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Movement of Air Through Submerged Air Vents

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MOVEMENT OF AIR THROUGH SUBMERGED AIR VENTS

by

Clay W. Woods

A thesis submitted in partial fulfillment
of the requirements for the degree

of

MASTER OF SCIENCE

in

Civil and Environmental Engineering

Approved:

Steven L. Barfuss Major Professor	Michael C. Johnson Committee Member
Michael J. McFarland Committee Member	Mark R. McLellan Vice President for Research and Dean of the School of Graduate Studies

UTAH STATE UNIVERSITY
Logan, Utah

2011

ABSTRACT

Movement of Air Through Submerged Air Vents

by

Clay W. Woods, Master of Science

Utah State University, 2011

Major Professor: Steven L. Barfuss
Department: Civil and Environmental Engineering

A series of physical models consisting of three different diameter pipes at the same 4% slope were studied at the Utah Water Research Laboratory (UWRL). Various combinations of air flow and head on the pipe were used to determine the effect of pipe diameter, head, and air flow on the behavior of air bubbles introduced into the pipes and to determine the venting capacity of the pipes. It was determined that neither bubble velocity nor bubble length changes with pipe diameter or head changes within the range tested. It was also determined that bubble velocity and length will increase with increased air flow. Bubble velocity also increased with increasing bubble length consistent with prior research. Overall the venting capacity of a pipe is dependent upon having a large enough pipe to prevent slug flow. A procedure was developed to aid in the sizing of submerged vent piping during the design of pipelines based on the data collected during this study and utilizing prior research.

(63 pages)

PUBLIC ABSTRACT

Movement of Air Through Submerged Air Vents

by

Clay W. Woods, Master of Science

The Utah Water Research Lab (UWRL) proposes to study the behavior of air bubbles in submerged vent tubes. This study is coordinated with a study for the Las Vegas wastewater treatment system that discharges into Lake Mead. The UWRL collaborates with government agencies and private companies to research water-related issues around the world. The behavior of air bubbles is of interest in order to more efficiently vent air from pipelines with submerged vent tubes. The Las Vegas wastewater treatment system discharges into Lake Mead and is required to meet an environmental guideline that no air bubbles are discharged into the lake.

The project team proposes a study of the behavior of air bubbles in different pipe sizes filled with water with varying amounts of air being admitted into the pipe. The bubbles formed in the pipe will be recorded and analyzed to determine the behavior of the air bubbles based on pipe size, water level differences, and the amount of air present. Based on the experiments conducted with this study, a design procedure will be developed to aid in designing piping systems with submerged vent tubes. Considerable amounts of money are spent in the design and installation of vent valves and piping, so the information gathered in this study will be beneficial to more efficiently design venting systems.

ACKNOWLEDGMENTS

I would like to thank my wonderful wife, Crystal, for supporting me while I completed my graduate degree. Her sacrifices allowed me to finish my research and my thesis. I would like to thank Steve Barfuss for employing me at the Utah Water Research Laboratory (UWRL), giving me the chance to finish my research, and providing valuable guidance and information during the project. I would also like to thank my other committee members, Mike Johnson and Michael McFarland, for their support and assistance in helping to make this a quality research project. In addition, I would like to thank the employees at the UWRL for their help and support in constructing my models and helping with data collection.

Clay W. Woods

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LIST OF ACRONYMS, ABBREVIATIONS, AND SYMBOLS

cfs	cubic feet per second
cfm	cubic feet per minute
fps	feet per second
ft	feet
cm	centimeters
psi	pounds per square inch
mm	millimeters
PVC	polyvinyl chloride
ft H_2O	feet of water
Vair	air velocity
Qa	air flowrate
H	head
D	diameter
Vbubble	bubble velocity
n	number of variables in pi term calculation
m	number of fundamental dimensions in calculating pi terms
k	reduction number
Π	pi, used in creating pi terms
V	bubble velocity (fps)
X	space between bubbles (in)
L	length of bubbles (in)

CHAPTER 1

INTRODUCTION

Background

Air can be introduced into a water pipeline by vortices at pipe inlets, pumps, turbulence, hydraulic jumps, or when filling a water line. Entrained air bubbles can be released by the water if the pressure changes or if the flow becomes less turbulent. The presence of air in pipelines can cause problems including loss of capacity, lower efficiency, damage from water hammer, surging or blowbacks, and environmental problems when air is discharged into a receiving water reservoir. When it is not possible to limit the amount of air present in a pipeline, it is often necessary to remove the air to prevent damage associated with the air. In general, air is removed from water lines either using mechanical means such as a vent valve or hydraulically using the water flowing in the line to clear air pockets (Wisner, Mohsen, and Kouwen, 1975).

Considerable amounts of money are spent releasing air from pipelines using vents and air release valves. It would benefit the designers of venting systems if more information about the behavior of bubbles in submerged vent tubes was known. This information could be used to efficiently design submerged vent systems to remove air from pipelines.

Objective

The purpose of this research is to determine the effects of pipe size (submerged vent pipe diameter) and head on the amount of air that can be carried when the vent pipe is full of water. In addition, this research will correlate air flow volumes with bubble behavior in order to better understand the mechanism for the movement of air through submerged air vents. The data collected during these experiments is compared to previous related experiments to more fully understand the results obtained. A design procedure to aid in the selection of properly sized vent piping is presented based on the data collected in this study. Having a properly sized vent pipe and a better understanding of the motion of air bubbles in vent piping will ensure smooth air bubble flow through water and limit slug flow in the vent piping, preventing pipeline damage and limiting the costs associated with removing air from pipelines. Slug flow is a flow pattern in which sequences of long bubbles, almost filling the pipe cross section are followed by liquid slugs that may contain smaller bubbles (Fabre and Line, 1992). Slug flow is undesirable in submerged vent lines because the venting is not at a continuous rate and the behavior of the air bubbles cannot be predicted.

Overview

A literature review was conducted in order to determine what, if any, information related to this topic had been published previously. This literature review is presented in Chapter 2. Chapter 3 covers the scope of research and how prior research differs from the research presented herein. Chapter 3 also shows how prior research can be compared to the current study. Chapter 4 gives information detailing the experimental set up and data collection. Information on instrumentation and how the experiments were conducted can be found there. Experimental results and analysis are contained in Chapter 5. This section also discusses how the data gathered in this research compared to previous published research. The application of collected data in the form of a design procedure is contained in Chapter 6. A conclusion, summary of test results, and recommendations for further research are presented in Chapter 7.

CHAPTER 2

LITERATURE REVIEW

There has been a considerable amount of research conducted related to the movement of bubbles in different liquids. These studies, conducted since the 1960's, include experiments that varied bubble size, fluid viscosity, fluid velocity, and pipe slope. Zukoski (1966) was one of the first researchers to study bubble motion in fluids. He studied the effect of tube inclination, viscosity, and surface tension on bubble rise velocity. Zukoski's study focused on tube-draining bubbles in water and other liquids with varying viscosity. A tube draining bubble is the bubble of air that rises in a tube as the fluid in the tube is emptied out.

Spedding and Nguyen (1978) also studied tube draining bubbles at various pipe inclinations, but their research was limited to water, and pipe sizes ranging from 1.94 to 5.67 cm in diameter. This research showed that bubble volume can be very important in determining bubble rise velocity, which was not considered by Zukoski. They demonstrated that bubble volume has an effect on bubble rise velocity as long as pipe slope is less than 20 degrees. Spedding and Nguyen also demonstrated that tube diameter does play a role in rise velocity with velocity increasing with tube diameter in general up to a tube diameter of 12 inches, with the greatest effect from about 1 to 3 inches (Spedding and Nguyen, 1978). The effect of tube diameter on bubble velocity is also variable with tube angle, with tube diameter having a larger effect with smaller slopes. Spedding and Nguyen (1978) showed that bubble rise velocity is also a function of pipe slope. A representation of the data gathered for this experiment is given in

Appendix A. Bubble velocity will increase with tube inclinations above horizontal, reaching a maximum bubble velocity at a slope of about 35 degrees, and then velocity will decrease with increasing pipe slope (Spedding and Nguyen, 1978).

Wisner, Mohsen, and Kouwen (1975) and Escarameia (2007) studied the water velocity required to clear air pockets from pipelines using fluid flow rather than mechanical vents. In addition, Wisner, Mohsen, and Kouwen (1975) acquired some baseline data with bubbles rising in stagnant water in a pipeline with an 18.5% slope showing that rise velocity will increase with bubble size.

Weber and Alarie (1986) studied the velocity of both tube draining and extended bubbles in various liquids at various tube inclinations. An extended bubble is one where the volume-equivalent diameter is more than 30% larger than the tube diameter (Weber and Alarie, 1986). This study showed that the velocity of tube draining bubbles and extended bubbles are the same unless the tubes are horizontal (Weber and Alarie, 1986).

The influence of liquid properties on bubble shape and bubble motion under an inclined surface was studied by Perron, Kiss, and Poncsak (2006). These researchers determined that liquid properties have a strong influence on bubble shape and terminal velocity.

Che, Chen, and Taylor (1990) did experiments to determine the bubble volume and terminal velocity while rising under an inclined plate. They concluded that bubble velocity will always increase with an increase in inclination angle (Che, Chen, and Taylor, 1990). The inclination angles used for their study varied from 2.35 to 28.13 degrees, and injection tube diameters of 2-mm and 5-mm were used. Che, Chen, and

Taylor found that the bubbles reached terminal velocity very quickly after entering the tube and moved at a constant velocity up the tube. They also found that there was no significant difference in bubble volume or rise velocity when the injection tube diameter was changed, meaning that bubble size is not influenced by injection tube diameter, and that rise velocity depends on bubble volume for a given inclination angle (Che, Chen, and Taylor, 1990). The data from Che, Chen, and Taylor (1990) shows that as more air is injected into a pipe, the bubble size and bubble volume will increase.

Maneri and Zuber (1974) did experiments dealing with bubble motion in inclined situations also. Their study investigated single bubbles rising through square tanks. Maneri and Zuber (1974) demonstrated that larger bubbles will have a higher velocity when rising in an inclined tube and that the size of the pipe has a small effect on rise velocity if the pipe is at a slope less than ten degrees. They also found that bubble velocity will increase as tube inclination increases with a maximum at 35 degrees (Maneri and Zuber, 1974). A representation of their experiments is given in Appendix B.

CHAPTER 3

SCOPE OF RESEARCH

Current Research

The testing completed for this study examined the behavior of air bubbles in submerged vent tubes at a constant slope. The scope of this research is limited to a single slope of 4% for each pipe diameter tested. The research tested three different pipe diameters; 4-inch, 7-inch and 12-inch. Each pipe was tested with three different water levels to change the head present where the air bubbles are formed. An application procedure is presented to aid in sizing submerged vent pipes. Since prior research has shown that bubble velocity will change with pipe slope and the research presented herein only examines a single slope; prior research is used to apply the data from this study to pipes of multiple slopes.

Comparison to Literature Review

The prior research involving tube draining bubbles done by Spedding and Nguyen (1978) has limited applicability to this study because the current study deals with a continuous flow of air into water, not a single bubble. In addition, the water in the study detailed here is stagnant with the bubbles moving through the water rather than the tube draining bubbles used in previous studies. However, the studies involving tube draining bubbles give some insight to the behavior of air bubbles in water and will provide a comparison point with data collected in this study.

The studies by Wisner, Mohsesn, and Kouwen (1975) and Escarameia (2007) provide valuable information about air pocket shape and behavior in flowing water, which can be related to the current study. However, the bulk of their research is not applicable to the study presented herein. The information presented by their prior research will be compared to data from the study presented herein to determine if any correlations can be made.

The data presented by Weber and Alarie (1986) provides another opportunity for data comparison to determine how the data collected in the current study compares to the behavior of extended bubbles in inclined tubes studied by Weber and Alarie (1986).

Research carried out by Che, Chen, and Taylor (1990) is related to the current research in that they used a continuous supply of air bubbles instead of a single bubble. Their experiments were performed with very low air flows compared to the research presented herein and provide a comparison to determine if bubbles react differently with significantly larger air flows.

The study conducted by Maneri and Zuber (1974) is valuable in that it gives information on the effect of tube inclination on bubble velocity. This information is used to extend the data collected in this study to pipes of various slopes. The data collected by Maneri and Zuber (1974) can also be compared to data collected in other previous studies and to validate the data presented herein.

The majority of the past research used single air bubbles or tube draining bubbles, which is different than the research performed here. The research done here used a continuous flow of large air bubbles. The scale of the current research experiments is also different from the literature. For the most part, previous testing utilized small diameter pipes and small bubbles. The current research uses large diameter pipes and very large air bubbles in order to find the venting capacity of the pipes under submerged conditions. Even though there is very little literature that deals with exactly the same topic as the research discussed in this document, prior work can be used for comparison and validation purposes. This study will help to correlate previous research and provide information on conditions that have not previously been studied.

CHAPTER 4

EXPERIMENTAL SET UP AND DATA COLLECTION

All tests performed during this project were conducted at the Utah Water Research Laboratory at Utah State University. The testing included data collection on three different test rigs. These rigs consisted of 4-, 7-, and 12-inch diameter pipe models, each constructed out of clear Acrylic pipe. In each case, the pipes were set at a 4% slope and were filled with stagnant water to different levels. Air was injected into the lower section of pipe using an air compressor. The resulting bubbles were captured on a digital camcorder and played back in slow motion. A scale attached to the pipes allowed bubble size, spacing, and velocity to be documented. Tests were conducted on each pipe with different water levels and air flows to determine the effect these variables had on the venting capacity of the pipe. The variables tested during this study include pipe diameter, water level in the inclined pipe, and the amount of air introduced into the pipe.

Test Setup

Each test rig consisted of a sloping section of clear Acrylic pipe. In each case, the pipe had a constant slope of 4%. The slope was set using a surveying level and adjustable pipe stands. The three pipe diameters used for this study were 4-inch, 7-inch, and 12-inch, with each diameter set at the same 4% slope. The slope was not changed since this research did not study the effect of slope on venting capacity. The lower end of each pipe was covered with a blind flange so that the pipe could be filled with varying levels of water. The upper end of the model was left open to atmosphere so that the only pressure change would come from the level of water in the model. In addition, air injected into the pipe could freely escape with the upper end open to atmosphere without affecting the experiment. Figure 1 shows a basic diagram of the test set up indicating where the head measurements were taken. Figures 2 and 3 show pictures of the 7-inch set up with the adjustable pipe stands adjusted to a 4% slope. The lower section of each model had a ¼-inch connection into the bottom to inject air into the pipe from an air compressor. A scale was attached to the side of each model so that bubble size, spacing, and velocity could be measured. Figure 4 shows a small scale attached to the side of the model that was used to measure the small bubbles created during low air flow rates. A larger scale was used to measure the bubbles created during higher air flows and is shown in Figure 5. These measurements were taken by recording bubble motion with a digital camcorder and playing the recordings back in slow motion.

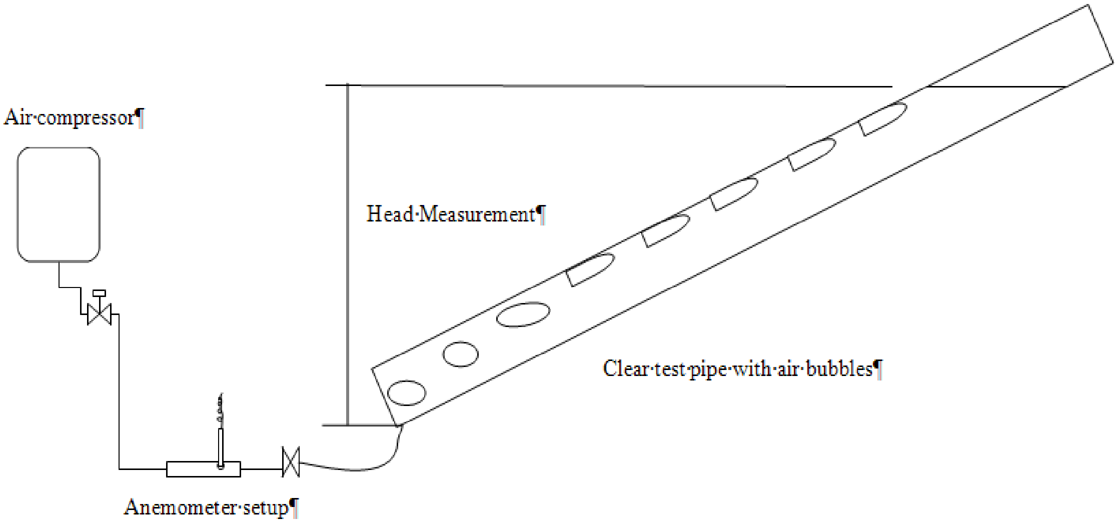


Figure 1: Diagram of test setup

Figure 2: 7-inch test setup

Figure 3: 7-inch model showing pipe supports

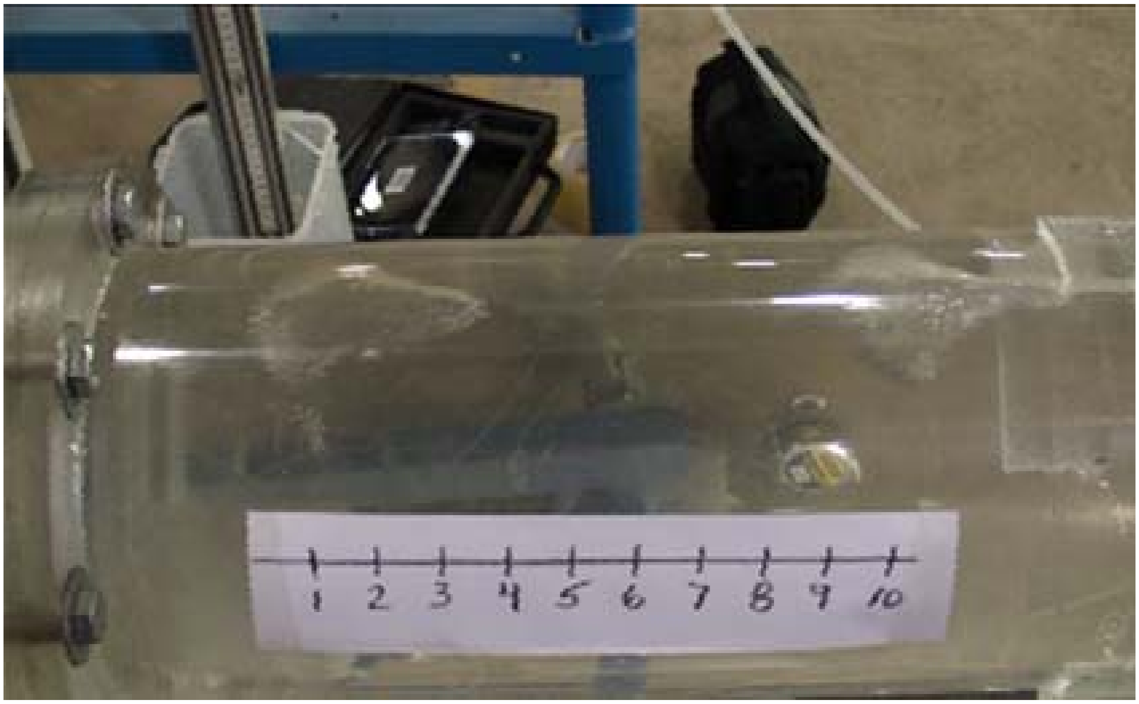


Figure 4: Small scale attached to pipe

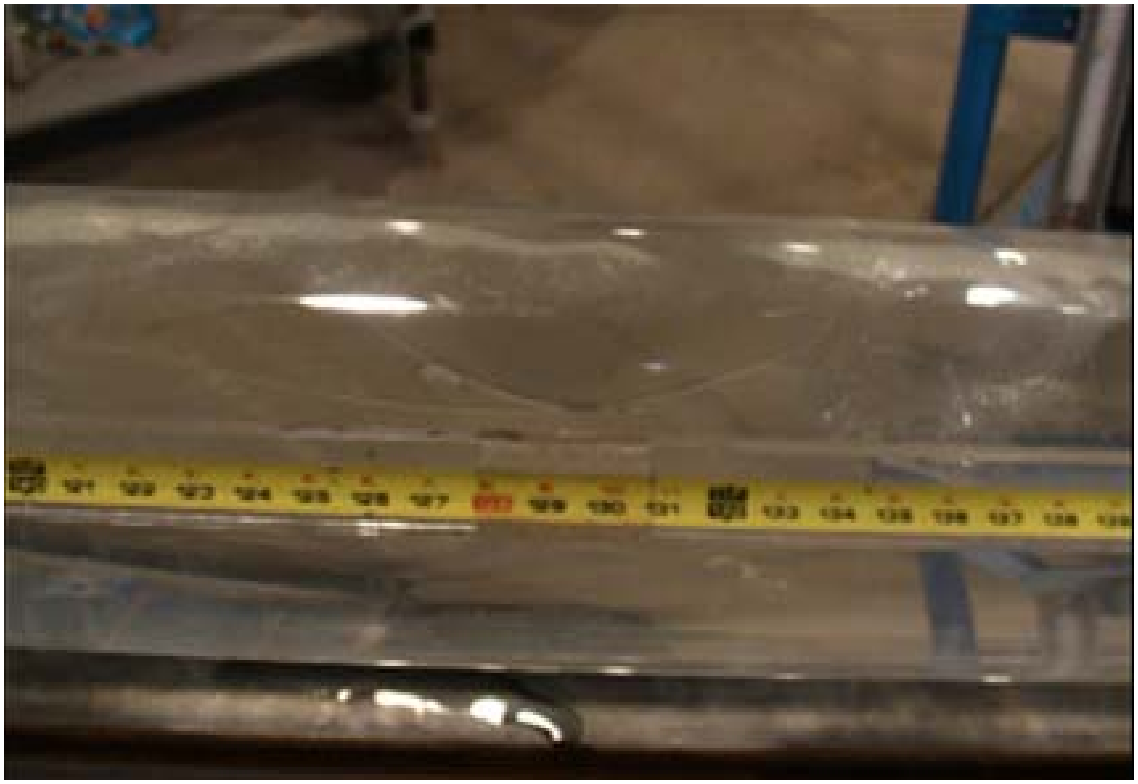


Figure 5: Large scale attached to 7-inch model

Air Flow

Air was injected into the lower portion of each model as shown in Figure 6 using a 20-gallon air compressor with a five horsepower motor and a maximum working pressure of 135 pounds per square inch (psi). A pressure regulating valve on the air compressor was used to control the outlet pressure from 12 psi to 48 psi for multiple test runs. The amount of air injected into the model was also controlled by a ball valve that was throttled to control the flow of air. The amount of air being injected into the model was measured using a vane style anemometer and is shown in Figure 7. The anemometer used for this study was manufactured by Omega Engineering and has a vane diameter of 13 millimeters (mm). The resolution of the anemometer is 1 foot per minute (fpm) with accuracy of ± (2% plus 20 fpm). In order to use the anemometer a 2-inch polyvinyl chloride (PVC) pipe was connected to the air compressor and the model with compressed air hoses. The PVC pipe had a hole drilled into it so that the anemometer could be inserted into the air flow with a rubber seal around it to prevent air from escaping. The air velocity indicated on the anemometer and the known diameter of the PVC pipe was used to calculate the volume flow rate of air being injected into the test pipe line. Velocities for these experiments varied from 71 to 345 feet per minute (fpm) corresponding to a volume flow rate of 1.6 to 7.9 cubic feet per minute (cfm). Equal air velocities were tested for each pipe diameter and water level to determine how the pipe diameter and head affected the bubble motion and the venting capacity of the pipe.

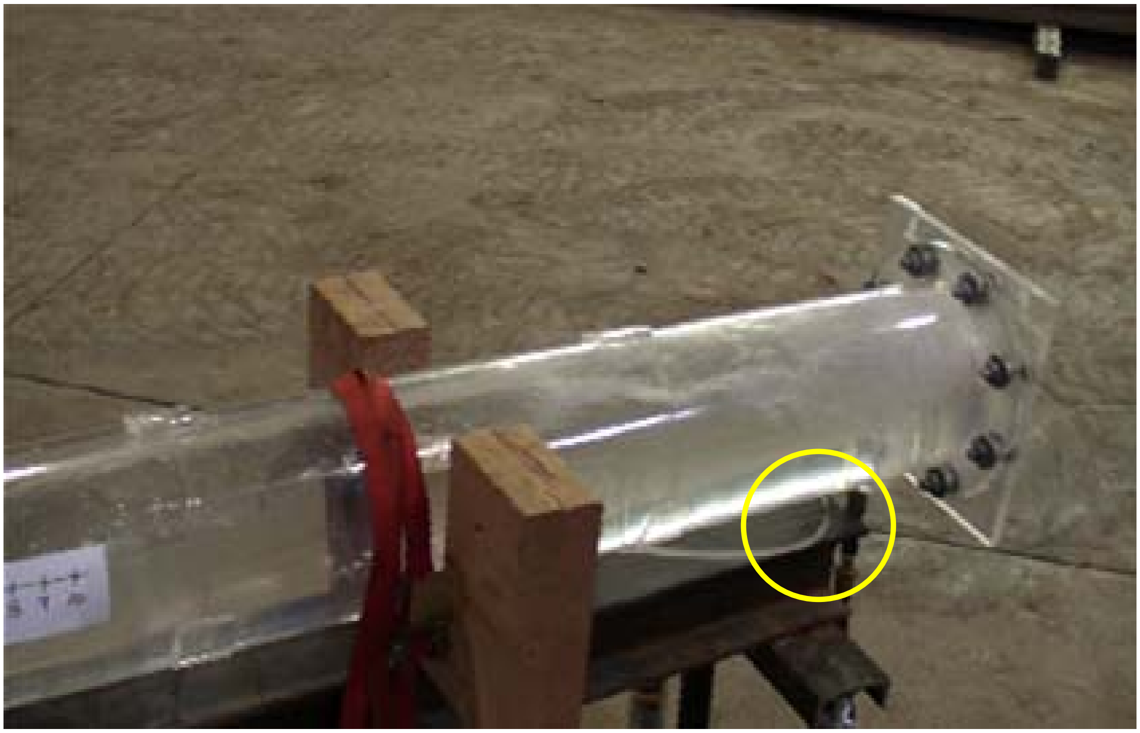


Figure 6: Air injection hose in the end of the pipe

Figure 7: Vane style anemometer used in the experiments

Data Collection

Data collection for this study consisted of videotaping the bubbles produced by the air introduced into the pipe model. The camcorder used for this study was a Samsung SC-HMX20C that has a super slow motion recording setting that can record 300 frames per second. The video was then viewed in slow motion and the bubble length, spacing, and velocity were calculated using the scale attached to the pipe for length measurements. Time was calculated using the frame counts available on the videotape. Images of bubbles that were produced during the experiments and used in the calculation of bubble parameters are shown in Figures 8 and 9.

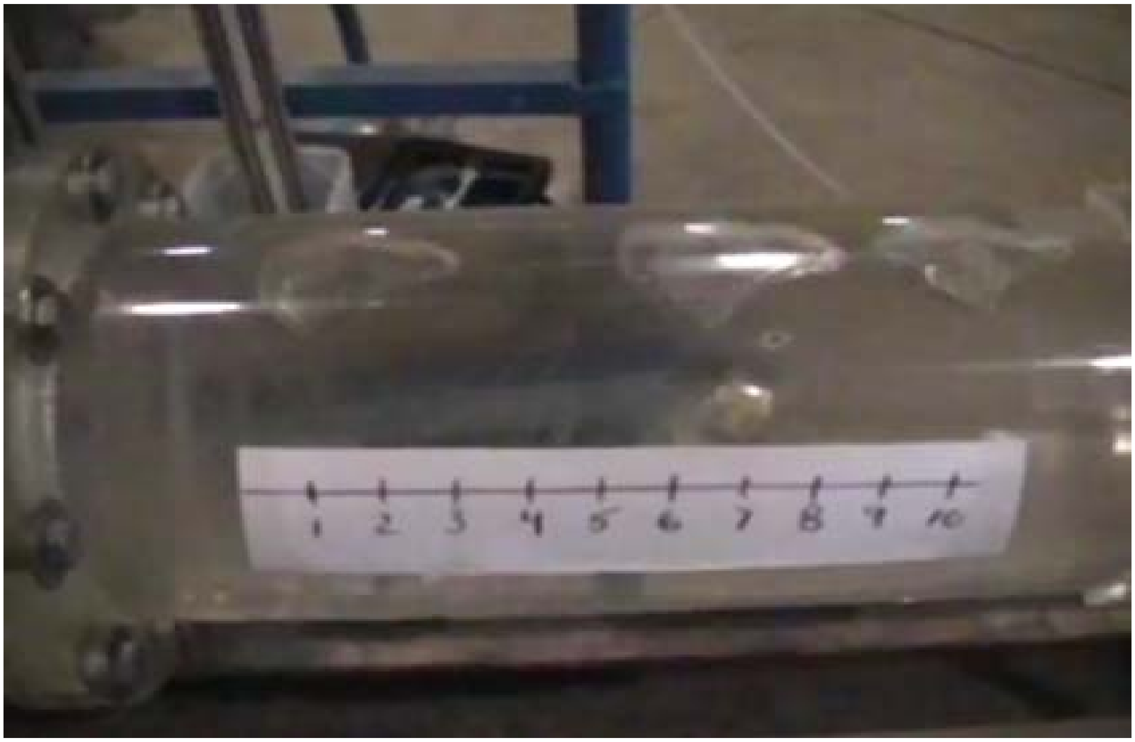


Figure 8: Small bubbles produced in the 7-inch model

Figure 9: Large bubbles showing slug flow

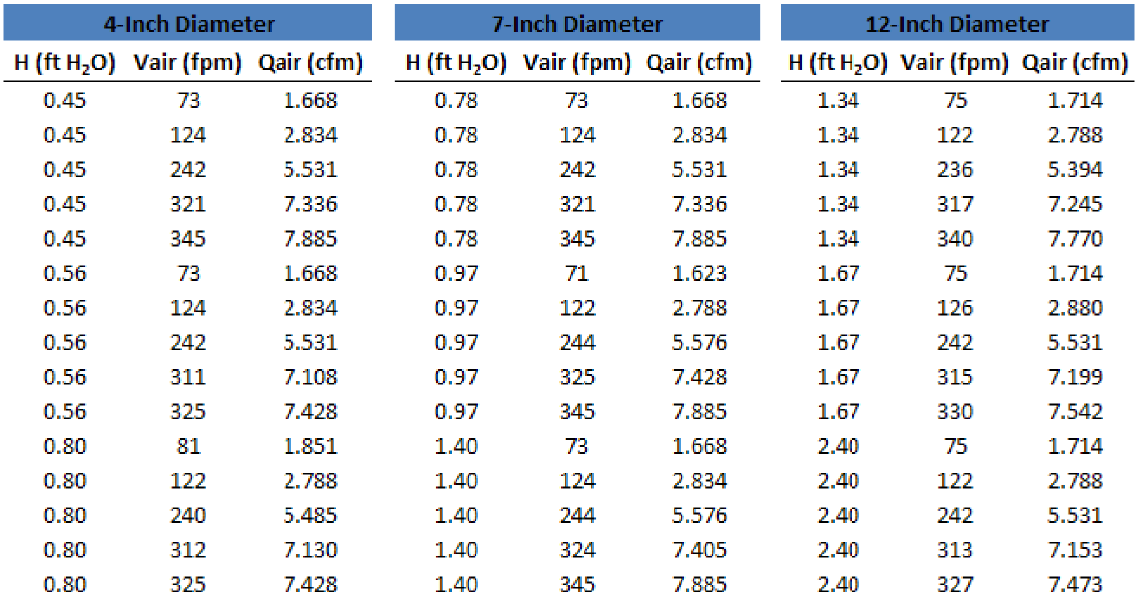
CHAPTER 5

EXPERIMENTAL RESULTS AND ANALYSIS

Experimental Results

Table 1 shows the head and airflow combinations that were tested for each of the three pipe diameters. Each pipe was tested with three different water levels as is shown in Table 1. Each water level was tested with five different air flows. These air flows were chosen based on the capacity of the air compressor and the minimum sensitivity of the anemometer used to measure the air flow. Each pipe diameter and head combination was tested with nearly the same air flow so that a determination on the effect of pipe diameter and head on bubble characteristics could be made. The test results for each of the three tested pipe diameters are given in the following sections.

Table 1: Testing parameters for each pipe



4-Inch Diameter			7-Inch Diameter			12-Inch Diameter		
H (ft H_2O)	Vair (fpm)	Qair (cfm)	H (ft H_2O)	Vair (fpm)	Qair (cfm)	H (ft H_2O)	Vair (fpm)	Qair (cfm)
0.45	73	1.668	0.78	73	1.668	1.34	75	1.714
0.45	124	2.834	0.78	124	2.834	1.34	122	2.788
0.45	242	5.531	0.78	242	5.531	1.34	236	5.394
0.45	321	7.336	0.78	321	7.336	1.34	317	7.245
0.45	345	7.885	0.78	345	7.885	1.34	340	7.770
0.56	73	1.668	0.97	71	1.623	1.67	75	1.714
0.56	124	2.834	0.97	122	2.788	1.67	126	2.880
0.56	242	5.531	0.97	244	5.576	1.67	242	5.531
0.56	311	7.108	0.97	325	7.428	1.67	315	7.199
0.56	325	7.428	0.97	345	7.885	1.67	330	7.542
0.80	81	1.851	1.40	73	1.668	2.40	75	1.714
0.80	122	2.788	1.40	124	2.834	2.40	122	2.788
0.80	240	5.485	1.40	244	5.576	2.40	242	5.531
0.80	312	7.130	1.40	324	7.405	2.40	313	7.153
0.80	325	7.428	1.40	345	7.885	2.40	327	7.473

4-inch pipe

Graphical results for the testing of the 4-inch diameter pipe are shown in Figures 10, 11, and 12, respectively. The data measurements for this model are given in Appendix C.

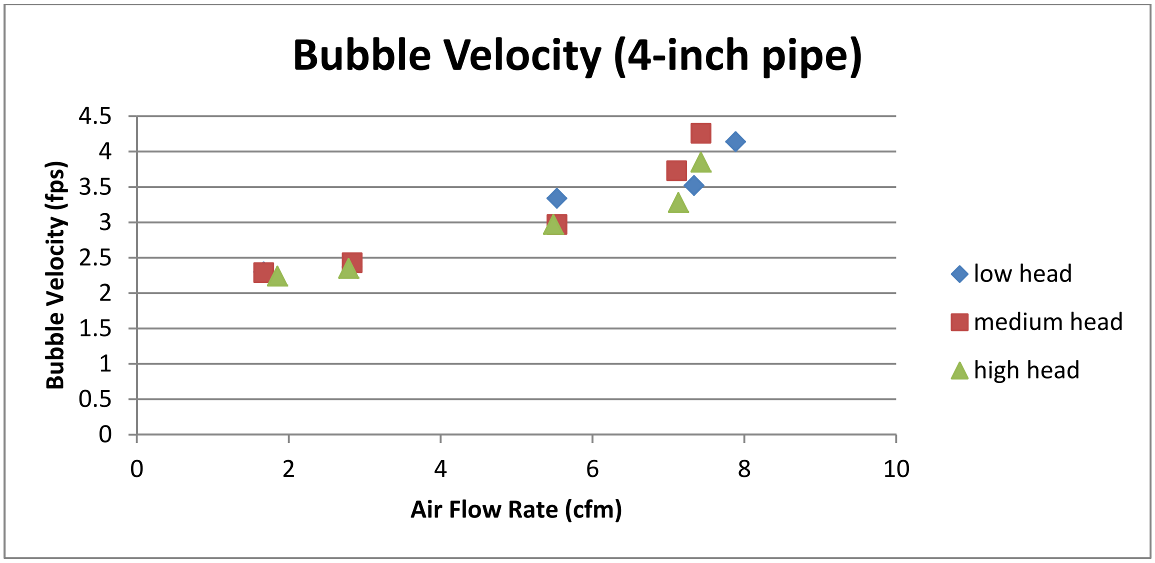


Figure 10: Bubble velocities for 4-inch pipe

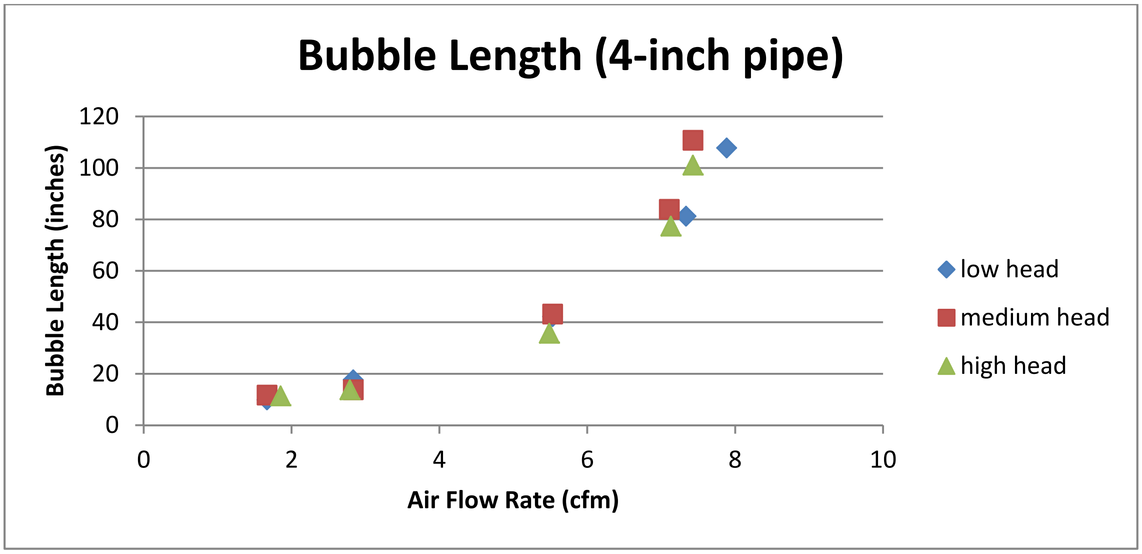


Figure 11: Bubble length for the 4-inch pipe

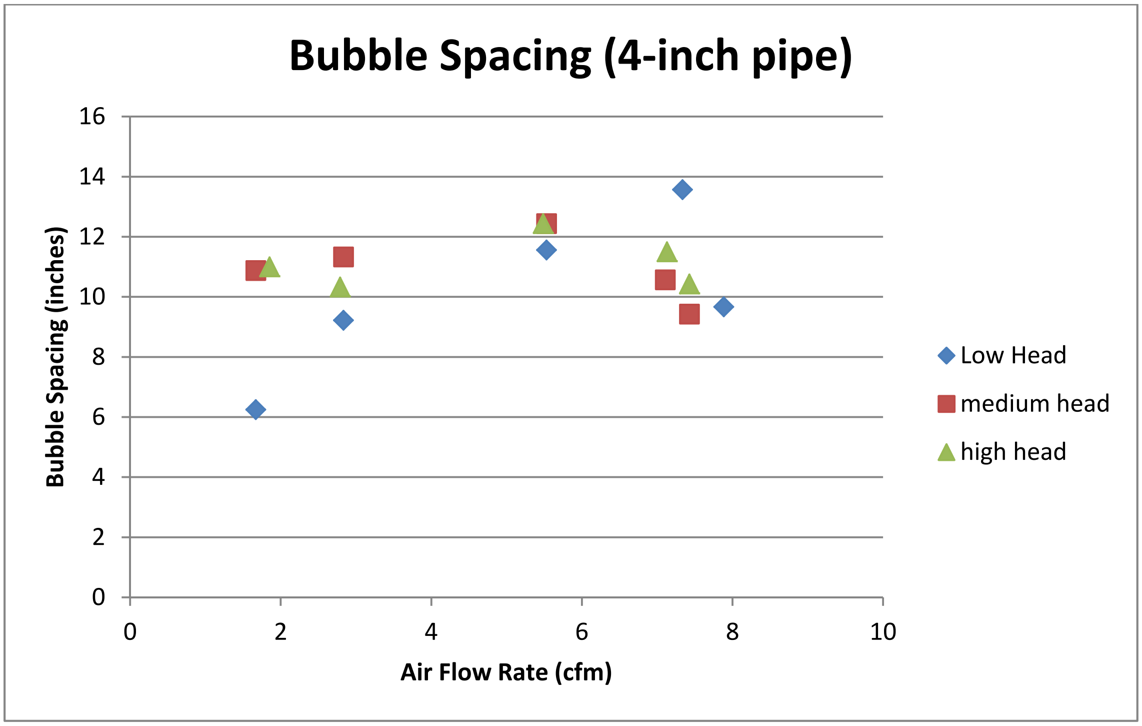


Figure 12: Bubble spacing for the 4-inch pipe

Both bubble velocity and bubble length are unaffected by the changes in head over the range tested as shown in Figures 10 and 11. Also bubble velocity and length increase with increased air flow indicating that as more air is introduced into the pipeline larger and faster bubbles are produced in order to carry the air through the stagnant water and up the pipe. The bubble spacing was more erratic especially at higher air flows, with bubbles combining and large air pockets surging through the pipe. This was due to the large amount of air being injected into the smaller pipe diameter. Overall, the spacing had a small change compared to the bubble length as the air flow went up suggesting that air flow has a smaller effect on spacing between bubbles than on bubble size.

7-inch pipe

Test results for the 7-inch pipe are shown in Figures 13, 14, and 15, with the complete data set in Appendix C. Once again different values of head showed little effect on velocity or bubble length in the inclined pipe. In addition, the bubble spacing was less erratic and showed more space between bubbles as the airflow increased. The bubble spacing was much less erratic than in the 4-inch pipe, but still in the same range of values, from about 6 inches to 12 inches in between bubbles. Less erratic values for the spacing show that there was less surging or slug flow during the high air flows in the 7-inch pipe showing that it could carry more air with smooth flow.

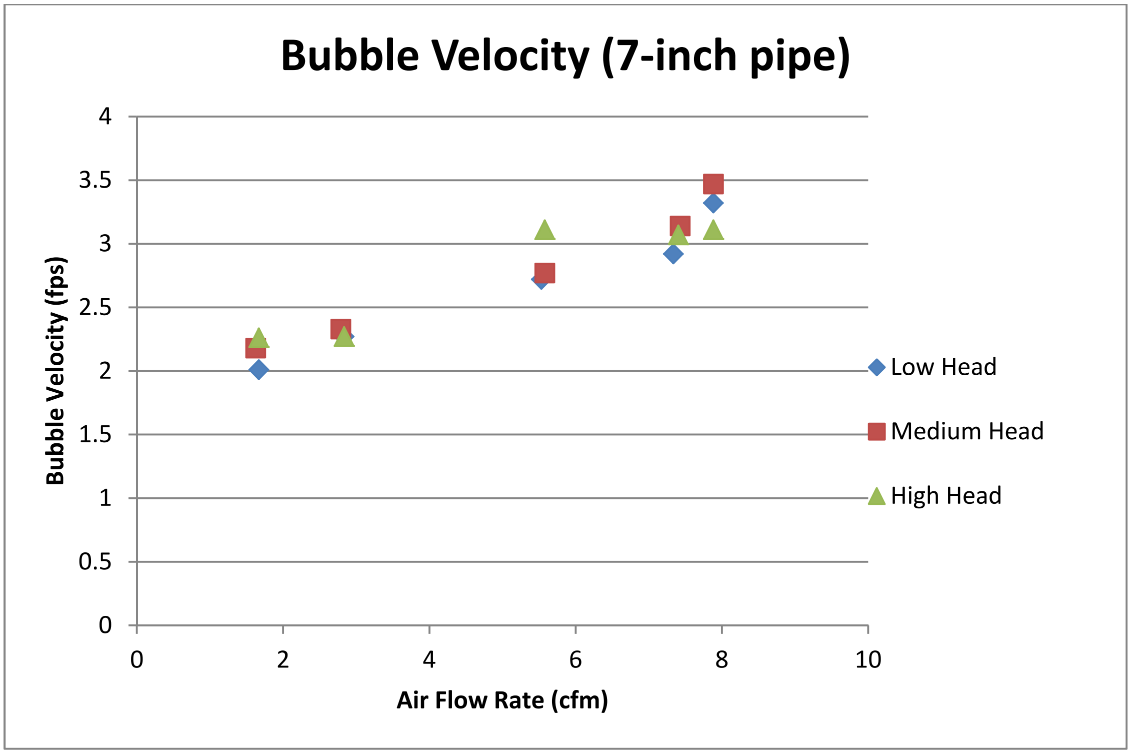


Figure 13: Bubble velocity for the 7-inch pipe

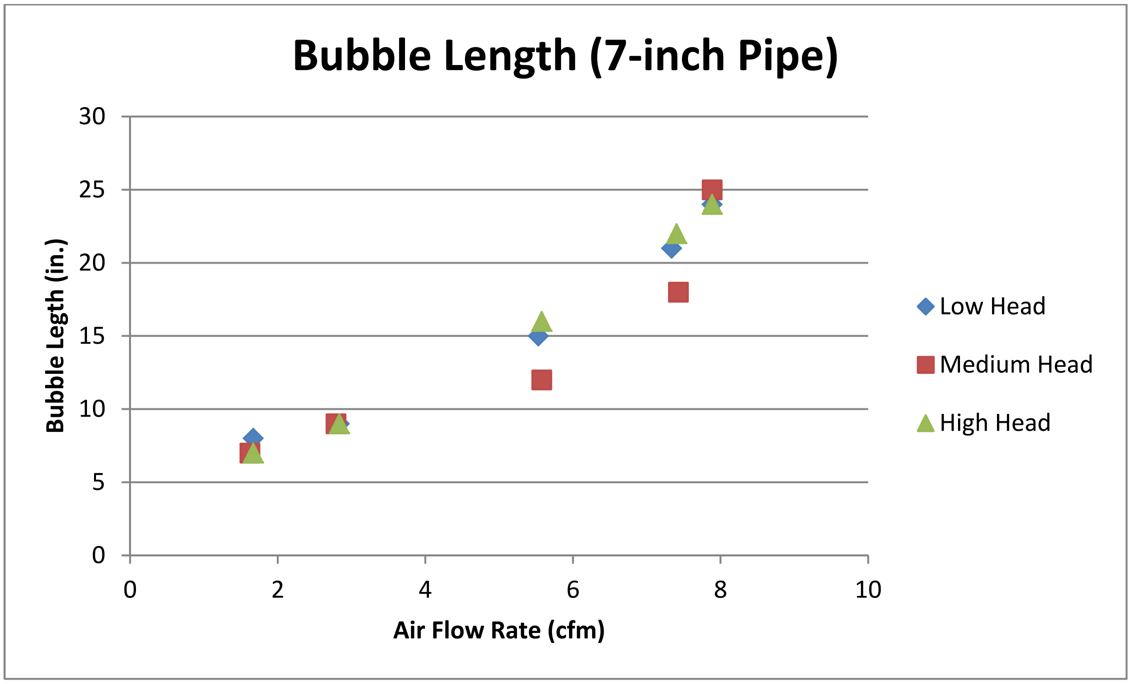


Figure 14: Bubble length for 7-inch pipe

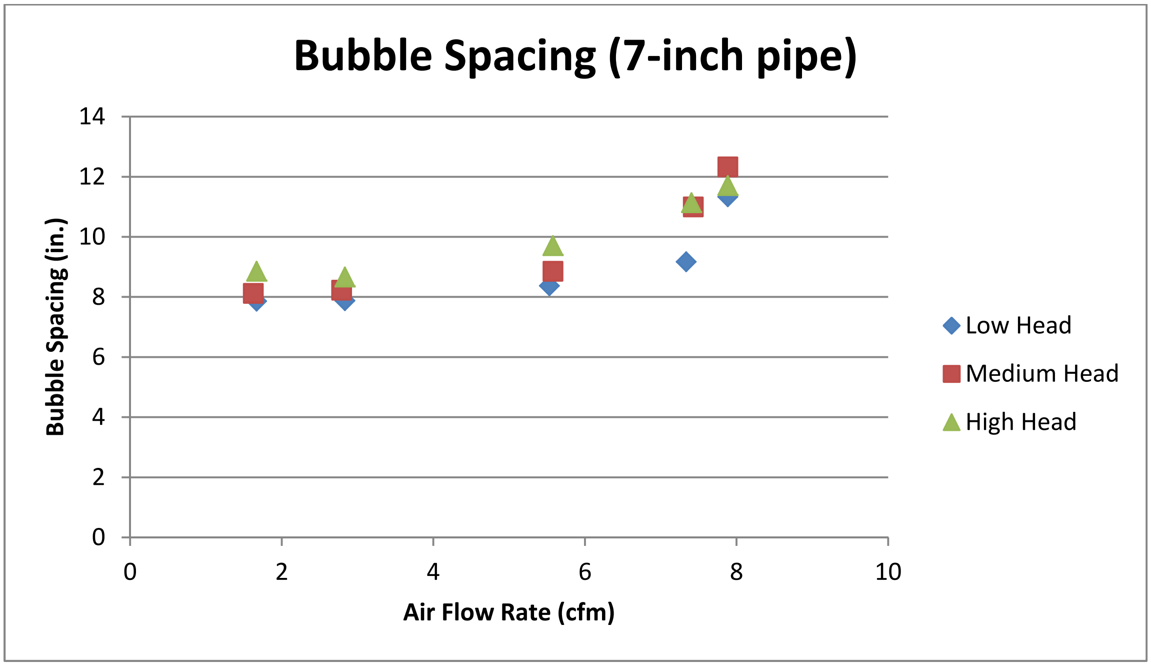


Figure 15: Bubble spacing for 7-inch pipe

12-inch pipe

The results from testing the 12-inch diameter pipe are shown in Figures 16, 17, and 18, and Appendix C contains the complete data set collected. The bubble velocity was again unchanged with varying head values and also increased with increased air flow. The bubble length with these tests showed an increase higher head values with the effect more pronounced at higher air flow rates. Bubble spacing was again erratic however the same range of distances was observed in comparison to the 4-inch and 7-inch pipes. The bubbles in the 12-inch diameter pipe combined to form larger bubbles much faster than in the 7-inch diameter pipe leading to the erratic spacing.

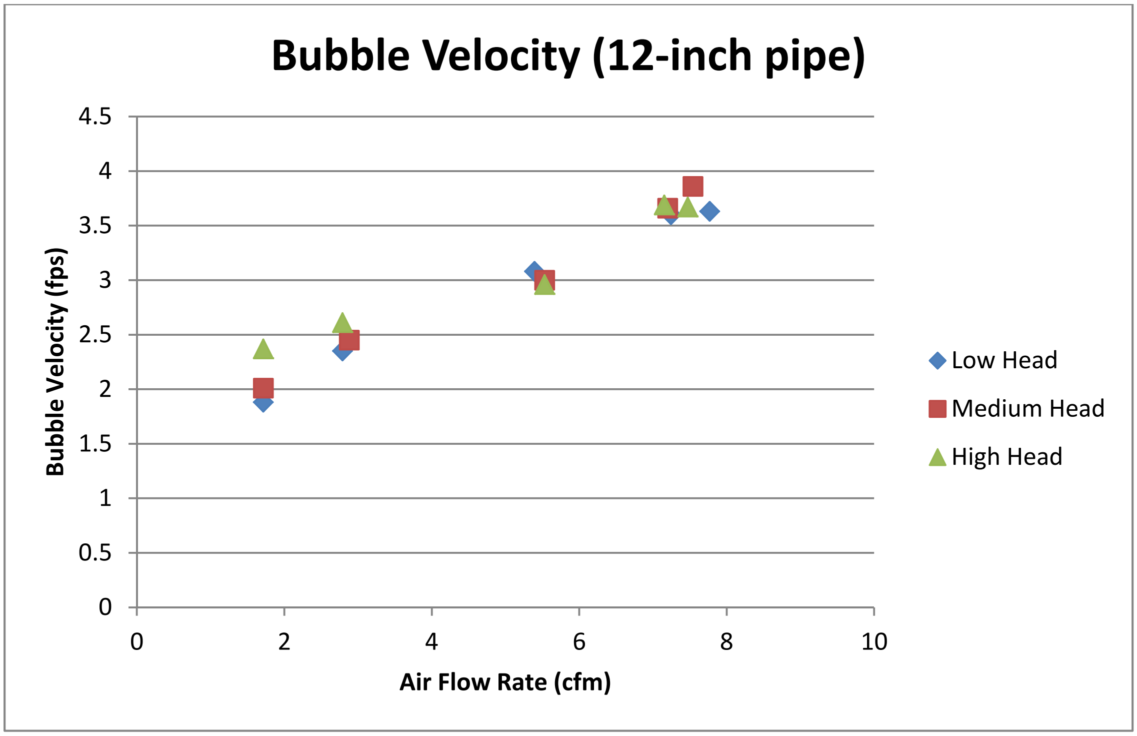


Figure 16: Bubble velocity for the 12-inch pipe

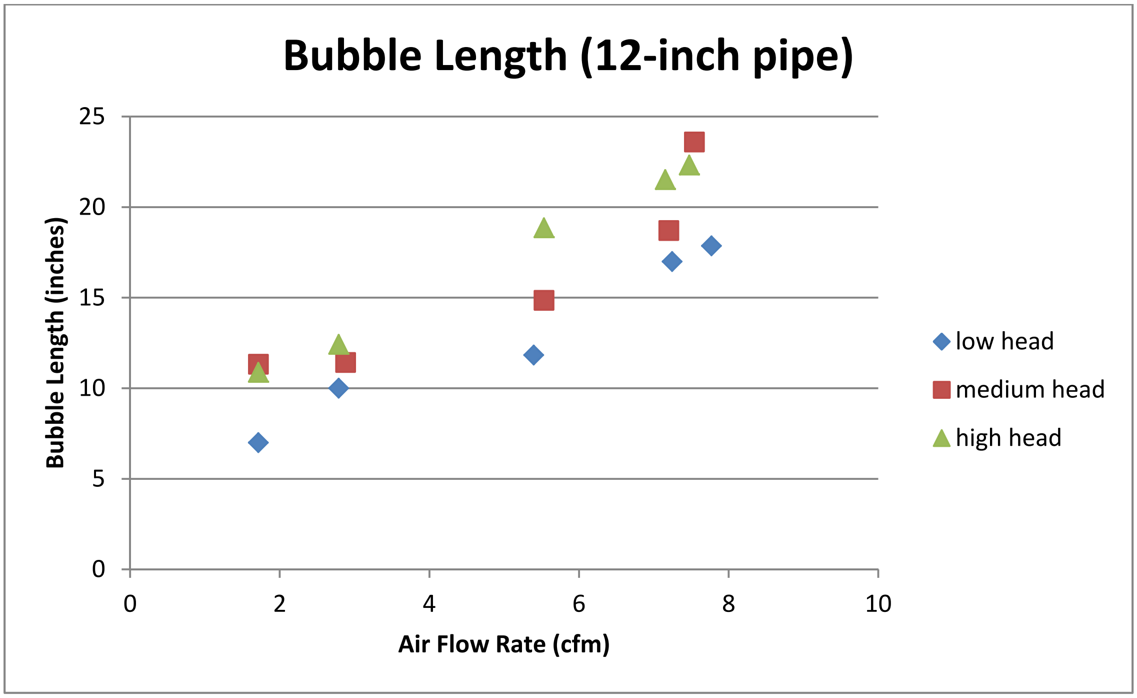


Figure 17: Bubble length for the 12-inch pipe

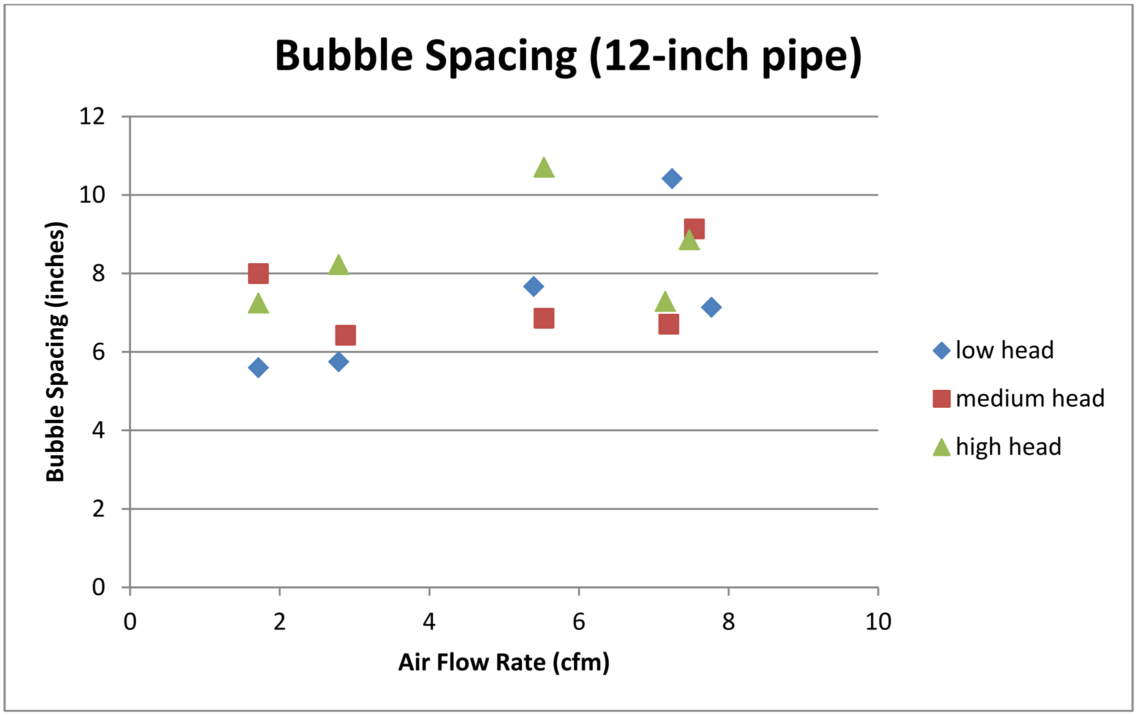


Figure 18: Bubble spacing for the 12-inch pipe

Data Comparison

Bubble velocity

Another goal of this research was to determine if changing the diameter of the pipe will change the characteristics of the bubbles formed. Figure 19 shows the velocities of each pipe plotted by air injection rate. The overall trend indicates that as pipe diameter increases the bubble velocity will increase a small amount, with the effect greater at higher air flows. The values for the 4-inch pipe in the higher air flows are showing high velocities because slug flow was occurring during these air flow rates. It is shown that the quantity of air injected into the pipe has a much larger impact on bubble velocity than the tube diameter. Spedding and Nguyen showed that for tube draining bubbles, the pipe diameter will have an impact on bubble velocity up to 30 centimeters (cm), or 11.8 inches, in pipe diameter as long as the slope is less than 25 degrees (1978). Maneri and Zuber (1974) found that tube diameter has a minimal effect on bubble velocity as long as the slope of the pipe is less than ten degrees. While the current experiment differed in that there was a continuous injection of air versus a single tube draining bubble used in the prior research, similar results were seen in bubble behavior.

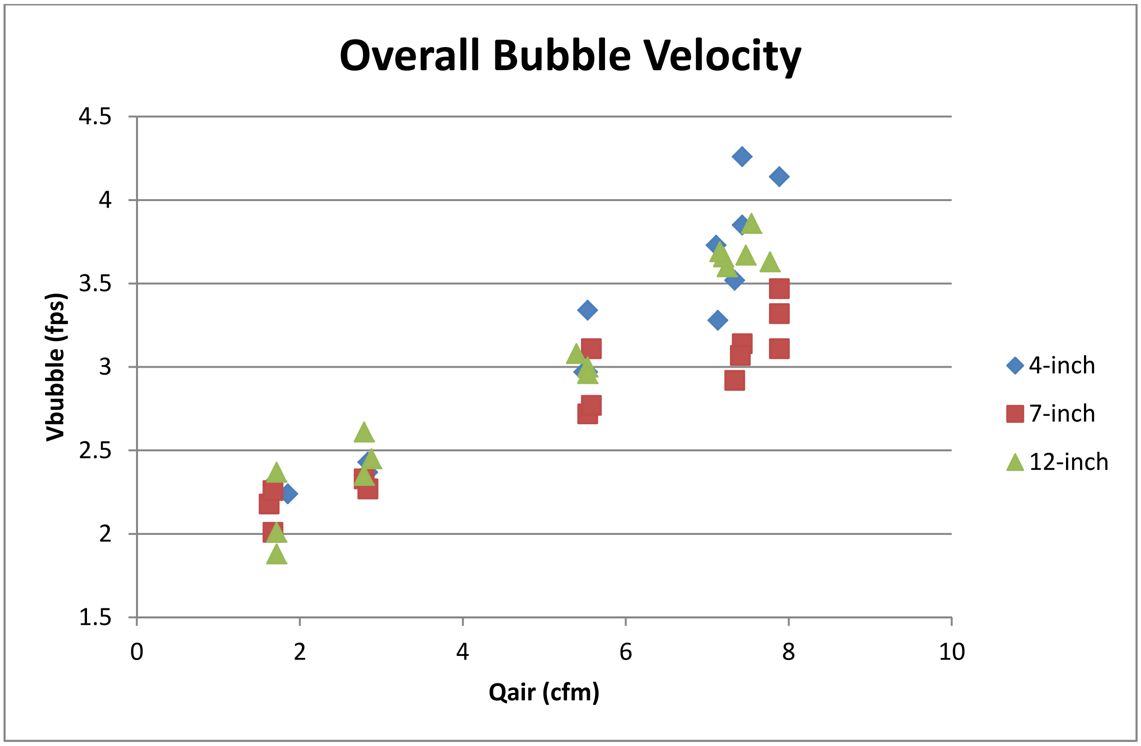


Figure 19: Pipe diameter effect on bubble velocity

Bubble length

Figure 20 shows the changes in bubble length with increasing air flow in the different diameter pipes. This graph shows that the 7-inch and 12-inch pipes have almost identical data while the 4-inch pipe has rapidly rising bubble lengths. This is a product of the 4-inch pipe reaching slug flow conditions causing very long bubbles filling up the small 4-inch pipe. Based on this information it is assumed that as long as the air bubbles are moving through the pipe line in a constant manner with no slug flow the pipe diameter will not affect the length of the bubbles formed.

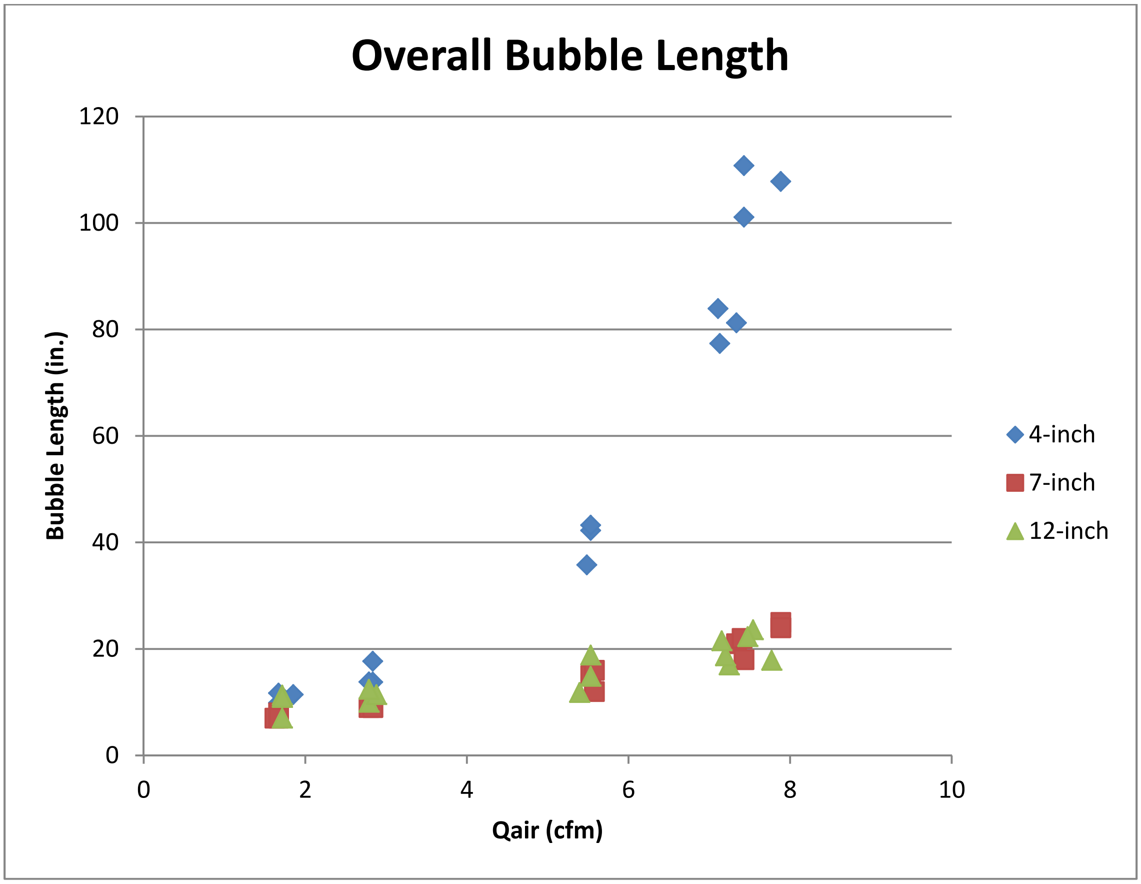


Figure 20: Effect of diameter on bubble length

<u>Bubble spacing</u>

The effects of tube diameter on bubble spacing are shown in Figure 21. The data for bubble spacing is much more scattered, varying with head and the 4-inch pipe subjected to slug flow. A trend is evident, however, indicating that a larger diameter pipe produces less space between bubbles. It is assumed, because of this trend that as a pipe approaches slug flow the bubbles moving in the pipe will remain farther apart.

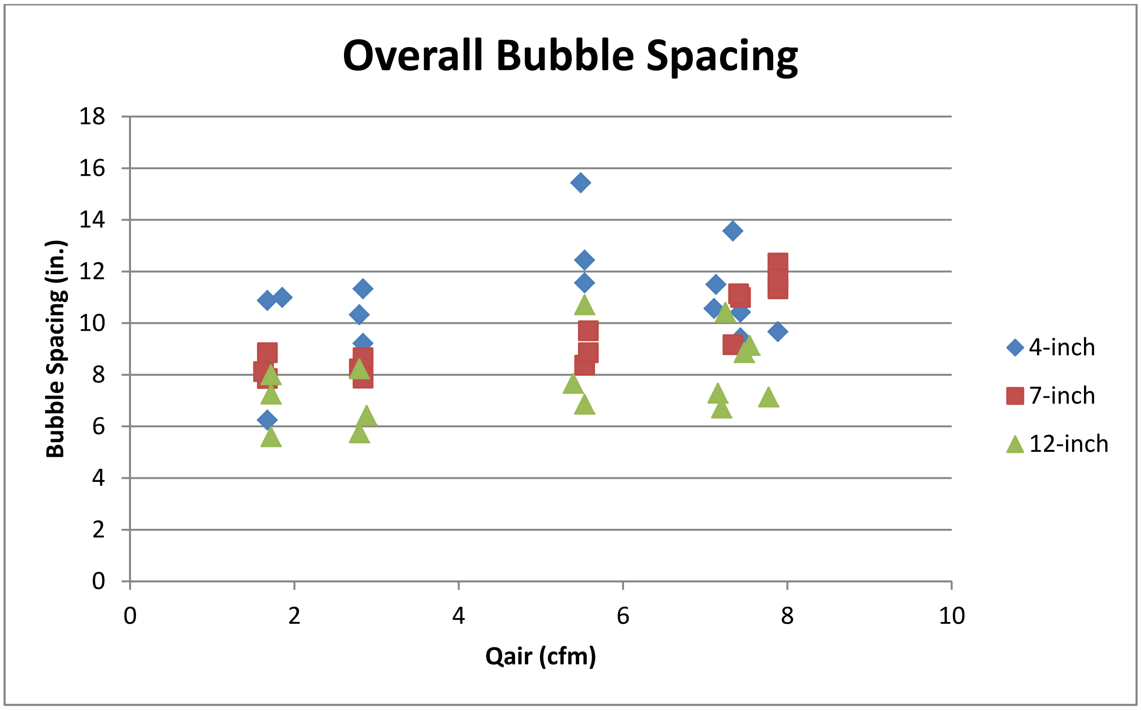


Figure 21: Changes in bubble spacing with pipe diameter

Bubble size and velocity

Wisner, Mohsen, and Kouwen (1975) performed some experiments with the rise velocity of air pockets in an inclined pipe. In their experiments the pipe was inclined to 18.5 degrees, and single bubbles of varying sizes were released and the rise velocity of the bubbles was recorded. Based on these experiments, it was shown that bubble velocity rises with increasing bubble size up to a limiting bubble size (Wisner, Mohsen, and Kouwen, 1975). By plotting the bubble velocity and bubble length of the current research, it can be seen in Figure 22 that this testing supports their finding with bubble velocity increasing with bubble length until slug flow is reached. This data also corresponds to the findings of Maneri and Zuber (1974), and Spedding and Nguyen (1978).

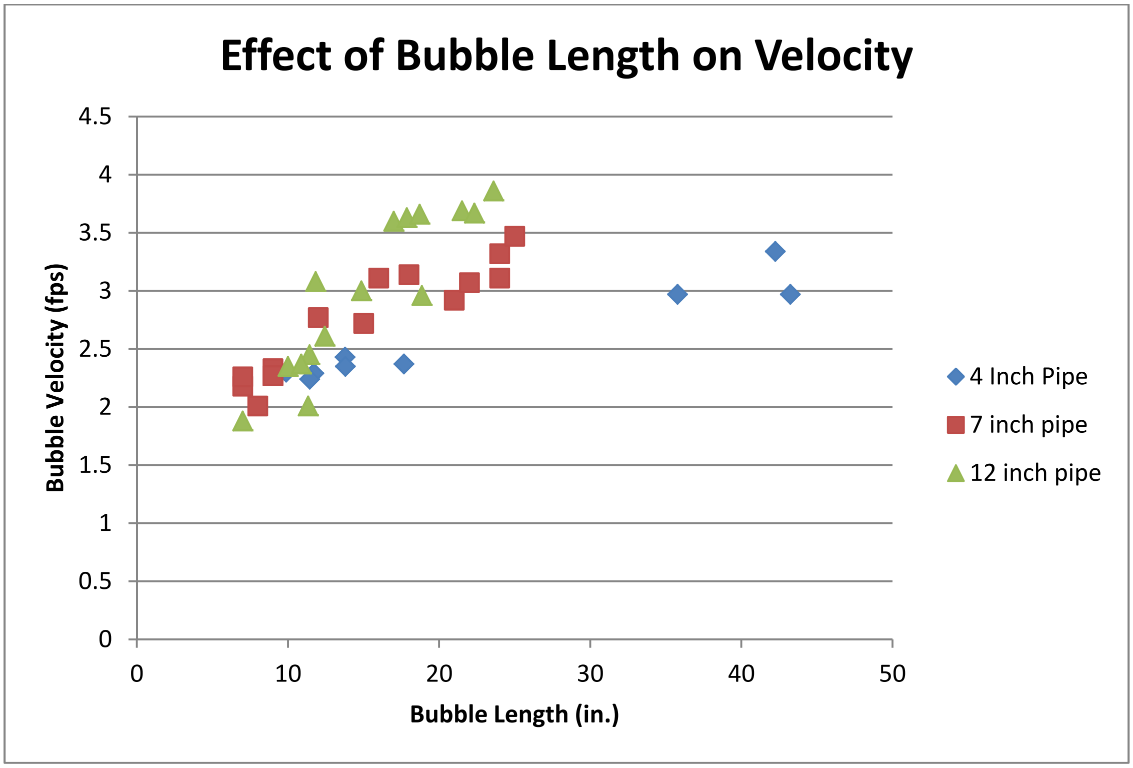


Figure 22: Effect of bubble length on velocity

Air flow and bubble velocity

A study conducted in 1990 by Che, Chen, and Taylor dealt with gas bubble rise velocity beneath an inclined surface. This study is similar to the one detailed in this report, and provides valuable data for comparison. The study by Che, Chen, and Taylor (1990) used continuous injection of air bubbles in water under atmospheric pressure and gathered data on the bubbles formed. Some differences include the shape of the model. Che, Chen, and Taylor used a square chamber rather than a pipe and the air injection point was on the top of the chamber rather than on the bottom of the pipe. They also varied the inclination angle from 2.35 degrees to 28.13 degrees and varied injection tube diameter from 2 mm to 5 mm. The current research uses a 2.29 degree (4%) slope, with an injection tube diameter of 6.35 mm (1/4-inch). The biggest difference between the two studies is the rate of air addition into the stagnant water. This research used air injection rates of between 1.0 and 10.0 cfm and Che, Chen, and Taylor used flow rates of 0.004 and 0.035 cfm (1990). Che, Chen, and Taylor found no effect on bubble volume and velocity with different sizes of injection tubes, and that bubble rise velocity depends upon bubble volume for a given inclination angle (1990). In addition, they found that increasing the inclination angle will always increase the bubble rise velocity (Che, Chen, and Taylor, 1990).

Figure 23 shows the bubble rise velocity based on injected air flow rate for the tests performed by Che, Chen, and Taylor at a slope of 2.35 degrees and current test data for the 12-inch diameter pipe. The 12-inch pipe was used for the chart

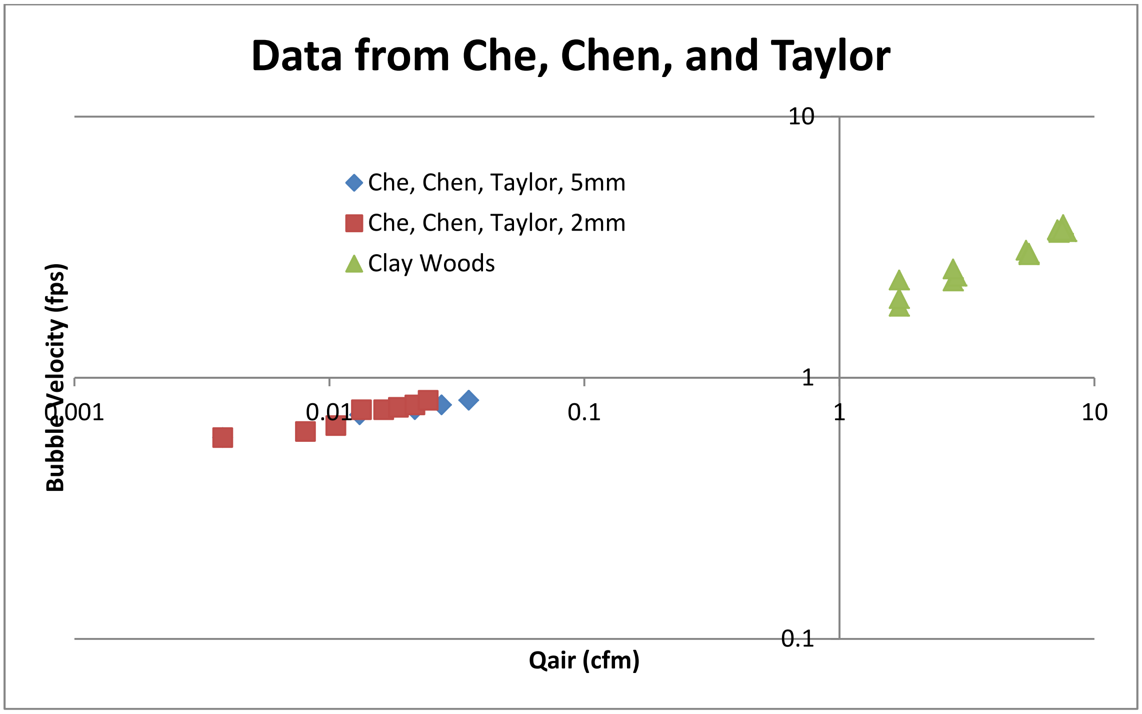


Figure 23: Display of data collected by Che, Chen, and Taylor (1990)

because it is similar in size to the model used by Che, Chen, and Taylor. The large difference in air injection rates requires that the data be plotted on a log scale. It is difficult to compare the two sets of data because the air injection rates differ by such a large magnitude. However, the plot does show that the bubble velocity increases with air flow in the range tested by Che, Chen, and Taylor (1990) and also over the range of air flow tested in this study.

CHAPTER 6

APPLICATION

The presence of air in pipelines can cause many problems ranging from reduction in flow, reduction in pump or turbine efficiency, damage to pipe materials, and the environmental impact of air bubbles discharging into an environment causing algal growth and changing dissolved oxygen levels (Escarameia, 2007). One of the ways to remove air from submerged pipelines (outfall diffusers) is to vent any air in the pipeline through valves or air collection chambers. This collected air may then be released through a pipe filled with stagnant water. If the vent pipe is sized correctly, the escaping air will travel through the water with no surging or slug flow. Surging can reduce the capacity of the pipe resulting in less air being removed from the main pipeline and cause transients that could damage the vent pipe. It would be beneficial for designers to be able to size the vent line in the original design of a project in order to maintain steady smooth air flow and still minimize cost by installing the smallest diameter pipe needed for the anticipated air flow. The following section shows how the data collected during this study combined with prior research can be applied in the design of a vent pipeline that is full of water.

Assumptions and Limitations

This design procedure has some limitations based on the data collected during this study. This study was based on a non-varying slope of 4%, or 2.29 degrees, and it has been shown that the bubble velocity will increase with increased slope (Che, Chen, and Taylor, 1990). The literature shows that the bubble velocity reaches a maximum at about 35 degrees and then decreases if the slope continues to increase (Alves, Shoham, and Taitel, 1993). While data for only a 4% slope was collected for this study, previous studies have been used to calculate a correction factor to adjust the data to apply to slopes up to 20%. This design process also calculates bubble velocity based on air flow. This assumption is made because the effect of head and pipe diameter were shown to have little effect on bubble velocity over the range tested in this study as long as slug flow is not present in the pipe. Since the design of the pipe is to prevent slug flow, it is reasonable to assume that air flow is the main factor in bubble velocity for a given slope. The data points for the 4-inch and 7-inch diameter pipes that showed slug flow were omitted in the design process since the goal of the design is to prevent slug flow from occurring. The design procedure also assumes that the flow rate of air to be vented in known and that the head on the water in the vent pipe is known. It is also assumed that the flow rate of air to be vented is uniform. It is possible to encounter situations where large bursts of air will enter the vent tube. In this situation, slug flow is likely to develop in any size of submerged vent tube. When using the given equations air flow rate must be in the units of cfs, velocities are in fps, and length units must be in feet.

Determining Dimensionless Terms

In order to compare all of the data collected in the study it was necessary to display them graphically with dimensionless (Pi, Π) terms. The procedure for determining the pi terms was taken from the textbook Fluid Mechanics with

Engineering Applications by Finnemore and Franzini, 10th edition (2001). Determining the pi terms was done as follows:

1. Consider factors that are of influence and list and count *n* variables.
2. Choose a dimensional system and list the dimensions of each variable and find *m*, the number of fundamental dimensions involved.
3. Find the reduction number *k*. This is usually equal to *m* but can be less if there are dimensional variables that can be formed into dimensionless groups.
4. Determine $\Pi = n-k$
5. Select primary variables
    a. Must contain all of the m fundamental dimensions and not form a Π among them.
    b. Generally variables relating to mass, geometry, and kinematics are chosen.
    c. Form Π groups by multiplying the product of primary variables, with unknown exponents, by each of the remaining variables one at a time.
6. Equate exponents on each dimension on both sides of each Π equation and solve for the exponents.
7. Rearrange Π groups if desired.

The selection of which Pi terms to use in the application depended on using a term that has known values combined with a term containing pipe diameter, which we are trying to determine. Terms containing physical properties such as surface tension and density were avoided since our testing consisted of a single substance, water, and also because Spedding and Nguyen (1978) found that surface tension does not play a significant role in bubble shape and velocity except in very small diameter pipes. The dimensionless terms selected for the application and how they are used are examined in the following section.

Procedure

An analysis of dimensionless terms found using the procedure stated in the previous section resulted in selecting the terms VH^2/Qa, with V being the bubble velocity in fps, H is the head in feet of water in the vent pipe, and Qa the flowrate of air injected into the submerged vent tube in cfs. The other chosen term is XL/HD with X the space between bubbles in feet, L the length of the bubble in feet, H the head in feet of water, and D the diameter of the pipe in feet. These two dimensionless terms and their relationship based on collected data are shown graphically in Figure 24.

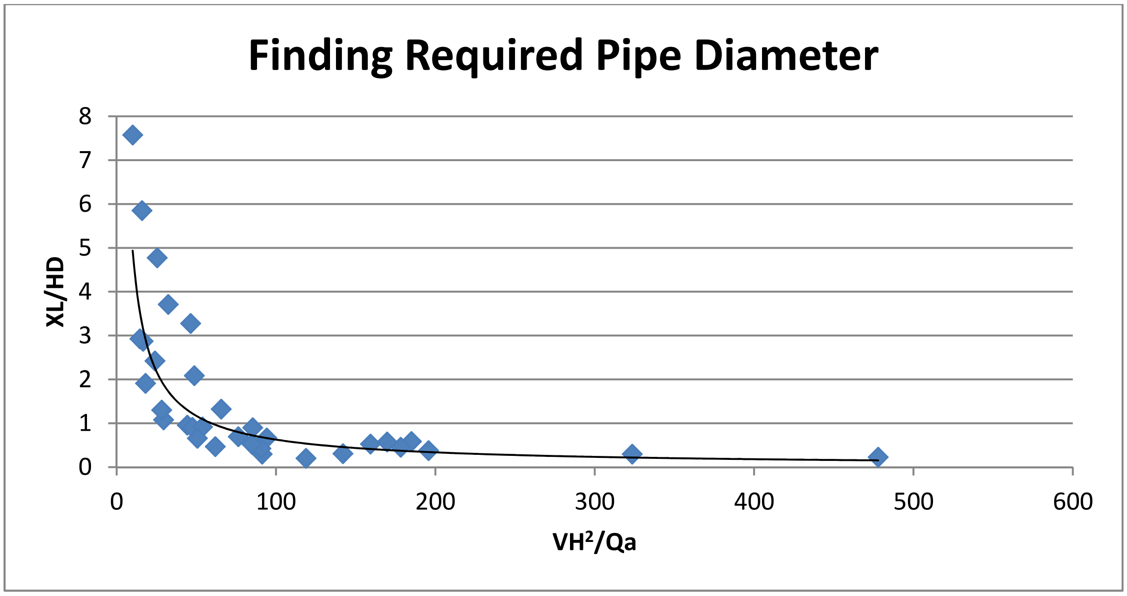


Figure 24: Determining required pipe diameter

The velocity component in the Π term on the X axis can be approximated using the known air flow rate using Figure 25 or Equation 1, where Q_a is the air flow rate into the vent pipe in cfs and V_{bubble} is the resulting bubble velocity in fps. Estimating the velocity in this way enables all of the variables in this Π term to be used to calculate the required pipe diameter.

$$V_{bubble} = 13.60Q_a + 1.758 \quad (1)$$

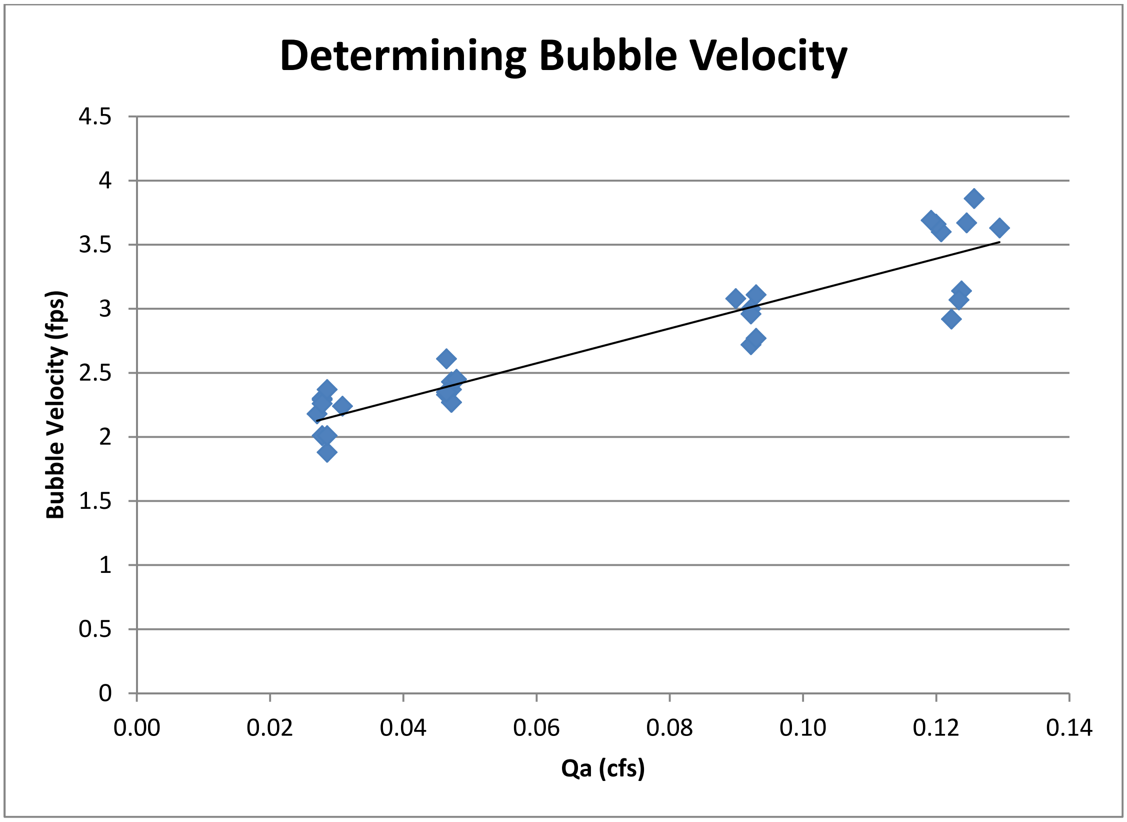


Figure 25: Estimating bubble velocity

The bubble velocity calculated using Equation 1 applies to only a 2.29 degree slope. In order to apply this design to other slopes, information from Maneri and Zuber (1974) and Spedding and Nguyen (1978) are used. Both of these studies presented results illustrating how bubble velocity changes with slope. Figure 26 shows graphically the results of each study. By utilizing the average slope of the data shown in Figure 26, the slope-effect on bubble velocity and a corresponding correction factor can be calculated and applied to the data found in this study. Based on the two studies, each degree of slope change causes a corresponding increase or decrease in bubble velocity of 0.01 fps. Equation 2, where S is the slope of the vent pipe in degrees and V_{bubble}' is the corrected bubble velocity in fps, uses the information from previous studies to calculate a bubble velocity that is corrected for slope.

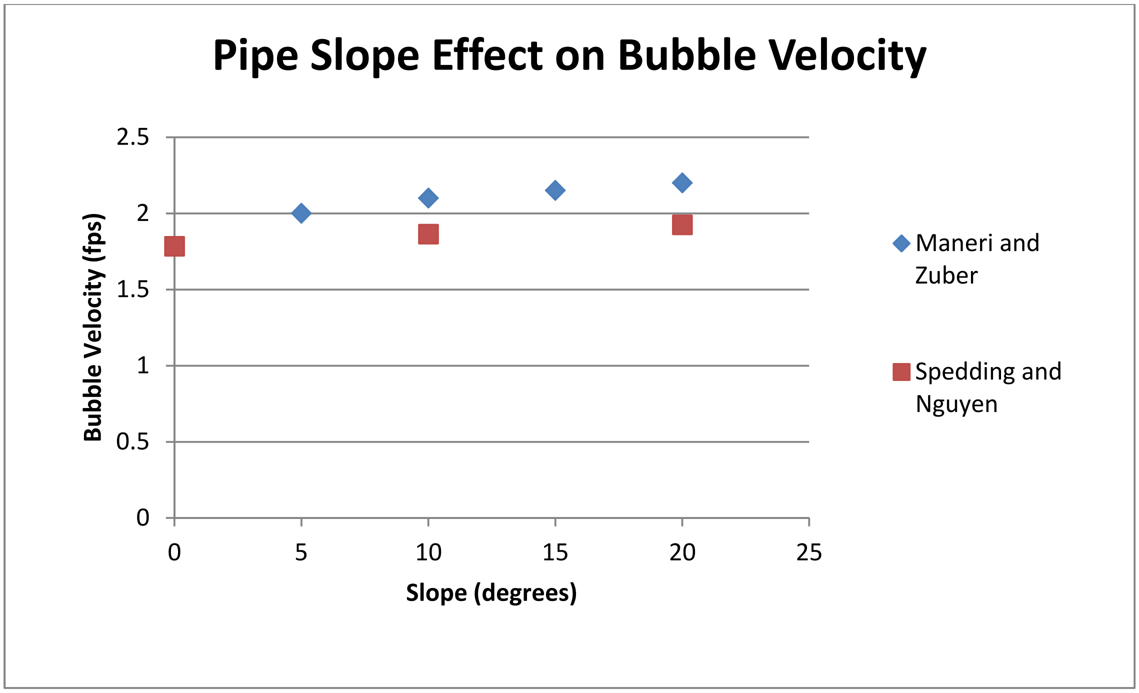


Figure 26: Effect of slope on velocity derived from Maneri and Zuber (1974) and Spedding and Nguyen (1978)

$$V_{bubble}' = 0.01(S - 2.29) + V_{bubble} \tag{2}$$

A corrected air flow rate (Qa′) must then be calculated using the corrected bubble velocity. This is done be rearranging Equation 1 and using the corrected value for bubble velocity and solving for Qa′, a corrected air flow rate. The air flow found in Equation 3 should be used as the true air flow in future equations.

$$Q_a' = \frac{V_{bubble}' - 1.758}{13.6} \tag{3}$$

Equation 4 is formed by combining Equation 1 with the dimensionless term on the x-axis of Figure 24. This equation can then be used to find the value of the dimensionless term XL/HD, represented by the variable Z.

$$\frac{\left(13.60Q_a' + 1.758\right)H^2}{Q_a'} = Z \tag{4}$$

The equation of the line in Figure 24 is shown as Equation 5. This equation can also be used to estimate the term XL/HD numerically by substituting Equation 4 into Equation 5. This equation is shown as Equation 6.

$$39.44Z^{-0.9} = \frac{XL}{HD} \tag{5}$$

$$39.44\left[\frac{\left(13.60Q_a{}' + 1.758\right)H^2}{Q_a{}'}\right]^{-0.9} = \frac{XL}{HD} \qquad (6)$$

In order to use Equation 6 to find the required pipe diameter, D, a value must be assumed for XL. This value can be estimated using Figure 27 or Equation 7.

$$XL = 7.178Q_a{}' + 0.341 \qquad (7)$$

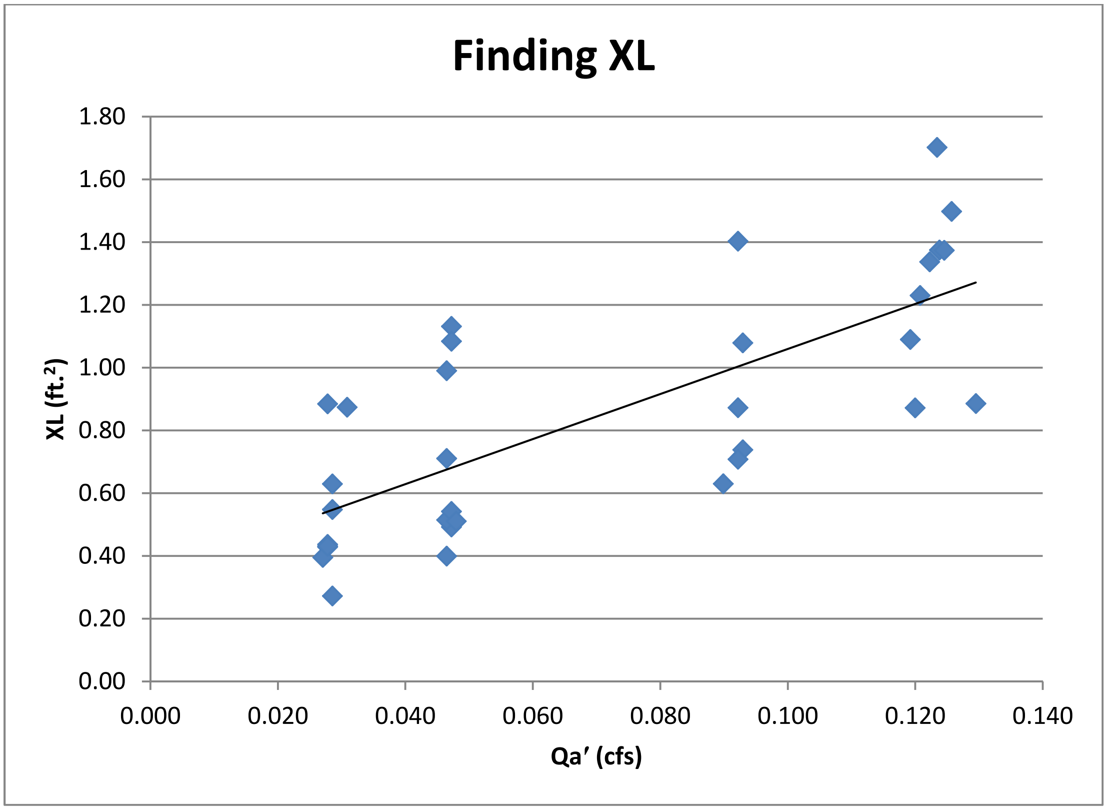


Figure 27: Finding XL

By rearranging Equation 6 and substituting the results of Equation 7, an equation for required pipe diameter, in feet, is shown as Equation 8.

$$D = \frac{7.178Q_a' + 0.341}{39.44H\left(\frac{\left(13.60Q_a' + 1.758\right)H^2}{Q_a'}\right)^{-0.9}} \tag{8}$$

By using either Equation 8 and solving for D numerically or using Figures 24 through 27 an estimated value for the required pipe diameter (D), measured in feet, can be found to prevent slug flow from occurring in the vent line. This information can be valuable in lowing costs and ensuring that the system will operate as designed with no reworking.

CHAPTER 7

CONCLUSIONS

This research presents a study of air bubble behavior in a water-filled vent tube vented to atmosphere. Having the ability to vent air out of a piping system is very important to prevent damage to the pipeline, piping supports, and equipment such as pumps. An important part of being able to vent air through a submerged vent line is having a submerged vent that will vent air steadily with no slug flow. Previous studies dealing with the topic of bubble movement in pipes were studied and experiments determining the effect of pipe diameter, head, and air flow rate on bubble size, spacing, and velocity were conducted. The results of these experiments were analyzed and compared to the results of previous experiments. Using data from these experiments and on information from the literature review a design procedure was created to estimate the required diameter to prevent slug flow in a vent pipeline.

The following conclusions can be made from these experiments:

- Bubble velocity changed very little with changes in pipe diameter until slug flow occurs.
- Bubble length does not change with pipe diameter until slug flow occurs.
- Bubble velocity does not change with head changes within the range of this study.
- Bubble length can change as head changes.

- Bubble velocity will increase with increased air flow.
- Bubble length will increase with increased air flow.
- Bubble velocity increases with increased bubble length. This is consistent with data found in the literature covering previous studies.
- Based on previous studies the bubble velocity will increase with increasing slope up to a slope of about 35 degrees.
- Overall, the venting capacity of a submerged tube depends on having a large enough diameter to prevent slug flow.

Further study on the effect of slope on bubble characteristics would be required to confirm the results of prior research and could extend the data collected to other pipe slopes. In addition, further research in which additional air flow rates are tested would be valuable to better understand the relationship between air flow and bubble velocity. Research dealing with the temperature effects on bubble formation would also be valuable since all tests in this study used the same temperature water and air. A study dealing with large changes in head would be valuable since the head changes in this study were very small and it is possible that large changes in head would affect bubble size and velocity.

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APPENDICES

Appendix A: Data Collected by Spedding and Nguyen (1978)

Figure 28 shows a graphical representation of data collected by Spedding and Nguyen (1978) from pipe slopes ranging from zero to forty degrees from the horizontal. The linear portion of this graph was then used in Figure 29 to show the effect of slope on bubble velocity. The Froude number (Fr) used in Figure 28 was converted to bubble velocity using the properties of water and the pipe diameter used by Spedding and Nguyen (1978). The line shown the graph in Figure 29 is used to apply slope corrections to bubble velocity.

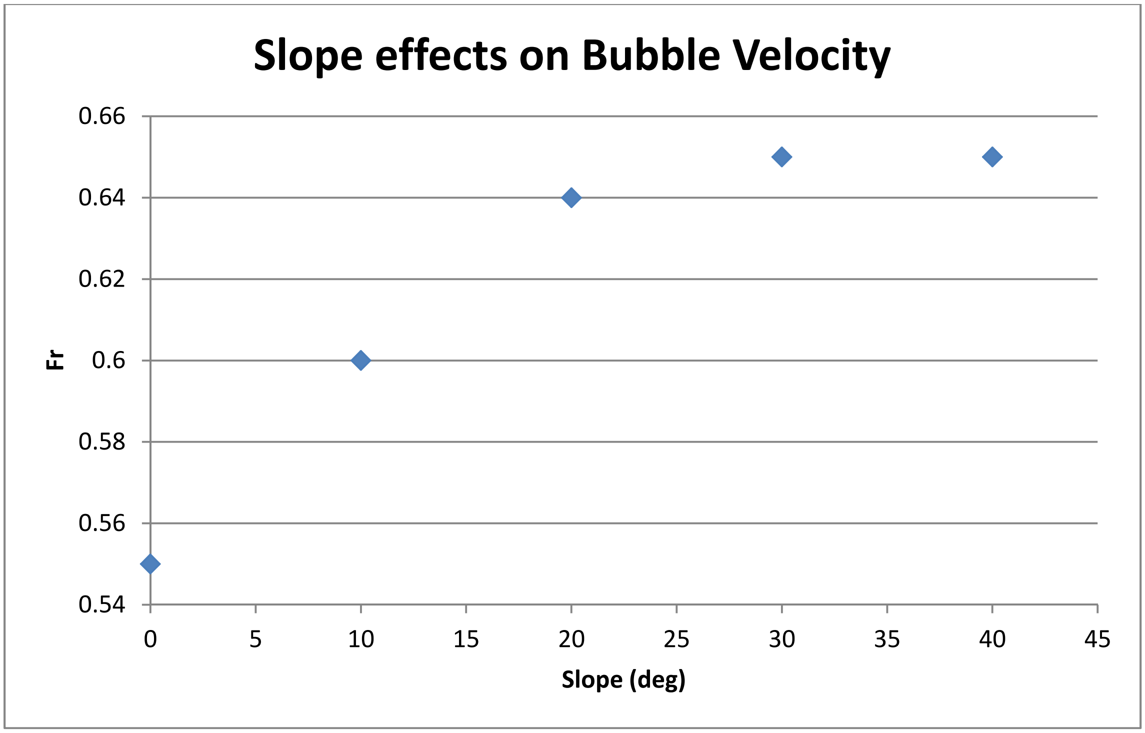


Figure 28: Slope data displayed from Spedding and Nguyen (1978)

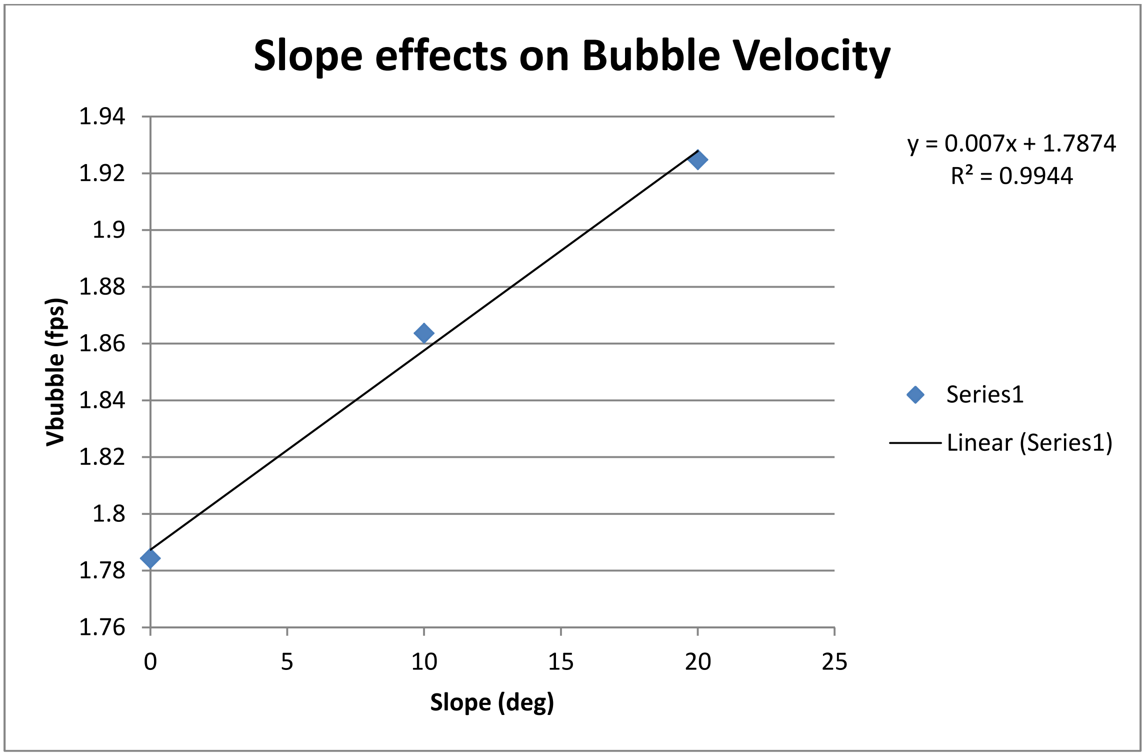


Figure 29: A portion of data converted to show bubble velocity (Spedding and Nguyen, 1978)

Appendix B: Data Collected By Maneri and Zuber (1974)

Maneri and Zuber (1974) collected data relating slope and bubble velocity. A representation of this data is given in Figure 30. The linear portion of this data is taken and shown in Figure 31. The slopes of the lines in Figure 31 show the change in bubble velocity for a given change in pipe slope. This information is used to apply the data collected in the current research to multiple pipe slopes.

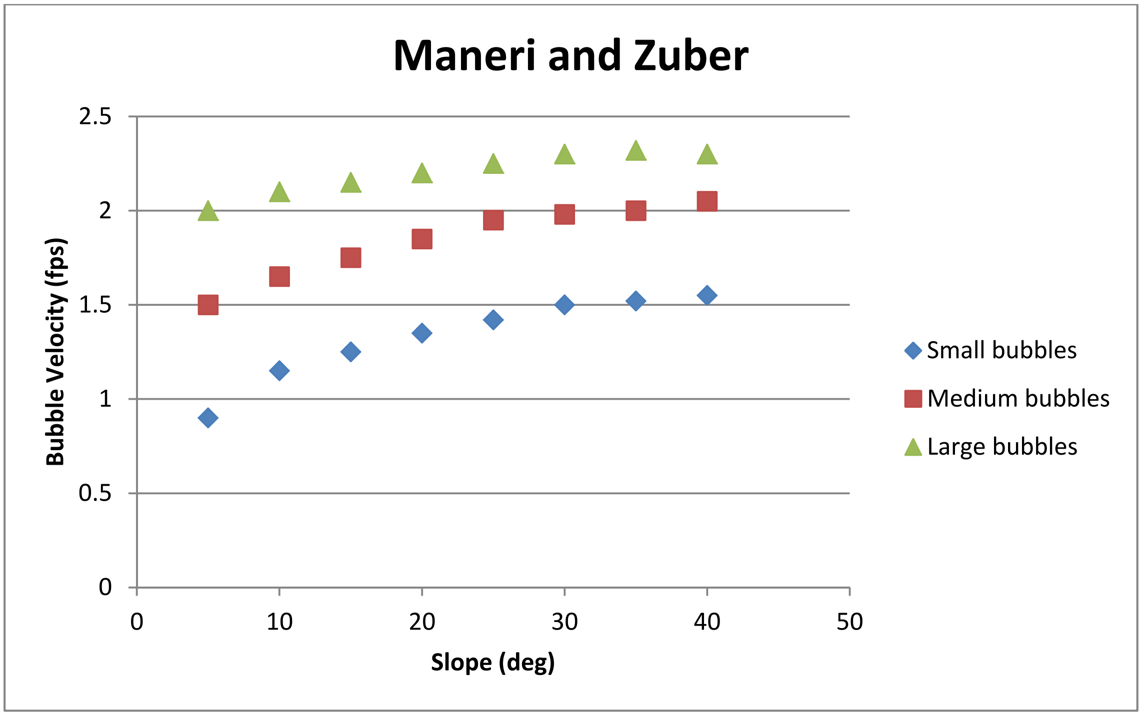


Figure 30: Data display from a study conducted by Maneri and Zuber (1974)

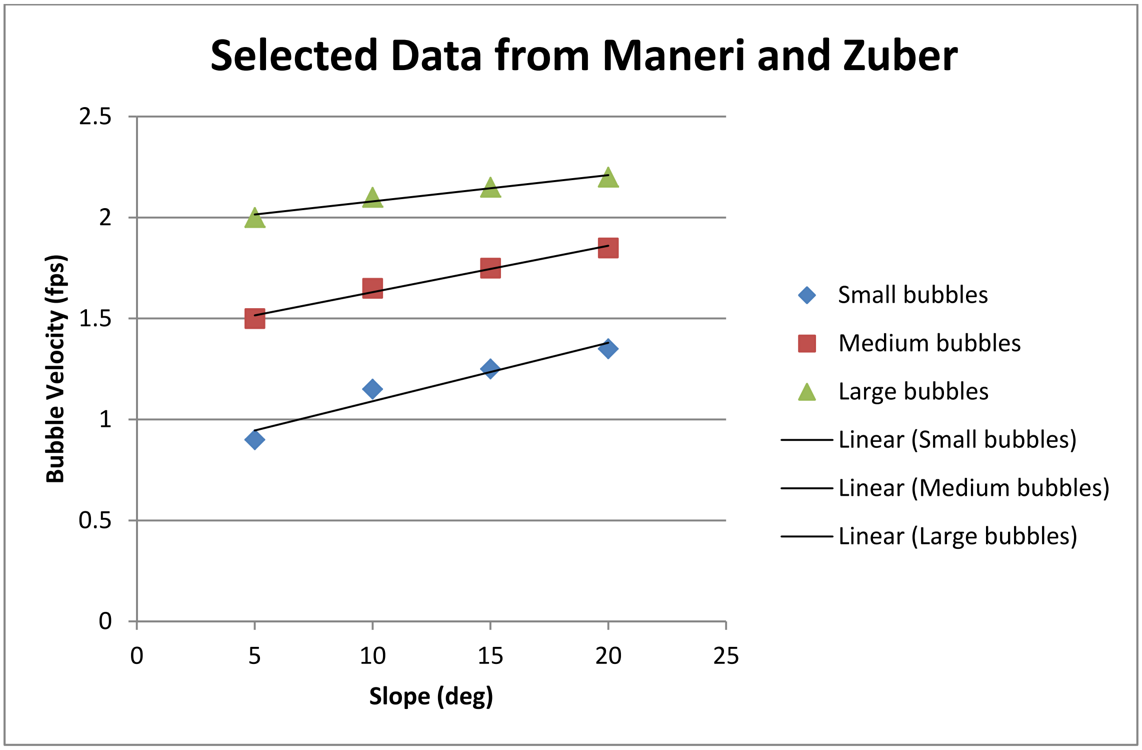
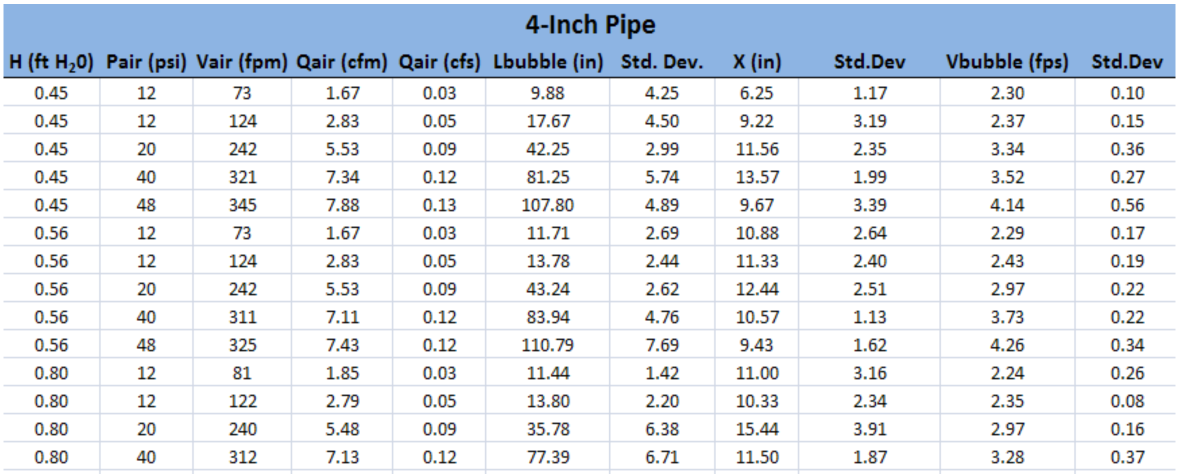


Figure 31: Linear portion of data by Maneri and Zuber (1974)

Appendix C: Experimental Data

The data collected for each test pipe is shown in Tables 2, 3, and 4 giving the bubble velocity, bubble length, and bubble spacing for each pipe diameter and head combination that was tested.

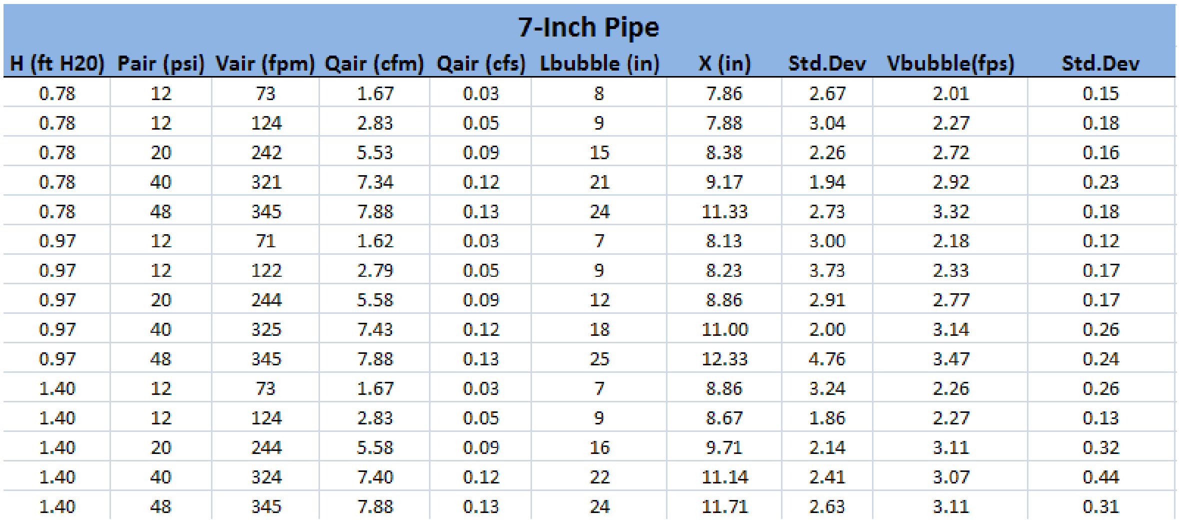
Table 2: Test data from the 4-inch pipe



4-Inch Pipe

H (ft H$_2$0)	Pair (psi)	Vair (fpm)	Qair (cfm)	Qair (cfs)	Lbubble (in)	Std. Dev.	X (in)	Std.Dev	Vbubble (fps)	Std.Dev
0.45	12	73	1.67	0.03	9.88	4.25	6.25	1.17	2.30	0.10
0.45	12	124	2.83	0.05	17.67	4.50	9.22	3.19	2.37	0.15
0.45	20	242	5.53	0.09	42.25	2.99	11.56	2.35	3.34	0.36
0.45	40	321	7.34	0.12	81.25	5.74	13.57	1.99	3.52	0.27
0.45	48	345	7.88	0.13	107.80	4.89	9.67	3.39	4.14	0.56
0.56	12	73	1.67	0.03	11.71	2.69	10.88	2.64	2.29	0.17
0.56	12	124	2.83	0.05	13.78	2.44	11.33	2.40	2.43	0.19
0.56	20	242	5.53	0.09	43.24	2.62	12.44	2.51	2.97	0.22
0.56	40	311	7.11	0.12	83.94	4.76	10.57	1.13	3.73	0.22
0.56	48	325	7.43	0.12	110.79	7.69	9.43	1.62	4.26	0.34
0.80	12	81	1.85	0.03	11.44	1.42	11.00	3.16	2.24	0.26
0.80	12	122	2.79	0.05	13.80	2.20	10.33	2.34	2.35	0.08
0.80	20	240	5.48	0.09	35.78	6.38	15.44	3.91	2.97	0.16
0.80	40	312	7.13	0.12	77.39	6.71	11.50	1.87	3.28	0.37

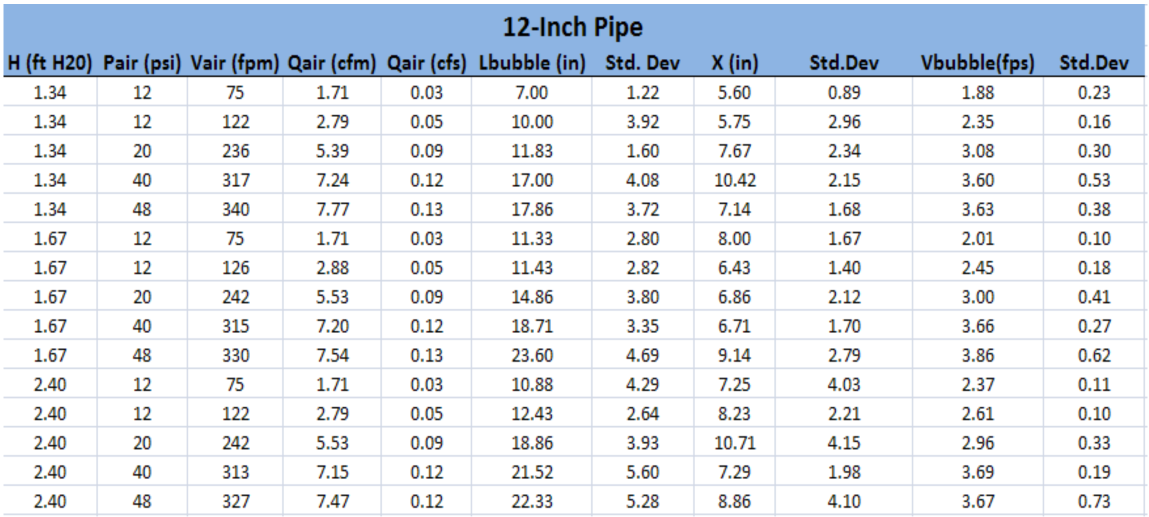
Table 3: Test data from the 7-inch pipe



7-Inch Pipe

H (ft H20)	Pair (psi)	Vair (fpm)	Qair (cfm)	Qair (cfs)	Lbubble (in)	X (in)	Std.Dev	Vbubble(fps)	Std.Dev
0.78	12	73	1.67	0.03	8	7.86	2.67	2.01	0.15
0.78	12	124	2.83	0.05	9	7.88	3.04	2.27	0.18
0.78	20	242	5.53	0.09	15	8.38	2.26	2.72	0.16
0.78	40	321	7.34	0.12	21	9.17	1.94	2.92	0.23
0.78	48	345	7.88	0.13	24	11.33	2.73	3.32	0.18
0.97	12	71	1.62	0.03	7	8.13	3.00	2.18	0.12
0.97	12	122	2.79	0.05	9	8.23	3.73	2.33	0.17
0.97	20	244	5.58	0.09	12	8.86	2.91	2.77	0.17
0.97	40	325	7.43	0.12	18	11.00	2.00	3.14	0.26
0.97	48	345	7.88	0.13	25	12.33	4.76	3.47	0.24
1.40	12	73	1.67	0.03	7	8.86	3.24	2.26	0.26
1.40	12	124	2.83	0.05	9	8.67	1.86	2.27	0.13
1.40	20	244	5.58	0.09	16	9.71	2.14	3.11	0.32
1.40	40	324	7.40	0.12	22	11.14	2.41	3.07	0.44
1.40	48	345	7.88	0.13	24	11.71	2.63	3.11	0.31

Table 4: Test data from the 12-inch pipe



12-Inch Pipe

H (ft H20)	Pair (psi)	Vair (fpm)	Qair (cfm)	Qair (cfs)	Lbubble (in)	Std. Dev	X (in)	Std.Dev	Vbubble(fps)	Std.Dev
1.34	12	75	1.71	0.03	7.00	1.22	5.60	0.89	1.88	0.23
1.34	12	122	2.79	0.05	10.00	3.92	5.75	2.96	2.35	0.16
1.34	20	236	5.39	0.09	11.83	1.60	7.67	2.34	3.08	0.30
1.34	40	317	7.24	0.12	17.00	4.08	10.42	2.15	3.60	0.53
1.34	48	340	7.77	0.13	17.86	3.72	7.14	1.68	3.63	0.38
1.67	12	75	1.71	0.03	11.33	2.80	8.00	1.67	2.01	0.10
1.67	12	126	2.88	0.05	11.43	2.82	6.43	1.40	2.45	0.18
1.67	20	242	5.53	0.09	14.86	3.80	6.86	2.12	3.00	0.41
1.67	40	315	7.20	0.12	18.71	3.35	6.71	1.70	3.66	0.27
1.67	48	330	7.54	0.13	23.60	4.69	9.14	2.79	3.86	0.62
2.40	12	75	1.71	0.03	10.88	4.29	7.25	4.03	2.37	0.11
2.40	12	122	2.79	0.05	12.43	2.64	8.23	2.21	2.61	0.10
2.40	20	242	5.53	0.09	18.86	3.93	10.71	4.15	2.96	0.33
2.40	40	313	7.15	0.12	21.52	5.60	7.29	1.98	3.69	0.19
2.40	48	327	7.47	0.12	22.33	5.28	8.86	4.10	3.67	0.73