Study of Liquid Flow with Air Bubbles in a Pipe

by

Nur Azmel Zaa Kamarudin

Dissertation submitted in partial fulfillment of
the requirements for the
Bachelor of Engineering (Hons)
(Mechanical Engineering)

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CERTIFICATION OF APPROVAL

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A project dissertation submitted to the
Mechanical Engineering Programme
Universiti Teknologi PETRONAS
in partial fulfilment of the requirement for the
BACHELOR OF ENGINEERING (Hons)
(MECHANICAL ENGINEERING)

Approved by,

____
(AP Ir. Dr. Shaharin Anwar Bin Sulaiman)

UNIVERSITI TEKNOLOGI PETRONAS
TRONOH, PERAK
MAY 2011

CERTIFICATION OF ORIGINALITY

This is to certify that I am responsible for the work submitted in this project, that the original work is my own except as specified in the references and acknowledgements, and that the original work contained herein have not been undertaken or done by unspecified sources or persons.

NUR AZMEL ZAA BIN KAMARUDIN

ABSTRACT

The existence of bubbles in liquid flow causes problems in various applications involving pipelines such as pressure drop through pipeline, vibration, cavitation and multiphase metering. Bubble sizes are critical in determining the production rate of gas lift mechanism. Thus, the objective of this project is to conduct fundamental study of the behavior of bubbles in liquid flow in pipe is required as to control bubbles which would help to reduce pressure drop and vibration as it could minimize energy loss, besides reduces the chances of cavitation. The study would involve experimental analysis of the characteristics of fluid flow, the effects of existence of bubbles or air in turbulent liquid flow on bubble velocity and bubble size distribution. Experiments were conducted by using cavitation pump rig which includes motor pump, water flow rate meter, air injector and ball valve, been combined with Laser Doppler Anemometry (LDA) and Phase Doppler Anemometry (PDA) to analyze the bubbles' diameters and also both vertical and horizontal velocity of the bubbles injected. The bubbles in liquid flow change their characteristics across the cross section of the pipe and also from lower elevation to higher elevation as the eddies phase changes towards steady flow. There is a variation in the diameter of bubbles along the liquid flow. A higher water flow rate results in smaller bubbles diameter probably due to high kinetic energy in the water and hence it has less chance to merge. Large bubbles normally occur near pipe wall and at sections where the velocity of water is relatively slower.

ACKNOWLEDGEMENT

The author would like to express the utmost gratitude and appreciation to Allah because of His blessings along the journey, Alhamdulillah, all praises to Him, even with so much challenges the Final Year Project managed to be completed on time.

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CHAPTER 1
INTRODUCTION

1.0 Background Of Study

1.0.1 Multiphase Flow

Disperse flow are those consisting of finite particles, drops or bubbles which were distributed in a connected volume of the continuous phase. Only disperse flow is to be considered and analyzed in this project. For frictional loss in a disperse flow, vertically-oriented pipe flow can experience partially separated flows in which large relative velocities develop due to buoyancy and the difference in the densities of the two-phases or components. These large relative velocities complicate the problem of evaluating the pressure gradient (Brennen, 2005). The entrapment or release of air caused many natural and technical fluid flows to be as two-phase flows. In high-speed flows in open channels, air is entrapped by macroturbulence reaching the free surface. Vapour bubbles develop as a result of cavitation.

1.0.2 Fluids and Fluid Flow

Definitively, fluid is the substance in the liquid or gas phase. Both type of fluid are to be considered in this project. Fluid viscosity is an essential element in laminar and turbulent liquid flow. Fluid layers in which are assumed to slide over one another, which means it's a well ordered pattern, is called laminar flow. A transition flow is the flow which will take place after the laminar flow to an unstable type of flow. As the flow rate was increased beyond a critical value, the flow broke into an irregular motion, indicating the presence of macroscopic mixing motion perpendicular to the direction of flow and such chaotic motion is called turbulent flow, which is the most common type of flow.

1.1 Problem Statement

The existence of bubbles in liquid flow causes problems in various applications involving pipelines such as pressure drop through pipeline, vibration, cavitations and multiphase metering. Bubble sizes are critical in determining the production rate of gas lift mechanism. Multiphase metering could be less complicated as the number of phases is decreased when bubbles are removed. However, the characteristics of bubbles in flowing liquid are complicated, partly due to the effect of drag, viscosity of the fluids involved, friction and wall shearing stress. Thus, a fundamental study of the behavior of bubbles in liquid flow in pipe is required as to control bubbles which would help to reduce pressure drop and vibration as it could minimize energy loss, besides reduces the chances of cavitations.

1.2 Objective & Scope of Study

The objective of the present project is to study the behavior of air bubbles in flowing liquid in pipes. The information from this work could lead to further investigation of the effects of the bubbles in various pipeline applications. The study would involve experimental analysis of the characteristics of fluid flow, the effects of existence of bubbles or air in turbulent liquid flow on bubble velocity and bubble size distribution. Experiments have been conducted on fluid flow with vertical upstream/upwards pipelines section. Accuracy and precision will be crucial factors in this experiment, so the data collected by using Dantec Dynamic BSA Flow Software should be scaled down to achieve these constraints.

CHAPTER 2
LITERATURE REVIEW

2.1 Forced or Natural Fluid Flow

Fluid flow can be classified either forced or natural fluid flow, depending on how the fluid motion is initiated. In natural flows, any fluid motion which due to natural means such as buoyancy effect, which manifests itself as the rise of the warmer, which is also lighter fluid and the fall of cooler which is denser fluid, is called natural flow (Cengel et al, 2006) while forced flow is a fluid which is forced to flow over a surface or in a pipe by external means such as a pump or a fan (Cengel et al, 2006). A flow field is best characterized by the velocity distribution, and thus a flow is said to be one-, two- or three-dimensional. In this project, only two-dimensional flow is to be considered as it is easier to analyze into bubbles with a log-normal size distribution as the air stream enters into the flowing water stream through a T-injector (Razzaque et al, 2003). By using different air injectors of different inner diameters, size of the bubbles can be controlled. Ironically, T-injector does give a good choice of introducing bubbles into a liquid flow.

2.2 Bubbles Effect on The Wall Drag

According to Murai et al (2007), to create microbubbles and maintain them in the turbulent boundary layer is difficult, but by having small bubbles of a few milimetre in dimension, wall drag can also be reduced. However, the wall drag can be increased with the presence of bubbles under certain conditions. So by having bubbles in turbulent flows, there will be some significant effect on the wall drag. A simulation of a bubbly channel flow conducted by Lu et al (2005) shows that drag is increased when bubbles travel close to the wall and this depends on the deformability and motion with respect to the wall. After that, another experiment is conducted to prove that pressure gradient is reduced more effectively compared to larger bubbles, typically larger than 5 mm, in vertical air-water upward flow containing small bubbles up to a few milimeters.

2.3 The Control of Fluid Flow

Pressure drop was caused by drag, which happens with the existence of bubbles in liquid flow. In order to have a full control on liquid flow, the usage of valves were introduced. When valve is opened, full flow of liquid were allowed in a pipe and bubble will relatively formed by a rapid mixture of liquid and air that originally occurred in the respective pipe. (Mezic, 2006). Multiphase turbulent flow is produced when velocity is high enough. Liquid particle motion path is complex enough to be detected. The best and the only way to analyze its behavior is by using Laser Doppler Anemometry (LDA) / Phase Doppler Anemometry (PDA) (Sleigh, 2009).

2.4 Laser Doppler Velocimetry Measurement of Turbulent Bubbly Channel Flow

An experiment has been performed by Morikita et al (2002), where measurements of the turbulence properties of gas–liquid bubbly flows with mono-dispersed 1-mm-diameter bubbles are reported for upward flow in a rectangular channel. Bubble size and liquid-phase velocity were measured using image-processing and laser Doppler Velocimetry (LDV), respectively. An investigation of the channel flow with dispersed spherical bubbles was conducted using image processing and the 2-D LDV systems. By adding a small amount of 3-pentanol as surfactant, mono-dispersed small spherical bubbles of 1 mm diameter were uniformly generated across the channel. The addition of the surfactant drastically changed not only the bubble size and the size distribution but also the macroscopic flow structures. A 2-D LDV measurement system was carefully set up to reliably measure the statistical properties of turbulent bubbly flows. Special arrangements were made for the laser beam path to avoid interruption by the bubbles and for the signal processing to select the light from seeding particles.

2.5 Bubble Size in Turbulent Air-water Flow through Horizontal Pipes

Experiments are performed to determine bubble size distributions for three average water velocities for each of the three test section pipe lengths. Three air volume fractions and two air injectors of different inner diameters are used. Bubbles became highly deformed at large air volume fractions and small water velocities (Razzaque, 2003). An experimental study has been performed in a pipeline to assess the development of the distribution of bubble size in the horizontal flow of an air–water system. Air will break into bubbles with a log-normal size distribution as the air stream enters into the flowing water stream through a T-injector (Razzaque, 2003). As the conclusions, T-injector does give a good choice of introducing bubbles into a liquid flow. By using different air injectors of different inner diameters, size of the bubbles can be controlled.

2.6 Sauter Mean Diameter (SMD)

One of the commonly used mean sizes is the Sauter Mean Diameter (SMD), or D_{32}, which is given by

$$D_{32} = \frac{\sum_{i=1}^{k} n_i D_i^3}{\sum_{i=1}^{k} n_i D_i^2} \tag{2.1}$$

where, n_i is the number of droplets within a range centred on diameter D_i, and k is the number of ranges. The Sauter Mean Diameter is an average diameter with a volume to surface area ratio equal to that of the droplets. It is an indicator of the degree of atomization produced by an injector.

It is worth to consider another representative of droplet diameters which is the Surface Mean Diameter, D_{20}, which represents an average diameter with a surface area equal to the mean surface area of all the droplets. This is given by:

$$D_{20} = \sqrt{\frac{\sum_{i=1}^{k} n_i D_i^2}{\sum n_i}} \tag{2.2}$$

The surface mean diameter is used for surface controlled applications such as absorption. Normally, a catalyst engineer will want to use D_{20} to compare the spheres on the basis of surface area because the higher the surface area the higher the activity of the catalyst (Rawle, 2005).

2.7 Liquid's Velocity Profile At Upward Flow Pipe Section

According to Shang Pei (2010), as the bubbles moved upward, the horizontal velocity at the center of pipe remained constant and even negligible as it was near 0 m/s. The bubbles were rather steady at this region as they only moved in the upward vertical direction. Therefore, the fluid flow at the center of pipe was linear and upward. For 5 gpm of water flow rate, the water velocity was 0.5943 m/s and the bubbles were injected at 1.5 m/s. As the bubbles entered the boundary layer region, their velocity at the center of pipe was smaller than both the water and initial velocity. This clearly shows that as the mass of air bubble are small, it has less energy and water tends to push the weak mass aside towards the low velocity region, which is the pipe wall.

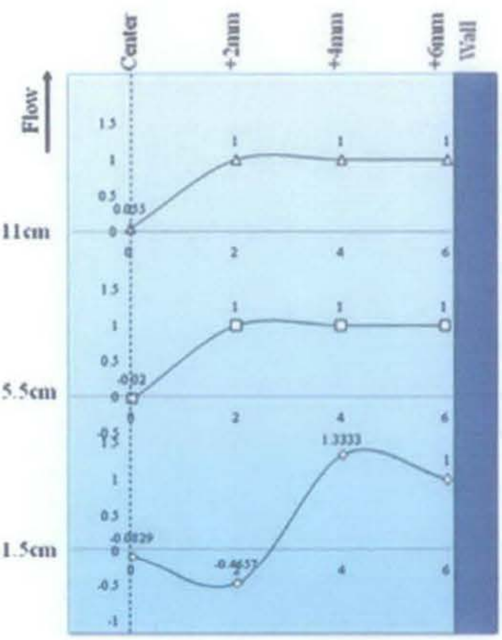


Figure 2.1 : Horizontal velocity profile at 5 gpm (Shang Pei, 2010)

The vertical velocity increased constantly as the bubbles travelled towards the pipe wall could also be explained by using the theory of buoyancy. Buoyancy acted along this path, along with the gravitational downward acceleration, bringing the bubbles upward. The net upward buoyancy force is equal to the magnitude of the weight of fluid displaced by the air bubbles. This force enables the bubbles to float. From the development of velocity boundary layer, due to no-slip condition, the fluid particles in the layer in contact with the surface of the pipe come to a complete stop. As the weight of air (bubbles) is lighter than the weight of water, the density of air is less than water. Thus, the buoyancy of air is greater than its own weight and will float to a level where it displaces the same weight of water as the weight of itself.

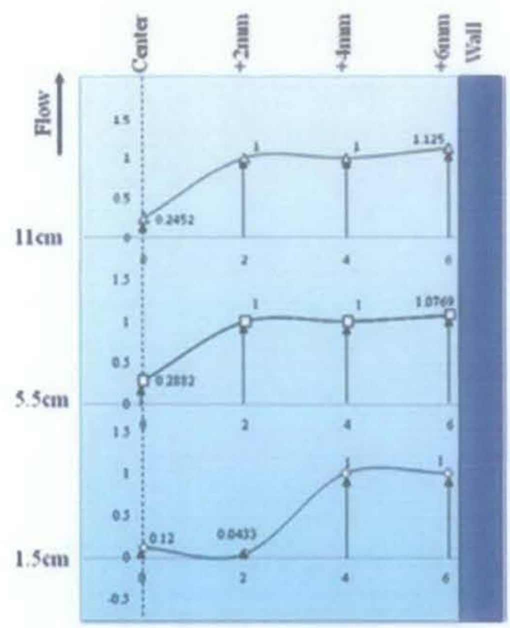


Figure 2.2 : Vertical velocity profile at 5 gpm (Shang Pei, 2010)

Assumptions have been made by Shang Pei which is the fluid swirls and creates reverse current as there was a drastic change in the bubble's horizontal and vertical velocities at an elevation of 1.5 cm above the pipe coupling, 2 mm away from the center of pipe.

2.8 Visualization of the Flow around a Bubble Moving in a Low Viscosity Liquid

The shape and position of the bubble were obtained, in the same photo plate, by simultaneously illuminating the flow with a stroboscopic light. An experiment has been conducted in a closed acrylic tank of 50×50×50 cm^3, in which bubbles are injected using a capillary tube. According to Lima-Ochoterena and Zenit (2003), the visualization of the streak lines is obtained by open-diaphragm photography of laser-sheet illuminated micro-tracers.. The schematic of experimental setup is shown in Figure 2.3. The working fluid here is filtered water while pure nitrogen is used to form the bubbles. In this experiment, a range of bubble sizes are used and the sizes are controlled by a fixed volume switch valve. The result from this experiment is a change of the bubble trajectory, from rectilinear to the form of zigzag, as the volume increases.

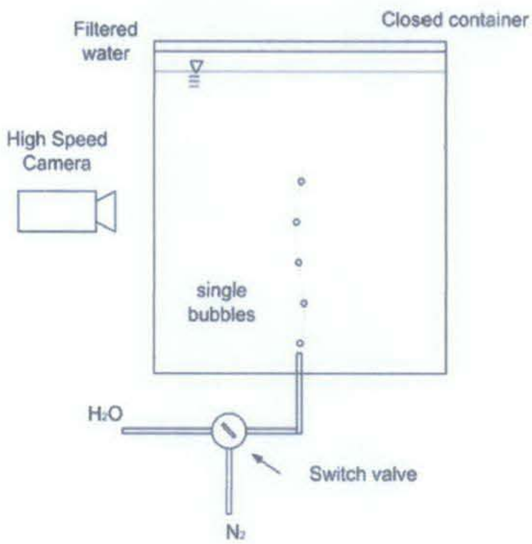


Figure 2.3 : Schematic of experimental setup (Lima-Ochoterena and Zenit, 2003)

2.8 Turbulent Flow Separation in Pipe Elbow Using ANSYS CFD Flotran

The friction in viscous fluid flows in pipe is normally caused by the interaction between the fluid and the internal wall of the pipe. On the other hand, change in the geometry of the flow path by the introduction of elbow in the piping system also contributes the friction in flow, as a result of flow separation, especially if the bend is sharp. (Sulaiman et al, 2002). A study has been conducted by using ANSYS CFD Flotran on the water flows in three types of 2-dimensional elbow models of various bending radii. From the simulation, the occurrences of backward flow, which is inter-related with flow separation, are observed.

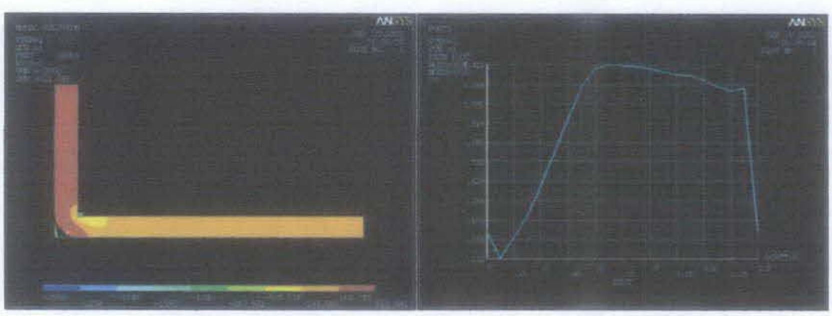


Figure 2.4 : Pressure contour plot (left) and its velocity profile (right) (Sulaiman et al, 2002)

CHAPTER 3
METHODOLOGY

3.1 Project Process Flow

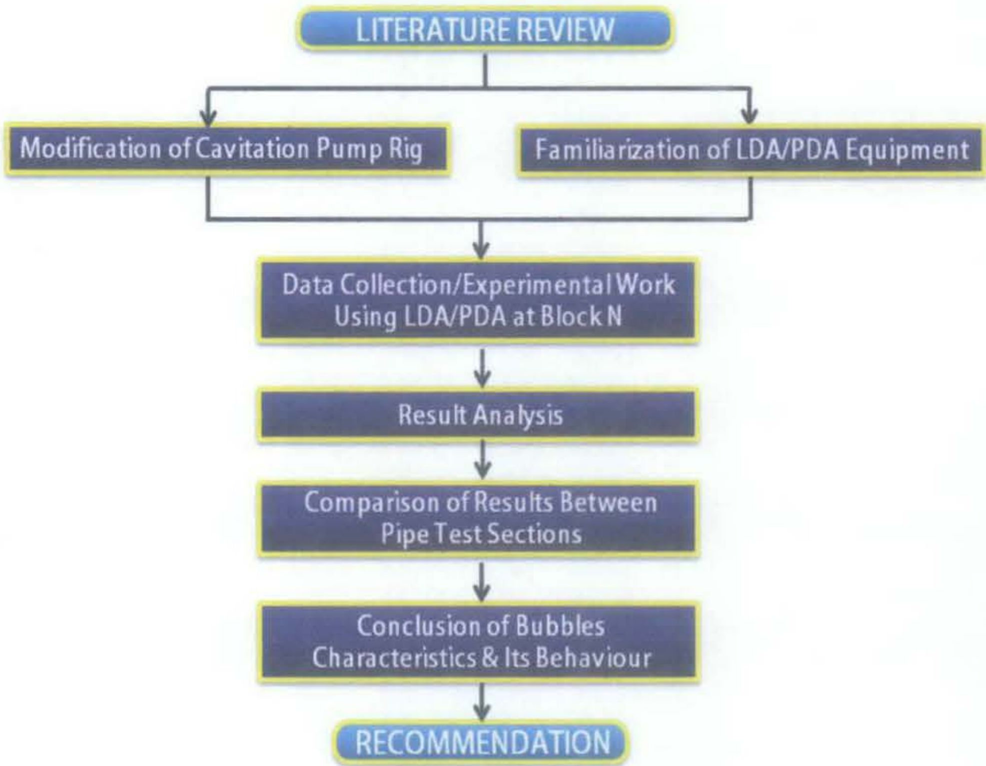


Figure 3.1 : Full Project Process Flow

Shown in Figure 3.1 is the process flow of the project. The process involved in the project includes the choice and submission of titles and preliminary research work to get more exposure on the title of project. An introduction to the equipment, cavitation pump rig, was conducted by running the equipment without introducing bubbles to the water flow in pipe. The sequence of manually operating the equipment was learned and practiced so as to familiarize the equipment. Then, a briefing for Laser Doppler Anemometry (LDA)/Phase Doppler Anemometry (PDA) was conducted to introduce the parts of the equipment and the basic working principles.

After knowing the working principles of the equipments, bubble injection method was created to support the mechanism of introducing micron bubbles into the pump system.

A modification of the pipe was needed in order to keep the water flow meter in place while conducting experiments. In order to create bubbles in the cavitation pump system, a hole had been punctured at the pipe and bubbles are injected with an air pump. The experimental works and full documentations have been conducted and be summarized in Gantt Chart and in the next chapter.

3.2 Gantt Chart and Milestones

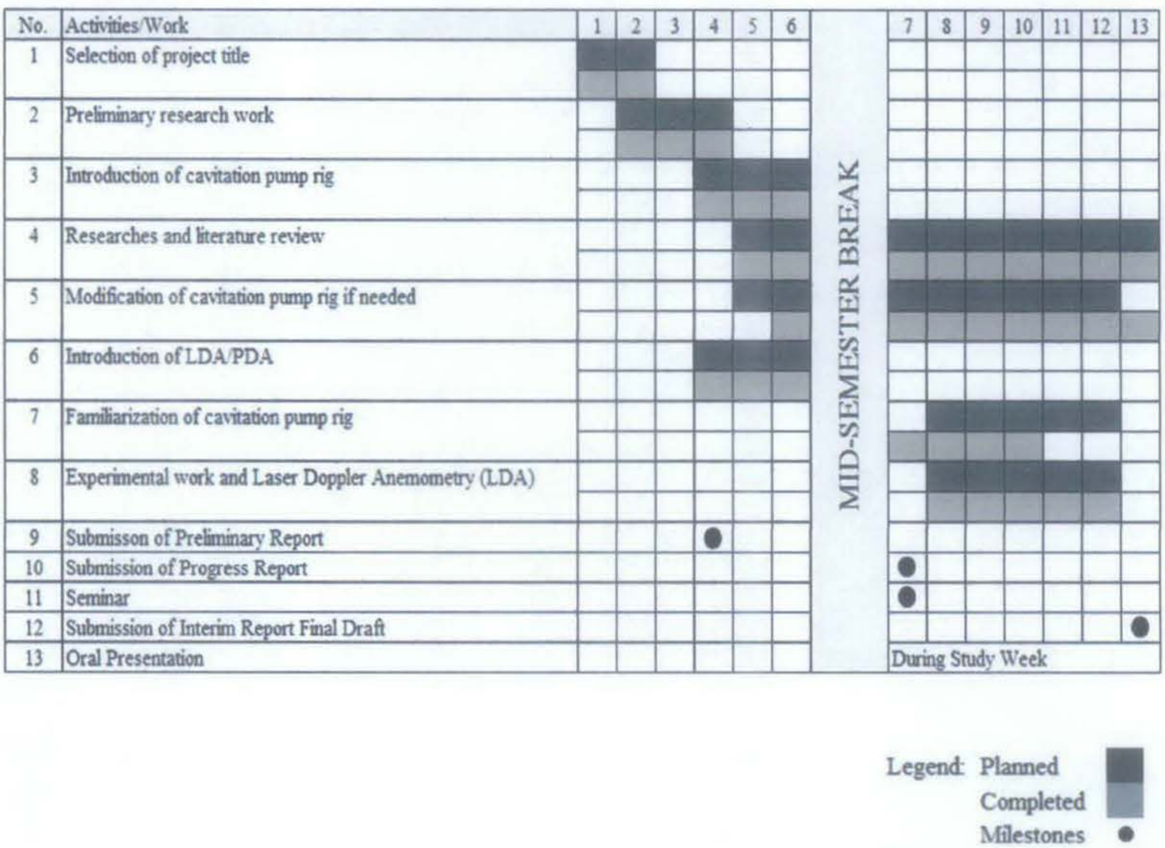


Figure 3.2 : Gantt chart and milestone for activities for Semester I

Figure 3.2 shows the Gantt Chart for activities for the first semester. It illustrates the planned and actual working schedule of the project from the very start until the end. Figure 3.3 shows the expected plan and progress for the second semester which is May 2011. Transportation of cavitation pump rig to LDA/PDA lab process had initially been started on Week 5 and finished during Week 8. The combination of cavitation pump rig and LDA/PDA had been done on Week 8. Adjustment of both equipment was performed to obtain the desired position for the laser beam to be aligned at the correct measurement points in the pipe. Additional research and literature reviews were completed in the period between Week 2 and Week 11. Experimental work and data collection for all test section pipes were finished on time as scheduled in Week 13.

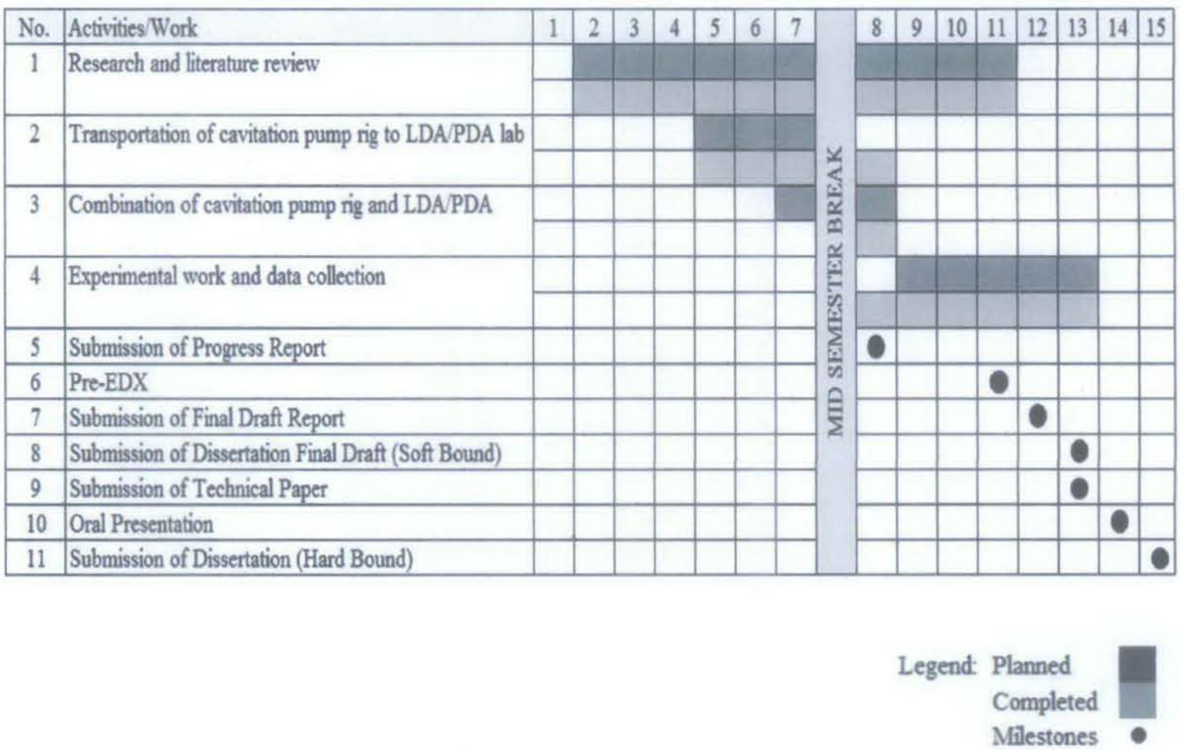


Figure 3.3 : Gantt chart and milestone for activities for Semester II

CHAPTER 4
EXPERIMENT SETUP

4.1 Cavitation Pump Rig

In order to study the liquid flow, a pipe system consists of water pump motor, air pump injector, water flow meter and control valve need to be setup as cavitation pump rig model. Figure 4.1 shows the cavitation pump rig. The main components of cavitation pump rig are water pump, pipe system and water tank. Bubbles are introduced to the water flow to create bubbly flow. The transparent pipe system is the most important element as the transparency allows the laser to penetrate through the pipe wall and reach the bubbly flow inside the pipe. With this, the laser beam could be transmitted to the desired area of interest and laser signals could then be received and transmitted to the software for further analysis. Experiments were conducted on fluid flow with two types of pipelines sections which are vertical upwards and vertical downwards. Accuracy and precision will be crucial factors in this experiment, so the data collected should be scaled down to achieve these constraints. The schematic of the cavitation pump rig is illustrated in Figure 4.2.

Figure 4.1 : The Cavitation Pump Rig

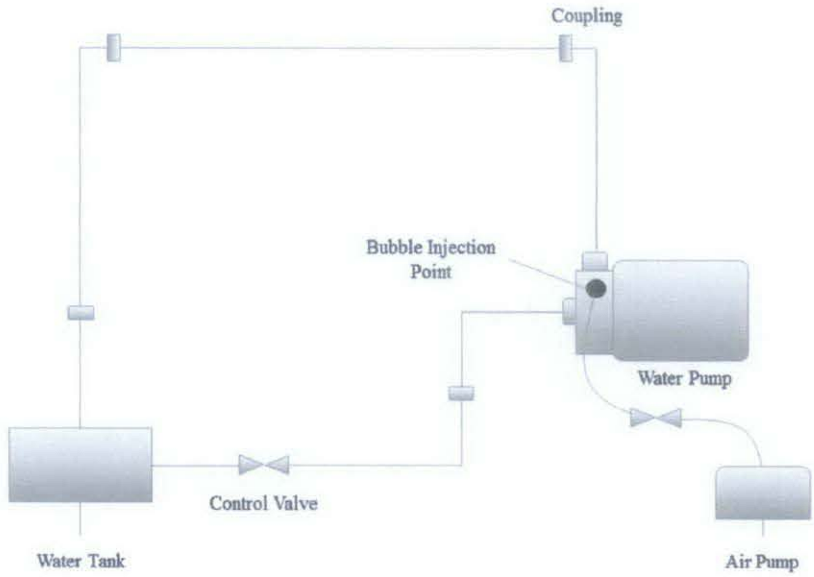


Figure 4.2 : Schematic diagram of cavitation pump to be used with LDA/PDA

The water in the pump system flows in a circulation. Figure 4.3 shows the water circulation in the cavitation pump rig. Water is sucked up by the water pump from the water tank, through the control valve and rotor blade. The water flows up vertically along the pipe system and then goes back to the water tank. Bubbles injected are carried upward by the flowing water.

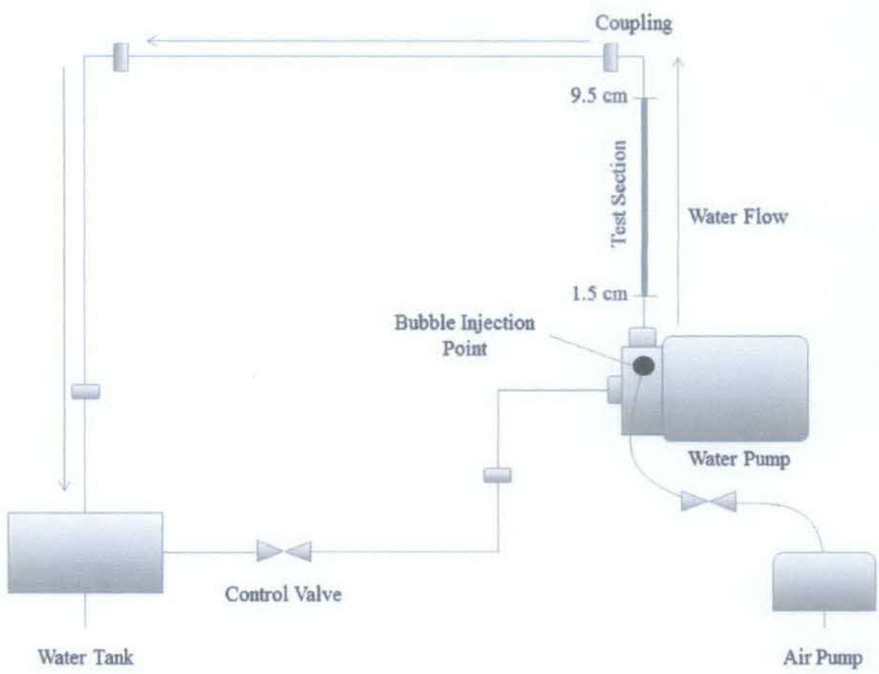


Figure 4.3 : Water circulation in cavitation pump rig

4.2 Experiment Data Points

Laser Doppler Anemometry (LDA) had been used to measure velocity and turbulence at specific points in liquid while with Phase Doppler Analysis (PDA), the size and velocity of spherical particles had been measured simultaneously before the details of droplet size and velocity measurements were obtained by using BSA Flow Software of Dantec Dynamics. Figure 4.4 represents the graphical summary of procedures for vertical upstream/upwards pipe section.

Water Flow Rate (gpm)	Position (cm)	Side of Pipe
5.0 / 10.0 / 15.0	1.50	Right
		Center
		Left
	3.50	Right
		Center
		Left
	5.50	Right
		Center
		Left
	7.50	Right
		Center
		Left
	9.50	Right
		Center
		Left

Figure 4.4 : Procedures for vertical upstream/upwards pipe section

Figure 4.5 graphically shows the measurement points for the vertical downwards pipe. For each section of pipes which are left, center and right section, there were 5 points of experimental data (A,B,C,D and E). So there were a total of 75 measurement points in the experiment.

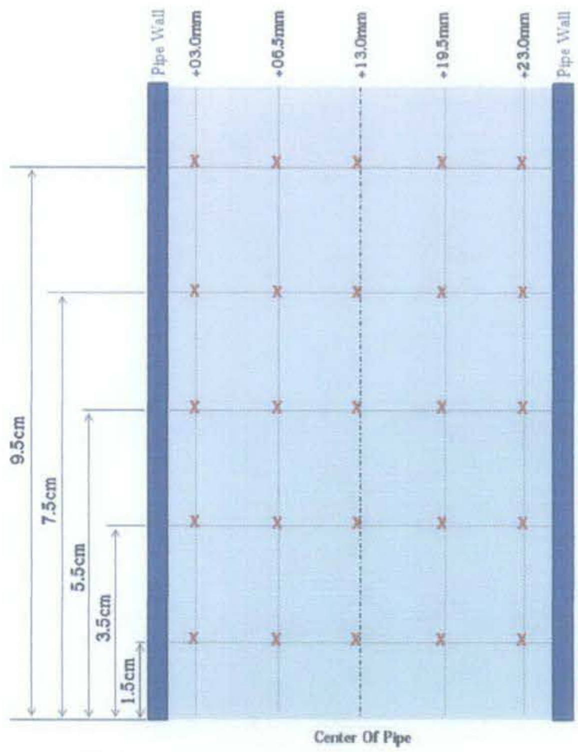


Figure 4.5 : Data points of vertical upstream/upwards pipe

For the horizontal displacement, data was taken from the displacement of 3.0 mm until 23mm as the inner diameter of the pipe is 26 mm. As for vertical displacement, data were taken at 1.5 cm, 3.5 cm, 5.5 cm, and 7.5 cm from the bottom coupling of vertical upwards pipe.

4.3 Water Flow Rate

The flow rate of water will be indicated by the water flow meter. Figure 4.6 shows the water flow meter used in this experiment. The water flow rates are determined first before the experiments are conducted. The unit for the water flow rate is gallon per minute (gpm). The minimum water flow rate is 1 gpm while the maximum water flow rate is 23 gpm. Three water flow rate were considered in this experiment which is 5 gpm, 10 gpm and 15 gpm.

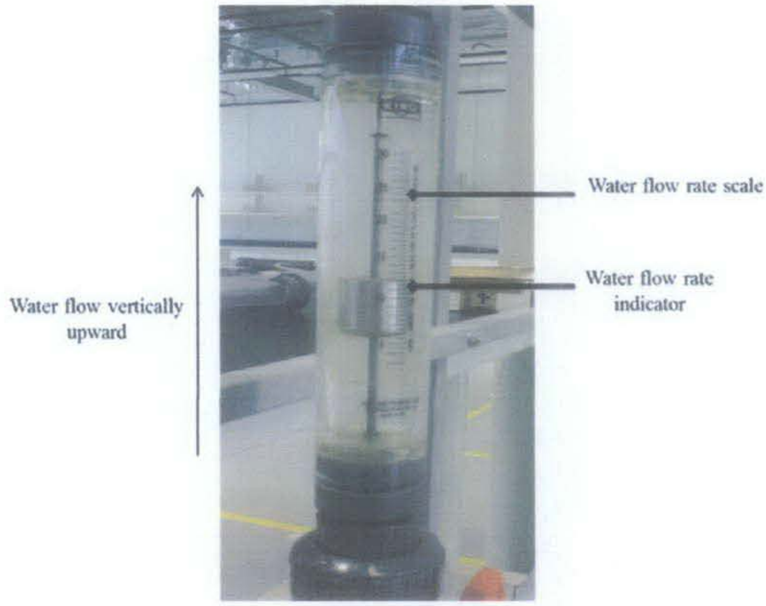


Figure 4.6 : Water flow meter

4.4 Control Valve

Figure 4.7 : Control valve & water tank of the system

Figure 4.7 shows a control valve (ball valve type) placed in between the tank and water pump to control the flow of water from the tank to the pump and prevent too much reverse flow when the pump is switched off. This will help ease the start up of the whole system for the next time.

4.5 Laser Doppler Anemometry (LDA) / Phase Doppler Anemometry (PDA)

Laser Doppler Anemometry (LDA) was used to measure velocity and turbulence at specific points in gas or liquid flows. With this equipment the movement of the air bubbles that have very small diameter, normally in micron can be investigated. Data for vertical velocity, horizontal velocity and diameter of the air bubbles could be obtained.

Phase Doppler Anemometry (PDA) is an optical technique to measure the size and velocity of spherical particles simultaneously. These particles can be droplets, bubbles or solid particles, as typically occur in sprays, liquid atomization, bubbly two-phase flows and multiphase flows with, for example, glass beads. The measurement point is defined by the intersection of two focused laser beams and the measurements are performed on single particles as they move through the sample volume. Particles thereby scatter light from both laser beams, generating an optical interference pattern.

Figure 4.8 shows the orientation of the LDA/PDA lab in Universiti Teknologi PETRONAS (UTP). The laser source is shown in Figure 4.9.

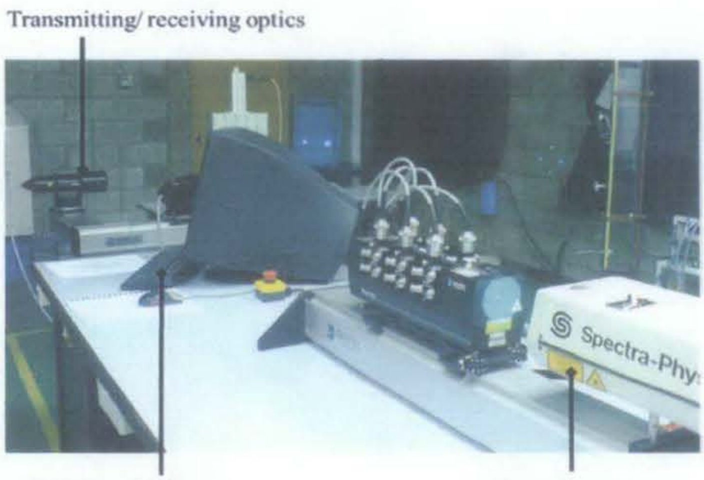


Figure 4.8 : LDA/PDA orientation in UTP lab

Figure 4.9 : Laser source for LDA/PDA

Figure 4.10 : Transmitting and receiving probes

Figure 4.10 shows the orientation of transmitting and receiving probes. There are two transmitting probes, which are one-component probe and two-component probe. For this project, only two-component had been used for 2-D results. There are 4 laser beams transmitted from the laser source which then converge to form an intersection point. As for the one-component probe, which will give 3-D results, is neglected.

The receiving probe takes in laser signals from the intersection point and transmits them to the BSA software (from the computer) to be interpreted.

4.5.1 Laser Doppler Anemometry (LDA)

Laser Doppler Anemometry (LDA) is shown a non-intrusive optical technique used to measure velocity and turbulence at specific points in gas or liquid flows as in Figure 4.11. Applications of LDA include measurements of free flows around road vehicles, aircrafts and ships and internal flows in pump, mixers, turbines and engines. Measurements improve knowledge about the flow and can lead to better efficiency and reduced noise. With this equipment the movement of the air bubbles that have very small diameter, normally in micron can be investigated. Data for vertical velocity, horizontal velocity and diameter of the air bubbles could be obtained.

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 photo Detector.
- A signal conditioner and a signal processor.

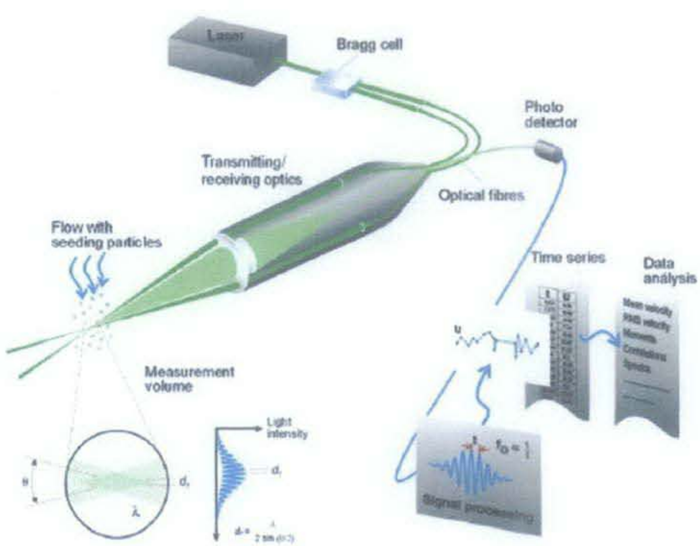


Figure 4.11 : LDA working principle

4.5.2 Phase Doppler Anemometry (PDA)

Phase Doppler Anemometry (PDA) is an optical technique to measure the size and velocity of spherical particles simultaneously. These particles can be droplets, bubbles or solid particles, as typically occur in sprays, liquid atomization, bubbly two-phase flows and multiphase flows with, for example, glass beads. The measurement point is defined by the intersection of two focused laser beams and the measurements are performed on single particles as they move through the sample volume. Particles thereby scatter light from both laser beams, generating an optical interference pattern as shown in Figure 4.12.

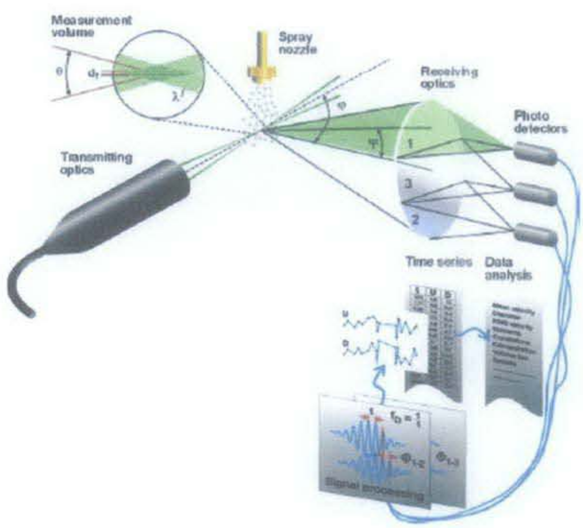


Figure 4.12 : PDA working principle

4.6 Vane Anemometer

A vane anemometer is a device that measures the velocity of the air or wind, as well as air pressure. The vane anemometer used in this project is called handheld anemometer and was used to take measurement of velocity of the air flow from the air pump. The maximum velocity of air injected into the pipe is 1.50 m/s. Figure 4.13 shows the vane anemometer set used in this project to measure the velocity of the air pumped into the pipe system in order to induce air bubbles.

Figure 4.13 : Vane anemometer set

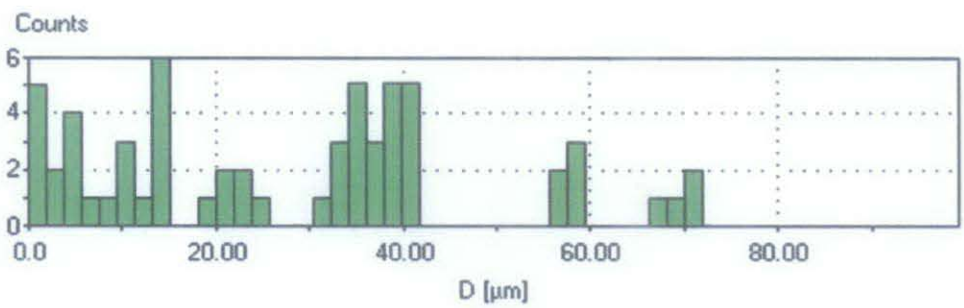
4.7 Integrated PDA Solutions

Dantec Dynamics' Particle Dynamics Analysis (PDA) systems measure on-line the size, velocity and concentration of spherical particles, droplets or bubbles suspended in gaseous or liquid flows. The principles of Particle Dynamics Analysis (PDA)

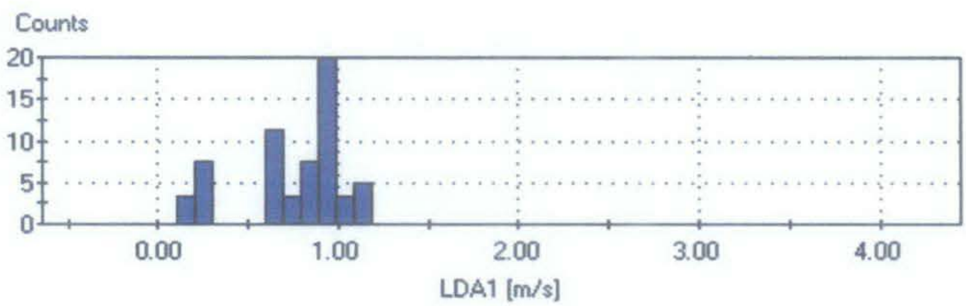
1. The measurements are performed at the intersection of two laser beams, where there is an interference fringe pattern of alternating light and dark planes.
2. Particles scatter the light, which appears to flash, as the particles pass through the bright planes of the interference pattern. Receiving optics placed at an off-axis location focus scattered light onto multiple detectors.
3. Each detector converts the optical signals into a Doppler burst with a frequency linearly proportional to the particle velocity.
4. The processor measures the phase difference between the Doppler signals from different detectors. This is a direct measure of the particle diameter.
5. Results are processed by the BSA Flow Software Packages.

4.8 BSA Flow Software Data Sheet

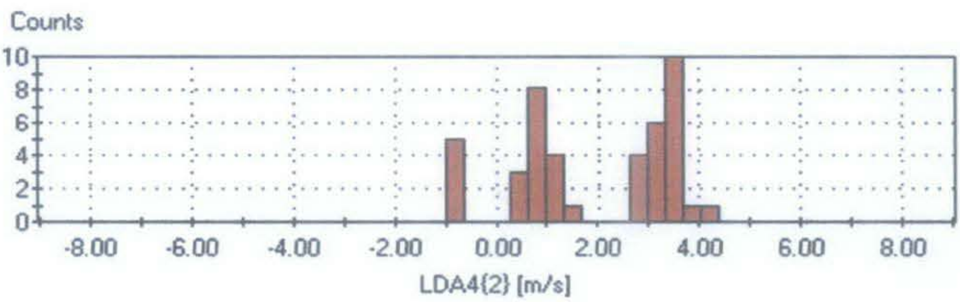
BSA Flow Software data sheets were obtained for further analysis. It is displayed on the monitor screen once the receiving probe has received enough data to be tabulated into histogram. Figure 4.14 shows a data sheet example for 5 gpm water flow rate at an elevation of 1.5 cm from the coupling at the center of pipe.



(a) Diameter



(b) Horizontal velocity



(c) Vertical velocity

Figure 4.14 : Typical histograms of frequency of measurements

Figure 4.14 shows the sample result from the experiment. From the sheet produced, the result is divided into three sections which are diameter, horizontal velocity and vertical velocity of the bubbles. It summarized the counts for individual measurement, for example at the vertical velocity data results. Five counts of bubbles with downward velocity of 1 m/s is recorded at the measured point. The reading is in negative value as it opposed the flow direction of the water which is in the upward direction.

CHAPTER 5
RESULTS AND DISCUSSIONS

5.1 Preparation Summary

Data is analyzed for 3 water flow rates to characterize the bubble flow and behaviour in water flow. An upward force was exerted on both the water and bubbles by water pump and air pump respectively along with gravitational force acting downward of the pipe. Air was injected through a quick release connector at a velocity of 1.5 m/s. In this chapter, discussion is included along with the graphs plotted to show the relationship between sauter mean diameter, horizontal and vertical velocity with the data positions. The results are then compared with the pictures taken during the experiments.

5.2 Water Velocity

The velocity of water flowing upward of each water flow rate was calculated by using the equation:

$$V = Q/A \tag{5.1}$$

A is the cross sectional area of pipe (m^2) while Q is water flowrate (m^3/s) and V is equal to water velocity (m/s). The cross sectional area of pipe was calculated using the formula:

$$A = \pi D_i^2/4 \tag{5.2}$$

Table 5.1: Unit conversion for motor speed and water flow rate

Water flow rate (gpm)	Water flow rate (m^3/s)	Water velocity (m/s)
5	0.000315	0.5943
10	0.000630	1.1887
15	0.000945	1.7830

5.3 5 gpm Water Flowrate (V_{water} = 0.59 m/s)

5.3.1 Sauter Mean Diameter, D_{32}

Figure 5.1 is plotted for sauter mean diameter, D_{32} (µm) at vertical displacement from the edge of pipe up to its diameter (cm) versus horizontal displacement from the center of pipe (cm).

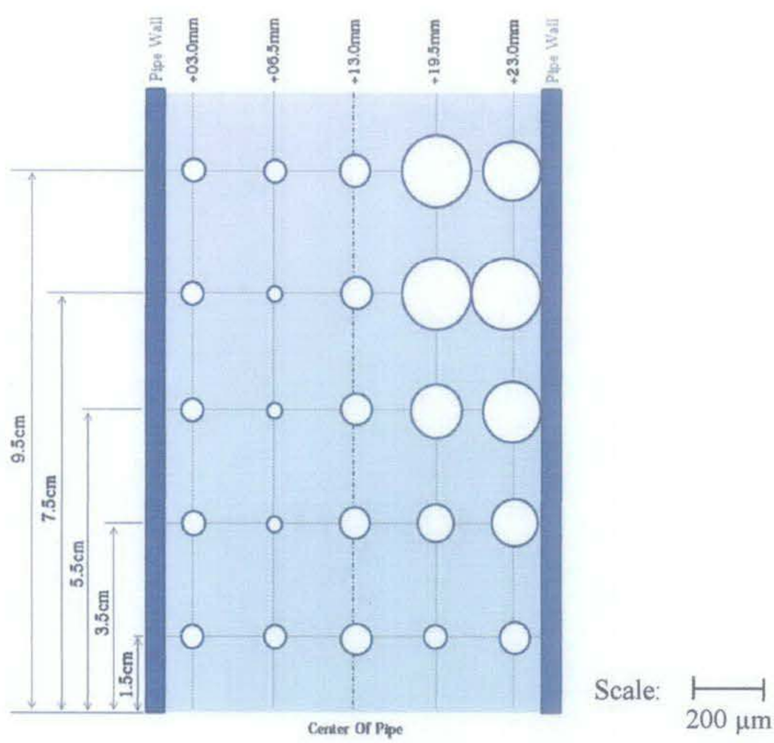


Figure 5.1 : Distribution of average bubble diameter for 5 gpm

It is shown in Figure 5.1 that the bubbles flowing upward along the center of pipe have a constant size range at different heights of the pipe with the average size of 65 µm. As small bubbles dispersed through a continuous fluid, it indicates that the flow at the center of pipe was a bubble flow where in bubbly flow, each fluid moves at a different speed due to different gravitational forces and other factors, like upward forces and wall drag with the heavier phase which is water, is moving slower than the lighter phase, which is bubbles or air in this case. The effect of buoyancy force affected the bubbles diameter to increase dynamically on the right side of pipe, which is on the 19.5 cm and 26.0 cm horizontal displacement. Due to no-slip condition, from the development of velocity boundary layer the fluid particles in the layer in contact with the surface of the pipe come to a complete stop. As the weight of air is way lighter than the weight of water, the density of air is less than water. Thus, the buoyancy of air is greater than its own weight and will float to a level where it displaces the same weight of water as the weight of itself. As the bubbles slowed down at the wall, they merged and become bigger in diameters. Those bubbles at the center of the pipe, which are faster, have less chance to merge It shows that the bubbles at center of the pipe were almost uniform in diamaters, same as the bubbles at the left side which is at the horizontal elevation of 0.0 cm and 6.5 cm. Bigger bubbles were mostly located on the right side of the pipe, which are at the elevation of 19.5 cm and 26 cm. At 5gpm flow rate of water, non-symmetrical flow were observed. This may due to the flow separation after passing the elbow before reach the vertical upwards pipe. In a diverted flow of liquid such as in a 90-degree elbow, the resulted adverse pressure gradient causes the thin boundary layer to break off or separates into a broad pulsating wake. As a result, flow separation, which is normally accompanied by some backward motion flow, occurs at the upstream side of the elbow, thus causing pressure head loss and almost no bubbles were observed at the left side of pipe.

5.3.2 *Velocity Profile*

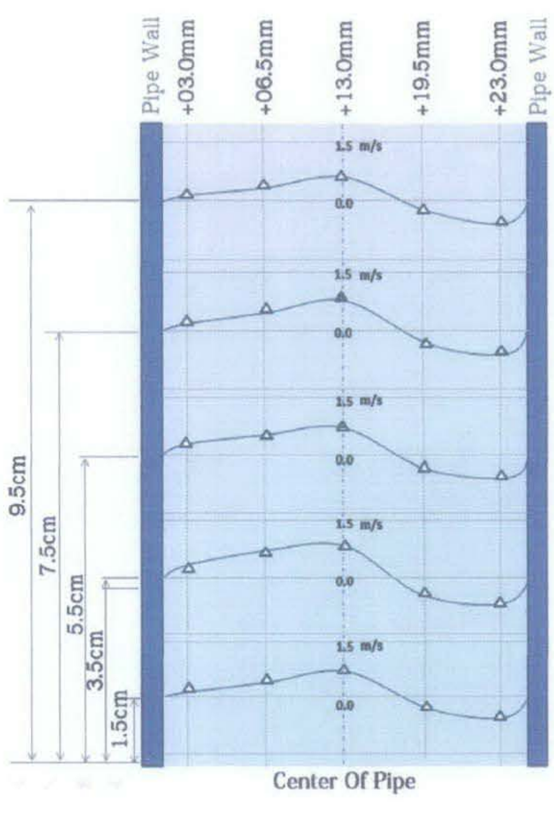


Figure 5.2 : Horizontal velocity profile of the air bubbles at 5 gpm

It is shown in the figure that the bubbles moved upward, the horizontal velocity at the center of pipe remained almost constant at the velocity of 0.6-0.8 m/s, only at the elevation of 1.5 cm from the bottom pipe recorded a quite low reading, which is 0.5793 m/s. The negative readings of horizontal velocity indicate that the bubble is moving to the right in horizontal elevation, while the positive readings obviously show that bubbles are moving to the left side of the test pipe. As the bubbles move towards the pipe walls, there are decrements in the velocities. Bubbles which are closer to the pipe move with a very low velocity. Theoretically, bubbles at the wall pipe have 0 m/s of velocity.

The bubbles were rather steady at this region as they only moved in the upward vertical direction. The bubbles were injected at the speed of 1.5 m/s in the water velocity of 0.5943 m/s for 5 gpm of water flow rate. As the weight of air is way lighter than the weight of water, the density of air is less than water.

Thus, the buoyancy of air is greater than its own weight and will float to a level where it displaces the same weight of water as the weight of itself. As the bubbles slowed down at the wall, they merged and become bigger in diameters. Those bubbles at the center of the pipe, which are faster, have less chance to merge. There are almost no bubbles at the left side of pipe because of flow separation after passing the elbows which caused the bubbles tend to visibly occur at the center of pipe and right side of pipe.

Figure 5.3 shows the development of vertical velocity of bubbles at 5 gpm of flow rate and the comparisons of all the vertical points had been combined. It was observed that bubble vertical velocity increased as it moved from elevation 1.5 cm to 9.5 cm. Theory of velocity boundary layer in a pipe for laminar flow was confirmed for the issue whereby the velocity of fluid increases at the center of pipe. As the bubbles travelled towards the pipe wall, the vertical velocities decrease constantly at most of the points measured. It is shown that the velocity at the wall is zero and the maximum velocity occurs at the center line of the pipe.

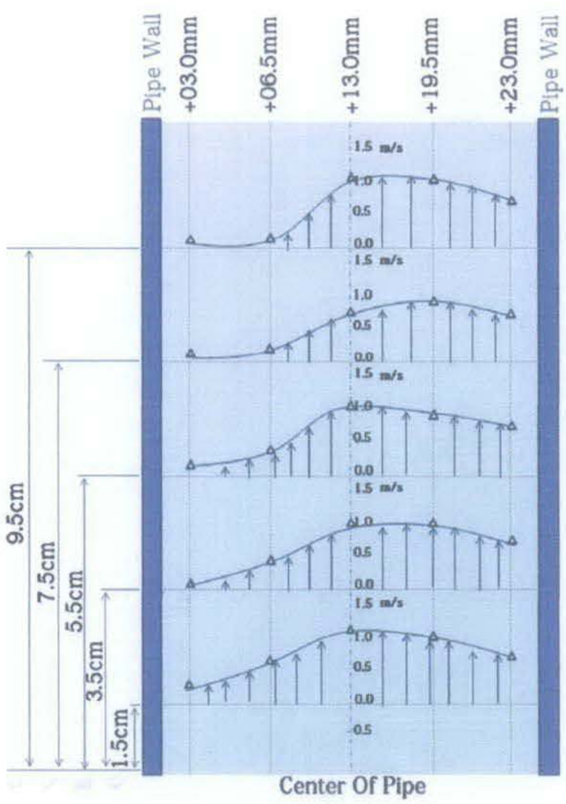


Figure 5.3 : Vertical velocity profile of the air bubbles at 5 gpm

This could be explained by using the theory of buoyancy. Buoyancy acted along this path, along with the gravitational downward acceleration, bringing the bubbles upward. The net upward buoyancy force is equal to the magnitude of the weight of fluid displaced by the air bubbles. This force enables the bubbles to float.

From the development of velocity boundary layer, due to no-slip condition, the fluid particles in the layer in contact with the surface of the pipe come to a complete stop. As the weight of bubbles is lighter than the weight of water, the density of air is less than water. Thus, the buoyancy of air is greater than its own weight and will float to a level where it displaces the same weight of water as the weight of itself.

In most cases the observation were paralled with the theory, which states that the maximum velocity will occurs at the center of the pipe or distribution profile but there are some cases as shown in the graph which not abiding the theory. For vertical displacement of 7.5cm from the bottom of the pipe, the maximum velocities occurred at the horizontal displacement of 19.5 cm, which is at 0.97 m/s. This may be due to some laser allignment errors during data collection and also from the pump motor of the system. There are some problems regarding the pump condition and from all the data taken, this is the best result that could be presented, yet it is still not abiding the theory.

5.4 10 gpm Water Flow Rate (V_{water} = 1.2 m/s)

5.4.1 Sauter Mean Diameter, D_{32}

Figure 5.4 shows the sauter mean diameter, D_{32} (μm) of the air bubbles at vertical displacement from the edge of pipe up to its diameter (cm) versus horizontal displacement from the center of pipe (cm).

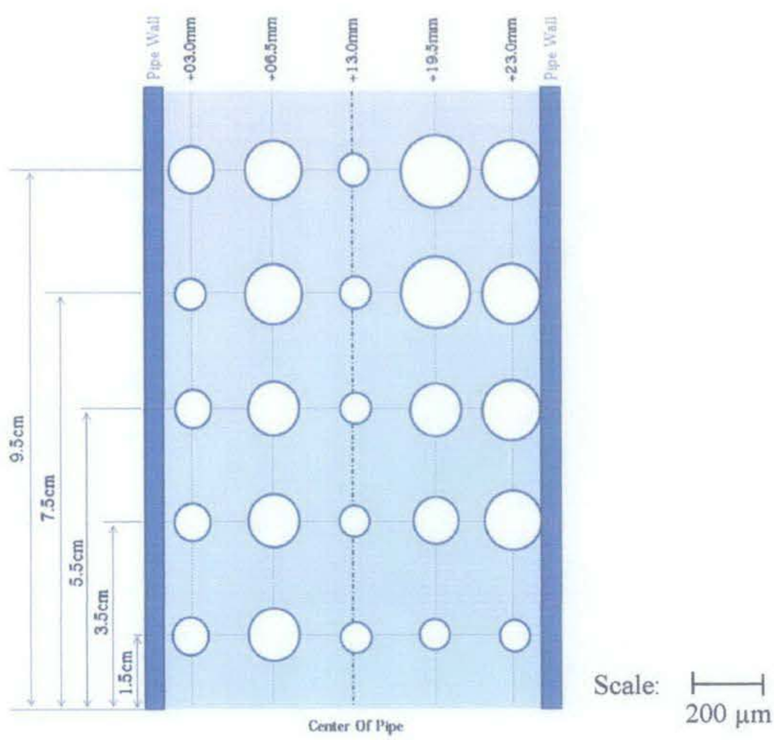


Figure 5.4 : Distribution of average bubble diameter for 10 gpm

The bubbles flowing upward along the center of pipe have a constant size range at different heights of the pipe with the average size of 64 μm, slightly smaller from the average diameter of bubbles at the center pipe of 5 gpm which is 65 μm. As small bubbles dispersed through a continuous fluid, it indicates that the flow at the center of pipe was a bubble flow where in bubbly flow, each fluid moves at a different speed due to different gravitational forces and other factors, like upward forces and wall drag with the heavier phase which is water, is moving slower than the lighter phase, which is bubbles or air in this case.

It was observed that the flow has become almost symmetrical at 10 gpm flow rate. From the graphs, the bubbles flowing upward at the center of pipe had constant size range at different heights. This is a sign of bubble flow, where the air pumped into the pipe moves as small dispersed bubbles through a continuous fluid. Also, it is true that this bubble flow occurs at a relatively low flow rate of 10 gpm and low holdup of the bubbly fluid. In bubbly flow, each fluid moves at a different speed due to different gravitational forces and other factors, like wall drag and upward forces, with the heavier phase than the lighter phase. Water is the heavier phase and the lighter phase is air/bubbles in this case.

Due to no-slip condition, from the development of velocity boundary layer the fluid particles in the layer in contact with the surface of the pipe come to a complete stop. As the weight of air is way lighter than the weight of water, the density of air is less than water. Thus, the buoyancy of air is greater than its own weight and will float to a level where it displaces the same weight of water as the weight of itself. As the bubbles slowed down at the wall, they merged and become bigger in diameters. Those bubbles at the center of the pipe, which are faster, have less chance to merge.

The bubbles also were not stable as the bubbles moved towards the pipe wall. The trend is rather indistinct as there is different size ranges, from the smallest to the largest. This could be due to the higher water flow rate been used which is 10 gpm, rather than 5 gpm for the previous experiment. The air could have moved as large bubbles dispersed within continuous water flow and these large bubbles probably formed by small bubbles coalescence. With the analysis, this flow could possibly be plug flow or slug flow because it contains both small and large bubbles but it also may due to the decrease of velocity due to drag and friction. Drag could be caused by pipe wall or the fluid itself. Drag or fluid resistance is the forces that oppose the relative motion of an objective through fluid. In this case, the drag forces act downward, which is the opposite direction of the oncoming flow velocity.

5.4.2 Velocity Profile

Figure 5.5 shows as the bubbles moved upward, the horizontal velocity at the center of pipe remained almost uniform at the velocity of 1.0-1.3 m/s. The negative readings of horizontal velocity indicate that the bubble is moving to the right in horizontal elevation, while the positive readings obviously show that bubbles are moving to the left side of the test pipe. As the bubbles move towards the pipe walls, there are decrements in the velocities. Bubbles which are closer to the pipe move with a very low velocity. Theoretically, bubbles at the wall pipe have 0 m/s of velocity. The bubbles were rather steady at this region as they only moved in the upward vertical direction. The bubbles were injected at the speed of 1.5 m/s in the water velocity of 1.1887 m/s for 10 gpm of water flow rate. As the weight of air is way lighter than the weight of water, the density of air is less than water.

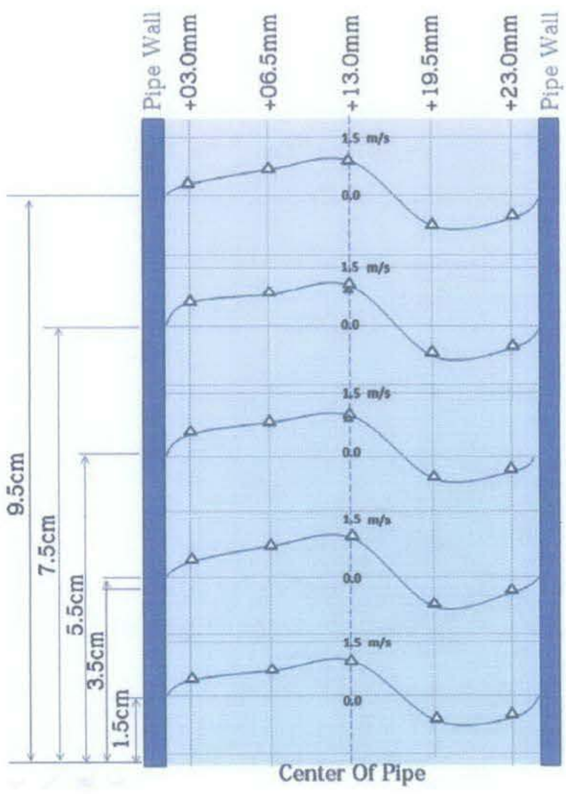


Figure 5.5 : Horizontal velocity profile of air bubbles at 10 gpm

Thus, the buoyancy of air is greater than its own weight and will float to a level where it displaces the same weight of water as the weight of itself. As the bubbles slowed down at the wall, they merged and become bigger in diameters. Those bubbles at the center of the pipe, which are faster, have less chance to merge. So as the result, it can be observed that the velocity is lower at the right and left side of pipe than at the center of pipe, neglecting the negative signs. From Figure 5.6, it was observed that bubble vertical velocity increased as it moved from elevation 1.5 cm to 9.5 cm. Theory of velocity boundary layer in a pipe for laminar flow was confirmed for the issue whereby the velocity of fluid increases at the center of pipe, which also stated that maximum velocity occurred at the center of the pipe. As the bubbles travelled towards the pipe wall, the vertical velocities decreased constantly at most of the points measured. This could be explained by using the theory of buoyancy.

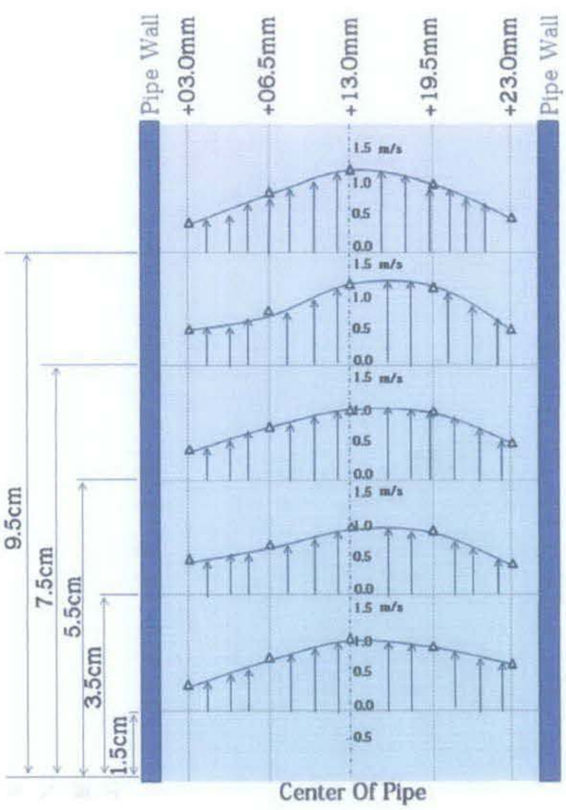


Figure 5.6 : Vertical velocity profile of air bubbles at 10 gpm

Buoyancy acted along this path, along with the gravitational downward acceleration, bringing the bubbles upward. The net upward buoyancy force is equal to the magnitude of the weight of fluid displaced by the air bubbles. This force enables the bubbles to float. From the development of velocity boundary layer, due to no-slip condition, the fluid particles in the layer in contact with the surface of the pipe come to a complete stop. As the weight of bubbles is lighter than the weight of water, the density of air is less than water. Thus, the buoyancy of air is greater than its own weight and will float to a level where it displaces the same weight of water as the weight of itself.

5.5 15 gpm Water Flow Rate (V_{water} = 1.8 m/s)

5.5.1 Sauter Mean Diamter, D_{32}

Figure 5.7 shows the sauter mean diameter, D_{32} (μm) at vertical displacement from the edge of pipe up to its diameter (cm) versus horizontal displacement from the center of pipe (cm). The bubbles flowing upward along the center of pipe have a constant size range at different heights of the pipe with the average size of 54.58 μm, which is smaller from the average diameter of bubbles at the center pipe of 10gpm which is 64.14 μm. As small bubbles dispersed through a continuous fluid, it indicates that the flow at the center of pipe was a bubble flow where in bubbly flow, each fluid moves at a different speed due to different gravitational forces and other factors, like upward forces and wall drag with the heavier phase which is water, is moving slower than the lighter phase, which is bubbles or air in this case.

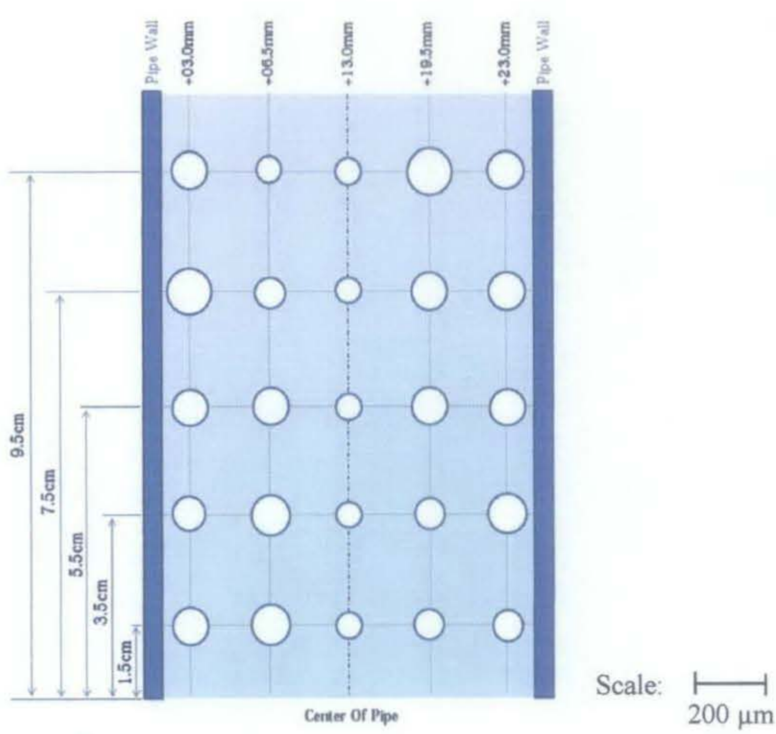


Figure 5.7 : Distribution of average bubble diameter for 15 gpm

By comparing the three graphs, it is obvious that the bubbles flowing upward at the center of pipe for each water flow rates showed a significant change in multiphase flow regime. The flow regime is identified as churn or froth flow whereby large, irregular slugs of air move up the center of pipe, usually carrying droplets of water with them. The remaining water flows up along the pipe walls. The phases are not continuous. The air slugs are relatively unstable, and take on large, elongated shapes. At a water flow rate of 15 gpm, it could be concluded that churn or froth flow occurs at high velocity.

5.5.2 Velocity Profile

Figure 5.8 showed as the bubbles moved upward, the horizontal velocity at the center of pipe remained almost constant and at the velocity of 1.0 – 1.1 m/s. The fluid flow at the center of pipe was linear and upward and the bubbles were rather steady at this region as they only moved in the upward vertical direction.

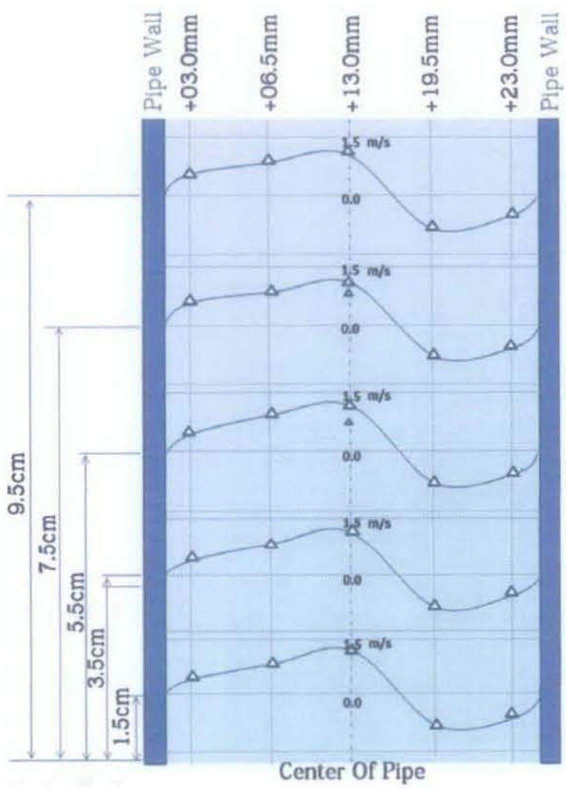


Figure 5.8 : Horizontal Velocity Profile at 15 gpm

The bubbles were injected at the speed of 1.5 m/s in the water velocity of 1.7830 m/s for 15 gpm of water flow rate. As the weight of air is way lighter than the weight of water, the density of air is less than water. Thus, the buoyancy of air is greater than its own weight and will float to a level where it displaces the same weight of water as the weight of itself. As the bubbles slowed down at the wall, they merged and become bigger in diameters. Those bubbles at the center of the pipe, which are faster, have less chance to merge. So as the result, it can be observed that the velocity is higher at the right side of pipe than at the center of pipe. The negative sign indicates that the direction of bubbles to the right. Positive reading shows that the bubbles are moving to the left side of pipe section. Comparisons were made by neglecting those negative signs.

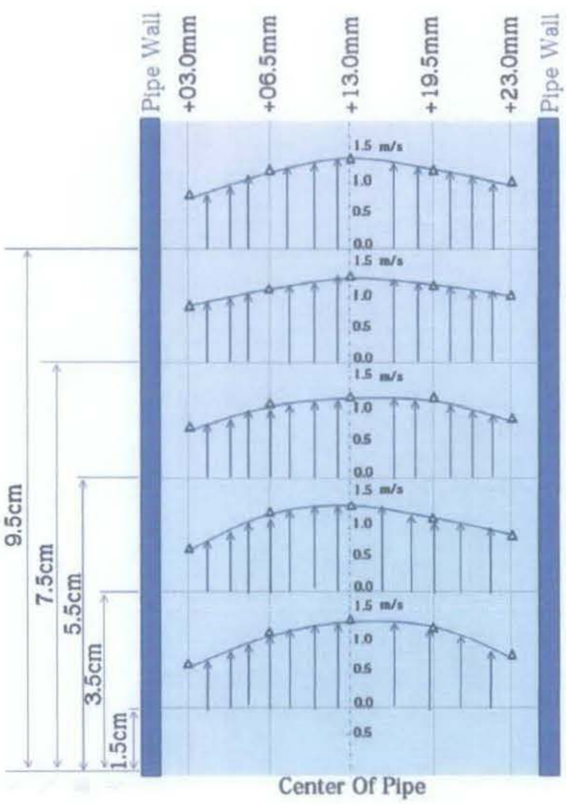


Figure 5.9 : Vertical velocity profile of air bubbles at 15 gpm

From Figure 5.9, it was observed that bubble vertical velocity increased as it moved from elevation 1.5 cm to 9.5 cm generally. As the bubbles travelled towards the pipe wall, the vertical velocities increased constantly at most of the points measured. This could be explained by using the theory of buoyancy. Buoyancy acted along this path, along with the gravitational downward acceleration, bringing the bubbles upward. The net upward buoyancy force is equal to the magnitude of the weight of fluid displaced by the air bubbles. This force enables the bubbles to float. From the development of velocity boundary layer, due to no-slip condition, the fluid particles in the layer in contact with the surface of the pipe come to a complete stop. As the weight of bubbles is lighter than the weight of water, the density of air is less than water. Thus, the buoyancy of air is greater than its own weight and will float to a level where it displaces the same weight of water as the weight of itself.

5.6 Comparisons With Previous Project

5.6.1 Velocity Profiles

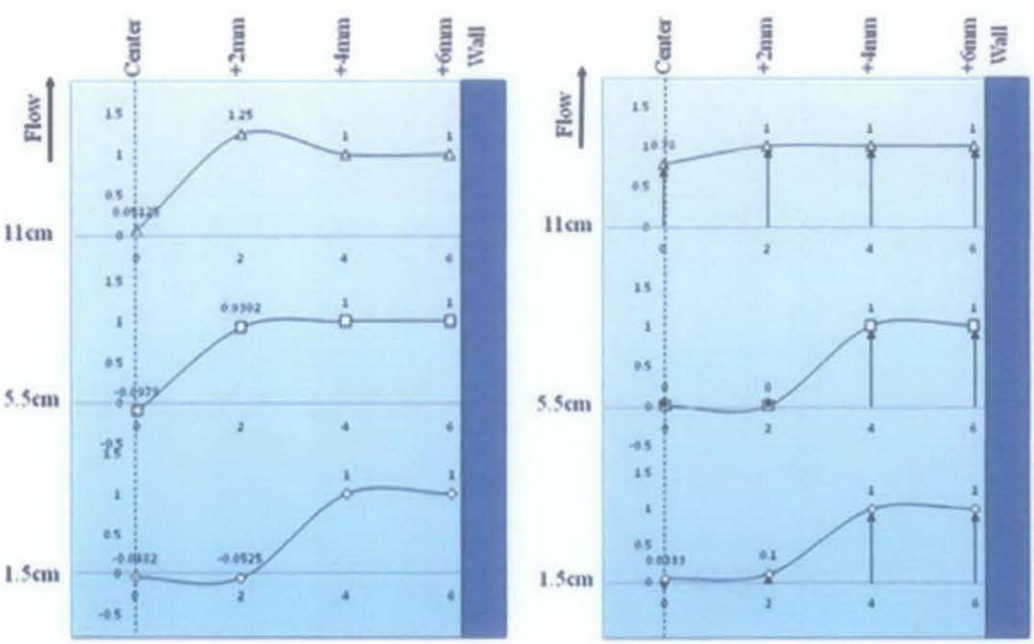


Figure 5.10 : Horizontal & vertical velocity for 15 gpm (Shang Pei, 2010)

From the previous result at Figure 5.10, the maximum velocity of bubbles mostly were observed near the pipe wall. From the theory of laminar boundary layer on the distribution of bubbles, not all of the velocities of particles have the similar velocity with water but obviously, the maximum velocity of water will be at the center of the pipe. The mass of particles, which is air bubbles in this case, is small, thus it has less energy. Water, which is of greater mass and higher energy level, pushes the weak mass of air aside towards the low velocity region. This low velocity region refers to the pipe wall. At the pipe wall region, these bubbles slow down, merge and become bigger in size. At the centerline of the boundary layer, the water flow is faster and bubbles have less chance to merge. The shape of the velocity profiles depends upon whether the flow is laminar or turbulent. If the flow in a pipe is laminar, the velocity distribution at a cross section will be parabolic in shape with the maximum velocity at the center being about twice the average velocity in the pipe. In turbulent flow, a fairly flat velocity distribution exists across the section of pipe, with the result that the entire fluid flows at a given single value.

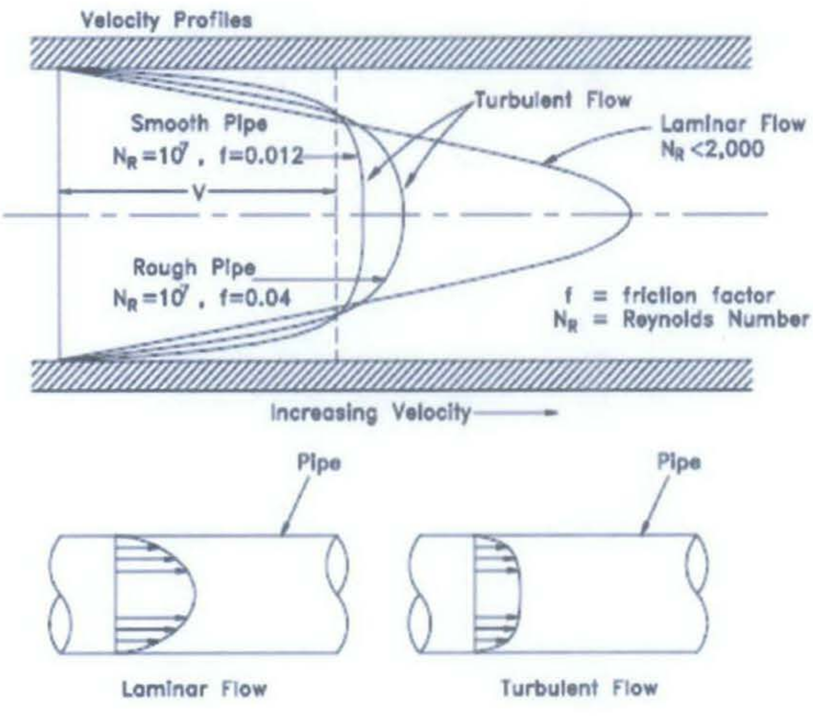


Figure 5.11 : Laminar & turbulent flow velocity profiles

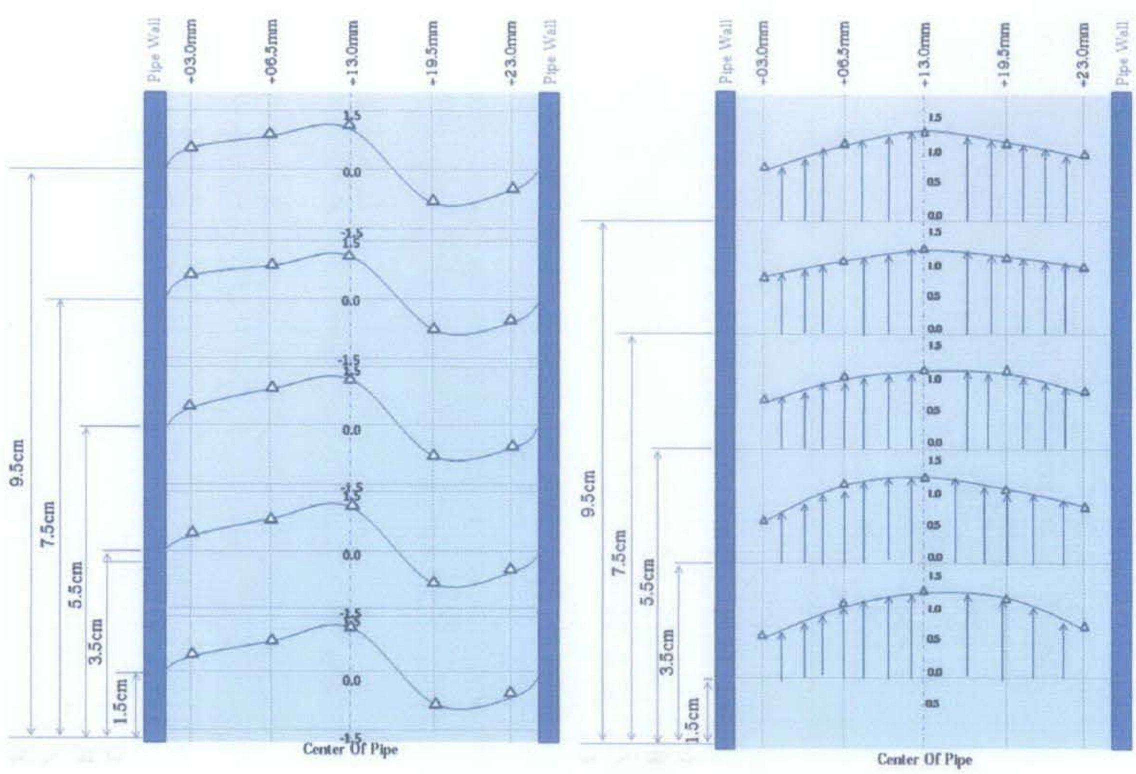


Figure 5.12 : Current horizontal & vertical velocity for 15gpm

From velocity profiles in Figure 5.12, it is obvious that the fluid is having a turbulent flow as there are fairly flat velocity distribution exists across the section of pipe. Errors may be accounted in the previous project as the Laser Doppler Anemometry (LDA) settings for experiment is quite difficult because of the laser alignment limited constraints.

CHAPTER 6
CONCLUSIONS & RECOMMENDATIONS

6.1 Conclusions

The bubbles in liquid flow changes its characteristics when it travels from center of pipe to near pipe wall and from lower elevation to higher elevation as it move from eddies phase towards steady flow and this is all because bubbles in liquid will create multiphase fluid flow as the result. There are variations of bubbles characteristics in terms of diameter along the liquid flow and the variation also happens because of water flow rates. The higher water flow rate will result in smaller bubbles diameter as it have less chances to merge when travelling along the pipe towards the upper elevation, where the liquid slowly become steady flow. Very large bubbles normally occur near pipe wall at where the heavier medium, which is water, would travel slower. As all of this processes or incidents occurred from natural inclinations or impulses and not from external incitement or constrain, they were considered spontaneous processes.

As the conclusion, the fluid flow is heavily affected by boundary layer, buoyancy force, drags and frictions. Thus, the objective of experiment to study the bubbles characteristic was achieved.

6.1 Recommendations

There are several unexpected cases happen along the project experimental activities. Initially the project is to analyze the characteristic of bubbles at another two different pipe sections which are vertical downstream/downwards and horizontal but due to the bad pump motor condition, those experiments could never been done in the very limited time constraints. The length of the pipe could be considered for variables of experiment but there are some alignment constraint of LDA/PDA equipment and the lab space as well. The effect of vibration as a factor of the presence of vibrant bubbles in pipeline could be one of the options to improve this project. LDA/PDA laser need to be adjusts and aligns at most of the time for the same data point for the correct reading, which will basically wasting the time. Installing a "cushion" for at the base of the pump motor will reduce the vibration as the current pump is simply connected with metal base and be attached to metal frames and this will caused the vibration to happen at overall system, not just at the vertical upstream/upwards pipe.

It is recommended that a new cavitation pump rig system need to be built with new pump in the same building as the new LDA/PDA system which will be placed in the coming months. So the problems of transferring the rig, which need to undergo several authorization signature and transportation booking problems, will not occur, as the experiment will be done exactly in the same laboratory at which will be equipped with new LDA/PDA system. If there is a new power motor to be bought later, it also needs to be serviced from time to time by technical staff to ensure it can be used for future experiments by students or lecturers and if all these basic recommendations are to be given high priority and could be solved, the experiments on bubble characteristic on cavitation pump rig can be elaborate widely and conducted with several new variables such as length and type of fluids with precise procedures without giving attention to these basic and unfavorable issues.

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APPENDICES

APPENDIX A

Sauter Mean Diamater, D_{32} at 5gpm

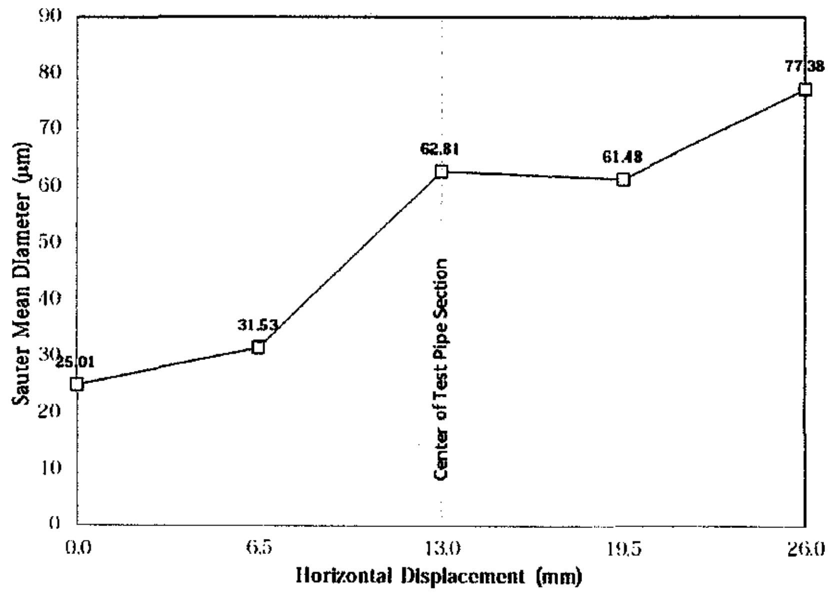

Figure A-1 : Vertical Displacement = 1.5cm

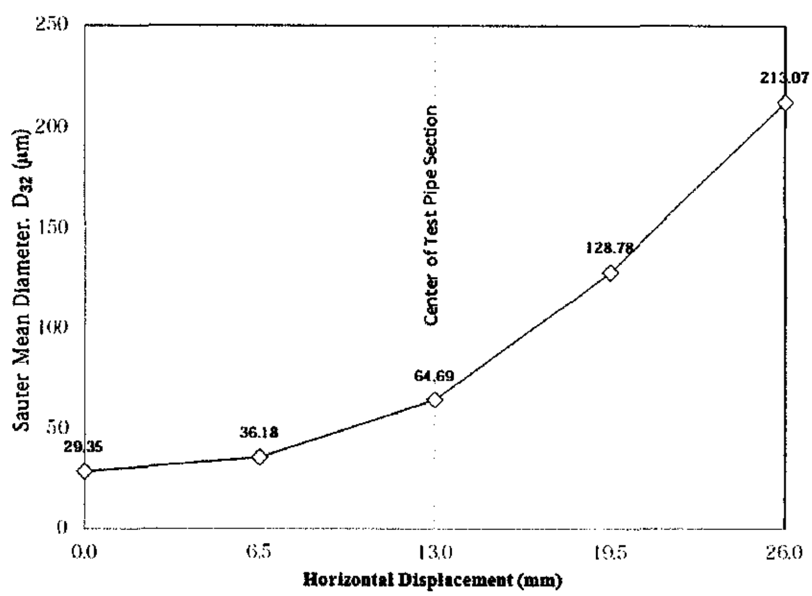

Figure A-2 : Vertical Displacement = 3.5cm

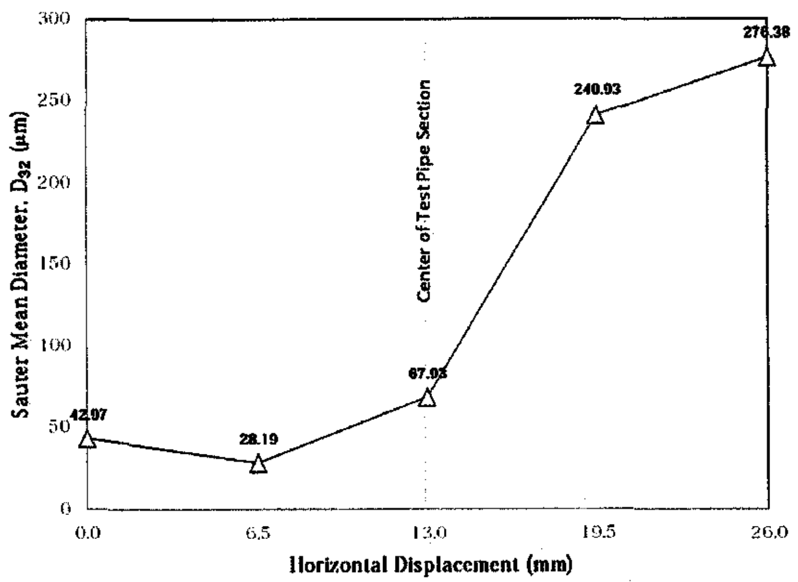

Figure A-3 : Vertical Displacement = 5.5cm

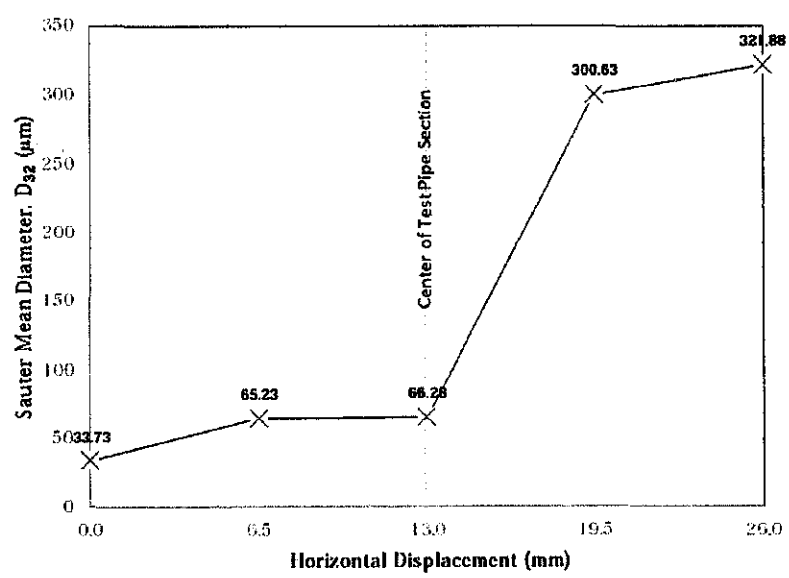

Figure A-4 : Vertical Displacement = 7.5cm

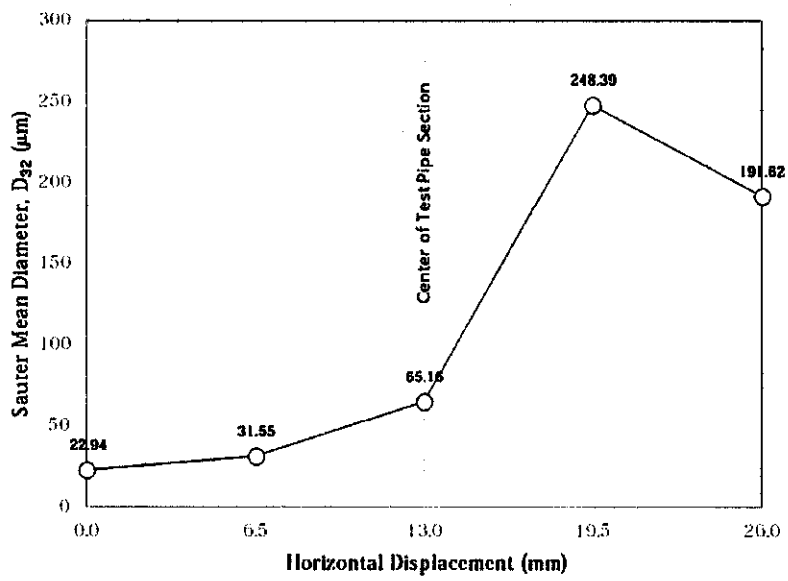

Figure A-5 : Vertical Displacement = 9.5cm

APPENDIX B

Sauter Mean Diamater, D_{32} at 10gpm

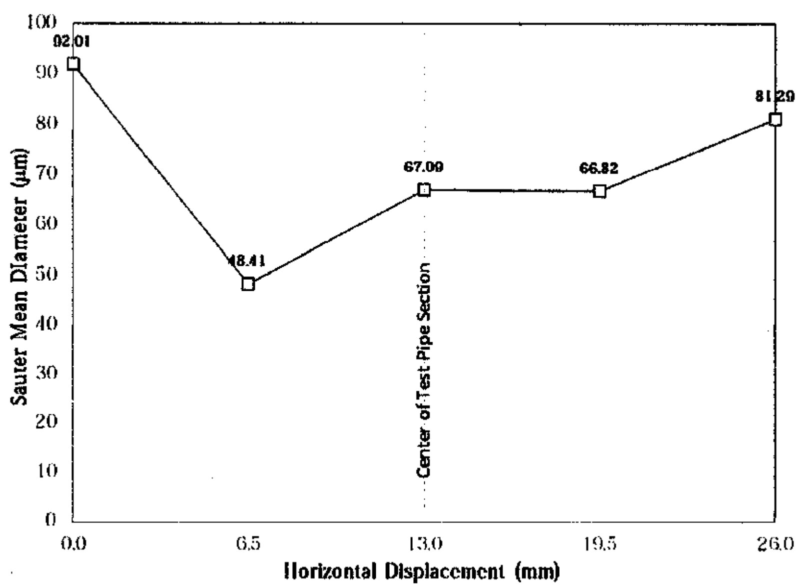

Figure B-1 : Vertical Displacement = 1.5cm

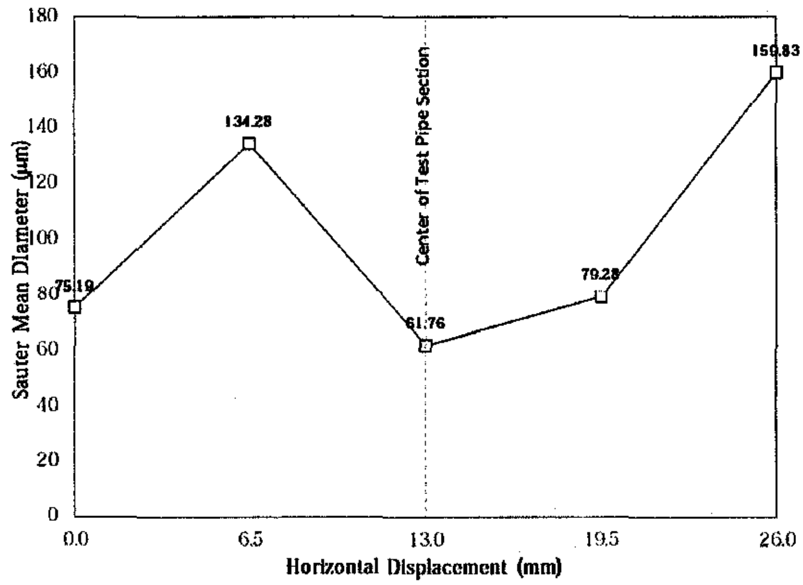

Figure B-2 : Vertical Displacement = 3.5cm

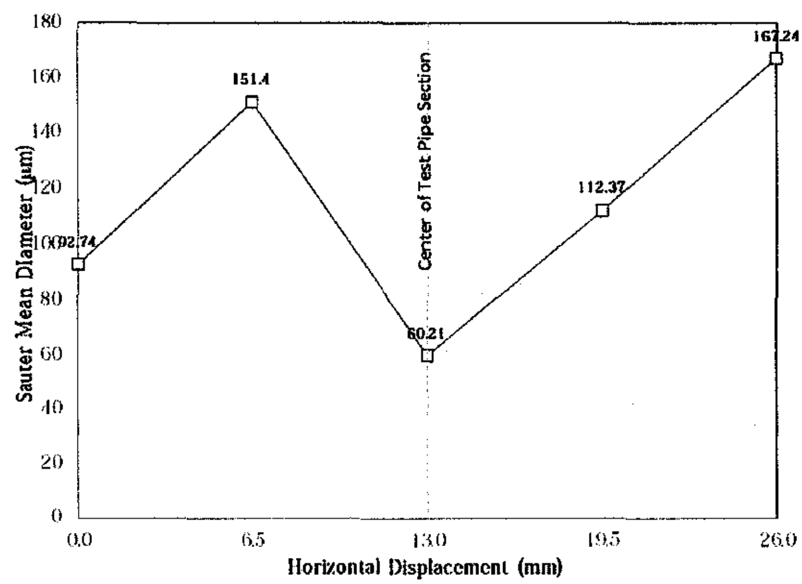

Figure B-3 : Vertical Displacement = 5.5cm

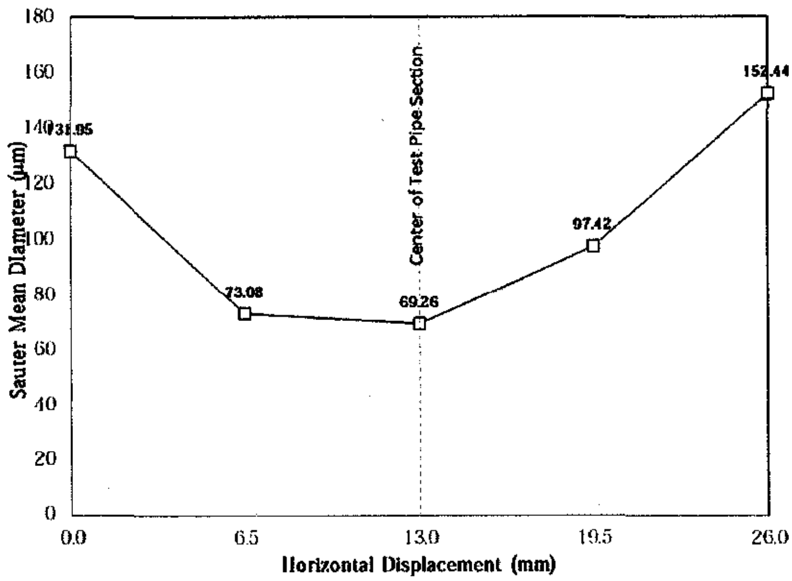

Figure B-4 : Vertical Displacement = 7.5cm

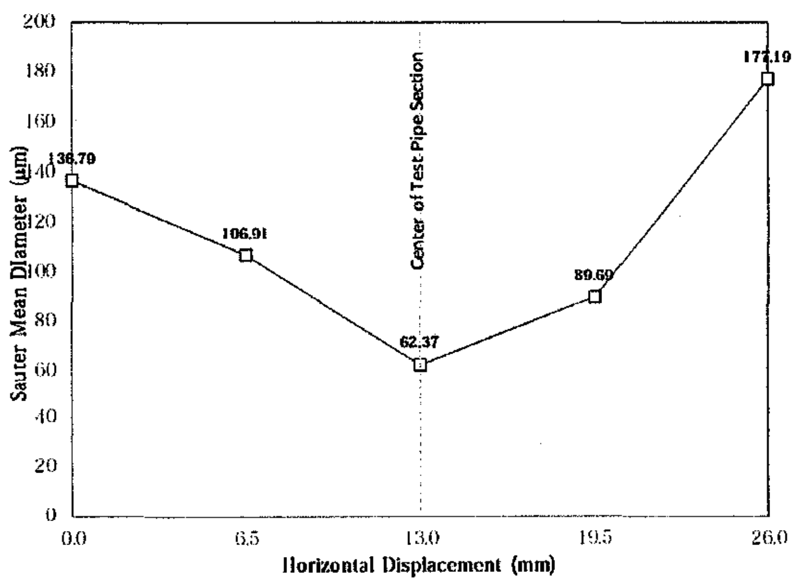

Figure B-5 : Vertical Displacement = 7.5cm

APPENDIX C

Sauter Mean Diamater, D_{32} at 15gpm

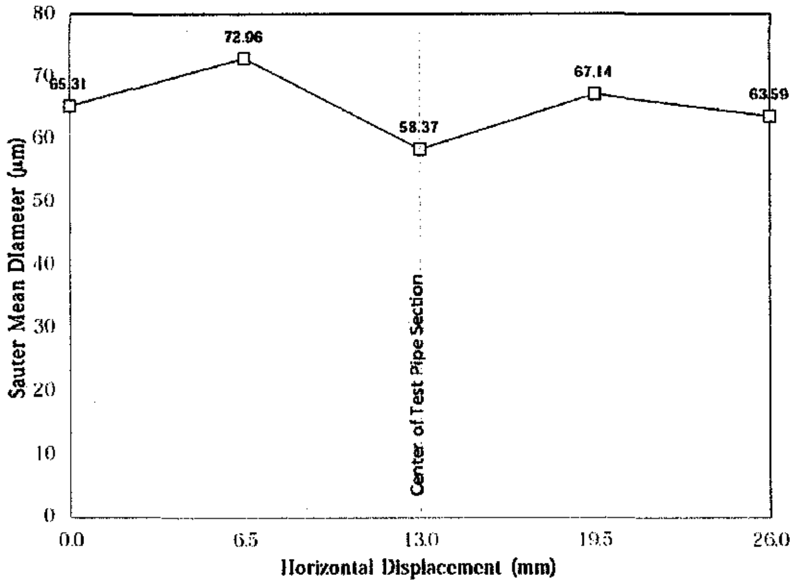

Figure C-1 : Vertical Displacement = 1.5cm

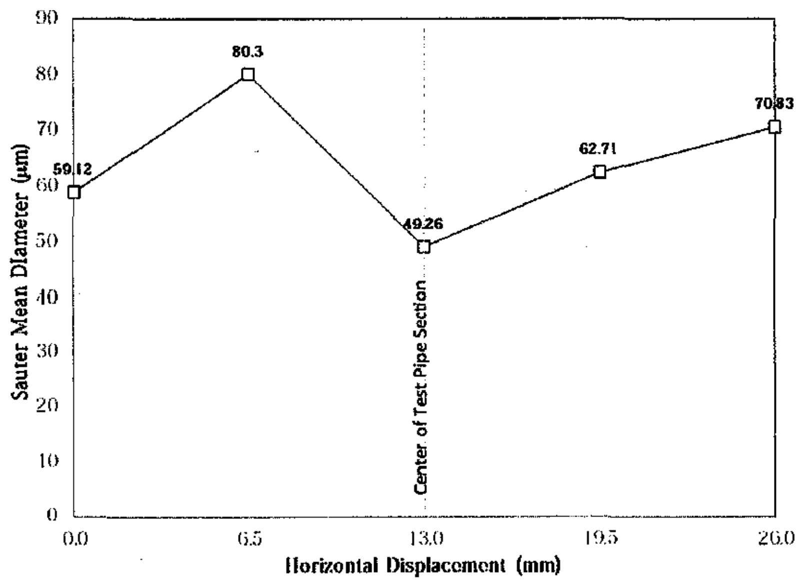

Figure C-2 : Vertical Displacement = 3.5cm

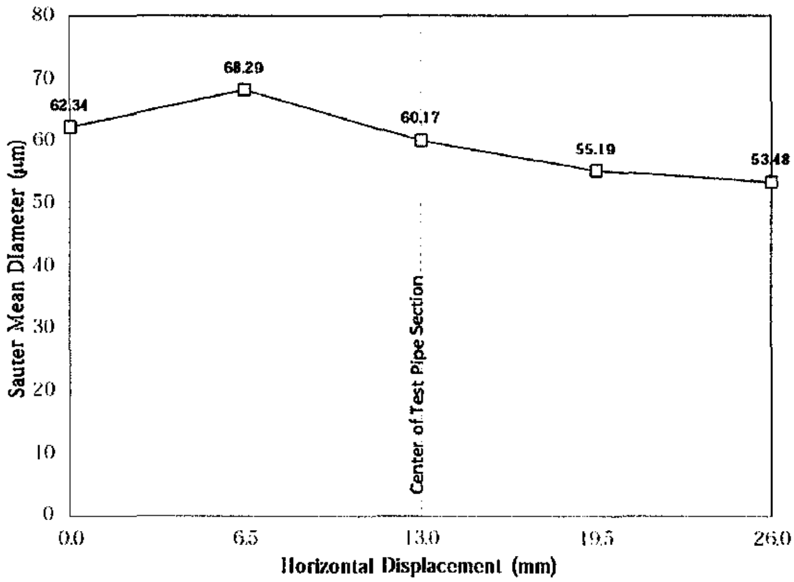

Figure C-3 : Vertical Displacement = 5.5cm

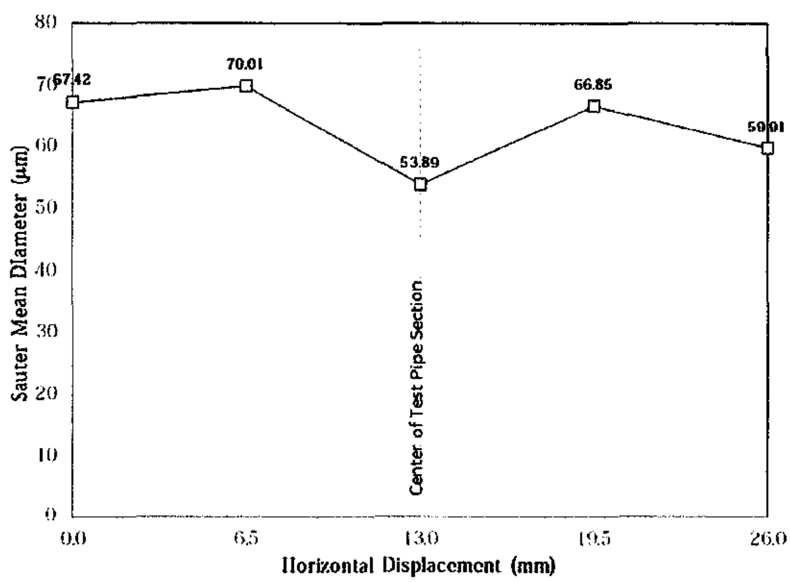

Figure C-4 : Vertical Displacement = 7.5cm

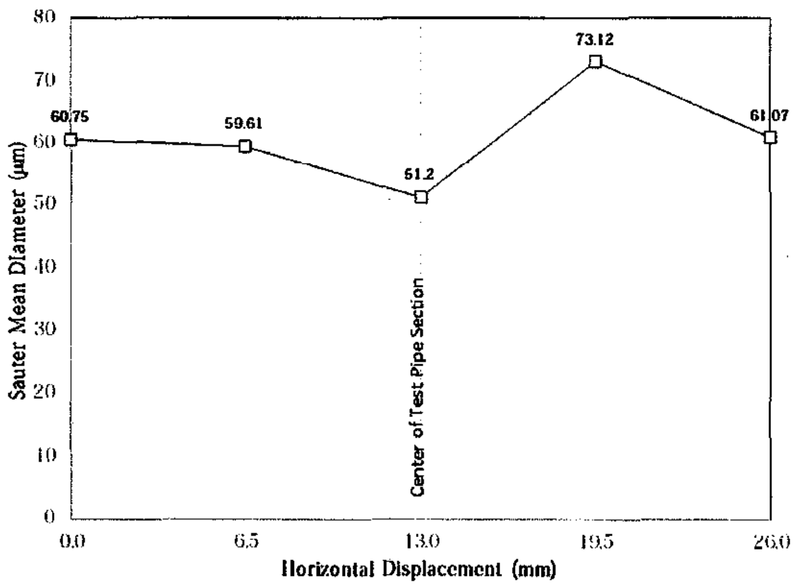

Figure C-5 : Vertical Displacement = 9.5cm

APPENDIX D

Horizontal Velocity at 5gpm

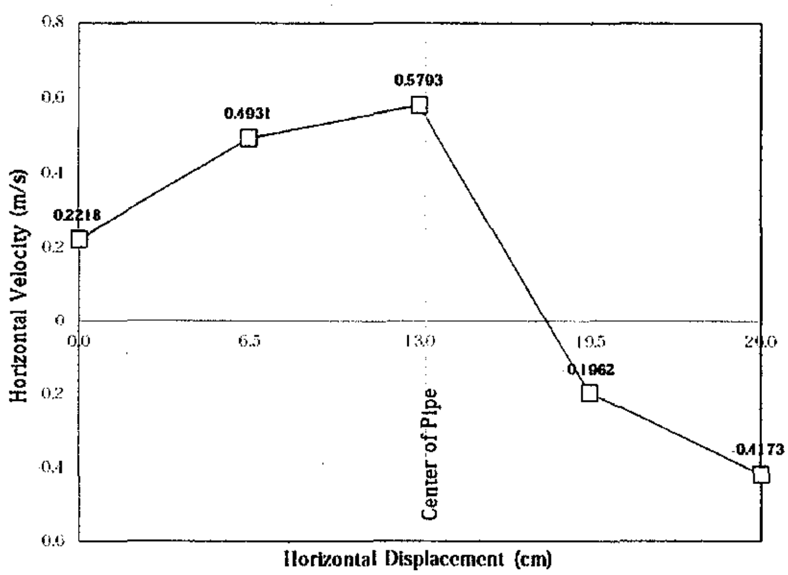

Figure D-1 : Vertical Displacement = 1.5cm

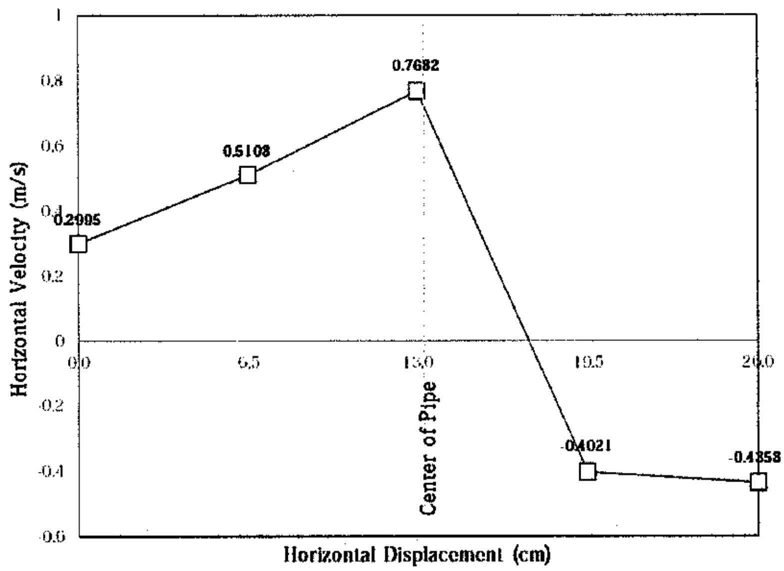

Figure D-2 : Vertical Displacement = 3.5cm

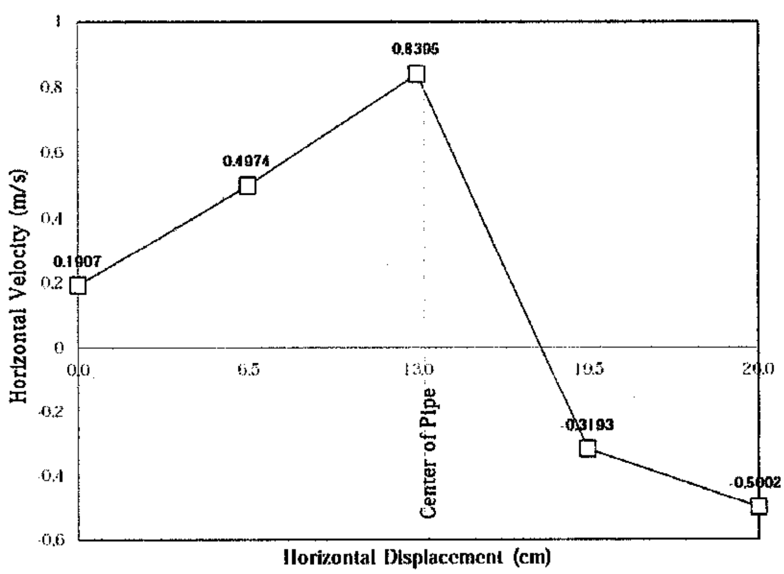

Figure D-3 : Vertical Displacement = 5.5cm

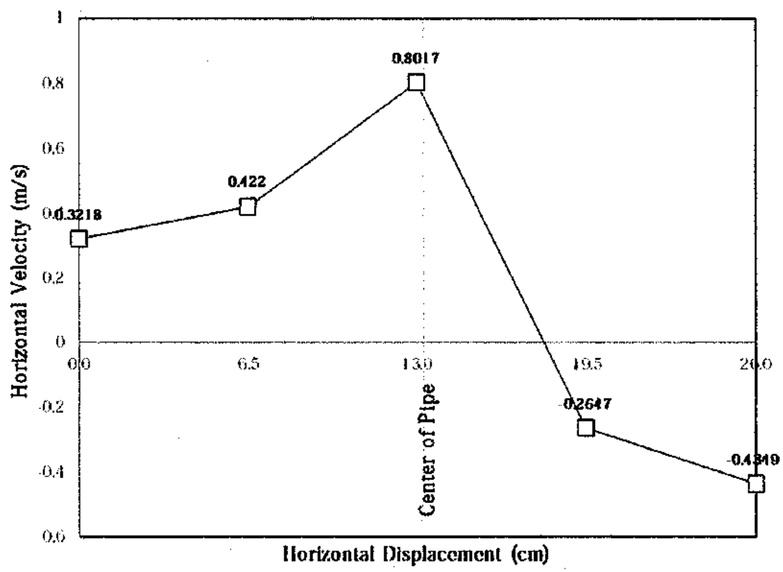

Figure D-4 : Vertical Displacement = 7.5cm

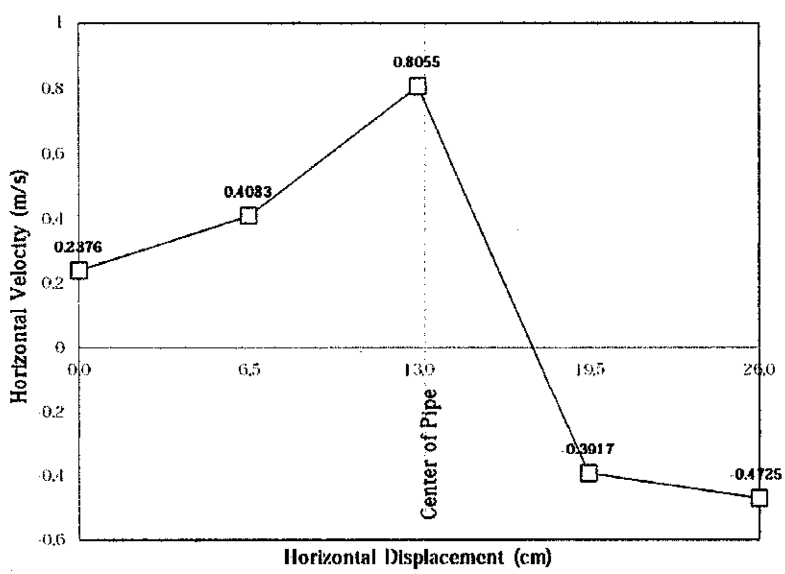

Figure D-5 : Vertical Displacement = 9.5cm

APPENDIX E

Horizontal Velocity at 10gpm

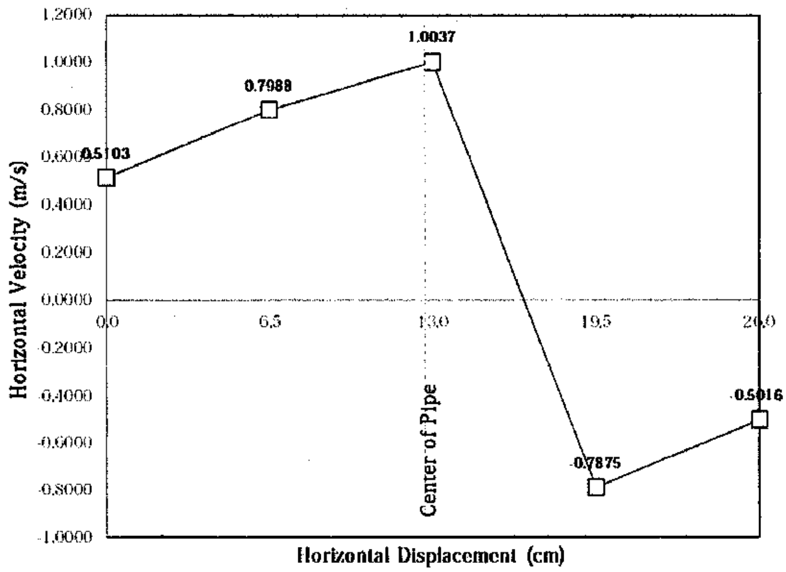

Figure E-1 : Vertical Displacement = 1.5cm

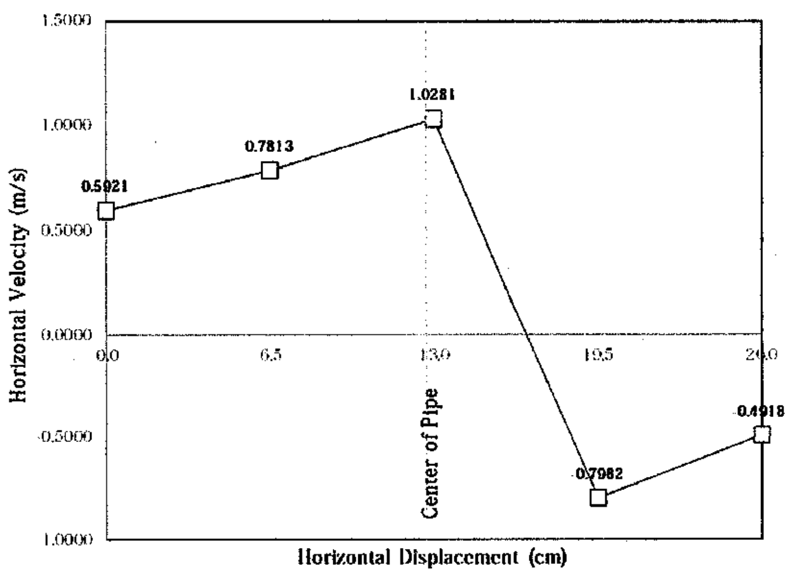

Figure E-2 : Vertical Displacement = 3.5cm

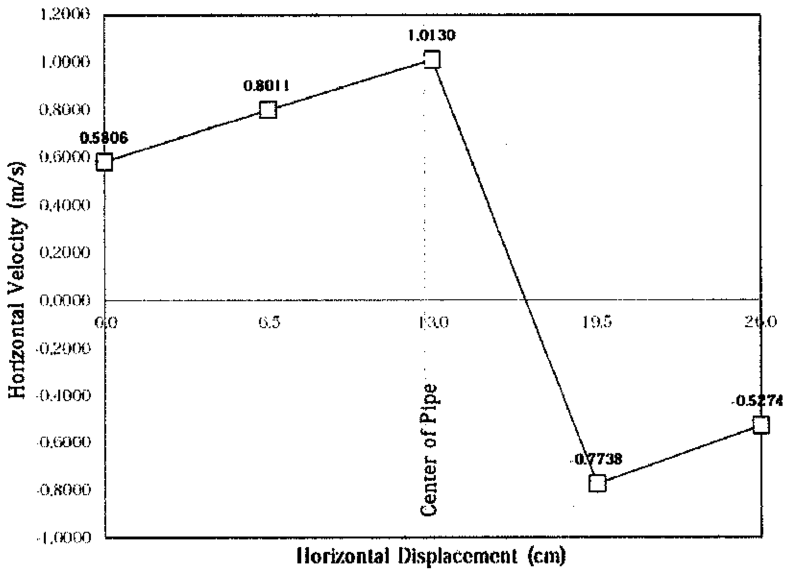

Figure E-3 : Vertical Displacement = 5.5cm

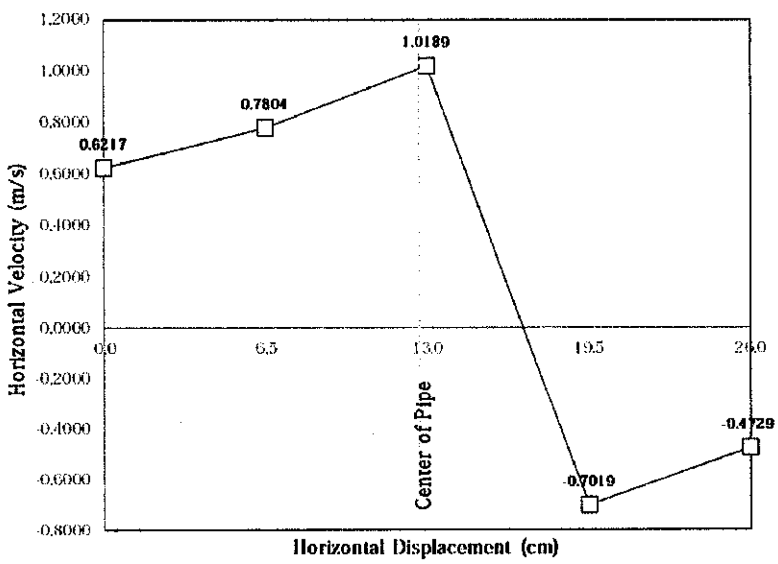

Figure E-4 : Vertical Displacement = 7.5cm

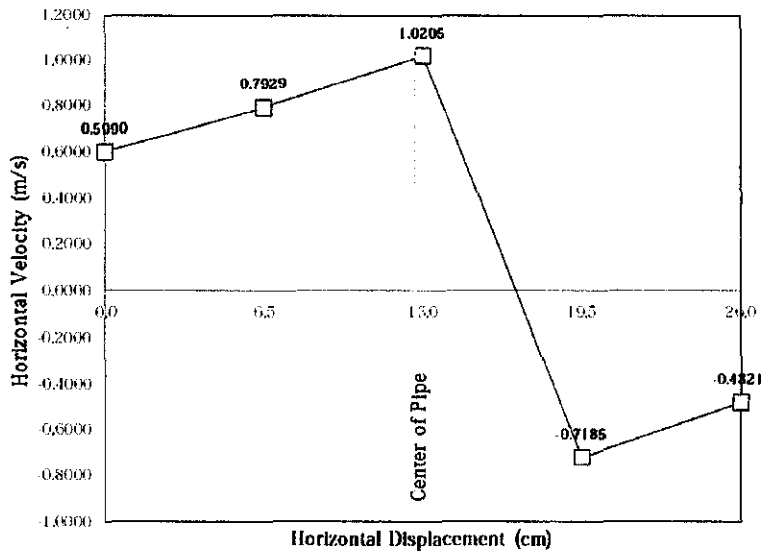

Figure E-5 : Vertical Displacement = 9.5cm

APPENDIX F

Horizontal Velocity at 15gpm

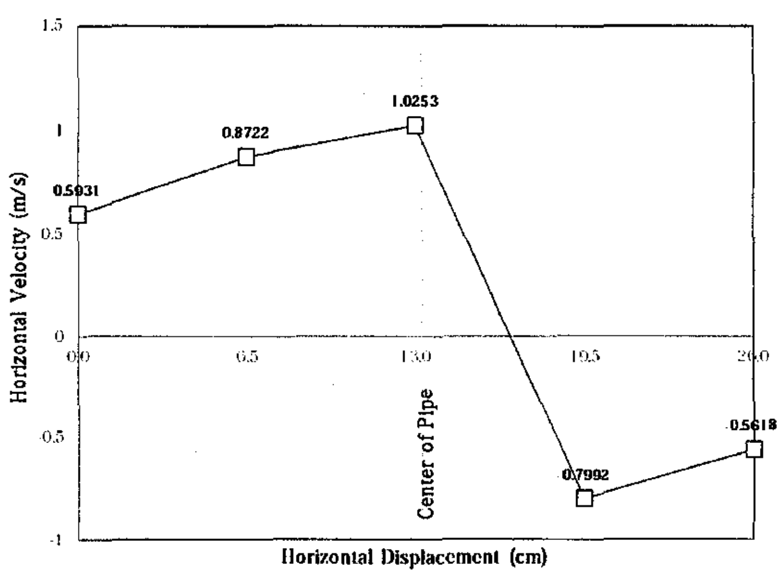

Figure F-1 : Vertical Displacement = 1.5cm

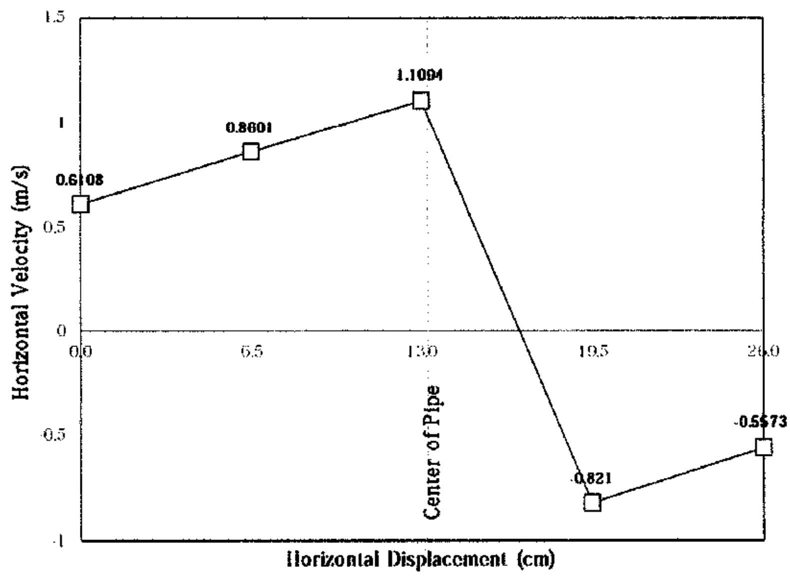

Figure F-2 : Vertical Displacement = 3.5cm

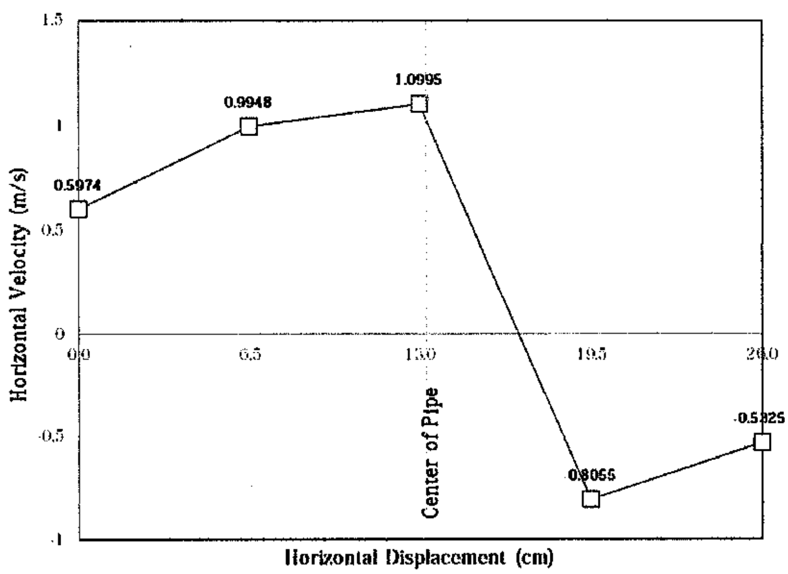

Figure F-3 : Vertical Displacement = 5.5cm

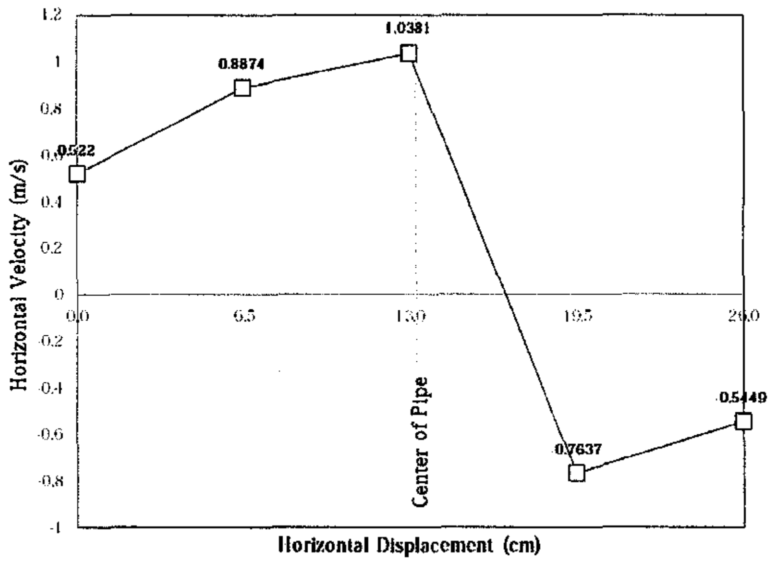

Figure F-4 : Vertical Displacement = 7.5cm

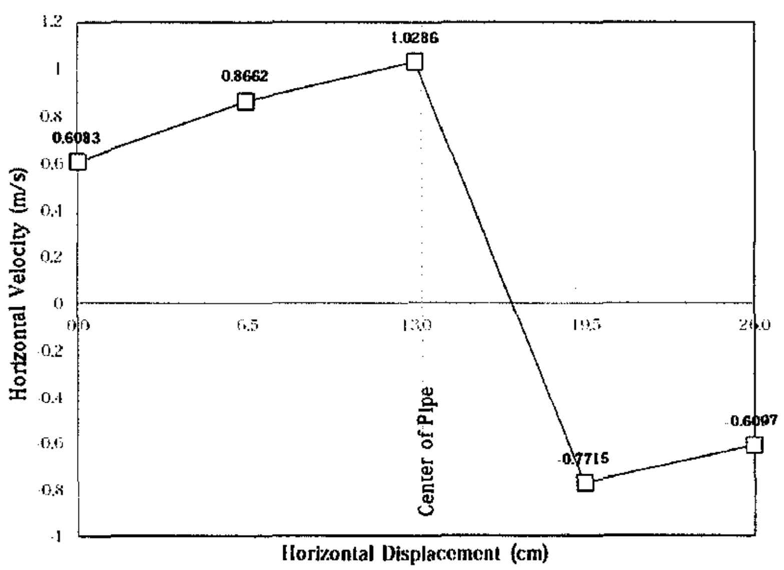

Figure F-5 : Vertical Displacement = 9.5cm

APPENDIX G

Vertical Velocity at 5gpm

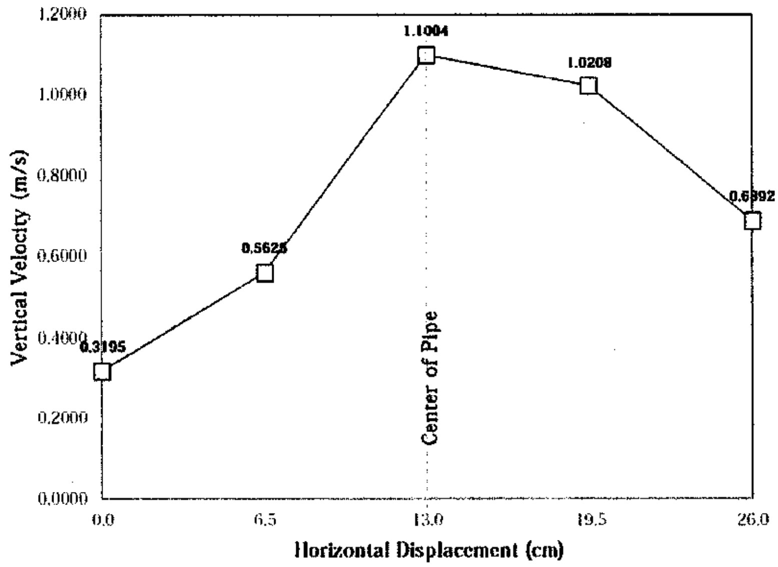

Figure G-1 : Vertical Displacement = 1.5cm

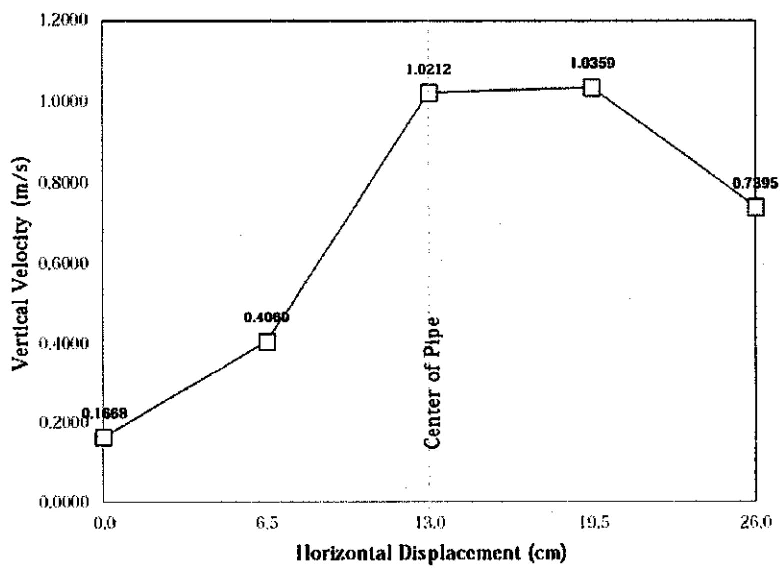

Figure G-2 : Vertical Displacement = 3.5c

m

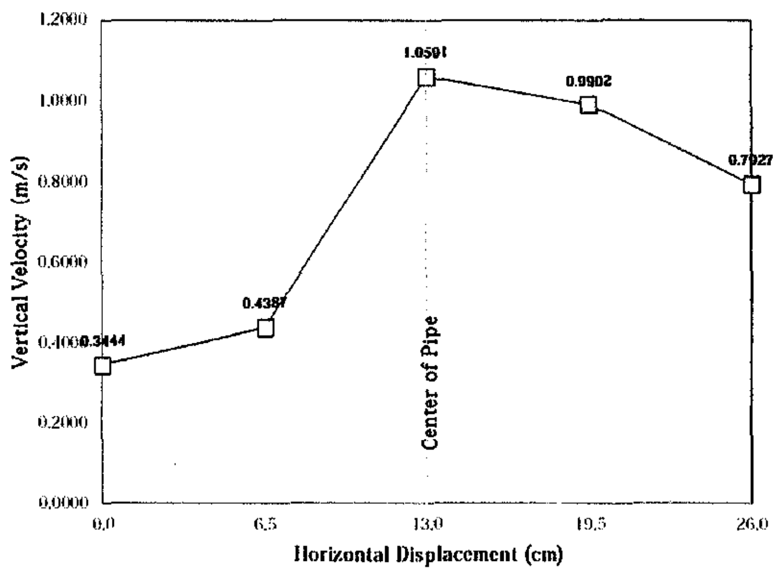

Figure G-3 : Vertical Displacement = 5.5cm

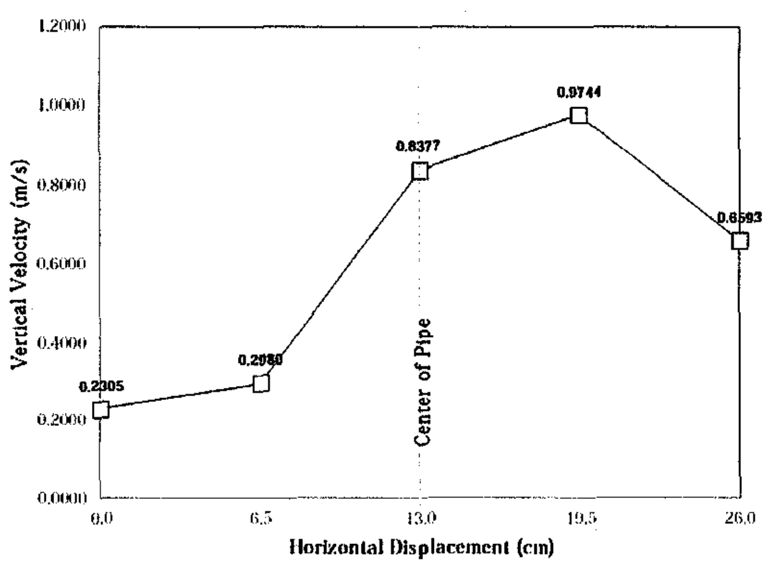

Figure G-4 : Vertical Displacement = 7.5cm

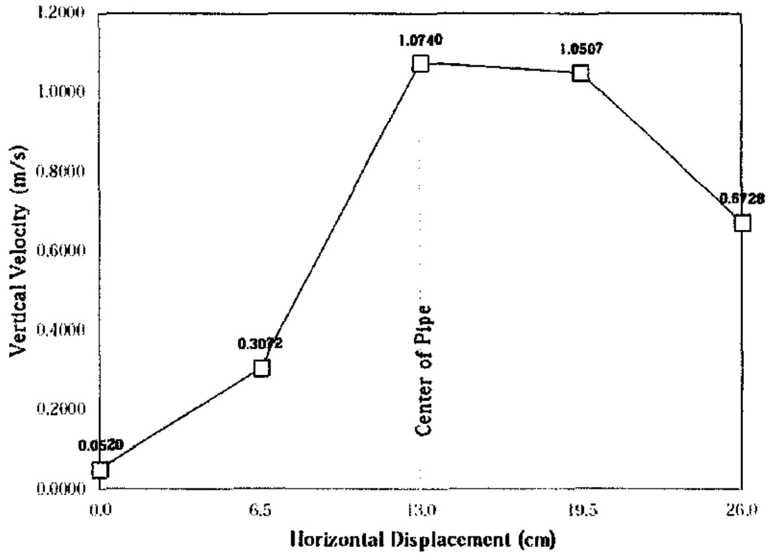

Figure G-5 : Vertical Displacement = 9.5cm

APPENDIX H

Vertical Velocity at 10gpm

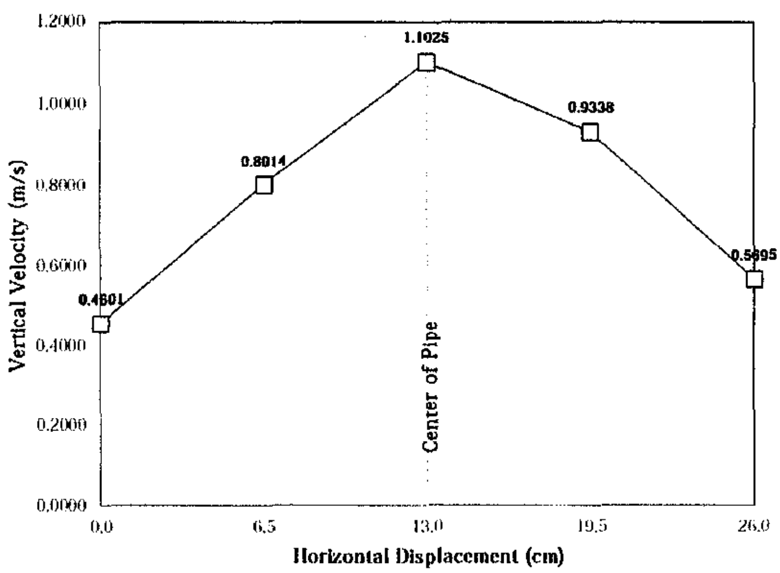

Figure H-1 : Vertical Displacement = 1.5cm

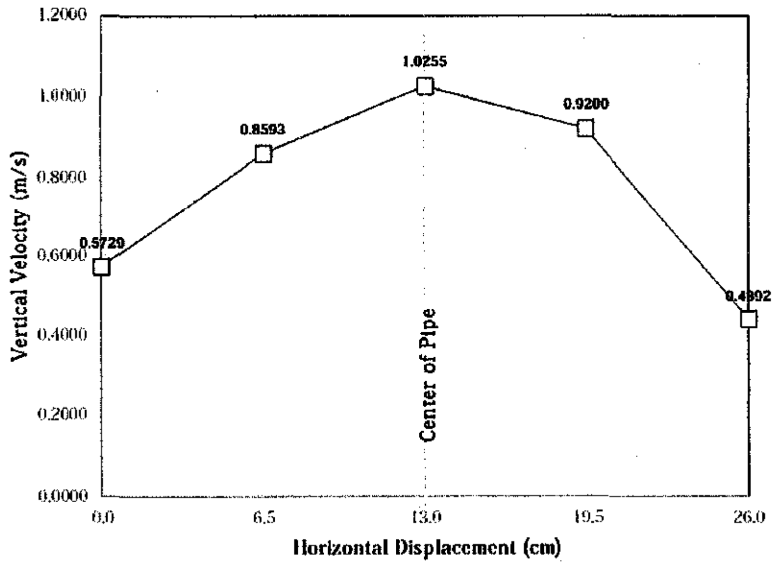

Figure H-2 : Vertical Displacement = 3.5cm

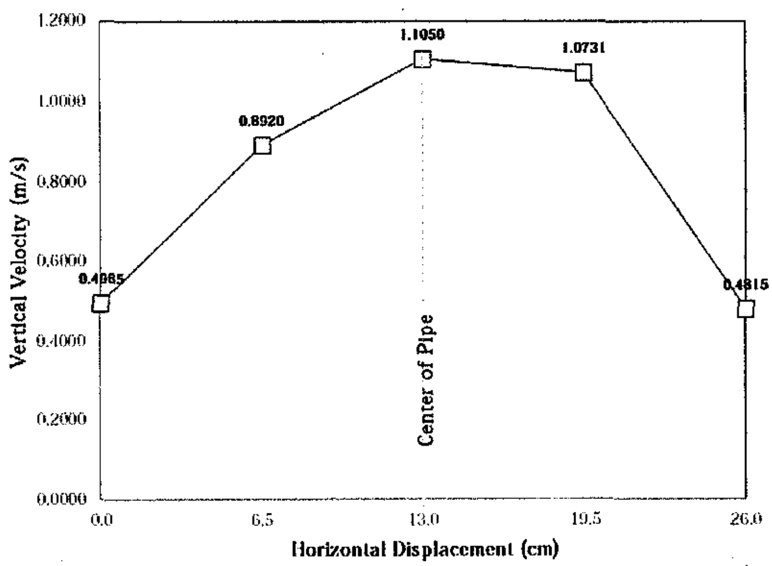

Figure H-3 : Vertical Displacement = 5.5cm

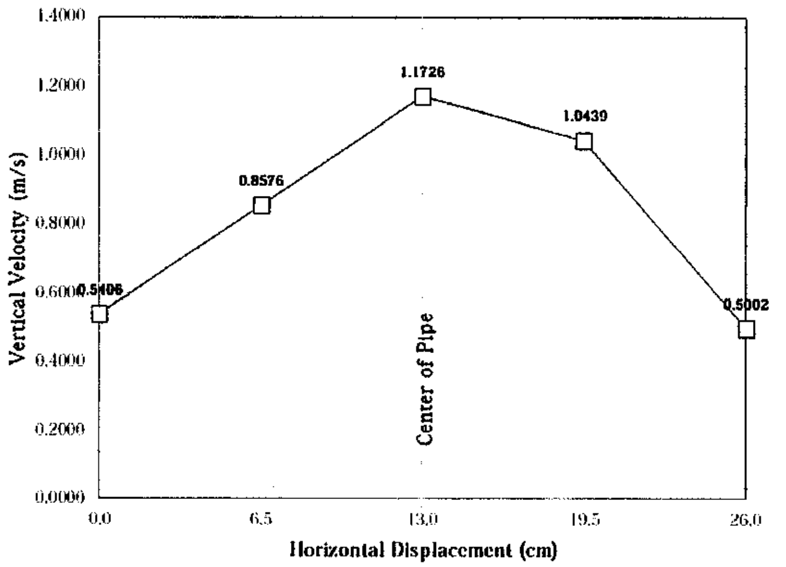

Figure H-4 : Vertical Displacement = 7.5cm

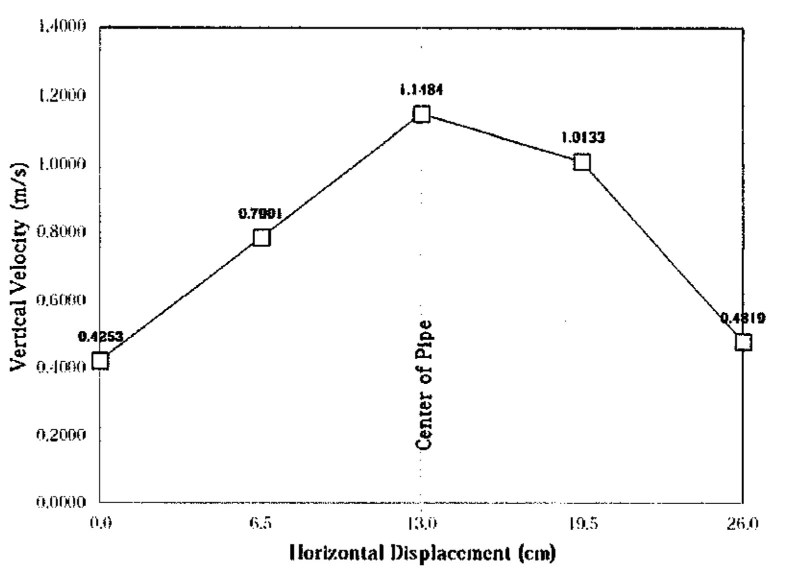

Figure H-5 : Vertical Displacement = 9.5cm

APPENDIX I

Vertical Velocity at 15gpm

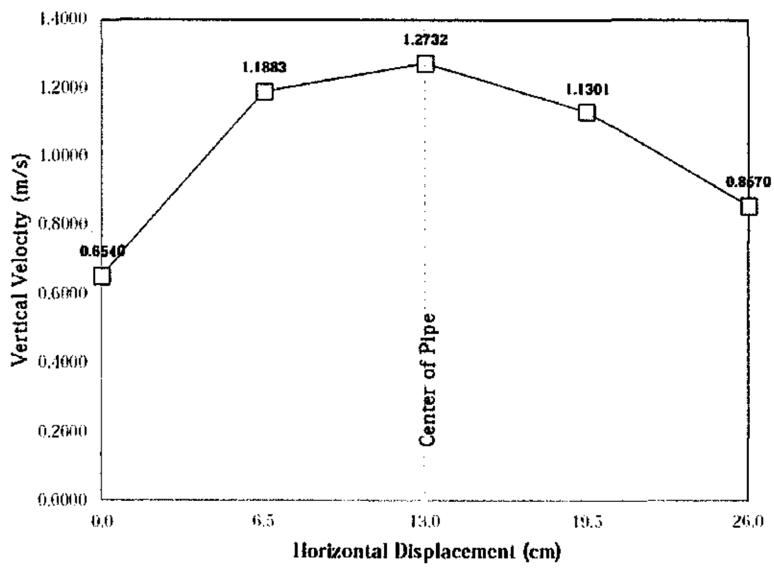

Figure I-1 : Vertical Displacement = 1.5cm

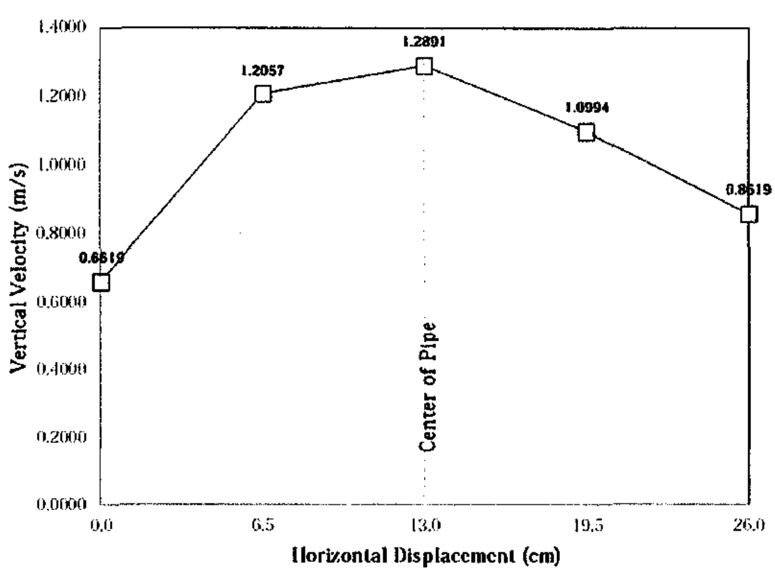

Figure I-2 : Vertical Displacement = 3.5cm

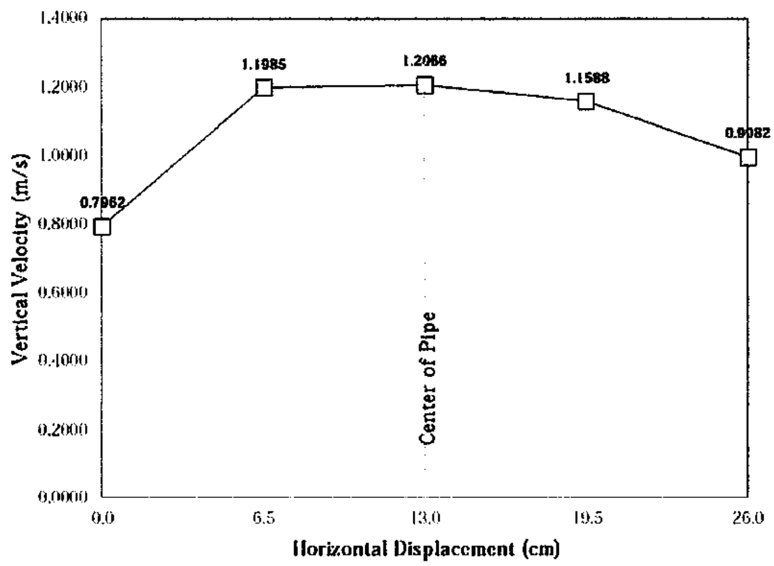

Figure I-3 : Vertical Displacement = 5.5cm

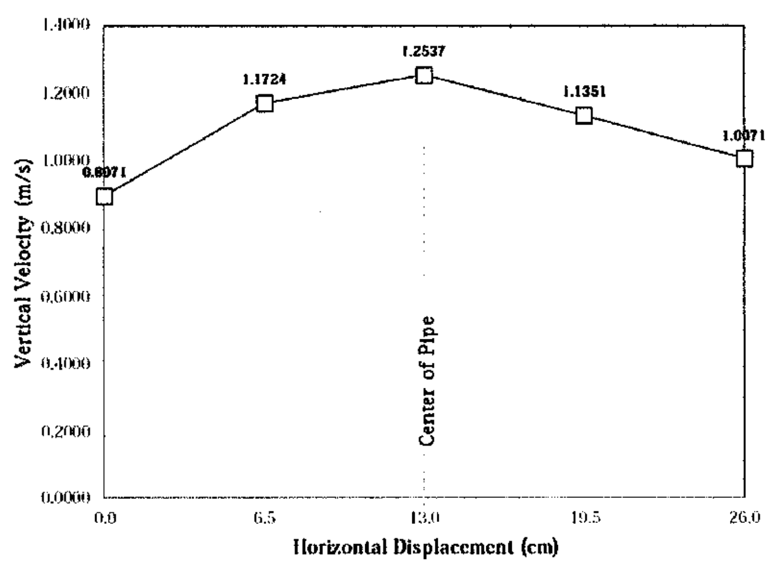

Figure I-4 : Vertical Displacement = 7.5cm

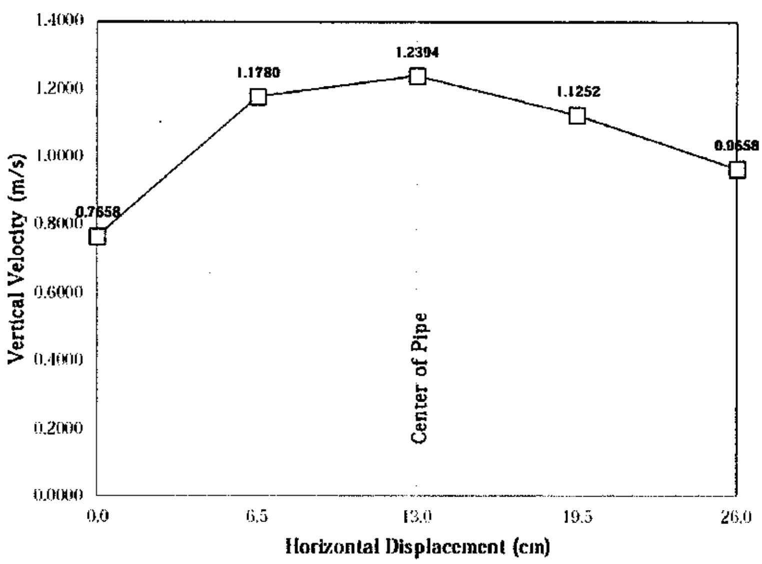

Figure I-5 : Vertical Displacement = 9.5cm

APPENDIX J

Calculations of Sauter Mean Diameter, Horizontal & Vertical Velocity

Table J-1 : Data extracted from BSA Flow Software

Counts	Diameter (μm)	Horizontal Velocity (m/s)	Vertical Velocity (m/s)
6	75	-1.0533	1.2894
8	62	-0.9448	1.0173
3	53	-1.0027	1.4650

Sauter Mean Diameter (SMD) = $D_{32} = \frac{\sum_{i=1}^{k} n_i D_i^3}{\sum_{i=1}^{k} n_i D_i^2}$

$$= \frac{(6)(75^3) + (8)(62^3) + (3)(53^3)}{(6)(75^2) + (8)(62^2) + (3)(53^2)}$$

= **66.97 μm**

Average horizontal velocity = $\frac{\Sigma V}{n}$

$$= \frac{(-1.0533)(6) + (-0.9448)(8) + (-1.0027)(3)}{17}$$

= **-0.9933 m/s (moving to the right side of pipe)**

Average vertical velocity = $\frac{\Sigma V}{n}$

$$= \frac{(1.2894)(6) + (1.0173)(8) + (1.4650)(3)}{17}$$

= **1.1923 m/s**