up
A square optical correction box (5 cm x 5 cm x 5 cm) was installed on the outside of the polycarbonate pipe at the location of a bubble injection hole and used to minimize the curvature effect of the poly-carbonate pipe. Degassed tap water was circulated from a transparent storage tank (2 gallon capacity). A thin plate was installed between the inlet and outlet of the tank to prevent re-entry of returning water containing small bubbles from the test section directly to the pump's suction line. In order to obtain a steady liquid flow in the system, a flexible impeller pump (Emerson, Model No. SASSCXFJN-3542, 1/4 HP, 6 gpm capacity) was used. This pump has a wear-resistant flexible rubber impeller that can handle suspended solid particles such as tracer particles used for PIV measurements. The liquid flow rate was controlled by a digital flow meter (GPI Meter.com, Model No. G2So5 No9 GMA). The maximum bulk velocity of water in the test section can vary up to 0.65 m/s.

The air injection rate is controlled by using a programmable variable speed syringe pump (New Era Pump System, Inc "Just Infusion Pump", NE-300). The syringe pump is connected to the top of the test section with a flexible transparent tube (I.D. = 1/16" and 38" long). In order to continuously inject air bubbles into the water stream, a solid rod with a 1 mm deep groove is inserted into the inconel tube from the top to reduce the volume of the air passage between the syringe pump and 400 micron air injection hole. The bottom part of the test section is sealed with a silicone glue to prevent leakage. Figure 2 shows a photograph of the experimental facility.
2.2. Particle Image Velocimetry (PIV):

Particle Image Velocimetry (PIV) is a non-intrusive technique that was first developed as an experimental technique to measure the velocity vector in a measurement plane by measuring the displacement of small particles (PIV seed particles) that are illuminated by a laser sheet and follow the fluid motion (Adrian, 1986). The displacement ($x$) of the particles is measured by comparing the particle positions in two consecutive images over a known time difference, $\Delta t$, between the two images so that $V = x/\Delta t$. The great advantage of the non-intrusive nature of the technique is that it allows experimentalists to obtain the local and global velocity information in fluid.
Identifying the same particle in each frame was previously done in Particle Tracking Velocimetry (PVT) to measure the fluid velocity. Low particle density images are required and it gives few velocity vectors. To get a complete velocity field, PIV relies on using much higher particle densities in the flow field, for which the PVT technique cannot always give good results because it is impossible to identify the same particle in both images. For this reason a correlation method is used in the PIV method to identify a pattern of a group of particles.

2.3 PIV System Components

The basic PIV system contains the following components for this experiment:

1. High speed video camera system capable of capturing images with a small time interval
2. Light source (Pulsed laser system)
3. Seeding particle to scatter the light.
4. LaVision Davis Ver.8.0.8 Software

Figure 3: Sketch of a typical setup for PIV measurements
2.3.1 High Speed Video Camera System:

The PIV technique puts special demands on the video camera to be used, especially when the flow velocity is high, if the imaged area is small and the particles are very small. Phantom V310 digital video camera has been used to capture the image of the flow field throughout this research. The camera is a high speed video camera with an image acquisition rate of up to 500,000 fps and a high-resolution (1280x800 pixels). The PIV method requires the video camera to be able to capture two images within a very short period of time in order to get the same individual particles to appear in both images. Short exposure times can be achieved either by having a high speed camera which continuously records images at a rate of several kHz. This is achieved by letting the first laser pulse be fired at the end of the exposure of the first image and second pulse coming the beginning of the exposure of the second image, as illustrated in figure 4.

![Diagram](image.png)

Figure 4: Double image capturing using a high speed camera
2.3.2 Laser System:

Figure 5 shows the principal layout of the PIV laser used: 532nm Nd: YAG laser (Liton NANO-s-35-15-PIV with a double pulse rate up to 15Hz) is used as an illumination source for the PIV measurement because of its high light intensity. Pulsed lasers require some time to build up energy before they can deliver a new pulse and the two images in a PIV image pair has to be taken within very a short period of time. Therefore, it is common in PIV to use a laser with two cavities. The laser pulse interval is 100 µs and the energy is 2x30 mJ/pulse.

![Figure 5: Double pulse Nd: YAG laser](image)

2.3.3 Seeding Particles:

Seeding the liquid with light reflecting particles is necessary in order to image the flow field. The particles should be small enough to follow the flow but large enough to reflect large amounts of light. In this experiment hollow glass spheres with a 10 µm diameter particle were used. A good rule of thumb for the particle density is about ten particles need to be correlated for each measured velocity vector.
For tracing the motion of the particle, it is anticipated that the relative motion between the particles and the flow can be calculated from Stokes' law for a spherical particle at very low Reynolds numbers.

\[ U_s = \frac{d_p^2 (\rho_p - \rho)}{18\mu} a \]

where \( d_p \) is the particle diameter, \( \rho_p \) and \( \rho \) are the particle density and liquid density respectively, \( \mu \) is the dynamic viscosity of the fluid and \( a \) is the relative acceleration of the moving particle. Images with seeding particles are shown in figure 6.

Figure 6: Images with seed particles in frame 0 and frame 1
2.3.4. LaVision DaVis Ver. 8.0.8

LaVision Davis is a complete software package for intelligent (laser) imaging applications for non-reactive and reactive flow fields, material surface imaging and tracking and high speed imaging. The software integration of the selected imaging system is achieved with flexible acquisition modes, customized DaVis software interfaces and application and specification imaging packages. The interrogation area is 24 x 24 pixels that can be reduced to 8 x 8 pixels with 25% overlap with post processing (denoising 7x7).

2.4 Measurement technique:

Two sets of experiments were performed with the same experimental set up. The types of experiments were as follows:

1. Experiments with laser illumination

2. Experiments without laser illumination

2.4.1 Experiment with laser illumination:

These experiments were done with different liquid flow rates and different air bubble injection rates. The PIV measurement was performed to investigate the flow in the liquid around clusters of rising bubbles. For this purpose the water was seeded with PIV seed particles (hollow glass sphere of 10μm diameter). The liquid flow and air injection rates were set using the digital flow meter and syringe pump respectively. The optical correction box was filled with fresh water before any measurement. The DaVis 8.0.8 was opened from desktop to synchronize the laser with high speed camera and visualize the movement of the hollow glass particles inside the
water. While the test section was illuminated by a green laser light sheet, the high speed video camera captured images of the flow field.

Two consecutive images with a very short controllable time delay were captured at a 15Hz frame rate. Images of the flow field were captured with bubbles and without bubbles at different flow rates. The average diameter of the bubbles was larger for a low liquid flow rate than at a higher liquid flow rate. The experiments were done at room temperature (298 K) and 1 atmospheric pressure. Figure 7 shows the bubble size decreasing with an increase in the liquid flow rate.

Figure 7: Images for water flow rate of 0.58 GPM (left) and 2.34 GPM (right)
2.4.2 Experiment without laser illumination:

The procedure for experiments without laser illumination was the same as before but a halogen lamp (2,000 W) was used instead of a laser to illuminate the test section. To determine the size and shape (major and minor axes) of bubbles, it is necessary to increase the frame rate so the Phantom camera software (P.C.C 1.1) with 4,000 fps was set up to capture the images. Figure 8 shows the images captured under different flow rates.

![Figure 8: Images for water flow rates of 0.58 GPM (left) and 2.34 GPM (right)](image)

2.5: PIV Image Processing:

The digitally recorded PIV images were processed with an advanced cross-correlation method. The algorithm was extended to applications in multiphase flow (Linkden, R., 2000). Since the two phases, air bubbles and water, move at different speeds, it is necessary to separate the signals from the two phases in PIV recordings. The idea of applying a digital mask to
separate the two signals was introduced by Gui, L. and Merzhirch (1997) so that the velocity of liquid and the rise velocity of air bubbles can be determined separately but simultaneously. By using this digital mask technique the water velocity can be measured accurately also in close proximity of interface separating the two phases Gui, L and Merzhirch (1996). A 3-pixel wide border mask was used to detect the bubble area in order to compensate for blur and reflection on the bubble surfaces. Finally the image is binarized. The image processing software used our experiments can detect more than 97.7% of bubble images automatically. Overlapping bubbles are correctly detected and counted as one bubble Gui, L and Merzhirch (2002). The digital mask is not an image-processing algorithm, but a 2D array of values. The digital mask $\Delta(i, j)$ is generated such that

$$\Delta(i, j) = \begin{cases} 1 & \text{if a pixel } (i,j) \text{ belongs to the continuous (water) phase} \\ 0 & \text{otherwise} \end{cases}$$

$$\Delta(i, j) = \begin{cases} 1 & \text{if a pixel } (i,j) \text{ belongs to the continuous (bubble) phase} \\ 0 & \text{otherwise} \end{cases}$$

This array is combined with the PIV evaluation algorithm as described by Gui, L and Merzhirch, (2000). Figure 9 shows the images with a digital mask.
Figure 9: Image with a digital geometric mask. Figure 10: Reference Points in PIV image

It is important to scale the window before PIV processing. Since we are interested in getting our result in a certain area, reference points were selected: one at the bubble injection point and the other at 4.65 mm from the injection point.

2.5.1: Cross Correlation of images:

The aim of the cross-correlation technique is to find the displacement that the particle pattern has moved during the inter image time and translate this into a velocity measure. The relation between velocities $U$ and displacement of the particle $d$ can be presented as,

$$ U = \frac{d}{M \Delta t} $$

where $M$ is the magnification and $\Delta t$ is the inter image time. The smallest part of the image that the cross-correlation function can calculate is called the interrogation area (IA) as shown in Figure 11.
Figure 11: Cross-correlation of pair of images

The cross-correlation of one IA gives only one velocity vector. The cross-correlation can be seen as finding which relative displacement of the IAs that gives the best pattern match. The displacement should be proportional to the average velocity in the IAs. Figure 11 shows the cross-correlation of a pair of images.
Chapter 3:

**Results and Discussions:**

The measurement of this experiment serves to investigate the velocity profiles and their fluctuations for laminar and turbulent flows with and without bubble injection. Also, the variations with time of the bubble size and shape based on the major and minor axes and their ratio referred to as the aspect ratio were investigated for both laminar and turbulent flow cases. The water and bubble velocities were measured simultaneously while air bubbles were passing through the measurement plane. As it always applies to PIV experiments, the measurements were not taken continuously in time, but it was ensured that they would always be taken under the same flow conditions. Figure 12 shows typical PIV measurements of single-phase water flow and bubbly flow in terms of a velocity vector plot. The vectors show the instantaneous velocity distribution in the liquid phase. Air bubbles occupy the regions without any vector. To get the average velocity, 100 to 150 images were considered for calculation.

![Figure 12: Velocity distribution of air bubble and surrounding water](image)

Figure 12: Velocity distribution of air bubble and surrounding water
3.1 Laminar Flow:

For a laminar flow with Reynolds number, Re=1625, the water flow rate was set at 0.58gpm (0.18 m/s) and to inject air bubbles into water stream continuously the air bubble injection rate was set at 5.4 ml/min.

The liquid velocity plays a decisively important role in characterizing the flow structure. This information is definitely required for two phase flow investigation. Figures 13 and 14 show the time averaged streamwise (y) and spanwise (x) velocity profiles at different positions from the reference line (bubble injection point). The result is based on the average of over 100 instantaneous velocity profiles. The velocity profiles at two locations are almost the same; therefore the flow is considered to be nearly fully developed. The velocity fluctuations near the wall of the inconel tube and the polycarbonate pipe in Fig 13 are larger in magnitude than those at the center of the annular flow channel. The time averaged spanwise velocity is nearly zero in figure 14, because the flow is one dimensional and the PIV seed particles move only in the streamwise direction. These results give us a very good indication for the system set up. The average liquid velocity found from the PIV is close to the liquid velocity from a digital flow meter.
Figure 13: Mean velocity profiles without air injection at $y=-1.01\, \text{mm}$

Figure 14: Mean velocity profiles without air injection at $y=3.98\, \text{mm}$
In Figures 15 and 16 the time averaged streamwise and spanwise velocity profiles of liquid with air bubbles injected are presented for different locations of the test section. When the bubbles are injected into the liquid stream, the liquid velocity showed large fluctuations especially near the inconel tube wall. Figures 15 and 16 show that the velocity fluctuations are also greater at the injection hole ($y=0.15$ mm) than at a higher elevation ($y=3.98$ mm).

Figure 15. : Mean velocity profiles with air injection at $y = 0.15$ mm
The effect of moving bubbles on flow is smaller than it is for stagnant ones.

Figure 16.: Mean velocity profiles with air injection at y=3.98 mm

Figure 17 shows the movement of the bubbles injected into the liquid stream. This experiment was done without a laser sheet. A halogen lamp was used to illuminate the test section. These images were processed using a Matlab code. The edge of the bubble was determined by detecting the pixel intensity and then the centroid of the bubble was calculated. For a laminar flow the bubble size was larger than that in a turbulent flow, and the bubble moved slowly so that coalescence occurred as indicated in Figure 17 by a red circle. This coalescence increased the size of the bubble and affected the rising motion of the bubble. When coalescence occurred the larger bubble sucked the smaller bubble and caused the fluctuations in both the streamwise and spanwise velocities. Bubbles moved upward due to a buoyancy force and from the displacement the average velocity of the air bubble was calculated to be 160 mm/s in the y
direction and 100 mm/s in the x direction. At the very beginning of bubble injection, the bubble velocity in the flow direction is smaller than that in the radial direction.

In Figure 17, the movement of the bubble centroid with time is shown. Figure 18 illustrates the major and minor axes of a single bubble varying with time. The magnitude of the major axis is 20-30% higher than the minor axis. A peak in the major axis followed by a sudden drop at t = 0.01 ~ 0.12 seconds indicates that bubble coalescence occurred.
at that time. After the coalescence the length of the minor axis decreased slightly. The aspect ratio (major to minor axis ratio) plotted in Fig. 19 shows the bubble to stay nearly spherical in shape over time. Immediately after bubble departure, the fluctuation in the aspect ratio is large but after about 0.015 seconds, the fluctuation became small and the aspect ratio was almost constant.

Figure 18: Changes in major and minor axes of a single bubble
3.2 Turbulent flow:

For the turbulent flow case the liquid flow rate was set at 2.24gpm (the average velocity $= 0.66$ m/s, $Re = 6555$), and the air injection rate was 5.4 ml/min. About 150 images were considered for the time average velocity calculation. Some of the images were deleted manually due to poor quality of the PIV particle images. They did not have a significant number of velocity vectors to contribute to the average velocity calculation.

Figures 20 and 21 show the time averaged streamwise and spanwise velocity profiles at different elevations from the reference point for turbulent flow without any bubble injection. The solid line represents the time averaged velocity profiles and vertical bars represent the R.M.S. fluctuations. Figures 20 and 21 show the velocity fluctuations near both the inner and outer walls to be higher than those at the center of the annulus. The velocity profile for the turbulent case is flatter than the laminar case. The spanwise velocity fluctuations are also small but near the polycarbonate wall the streamwise and spanwise velocities show some fluctuations. The mean velocity profiles at $y = -1.04$mm and $y = 4.01$mm locations are almost the same, therefore
the flow is considered to be fully developed. The radially averaged velocity from the figure is 0.67 m/s which is consistent with liquid flow rate measured by a digital flow meter.

Figure 20: Mean velocity profile without air injection at $y = 4.01\text{mm}$
Turbulent bubbly flow is a common phenomenon and has a lot of engineering applications. The velocity distribution for turbulent flow with air bubble injection was measured using the same cross-correlation technique as in the laminar flow case. The calculation was done from phase weighted averaging of over 100 frames. The solid lines in Figures 22 and 23 show time averaged streamwise and spanwise velocity profiles for turbulent flow with air bubbles. The vertical bars represent R.M.S fluctuations of velocity. Figure 22 shows the velocity fluctuations close to the injection point ($y = 0.19$) are greater in both directions than those at a higher elevation ($y = 4.01$). In the center of the flow channel ($r = 2~3$ mm) the fluctuations are small. There was no bubble coalescence observed at $Re = 6555$. The reason for large velocity fluctuations...
fluctuations near the injection point was already explained in the laminar flow case. The velocity fluctuation near the inconel tube wall is higher for turbulent flow with bubble injection than the laminar flow with bubble injection.

Figure 22: Mean velocity profiles with air bubble injection (y = 0.19 mm)

Figure 23: Mean velocity profiles with air bubble injection (y = 4.01 mm)
Figure 24 shows the same pattern of bubble movement as in laminar flow, but the bubbles move faster than in laminar flow because of a higher liquid flow rate. Figure 24 also shows that all the bubbles are following nearly the same trajectory over time.

![Figure 24: Ensemble average trajectory of bubbles bubble centroid with time](image)
Figure 25: Variation of major and minor axes of 10 bubble

Figure 25 shows the variation of major and minor axes over time and aspect the ratio of major to minor axis. The fluctuations in major and minor axes are higher than in the laminar flow case but the bubble size is smaller than in laminar flow. From the aspect ratio it can be concluded that the shape change is larger in the turbulent flow case.
Figure 26 shows the bubble trajectory data averaged over 10 bubbles. There is no significant difference from the case of a single bubble but the fluctuations are larger than in the single bubble case. Figure 27 shows the variation of the major or minor axes and their fluctuations. They also follow the same pattern as for the single bubble case. Therefore, every bubble shows the same kind of behavior when it travels through the liquid.

**Bubble position (Ensemble Average over 10 bubbles)**

![Diagram](image)

Figure 26: Ensemble average of bubble trajectory data over 10 bubbles
**Bubble major/minor axes (Ensemble Average over 10 bubbles)**

![Graph showing Bubble Major and Minor Axes](image)

**Aspect Ratio**

![Graph showing Aspect Ratio](image)

Figure 27: Ensemble average of major and minor axes and aspect ratio over 100 bubbles

### 3.3 Data comparison with theoretical result:

Figures 28 and 29 show comparisons of the measured streamwise velocity profiles with theoretical profiles for laminar flow in an annulus. The theoretical profiles match the experimental data reasonably well at different elevations from the bubble injection point. However, Figure 28 shows some velocity fluctuations in the experimental result which should be zero or negligibly small. This is because of processing and calculation of data. The laser used in this experiment is a pulsed laser and it could not illuminate the PIV particles evenly, therefore some images did not contain significant velocity vectors. This problem was resolved by screening the images. The images with a small number of velocity vectors were deleted.
Figure 28. Comparison of measured and theoretical velocity profiles in laminar flow (y = 8.73mm and y = 3.98mm)
Figure 29: Comparison of velocity profile with theoretical result in laminar flow

\( y = 3.98 \text{ and } y = 0.15 \text{ mm} \)
Chapter 4

Uncertainty Analysis:

The PIV measurement system consists of several sub-systems, and the evaluation of the measurement uncertainty needs to consider the coupling between the sub-systems. The PIV measurements is based on the visualized flow image, and the information from the image can differ from the actual flow field due to the velocity lag between the tracer particle and fluid, and the projection procedure from the 3-D physical space to 2-D image plane.

It is a common practice to oversample a PIV recording during interrogation by at least twice in order to bring out small-scale features in the flow. Because of this oversampling, neighboring velocity data are estimated partially from the same particle image and therefore are correlated with each other. This effect can be partially reduced by advanced processing scheme such as iterative image deformation technique Rafel et al.(2002).

The size of interrogation in an object plane ($\Delta X \times \Delta Y$) defines the spatial resolution in the recovered velocity data. The spatial resolution in the velocity field, in turn limits the obtainable spatial resolution of the differential estimate. Depending on the utilized differentiation scheme the spatial resolution will be reduced to some degree due to smoothing effect Rafel et al.(2002). The curvature of the polycarbonate pipe affects the velocity fluctuation near the wall. By a delay in the illuminating pulses, $\Delta t$, this effect can be reduced at the cost of increased noise in differential estimates due to the velocity uncertainty.
4.1 Uncertainty calculation:

The error bars depicting fluctuation values in velocity represents root mean square R.M.S values of the instantaneous velocity from the time averaged values. The uncertainty values for individual bubble position and major or minor axis follow from the pixel span of the bubble interface multiplied by the scale factor. For ensemble average of the bubble trajectory and major or minor axis the uncertainty equals the fluctuation values. The aspect ratio uncertainty is derived as follows:

\[
\text{Aspect Ratio} = \frac{b}{a} \\
\Delta \left( \frac{b}{a} \right) = \frac{\Delta b}{c} + \frac{b \Delta c}{a^2}
\]
Chapter 5

Conclusion:

A considerable amount of information has been obtained from the experiment of air bubble injection into laminar and turbulent flow of water in a vertical annular flow channel. The PIV measurement technique with digital masking technique has been applied to single and two-phase flow. Only one video camera was used to simultaneously measure the velocity distributions of the continuous phase (water) and dispersed phase (bubble).

The experimental results indicate that air bubble injection into both laminar and turbulent liquid streams causes large increases in streamwise and spanwise velocity fluctuations. At a low liquid flow rate bubble coalescence can also occur. The measurements show that the PIV method for multiphase flow is able to measure velocities in two-phase flow with a high precision. The accuracy of the data can be increased by further refining the PIV image processing technique.
References:


