EXPERIMENTAL INVESTIGATION OF CUTTINGS TRANSPORT IN HORIZONTAL WELLS USING AERATED DRILLING FLUIDS

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ABSTRACT

EXPERIMENTAL INVESTIGATION OF CUTTINGS TRANSPORT IN HORIZONTAL WELLS USING AERATED DRILLING FLUID

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A new experimental approach has been introduced in this thesis for the cuttings transport in horizontal wellbores with the introduction of drag reducers into the aerated drilling fluids. Advanced Flow Loop System (annular test section of 21 ft. long 2.91-in. ID transparent casing and 1.85 in. OD inner drill pipe) in Middle East Technical University Petroleum and Natural Gas Engineering Department have been used for the experiments. The liquid phase has been water and water-PHPA copolymer mixture where the gaseous phase has been dried air. Water and water-polymer mixture experiments have been conducted in 0.05%V/V, 0.07%V/V, and 0.10% V/V PHPA polymer concentrations.
It was observed that optimum concentration of PHPA polymers in water for the given experimental test section is 0.07% with average drag reduction of 41.88% in single phase flow. Moreover, increasing water and gas flow rates increases the differential pressures.
Four main flow regimes were observed in the experiments which are a bubble, elongated bubble, slug and wavy annular. It was also observed that adding PHPA polymers in water shifts the flow regime transition boundaries to higher y values and water is the main phase in cuttings transport. Effect of increasing gas velocities is much lower compared with the effect of increasing liquid velocities in cuttings transport. Using PHPA polymers in 0.07% reduced the cuttings area by an average of %4.05 while reducing the differential pressures by an average of %23.90 with the existence of cuttings at the rate of penetration of 115 ft./hr.

Keywords: Underbalanced Drilling, Horizontal Drilling, Cuttings Transport, Drag Reduction

ÖZ

HAVALI SONDAJ SIVILARI KULLANILARAK YATAY KUYULARDA KESİNTİ TAŞINMASININ DENEYSEL ARAŞTIRMASI

Gül, Sercan
Yüksek Lisans, Petrol ve Doğalgaz Mühendisliği Bölümü
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Bu araştırmada yatay kuyularda kesintilerin taşınmasında basınç düşürücü sıvılar ile su beraber kullanılarak yeni bir yöntem deneysel olarak incelenmiştir. Deneysel çalışmalar için Orta Doğu Teknik Üniversitesi Petrol ve Doğalgaz Mühendisliği Bölümü'nde bulunan İleri Seviye Akışkan Laboratuvarı (21 ft. uzunluğunda 2.91 inç iç çapındaki saydam dış boru ve 1.85 inç dış çapındaki sondaj borusundan oluşan test düzeneği) kullanılmıştır. Sıvı fazı olarak su ve polimer solüsyonu, gaz fazı olarak ise kurutulmuş hava kullanılmıştır.

Birinci bölümde su ve su-polimer karışımının basınç kayıpları üzerindeki etkisi incelenmiştir. Deneyler sonucunda en uygun polimer karışım oranının basınç kayıplarını 41.88% düşüren 0.07% oranı olduğu gözlemlenmiştir. Hava veya su akış hızlarındaki artışların basınç kayıplarını artırdığı gözlemlenmiştir. Ayrıca deneylerde dört ana akış rejimi gözlemlenmiş, akış haritaları oluşturulmuştur. Deneylerde polimer kullanıldığı zaman ise bu akış haritasının sağa doğru kaydığı gözlemlenmiştir. Bunların dışında kesintilerin taşınmasındaki ana etkenin sıvı akış hızı olduğu görülmüştür. Ayrıca 0.07% oranında PHPA polimer sisteme dâhil edildiğinde kesintilerin yatay deney düzeneğinde kapladığı alanda 4.05% lik bir azalma, belirlenen noktalar arasındaki basınç kayıplarında ise 23.90% lık azalma gözlemlenmiştir. Deneylerde saatlik 115 feet değerinde sabit bir sondaj ilerleme hızı kullanılmıştır.

Anahtar Kelimeler: Denge Altı Sondaj, Yönlü Sondaj, Kesinti Taşınması, Sürtünme Azaltıcı

To My Parents

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NOMENCLATURE

RPM	Rotation per Minute, 1/min
ΔL	Length of Borehole, ft.
ROP	Rate of Penetration, ft./hr.
R	Radius, inch
2L	Perimeter, inch
A	Cuttings Deposition Area, in^2
d	Diameter, in.
Q	Flow Rate, gallons/min.
V	Velocity, ft./sec.
Re	Reynolds Number
f	Friction Factor

Subscripts

ann	Annulus
in	Inside
out	Outside

Greek

ρ	Density, lb./gal
μ	Viscosity, cp.
ε	Roughness, in.

CHAPTER I

INTRODUCTION

1.1. Background

In the conventional methods, drilling is done with water or oil based muds and the hydrostatic pressure of the drilling fluid is generally quite larger than the formation pressure to protect the well against influxes. But in some cases, it is required to use unconventional techniques and perform more challenging operations.

One of these cases is drilling depleted reservoirs. These are generally the mature fields or gas storage reservoirs. While drilling these zones, many issues are encountered about partial or total fluid losses in circulation. These losses result in kicks from the formation which therefore means additional time loss for well control. If the kick cannot be controlled, subsurface blowouts may occur which may result in losing the well completely. Therefore, lower mud weights are required and it is sometimes not possible to lower the mud weight after a certain point, which is basically the weight of water. The use of oil-based mud helps to decrease the weights to a certain extent, but after that point of interest, the mixture of water and air is required to decrease the hydrostatic pressure exerted by the drilling fluids further. This is the basic of underbalanced drilling, and the aim is to keep the hydrostatic pressure of the drilling fluid lower than the pressure exerted by the formation intentionally. There are many advantages of underbalanced drilling applications such as higher rate of penetration, longer bit life and increased productivity from the reservoirs.

But there exist some other issues with this unconventional method, and the one author is interested in is the cutting transport capabilities of aerated drilling fluids in horizontal wells.

1.2. Statement of the Problem

When the well has an inclination, the main problem is the occurrence of cuttings beds. If the formation of cuttings bed is not controlled, that may result in stuck pipes, therefore increased nonproductive times and dramatic increases in drilling costs. The main controlling element of cuttings bed are the liquid flow rates and flow regimes obtained during drilling. Therefore, if there is the need for using aerated drilling fluids, there is a strong need to find out what the optimum parameters of fluid and gas flow rates will be and which flow regimes help to minimize the cuttings bed formations. There has been extensive research done for this so far mainly at the University of Tulsa and Middle East Technical University.

Moreover, with the recent technology, the uses of drag reducing additives are becoming more common due to their effect in reducing system pressure losses. Reducing the system pressure losses have many advantages in extended reach wells because the maximum pump pressure is generally the limiting factor in these cases. To be able to drill deeper and wider, some applications to decrease the pressure losses in the system are to be considered. One of these applications used today is the PHPA (partially hydrolyzed polyacrylamide/polyacrylate) copolymers. There are many studies on PHPA copolymers and their drag reduction effect. Moreover, the latest studies are interested in the effect of these polymers on cuttings transport and removing or minimizing the cuttings bed in horizontal wellbores.

In the horizontal wells, the cuttings form a cuttings bed and that results in high torque values during drilling. If the hole cannot be cleaned, the cuttings can form a bed at higher levels and then result in stuck pipe problems. The general field application for the removal of this bed is stopping drilling when high torques are observed and spending a lot of time to circulate the hole until the bed is thinner. The time spent directly reflects costs especially in offshore wells and the aim in drilling is always to do the job with minimum costs.

In the underbalanced drilling, even when the hole is drilled vertical, cuttings transport is a big problem. That is mainly because the cuttings carrying phase is the liquid phase, and in underbalanced applications, the percentages of the liquid phase in the annulus are less than conventional applications due to the use gaseous state to decrease the hydrostatic heads.

Therefore, the problems associated with cuttings transport in directional drilling with underbalanced drilling fluids is more obvious than the ones with conventional drilling fluids in horizontal wells, or just the use of aerated drilling fluids in vertical wells. There is the need to do some experimental research to overcome the cuttings transport problems of this combination.

1.3. Objectives of the Research

It was observed from the previous studies that, in underbalanced cuttings transport experiments, the formed cuttings bed heights vary with different flow regimes and fluid or gas flow rates. Looking at the literature, there are some studies conducted in cuttings transport in horizontal wells with aerated drilling fluids but the results are believed to be improved in minimizing the cuttings beds during drilling with drag reducer polymers.

If there is the need to use the aerated drilling fluids, the field personnel should be aware of the advantages and disadvantages of the flow regimes obtained down in the hole, the optimum gas and liquid flow rates, and the optimum drag reducer additive concentrations in terms of cuttings transport performance and to minimize the bed formations to prevent the nonproductive times and unnecessary costs.

The main objective of the study is to work on the effect of drag reducing fluids in the flow patterns, cuttings transport efficiencies and differential pressure losses of aerated drilling fluids in horizontal annulus sections during drilling.

1.4. Most Important Contributions of the Thesis

As to be explained in further detail in the literature survey section, there are many studies on cutting transport with conventional water or oil based drilling fluids and PHPA copolymer and water mixtures in horizontal, vertical or deviated wellbores. On the other hand, many experimental or empirical studies have been done on the cutting transport mechanism of underbalanced drilling fluids in horizontal and deviated wellbores. But there are basically no studies performed on the effect of the mixture, PHPA copolymers in the efficiency of cuttings transport in horizontal wellbores for underbalanced situations. Many parameters, such as liquid and gas flow rates, the flow patterns, and different drag reducer concentrations have been investigated and the optimum conditions have been given in the conclusion part.

Not only being the first, this study is believed to lead other scientists to work on that area and improve this work in more developed laboratory conditions in different wellbore angles, and different pipe sizes.

1.5. Structure of the Thesis

Chapter 1: This is an introduction chapter which includes background, statement of the problem, objectives of the research and most important contributions of the thesis.

Chapter 2: This chapter explains the most relevant studies about this thesis with the basics of the theory in single phase and two phase flows in horizontal wellbores.

Chapter 3: This is the chapter where the experimental program, set up as well as the materials used have been described in detail.

Chapter 4: This is the chapter with the procedure and results of single phase flow.

Chapter 5: This is the chapter where procedure, results, air-water flow patterns as well as air-polymer flow patterns have been obtained in single phase flow experiments.

Chapter 6: This is the chapter where cuttings transport experiment results have been explained with the procedure and results.

Chapter 7: This chapter is the conclusion chapter where all the results are combined.

Chapter 8: This chapter includes the recommendations for the future studies.

CHAPTER II

LITERATURE REVIEW AND THEORY

2.1. Literature Review

The literature research for this thesis was made in three main titles. These are;

1. Cuttings Transport with Single Phase Drilling Fluids
2. Two-Phase Flow Patterns for Horizontal Pipe and Annulus Flow
3. Cuttings Transport with Two-Phase Drilling Fluids

Therefore, it was observed that many studies have been performed experimentally or empirically for cuttings transport in vertical or horizontal wellbores. The effect of many parameters, such as drilling rate, drill pipe rotation, fluid and gas flow rates, the rheology of the fluid etc. have been investigated for both single and two-phase drilling fluids in vertical, horizontal or deviated wellbores.

It was observed that the PHPA Chemicals were very useful for cutting transport with single phase flow but not many works have been done for the effect of PHPA chemicals in cuttings transport with two phase drilling fluids.

The studies about polymers in multiphase flow are mainly interested in the optimum concentrations of polymers to obtain the maximum drag reduction. Some of these studies are made in horizontal pipes, and the others are made in inclined wellbores. There exist studies in pipe flows, but not many exist in annular flows. Moreover, there exists almost no work in the literature about the effects of drag reducing polymers such as PHPA copolymers in cuttings transport with two-phase fluids in horizontal annulus sections.

2.1.1. Cutting Transport with Single Phase Drilling Fluids

Tomren et al. [1] made one of the earliest studies in the area is the experimental studies of cutting transport in vertical, horizontal and directional annular test sections. The test section used for the experiments was 40 ft. long to obtain steady state conditions and the annulus dimension was 5 in. x 1.9 in. during the study. The variables during the study were the rotation speed of the inner drill pipe, types of the drilling fluids, flow regime changes and eccentricity. The inclinations have been changed incrementally with 10 degrees from zero to 90 degrees. The liquid flow rate was in the range 50-225 gpm, inner pipe rotary speed was 0, 50 and 100 rpm. The average injection rate of particles was 20 lbm/min while the particle density was 163.5 lbm/cuft. Different flow types used were water, low-viscosity bentonite, carbopol, high viscosity bentonite and standard bentonite. The conclusions of the study were that the main factors in the cutting transport performance are the annular velocity of drilling fluids, the angle of inclination from the vertical position and the rheological properties of the drilling fluids used. Comparing to the vertical wells, for the effective cleaning, there is the need for higher drilling fluid velocities in horizontal well sections. Similarly, the increase in the angle from the vertical decreases the performance of hole cleaning of the drilling fluids and the most critical section were found to be the angle of 40-50 degrees due to the buildup of cuttings and the sliding of the bed. In the rheology experiments, it was observed that mud with higher viscosity results in formation of smaller beds, therefore better transport efficiency of cuttings was observed compared to the low viscosity ones in laminar flow. On the other hand, in turbulence, the formation beds were observed to be almost equal for both higher and lower viscosity fluids.

Rishi et al. [2] have investigated the cuttings transport in single-phase drilling fluids. The researchers have worked in Tulsa Flow Loop in an 80-ft. long test section with 8 in x 4.5 in annulus body. They have worked on to develop a methodology to determine optimum fluid flow regimes and flow rates to minimize the cuttings bed height and circulation times in high angle and horizontal wellbore sections. They recorded many parameters during the experiment which were pressure, the temperature of the liquid, liquid velocity and the rate of penetration values. Four different drilling fluid types have been used in the experiments with n/K values of 0.58/97 for mud A, 0.63/110 for mud B, 0.52/855 for mud C and 0.68/157 for mud D. The liquid flow rates used in the experiment were 200, 250, 300, 350 and 400 gpm.

The main conclusions of the study were that:

- As fluid flow rate increases, cutting bed erosion occurrence rate increases.
- As the viscosity of the fluid increases for a given fluid flow rate, lower cuttings bed height is achieved.
- Turbulent flow is more efficient in cuttings removal comparing to laminar flow.
- As wellbore inclination increases, cuttings accumulation in the well as well as the circulation time required to clean the borehole increases.

Another study by Li et al. [3] worked on the development of a transient mechanistic model for the transport of cuttings through horizontal annulus sections using single-phase drilling fluids. The information required for the developed model is the drilling parameters such as liquid flow rate, the rheological properties of the drilling fluid used, the rate of penetration, and the wellbore geometry and eccentricity. The outcome of the developed model is the cuttings bed height in given conditions. There were three types of drilling fluids used for the sensitivity analysis; water, thin mud and thick mud. Thin mud has the shear stress value of 32 lb./100ft^2 at 300 rpm and 60 lb./100ft^2 at 600 rpm while the thick mud has 120 lb./100ft^2 and 195 lb./100ft^2 respectively. The conclusion of the study is that the main factors affecting the cuttings bed height in horizontal wells are the rate of penetration and the flow rate of the liquid. On the other hand, the thick mud had better performance in cleaning the drilled zone comparing to the thin one. But using the thick mud will result in higher standpipe and bottom hole pressures in the well. On the other hand, it was observed that the density of the drilling mud, the diameter of the drilled cuttings and the eccentricity of the pipe do not influence the performance of cuttings transport.

Bilgesu et al. [4] made some analysis on hole cleaning in horizontal and deviated wells with computational fluid dynamics application. According to the researchers, the factors affecting the hole cleaning can be studied in 3 main parts. First part is the parameters related to fluid properties and the rheology. This also includes the fluid density, flow rate, and the viscosity. The second part is the parameters related to the cuttings. These include the cutting density as well as the cutting shape and diameter. Third part can be classified as the other parameters in drilling operations such as the pipe rotation speed, the inclination of the hole angle or the eccentricity of the wellbore. Researchers have worked with a 45 ft. long, 6 in x 3.5in annulus section. The hole angle from the vertical situation was 90, 75 and 60 degrees. For 75 degrees, the flow rate was varied between 180 to 220 gpm, for 60 degrees 260 to 300 gpm and for the horizontal situation, 120, 150 and 180 gpm. Drilling rates were changed between 50, 75 and 100 ft./hr. The results of this analysis have shown that the bigger the particles, the easier their transport is due to the increased surface area and therefore increased drag force. The effect of pipe rotation is more obvious for smaller particles comparing to the larger particle cuttings. Moreover, increase in the liquid flow rate is the most important parameter for hole cleaning performance.

A study performed by Ozbayoglu et al. [5] mainly concentrated on the effects of pipe rotation in cuttings transport using water based drilling fluids in horizontal and deviated wellbores. The flow loop used had 3 in – 1.5 in annulus section with a length of 12 ft. Three different types of fluids have been used in the experiments. The first one was water, the second one was Mud consisting of xanthan biopolymer, KCl, starch and soda ash and the third one was named as Mud-H consisting of xanthan biopolymer, KCl, starch, soda ash, and barite. The apparent viscosity of the fluids was in the range 1 cp – 12 cp while the specific gravities were changing between 1.0 – 1.2. Fluid velocity has been changed starting from 2.1 m/s to 7.2 m/s. ROP was in the range 15 ft./hr. to 45 ft./hr. The inclination was 50-90 degrees from vertical and the pipe rotation was 0-120 rpm. This study concluded that in all three different mud types, pipe rotation was effective in improving the cuttings transport. Pipe rotation increases the frictional pressure losses while there exist no cuttings, but when the cuttings are introduced, the increase in pipe rotation decreases the cuttings concentration, therefore, decreases the pressure drops as well. Moreover, it was observed that increasing viscosity increases the cuttings transport efficiency in low rotation speeds but the effect diminished in the higher pipe rotation speeds.

Recant and Ozbayoglu [6] made a study with PHPA was conducted in Turkish Petroleum Corporation with polyacrylamide/polyacrylate copolymers. In the study, different concentrations of copolymers (in the range of 0.000313 v/v – 0.002500 v/v) were used. The appearance of the copolymer was thick, opaque white liquid, density was 8.5 lb./gal, pH was 8.5. The experimental set up was a cylindrical pipe with an inner diameter of 0.42 inches. The liquid flow rate was in the range of 2-5 gpm. The results of the experiments were that, as the PHPA concentration increases, significant amounts of drag reduction can be obtained which is as high as 60%. The optimum concentration for drag reduction was found to be 0.0020 V/V for the highest drag reduction in the experiments.

Sorghum [7] includes many works of cuttings transport in high inclination wellbores with pipe rotation. The studies have been done in METU Flow Loop. For the experiments, the researcher has used water and other water-based drilling fluids with varying amounts of KCL, starch, soda ash and barite in horizontal wellbore condition and 60 degrees from the vertical situation. The flow rate has varied between 0.64 m/s and 3.05 m/s while the pipe rotation was between 0-120 RPM. The rate of penetration was in the range between 0.00127 m/s and 0.0038 m/s. The researcher has also used the KCL-polymer and PAC systems other than water for the experiments but he was mainly interested in the effect of pipe rotation and the CFD modeling. The researcher has measured the pressure losses and the bed height thicknesses in different conditions. The resulting observation of this study is that the major factor affecting the cuttings transport is the flow rate of the liquid used. On the other hand, the pipe rotation was observed to be beneficial for the cutting transport, decreasing the critical fluid velocity needed to omit the formation of cuttings bed. Moreover, as the pipe rotation speed increases, it was observed that the pressure losses in the test section decrease. The researcher also mentioned that the increase in viscosity of the drilling mud increases the cuttings transport efficiency while there is no pipe rotation but the viscosity of the fluid has no effect in transport when there exists pipe revolution. Other than these, the researcher has developed a CFD model and correlated it with the experimental results obtained during the research.

One of the recent studies by Kuru et al. [8] about drag reducing fluids was done in Canada, Alberta University. The experiments were conducted in a horizontal flow loop with Particle Image Velocimetry technique and mainly interested in removing the cuttings beds. According to the study, it was suggested that using "a drag reducing fluid with good hole cleaning ability" is the solution to good hole cleaning while keeping the bottom hole pressure in operation mud window. Experiments were done in single phase flow. In the experiments, there was no rate of penetration motors, therefore cutting beds were formed before conducting the experiments, and the critical fluid velocities to remove the beds were investigated. The experimental set up was 9m long and the pipe has 95 mm outer diameter and 38mm inner diameter. For the study 0.07%V/V, 0.10%V/V, 0.12%V/V drag reducers were used. The cuttings used were industrial sand with d50 0.35mm and 1.2mm. The conclusion of the study was that higher critical velocities are required to transport the solids with drag reducing fluids. Comparing the cuttings types, it was observed that for coarse-grained particles more water flow rates were required than the fine-grained particles. It was observed that maximum pressure drop was obtained in 0.1%V/V polymer concentration. The liquid velocity was in the range 0-1.3 m/s. The polymer used in the experiments was Poly Plus RD by M-I Swaco. The conclusions of the study were that:

- While using drag reducing polymers, higher liquid velocities are required
- While using water as the drilling fluid, coarser particles need more liquid velocity to initiate the movement but while using the PHPA polymers, coarser particles need less liquid velocity for initiation.

Another study made by drag reducers was conducted in Middle East Technical University Advanced Flow Loop by Allahverdizadeh et al [9]. The study was presented as the Master Thesis of the researcher. In this experimental work, the aim was to find the optimum polymer concentration for maximum drag reduction in cuttings transport in horizontal annulus well sections. Experiments were done with water and water-polymer mixtures in different concentrations which are 0.05%W/W, 0.07%W/W and 0.10%W/W. The experimental set up had 2.91'' Casing ID and 1.85'' Drill Pipe OD in 21 ft. horizontal wellbore test section. According to the study, maximum drag reduction was obtained in 0.07%W/W polymer concentration. The effect of cutting transport performance was also similar. Tests were made in different ROPs and the stationary cuttings bed height was the lowest in 0.07 %W/W drag reduction polymer concentration. The maximum drag reduction for this wellbore and the industrial sand was 38% at the optimum flow rate of 100 gpm. According to the researcher, viscosity helps in cuttings transport up to a certain extent. Therefore, increasing viscosity does not always provide better hole cleaning.

Summary

Many studies with different wellbore sections, different capacities, different fluids, different hole angles and cuttings sizes in cuttings transport with single-phase drilling fluids have been investigated and the conclusions can be summarized as:

- The main factor in the cuttings transport in single-phase drilling fluids is the liquid flow rate,
- Horizontal wells require higher fluid flow rates comparing to vertical wells,
- Mud with higher viscosity cleans the annulus more efficiently,
- Turbulent flow is more efficient in hole cleaning comparing to laminar flow,
- Increase in wellbore angle increases the cuttings accumulation rate in the well,
- Increase in pipe rotation increases the cuttings transport efficiency,
- The optimum PHPA Drag Reducer concentration differs according to the wellbore annulus sizes but there exists an optimum value for each size.

2.1.2. Two-Phase Flow Patterns for Horizontal Pipe and Annulus Flow

Griffith [10] has made a study of multiphase flow and introduces 6 main flow regimes in horizontal pipes which are stratified smooth flow, stratified wavy flow, plug flow, slug flow, and annular flow and dispersed annular flow. On the other hand, for vertical up flows in pipes, there are 4 main regimes which are bubble flow, slug flow, churn flow and annular flow.

Another study by Al-Ne'Aim et al. [11] concentrates on the large diameter pipes and high flow rates in two-phase flow regimes and mathematical models. Field tests have been performed in pipes sizes ranging from 6 in. to 10 in. in diameter and oil flow rates of 2200-25600 stb/day with water cuts up to 60% and the maximum gas-oil ratio of 984 scf/stb. The conclusion of the study is that the best mathematical prediction is made by Beggs and Brill correlation.

One of the very informative books in that subject by Brill and Mukherjee [12] summarizes the flow concepts, flow regimes, pressure gradient prediction methods and design applications in two-phase flows. According to the book, there are 5 main flow regimes in upward vertical flow which are bubble flow, dispersed bubble flow, slug flow, churn flow and annular flow. On the other hand, in the horizontal pipe flows, the regimes are in 3 main categories, which are segregated, intermittent and distributed flows. The segregated flow includes stratified, wavy and annular flows, the intermittent flow includes plug and slug flow and distributed flow includes bubble and mist flow regimes.

Research made in OHIO University by Kang and Jepson [13] has concluded some results about the effects of drag reducers. An experimental work has been conducted in a multi-phase horizontal system. The flow system was 36 m long and have a diameter of 10 cm. As a liquid phase, oil which has a viscosity of 2.5 cp was used. For the gas phase, carbon dioxide was used. Liquid velocities were in the range of 0.5 to 1.5 m/s while the gas velocities were 2 to 12 m/s. Drag reducer additive concentrations were 0, 20 and 50 ppm for the experiments. It was observed that the additive used was effective in reducing the pressure drops. Researchers only observed slug and annular flow regimes in the given liquid and gas velocity regions. In slug flow, the drag reduction was up to %82 and in the annular flow, it was 47%. It was observed that additive concentration of 50 ppm was more effective comparing to the 20-ppm concentration. It was also observed that, with the addition of drag reducing agents, the liquid film got spread around the pipe wall and decreasing the height of the liquid film in the system, therefore reducing the pressure losses in the system [13].

Research by Sunthankar et al. [14] gives much information about the flow patterns of aerated drilling fluids in inclined wellbore sections. The research was made by experimental analysis. The flow loop used was 90 ft. long, having a diameter of 8 in – 4.5in. The inclination of the wellbore was 15° and 45° from vertical. Two different liquids have been used for the experiments. First one was water and the second one was a viscous non-Newtonian polymer including water, CMC and XCD polymers. Gas phase was air. In the experiments with no drill pipe rotation, the flow patterns observed were mostly bubble or slug flow regimes while with the drill pipe rotation the flow regimes were bubble and churn flows.

A study in METU Drilling Research Group multiphase drilling loop by Obeyable and Omurlu [15] gives much information about the underbalanced drilling flow models in horizontal pipes. The main objective of the study was to obtain the flow pattern transition boundaries. The flow loop in those experiments was 15 ft. long and had 5 in a circular pipe, 5 in – 2 in wellbore configuration and 5 in – 3.5 in wellbore configuration. Liquid density was changed from 8.33 peg to 10.0 ppg and the viscosity was either 1.0 cp or 10.0 cp. In the study, stratified smooth flow, stratified wavy flow, intermittent flow, mist flow, annular flow and dispersed bubble flow have been observed. According to the study, as the geometry is changed from pipe flow to an annulus, flow patterns were observed to be slightly changing in the same liquid and gas flow rates. Moreover, it was observed that, as the gap decreases in the annulus section, the differential pressure losses increase in the same liquid and gas flow rates. According to the study, the increase of oil or gas viscosity shifts the transition boundaries in the flow pattern map to the left with an increase in the frictional pressure. Another conclusion of the study is that, as the density of the liquid phase is increased, the frictional pressure losses increase but there is no change in the flow pattern map transition lines.

Another work by Al-Sarkhi et al. [16] has investigated the effect of drag reducers in two-phase flow in an inclined wellbore. In the study, the pipe had a diameter of 0.0127m and was inclined upward with different angles such as 1.28 degrees and 2.4 degrees from horizontal. As the drag reducing agent, the researchers have used Magnafloc 110L in the concentration of 100 ppm. The polymer was prepared a day before the experiment in 150 liters of the tank and then directed to a smaller pressurized tank and then to the flow loop system to prevent the degradation occurrences while using pumps. The superficial velocities were in the range 19-38 m/s for gas flow and 0.04-0.10 for liquid flow. The flow patterns observed were annular-clear, annular-stratified, stratified, annular-pseudo slug and annular-mist. The maximum drag reduction, which was 71%, was obtained with the polymer concentration of 100 ppm. The flow regime in the maximum drag reduction was an annular-stratified or stratified pattern. The result of the experiment is that the drag reduction depends on liquid, gas flow rates and the inclination rate. The maximum reduction was obtained at 1.28 degrees of inclination, in lowest superficial gas velocity and the highest superficial liquid velocity.

Al Sarkhi [17] investigates the drag reducing polymers in two-phase pipe flow. In the experiment, two different pipes, in the vertical direction, were used. These were 95.3mm pipe, which was 23m in length, and 25.4 mm pipe, which was 14m in length. The polymer used in the experiments was high molecular weight anionic polyacrylamide flocculants. The maximum drag reduction was obtained with 10 ppm polymer in 95.3 mm pipe and with 30 ppm polymer in 25.4 mm pipe. It was observed that addition of polymers changes the flow pattern transition lines. It was observed that at the point where maximum drag reduction happens the flow regime is stratified flow. The effect of drag reduction was also more observable in annular flows comparing to the slug flow.

Hamouda [18] have worked in drag reducers in University of Norway. The flow loop system had a 35.4-meter long piping system, which has an inner diameter of 0.0143m. The experiments were conducted under the pressure of 10 bars while the temperature was 40 °C. Differential pressures were measured at 12.4 and 24 meters as well as at the outlet. The multiphase system used crude oil and natural gas in experiments. The liquid and gas flow rates were measured with flowmeters. The experiments were done in different gas and liquid flow rates. Gas flow rates were set to 0.48, 0.53 and 0.57 kg/min and the liquid flow rates were 4.5, 5, 6 and 7 l/min. The polymer was prepared by mixing diesel oil and the drag reducing chemicals. During the preparation, the polymer was injected into the mixer by using a mixer and was rotated with the mixer for at least 12 hours until the polymer was observed to be fully dissolved. In the experiments, different polymer concentrations; 5 ppm, 20 ppm, 50 ppm and 100 ppm were used and the maximum value, up to 30% drag reduction was observed at 100 ppm. It was also observed that increasing the liquid flow rate increases the drag reduction in the same polymer concentration. The type of polymer used was a high molecular weight oil-soluble poly-alpha-olefin.

One of the most recent studies in oil-gas multiphase flow by Archibong-Eso et al. [19] worked on the viscous liquid-gas two-phase flow mechanisms in horizontal pipe flows. In the experiments, the liquid viscosity was in the range 1000-5000 cp. The flow loop used was 5.5m long with a diameter of 0.0254m. The test fluids were air and CYL680 oil manufactured by TOTAL. Air has a density of 1.293 kg/m3 viscosity of 0.000017 Pa.s at 25°C and interfacial tension of 0.033 N/m at 25°C. Oil has a density of approximately 918 kg/m3, the viscosity of 2.5 Pa.s at 25°C and API gravity of 22.67. There were 4 main flow patterns as the result of these experiments which were plug flow, slug flow, pseudo-slug flow and wavy annular flow regimes. It was observed that the main flow regime was slug flow. It was also observed that liquid hold up decreases as the gas velocity increases.

Summary

Many studies with different pipe and annulus sizes, different flow rates, different fluids, hole angles and viscosities have been investigated. The conclusions can be summarized as:

- Flow regimes observed varies according to pipe sizes and the annulus configurations.
- The increase in fluid viscosity shifts the transition boundaries in the flow pattern map to the left and increase the frictional pressure drops.
- Drag reducers were observed to be very effective in two-phase flows in annulus configurations but the effectiveness differs according to the fluid types and wellbore configurations.
- It is observed that liquid hold up decreases as gas flow rate increases.

2.1.3. Cutting Transport with Two-Phase Drilling Fluids

Vieira et al. [20] have made one of the earliest studies in cutting transport with two phase drilling fluids was made on a Low Pressure-Ambient Temperature flow loop (LPAT) with high angle and horizontal situations. The loop was 100 ft. long and has 8 in ID casing and 4.5 in OD inner pipe to simulate the drilling conditions. The liquid was pumped by a pump with 650 gpm capacity and the gas was pumped into the annulus with a compressor which has the capacity of pumping up to 1200 scfm. The liquid was stored in a 1000-gallon tank with an additional capacity of 800 gallons. The flow rates were measured with mass flow meters. There were 3 pressure transducers, one on each end and one with 36.45 ft. from the upstream end. Experiments were done with commercial gravel with a diameter of 3.29 mm. ROP values were 30, 50 and 70 ft./hr. All the data were collected with the data system and this system recorded annular pressure, differential pressure, temperature, gas and liquid flow rates with tank weights. The hole angle was 80 and 90 degrees from vertical during the experiments. The flow patterns of the cuttings were investigated and were concluded that there are three of them which are ‘’stationary’’, ‘’moving’’ and ‘’mostly dispersed’’ cuttings beds. Another result was that as the rate of penetration increases, the cuttings accumulation also increases. Moreover, according to the research, the presence of solids should always be included in the calculations of pressure drop calculations in drilling operations since the existence of solids increases the flow resistance.

Another study by Shigemitsu et al. [21] was done in a flow loop which was 9m long and has different pipe sizes such as 5 in x 2.063 in and 5 in x 2.875 in. The study has investigated angles between zero and 90 in 15 degrees on increments. The rate of penetration was changed between 0.5 to 50 m/hr. The cuttings in the experiment were ceramic balls with an average diameter of 3.66 mm and specific gravity of 2.4 g/cm3. In the study, two types of aerated mud were used. One of them had the liquid phase as water while the second one had 0.15 % PHPA solution. The conclusion was that, for these borehole sizes, bubbly, churn or slug and stratified wavy flows were observed and in the PHPA solution aerated mud; the critical flow rates were lower than the water case.

Therefore, the use of PHPA was suggested but the only concentration in the experiments was 0.15% by weight. It was also observed that the reduction in critical flow rates was more in churn flow comparing to the other flow regimes.

Zhoue [22] made an experimental study in 73 ft. long 6 in – 3.5 in wellbore was carried out to understand the cutting transport mechanisms of underbalanced drilling fluids. In the experiments, the flow rates of water and air, the weight of cuttings in the annulus, liquid holdup, mixture density and the pressure losses were measured. Researchers observed and described four different flow patterns. The observed regimes are stratified flow, annular flow, and slug flow and dispersed bubbly flow. It is observed the main phase affecting the cuttings concentration in the wellbores is the liquid phase. The increase in liquid flow rate decreases the cuttings concentration. Effects of gas phase are more obvious when the liquid viscosity is higher. Therefore, in stratified and annular flow (since the liquid velocity is low) the cuttings transport is not efficient. As a result, the efficient flow regimes for the cuttings transport are found to be a slug and dispersed bubbly flow for the experiments. Another result was that increasing the mud weight helps hole cleaning. Moreover, as hole angle and cuttings size increase, the cuttings transport efficiency decreases. Another test was performed with the effect of pressure and temperature and the result was that increasing temperature or pressure decreases the efficiency of cuttings transport.

Avila et al. [23] worked with a large-scale facility which was 100 ft. long, 8 in – 4.5 in wellbore configuration. The angles of the wellbore were set as 30, 45 and 60 degrees from vertical. Researchers have worked in 4 different pipe rotation speeds which are 0, 40, 80 and 110 rpm. One of the results of these experiments was that an increase in liquid or gas flow rate decreases the cuttings concentration but the effects are more when liquid phase velocity increases. Increasing the angle of inclination, taking all other parameters constant, increases the cuttings concentration inside the wellbore. Researchers also worked on the mathematical models and provided empirical correlations to predict the cuttings transport efficiency in different conditions.

One of the latest experimental studies was conducted on the Multiphase Flow Loop Laboratory in Middle East Technical University by Osgouei [24]. This study is one of the large-scale studies on the subject and presented as the Ph.D. thesis by the researcher. In the study, 2.91 in x 1.86 in 21 ft. long experimental set up was used in inclined, near vertical and horizontal situations. The researcher has observed 8 different flow regimes during his studies. These are Smooth Stratified Flow, Wavy Stratified Flow, Plug Flow, Slug Flow, Chur Flow, Wavy Annular Flow, Dispersed Bubbles Flow, and Dispersed Annular Flow. The first outcome of the study is that the increase in the rate of penetration values increases the cuttings concentrations in many situations except in fully dispersed flow pattern. Another result is that the increase in the pipe rotation speeds decreases the cuttings concentration inside the wellbore. The pressure drops were observed to be increasing when the rate of penetration or the cuttings bed height was higher. Moreover, with the presence of cuttings, it was observed that there is no significant effect of pipe rotation speeds in the pressure drops. It was observed in the experiments that the increase in gas flow rate decreases the cuttings concentration in horizontal test sections. But the height of cuttings bed is more when the rate of penetration is higher. Another result related to the pressure drops was that, in horizontal wellbore section, pressure drop values decrease up to a certain point and then starts increasing after the critical value when the gas flow rate is increasing taking all the other parameters as constant in low liquid superficial velocities up to 4 ft./sec. A similar situation exists in cuttings transport with water phase in the horizontal wellbores also. In low liquid velocities (1.5 ft./sec – 3 ft./sec), there is a slight increase in pressure drop because of cuttings bed formation, afterward, pressure drops decrease suddenly with the effect of the disappearance of the cuttings formation and then starts increasing while the liquid flow rates are increasing.

Summary

Many studies with different pipe and annulus sizes, different flow rates, different fluids, hole angles and viscosities, different cuttings sizes and rate of penetration values have been investigated. The conclusions can be summarized as:

- As the rate of penetration increases, cuttings accumulation also increases,
- In the cuttings transport, increase in liquid flow rate is more effective comparing to the gaseous phase, but the effects of gas phase is more obvious in the high viscosity drilling fluids,
- As hole angle and cuttings size increase, cuttings transport efficiency decreases,
- The use of PHPA polymers is suggested in one study, it is decreasing both pressure drops and cuttings concentrations, but the cuttings were ceramic balls in that case. The main flow pattern where the drag reducers effective is the churning flow,
- Efficient flow regimes for the best cuttings transport are slug and dispersed bubbly flow,
- The increase in inner pipe rotation decreases the cuttings concentration, therefore, decreasing the pressure drops in cuttings transport cases.

2.2. Theory

2.2.1. Water Phase Flow Theory

In this section, the theory of single phase fluid flow in annulus sections will be discussed. The results are to be discussed in the next chapter as water phase flow experiment results.

2.2.1.1 Relative Roughness of the Pipe and Theoretical Pressure Losses

In the experiments, the pressure losses for the test section (for 1.52 ft.) are measured according to pre-set flow rates. Therefore, in single phase flow experiments the pressure losses and the flow rates are known. The first requirement is to calculate the relative roughness of the pipe used.

Relative roughness is the dimensionless roughness value which occurs since the inside wall of the pipes are not always smooth. This value may have significant effects on pressure drops and friction factor values. The relative roughness is a function of the material used in the pipes manufacture, the age of the material and pipe and the environmental situations [12].

For this calculation, we need the Reynolds number. Azar and Samuel [25] provides the general formula to calculate the Reynolds number as in equation 1.

$$N_{RE} = \frac{928\ \rho v d}{\mu} \qquad [1]$$

Here, the diameter used is the hydraulic diameter concept. The hydraulic diameter for annulus configurations is given as in equation 2 [12].

$$d_h = d_c - d_t \qquad [2]$$

Fanning equation is used to calculate the fanning friction factor.

$$\Delta p_f = \frac{dpf}{dL} \Delta L = \frac{f p v^2}{25.8\ d} \Delta L \qquad [3]$$

Colebrook [28] provided an equation that provides the solution for relative roughness when the fanning friction factor and Reynold's number are given.

$$\frac{1}{\sqrt{f}} = -4\log\left(0.269 * \frac{e}{d} + \frac{1.255}{N_{RE}\sqrt{f}}\right) \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots[4]$$

This equation is modified by the researcher solving for the relative roughness as in equation 5.

$$\left(10^{\frac{1}{-4\sqrt{f}}} - \frac{1.255}{N_{Re}\sqrt{f}}\right)/\,0.269 = \frac{e}{d} \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots[5]$$

Jones and Leung [27] provided an equation that also provides a correlation for fanning friction factor.

$$\frac{1}{\sqrt{f}} = 2\log\ \mathrm{Re}\sqrt{f} - 0{,}8 \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots[6]$$

where:

f: Fanning friction factor;

Re*: Modified Reynolds number.

$$\mathrm{Re}* = \frac{\rho v dL}{\mu}$$

$d_L = d\phi*(a)$

$\phi*(a) = 1/\,(1-a)^2 * [\,1 + a^2 - (1-a^2)/(\ln\,(1/a))]$

where:

d_L: Laminar equivalent diameter;

ϕ * (a) : shape function;

a: radius ratio

2.2.1.2 Non-Newtonian Fluids – Rheological Models

The fluid rheology is also an important parameter for the experiments. Water behaves as Newtonian Fluid in the experiments but when the drag reducers are involved, the rheology will behave differently than Newtonian which is called as Non-Newtonian behavior. Figure 30 shows the rheological models which are Plastic Flow, Pseudoplastic Flow, Newtonian Flow and Dilatant Flow [28].

The Power Law model describes this Non-Newtonian Behavior. The Power Law stress-strain model can be expressed as:

$\tau = K\,\gamma^n$ ……………………………………………………………………………….[7]

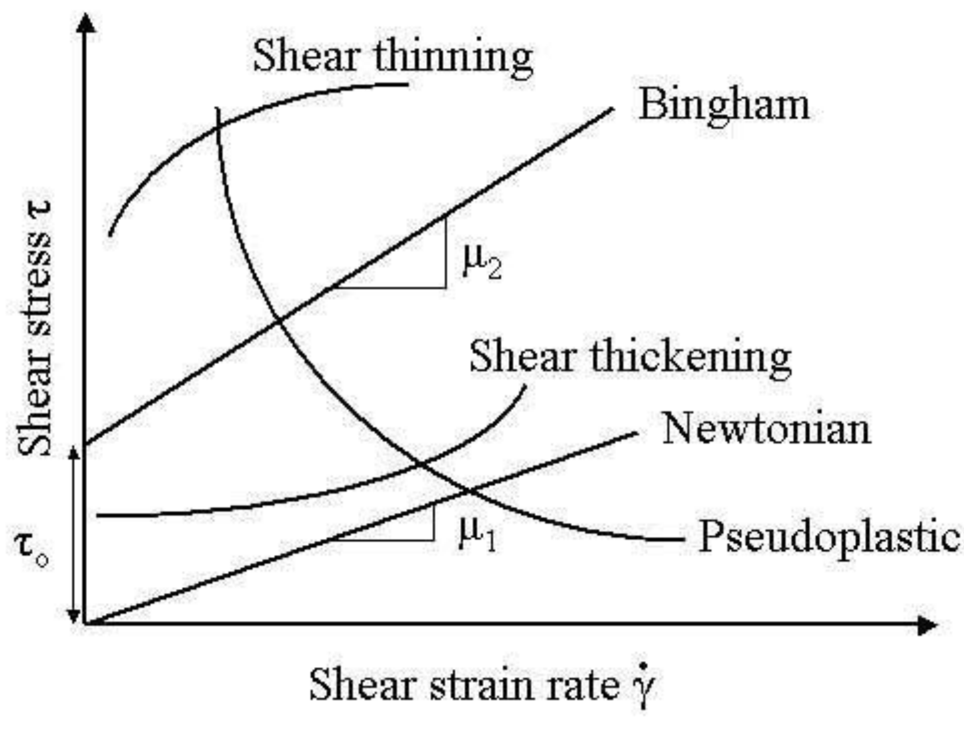

Figure 1. Rheological Models [28]

If n is unity, the model describes Newtonian behavior and K is equal to the constant viscosity. For oil/water mixtures and the mixture of drag reducers with water, n generally less than unity. This describes pseudoplastic behavior (shear thinning). It is also possible to obtain then value higher than unity; in that case, the fluid is acting in dilatant behavior (shear thickening). The rheological models can be determined by experiments using viscometers [12].

Shear Stress in the graph is the force required for the fluid to manage the resistance to flow divided by the area of action. The shear stress is measured in dynes/cm^2. The equation can be illustrated as in Figure 31. The basic formula is provided by Gucuyener [29] is $\tau = F/A$ where F= Force applied (dynes) and A= Surface area under stress (cm^2).

In the viscometer, Shear Stress, lbs./100ft^2 = Dial Reading (VG Meter) x 1.0678

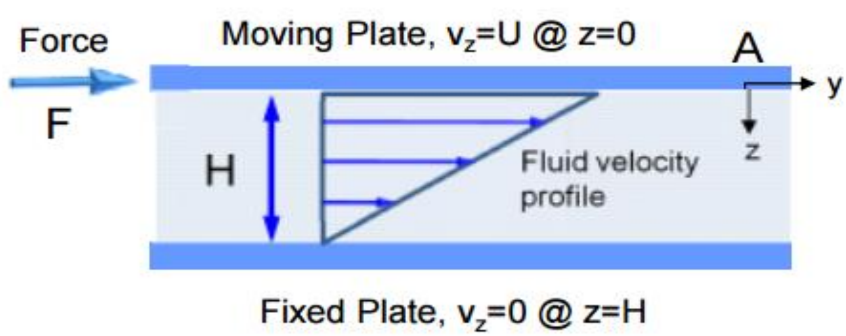

Figure 2. Shear Stress – Shear Rate Illustration in Plates

Shear Rate is defined as the velocity of the layers divided by the separation distance. Shear rate is expressed in reciprocal seconds (sec^{-1}).

Basic formula is γ = U / H where U = Velocity (cm/sec) and H = Distance (cm)

In the viscometer, shear rate is equivalent to the rpm's of a viscometer multiplied by 1.7033. Shear Rate, (1/sec) = RPM (VG Meter) x 1.7033

2.2.2. Air – Water Two-Phase Flow Theory in Pipe Flow

In this section, the theory of air-water two-phase fluids flow in pipe flow will be discussed. The results are to be discussed in the next chapter as air – water two-phase flow experiment results.

There exists the need to classify the flow types in horizontal pipes, some equations such as liquid and gas superficial velocities and liquid and gas hold up equations as well as the theoretical flow pattern map of aerated drilling fluids in horizontal pipes.

According to Brill and Mukherjee [12], Beggs and Brill were the first one to work on flow behavior at different wellbore inclinations. They have developed the flow pattern maps and pressure gradient equations for horizontal wellbores. The flow regimes are classified as Segregated, Intermittent and Distributed. Segregated includes Stratified, Wavy and Annular Flow Regimes while Intermittent has Plug and Slug and Distributed have bubble and Mist flows as in Figure 3.

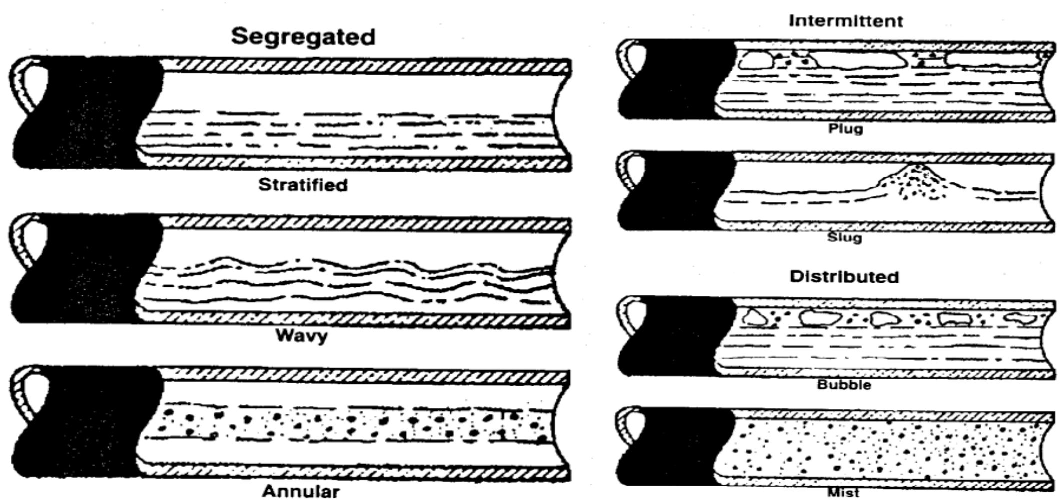

Figure 2. Flow Types in Horizontal Pipes

The general equations for liquid and gas hold up, no-slip hold up and gas and liquid superficial velocities are as below.

Equations 8 and 9 are the equations for calculating the liquid hold up.

$$H_L = \frac{A_L}{A_L + A_G} \quad \text{[8]}$$

$$H_L = \frac{\text{Volume of Liquid in Pipe Element}}{\text{Volume of Pipe Element}} \quad \text{[9]}$$

Equation 10 is the formula of gas hold up, which is one minus the liquid hold up.

$$H_G = 1 - H_L \quad \text{[10]}$$

Equations 11 and 12 are the no-slip liquid hold up and no slip gas hold up equations.

$$\lambda_L = \frac{q_L}{q_L + q_g} \quad \text{[11]}$$

$$\lambda_g = 1 - \lambda_L = \frac{q_g}{q_L + q_g} \quad \text{[12]}$$

Equations 13 and 14 are the superficial gas and liquid velocities while equations 15 and 16 are the equations for actual gas and liquid velocities.

$$v_{SG} = \frac{q_g}{A} \quad \text{[13]}$$

$$v_{SL} = \frac{q_L}{A} \quad \text{[14]}$$

$$v_g = \frac{q_g}{A H_g} \quad \text{[15]}$$

$$v_L = \frac{q_L}{A H_L} \quad \text{[16]}$$

Figure 3 shows the theoretical transition lines from wave flow, annular and annular/mist flow, stratified flow, plug flow, elongated bubble flow and disperse flow in two-phase horizontal flow with air and water in pipe flows.

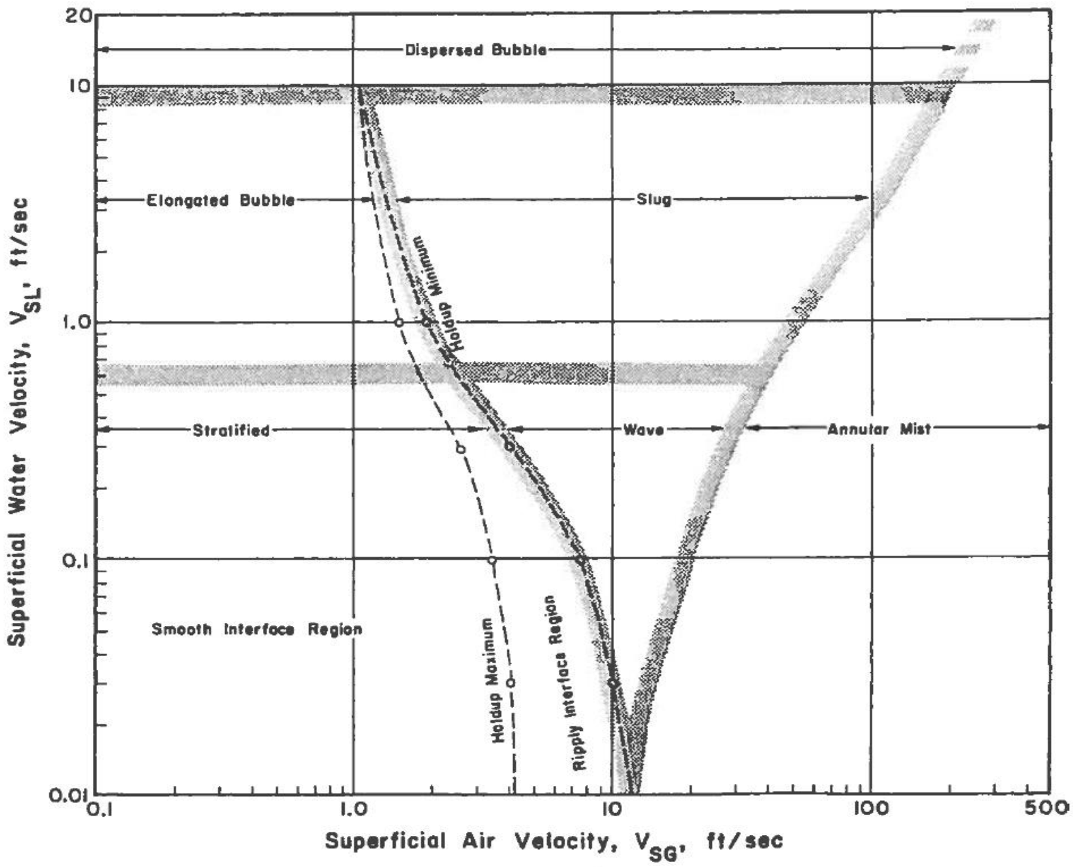

Figure 3. Theoretical flow regime boundaries for pipe flow [30]

2.2.3. Air – Water Two-Phase Flow Theory in Annulus Sections

In this section, the theory of air-water two-phase fluids flow in annulus sections will be discussed. The results are to be discussed in the next chapter as air – water two-phase flow experiment results.

There exists the need to classify the flow types in horizontal annulus sections. A study made in University of Tulsa [14] have classified the flow patterns in 4 main categories in the case of annulus flow without drill pipe rotation. Accordingly, there exist four flow patterns in horizontal wellbores;

a) Stratified Wavy Flow,

b) Elongated Bubble Flow,

c) Slug Flow,

d) Wavy Annular Flow.

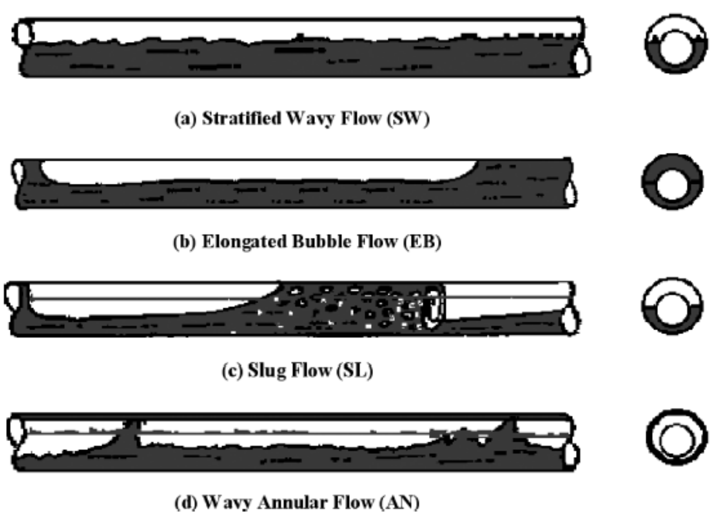

Figure 4. Flow Types in Horizontal Wellbore Sections without drill pipe rotation [14]

The researchers have developed the flow patterns by visual inspection, they have resulted in four different flow regimes, but there is also the need to add the fifth one which is bubble flow as explained below.

Stratified Wavy Flow (SW): This pattern exists in very low gas and liquid flow rates. The phases are separated by the effect of gravity.

Bubble Flow (BF): This pattern occurs when there is very low gas flow rate with higher liquid flow rates and the first shows of gas states exist.

Elongated Bubble Flow (EB): This pattern occurs when the liquid flow rates are increased after stratified flow regimes. The liquid is filling the whole annulus section but separated with the effect of gas pockets.

Slug Flow (SL): This pattern occurs when the gas flow rates are increased after elongated bubble flow. In this pattern, there exits liquid films as well as the liquid slugs but since the liquid slugs are moving faster, they are making a combination. The liquid slugs are a combination of liquid and gas and they are moving fast with the speed of the gas state.

Wavy Annular Flow (AN): This pattern occurs at very high gas flow rates. In this case, there exists a thin layer of liquid in the wavy mode as shown in figure 33d.

In some cases, there was no direct interpretation possible, this situation was termed as transition section for these flow regimes.

2.2.4. Calculation of Cuttings Bed Heights in Test Section

Cuttings Bed Heights were calculated by the help of a ruler which was placed around the outer tube of experimental setup. The length of the ruler is then converted to cuttings bed height and area occupied by cuttings with below equations. The cuttings were always observed to be touching the inner pipe and not going above the half volume of the pipe. Therefore, the equations were obtained according to Figure 5 and are valid for 5.81 cm > L > 3.26 cm.

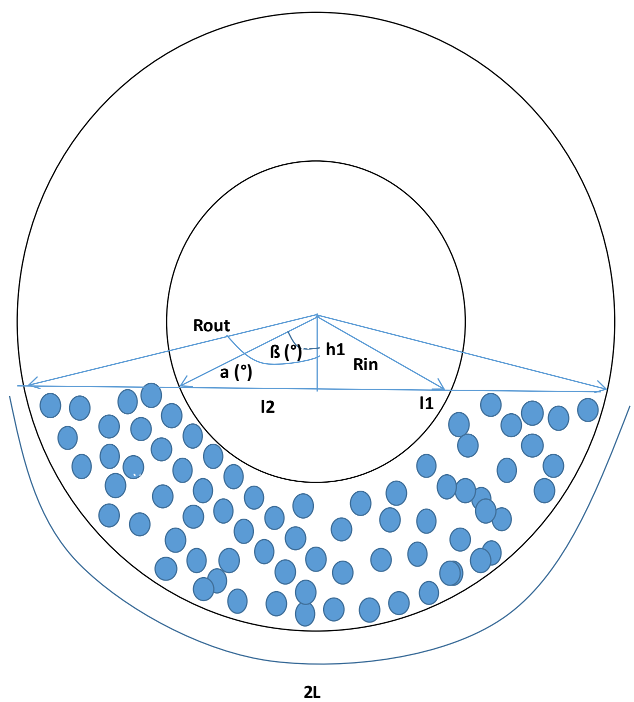

Figure 5. Schematic Diagram of Cuttings Bed in Experimental Set Up

Where:

Rout = Outer Diameter of the Outer Pipe, cm;

Rin = Outer Diameter of the Inner Pipe, cm;

2L = Measured Perimeter by Ruler, cm;

A = Cuttings Deposition Area, cm2;

Aann = Total Annulus Area, cm2;

$2L = 2\pi * Rout * 2a/360$ ....[17]

$2a = (360 * 2L) / (2\pi * Ro)$ ....[18]

$h1 = Rout * \cos a$ ....[19]

$l1^2 = Rout^2 - h1^2$ ....[20]

$S = l1 * h1$ ....[21]

$\beta = \arccos (h1/Rin)$ ....[22]

$l2 = \sin \beta * Rin$ ....[23]

$K = l2 * h1$ ....[24]

$L = (\pi * Rin^2 * 2 \beta / 360) - K$ ....[25]

$A = (\pi * Rout^2 * 2a / 360) - S - L$ ....[26]

$Aann = (\pi * Rout^2 - \pi * Rin^2)$ ....[27]

CHAPTER III

EXPERIMENTAL PROGRAM

3.1. General Description of the Experimental Program

The set up used for this work is the Advanced Flow Loop System in Middle East Technical University Petroleum and Natural Gas Engineering Department. This set up has a liquid tank, cuttings collection and injection tanks, two mud pumps, one air compressor pump, several valves to direct the flow, and a computer software connected to the flow loop named as LabVIEW.

Before starting the experiments, all the pipelines and valves have been function tested. Some of the lines were found to be leaking and some of the valves have been malfunctioning. Therefore, these valves and pipe systems have been changed with the new ones.

After that, all the calibrations have been made again. The Lab View Software gives the Ampere or Voltage values; therefore, these values have been calibrated with the values on the devices to see the results in the electronic form. These calibrations should be checked before starting to each experiment in the case of any fault. The experiments have been done in four subdivisions. For all these phases, the valves have been arranged so that the fluid flows only in one direction so that the Toshiba flow meter measurements are the actual flow meters that flow in the test section.

Experiments have been performed in three different steps.

- Single Phase Flow Experiments
- Air – Water Two-Phase Flow Experiments
- Water – Air – Cutting Three Phase Flow Experiments

3.2. Experimental Set Up

The experimental setup used for this work is the Advanced Flow Loop System in Middle East Technical University Petroleum and Natural Gas Engineering Department. The main schematic of the setup is given in Figure 1. Experimental components are Gas Compressor and Accumulator Tank, Air Dryer, Pneumatic Valves, Mud Pump, Liquid Tank, Solid Separation System (Shale Shakers), Rate of Penetration Motor for Injection Tank, RPM Motor for Inner Wellbore in Test Section, Toshiba Flow Meter (for liquid phase), Dwyer Gas Flow Meter, Honeywell Differential Pressure, Lighting System, Slow Motion Camera, Load Cells and Lab View Software. Details of some of these components are provided in Table 1.

Table 1. Experimental Components and Technical Capacity

Component	**Technical Capacity**
Gas Compressor	3000 L/min at 6 atm
Air Dryer	700 L/min at 6 atm
Mud Pump	1.136 m3/min
Liquid Tank	2000 lt.
Toshiba Flow Meter	1.136 m3/min
Dwyer Gas Flowmeter	0 - 1000 L/min at 25 psi
Honeywell Differential Pressure	0 - 2.5 psi
Load Cells	0 - 5000 kg

This set up was used previously by other scientists but no one has used it after October 2010. Therefore, most of the valves and pipes have been changed with new ones. Moreover, Honeywell Differential Pressure system has been installed. Both liquid and gas pipelines have check valves to prevent the backflow of the liquid and gas.

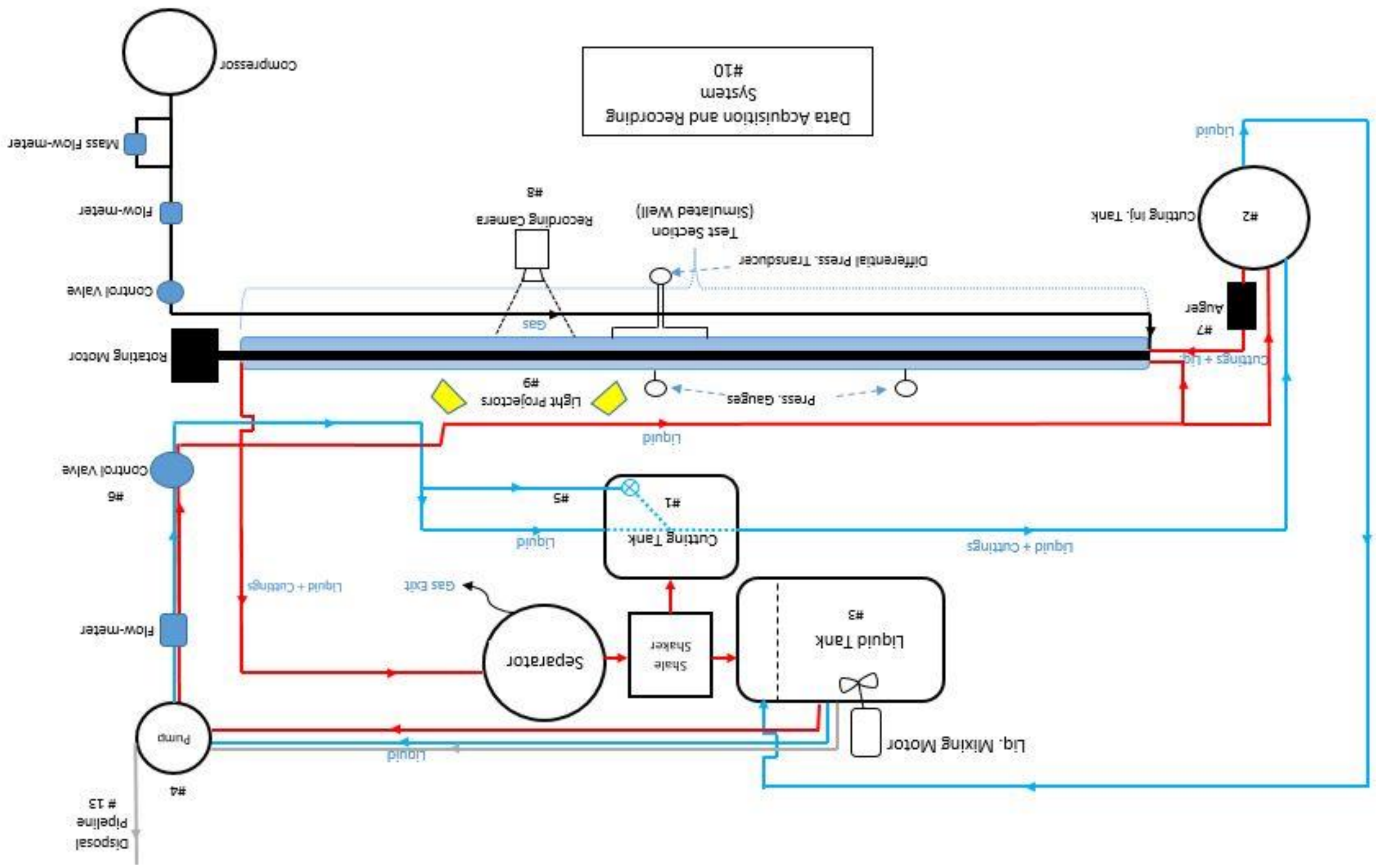

Figure 6. Schematic of Flow Loop Used in the Experiments [1]

There were two led lights used in the experiments to be able to observe the fluid flow mechanisms and cuttings transport performance of designed fluids. For these observations, researchers closed all the lights and curtains in the room. Only these two lighting systems have been used to enlighten the test section area for observations.

Figure 7. Lighting System

Gas Compressor (Figure 8) is the main device that produces air and pumps it through the flow loop and then the test section. The air accumulates in the accumulator tank and when it reaches a certain pressure, it starts to pump the air into the system. The air from the accumulator is also used to open/close the pneumatic valves also. The air dryer is used to dry the air and is required since the flow meters and pressure systems do not work efficiently with wet-air. Therefore, the air has been always dried and used in that way during the experiments.

Figure 8. Gas Compressor and Accumulator Tank

Figure 9. Air Dryer

Dwyer gas flowmeter is used to measure the Gas Flow Rates in L/min. It has a working interval of 0 - 1000 L/min. The measurements obtained afterward are converted to scf/min and then used to evaluate the annulus gas velocity in the test section.

Figure 10. Dwyer Gas Flowmeter

Pneumatic valves (Figure 11) have been used during the research to control the gas and liquid flow rates. They are controlled by a remote controller which is placed by the computer. The main drive mechanism is the air pumped by the compressor to open/close the pneumatic valves in the flow loop system.

Figure 11. Gas and Liquid Pneumatic Valves

The test section (Figure 12) is where the main values of the research have been obtained. There are two lines connected to the test section as in Figure 8. These lines are connected to the Honeywell Pressure Transmitter on the other connection and are used to measure the pressure losses in the certain interval. The annular test section consists of 21 ft. long 2.91 inches ID transparent casing and 1.85 inches OD inner drill pipe. There is also the measurement level showing the perimeter of the casing which is used to evaluate the bed height during cuttings transport experiments. It should also be noted that the inner drill pipe was in an eccentric situation due to the weight of the pipe and is not rotated during the experiments.

Figure 12. Test Section

Figure 13. Lines Connecting to the Honeywell for Differential Pressure Measurements

In the inlet of the test section (Figure 14 and 15), there are three lines which enable three phase flow. The yellow line is the gas flow line which comes from the gas accumulation tank which has the dried air from the gas compressor. The flex-hose is the liquid line which has the mud pumped from the liquid tank. The solid black line is the cutting line which has the cuttings from the injection tank pumped by the ROP motor. The gas line is connected to the test section in V-shape which enables the best liquid and gas mixture. The inlet of the test section is a movable corner which enables giving some angle to the test section up to almost vertical. But in this experiment, researcher always worked in the horizontal situation, therefore, this movable corner was not used.

Figure 14. Gas Liquid and Cuttings Inlet to the Flow Loop Test Section – 1

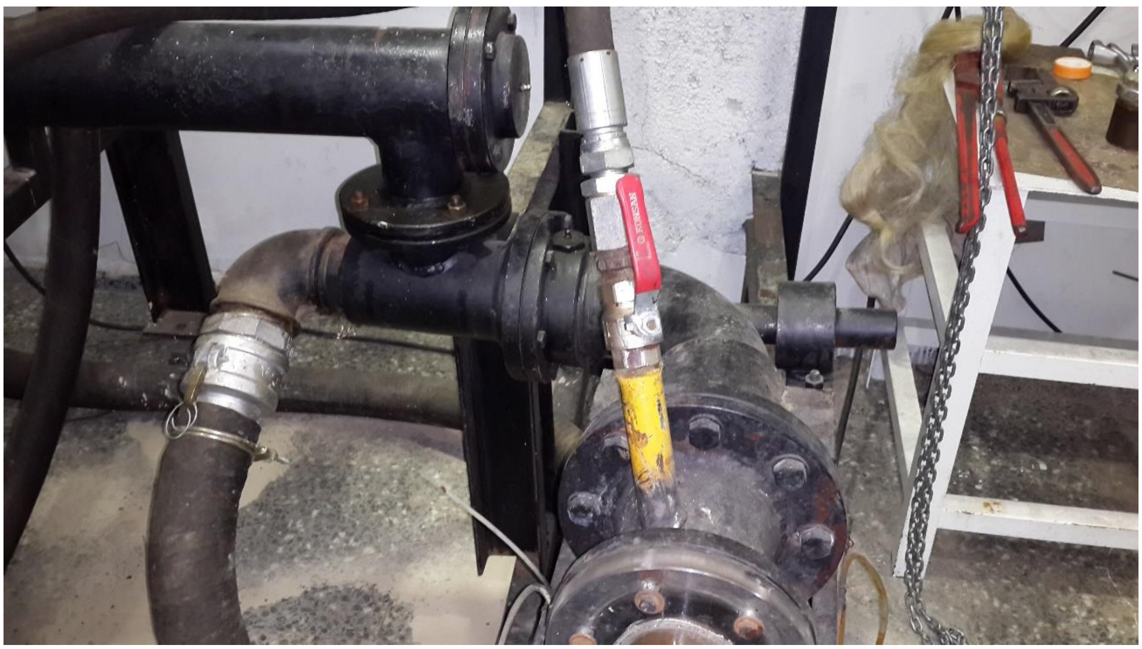

Figure 15. Gas Liquid and Cuttings Inlet to the Flow Loop Test Section - 2

After all the cuttings are cleaned from the test section and the pipes, all the cuttings were accumulated in the cuttings collection tank (Figure 19). Afterwards the valves of the surface lines were arranged so that the liquid flowed through the cuttings collection tank and transported all the cuttings to the cuttings injection tank via the flex-hose going through the top of the tank. Figure 16 shows the cutting injection tank.

Figure 16. Cuttings Injection Tank

Figure 17. Rate of Penetration Motor for Injection Tank

After cutting injection tank is filled with cuttings, the blue valve of Figure 17 is opened and the rate of penetration motor is used to change the injection rates of the solid particles into the test section of the flow loop.

Solid Separation System (Figure 18 & 19) is used to separate the liquid and solid particles from each other. For that purpose, the Shale Shaker is used and the cuttings separated have been diverted to the cuttings collection tank and the liquid directly goes through the liquid tank again.

Figure 18. Solid Separation System - Shale Shaker

Figure 19. Solid Separation System and Cuttings Collection Tank

Honeywell ST 300 Differential Pressure System is shown in Figure 20 and it is used to evaluate the frictional pressure drops in the test section during the experiments.

Figure 20. Honeywell ST 300 Differential Pressure System

Two of the lines in the Honeywell Differential Pressure System are the ones coming from the Flow Loop Test Section. The other lines are connected to the tap and are used to fresh the lines to prevent gas influx to the lines and if happens, to clean and take the gas out of the system again. In the normal experimental process, all the valves of this manifold were closed except the two valves connected to the lines of the test section.

Figure 21. Lines from Test Section to Honeywell

The end of the test section has an RPM motor which is used to give rotation to the inner drill pipe connected. The RPM values change between 0 – 120 RPM and are controlled using the control panels. Also, the end of the line is connected to the solid separation system by a flex hose.

Figure 22. The End of Test Section and RPM Motor

The control panel on the Left Side of Figure 23 is the panel used for ROP motor and the one on the right side is used for the RPM motor. These two panels have been used to change the values of pipe rotation and cuttings injection speeds. Both have emergency stop buttons to stop the motors immediately in case any emergency happens.

Figure 23. Control Panels of ROP and RPM Motors (for Motor Revolution Speeds)

Figure 24. Toshiba Flow Meter

Figure 25. Mud Pumps

Figure 26. Pump Control Panels (On/Off)

There were two mud pumps used to pump liquid into the test section. One has a bigger capacity while the other one has a smaller capacity (Figure 25). They have been controlled (open/close) by the control panels connected to them (Figure 26). The liquid flow rate has been measured using the Toshiba flow meter (Figure 24).

Figure 27. Mud Mixer

Mud mixer (Figure 27) is used to mix the liquid in the liquid tank. The use of mixing tank has been controlled by the control panel (Figure 28) and is necessary when the liquid in the tank stays stationary for a while. Mixing makes a more homogenous mixture, therefore, results in better data.

Figure 28. Mud Mixer Control Panel (On/Off)

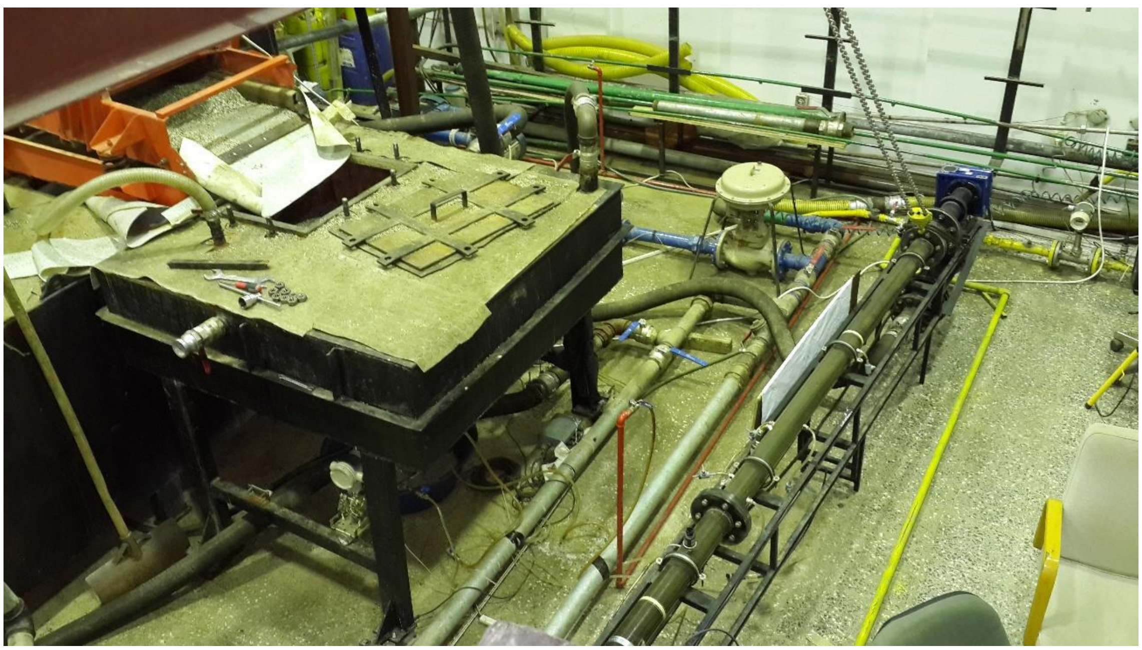

Figure 29. Top View of the Flow Loop

Figure 30. A View of Liquid Tank, Solid Separation System and Collection Tank

Figure 31. View of Test Section

Lab View Software has been used for these experiments. The Data Processor (Figure 32) have been connected to the computer in the lab (Figure 33) and the data have been calibrated accordingly. Regular calibration checks have been performed during the experiments to obtain data accuracy. Front Panel of Lab View Software is shown in Figure 34 that is where the researchers have followed the data obtained during the experiments and to save and collect the data.

Figure 32. Lab View Data Processing

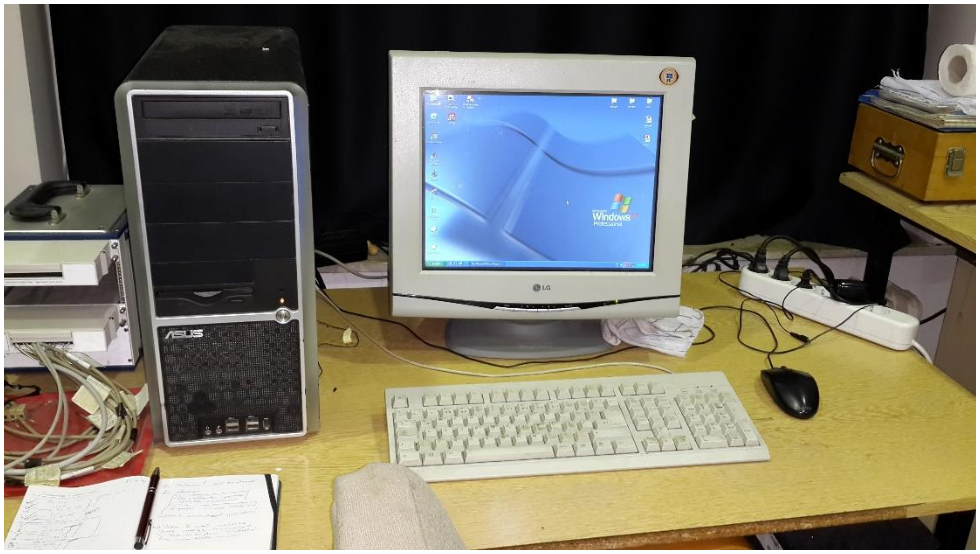

Figure 33. Computer Used for Laboratory Work

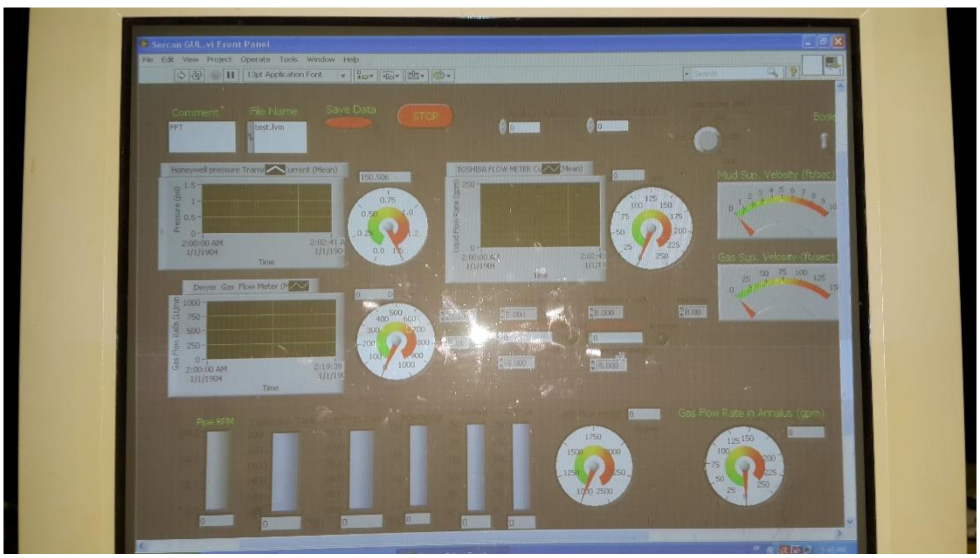

Figure 34. Front Panel of Lab View Software

3.3. Material Used

There exist two main materials to be introduced which are the cuttings and the drag reducer used in the experiments.

The cuttings used are industrial sands which have a particle diameter, D50, of 2.75 mm and density of 23.05 lb./gal. The D50 value of the cuttings are determined by Sieve Analysis as in Figure 35. Figure 36 provides a picture from the drilling cuttings used in the experiments [9].

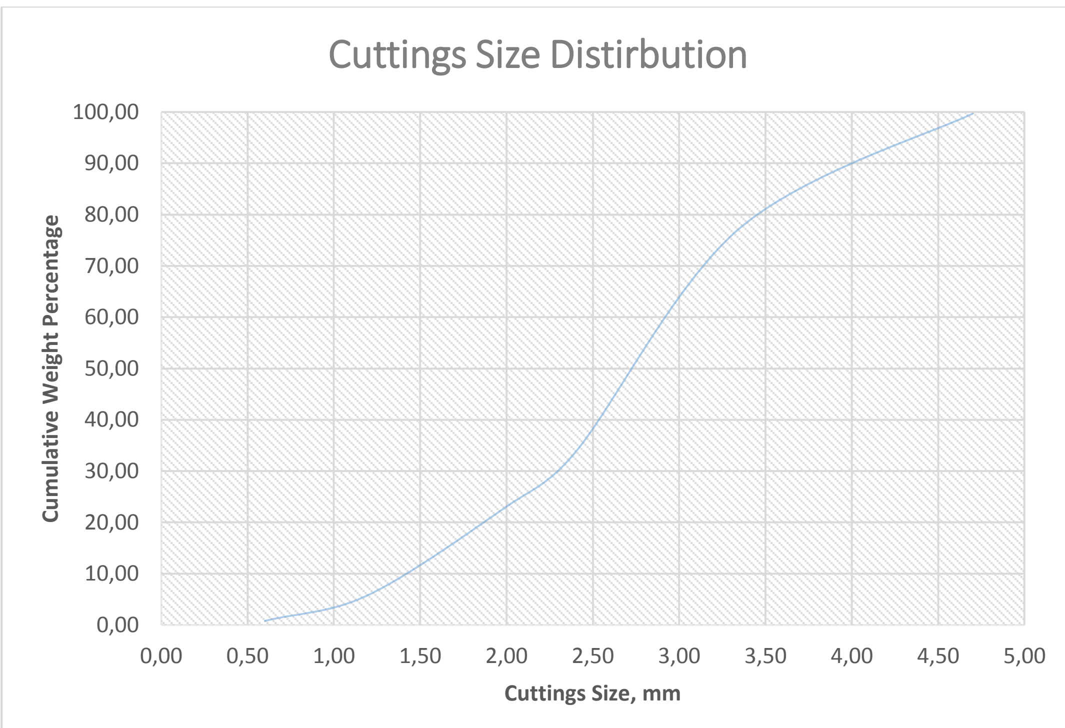

Figure 35. Sieve Analysis of Drilling Cuttings

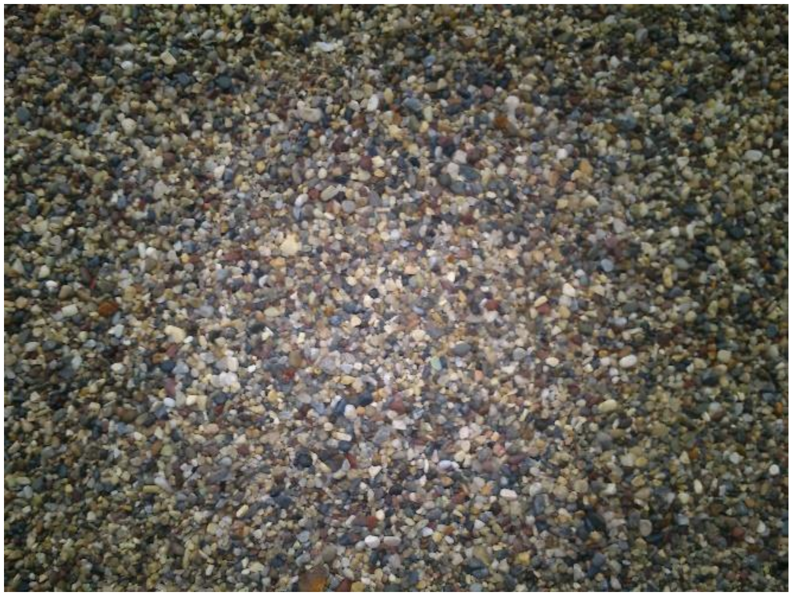

Figure 36. Drilling Cuttings' Picture

As the drag reducing agent, PHPA copolymer is used. The commercial name of the polymer is Poly Bore which is white colored, 8.5-9.0 in pH range and 52 lb./ft^3 in density.

Figure 37. PHPA Co-Polymer (Poly Bore) Used in Experiments

Tables 2, 3 and 4 provides the details of Viscometer readings of different concentrations (0.05%, 0.07%, and 0.10%) of drag reducers in water.

Table 2. Viscometer Reading Results of 0.05% PHPA Concentration

0.05 % W/W PHPA (Poly-Bore)			
Viscometer Speed (rpm)	**Shear Rate (1/s)**	**Dial Reading (Fann)**	**Shear Stress (lb/100ft2)**
600	1021,98	**5,7**	6,082
300	510,99	**3,5**	3,735
200	340,66	**2,8**	2,988
100	170,33	**2**	2,134
6	10,22	**1**	1,067
3	5,11	**0,9**	0,960

Table 3. Viscometer Reading Results of 0.07% PHPA Concentration

0.07 % W/W PHPA (Poly-Bore)			
Viscometer Speed (rpm)	**Shear Rate (1/s)**	**Dial Reading (Fann)**	**Shear Stress (lb/100ft2)**
600	1021,98	**6**	6,402
300	510,99	**4,2**	4,481
200	340,66	**3,15**	3,361
100	170,33	**2,2**	2,347
6	10,22	**1,2**	1,280
3	5,11	**0,95**	1,014

Table 4. Viscometer Reading Results of 0.10% PHPA Concentration

0.10 % W/W PHPA (Poly-Bore)			
Viscometer Speed (rpm)	**Shear Rate (1/s)**	**Dial Reading (Fann)**	**Shear Stress (lb/100ft2)**
600	1021,98	**7,65**	8,163
300	510,99	**5,6**	5,975
200	340,66	**3,95**	4,215
100	170,33	**2,85**	3,041
6	10,22	**1,2**	1,280
3	5,11	**1**	1,067

Shear stress versus shear rate graph of different combinations of the PHPA polymer is given in Figure 38.

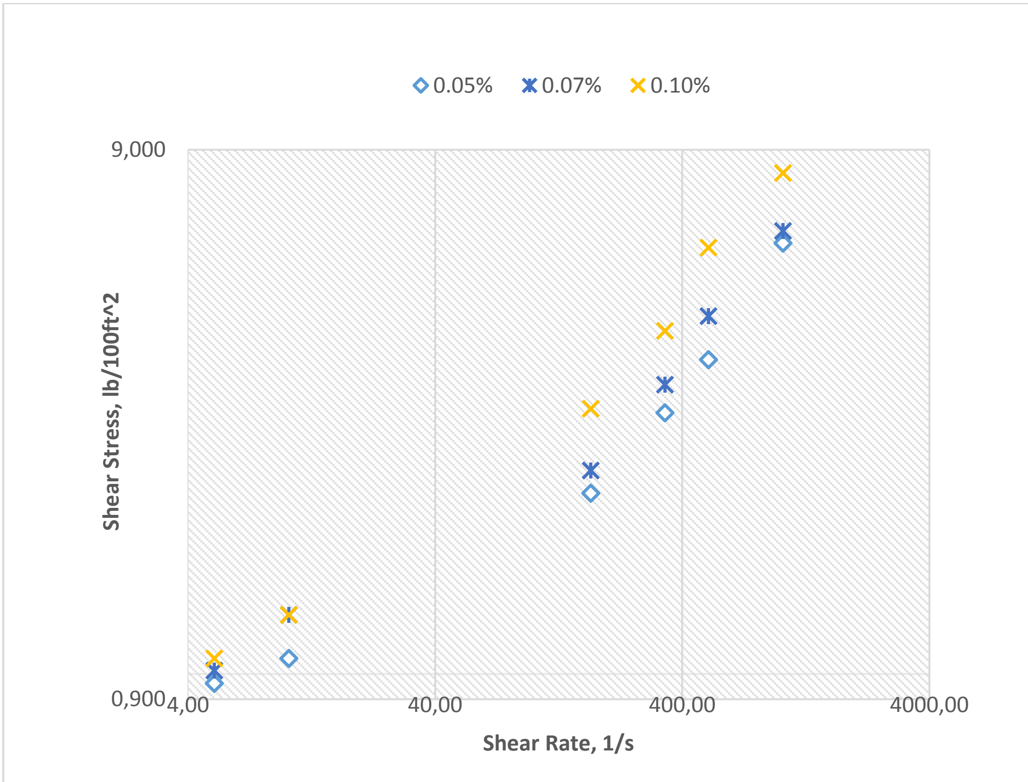

Figure 38. Shear Stress vs Shear Rate Graph of 0.05%, 0.07% and 0.10% Concentrations of PHPA Polymers

To obtain the right concentration, 75% of the mud tank (1500 liter) is filled with water and 1500*0.07/100 = 1.05 kg (considering density of water is 1 gr/cm^3) = 1050 gr polymer is poured from the top of the water tank while the mixers are working to obtain 0.07% polymer concentration. The tank was filled 75 percent to eliminate the losses of drilling fluid while mixing. After mixing and waiting for necessary time, the viscometer readings of the mixture was controlled to make sure the right concentration of polymer is obtained.

CHAPTER IV

SINGLE PHASE FLOW EXPERIMENTS

4.1. Single Phase Flow Experiment Procedure

1. Turn on the computer and the Lab View Software
2. Turn on the data acquisition system
3. Start running the air compressor and gas dryer
4. Flush the Honeywell Pressure System Lines with fresh water
5. Arrange the valves so that water only flows in one direction
6. Make sure all the gas valves are in closed position
7. Check if the liquid tank is filled. (If the polymer is used, the desired liquid with a necessary concentration of polymer will be prepared 15 hours before the experiments for optimum mixing. If not, fill the tank with water)
8. Open the hand valve in front of the pump which is selected to be used
9. Start running the mud pump to flush the test section and the lines
10. Arrange the flow rate to the desired value with the pneumatic valve remote controller
11. Wait until the differential pressure and flow rate values have reached to steady state
12. Save the data for 60 seconds
13. After 60 seconds, arrange the flow rate to the second desired value with the pneumatic remote controller
14. Repeat steps 10-13 for each desired value and then empty the liquid tank and flush the test section with air to prevent the liquid freezing inside the pipe.

4.2. Single Phase Flow Experiment Results

The first data set is the water flow experiment data set which is given in Appendix A. The data obtained have been used to estimate the relative roughness of the wellbore in METU Advanced Flow Loop.

The distance between 2 lines connecting to the Honeywell is 0.465 m = 1.52 ft., fluid density is taken as 8.33 lb./gal and viscosity = 1cp. Outer diameter is 2.91 in. while the inner diameter of the drill pipe is 1.85 in.

Therefore, using these input and necessary equations, Table 5 have been obtained using Equations 1, 2 and 4. (Data obtained as in appendix A).

Table 5. The calculation of Relative Roughness

ΔL [ft]=	1,52
ρ [lb/gal]=	8,34
μ [cp]=	1,00
d1 [in]=	2,91
d2 [in]=	1,85
d_{hyd} [in]=	1,06
R_i [in]=	0,93
R_o [in]=	1,46
a =	0,64
R_m [in]=	1,18
φ*=	0,67
d_L [in]=	0,71
d_e [in]=	0,86
C =	928

DP [psi]	**Q [gal/min]**	**V [ft/sec]**	**Re**	$f_{fanning}$	**ε/d**
0,692	73,918	5,984	49079,155	0,0095	0,00926
0,713	75,930	6,147	50415,058	0,0093	0,00858
0,730	78,622	6,365	52202,458	0,0089	0,00735
0,736	81,502	6,598	54114,685	0,0083	0,00587
0,754	84,574	6,847	56154,393	0,0079	0,00488
0,755	85,361	6,911	56676,936	0,0078	0,00456
0,761	87,382	7,075	58018,814	0,0075	0,00391
0,766	99,783	8,079	66252,676	0,0058	0,00100
0,777	101,955	8,254	67694,814	0,0056	0,00081
0,815	107,847	8,731	71606,911	0,0053	0,00045
0,831	110,804	8,971	73570,263	0,0051	0,00028

Standard Deviation	Median	Average
0,0021	0,0059	0,0063

Last four data from the table are omitted in the calculations due to high oscillations and variations at flow rates of 100 gpm and higher. The standard deviation, average and median values are also calculated without including the last four data.

Friction Factor vs. Reynold's Number graphs have been drawn in log-log plot as in Figure 39. The general equation is y = 495148 $x^{-1.643}$ which is in the form $f = CN_{Re}^{n}$ where C = 495148 and n = -1.643.

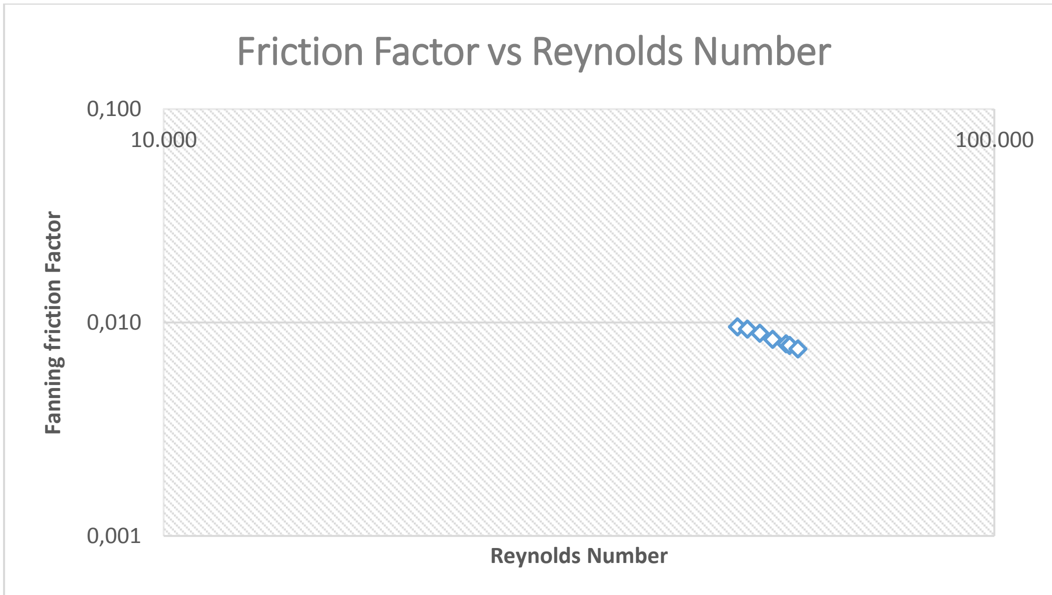

Figure 39. Friction Factor vs Reynolds's Number Graph (Log-Log)

Finally, the relative roughness of the pipe is accepted as the average value which is 0.0063. The median of relative roughness is 0.0059 with the standard deviation of 0.0021 as in Table 6.

Table 6. Variance, Median and Average Results of Relative Roughness

Standart Deviation	Median	Average
0,0021	0,0059	0,0063

4.3. Polymerized Water Single Phase Flow Experiment Results

A mixture of water-polymer has been used to investigate the effects of PHPA (Partially Hydrolyzed Poly Acrylamide) in underbalanced drilling conditions. The first experiments conducted with PHPA are mixing the polymer with water as single-phase drilling fluid without the use of air. For that purpose, 0.05% W/W, 0.07% W/W and 0.10% W/W polymer concentrations were used. The mud mixing tank has been used to obtain the best mixture of polymer with water. The necessary amount of polymer has been added to the tank which was filled with water and then mixed for 30 minutes. After the mixing, the polymer was rested for at least 15 hours. Before use, the polymer has been mixed in the tank for another 30 minutes and then it is pumped into the well using the centrifuge pumps. After the results were taken, the well was cleaned with water and air to remove the polymer particles inside the wellbore and hoses. Experimental results obtained with different phpa concentrations are in Figure 40 and the data obtained is given in Appendix A.

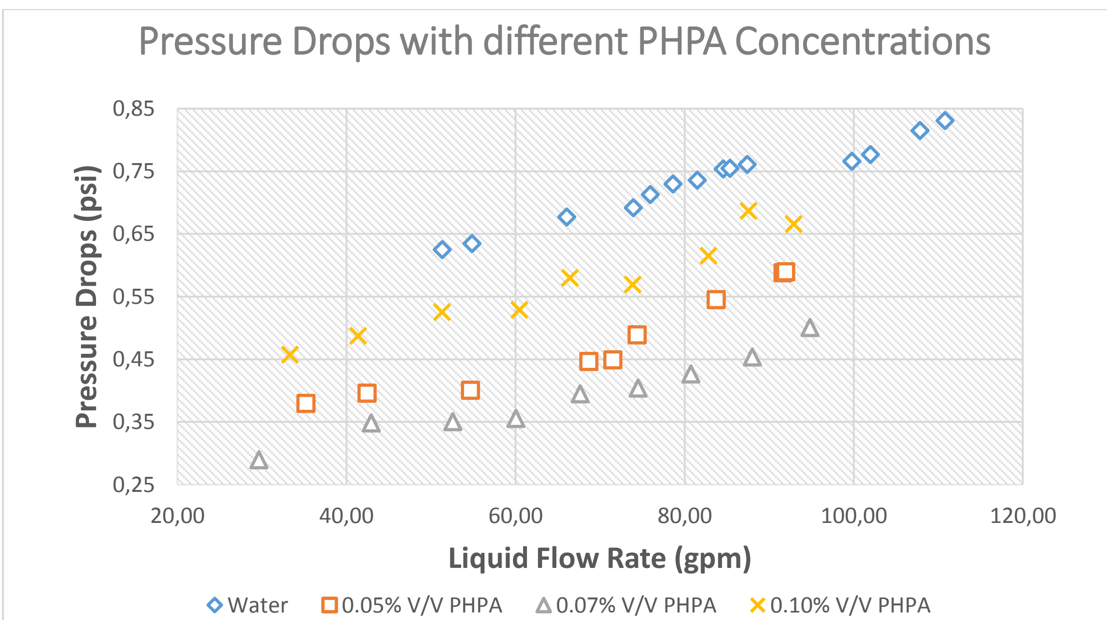

Figure 40. Pressure Drops with Different PHPA Concentrations

As seen in Figure 40, the maximum pressure drops have been obtained using water but the minimum values have been obtained in 0.07% W/W PHPA polymer concentrations. 0.05 % W/W polymer concentration gives the second-best results while 0.10% W/W polymer concentration gives the worst results amongst other percentages of polymers. Which means that there is an optimum value of polymer concentration in PHPA's and that values are 0.07% W/W in our wellbore schematic.

Data were taken with water and PHPA polymers are compared as in Table 7. Accordingly, in average, PHPA polymers in the concentration of 0.07% gave an average of 41.88% drag reduction in the provided experimental setup.

Table 7. Polymerized Water Single Phase Flow Experiment Results

DP [psi] - Water	**DP [psi] – 0.07% PHPA**	**Liquid Flow Rate**	**Drag Reduction (%)**
0.76	0.45	87.98	40.34
0.74	0.43	80.73	42.01
0.69	0.40	74.49	41.54
0.68	0.40	67.66	41.61
0.63	0.35	52.60	43.90
		Average	**41.88**

4.4. Single Phase Flow Experiments Comparison of Measured Frictional Pressure Losses with Model Predictions

The results of Single Phase Flow Experiments have been compared with the predictions from Jones & Leung [26] and Colebrook Equations [27]. The "f" in the provided equations are Fanning friction factor which is 1/4 of Moody friction factor. So, the calculated "f" is divided by 4 to calculate the pressure drop with above equation.

Table 8. Comparison of Measured Pressure Losses vs Jones & Leung

Q [gal/min]	V [ft/sec]	Re	Re*	Moody Friction Factor	Calculated "ΔP_f" [psi]	Measured "ΔP" [psi]	% Difference
73,92	5,98	49079	32831	0,0352	0,639	0,692	7,6
75,93	6,15	50415	33724	0,0350	0,670	0,713	6,0
78,62	6,37	52202	34920	0,0347	0,712	0,730	2,4
81,50	6,60	54115	36199	0,0344	0,759	0,736	3,1
84,57	6,85	56154	37563	0,0341	0,810	0,754	7,4
85,36	6,91	56677	37913	0,0340	0,823	0,755	9,0
87,38	7,07	58019	38811	0,0338	0,858	0,761	12,7
84,57	6,85	56154	37563	0,0341	0,810	0,754	7,4
85,36	6,91	56677	37913	0,0340	0,823	0,755	9,0
87,38	7,07	58019	38811	0,0338	0,858	0,761	12,7

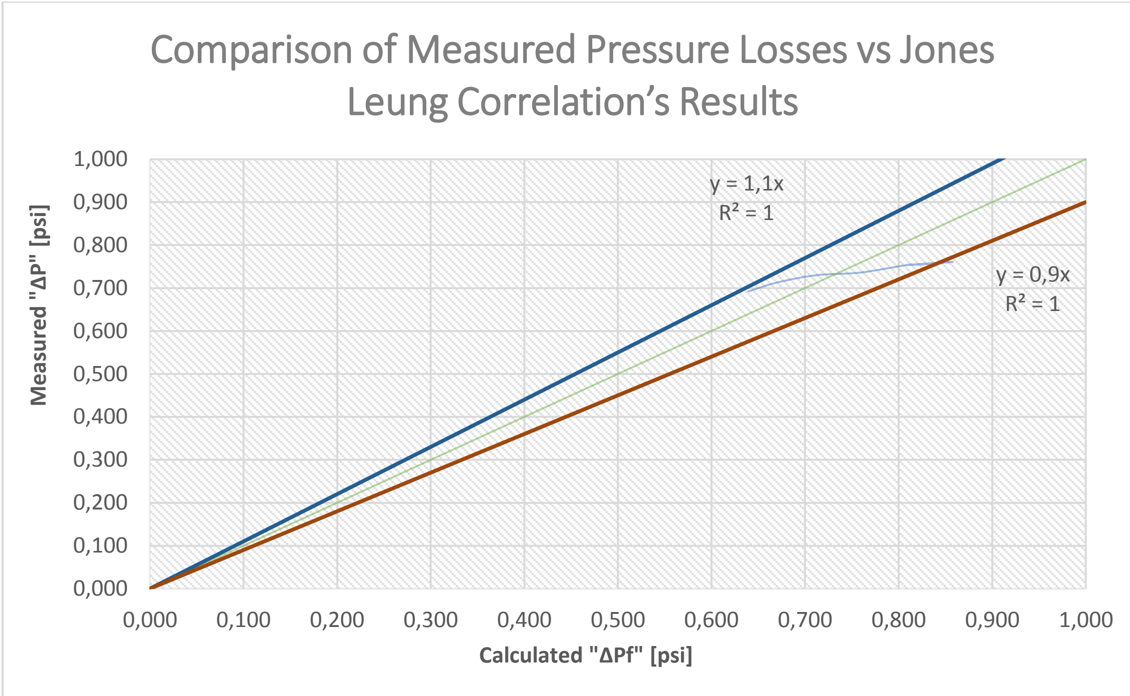

Figure 41. Comparison of Measured Pressure Losses vs Jones Leung Correlation’s Results

It was observed that the minimum difference is 3.1% while the maximum is 12.7% in the comparison with Jones & Leung correlation.

The blue line and red line shows the 10% percent error margin where the light blue line is the line drawn through the calculated and measured pressure loss data.

Table 9. Comparison of Measured Pressure Losses vs Collebrook Equation Results

Measured "ΔP" [psi]	Q [gal/min]	V [ft/sec]	Re	Fanning Friction Factor	Calculated "ΔPf" [psi]	% Error
0,692	73,918	5,984	49079,155	0,00843	0,612	11,606
0,713	75,930	6,147	50415,058	0,00842	0,645	9,586
0,730	78,622	6,365	52202,458	0,00841	0,690	5,465
0,736	81,502	6,598	54114,685	0,00839	0,740	0,605
0,754	84,574	6,847	56154,393	0,00838	0,796	5,583
0,755	85,361	6,911	56676,936	0,00838	0,811	7,374
0,761	87,382	7,075	58018,814	0,00837	0,849	11,526
0,754	84,574	6,847	56154,393	0,00838	0,796	5,583
0,755	85,361	6,911	56676,936	0,00838	0,811	7,374
0,761	87,382	7,075	58018,814	0,00837	0,849	11,526

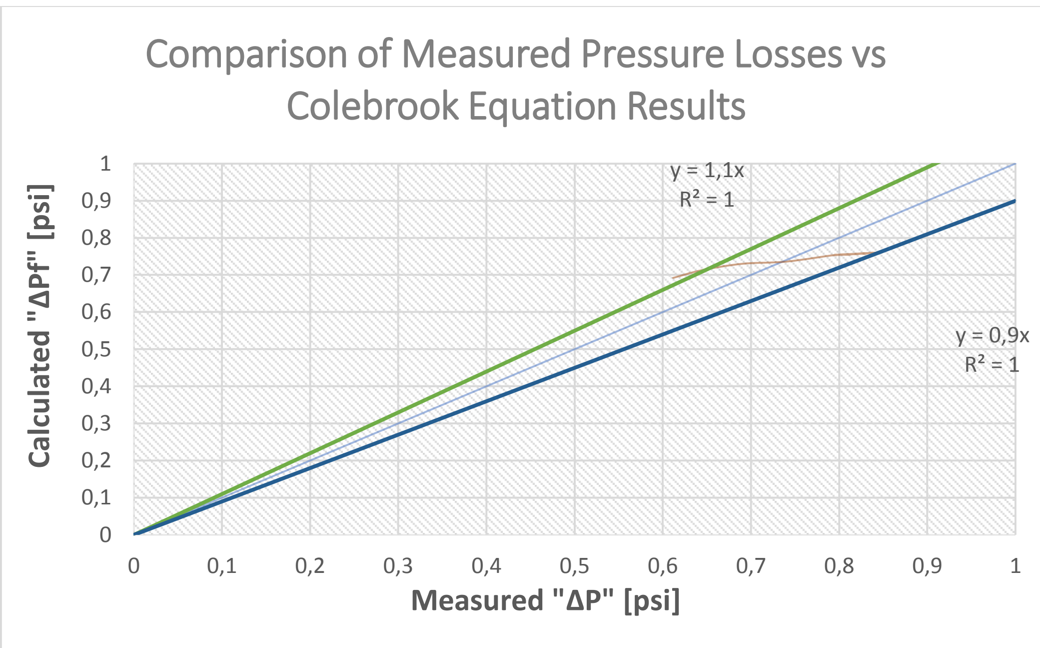

Figure 42. Comparison of Measured Pressure Losses vs Colebrook Equation Results

It was observed that the minimum difference is 0.6% while the maximum difference is 11.61% in the comparison with Colebrook equation results. The blue line and green line shows the 10% percent error margin where the red line is the line drawn through the calculated and measured pressure loss data.

4.5. Single Phase Flow Experiments Repeatability Analysis

The results of Polymerized Water Single Phase Flow Experiments have been repeated two times and the repeatability analysis is made comparing the data within itself. In figures 43, 44 and 45, the yellow line gives the equation y=1.05x and the grey line gives the equation y=0.95x which refers to 5% error margin.

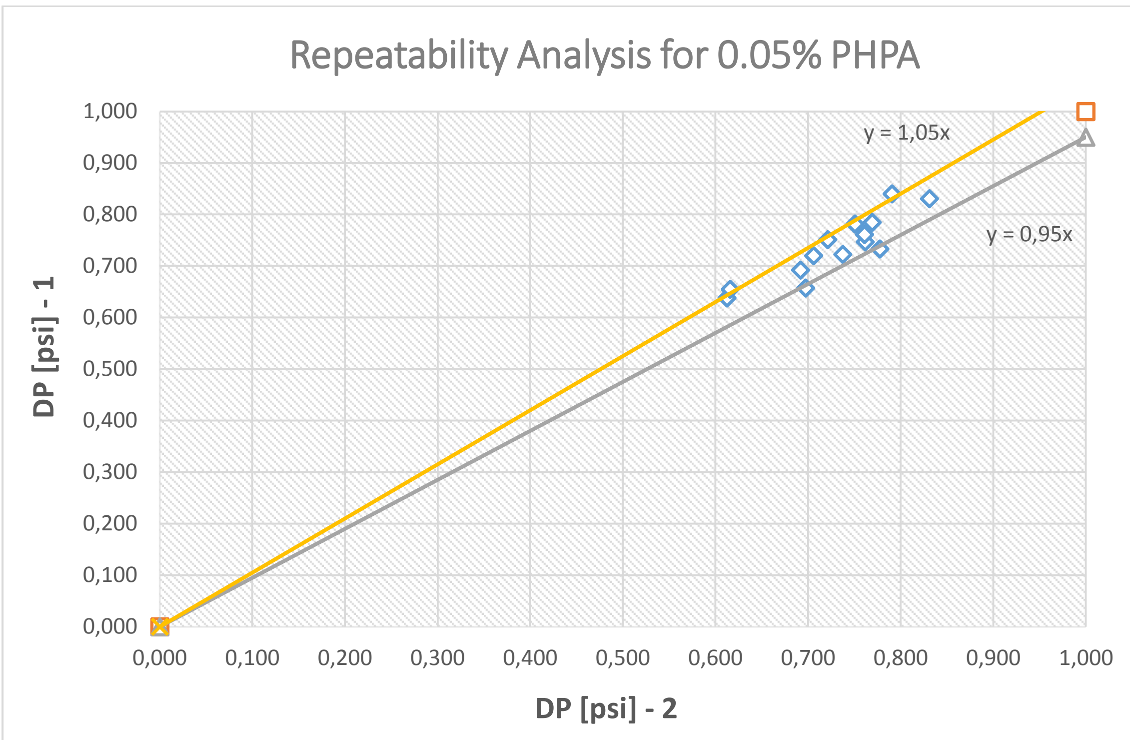

Figure 43. Repeatability Analysis for 0.05% PHPA

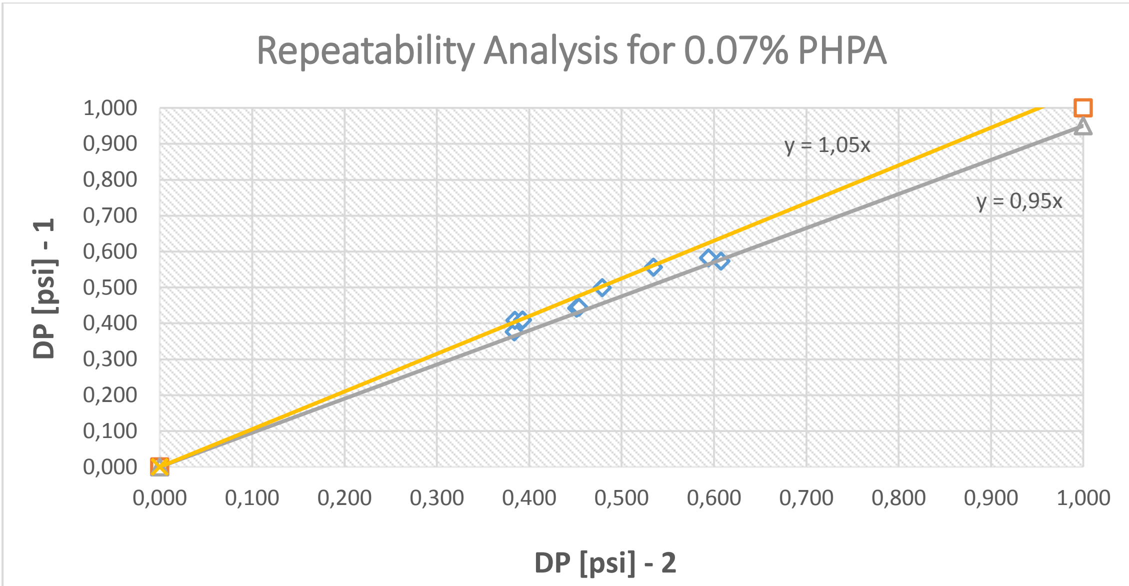

Figure 44. Repeatability Analysis for 0.07% PHPA

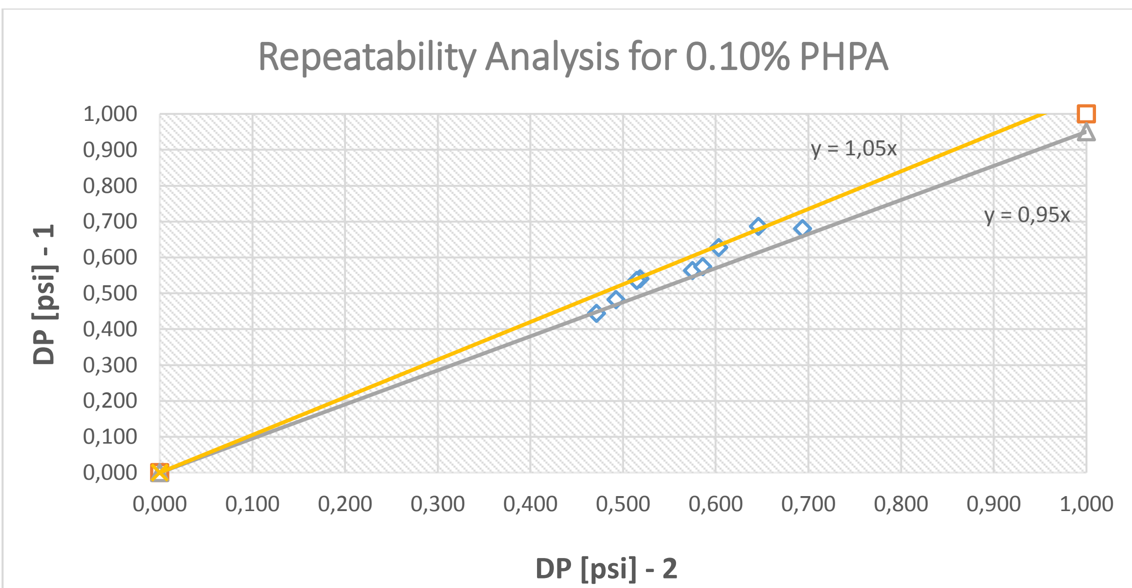

Figure 45. Repeatability Analysis for 0.10% PHPA

It was observed that all the data is accurate within %5 percent of experimental error. Maximum error of 5% is observed in all three-different composition of PHPA polymers.

CHAPTER V

TWO-PHASE FLOW EXPERIMENTS

5.1. Two Phase Flow Experiment Procedure

1. Turn on the computer and the Lab View Software
2. Start running the data acquisition system
3. Open the air compressor and gas dryer
4. Flush the Honeywell Pressure System Lines with fresh water
5. Arrange the valves so that water only flows in one direction
6. Open the gas valves
7. Check if the liquid tank is filled. (If the polymer is used, the desired liquid with a necessary concentration of polymer will be prepared 15 hours before the experiments for optimum mixing. If not, fill the tank with water)
8. Open the hand valve in front of the pump which is selected to be used
9. Start running the mud pump to flush the test section and the lines
10. Arrange the liquid flow rate to the desired value with the pneumatic valve remote controller
11. Arrange the gas flow rate to the desired value with the pneumatic valve remote controller
12. Wait until the differential pressure and flow rate values reach to steady state
13. Save the data for 60 seconds
14. After 60 seconds, arrange the gas flow rate to the second desired value with the pneumatic remote controller
15. Repeat step 11-14 for each desired gas flow rate value.
16. After finished with the desired fluid flow rate, arrange the fluid flow rate to the second desired value and repeat steps 11-14 for each desired gas flow rate value.

17. Afterward, repeat the steps for all desired fluid flow rates. When finished, empty the liquid tank and flush the test section with air to prevent the liquid freezing inside the pipe.

5.2. Two Phase Flow Experiment Results (Air + Water)

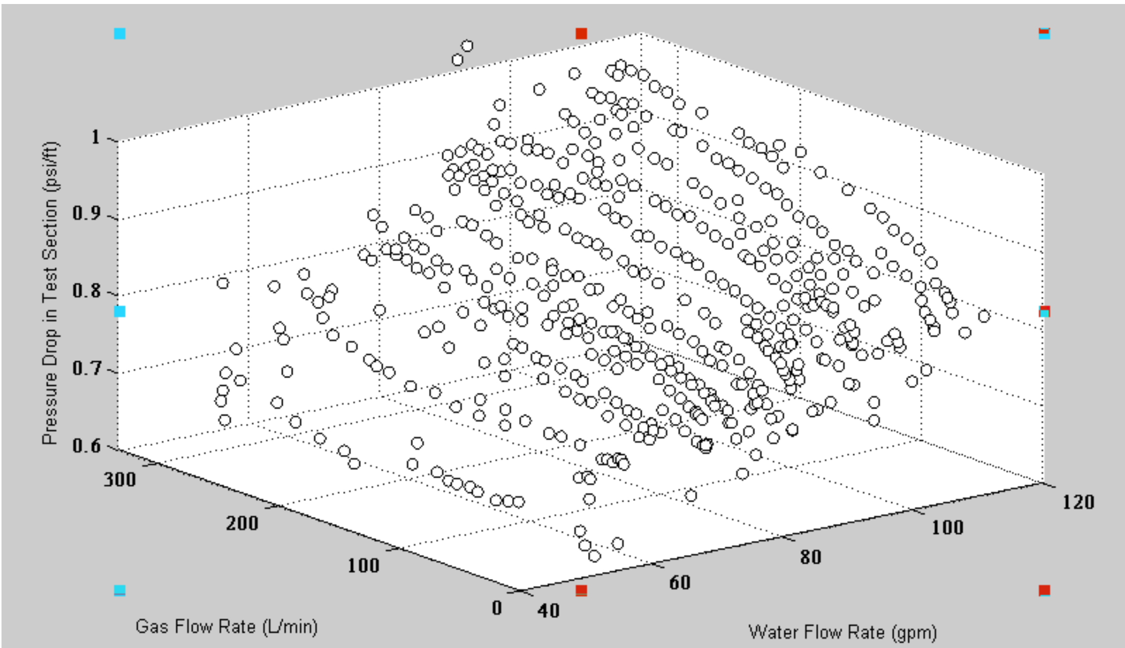

Figure 46. 3D Scatter Plot by MATLAB

The second data set is the air-water two-phase flow experiment data set which is given in detail in Appendix A. The data obtained have been drawn in Matlab using the Scatter 3D. According to the results, increasing the water and gas flow rates both increase the pressure drops.

The flow pattern map has been obtained as in Figures 47. According to the flow pattern map, the only patterns observed in this wellbore configuration are bubble, elongated bubble, slug and wavy annular flows.

The flow pattern maps were obtained by visual observation through the recordings of high-speed cameras.

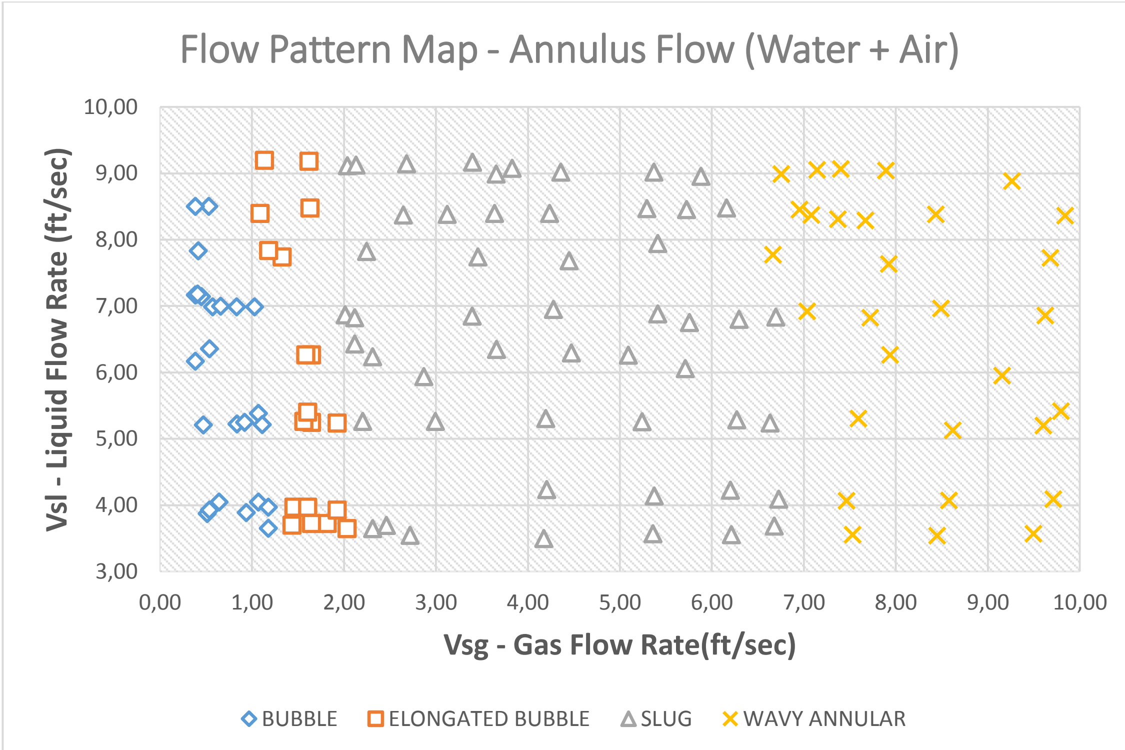

Figure 47. Flow Pattern Map in Annulus Flow with Water + Air Flow in Linear Scale

5.3. Two Phase Flow Experiment Results (Air + Polymerized Water)

It was observed from Figure 40 that the optimum PHPA polymer concentration in drag reducing is 0.07% V/V. Therefore, to understand the flow regime changes in drag reducing polymers, 112 data have been taken with different polymerized liquid and gas flow rates and the pressure drops as well as the flow regimes have been recorded.

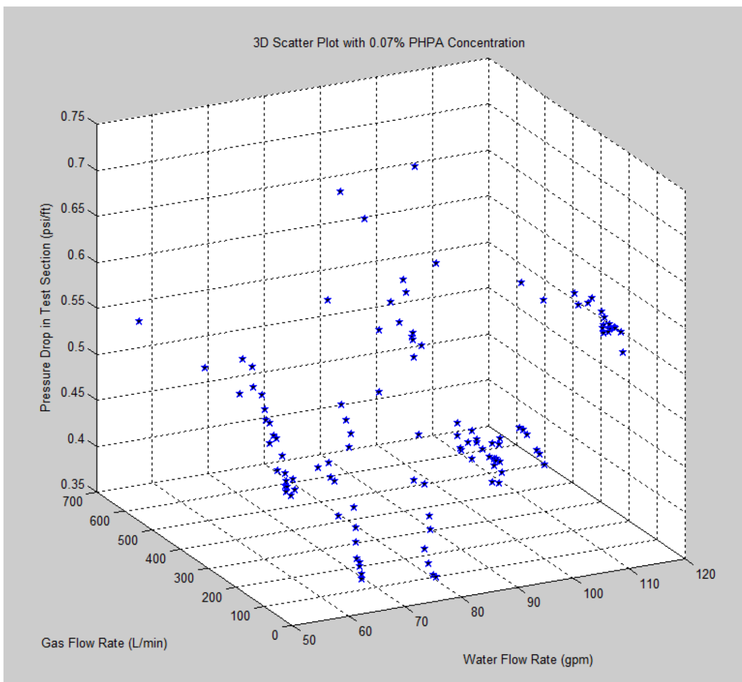

Figure 48. 3D Scatter Plot by MATLAB for 0.07 % Polymer

Moreover, these data have been investigated to understand the flow pattern differences of Polymerized Water + Air and Water + Air experiments.

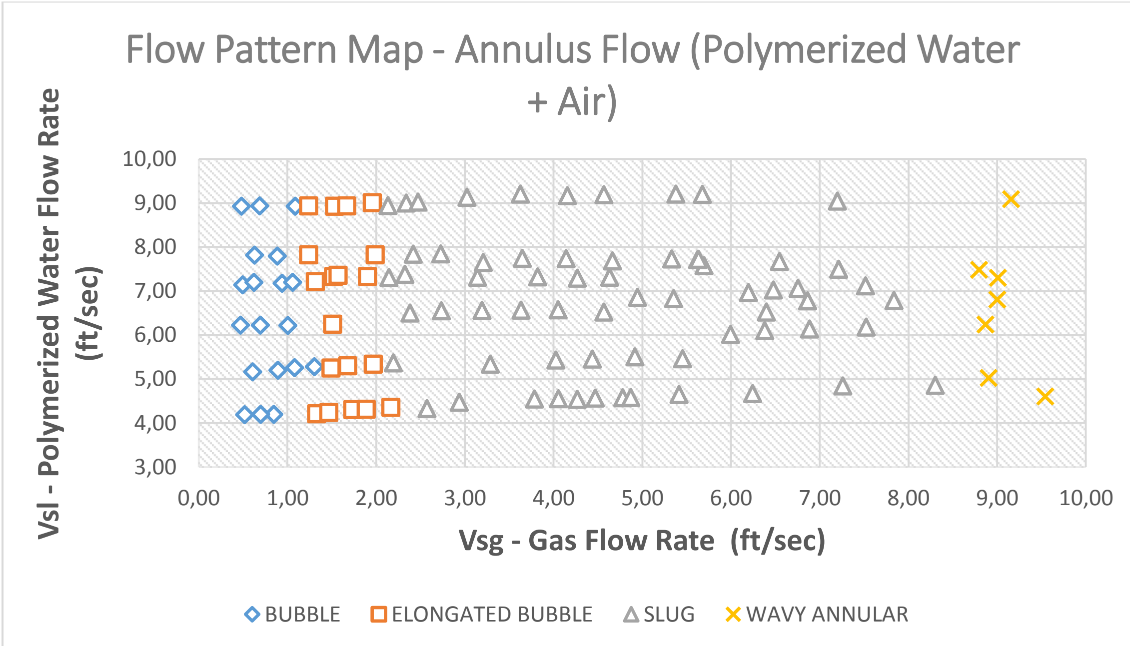

Figure 49. Flow Pattern Map for Polymerized Water + Air Experiments with 0.07% V/V PHPA Polymer Concentration

The flow pattern map has been obtained as in Figures 49. According to the flow pattern map, the only patterns observed in this wellbore configuration are bubble, elongated bubble, slug and wavy annular flows. In figure 50, two flow patterns were compared to understand the effect of PHPA polymers in the flow pattern maps.

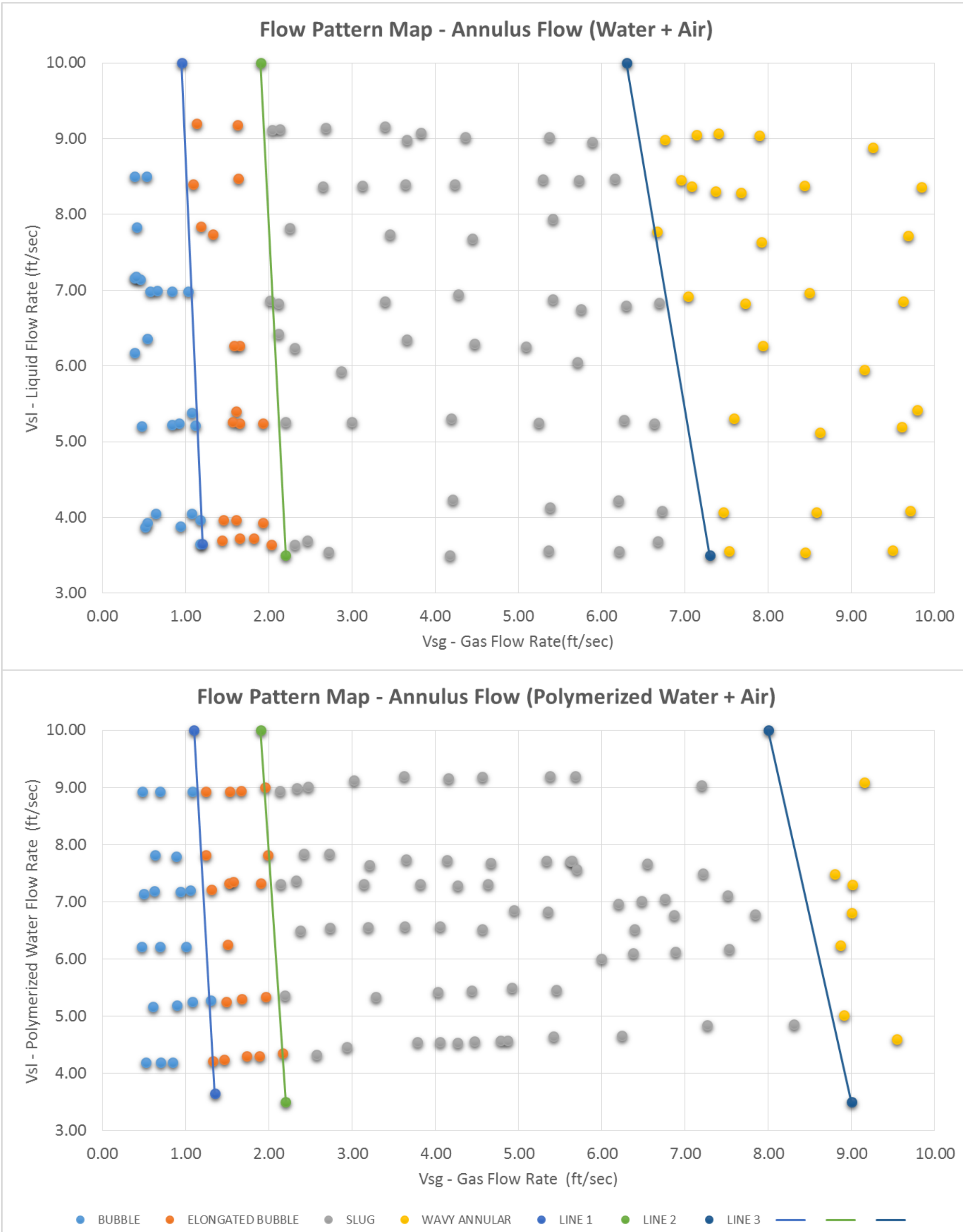

Figure 50. Comparison of Flow Pattern Maps in Polymerized Water and Pure Water Cases

The transition from Bubble to Elongated Bubble:

It was observed from figures 50 that the transition line from bubble to elongated bubble flow can be drawn from a higher gas flow rate with the addition of polymers into the system extending the bubble flow regime.

The equation of transition line in the case with no polymer: $y = -25.4x + 34.13$

The equation of transition line in the case with 0.07% polymer: $y = -25.4x + 37.94$

The difference in y value is 3.81 units.

The transition from Elongated Bubble to Slug:

The transition line of the elongated bubble to slug flow stays the same with the extension of bubble flow and the compression of elongated bubble flow.

The equation of transition line in the case with no polymer: $y = -21.667x + 51.167$

The equation of transition line in the case with 0.07% polymer: $y = -21.667x + 51.167$

The transition from Slug to Wavy Annular:

The transition line of slug flow to wavy annular flow can be drawn from a higher gas flow rate with the addition of polymers into the system extending the slug flow regime.

The equation of transition line in the case with no polymer: $y = -6.5x + 50.95$

The equation of transition line in the case with 0.07% polymer: $y = -6.5x + 62$

The difference in y value is 11.05 units.

These flow pattern maps of air-water and air-polymerized water cases have also been compared with the theoretical flow pattern map of horizontal pipe flow by Govier&Aziz [30] as shown in figures 52 and 53.

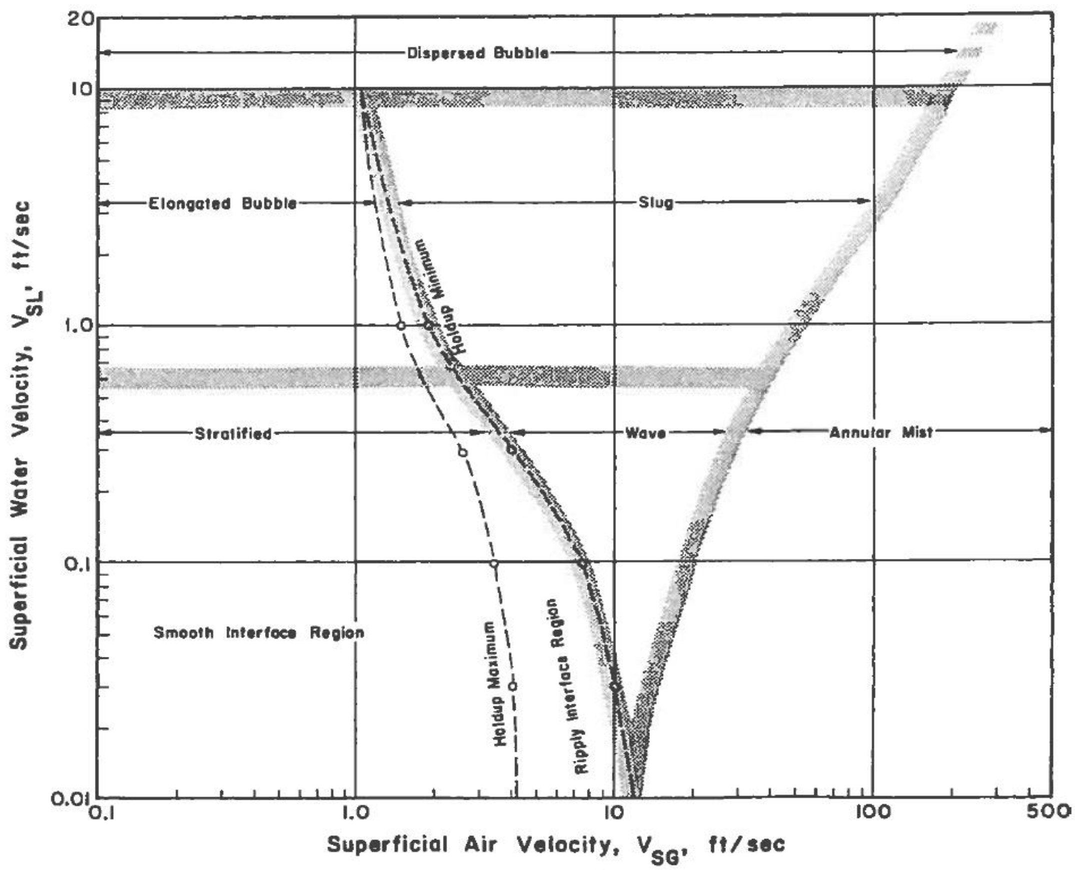

Figure 51. Theoretical flow regime boundaries for pipe flow [30]

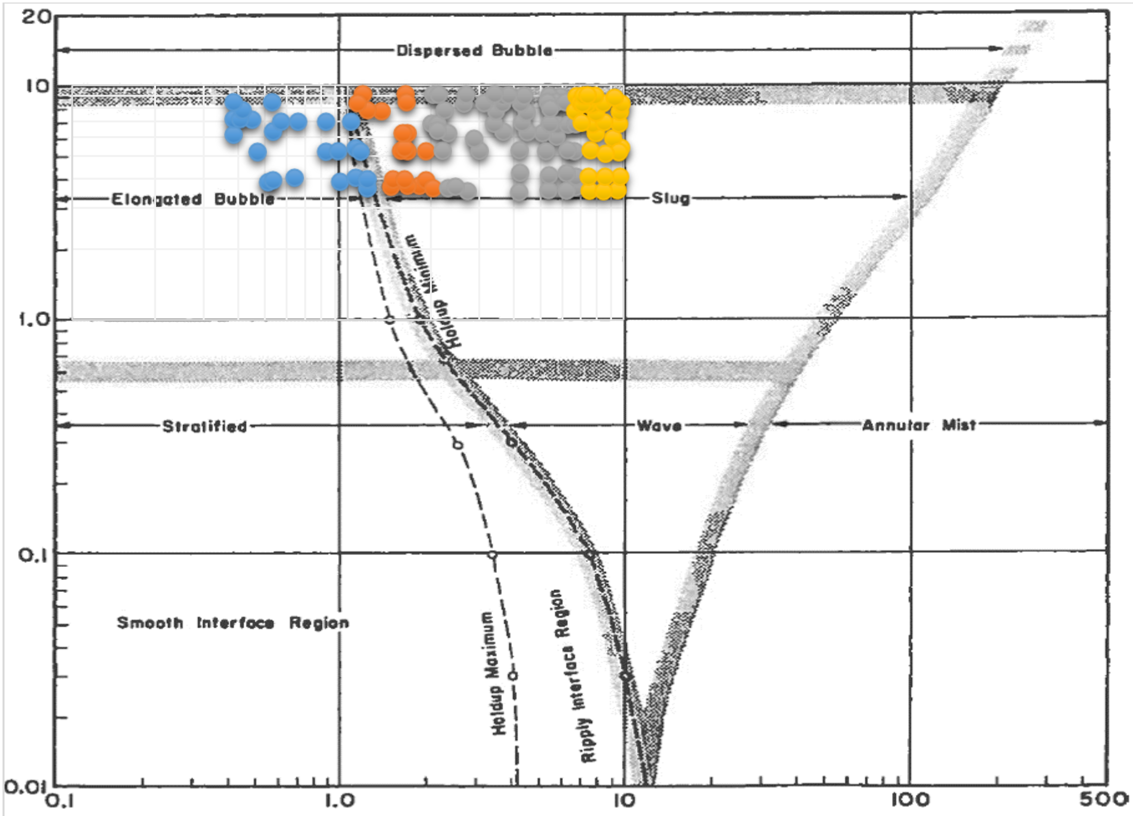

Figure 52. Comparison of Experimental Data of Water+Air Two-Phase Flow in Horizontal Wellbore (Blue: Bubble Flow, Orange: Elongated Bubble Flow, Grey: Slug Flow, Yellow: Wavy Annular Flow) with Theoretical Flow Regime Map for Horizontal Pipes [30]

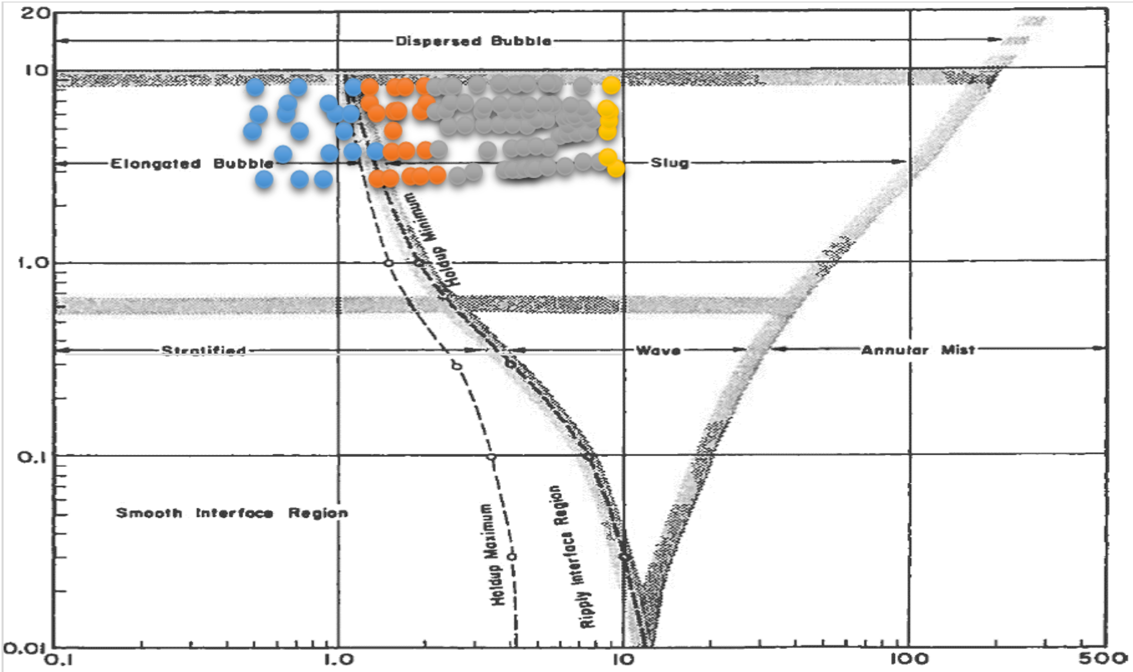

Figure 53. Comparison of Experimental Data of Polymerized Water (0.07%) +Air Two-Phase Flow in Horizontal Wellbore (Blue: Bubble Flow, Orange: Elongated Bubble Flow, Grey: Slug Flow, Yellow: Wavy Annular Flow) with Theoretical Flow Regime Map for Horizontal Pipes [30]

It has been observed from figures 52 and 53 that the flow pattern maps are following the trend from elongated bubble to slug and then to annular mist flow but the experimental data is compressed in the annulus flow comparing to the pipe flow in the horizontal situation.

8 data points have been selected as in Table 10 from the flow pattern maps, where these points are in the same flow patterns for both the Water-Air Flow as well as the Polymerized Water – Air Flow.

Table 10. Data Points Selected for Cuttings Transport Experiments

#	Water Flow Rate (gpm)	Gas Flow Rate (L/min)	Gas Flow Rate (gpm)	VsL (ft./sec)	Vsg (ft./sec)	Flow Pattern
1	61.8	23.5	6.204	5.00	0.50	Bubble
2	98.8	23.5	6.204	8.00	0.50	Bubble
3	61.8	70.3	18.5592	5.00	1.50	Elongated Bubble
4	98.8	70.3	18.5592	8.00	1.50	Elongated Bubble
5	61.8	234	61.776	5.00	5.00	Slug
6	98.8	234	61.776	8.00	5.00	Slug
7	61.8	421	111.144	5.00	9.00	Wavy Annular
8	98.8	421	111.144	8.00	9.00	Wavy Annular

Using the data points, drag reduction of 0.07% PHPA polymers have been investigated as in Table 8. Accordingly, the average drag reduction obtained using 0.07% PHPA polymers is 40.47% while the maximum drag reduction was obtained at Data Point #1 as 46.79% and the lowest was obtained at Data Point #7 as 30.12%.

Table 11. Experiment Results of 0.07% PHPA Polymers in Aerated Drilling Fluids

#	VsL (ft./sec)	Vsg (ft./sec)	Flow Pattern	Differential Pressure (Honeywell) - Water	Differential Pressure (Honeywell) - PHPA 0.07%	Drag Reduction %
1	5.00	0.50	Bubble	0.716	0.381	46.79
2	8.00	0.50	Bubble	0.809	0.473	41.53
3	5.00	1.50	Elongated Bubble	0.723	0.419	42.05
4	8.00	1.50	Elongated Bubble	0.872	0.499	42.78
5	5.00	5.00	Slug	0.732	0.481	34.29
6	8.00	5.00	Slug	0.918	0.515	43.90
7	5.00	9.00	Wavy Annular	0.777	0.543	30.12
8	8.00	9.00	Wavy Annular	0.986	0.569	42.29
					Average	**40.47**

From the experiment result, it was observed that higher drag reduction occurs at higher liquid flow rates when the gas flow rate is constant except the bubble flow. Therefore, increasing the liquid flow rates for a constant gas flow rate increases the drag reduction in elongated bubble, slug and wavy annular and decreases the drag reduction in bubble flow regime. On the other hand, increasing the gas flow rates decreases the drag reduction in low liquid flow rates (5 ft/sec) but the effect of increase in the gas flow rates in negligible when the liquid flow rate is higher (8 ft/sec).

5.4 Two-Phase Flow Experiments Repeatability Analysis

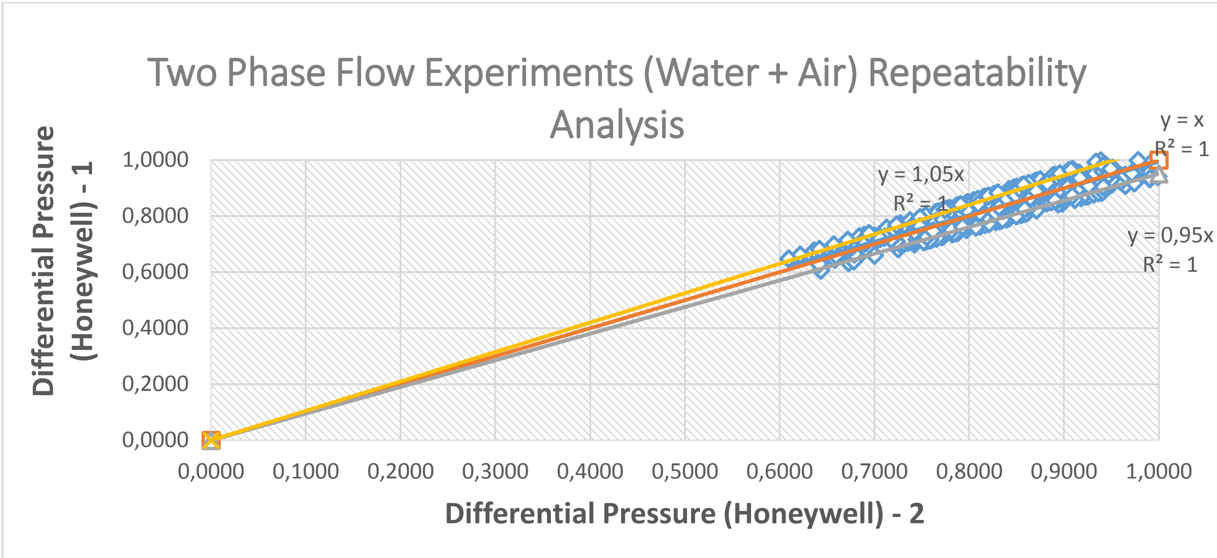

Figure 54. Two Phase Flow Experiments (Water + Air) Repeatability Analysis

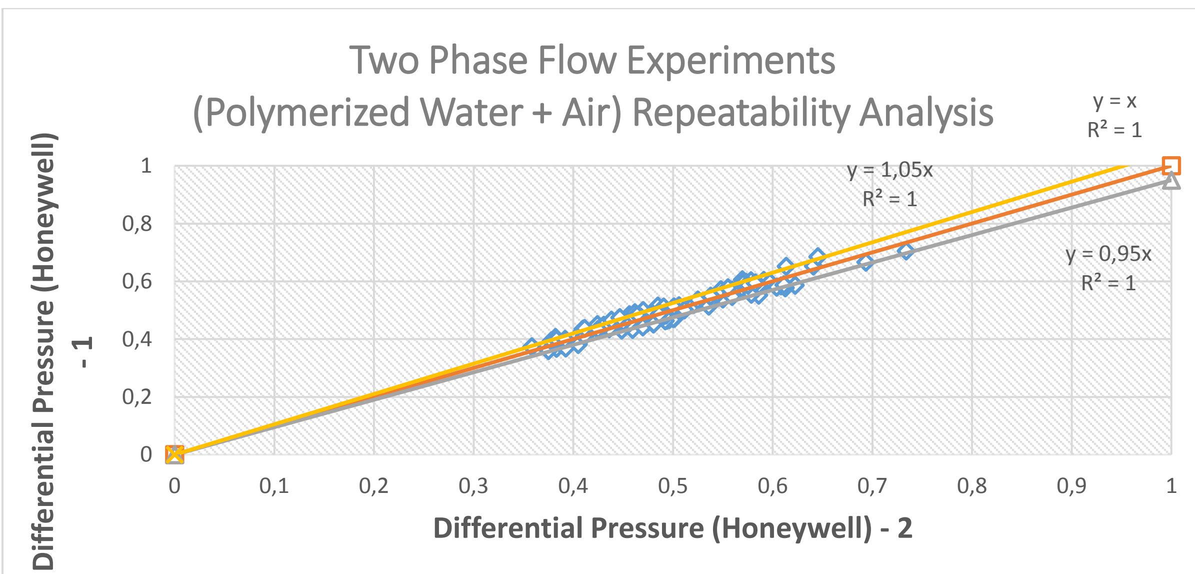

Figure 55. Two Phase Flow Experiments (Polymerized Water + Air) Repeatability Analysis

For the two-phase flow experiments, repeatability analysis is done to see the experimental errors. In figures 54 and 55, the yellow line has the equation $y = 1.05x$ and the grey line has the equation $y = 0.95x$. These two lines provide the 5% error margin in the figures.

It was observed that all the data is accurate within %5 percent of experimental error.

CHAPTER VI

THREE PHASE FLOW EXPERIMENTS

6.1. Three Phase Flow Experiment Procedure

1. Turn on the computer and the Lab View Software
2. Open the data acquisition system
3. Start running the air compressor and gas dryer
4. Flush the Honeywell Pressure System Lines with fresh water
5. Make sure all the gas valves are in closed position
6. Check if the liquid tank is filled. (If the polymer is used, the desired liquid with a necessary concentration of polymer will be prepared 15 hours before the experiments for optimum mixing. If not, fill the tank with water)
7. Open the hand valve in front of the pump which is selected to be used
8. Arrange the valves to fill up the liquid injection tank with solids
9. Fill up the liquid injection tank with the solids and then stop the pumps
10. Arrange the valves so that fluid flows through the test section
11. Make sure the valves are arranged so that water only flows in one direction
12. Start running the mud pump to flush the test section and the lines
13. Arrange the flow rate to the desired value with the pneumatic valve remote controller
14. Arrange the gas flow rate to the desired value with the pneumatic valve remote controller
15. Arrange the rate of penetration to the desired value
16. Wait until the differential pressure and flow rate values reach to steady state
17. Save the data for 60 seconds
18. After 60 seconds, arrange the rate of penetration value to the next desired value and repeat steps 14-17 for the desired rate of penetration values.

19. Stop the pumps and repeat step 9 – 18 for the next liquid and gas flow rates
20. When finished, empty the liquid tank and flush the test section with air to prevent the liquid freezing inside the pipe

6.2. Three Phase Flow Experiment Results (Water + Air + Cuttings)

In the cutting transport experiments, the ROP was set at 115 ft./hr. and the experiments were all done with the same ROP value. The ROP value was set using the ROP motor in the experimental setup.

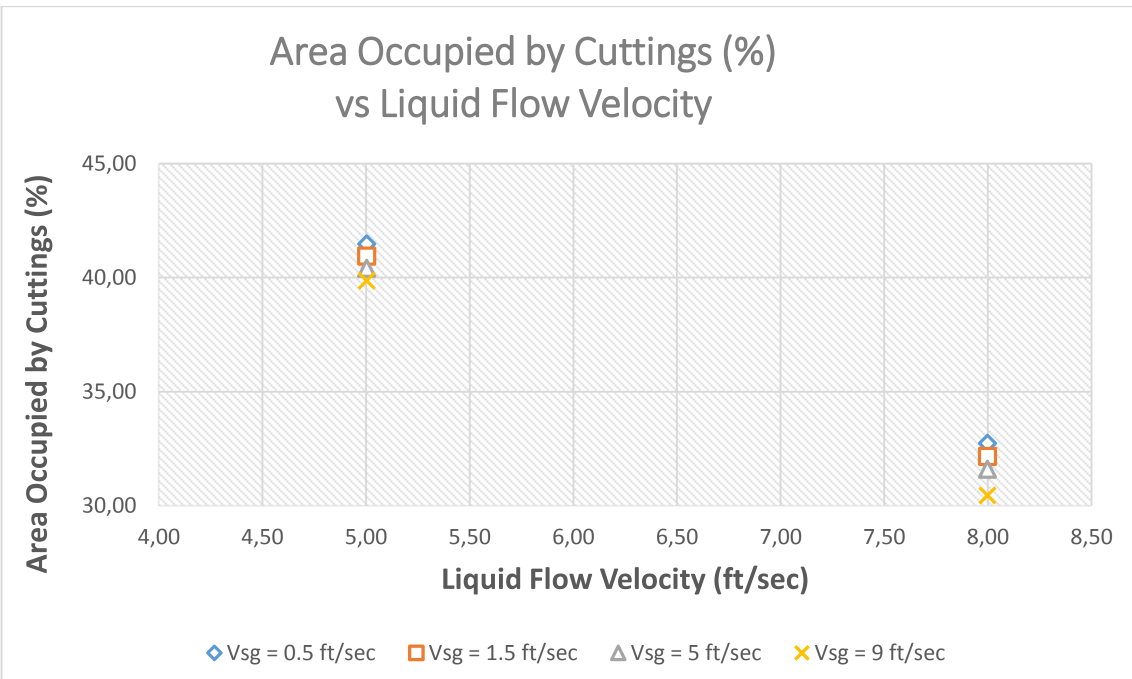

Figure 56. Area Occupied by Cuttings (%) vs. Liquid Flow Velocity

The experiments were done with the 8 data points with the rate of penetration value of 115 ft./hr. in the horizontal wellbore situation. The area occupied by cuttings have been calculated by equations 17-27. The measurements were done when the cuttings were in stationary phase, and the measured lengths are for the stationary bed.

According to the experimental results, it was observed that the cuttings area is decreasing with the increase of liquid and gas flow rate but the main mechanism in the cuttings transport is the liquid phase flow.

6.3. Three Phase Flow Experiment Results (Polymerized Water + Air + Cuttings)

Three-phase flow experiments were conducted by 0.07% PHPA, with 8 different liquid and gas flow rates. It was observed that the cuttings area is decreasing with the increase of liquid and gas flow rates but the main mechanism in the cuttings transport is the liquid phase flow.

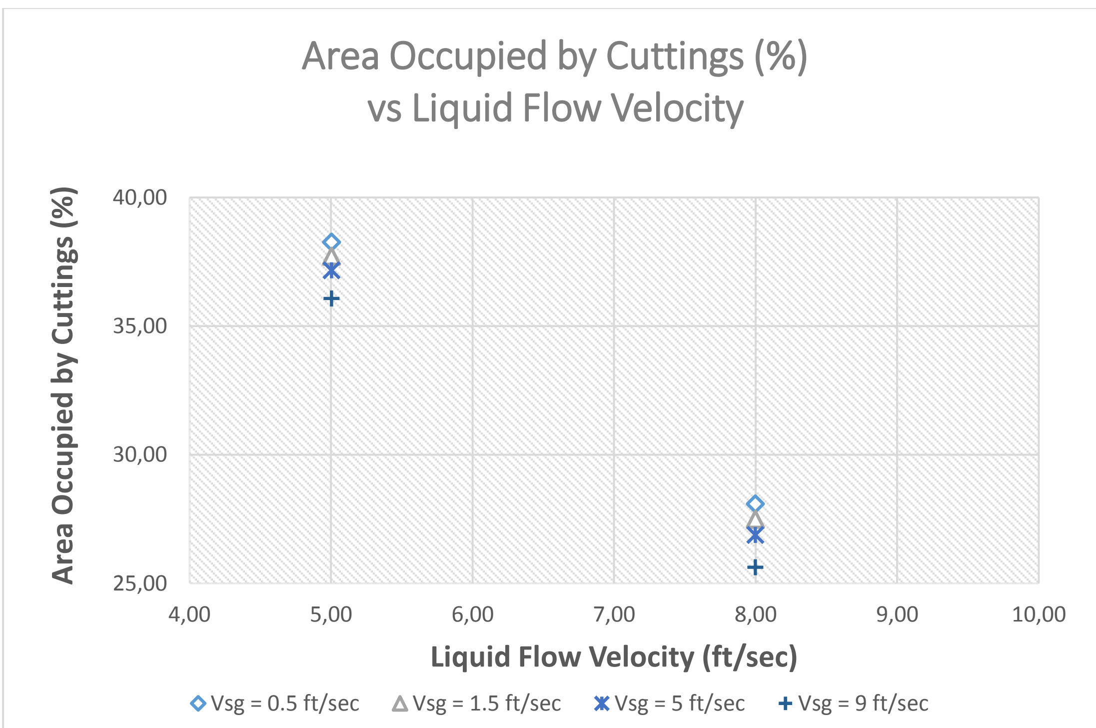

Figure 57. Area Occupied by Cuttings (%) vs Liquid Flow Velocity - Polymerized Water Case

Table 12. Drag Reduction with Polymerized Water

			Differential Pressure with ROP = 115 ft./hr.		
#	**Water Flow Rate (gpm)**	**Gas Flow Rate (L/min)**	**Water Experiments [psi]**	**PHPA Polymer Experiments - 0.07% [psi]**	**Drag Reduction (%)**
1	61.8	23.5	0.944	0.695	26.38
2	98.8	23.5	1.033	0.777	24.78
3	61.8	70.3	0.956	0.732	23.43
4	98.8	70.3	1.053	0.815	22.60
5	61.8	234	0.951	0.750	21.14
6	98.8	234	1.156	0.866	25.09
7	61.8	421	0.998	0.766	23.25
8	98.8	421	1.212	0.915	24.50
				AVERAGE	**23.90**

Differential pressure losses in the experimental set up with the rate of penetration value of 115 ft./hr. have been compared as shown in Table 12. The drag reduction was 23.90% in average with the existence of cuttings. The maximum drag reduction was observed in data point #6 as 25.09% and the minimum drag reduction was observed in data point #5 as 21.14%.

It was expected to observe higher drag reductions in higher liquid flow rates, but in some data points, degradation happened in the polymers, therefore lessening the effect of polymer in higher liquid and gas flow rates.

Table 13. Cuttings Area Reduction with Polymerized Water

#	VsL (ft./sec)	Vsg (ft./sec)	Flow Pattern	Area Occupied by Cuttings (%)		
				Water Experiments	**PHPA Polymer Experiment**	**Cuttings Area Reduction (%)**
1	5.00	0.50	Bubble	41.48	38.25	3.23
2	8.00	0.50	Bubble	32.73	28.09	4.65
3	5.00	1.50	Elongated Bubble	40.95	37.71	3.23
4	8.00	1.50	Elongated Bubble	32.17	27.48	4.68
5	5.00	5.00	Slug	40.41	37.17	3.24
6	8.00	5.00	Slug	31.60	26.87	4.73
7	5.00	9.00	Wavy Annular	39.87	36.07	3.80
8	8.00	9.00	Wavy Annular	30.45	25.62	4.82
					AVERAGE	**4.05**

The effect of 0.07% PHPA Polymers in Cuttings Area Reduction has been investigated as in Table 13. In average, using PHPA Polymers of 0.07% have resulted in 4.05% cuttings area reduction with the maximum value of 4.73% at data point #6 and the minimum value of 3.23 at data points #1 and #3. It was also observed that increasing gas and liquid flow rates decreases the cuttings area in each flow regime.

Table 14. Comparison of Cuttings Area Reduction, Drag Reduction and Cuttings Bed Height Reduction with 0.07% PHPA

#	VsL (ft/sec)	Vsg (ft/sec)	Cuttings Area Reduction (%)	Drag Reduction (%)	Cuttings Bed Height Reduction (%)
1	5,00	0,50	3,23	26,38	10,01
2	8,00	0,50	4,65	24,78	16,49
3	5,00	1,50	3,23	23,43	10,14
4	8,00	1,50	4,68	22,60	16,73
5	5,00	5,00	3,24	21,14	10,28
6	8,00	5,00	4,73	25,09	16,97
7	5,00	9,00	3,80	23,25	12,13
8	8,00	9,00	4,82	24,50	17,46
Average			**4,05**	**23,90**	**13,78**

Comparing all the data of cuttings transport experiments with 0.07% PHPA (ROP= 115 ft./hr.), it was observed that in average 4.05% of cuttings area reduction can be achieved with 23.90% drag reduction and 13.78% cuttings bed height reduction.

6.4 Three Phase Flow Experiments Repeatability Analysis

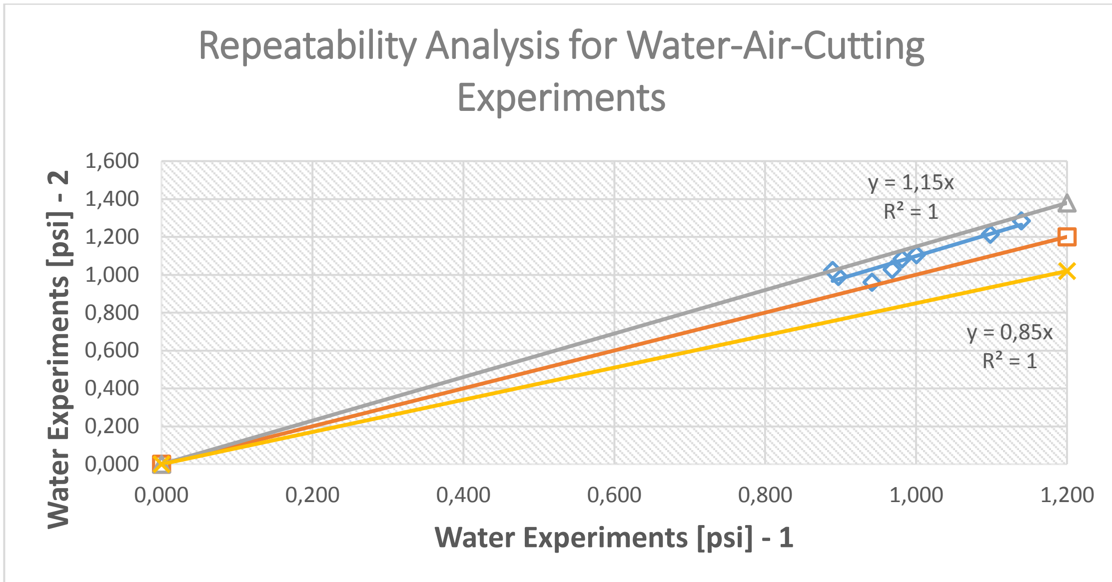

Figure 58. Repeatability Analysis for Water-Air-Cutting Experiments

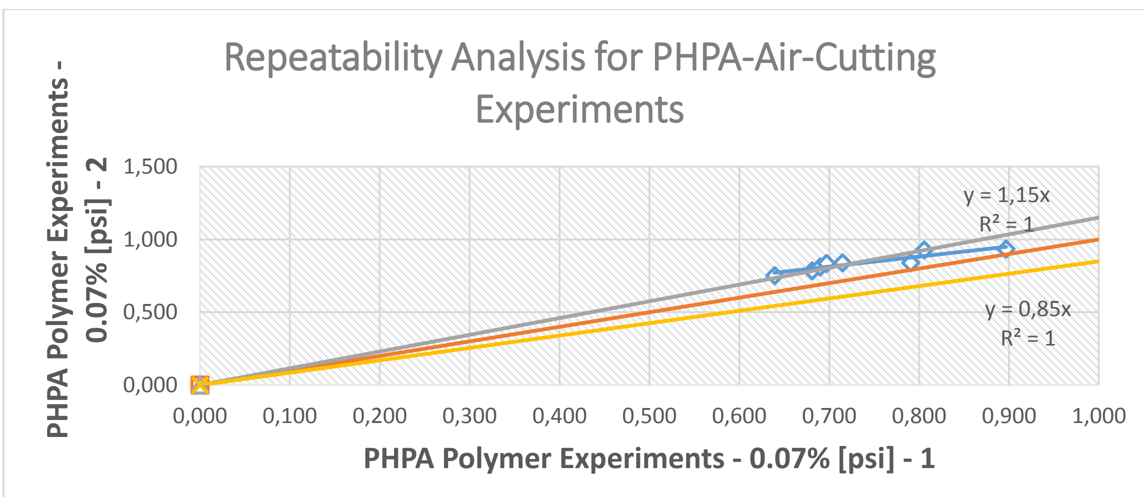

Figure 59. Repeatability Analysis for PHP-Air-Cutting Experiments

The grey line has the equation of y=1.15x and yellow line is y=0.85x giving the 15% error margin for the experiments. It was observed that all the data is accurate within %15 percent of experimental error. The data lies above the y=x line because of cuttings in the system.

CHAPTER VII

CONCLUSIONS

An extensive amount of experiments has been conducted to evaluate the effects of different flow regimes in horizontal wellbores during underbalanced drilling operations. Water and air flow rates have been differentiated to obtain the flow regimes and the effects of these different flow rates in cutting transport for the rate of penetration value of 115 ft./hr. have been investigated. Moreover, as an addition to aerated drilling fluids, 0.07% PHPA copolymers which are the obtained optimum concentration in a single phase, have also been introduced in the experiments. This thesis is currently the only work in the literature which takes account the effects of PHPA copolymers in aerated drilling fluids in horizontal wellbores.

In the beginning phase, the experiments were conducted with water only to evaluate the relative roughness of the wellbore. The average relative roughness of the horizontal wellbore was obtained as 0.0063.

Afterward, the air was introduced to the system to obtain the flow regime map for the test section. There were 4 main flow regimes observed which were bubble, elongated bubble, slug and wavy annular flow regimes. It was also observed that the differential pressure losses increase with the increase in liquid and gas flow rates.

Then, PHPA copolymers were introduced into the single-phase flow system to obtain the optimum concentration of PHPA in the test section. Experiments were done with 0.05%, 0.07%, and 0.10% polymer concentrations and it was observed that the best results were obtained with 0.07% with an average of 41.88% drag reduction in the system. Therefore, the value of polymer concentration for the following experiments was set at this value.

In the fourth stage, two-phase flow experiments were conducted with the addition of 0.07% PHPA copolymers to understand the effects of polymers into the flow regime map. It was observed that the flow regime transition lines are drawn from a higher y value in the transition from bubble to elongated bubble and from slug to wavy annular flows and stays the same in the transition from elongated bubble to slug flow regime when there exist PHPA polymers (0.07% in concentration) in the system. Moreover, it was observed that 40.77% average drag reduction was obtained using 0.07% PHPA copolymers during two-phase flow in the horizontal test section.

In the last phase of the experimental work, the rate of penetration was set as 115 ft./hr. using the motor system in the cuttings injection tank. Experiments were conducted with previously determined eight data points with and without PHPA copolymers. Using PHPA polymers in 0.07% concentration reduced the cuttings area by an average of %4.05 while reducing the differential pressure losses by an average of %23.90 with the existence of cuttings.

Therefore, PHPA copolymers were observed to be effective in both cuttings transport and drag reduction in the provided test section in the horizontal situation.

CHAPTER VIII

RECOMMENDATIONS FOR FURTHER STUDY

The only parameters changed during the experiments were liquid and gas flow rates and the PHPA concentrations. Therefore, to understand the main mechanism of PHPA polymers in annulus test sections, different pipe diameters and sizes in different operational parameters (ROP, RPM, Flow Rates, Polymer Concentrations, Cutting Types and Sizes, etc.) should be studied.

The effects of borehole pressure and temperature have not been investigated in the thesis work. These effects should also be studied to understand the mechanisms in HPHT wells.

Throughout the thesis work, there were many modifications done in the experimental setup. Many valves and piping systems have been modified to be more effective and time-saving. But, for the experimental errors in measurements, there should be cable protection systems and well-calibrated measurement tools used inside the laboratory.

Moreover, the polymers were mixed by pouring them from the top of the water tank and mixing for hours. To have better polymer mix, hopper system should be constructed and installed to the experimental set-up

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APPENDIX

RESULTS OF THE EXPERIMENTS

Water Phase Flow Experiment Results

Table 15. Water Phase Flow Experiment Results

Water Flow Rate (gpm)	Differential Pressure (Honeywell), psi
49.113	0.621
51.325	0.625
54.855	0.635
66.044	0.677
73.918	0.692
75.930	0.713
78.622	0.730
81.502	0.736
84.574	0.754
85.361	0.755
87.382	0.761
99.783	0.766
101.955	0.777
107.847	0.815
110.804	0.831

Air – Water Two-Phase Flow Experiment Results

Table 16. Air Water Two-Phase Flow Experiment Results

Water Flow Rate (gpm)	Gas Flow Rate (L/min)	Differential Pressure (Honeywell)	Differential Pressure (Honeywell) - 1	Differential Pressure (Honeywell) - 2
48.9189	290.5432	0.6442	0.6442	0.6442
49.0519	50.2971	0.6709	0.6575	0.6846
49.2170	59.2623	0.6670	0.6803	0.6539
49.2647	69.8238	0.6623	0.6623	0.6623
49.9741	299.3992	0.6616	0.6748	0.6486
50.0517	89.1894	0.6611	0.6611	0.6611
50.0990	190.4846	0.6409	0.6217	0.6607
50.3444	200.1235	0.6516	0.6581	0.6451
50.3882	97.3295	0.6620	0.6620	0.6620
50.8297	110.3738	0.6584	0.6716	0.6455
51.1109	224.3017	0.6529	0.6725	0.6339
51.3072	119.6631	0.6560	0.6363	0.6762
51.3111	129.2223	0.6617	0.6419	0.6822
51.3250	0.0000	0.6246	0.6433	0.6064
51.5711	306.5179	0.6692	0.6826	0.6561
51.7466	151.6939	0.6593	0.6593	0.6593
52.1968	250.2745	0.6583	0.6780	0.6391
52.2525	307.5690	0.6895	0.6826	0.6965
52.6634	15.2062	0.6283	0.6095	0.6478
52.8107	268.6584	0.6719	0.6786	0.6652
53.6569	303.2420	0.6796	0.6999	0.6598
53.9952	159.8436	0.6776	0.6709	0.6845
54.1507	19.3827	0.6827	0.6758	0.6896
54.8553	0.0000	0.6352	0.6415	0.6289
55.2683	24.8884	0.7038	0.7249	0.6833
55.3143	315.7519	0.7105	0.6892	0.7325
55.3172	273.7594	0.7048	0.6837	0.7266
55.9380	30.5759	0.7031	0.6891	0.7175
56.0522	38.3662	0.6970	0.6901	0.7041

Table 16. (continued)

Water Flow Rate (gpm)	Gas Flow Rate (L/min)	Differential Pressure (Honeywell)	Differential Pressure (Honeywell) - 1	Differential Pressure (Honeywell) - 2
59.1634	297.4332	0.7266	0.7411	0.7123
59.6460	118.0902	0.7140	0.7211	0.7069
59.7689	303.8777	0.7375	0.7227	0.7525
59.8046	21.6172	0.7173	0.7101	0.7245
59.8538	140.6449	0.7141	0.6998	0.7286
59.9703	160.4173	0.7139	0.7282	0.6999
60.0254	24.9625	0.7206	0.7422	0.6996
60.1558	28.2953	0.7200	0.7056	0.7347
60.2261	353.1019	0.7665	0.7818	0.7515
60.3276	179.2794	0.7213	0.7358	0.7072
60.4018	33.6422	0.7120	0.6977	0.7265
60.4151	38.2751	0.7130	0.7272	0.6990
60.4418	199.9695	0.7181	0.7109	0.7253
60.5408	43.5267	0.7102	0.7031	0.7174
60.8113	229.7273	0.7269	0.7269	0.7269
60.8407	219.7920	0.7240	0.7095	0.7387
60.8518	63.1751	0.7167	0.7311	0.7027
60.9597	79.1502	0.7194	0.7194	0.7194
60.9658	236.8692	0.7305	0.7232	0.7379
61.0779	89.6633	0.7166	0.7310	0.7026
61.1664	252.1797	0.7387	0.7608	0.7172
61.3139	110.6691	0.7207	0.7352	0.7066
61.6389	270.1135	0.7428	0.7651	0.7211
61.6479	128.6532	0.7246	0.7319	0.7175
61.7595	150.0612	0.7261	0.7116	0.7409
62.0273	280.5690	0.7585	0.7585	0.7585
62.5771	323.5117	0.7755	0.7832	0.7678
64.5868	298.3271	0.7645	0.7798	0.7495
64.8773	308.6433	0.7696	0.7542	0.7853
64.9357	25.1504	0.7498	0.7723	0.7280
65.1761	34.5209	0.7480	0.7705	0.7262
65.2131	29.6102	0.7347	0.7127	0.7574
65.2174	292.5537	0.7737	0.7969	0.7512
65.4597	50.3830	0.7419	0.7270	0.7570
65.4953	149.6510	0.7499	0.7274	0.7731
65.5596	40.0561	0.7320	0.7540	0.7107

Table 16. (continued)

Water Flow Rate (gpm)	Gas Flow Rate (L/min)	Differential Pressure (Honeywell)	Differential Pressure (Honeywell) - 1	Differential Pressure (Honeywell) - 2
65.7338	167.9507	0.7575	0.7726	0.7426
65.7431	66.6759	0.7440	0.7291	0.7592
65.8341	80.6472	0.7537	0.7386	0.7691
65.9798	198.3662	0.7593	0.7821	0.7372
66.0438	0.0000	0.6774	0.6571	0.6984
66.1299	295.2120	0.7801	0.7879	0.7724
66.1523	92.0086	0.7507	0.7432	0.7583
66.2365	219.8026	0.7674	0.7521	0.7831
66.2434	104.1581	0.7544	0.7544	0.7544
66.2652	318.7584	0.7874	0.8110	0.7645
66.3438	122.8147	0.7599	0.7447	0.7754
66.7556	157.0365	0.7665	0.7588	0.7742
66.8887	259.8871	0.7716	0.7639	0.7794
67.5629	215.4399	0.7743	0.7820	0.7666
68.8156	153.5678	0.7790	0.7946	0.7637
70.7466	49.8835	0.7232	0.7232	0.7232
70.9961	71.5522	0.7350	0.7570	0.7136
71.1275	79.2584	0.7355	0.7281	0.7429
71.1652	60.0370	0.7278	0.7424	0.7135
71.1729	88.0435	0.7839	0.7760	0.7918
71.1729	88.0435	0.7839	0.7996	0.7685
71.1747	109.0853	0.7914	0.7835	0.7994
71.2342	290.0308	0.8117	0.7954	0.8282
71.2370	177.7606	0.8024	0.7944	0.8105
71.3375	89.6599	0.7386	0.7386	0.7386
71.3467	189.4178	0.8046	0.7885	0.8210
71.4050	24.9098	0.7599	0.7751	0.7450
71.4138	16.8578	0.7243	0.7243	0.7243
71.4322	99.9720	0.7876	0.7640	0.8120
71.4322	99.9720	0.7876	0.8113	0.7647
71.4326	131.1758	0.8048	0.7887	0.8212
71.4878	198.9626	0.8078	0.8240	0.7920
71.5406	168.2933	0.8007	0.7767	0.8255
71.5466	20.6116	0.7549	0.7474	0.7625
71.6000	23.3645	0.7592	0.7516	0.7669
71.6420	31.7322	0.7651	0.7880	0.7428

Table 16. (continued)

Water Flow Rate (gpm)	Gas Flow Rate (L/min)	Differential Pressure (Honeywell)	Differential Pressure (Honeywell) - 1	Differential Pressure (Honeywell) - 2
71.6828	101.3320	0.7437	0.7363	0.7512
71.7081	232.7786	0.8076	0.8318	0.7841
71.8003	27.1466	0.7607	0.7531	0.7684
71.8091	148.9248	0.8058	0.8058	0.8058
71.8386	170.1270	0.8156	0.8238	0.8075
71.8763	150.9258	0.7580	0.7732	0.7432
71.9153	40.1796	0.7714	0.7637	0.7792
71.9417	120.6928	0.7478	0.7628	0.7331
71.9604	158.6150	0.7579	0.7428	0.7734
71.9760	126.4923	0.7532	0.7607	0.7457
71.9864	139.0234	0.7545	0.7696	0.7397
71.9897	187.9769	0.8080	0.8323	0.7845
72.1115	300.7877	0.8118	0.8037	0.8200
72.1383	50.2757	0.7753	0.7753	0.7753
72.2640	258.6713	0.8185	0.8021	0.8352
72.2674	248.4364	0.8170	0.8416	0.7932
72.2798	59.9417	0.7841	0.7684	0.8001
72.3028	21.5817	0.7156	0.6941	0.7377
72.3495	179.6890	0.7630	0.7554	0.7707
72.3799	78.5822	0.7926	0.8164	0.7695
72.5431	97.8819	0.7988	0.8068	0.7909
72.5500	23.0833	0.7187	0.7187	0.7187
72.6048	207.9742	0.7712	0.7634	0.7789
72.6324	119.7449	0.8042	0.8122	0.7962
72.6605	40.6423	0.7269	0.7342	0.7197
72.6925	269.0392	0.8215	0.7969	0.8469
72.6927	89.2915	0.7958	0.7958	0.7958
72.7114	277.7776	0.8314	0.8480	0.8151
72.7599	26.6717	0.7159	0.7231	0.7088
72.7699	129.6730	0.8072	0.7911	0.8237
72.8070	31.2478	0.7175	0.7175	0.7175
72.8203	223.5884	0.7792	0.7870	0.7715
72.9086	60.1728	0.7427	0.7278	0.7578
72.9098	137.5273	0.8134	0.8297	0.7975
72.9770	150.0695	0.8147	0.8391	0.7910
73.0182	50.2082	0.7356	0.7209	0.7506

Table 16. (continued)

Water Flow Rate (gpm)	Gas Flow Rate (L/min)	Differential Pressure (Honeywell)	Differential Pressure (Honeywell) - 1	Differential Pressure (Honeywell) - 2
73.1382	24.9066	0.7178	0.7106	0.7250
73.9182	0.0000	0.6923	0.6715	0.7137
75.1126	290.5717	0.8123	0.8204	0.8042
75.3046	229.9150	0.8138	0.8057	0.8220
75.3329	217.2815	0.8114	0.8114	0.8114
75.3394	30.5523	0.7604	0.7376	0.7839
75.5272	270.6799	0.8304	0.8138	0.8473
75.5413	34.6311	0.7636	0.7865	0.7413
75.6012	251.8995	0.8138	0.7975	0.8304
75.6252	260.0431	0.8206	0.8206	0.8206
75.7909	237.9681	0.8200	0.8036	0.8367
75.8104	41.8159	0.7704	0.7704	0.7704
75.8190	52.0601	0.7746	0.7823	0.7669
75.8354	60.8011	0.7790	0.7635	0.7949
75.9300	0.0000	0.7127	0.7056	0.7199
75.9459	22.1010	0.7421	0.7495	0.7348
75.9484	279.8120	0.8289	0.8123	0.8458
75.9762	69.8745	0.7826	0.7982	0.7672
76.0249	303.4086	0.8107	0.8269	0.7948
76.0454	20.3156	0.7434	0.7657	0.7218
76.0879	78.6211	0.7862	0.7862	0.7862
76.0946	35.7937	0.7642	0.7565	0.7719
76.1133	125.7615	0.8025	0.8185	0.7867
76.1878	289.9520	0.8328	0.8578	0.8086
76.2692	100.0393	0.7973	0.7973	0.7973
76.3134	25.0122	0.7557	0.7557	0.7557
76.3159	88.1772	0.7909	0.7671	0.8153
76.3183	120.4775	0.8045	0.8206	0.7888
76.4366	110.8545	0.8019	0.8100	0.7940
76.4518	30.1388	0.7592	0.7667	0.7516
76.4740	147.5102	0.8064	0.8225	0.7906
76.5540	160.8694	0.8142	0.8386	0.7905
76.5954	310.3438	0.8351	0.8434	0.8268
76.5979	40.5711	0.7677	0.7524	0.7834
76.6233	50.0319	0.7750	0.7750	0.7750
76.6877	139.3351	0.8055	0.8216	0.7897

Table 16. (continued)

Water Flow Rate (gpm)	Gas Flow Rate (L/min)	Differential Pressure (Honeywell)	Differential Pressure (Honeywell) - 1	Differential Pressure (Honeywell) - 2
76.8341	109.9729	0.8006	0.8006	0.8006
76.8352	59.4292	0.7773	0.7540	0.8014
76.9064	98.1356	0.7956	0.7717	0.8202
76.9282	179.2329	0.8176	0.8422	0.7938
77.0131	119.9969	0.8039	0.8281	0.7805
77.1414	78.0915	0.7885	0.7806	0.7965
77.1448	189.6789	0.8269	0.8104	0.8438
77.2045	70.3202	0.7848	0.7926	0.7770
77.2326	208.9748	0.8240	0.8240	0.8240
77.2951	321.1413	0.8428	0.8344	0.8513
77.3497	220.2721	0.8287	0.8370	0.8205
77.5165	159.2263	0.8155	0.7910	0.8407
77.7996	176.4621	0.8313	0.8313	0.8313
78.0375	17.1055	0.7304	0.7450	0.7161
78.6224	0.0000	0.7299	0.7518	0.7087
79.5957	281.6823	0.8401	0.8401	0.8401
79.8122	290.1107	0.8529	0.8444	0.8616
80.0471	108.9291	0.8095	0.8175	0.8014
80.1044	119.4626	0.8159	0.8159	0.8159
80.1905	140.0234	0.8205	0.8123	0.8287
80.2150	190.0057	0.8391	0.8140	0.8651
80.2480	159.5285	0.8306	0.8389	0.8223
80.3819	303.3775	0.8539	0.8539	0.8539
80.3987	128.3941	0.8187	0.8106	0.8270
80.4850	25.0941	0.7568	0.7492	0.7644
80.4899	23.0257	0.7601	0.7601	0.7601
80.5318	219.8813	0.8380	0.8548	0.8216
80.5642	180.2967	0.8370	0.8202	0.8541
80.5645	36.0990	0.7762	0.7685	0.7841
80.5887	27.3182	0.7686	0.7686	0.7686
80.6667	63.0454	0.7917	0.8076	0.7762
80.7691	41.4166	0.7729	0.7806	0.7652
80.8260	209.8187	0.8419	0.8167	0.8680
80.8592	54.0339	0.7903	0.7666	0.8147
80.9330	70.7167	0.7992	0.7992	0.7992
80.9848	31.2226	0.7456	0.7232	0.7686

Table 16. (continued)

Water Flow Rate (gpm)	Gas Flow Rate (L/min)	Differential Pressure (Honeywell)	Differential Pressure (Honeywell) - 1	Differential Pressure (Honeywell) - 2
81.0305	240.2951	0.8451	0.8451	0.8451
81.0480	248.5600	0.8496	0.8496	0.8496
81.0744	268.4865	0.8569	0.8740	0.8401
81.0952	260.5424	0.8569	0.8741	0.8401
81.0983	90.9499	0.8100	0.8100	0.8100
81.1473	100.6376	0.8149	0.8231	0.8069
81.2521	139.5560	0.8267	0.8433	0.8105
81.2529	79.7775	0.8061	0.8222	0.7903
81.3597	158.7454	0.8304	0.8387	0.8222
81.4364	118.5000	0.8225	0.8307	0.8143
81.5023	0.0000	0.7363	0.7584	0.7149
81.5436	21.3769	0.7574	0.7422	0.7728
81.5548	17.7138	0.7405	0.7553	0.7260
81.6588	25.5720	0.7720	0.7643	0.7798
81.7349	176.7409	0.8356	0.8607	0.8113
81.8380	198.9710	0.8387	0.8303	0.8471
81.9535	30.4551	0.7761	0.7916	0.7609
82.2540	39.1118	0.7862	0.7862	0.7862
82.4631	16.9943	0.7420	0.7420	0.7420
82.6181	60.3042	0.8035	0.7794	0.8284
82.6440	49.8632	0.7973	0.7894	0.8054
82.8456	66.4106	0.8043	0.7882	0.8207
83.9471	229.4066	0.8732	0.8732	0.8732
83.9928	290.4705	0.8805	0.8893	0.8718
84.1890	296.6114	0.8963	0.9232	0.8702
84.2799	218.5859	0.8719	0.8980	0.8465
84.5532	239.0774	0.8761	0.8498	0.9032
84.5738	0.0000	0.7541	0.7617	0.7466
84.6126	79.9435	0.8238	0.8403	0.8076
84.6604	260.3218	0.8761	0.8937	0.8590
84.7974	90.0079	0.8310	0.8393	0.8228
84.8274	270.4750	0.8900	0.8900	0.8900
84.8857	170.8826	0.8634	0.8461	0.8810
84.9769	149.2281	0.8523	0.8438	0.8609
85.0244	139.8309	0.8543	0.8372	0.8717
85.0342	178.9060	0.8698	0.8698	0.8698

Table 16. (continued)

Water Flow Rate (gpm)	Gas Flow Rate (L/min)	Differential Pressure (Honeywell)	Differential Pressure (Honeywell) - 1	Differential Pressure (Honeywell) - 2
85.0820	107.3062	0.8381	0.8549	0.8217
85.1156	280.1266	0.8969	0.9149	0.8793
85.1670	25.4201	0.7867	0.7788	0.7946
85.1753	20.7739	0.7711	0.7480	0.7950
85.1781	129.7951	0.8475	0.8475	0.8475
85.1952	196.0184	0.8693	0.8867	0.8522
85.2231	188.9812	0.8682	0.8943	0.8429
85.2244	27.4733	0.7909	0.7830	0.7989
85.2775	39.8687	0.8090	0.8333	0.7855
85.3284	293.6885	0.8949	0.8770	0.9132
85.3360	207.0481	0.8736	0.8911	0.8565
85.3377	159.3165	0.8589	0.8675	0.8504
85.3611	0.0000	0.7554	0.7479	0.7631
85.3687	34.4061	0.8027	0.7866	0.8191
85.4337	43.4302	0.8126	0.7882	0.8378
85.4469	30.7389	0.7979	0.7819	0.8142
85.4736	57.6134	0.8229	0.7983	0.8484
85.5147	23.6156	0.7799	0.7877	0.7722
85.5383	50.2724	0.8196	0.8196	0.8196
85.5515	229.6288	0.8787	0.8787	0.8787
85.8746	259.8731	0.8898	0.9075	0.8723
85.8772	301.8752	0.8980	0.8710	0.9257
86.0113	250.1801	0.8850	0.8850	0.8850
86.0321	270.6719	0.8995	0.8815	0.9178
86.2453	308.3548	0.9124	0.9397	0.8858
86.4464	280.3223	0.8996	0.8816	0.9179
86.5404	288.3885	0.9104	0.9286	0.8925
86.5684	22.2975	0.7992	0.7752	0.8239
86.6118	21.5107	0.7801	0.7723	0.7880
86.8766	33.8665	0.8143	0.8062	0.8226
86.8808	25.2024	0.7887	0.7887	0.7887
86.9568	58.9849	0.8296	0.8048	0.8553
86.9689	30.3904	0.8203	0.8203	0.8203
86.9946	49.8701	0.8222	0.8058	0.8390
87.1896	40.3259	0.8108	0.8351	0.7872
87.2588	68.3166	0.8297	0.8546	0.8055

Table 16. (continued)

Water Flow Rate (gpm)	Gas Flow Rate (L/min)	Differential Pressure (Honeywell)	Differential Pressure (Honeywell) - 1	Differential Pressure (Honeywell) - 2
87.3818	0.0000	0.7613	0.7841	0.7391
88.1800	282.0164	0.9042	0.9223	0.8865
88.2911	303.6529	0.8944	0.8765	0.9127
88.4347	260.3947	0.8989	0.9259	0.8728
88.4520	229.1217	0.8974	0.9064	0.8885
88.5433	238.9298	0.8960	0.8692	0.9237
88.6687	310.6291	0.9114	0.9114	0.9114
88.6709	248.2318	0.9023	0.9114	0.8934
88.7220	269.9979	0.9096	0.8914	0.9281
88.9114	40.2700	0.8118	0.8200	0.8038
88.9931	279.6524	0.9019	0.8748	0.9298
89.0030	290.5002	0.9176	0.8901	0.9460
89.0176	59.1642	0.8351	0.8601	0.8108
89.1117	44.0026	0.8211	0.8293	0.8129
89.1938	50.3962	0.8264	0.8182	0.8348
89.2054	97.9670	0.8559	0.8303	0.8824
89.2420	69.9444	0.8408	0.8156	0.8668
89.2862	79.3299	0.8454	0.8708	0.8208
89.2937	108.6950	0.8604	0.8518	0.8691
89.3451	178.8691	0.8915	0.9182	0.8655
89.3939	160.6951	0.8830	0.8918	0.8742
89.3939	169.4284	0.8793	0.8881	0.8706
89.4132	89.6771	0.8521	0.8606	0.8437
89.4213	300.2046	0.9178	0.9086	0.9271
89.4485	150.5440	0.8751	0.8663	0.8839
89.4553	138.2500	0.8753	0.8841	0.8667
89.4627	128.8888	0.8732	0.8470	0.9002
89.6188	121.4526	0.8683	0.8422	0.8951
89.7526	307.2428	0.9198	0.9198	0.9198
89.7577	189.8573	0.8900	0.9078	0.8726
89.7730	226.8910	0.9011	0.9011	0.9011
89.7760	218.8574	0.8992	0.8812	0.9176
89.9995	199.4880	0.8958	0.8868	0.9048
90.0796	241.0974	0.9043	0.9314	0.8780
90.7523	25.1053	0.7969	0.8208	0.7737
90.7857	22.9408	0.7972	0.7972	0.7972

Table 16. (continued)

Water Flow Rate (gpm)	Gas Flow Rate (L/min)	Differential Pressure (Honeywell)	Differential Pressure (Honeywell) - 1	Differential Pressure (Honeywell) - 2
90.8676	57.6443	0.8480	0.8311	0.8653
90.9151	30.5350	0.8155	0.8155	0.8155
90.9317	49.6586	0.8340	0.8090	0.8598
90.9791	39.7964	0.8264	0.8182	0.8348
91.7489	16.9958	0.7910	0.8068	0.7755
91.8547	273.3850	0.9286	0.9286	0.9286
92.0931	209.4709	0.9166	0.9166	0.9166
92.1275	228.8335	0.9164	0.8889	0.9447
92.2001	199.9568	0.9078	0.9169	0.8988
92.2603	219.5212	0.9136	0.8953	0.9323
92.3008	297.0100	0.9262	0.9447	0.9080
92.3421	289.6329	0.9275	0.9275	0.9275
92.3778	218.4711	0.9292	0.9107	0.9482
92.6261	247.9886	0.9239	0.9147	0.9332
92.6354	260.2443	0.9303	0.9489	0.9120
92.7515	269.5317	0.9288	0.9102	0.9477
92.7948	305.6263	0.9425	0.9425	0.9425
93.0762	44.9195	0.8521	0.8436	0.8607
93.0977	279.2940	0.9349	0.9162	0.9540
93.2409	35.4693	0.8572	0.8486	0.8659
93.3419	39.4631	0.8590	0.8418	0.8765
93.3750	51.1636	0.8456	0.8625	0.8290
93.3766	59.5654	0.8511	0.8255	0.8774
93.4062	30.4544	0.8557	0.8300	0.8821
93.4938	25.3795	0.8173	0.8255	0.8093
93.4951	90.9581	0.8756	0.8931	0.8585
93.5596	54.3159	0.8549	0.8463	0.8635
93.5901	104.4112	0.8816	0.8551	0.9089
93.6409	100.0188	0.8796	0.8971	0.8623
93.6432	128.4539	0.8943	0.9033	0.8855
93.6533	80.4951	0.8647	0.8820	0.8478
93.6645	70.5108	0.8598	0.8512	0.8685
93.6698	178.0307	0.9123	0.9031	0.9215
93.7570	159.8898	0.9037	0.8856	0.9221
93.7641	139.8221	0.8982	0.8802	0.9165
93.7878	150.0070	0.9072	0.9072	0.9072

Table 16. (continued)

Water Flow Rate (gpm)	Gas Flow Rate (L/min)	Differential Pressure (Honeywell)	Differential Pressure (Honeywell) - 1	Differential Pressure (Honeywell) - 2
93.7878	118.8851	0.8894	0.8627	0.9169
93.8671	206.5918	0.9226	0.9226	0.9226
93.8866	170.1600	0.9091	0.9364	0.8827
94.0862	197.3393	0.9196	0.9288	0.9105
94.2796	236.3922	0.9366	0.9646	0.9093
94.3473	309.2326	0.9615	0.9904	0.9335
94.3667	249.3661	0.9377	0.9283	0.9472
94.4630	228.7193	0.9317	0.9503	0.9134
94.8076	38.1702	0.8435	0.8435	0.8435
94.8820	21.1512	0.8270	0.8104	0.8438
94.9294	24.8017	0.8343	0.8343	0.8343
94.9379	95.5899	0.8913	0.9180	0.8653
94.9395	26.5285	0.8183	0.8101	0.8266
95.0053	22.8558	0.8107	0.7864	0.8358
95.0252	30.0418	0.8278	0.8361	0.8196
95.0502	23.9173	0.8081	0.7919	0.8246
95.0546	69.3025	0.8726	0.8552	0.8904
95.1647	51.1751	0.8588	0.8417	0.8764
95.1839	116.0405	0.9008	0.8918	0.9099
95.1929	86.7114	0.8837	0.8749	0.8926
95.2828	59.6575	0.8664	0.8490	0.8841
98.6134	34.9893	0.7834	0.8069	0.7605
98.8774	368.1353	0.9803	0.9901	0.9706
99.6427	239.5477	0.9201	0.9109	0.9293
99.7342	259.9954	0.9310	0.9123	0.9500
99.7833	0.0000	0.7660	0.7813	0.7509
100.0773	270.1374	0.9383	0.9383	0.9383
100.2649	287.5383	0.9519	0.9329	0.9714
100.3220	280.6801	0.9460	0.9460	0.9460
100.5761	103.2306	0.8685	0.8859	0.8515
100.6704	69.8948	0.8457	0.8203	0.8718
100.7758	80.2764	0.8577	0.8491	0.8663
100.8495	174.7890	0.9117	0.8935	0.9303
100.8683	90.6243	0.8615	0.8615	0.8615
100.9150	147.9812	0.8942	0.8942	0.8942
100.9410	134.0375	0.8895	0.8806	0.8985

Table 16. (continued)

Water Flow Rate (gpm)	Gas Flow Rate (L/min)	Differential Pressure (Honeywell)	Differential Pressure (Honeywell) - 1	Differential Pressure (Honeywell) - 2
100.9412	120.0077	0.8769	0.8681	0.8857
100.9420	163.4614	0.9039	0.8949	0.9130
101.0641	371.9165	0.9921	0.9921	0.9921
101.1985	313.4790	0.9676	0.9386	0.9976
101.2535	209.0050	0.9287	0.9473	0.9105
101.3255	188.1720	0.9155	0.8880	0.9438
101.3965	220.3103	0.9298	0.9112	0.9488
101.4760	39.9653	0.8456	0.8371	0.8541
101.5529	234.2436	0.9347	0.9347	0.9347
101.6969	49.4140	0.8328	0.8495	0.8165
101.7817	30.8824	0.7982	0.7742	0.8229
101.8390	254.3246	0.9420	0.9326	0.9515
101.8392	59.9158	0.8451	0.8367	0.8537
101.8585	20.9806	0.7948	0.7948	0.7948
101.8799	22.8615	0.8007	0.7927	0.8088
101.8941	25.5642	0.8098	0.8179	0.8018
101.9372	267.7734	0.9535	0.9630	0.9441
101.9545	0.0000	0.7772	0.7928	0.7620
101.9691	109.5299	0.8823	0.8911	0.8736
102.0198	90.0284	0.8724	0.8636	0.8812
102.2512	156.3912	0.9098	0.8916	0.9283
102.2868	129.1923	0.8980	0.8980	0.8980
102.3805	70.4076	0.8610	0.8610	0.8610
103.1389	81.9719	0.8735	0.8473	0.9005
103.3992	248.1092	0.9522	0.9617	0.9427
103.7028	259.4741	0.9609	0.9513	0.9706
104.1934	266.3311	0.9624	0.9336	0.9922
104.3156	286.8124	0.9731	0.9439	1.0032
104.3399	280.3394	0.9700	0.9991	0.9417
104.3421	70.5166	0.8755	0.8492	0.9025
104.5075	302.4308	0.9886	1.0084	0.9693
104.5826	89.2474	0.8849	0.9115	0.8591
104.6022	119.1872	0.9050	0.9141	0.8961
104.6195	99.7429	0.8957	0.8957	0.8957
104.7029	168.8267	0.9373	0.9091	0.9662
104.7282	108.4228	0.9035	0.9035	0.9035

Table 16. (continued)

Water Flow Rate (gpm)	Gas Flow Rate (L/min)	Differential Pressure (Honeywell)	Differential Pressure (Honeywell) - 1	Differential Pressure (Honeywell) - 2
104.7345	146.7639	0.9261	0.9168	0.9354
104.7727	129.5333	0.9137	0.9411	0.8871
104.8924	80.1225	0.8819	0.8555	0.9092
104.8966	59.0078	0.8645	0.8645	0.8645
104.9021	178.1065	0.9411	0.9599	0.9226
104.9445	158.9401	0.9325	0.9045	0.9613
104.9770	188.4176	0.9406	0.9500	0.9313
104.9834	138.6494	0.9231	0.9415	0.9050
105.1798	200.9011	0.9504	0.9409	0.9600
105.1869	247.2948	0.9629	0.9436	0.9825
105.3175	219.1050	0.9582	0.9486	0.9679
105.5802	226.6701	0.9563	0.9754	0.9375
105.5921	260.2119	0.9714	0.9423	1.0015
105.6083	278.4658	0.9693	0.9887	0.9503
105.8962	269.5987	0.9658	0.9755	0.9563
106.8581	53.8758	0.8729	0.8903	0.8558
106.9528	63.8878	0.8840	0.8575	0.9113
107.0194	20.5255	0.8072	0.7991	0.8153
107.2005	281.0307	0.9938	1.0236	0.9648
107.2174	25.0063	0.8195	0.8277	0.8114
107.2608	44.8185	0.8655	0.8482	0.8831
107.3286	22.6483	0.8110	0.8110	0.8110
107.3611	30.0157	0.8258	0.8093	0.8426
107.6173	35.1029	0.8548	0.8462	0.8634
107.3920	33.1464	0.8392	0.8560	0.8228
107.8425	149.1381	0.9459	0.9742	0.9183
107.8469	0.0000	0.8153	0.7908	0.8405
108.0484	159.1754	0.9552	0.9647	0.9457
108.2466	168.9799	0.9595	0.9499	0.9692
108.2693	218.2240	0.9779	0.9485	1.0081
108.2916	179.4523	0.9605	0.9413	0.9801
108.8077	239.6749	0.9774	0.9481	1.0076
108.8867	260.1731	0.9881	0.9782	0.9980
109.0405	269.9760	0.9975	1.0174	0.9779
109.0632	280.5837	0.9973	1.0273	0.9683
109.0633	251.0018	0.9852	0.9556	1.0156

Table 16. (continued)

Water Flow Rate (gpm)	Gas Flow Rate (L/min)	Differential Pressure (Honeywell)	Differential Pressure (Honeywell) - 1	Differential Pressure (Honeywell) - 2
109.4204	290.7522	0.9966	0.9767	1.0170
109.8633	300.6517	0.9836	0.9541	1.0140
109.8768	69.2475	0.9059	0.8878	0.9244
109.9266	35.1296	0.8560	0.8303	0.8825
109.9434	88.9603	0.9232	0.8955	0.9518
109.9635	21.6761	0.8249	0.8497	0.8009
109.9823	130.1038	0.9471	0.9471	0.9471
110.0232	78.9378	0.9167	0.9259	0.9076
110.0277	59.0849	0.9003	0.8823	0.9187
110.0344	23.6095	0.8369	0.8369	0.8369
110.0841	49.4575	0.8907	0.9085	0.8732
110.0868	26.3485	0.8416	0.8584	0.8251
110.1960	40.1065	0.8794	0.8706	0.8883
110.2548	165.3917	0.9620	0.9908	0.9340
110.2718	198.6268	0.9589	0.9493	0.9685
110.3539	30.0429	0.8463	0.8379	0.8549
110.3773	109.5349	0.9353	0.9072	0.9642
110.4937	148.8622	0.9618	0.9714	0.9523
110.8036	0.0000	0.8315	0.8315	0.8315

Air – Water Two-Phase Flow Experiment Flow Regimes

Table 17. Air-Water Two-Phase Flow Experiment Flow Regimes

VsL (ft./sec)	Vsg (ft./sec)	Flow Pattern
3.87	0.51	BUBBLE
3.89	0.94	BUBBLE
3.93	0.53	BUBBLE
4.05	1.07	BUBBLE
4.05	0.64	BUBBLE
5.21	0.47	BUBBLE
5.22	0.83	BUBBLE
5.25	0.92	BUBBLE
5.38	1.07	BUBBLE
6.17	0.38	BUBBLE
6.36	0.53	BUBBLE
6.99	1.03	BUBBLE
6.99	0.83	BUBBLE
6.99	0.57	BUBBLE
7.00	0.66	BUBBLE
7.14	0.45	BUBBLE
7.17	0.38	BUBBLE
7.18	0.41	BUBBLE
7.83	0.41	BUBBLE
8.50	0.53	BUBBLE
8.50	0.38	BUBBLE
3.65	1.18	BUBBLE
3.97	1.18	BUBBLE
5.21	1.11	BUBBLE
3.70	1.43	ELONGATED BUBBLE
3.97	1.45	ELONGATED BUBBLE
5.25	1.65	ELONGATED BUBBLE
5.26	1.56	ELONGATED BUBBLE
5.40	1.60	ELONGATED BUBBLE
3.72	1.82	ELONGATED BUBBLE
3.72	1.65	ELONGATED BUBBLE
3.93	1.92	ELONGATED BUBBLE

Table 17. (continued)

VsL (ft./sec)	Vsg (ft./sec)	Flow Pattern
3.97	1.60	ELONGATED BUBBLE
5.24	1.92	ELONGATED BUBBLE
6.27	1.65	ELONGATED BUBBLE
6.27	1.58	ELONGATED BUBBLE
7.74	1.33	ELONGATED BUBBLE
7.84	1.18	ELONGATED BUBBLE
9.18	1.62	ELONGATED BUBBLE
9.20	1.13	ELONGATED BUBBLE
8.40	1.09	ELONGATED BUBBLE
8.48	1.63	ELONGATED BUBBLE
3.64	2.03	ELONGATED BUBBLE
6.87	2.01	SLUG
6.83	2.12	SLUG
3.64	2.31	SLUG
5.26	2.20	SLUG
6.23	2.31	SLUG
6.43	2.12	SLUG
3.55	2.72	SLUG
3.69	2.46	SLUG
5.26	2.99	SLUG
5.93	2.87	SLUG
6.06	5.71	SLUG
6.26	5.09	SLUG
6.29	4.47	SLUG
6.35	3.66	SLUG
6.75	5.75	SLUG
6.80	6.29	SLUG
6.83	6.69	SLUG
6.85	3.39	SLUG
6.88	5.41	SLUG
6.95	4.28	SLUG
7.68	4.45	SLUG
7.74	3.46	SLUG
7.82	2.25	SLUG
8.37	2.65	SLUG
8.38	3.12	SLUG
8.40	4.23	SLUG
8.40	3.64	SLUG

Table 17. (continued)

VsL (ft./sec)	Vsg (ft./sec)	Flow Pattern
8.95	5.88	SLUG
8.99	3.65	SLUG
9.02	4.36	SLUG
9.02	5.37	SLUG
9.08	3.83	SLUG
9.12	2.04	SLUG
9.12	2.13	SLUG
9.14	2.68	SLUG
9.16	3.40	SLUG
8.45	5.72	SLUG
8.47	5.29	SLUG
8.48	6.16	SLUG
7.94	5.41	SLUG
3.50	4.17	SLUG
3.57	5.36	SLUG
3.68	6.68	SLUG
3.55	6.21	SLUG
4.23	4.20	SLUG
4.14	5.37	SLUG
4.09	6.73	SLUG
4.23	6.20	SLUG
5.30	4.19	SLUG
5.25	5.24	SLUG
5.24	6.63	SLUG
5.29	6.27	SLUG
7.77	6.66	WAVY ANNULAR
8.99	6.75	WAVY ANNULAR
8.45	6.95	WAVY ANNULAR
5.25	19.78	WAVY ANNULAR
5.32	15.29	WAVY ANNULAR
5.35	10.91	WAVY ANNULAR
5.40	17.97	WAVY ANNULAR
5.42	9.80	WAVY ANNULAR
5.45	12.83	WAVY ANNULAR
5.57	11.87	WAVY ANNULAR
5.95	9.15	WAVY ANNULAR
5.97	19.57	WAVY ANNULAR
5.99	14.14	WAVY ANNULAR

Table 17. (continued)

VsL (ft./sec)	Vsg (ft./sec)	Flow Pattern
6.07	11.78	WAVY ANNULAR
6.14	16.81	WAVY ANNULAR
6.27	7.93	WAVY ANNULAR
6.72	15.25	WAVY ANNULAR
6.74	18.10	WAVY ANNULAR
6.78	10.65	WAVY ANNULAR
6.78	14.14	WAVY ANNULAR
6.82	20.28	WAVY ANNULAR
6.83	7.72	WAVY ANNULAR
6.86	9.62	WAVY ANNULAR
6.88	17.50	WAVY ANNULAR
6.88	12.17	WAVY ANNULAR
6.92	7.03	WAVY ANNULAR
6.96	11.59	WAVY ANNULAR
6.96	8.49	WAVY ANNULAR
7.41	16.96	WAVY ANNULAR
7.49	20.51	WAVY ANNULAR
7.53	14.02	WAVY ANNULAR
7.63	11.71	WAVY ANNULAR
7.63	7.92	WAVY ANNULAR
7.72	9.68	WAVY ANNULAR
8.02	18.84	WAVY ANNULAR
8.02	17.66	WAVY ANNULAR
8.06	20.32	WAVY ANNULAR
8.08	19.44	WAVY ANNULAR
8.13	16.90	WAVY ANNULAR
8.14	15.48	WAVY ANNULAR
8.14	11.35	WAVY ANNULAR
8.22	10.84	WAVY ANNULAR
8.23	14.34	WAVY ANNULAR
8.28	10.09	WAVY ANNULAR
8.28	13.22	WAVY ANNULAR
8.29	7.67	WAVY ANNULAR
8.31	7.37	WAVY ANNULAR
8.36	9.84	WAVY ANNULAR
8.37	7.08	WAVY ANNULAR
8.38	8.43	WAVY ANNULAR
8.78	11.40	WAVY ANNULAR

Table 17. (continued)

VsL (ft./sec)	Vsg (ft./sec)	Flow Pattern
8.78	16.96	WAVY ANNULAR
8.88	9.26	WAVY ANNULAR
8.91	14.59	WAVY ANNULAR
9.04	7.89	WAVY ANNULAR
9.05	7.14	WAVY ANNULAR
9.07	7.40	WAVY ANNULAR
3.55	7.53	WAVY ANNULAR
3.57	9.50	WAVY ANNULAR
3.54	8.45	WAVY ANNULAR
4.06	7.46	WAVY ANNULAR
4.09	9.71	WAVY ANNULAR
4.07	8.58	WAVY ANNULAR
5.30	7.59	WAVY ANNULAR
5.20	9.60	WAVY ANNULAR
5.12	8.62	WAVY ANNULAR

Polymerized Water Single Phase Flow Experimental Data

Table 18. Water Single Phase Experimental Data

WATER			
DP [psi] Average	**DP [psi] - 1**	**DP [psi] - 2**	**Q [gal/min]**
0.625	0.613	0.638	51.33
0.635	0.616	0.655	54.86
0.677	0.697	0.657	66.04
0.692	0.692	0.692	73.92
0.713	0.706	0.720	75.93
0.730	0.737	0.723	78.62
0.736	0.721	0.751	81.50
0.754	0.762	0.747	84.57
0.755	0.778	0.733	85.36
0.761	0.761	0.761	87.38
0.766	0.751	0.782	99.78
0.777	0.769	0.785	101.96
0.815	0.791	0.840	107.85
0.831	0.806	0.857	110.80

Table 19. Experimental Data for 0.05% PHPA Polymer

5/10000 PHPA			
DP [psi] Average	**DP [psi] - 1**	**DP [psi] - 2**	**Q [gal/min]**
0.38	0.384	0.376	35.21
0.40	0.384	0.409	42.43
0.40	0.393	0.409	54.67
0.45	0.451	0.442	68.65
0.45	0.454	0.445	71.50
0.49	0.479	0.499	74.39
0.55	0.534	0.556	83.74
0.59	0.594	0.582	91.64
0.59	0.608	0.573	91.93

Table 20. Experimental Data for 0.07% PHPA Polymer

7/10000 PHPA			
DP [psi] Average	**DP [psi] - 1**	**DP [psi] - 2**	**Q [gal/min]**
0.50	0.506	0.496	94.80
0.45	0.440	0.468	87.98
0.43	0.418	0.435	80.73
0.40	0.409	0.401	74.49
0.40	0.399	0.391	67.66
0.36	0.349	0.363	60.02
0.35	0.344	0.358	52.60
0.35	0.352	0.345	42.93
0.29	0.299	0.282	29.63

Table 21. Experimental Data for 0.10% PHPA Polymer

10/10000 PHPA			
DP [psi] Average	**DP [psi] - 1**	**DP [psi] - 2**	**Q [gal/min]**
0.69	0.694	0.680	87.54
0.67	0.646	0.687	92.89
0.62	0.603	0.628	82.81
0.57	0.575	0.564	73.84
0.58	0.586	0.574	66.42
0.53	0.518	0.540	60.44
0.53	0.515	0.536	51.29
0.49	0.492	0.483	41.36
0.46	0.471	0.444	33.32

Polymerized Water – Air Two-Phase Flow Experimental Data

Table 22. Polymerized Water - Air Two-Phase Flow Pressure Data

Differential Pressure (Honeywell) - Average	Differential Pressure (Honeywell) - 1	Differential Pressure (Honeywell) - 2	Polymerized Water Flow Rate (gpm)	Gas Flow Rate (L/min)
0.49	0.47	0.50	51.79	24.19
0.48	0.50	0.47	51.85	39.52
0.50	0.37	0.50	51.87	32.51
0.38	0.39	0.37	63.80	28.28
0.38	0.37	0.38	76.79	46.93
0.37	0.36	0.37	76.83	21.96
0.37	0.45	0.37	76.83	32.45
0.46	0.48	0.46	88.14	23.13
0.48	0.48	0.48	88.61	43.85
0.47	0.49	0.46	88.88	28.98
0.48	0.47	0.48	88.90	49.47
0.48	0.48	0.47	96.23	41.36
0.47	0.58	0.47	96.50	29.41
0.58	0.59	0.60	110.21	22.45
0.60	0.59	0.61	110.27	50.69
0.60	0.39	0.60	110.30	32.09
0.39	0.37	0.40	64.19	41.59
0.38	0.38	0.39	64.90	50.45
0.39	0.61	0.38	65.19	60.93
0.60	0.47	0.61	110.24	71.54
0.48	0.58	0.50	96.62	57.88
0.60	0.37	0.62	110.33	57.88
0.39	0.48	0.39	77.15	70.41
0.48	0.49	0.48	52.04	62.00
0.49	0.49	0.48	52.35	68.47
0.48	0.47	0.49	53.19	81.13
0.48	0.42	0.47	53.24	88.10
0.41	0.38	0.42	64.85	69.66
0.39	0.41	0.39	65.52	78.41
0.42	0.49	0.40	65.92	91.87
0.47	0.48	0.46	89.07	61.30
0.47	0.50	0.46	90.46	88.83
0.49	0.46	0.50	90.47	70.97
0.47	0.57	0.49	90.83	73.36

Table 22. (continued)

Differential Pressure (Honeywell) - Average	Differential Pressure (Honeywell) - 1	Differential Pressure (Honeywell) - 2	Polymerized Water Flow Rate (gpm)	Gas Flow Rate (L/min)
0.59	0.58	0.59	110.37	77.85
0.59	0.50	0.57	111.25	91.40
0.49	0.49	0.49	53.80	101.09
0.49	0.50	0.48	96.60	92.86
0.49	0.50	0.49	53.43	120.18
0.50	0.49	0.52	55.21	137.22
0.50	0.51	0.50	56.05	199.44
0.51	0.53	0.49	56.17	176.94
0.51	0.53	0.50	56.21	189.48
0.52	0.53	0.51	56.43	208.93
0.52	0.54	0.51	56.50	223.48
0.53	0.56	0.51	56.57	227.66
0.54	0.53	0.55	57.37	253.15
0.54	0.54	0.56	57.64	291.90
0.55	0.51	0.55	59.83	339.44
0.51	0.41	0.52	59.99	388.17
0.42	0.44	0.42	65.94	153.51
0.44	0.45	0.44	66.24	102.45
0.45	0.43	0.46	67.08	188.17
0.45	0.46	0.44	67.36	207.44
0.45	0.45	0.45	67.44	254.98
0.46	0.46	0.46	67.98	229.73
0.46	0.47	0.46	74.23	280.20
0.47	0.46	0.48	75.38	298.18
0.48	0.49	0.47	75.77	321.89
0.49	0.39	0.50	76.31	351.74
0.40	0.51	0.40	80.26	111.25
0.51	0.67	0.49	80.55	299.02
0.65	0.42	0.63	80.58	213.45
0.41	0.44	0.41	80.88	127.81
0.44	0.49	0.44	81.03	149.19
0.49	0.56	0.50	81.12	169.72
0.57	0.62	0.55	81.19	189.37
0.60	0.55	0.61	83.66	320.92
0.56	0.43	0.55	83.78	366.43
0.42	0.56	0.43	84.34	250.25
0.57	0.58	0.57	84.68	231.07
0.57	0.56	0.57	86.02	289.61
0.56	0.56	0.56	86.73	302.86
0.56	0.58	0.58	87.20	315.84

Table 22. (continued)

Differential Pressure (Honeywell) - Average	Differential Pressure (Honeywell) - 1	Differential Pressure (Honeywell) - 2	Polymerized Water Flow Rate (gpm)	Gas Flow Rate (L/min)
0.60	0.47	0.59	87.88	351.30
0.46	0.47	0.46	90.04	199.38
0.47	0.47	0.47	90.27	100.20
0.47	0.49	0.45	90.32	216.48
0.48	0.46	0.49	90.35	146.78
0.47	0.42	0.49	90.37	178.57
0.44	0.62	0.45	91.12	108.60
0.63	0.43	0.64	92.61	337.16
0.44	0.48	0.43	93.59	266.22
0.47	0.45	0.48	94.45	149.80
0.46	0.45	0.46	94.75	306.02
0.45	0.44	0.45	94.86	218.08
0.43	0.46	0.43	95.25	262.82
0.46	0.45	0.46	95.33	263.40
0.45	0.45	0.46	95.40	249.14
0.46	0.48	0.45	95.49	193.64
0.47	0.48	0.47	95.62	170.42
0.49	0.48	0.49	96.83	112.91
0.49	0.60	0.48	96.86	127.45
0.59	0.57	0.60	110.44	99.71
0.59	0.57	0.60	111.11	109.23
0.58	0.57	0.58	111.40	115.48
0.57	0.59	0.57	111.65	336.59
0.59	0.60	0.59	112.78	141.24
0.60	0.58	0.61	113.21	194.18
0.59	0.59	0.59	113.49	213.48
0.59	0.58	0.60	113.57	265.45
0.59	0.58	0.59	113.65	169.44
0.58	0.51	0.60	113.69	251.34
0.53	0.55	0.52	56.83	446.09
0.54	0.59	0.54	62.07	416.30
0.59	0.69	0.57	77.03	414.56
0.67	0.67	0.67	84.02	420.78
0.68	0.54	0.70	84.21	510.78
0.55	0.71	0.56	90.17	421.22
0.72	0.58	0.70	92.43	411.27
0.57	0.00	0.56	112.22	428.08

Table 23. Polymerized Water - Air Two Phase Flow Flow Pattern Data

VsL (ft./sec)	Vsg (ft./sec)	Flow Pattern
4.19	0.52	BUBBLE
4.20	0.85	BUBBLE
4.20	0.70	BUBBLE
5.17	0.60	BUBBLE
6.22	1.00	BUBBLE
6.22	0.47	BUBBLE
6.22	0.69	BUBBLE
7.14	0.49	BUBBLE
7.17	0.94	BUBBLE
7.20	0.62	BUBBLE
7.20	1.06	BUBBLE
7.79	0.88	BUBBLE
7.81	0.63	BUBBLE
8.92	0.48	BUBBLE
8.93	1.08	BUBBLE
8.93	0.69	BUBBLE
5.20	0.89	BUBBLE
5.25	1.08	BUBBLE
5.28	1.30	BUBBLE
8.93	1.53	ELONGATED BUBBLE
7.82	1.24	ELONGATED BUBBLE
8.93	1.24	ELONGATED BUBBLE
6.25	1.51	ELONGATED BUBBLE
4.21	1.33	ELONGATED BUBBLE
4.24	1.46	ELONGATED BUBBLE
4.31	1.74	ELONGATED BUBBLE
4.31	1.88	ELONGATED BUBBLE
5.25	1.49	ELONGATED BUBBLE
5.30	1.68	ELONGATED BUBBLE
5.34	1.96	ELONGATED BUBBLE
7.21	1.31	ELONGATED BUBBLE
7.32	1.90	ELONGATED BUBBLE
7.32	1.52	ELONGATED BUBBLE
7.35	1.57	ELONGATED BUBBLE
8.94	1.66	ELONGATED BUBBLE
9.01	1.95	ELONGATED BUBBLE
4.36	2.16	ELONGATED BUBBLE
7.82	1.99	ELONGATED BUBBLE
4.33	2.57	SLUG
4.47	2.93	SLUG

Table 23. (continued)

VsL (ft./sec)	Vsg (ft./sec)	Flow Pattern
4.54	4.27	SLUG
4.55	3.78	SLUG
4.55	4.05	SLUG
4.57	4.47	SLUG
4.57	4.78	SLUG
4.58	4.87	SLUG
4.64	5.41	SLUG
4.67	6.24	SLUG
4.84	7.26	SLUG
4.86	8.30	SLUG
5.34	3.28	SLUG
5.36	2.19	SLUG
5.43	4.02	SLUG
5.45	4.44	SLUG
5.46	5.45	SLUG
5.50	4.91	SLUG
6.01	5.99	SLUG
6.10	6.38	SLUG
6.13	6.88	SLUG
6.18	7.52	SLUG
6.50	2.38	SLUG
6.52	6.40	SLUG
6.52	4.57	SLUG
6.55	2.73	SLUG
6.56	3.19	SLUG
6.57	3.63	SLUG
6.57	4.05	SLUG
6.77	6.86	SLUG
6.78	7.84	SLUG
6.83	5.35	SLUG
6.86	4.94	SLUG
6.96	6.19	SLUG
7.02	6.48	SLUG
7.06	6.76	SLUG
7.11	7.51	SLUG
7.29	4.26	SLUG
7.31	2.14	SLUG
7.31	4.63	SLUG
7.31	3.14	SLUG
7.32	3.82	SLUG
7.38	2.32	SLUG
7.50	7.21	SLUG

Table 23. (continued)

VsL (ft./sec)	Vsg (ft./sec)	Flow Pattern
7.58	5.69	SLUG
7.65	3.20	SLUG
7.67	6.55	SLUG
7.68	4.66	SLUG
7.71	5.62	SLUG
7.72	5.63	SLUG
7.72	5.33	SLUG
7.73	4.14	SLUG
7.74	3.64	SLUG
7.84	2.41	SLUG
7.84	2.73	SLUG
8.94	2.13	SLUG
9.00	2.34	SLUG
9.02	2.47	SLUG
9.04	7.20	SLUG
9.13	3.02	SLUG
9.17	4.15	SLUG
9.19	4.57	SLUG
9.20	5.68	SLUG
9.20	3.62	SLUG
9.20	5.38	SLUG
4.60	9.54	WAVY ANNULAR
5.03	8.90	WAVY ANNULAR
6.24	8.87	WAVY ANNULAR
6.80	9.00	WAVY ANNULAR
6.82	10.92	WAVY ANNULAR
7.30	9.01	WAVY ANNULAR
7.48	8.80	WAVY ANNULAR
9.09	9.16	WAVY ANNULAR

Water – Air – Cutting Three Phase Flow Experiments

Table 24. Pressure Data for Water-Air-Cutting Three Phase Experiments

			Differential Pressure with ROP = 115 ft./hr.		
#	**Water Flow Rate (gpm)**	**Gas Flow Rate (L/min)**	**Water Experiments [psi] - Average**	**Water Experiments [psi] - 1**	**Water Experiments [psi] - 2**
1	61.8	23.5	0.944	0.897	0.991
2	98.8	23.5	1.033	0.981	1.085
3	61.8	70.3	0.956	0.889	1.023
4	98.8	70.3	1.053	1.000	1.106
5	61.8	234	0.951	0.941	0.961
6	98.8	234	1.156	1.098	1.214
7	61.8	421	0.998	0.968	1.028
8	98.8	421	1.212	1.139	1.285

Table 25. Cuttings Data for Water-Air-Cutting Three Phase Experiments

#	**Water Flow Rate (gpm)**	**Gas Flow Rate (L/min)**	**Differential Pressure (Honeywell) with ROP = 115 ft./hr.**	**Gas Flow Rate (gpm)**	**VsL (ft./sec)**	**Vsg (ft./sec)**	**Area Occupied by Cuttings (%)**	**Cuttings Bed Height (cm)**
1	61.8	23.5	0.944	6.204	5.00	0.50	41.48	2.90
2	98.8	23.5	1.033	6.204	8.00	0.50	32.73	2.14
3	61.8	70.3	0.956	18.5592	5.00	1.50	40.95	2.85
4	98.8	70.3	1.053	18.5592	8.00	1.50	32.17	2.10
5	61.8	234	0.951	61.776	5.00	5.00	40.41	2.80
6	98.8	234	1.156	61.776	8.00	5.00	31.60	2.05
7	61.8	421	0.998	111.144	5.00	9.00	39.87	2.75
8	98.8	421	1.212	111.144	8.00	9.00	30.45	1.96

Polymerized Water – Air – Cutting Three Phase Flow Experiments

Table 26. Pressure Data for Polymerized Water-Air-Cutting Three Phase Experiments

			Differential Pressure with ROP = 115 ft./hr.		
#	**Water Flow Rate (gpm)**	**Gas Flow Rate (L/min)**	**PHPA Polymer Experiments - 0.07% [psi]**	**PHPA Polymer Experiments - 0.07% [psi] - 1**	**PHPA Polymer Experiments - 0.07% [psi] - 2**
1	61.8	23.5	0.695	0.639	0.751
2	98.8	23.5	0.777	0.715	0.839
3	61.8	70.3	0.732	0.681	0.783
4	98.8	70.3	0.815	0.791	0.839
5	61.8	234	0.750	0.690	0.810
6	98.8	234	0.866	0.805	0.927
7	61.8	421	0.766	0.697	0.835
8	98.8	421	0.915	0.897	0.933

Table 27. Cuttings Data for Polymerized Water-Air-Cutting Three Phase Experiments

#	**Water Flow Rate (gpm)**	**Gas Flow Rate (L/min)**	**Differential Pressure (Honeywell) with ROP = 115 ft./hr.**	**Gas Flow Rate (gpm)**	**VsL (ft./sec)**	**Vsg (ft./sec)**	**Area Occupied by Cuttings (%)**	**Cuttings Bed Height (cm)**
1	61.8	23.5	0.695	6.204	5.00	0.50	38.25	2.61
2	98.8	23.5	0.777	6.204	8.00	0.50	28.09	1.79
3	61.8	70.3	0.732	18.5592	5.00	1.50	37.71	2.56
4	98.8	70.3	0.815	18.5592	8.00	1.50	27.48	1.74
5	61.8	234	0.750	61.776	5.00	5.00	37.17	2.51
6	98.8	234	0.866	61.776	8.00	5.00	26.87	1.70
7	61.8	421	0.766	111.144	5.00	9.00	36.07	2.42
8	98.8	421	0.915	111.144	8.00	9.00	25.62	1.62