A COMPARATIVE STUDY OF CUTTINGS TRANSPORT PERFORMANCE OF WATER VERSUS POLYMER-BASED FLUIDS IN HORIZONTAL WELL DRILLING

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A COMPARATIVE STUDY OF CUTTINGS TRANSPORT PERFORMANCE OF WATER VERSUS POLYMER-BASED FLUIDS IN HORIZONTAL WELL DRILLING

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ABSTRACT

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High drilling fluid circulation rate is often needed for effective transportation of cuttings in horizontal and extended reach wells, which may not be always achievable due to the risk of fracturing the rock by increased bottom hole dynamic pressure and also limit of pumps capacity. Keeping the bottom hole pressure low enough while increasing the flow rate is, therefore, a major challenge in horizontal well drilling operations. A potential solution to this problem would be to use drag reducing additives in drilling fluids. An experimental study is designed and conducted in order to investigate if drag reducing fluid can be effectively used for cuttings transport while drilling horizontal wells. The main objective of this experimental study is to compare the performance of water and a water-based polymer fluid (i.e. PHPA polymer based drilling fluid) in terms of drilled cuttings transportation. Experiments are conducted by using the set-up consisting of a 21 ft long test section with transparent casing with 2.91 ID and an inner pipe of 1.85 OD, which was readily available at the METU-Petroleum and Natural Gas Engineering department laboratories.

In this study effect of drilling rate, drilling fluid flow rate and polymer concentration on transportation of the cuttings and pressure losses are investigated while keeping other variables constant. It was observed that using PHPA polymer reduces the frictional pressure losses up to 38% and using the optimum concentration of the PHPA gives the most efficient scenario of transportation of cuttings in horizontal well drilling.

Keywords: *Cuttings transport, Drag Reduction, Horizontal concentric annuli, Turbulent flow, Non-Newtonian Fluids.*

ÖZ

YATAY KUYU SONDAJLARINDA SU VE POLİMER BAZLI SONDAJ SIVILARININ KIRINTI TAŞIMA PERFORMANSLARI ÜZERİNE BİR KARŞILAŞTIRMA ÇALIŞMASI

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Yüksek Lisans., Petrol ve Doğal Gaz Mühendisliği Bölümü
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Yatay ve uzun erişimli kuyularda etken kırıntı taşınımı için yüksek hızlı sondaj akışkan dolaşımı sıklıkla gereksinim duyulmasına rağmen bu gereksinim kayaçların çatlatılma riski ve pormpa kapasitelerinin sınırları ile her zaman gerçekleştirilemememektedir. Dolayısıyla, kuyudibi basıncını yeterince düşük tutar iken debiyi arttırabilmek yatay sondaj operasyonlarının temel hedefleri arasındadır. Bu problemin olası çözümlerinden biri de sondaj akışkanlarına sürtünme düşürücü katkıların eklenmesidir. Bu amaçla, yatay kuyularda sürtünme düşürücü katkı maddelerinin etkenliğinin araştırılacağı bir deneysel çalışma tasarlanmış ve gerçekleştirilmiştir. Yapılan deneysel çalışmanın temel amacı su ve polimer bazlı polimer akışkanlarının (örneğin PHPA polimer bazlı sondaj akışkanı) performanslarının kırıntı taşıma yönünden karşılaştırılmasıdır. Deneyler, ODTÜ Petrol ve Doğal Gaz Mühendisliği Bölümü'nde mevcut 21 ft uzunluklu 2,91 inç iç çapına sahip saydam muhafaza borusu içerisinde 1,85 inç dış çaplı bir borudan oluşan deney düzeneğinde gerçekleştirilmiştir.

Yapılan çalışmada sondaj hızı, sondaj akışkanı debisi ve polimer derişiminin kırıntı taşıma ve basınç düşümü üzerindeki etkileri, diğer parametreleri sabit tutarak, çalışılmıştır. PHPA polimerinin sürtünmeden kaynaklı basınç düşümünü % 38 e kadar düşürdüğünü ve en uygun PHPA derişiminin yatay kuyularda kırınıt taşınımı için en uygun senaryoyu verdiği gözlemlenmiştir

Anahtar Kelimeler: *Kırıntı taşınımı, Sürtünme düşürümü, Yatay konsentrik anülüs, Turbulent akış, Newtonian olmayan akışkanlar.*

To My Family

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NOMENCLATURE

a : radius ratio

d_{hyd} : hydraulic diameter of annulus, inch

d_L : laminar equivalent diameter, inch

DR : drag reduction, %

ΔP_s : pressure drop due to flow of water, psi

ΔP_p : pressure drop due to flow of polymeric fluid, psi

f : Fanning friction factor

h : cuttings bed height, cm

K : consistency index, $lb - sec^n/100ft^2$

n : flow behavior index

N_{Re} : Reynolds number

Re^* : modified Reynolds number

R_{in} : inner diameter of the casing, cm

R_{out} : outer diameter of the casing, cm

S_1 : measured perimeter, cm

Greek Letters

ϵ/d : relative roughness of the pipe

γ : shear rate, $1/sec$

μ : fluid viscosity, cp

$\bar{v}$: fluid average velocity, ft/sec

ρ : water density, lb/gal

$\emptyset^*(a)$: shape function

τ : shear stress, $lb/100ft^2$

θ_n : viscometer dial reading at n rpm, Fann

Chapter I

INTRODUCTION

1.1. Overview

Fluid flow through annular spaces is very common in the field of oil and gas well drilling and completion applications. Drilling fluid used in these applications have many functions such as formation pressure control, stabilizing borehole wall, lubricating bit and the drill string, providing bit hydraulic horse power to clean the bit face from the cuttings, transporting drilled cuttings to the surface , etc. Among these many functions, removing the drilling cuttings from the wellbore is one of the most critical ones. The drilling fluid is a non-Newtonian fluid composed of aqueous or non-aqueous base fluid and several additives (i.e., viscosifying polymers, density controlling agent, fluid loss controlling additives, etc.) which generally adds up to make the drilling fluid one of the most costly element of drilling process.. Therefore, studying the drilling fluid behavior and its effect on cuttings removal from the borehole is an essential task to design the drilling hydraulic program and cuttings removal strategies, which result lower drilling cost.

Effective removal of drilled cuttings from the wellbore is a major challenge in oil and gas well drilling. This challenge seems to be well studied in case of vertical well drilling operations, but in the case of deviated well applications, cuttings removal is still a major problem resulting more costly operations.

Proper design of cuttings removal strategy is an important key to obtain a successful drilling operation. Poor cuttings removal may cause many problems such as [1]:

- Slow rate of penetration.
- Increase in torque (rotary power requirement) and drag forces.
- Higher possibility of pipe stock.
- Difficulty in casing landing and cementing.
- Difficulty in logging.

Due to the force of gravity, a deposit of drilled cuttings usually builds up along the low side of the deviated and horizontal wells if cuttings removal strategies does not work effectively. Such deposits of cuttings bed, , if not removed properly, may result problems such as high drag and torque, slow rate of penetration and pipe stuck (Figure 1. 1), which are usually difficult to solve and increase the cost of the operation. Cuttings bed presence may also cause difficulties later during cementing and completion. Therefore, optimum hydraulics design of a drilling operation, which ensures the cuttings bed removal with minimum cost is the main objective of the study of borehole cleaning and cuttings removal.

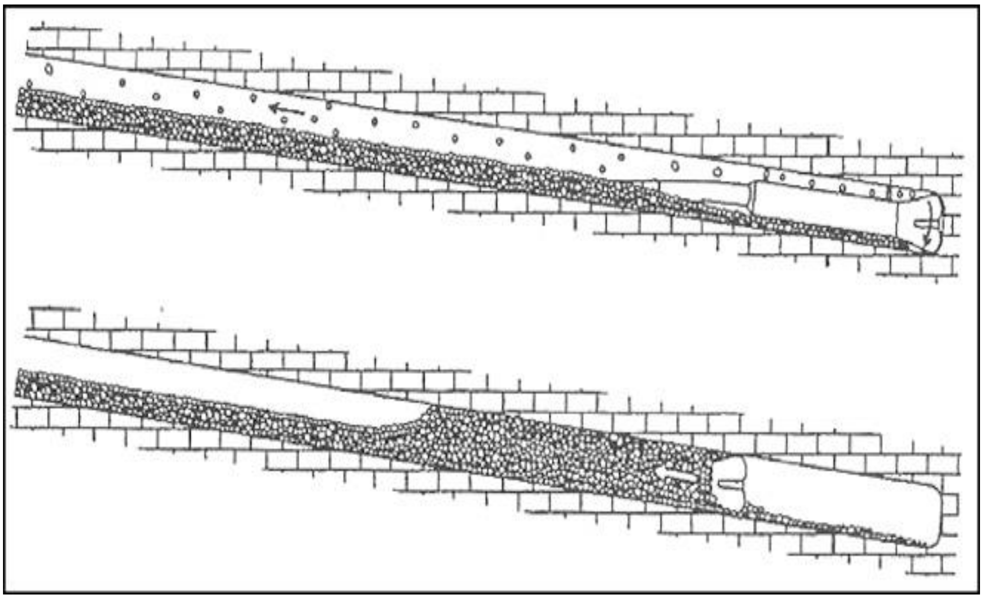

Figure 1. 1 Pipe stuck problem during tripping due to poor cuttings removal [1]

1.2. Statement of the Problem

Cuttings transport while drilling entails a complex multi-phase flow process affected by multitude of variables. Several researchers have listed the key variables that affect the drilling fluid carrying capacity. A summary of these key factors are given in Table 1. 1.

Table 1. 1 ***Parameters that influences cuttings removal*** *[2]*

Fluid parameters	**Cuttings parameters**	**Wellbore configuration + Operational parameters**
Mud Density	Cuttings Density	Angle of Inclination
Rheology	Cuttings Size	Pipe Rotation
	Cuttings Shape	Rate of Penetration
	Cuttings Concentration	Eccentricity of the hole
	Cuttings Bed Porosity	Flow Rate
	Angle of repose	Depth
		Hole Size/Casing well inside Diameter

Among these parameters, flow rate, fluid rheology and rate of penetration seem to have the strongest influence on the cuttings transport efficiency. Field control of three factors are also relatively easy compared to all the others.

Generally, increasing the drilling fluid flow rate translates into more effective removal of cuttings. This approach may be applicable in drilling of short horizontal or deviated well sections, however when drilling a long horizontal section or extended reach wells this method may not be feasible to use. High annular frictional pressure losses generally anticipated in long horizontal and extended reach wells could be very prohibitive causing operational problems such as lost circulation, limited pump flow rate, as well as high pumping costs.

In long horizontal wellbore sections, dynamic pressure losses in the annulus may increase to the rock fracture limit and any further increase in flow rate could cause lost circulation problem. In any case, reaching this point puts an end to the drilling capability. Therefore, to enhance the drilling of horizontal and extended reach wells by minimizing the cost and maximizing the length of the sections, removal of cuttings needs to be improved while keeping the frictional pressure losses as low as possible. In order to minimize the frictional pressure losses, alternative drilling fluid formulations are needed to be developed as part of an optimization of drilling fluids program [1].

Use of drag reducing polymer additives at very low concentration in drilling fluid applications has been proven to reduce frictional pressure losses significantly [3]. However, using low polymer concentration to reduce the frictional pressure losses may interfere with some other functions of drilling fluid such as cuttings removal performance. Therefore, when analyzing the polymer additives effect (drag reduction), it is necessary to study the effect of adding the drag reducers on the cuttings removal performance as well.

Although the problem seems to be well studied in case of vertical wells, transporting the drilled cuttings is still a challenge especially in long horizontal wells and extended reach wells. Poor cuttings transportation usually results in costly non-productive time situations. Effective strategies for transporting the drilled cuttings out of the well have to be designed to help with avoiding problems such as high drag and torque, pipe sticking, slow drilling, etc. which would also help decreasing the drilling cost and also would facilitate drilling longer directional hole sections.

The focus of this study is mainly on three most effective factors in cuttings transport phenomena; flow rate, fluid rheology and rate of penetration. Other parameters such as cuttings size, shape and density, hole inclination, pipe eccentricity are kept unchanged for all experiments conducted in this research.

1.3. Objectives of the Research

The primary goal of this research is the investigation of drilled cuttings transportation using water and a non-Newtonian drag reducing water-based polymeric fluid in horizontal well drilling applications. An experimental program is designed and conducted to see how cuttings are transported using water and a polymer based non-Newtonian fluid flow through horizontal concentric annuli under turbulent flow conditions.

The main objectives of this study is as follows:

- Experimentally investigate the turbulent flow of water and water-based drag reducing polymeric fluid through horizontal concentric annuli.

- Determine the optimum polymer concentration resulting the maximum drag reduction (measured in terms of frictional pressure drop).

- Conduct cuttings transport experiments using water and water-based polymeric fluids as carrier fluids.

- Determine effect of drilling rate, drilling fluid circulation rate and drilling fluid rheological characteristics on the cuttings bed height. Compare the cutting transport performance of water and non-Newtonian fluids with different polymer concentrations.

1.4. Methodology

An experimental study has been conducted to investigate the effects of drilling rate, drilling fluid flow rate and drilling fluid rheology on the efficiency of cuttings transport in horizontal concentric annuli. The advanced cutting transport facility available at the Middle East Technical

University, Petroleum and Natural Gas Engineering Department's Drilling Laboratory was used to accomplish the objectives of the study. A schematic of the set-up use is shown in figure 1. 2.

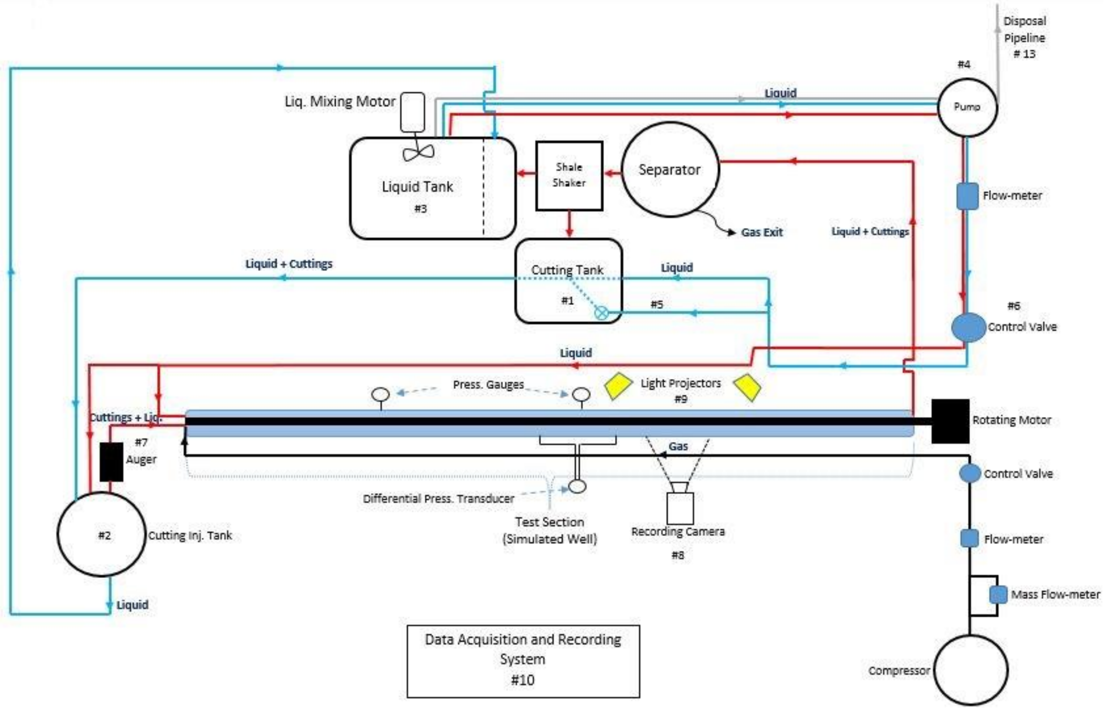

Figure 1. 2 Schematic of Laboratory Set-Up

1.5. Contribution of the Research

By investigating the pressure drop effect as well as fluid rheological effect on cuttings transportation, this study provides more experimental data to the discussion of the factors controlling cuttings transport in horizontal wells.

New experimental data provide more information on the effect of adding a drag reducing agent (PHPA polymer) on cuttings transport. Moreover, an optimum polymer concentration resulting maximum drag reduction is determined.

Results also show that drag reducing fluids can transport cuttings more effectively than water and/ or high viscosity polymer based fluids.

1.6. Structure of the Thesis

Chapter 1: This is an introductory chapter, where an overview, statement of the problem, thesis objectives, methodology and contribution of the research to the literature are presented.

Chapter 2: Second chapter is dedicated to literature review and background of past studies relevant to the current work. In the first part of the review, literature on drag reduction has been discussed.

Review of the literature relevant cuttings transportation is given in the second section of this chapter.

Chapter 3: This chapter discusses the experimental setup and procedures, which have been used to obtain the results of the presented work. Detailed information on equipment and techniques to collect the required data are provided.

Chapter 4: Characteristics of non-Newtonian fluids used in this research has been described in this chapter. Properties of the polymer additives, along with the instruction for how to mix it properly are provided. Physical properties of the solids and their size distributions are presented. Results of rheological measurements, frictional pressure drop and friction factor measurements for water and drag reducing fluid are also presented in this chapter.

Chapter 5: Experiments of cuttings transportation and results for these experiments are reported in chapter 5. Water and drag reducing fluid performance in terms of cuttings transportation in horizontal concentric annulus is compared in this chapter. Fluid rheology effect on hole cleaning is also reported in chapter 5.

Chapter 6: This chapter presents the summary of the most important findings, conclusions of the research and the recommendations for future work.

Chapter II

LITERATURE REVIEW

The main objective of this experimental study is to compare the cuttings transport performances of water and a drag reducing drilling fluid (a PHPA polymer based fluid). A thorough discussion of the factors controlling drag reduction as well as the cuttings transport need to be presented as a first step to accomplish the research objectives. This literature review is, therefore, comprised of two parts; in the first section of this chapter, past works relevant to drag reduction has been reviewed. Following the first section, review of the literature of cuttings transport is given in the second part of this chapter.

2.1. Drag Reduction

A brief summary of the drag reduction phenomenon is given is this section. First part is the description of the drag reduction following by the theories about mechanism of this phenomenon. After that a brief summary and conclusions of some important studies investigating drag reduction are reported following by factors affecting the drag reduction phenomenon.

2.1.1. Description of the Drag Reduction Phenomenon

Toms [4] discovered that by adding small amounts of high molecular weight polymers, frictional pressure losses of the single phase liquid flow can be reduced significantly. Tom’s finding received a lot of attention after wards because of its practical use in various engineering applications.

The reduction of drag in turbulent liquid flow caused by polymer additives is called Turbulent Drag Reduction (DR). Examples of polymer-solvent systems which cause DR can be found in Savings [5], Lumley [6] and Hoyt [7].

The drag reduction phenomenon mostly occurs when low concentrated solutions of long, flexible, expanded high molecular weight linear polymers are used [8]. Hand and Williams [9] , [10] showed that even more reduction in drag can be obtained using a flexible helical structured polymer than a flexible linear polymer.

By using a very high molecular weight polymers drag reduction can be observed at very low concentrations. Even at low polymer concentrations, these polymer fluids acts as Non-Newtonian fluids [8].

Figure 2.1 shows the onset of the drag reduction phenomenon (threshold wall shear stress) for 0.25 % poly-methyl methacrylate in mono-chlorobenzene as an example.

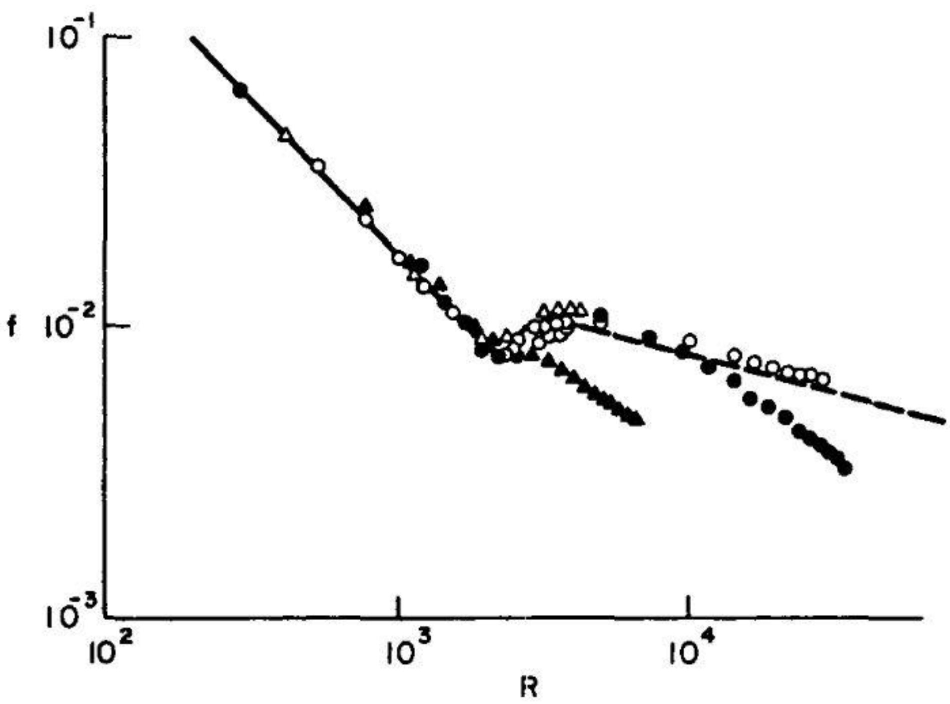

Figure 2. 1 Data of Toms for friction factor vs. Reynolds Number. The open points represent the solvent alone data and the solid points are for data obtained from polymer solutions. The circles refer to a 0.202 cm radius tube and the triangles to a radius of 0.0645 cm [8].

2.1.2. Drag Reduction Mechanism

Many researchers have investigated the drag reduction phenomenon to clarify the mechanism of the frictional drag reduction at the wall and the reason for this effect of high molecular weight polymers.

Black [11] claimed that the reason could be the reduction in burst frequency in turbulence flow caused by large polymer molecules. But this theory was not reliable for lower reductions in wall drag.

One of the most comprehensive study of drag reduction was done by Lumley [8]. He conducted several experiments to clarify the mechanism behind the drag reduction phenomenon. Lumley showed that long flexible expanded high molecular linear polymer are effective in enhancing the drag reduction performance. He also claimed that expansion of the polymer molecules at sufficiently high wall shear stress, damps the small eddies near wall. This causes a reduction of Reynolds stresses at buffer layer which delays the reduction of mean profile velocity slops (see Figure 2. 2).

Virk [12] investigated mechanisms of the drag reduction phenomenon. His researches showed that the affected area of the phenomenon is near wall region ($y^+ \cong 15$). His results showed that dilute polymer solutions exhibited striking anomalies by expansion of polymer molecule (most probably) in flow field near wall region which resulted in growth of wall layer and this reduced the turbulence bursts resulting in drag reduction [12].

More recent study of drag reduction mechanism has been conducted by Abubakar et al. [13]. According to their theory adding drag reducing polymers to flow field abolishes the turbulent bursts in the buffer layer and also formation and propagation of eddies which causes the energy provided by pumps to be more participated in moving the fluid rather than the being used for theses turbulent eddies [13]. Figure 2. 2 shows velocity profiles for solvent only (a) and when using a drag reducer polymer fluid (b).

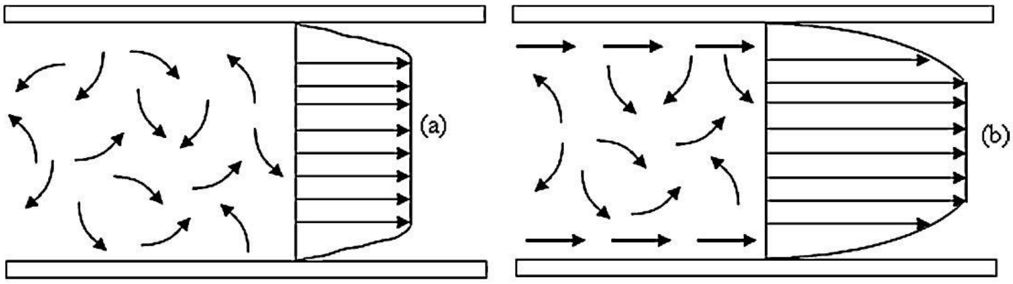

Figure 2. 2 Velocity profiles of the turbulent flow of (a) a pure liquid and (b) a liquid that contains a polymer additive [14].

2.1.3. Drag Reduction Literature

Crawford and Prutt [15] investigated the drag reduction of dilute polymer solutions. They reported that a drag reduction up to 80 % can be obtained with 100 ppm polymer. They showed that in laminar flow, addition of polymer increase the resistance to flow.

Fabula [16] reported that some polymers (high molecular weight polymers) are effective in decreasing the frictional pressure losses in low concentrations.

Savins [5] studied the effect of various polymer types on drag reduction in turbulent flow. He showed that high molecular weight polymers added to water and saline solutions flowing in turbulent motion are also capable of decreasing the pressure gradient of flow.

Virk [12] studied the drag reduction phenomena in pipe flow. According to his experiments drag reduction in turbulent flow is limited by two universal asymptotes boundaries; the Prandtl-Karman law (for Newtonian turbulent flow) and Maximum drag reduction. He also observed that macro-molecular extension is part of the drag reduction mechanism. His results show that drag reduction occur only in turbulent flow and high Reynolds number. He also reported that with increasing the Reynolds number, more reduction in frictional drag in turbulent flow occurs.

Ptasinski et al. [17] conducted experiments to investigate the effect of drag-reducing polymer (PHPA) additive in turbulent pipe flow. They used different polymer concentration (0 to 0.14 %) in which the drag reduction was about 60 to 70 %.

Ercan and Ozbayoglu [1] investigated the turbulent flow of a polymer based fluid (PHPA) in horizontal pipeline at different polymer concentrations. They showed that there is an optimum concentration for polymer to obtain maximum drag reduction of 60

%. They also proposed a new friction factor correlation as a function of polymer (PHPA concentration and Reynold number.

Rodriguez Corredor et al. [18] investigated the drag reduction of PHPA polymers in horizontal concentric annuli using Particle Image Velocimetry (PIV) technique. Polymer concentration of 0.07 % v/v to 0.12 % v/v was used and the optimum value was found to be 0.10 % v/v. Maximum drag reduction was about 26 % which occurred at 56,400 solvent Reynolds number. They showed that increasing the flow Reynolds number enhance the drag reduction phenomena.

2.1.4. Parameters Affecting Drag Reduction

Polymer concentration is not the only factor affecting the drag reduction phenomenon. Several investigations has been done to find all possible factors that may affect the performance of drag reducing agents [13]. A brief summary of some of these studies are as follows:

2.1.4.1. Pipe Geometry

Diameter effect on performance of drag reduction has been investigated by many researchers but the results are still not conclusive. However, Interthal and Wilski [19] presented results for three different pipe inner diameters. The results showed that using a 3-mm ID pipe give a drag reduction about 66% while increasing the diameter to 14-mm resulted in increase in drag reduction to a pick about 80 %; however increasing the ID more to 30-mm resulted in decrease in drag reduction to 76%. Another study is carried out by Karami and Mowla [20] which investigated the drag reduction for three different polymers at same concentration of 200 ppm in two rough pipes with 25.4 mm and 12.7 mm inner diameters. Results showed that lower drag reduction was obtained for all polymers with increasing the pipe diameter.

2.1.4.2. Wall Surface Roughness

Few studies are reported the effect of wall surface roughness on drag reduction effectiveness [13]. Virk [21] investigated the DR for different pipe roughness and presented the results in terms of fanning friction factor vs. Reynolds number. His results showed that increase in relative roughness resulted in increase of friction factor. Karami and Mowla [20] concluded that increasing the pipe relative roughness enhance the drag reduction performance.

2.1.4.3. Polymer Molecular Weight

The effect of polymer molecular weight on drag reduction performance is widely studied [13]. Almost all of the studies showed that drag reduction effectiveness can be enhanced by using higher molecular weight polymers.

2.1.4.4. Polymer Molecule Chain Flexibility

Sifferman and Greenkorn [22] showed that polymers with flexible structure are more effective in drag reduction phenomenon. It has been showed that polymers with longer and fewer PAM (Polyacrylamide) branches are more effective in terms of drag reduction and are more stable to shear comparing to those with shorter and more PAM branches [13].

2.1.4.5. pH and Temperature

Interthal and Wilski [19] have studied the effect of pH and temperature on performance of drag reduction phenomenon. They studied two different polymers, polyethylene oxide (PEO) and partially hydrolyzed polyacrylamide (PHPA) at 30 ppm concentration in a pipe with 14-mm ID and flow Reynolds number of 100,000. Their results showed that for PHPA which was resulted in 80 % of drag reduction, change in temperature (5 to 35 degree centigrade) does not affect the polymer effectiveness in drag reduction. However, for the PEO type polymer drag reduction decrease to 50 % from 70 % by increasing the temperature from 5 to 35 degree centigrade. They also showed that pH of polymer solution has a considerable effect on drag reduction effectiveness. It is better to use alkaline polymer solutions than acidic solutions.

2.1.5. Weakness of the Drag Reducing Polymers

The major problem of using of drag reducing polymers is degradation of the polymer molecules due to shear stresses in high turbulence flow fields (High Reynolds number). Degradation of the polymer molecules occurs at high shear conditions (increasing flow rate) or being passed through a centrifugal pump [13]. This cause the breakage of the polymer molecules which reduces and even eliminate the effectiveness of the drag reduction. Polymer degradation depends on polymer molecular weight, temperature, polymer-solvent interactions, polymer concentration, turbulence intensity, molecular weight distribution (MWD), method of preparation and storage of the solution and flow geometry [13].

Another issue of using drag reducing polymers is that they might be toxic. It is known that polymers that are soluble in hydrocarbon are toxic due to their non-biodegradability. However water-soluble polymer are mostly non-toxic [13].

Based on the results of the review study following conclusion can be offered:

- The addition of high molecular chain polymers into a single phase liquid flow decreases the frictional pressure drop.
- Up to 80 % reduction can be obtained by adding polymers to solvent.
- Drag reduction only occurs in turbulent flow
- Increasing the Reynolds number of the flow enhance the drag reduction effect.

- An optimum concentration exist for each kind of polymers to obtain maximum drag reduction
- Using drag reducing agents can be useful in horizontal and extended reach well drilling.

2.2. Cuttings Transport

In the past 70 years numerous studies have been done on cuttings transportation. Most of these researches were focused on cuttings transport phenomenon in vertical wells; but with increased interest in directional and horizontal well drillings, studies are shifted to experimental approaches nowadays trying to explain the cuttings transport for all inclination angles, especially horizontal wells.

Williams et al. [23] have done experiments to investigate the carrying capacity of drilling fluids. They reported that turbulent flow is the most desirable from the point of cuttings transportation. They also claimed that it is better to use low viscosity and low gel muds for good hole cleaning.

Charles [24] grouped cuttings transportation into three groups: transportation in form of capsules; settling slurries and non-settling slurries. He described the distinctions among homogenous suspensions, heterogeneous suspensions, sliding bed and stationary bed structures. He concluded that for short distances, settling slurries are more economic than the other forms, while for long distances, solids need to be transported in a non-settling form.

A mechanistic two-layer model was developed by Wilson [25] consisting of a stationary solids bed and a suspension layer. Wilson's model results were verified with experimental data for a Newtonian fluid.

A bed-slip model is introduced by Wilson [26], [27] that can determine the minimum fluid flow rate required for preventing a stationary bed of solids. The model equations were solved for an equilibrium point at which the bed just starts moving. Model results were compared with experimental data.

Televantos, et al [28] experimentally verified Wilson's (1974) two-layer model. They also determined in-situ concentrations and particle velocities.

Iyoho [29] studied the effects of flow rate, flow regime, eccentricity, rate of penetration and hole inclination on cuttings transport. He introduced a general cuttings transport ratio definition, which can be used for any inclination. Based on observations from experiments, he concluded that although laminar flow is enough to transport cuttings in a vertical well, turbulent flow is required for inclined wellbores.

Effect of drilling fluid rheology on transportation of cuttings in directional wells is investigated by Okranji [30] in terms of the ratio of yield stress over plastic viscosity. He claimed that increasing this ratio improved cuttings transport. He observed that mud rheology has no effect on cuttings transport in the turbulent flow regime.

Tomren et al. [31] conducted experiments to study cuttings transport in directional wells. They studied the effects of pipe rotation and eccentricity, different mud types, flow regimes, and different well deviation from 0 to 90 degree on the efficiency of cuttings transport. They concluded that for effective cuttings transport higher fluid velocities are needed in directional wells than in vertical wells. Increasing the hole angle and/or drilling rate decreases the transport performance of the drilling fluid. High-viscosity muds were observed to provide better cuttings transportation than low-viscosity muds.

Doron, et al. [32] developed a two-layer model that consists of a solids bed (either stationary or moving) and a suspension layer by using basic conservation principles. The model can be used for cases with a stationary bed, a moving bed and fully-suspended solids. They verified the model with experimental data.

Meano [33] conducted an experimental study on shale cuttings transport in inclined wellbores. He studied the effects of flow rate, inclination, rate of penetration, eccentricity and fluid rheology on in-situ cuttings concentration. He observed a decrease in cuttings concentration with increasing yield stress. Also, an increase in inclination causes an increase in cuttings concentration. He did not measure a significant difference in concentration as rate of penetration was changed.

Bin-Haddah [34] presented a mechanistic model based on the forces acting on a particle: gravitational force, buoyancy force, drag force and the lift force. He also presented another model derived from a slurry transport model which is valid for laminar and turbulent regimes. He introduced a suspension ratio term to estimate the bed thickness and cuttings concentration.

Brown, et al. [35] studied cuttings transport with water and HEC-polymer muds. They developed a two-layer model with a stationary bed and a fluid layer, and compared the model results with experiments. Their observations included bed movement as a block or as dunes observed at high flow rates with low viscosity fluids.

Sifferman and Becker [36] used a statistical approach to analyze the effect of flow rate, mud density, mud rheology, cutting properties, rate of penetration, and pipe rotation and eccentricity on bed thickness. They observed that the bed thickness is not constant along the test section. They also noted that bed build-up is less when the pipe is rotated at high inclination angles with smaller cuttings and low rates of penetration.

Ford, et al. [37] conducted an experimental study on cuttings transport. They introduced a minimum velocity definition to describe the interfacial shear stress. They observed the following flow patterns:

homogenous and heterogeneous suspensions, suspension and saltation, sand clusters, moving dunes, continuously moving bed and stationary bed.

Martins and Santana [38] developed a two-layer model with the presence of cuttings in the upper layer. They determine the interfacial stress by using a friction factor definition which includes the effect of cuttings. The model requires simultaneous solution of five equations for five unknowns: bed thickness, average velocities, cuttings concentration in the upper layer and pressure drop. They define four flow patterns: a stationary bed, a moving bed, heterogeneous suspension, and homogenous suspension. They noted a decrease in pressure drop when the flow rate is increased in the presence of a thick bed.

Hemphill [39] summarized the work conducted on cuttings transport in horizontal wells. He noted the positive effect of pipe rotation on cuttings transport because of agitation.

Sifferman, and Becker [40] performed a full scale hole cleaning experiments in an inclined well varying from 45-90 deg. The investigators evaluated the effects of drilling fluid velocity, density, rheology, and type, cuttings size, rate of penetration (ROP), drill pipe rotation, eccentricity, drill pipe diameter, and hole inclination angle on hole-cleaning. Drilling fluid velocity and density have the greatest effect on hole-cleaning. According to the investigators, as the mud weight increases a decrease was observed on cuttings bed height. The drill pipe rotation effect on cuttings buildup is greater under certain conditions such as at inclination angles near horizontal, for small cuttings (0.08 in. [2 mm]), and low ROP (50 ft/hr).

Doron and Barnea [41] improved their two-layer model by adding a third layer. The improved model assumes that there is a stationary bed, a moving bed and a heterogeneous layer. They verified the model with experimental data.

Saasen [42] showed that the frictional pressure losses in annulus is the major contributing part to hole cleaning problem in directional drilling. He reported that a high frictional pressure loss may be necessary for removing the drilled cuttings from the bed if it is well consolidated. His experience showed that it is better to avoid polymeric consolidation of the settled cuttings if extensive steering is expected due to this fact that bed consolidation as one of major issues in borehole cleaning.

Walker and Li [43] have experimentally investigated the effect of drilling parameters on transportation of cuttings. Their results indicated that a gelled fluid was more effective for cuttings transport than water in highly deviated wellbores.

Saasen et al. [44] explained the effect of the cuttings bed properties on hole cleaning. They showed that the primary cause of cuttings bed erosion problem is the drilling fluid gel formed in the cuttings bed. They also claimed that by using drilling fluids with low gel strength and low viscosity better hole cleaning has been achieved. They also concluded that it is better to use low molecular weight polymers for viscosifying the drilling fluid. High molecular weight polymers should only be used for preventing barite sag.

Kjosnes et al. [45] studied the effect of drilling fluid design to optimize the chemical performance (chemical interaction between drilling fluid and borehole) and the cuttings transportation performance in drilling operations in a specific North Sea field. They studied the contribution of a low gel/viscosity drilling fluid in improving drilling performance and cuttings transportation.

Li et al. [46] studied the effect of particle density and size on cutting transport. They presented the results on the effect of different fluid density and particle diameter ranging from 0.15 to 7 mm. They concluded that particle density and size play a significant role on the solids transport. For a given flow rate, higher density solids result in higher in-situ solids concentrations and lower wiper trip speed (i.e., the speed at which the coiled tubing is pulled-out-of-hole (POOH speed) and reduced transport efficiency. Wellbore deviation angle strongly influenced the solids transport for different particle sizes. In a near-vertical wellbore larger particles have the lower transport efficiency while in a horizontal wellbore the medium sized particles have the lowest transport efficiency. Based on experimental data, they developed new correlations in order to predict solids in-situ concentration, solids carrying capacity and optimum wiper trip speed for these tested solids under a given operating condition.

Ozbayoglu et al. [47] conducted experimental study in order to estimate the critical fluid flow velocity for preventing the development of a stationary bed . They have developed empirical correlations for field prediction of critical velocity. They also introduced a correlation for rough estimation of bed thickness if the flow velocity is lower than the critical velocity.

Bilgesu et al. [48] simulated annulus section by using Computational Fluid Dynamics (CFD) to determine the effects of different parameters such as fluid velocity, cutting size, rate of penetration, drill pipe rotation and inclination angle in deviated wells. From this study, it was found that fluid flow rate, angle of inclination and rate of penetration have a major impact on cutting concentrations and proper prediction of these parameters are important to avoid formation of cutting beds. It was also noted that drill pipe rotation could enhance cutting transport but it generally has a greater effect on smaller sized particles.

Yu et al. [49] conducted experimental research and theoretical analysis to enhance cuttings transport capacity in oil and gas well drilling operations by considering the effects of drilling fluid rheology, mud density, temperature, borehole inclination, pipe rotation, eccentricity, rate of penetration (ROP) and flow rates. They concluded that drill pipe rotation, temperature and rheological parameters of the drilling fluids have significant effects on cuttings transport efficiency. They also developed correlations that can be used for field applications by conducting a dimensional analysis. A user-friendly simulator was developed based on the results of the dimensional analysis and correlations.

Li et al. [50] developed a one-dimensional transient mechanistic model of cuttings transport with conventional (incompressible) drilling fluids in horizontal wells. The model was solved numerically to predict cuttings bed height as a function of drilling fluid flow rate and rheological characteristics (n, K), drilling rates, wellbore geometry and drill pipe eccentricity. The results of the sensitivity analysis showing the effects of various drilling operational parameters on the efficiency of solids transport were presented. The model developed in this study can be used to develop computer programs for practical design purposes to determine optimum drilling fluid rheology (n, K) and flow rates required for drilling horizontal wells.

Duan et al. [51] studied the critical conditions for effective cuttings transportation in horizontal and high angle wells. They reported that water is more effective than low-concentrated polymer solutions for cuttings bed erosion. However, polymer solutions are more helpful than water in preventing bed formation.

Duan, et al. [52] studied the transport behavior of small cuttings in extended-reach drilling. During this study, the effects of cuttings size, drill pipe rotation, fluid rheology, flow rate, and hole inclination on the cuttings transport were investigated experimentally and theoretically. They concluded that cuttings deposition is relatively more when using smaller sized cuttings and water as drilling fluid. However, using 0.25-ppb polyanionic cellulose (PAC) solution and smaller cuttings less deposition achieved. Fluid rheological properties and dill pipe rotation found to be the key factors in transporting of smaller sized cuttings while one the other hand the key factor for transportation of the larger cuttings is drilling fluid flow rate.

Piroozian et al [53] have experimentally investigated the influence of the drilling fluid viscosity, velocity and hole inclination on cuttings transport in horizontal and highly deviated wells. Authors have considered three types of drilling fluid Table 2. 1 shows the properties of these fluids.

Table 2. 1 Types of Drilling Fluids used by Piroozan et al.

Drilling Fluid #	Drilling Fluid Composition	Viscosity [cp]	Density [ppg]
No. 1	Water	1	8.345
No. 2	350 ml of Water + 9 g of Bentonite + 15 g of Barite	2.5	8.5
No. 3	350 ml of Water + 9 g of Bentonite + 15 g of Barite 0.5 g CMC	6	8.7

Experiments were conducted using a 17-feet long flow loop of 2-in. diameter as the test section. They have determined the cuttings transport performance (CTP) using weight measurements. The result of the experiments showed that for constant flow velocity, increasing drilling fluid viscosity has improved CTP by approximately 8 % at all angles, provided that the flow regime remained turbulent. They also showed that further increase of viscosity when the flow regime was laminar or transient flow, reduced the CTP by an average of 12 %.

Li and Luft [54] conducted a detailed experimental study of cuttings transport. They studied the effect of fluid velocity, deviation angle, sand injection rate, drilling fluid properties, pipe eccentricity and rotation and particle properties on solid concentration and bed erosion time.

Based on the results of the review study following conclusion can be offered:

- Turbulent flow is the best way to carrying the cuttings.
- Laminar flow may be enough for transporting the cuttings in a vertical well.
- Low viscosity and low gel muds are better in terms of hole cleaning.
- Increasing the yield stress to plastic viscosity ratio of drilling fluid improves the transportation of cuttings.
- Higher fluid velocities are needed to achieve a good hole cleaning in directional wells as compared to vertical wells.
- High viscosity muds are better in terms of cuttings transportation.
- Increasing the flow rate and pipe rotation enhance the cuttings transportation.
- Increasing the hole inclination and rate of penetration increase the cuttings accumulation in the wellbore.
- Drill pipe rotation effect becomes more in near horizontal wellbores for small cuttings (0.08 inch) and low ROPs (50 ft/hr).
- A high frictional pressure loss may be necessary for removing the cuttings settled in the lower side of the wellbore.
- Gelled drilling fluids are more effective in terms of cuttings transportation in highly deviated wells.
- Pipe eccentricity effect on cuttings transportation may be different depending on types of the fluid.

- Pipe rotation, temperature and fluid rheological properties have significant effect on transportation of the cuttings.
- For cuttings bed erosion using water is more effective than using a low-concentrated polymer solutions.
- Large cuttings are easier to carry compared to small drilled cuttings.

Chapter III

EXPERIMENTAL SETUP

In order to conduct the experimental program, cuttings transport facility available at the Middle East Technical University, Petroleum and Natural Gas Engineering Department was used. A schematic diagram of experimental facility is shown in Figure 3. 1.

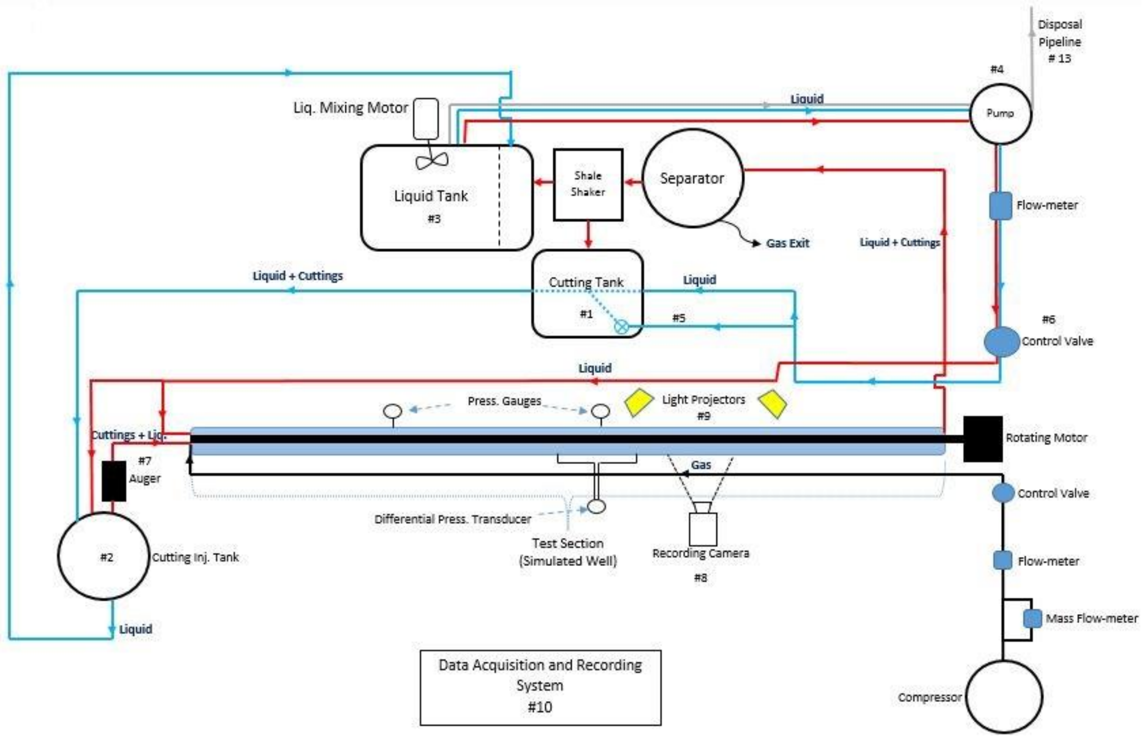

Figure 3. 1 Schematic of Laboratory Set-Up

The 21 ft. long horizontal flow loop consists of a transparent acrylic casing with 2.91 inch ID and an inner drill pipe with 1.85 inch OD, and various other equipment such as centrifugal pumps, air compressor, pneumatic control valves, magnetic flow meters, pressure transducers and a data acquisition system.. All experiments were conducted under atmospheric pressure and ambient temperature conditions. The inner pipe was not rotated during the experiments (i.e. simulating slide drilling conditions; In long horizontal well drillings or extended reach wells sometimes it is not possible to rotate the pipes and instead of rotating the whole drill pipe and bit down-hole motors can be used to rotate just the drilling bit). Experiments conducted in this study can be categorized as:

- Single phase -Water flow experiments
- Single phase - Polymer-based fluid flow experiments
- Two-phase - Cuttings-Water flow experiments
- Two-phase- Cuttings-Polymer-based fluid flow experiments

Details of the experimental set-up and materials used are explained in this chapter.

3.1. Experimental Setup

In order to conduct the experimental program, the Middle East Technical University Petroleum and Natural Gas Engineering Department's Cuttings transport facility was used with some modification to the existing setup. The available METU-PETE cuttings transport flow loop was completely unbounded for years and to bring the setup to working conditions some modifications were made as follow:

1. Renew all valves.
2. Calibrate all the measurement tools (flow meter, pressure transducers, differential pressure transducer, cuttings collection and injection tanks weight measurement tool, cuttings injection and pipe rotation motors and etc.).
3. Install the new data acquisition system (National Instruments) and LabVIEW 2013 software.
4. Modify the existing LabVIEW program codes in order to log and evaluate data acquired from measurement tools.
5. Add a new valve to disposal tank to clean the tank easily.

6. Modify the shale shaker by changing pathway of the bypass pipe in order to reduce cuttings accumulation on shale shaker.
7. Modify the cuttings transportation from collection tank to injection tank.
8. Add a new line to dispose the tested fluid.

Figure 3. 2 shows the METU-PETE cuttings transport test section which can be used for both two-phase and three-phase flow experiments. The annular test section consist of approximately 21 ft. long with 2.91 inch inner diameter transparent acrylic casing with an inner dill pipe with 1.85 inch outer diameter.

Figure 3. 2 METU-PETE Cuttings Transport Flow Loop

A motor is attached to the inner pipe (simulating drill pipe) controlled by a variable speed system. The test section is attached to a movable corner (see fig. 3. 3) in order to set the inclination of the section by pulling the other side of it between approximately 10° (nearly vertical) to 90° (figure 3. 4). The other end of the test section is connected to a separation tank consist of gas/liquid separator and a shale shaker in order to separate solid and liquid phase (see figure 3. 5).

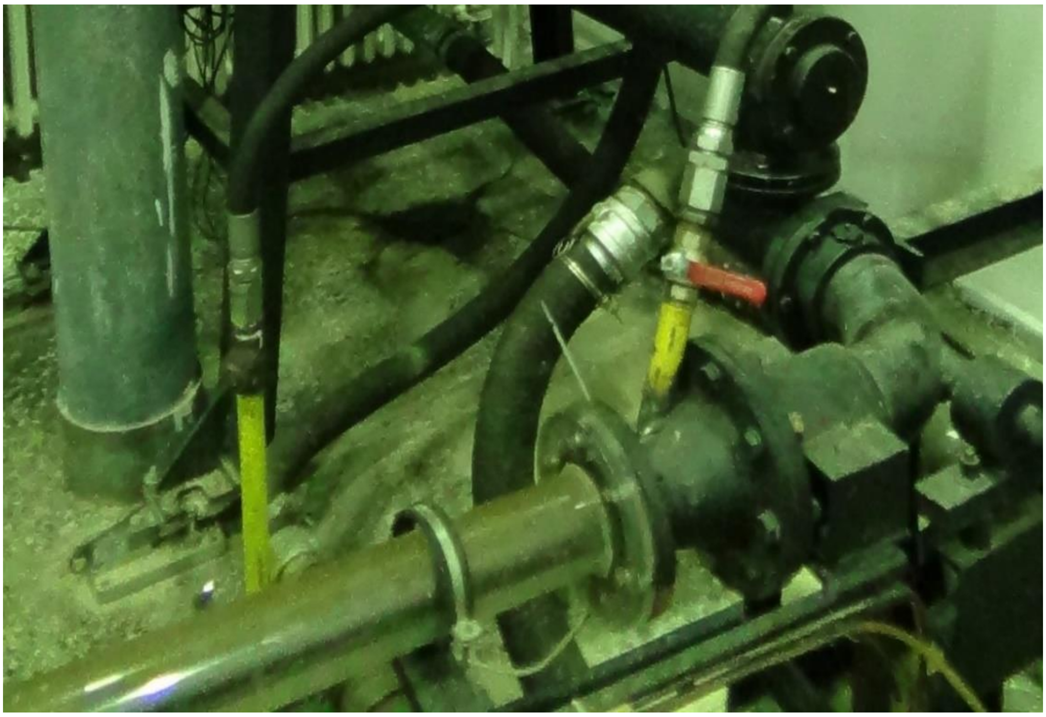

Figure 3. 3 Annular Test section Inlet and Movable Corner

Figure 3. 4 Test section connected to pulley to change the inclination

Figure 3. 5 Separation Section and Shale Shaker

The eccentricity of the drill pipe can vary from fully concentric to negative and positive eccentricities (see figure 3. 6).

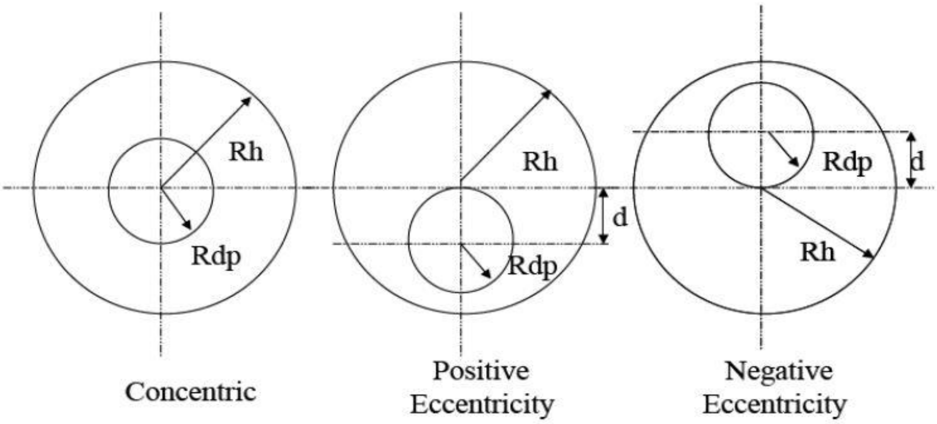

Figure 3. 6 Drill Pipe – Range of Eccentricities

The injection system has a 550-gallon capacity injection tank which injects the cuttings by a rotating auger system (Figure 3. 7). Cuttings coming out of the test section are separated from fluid in a shale shaker then are collected into a 850-gallon capacity collection tank (Figure 3. 8).

Figure 3. 7 Cuttings Injection Tank

Figure 3. 8 Cuttings Collection Tank

The test fluid is prepared in a 2100-liter capacity tank (Figure 3. 9) and then pumped and circulated through the test section by two centrifugal pumps which provide a maximum capacity of 250 gpm (see figure 3. 10). The fluid flow rate is controlled by a pneumatic control valve (Figure 3. 11) and measured by a magnetic flow meter which is installed between the pumps and the control valve (see figure 3. 12).

Figure 3. 9 Liquid Tank

Figure 3. 10 Centrifugal Pumps for Circulating the Fluid through the System

Figure 3. 11 Fisher Pneumatic Control Valve

Figure 3. 12 Toshiba Flow Meter

An air compressor (see figure 3. 13) with working capacity of 0 to 1200 scfm at delivery pressure of 125 psi is used to supply the compressed air to operate the pneumatic valves and also cleaning the test section through experiments. The air is stored into an accumulator tank (see figure 3. 14) and dehydrated by an air dryer (see figure 3. 15) before entering into the system.

Figure 3. 13 Air Compressor

Figure 3. 14 Air Accumulator Tank

Figure 3. 15 Air Dryer

In order to control the pressure of gas before entering the system a pressure regulator is used as a safety measure. Usually the air pressure is decreased from 125 psi to 20-25 psi. Check valves are used in both liquid and gas flow lines to prevent the fluid flow in reverse direction. During the experiments, pressure drop is measured at a fully developed section using a differential pressure transducer. A digital camera is also used in order to record the experiments.

Figure 3. 1 shows a schematic diagram of the experimental facility. As shown in the figure 3. 1, two pressure taps are located in the middle of the test section with suitable distance from inlet and outlet of the annular section in order to avoid the end effect and also acquire data from fully developed flow section (84.5 inch from inlet, L/D=29; 57 inch from outlet, L/D=19.6). These taps are connected to a differential pressure transducer (Honeywell Inc.) by flexible lines filled with water, which are regularly bled in order to eliminate the contamination problem of the pressure taps.

A data acquisition system is mounted on the control panel located near the test section (see figure 3. 16). The air and water flow rates, cuttings injections rate and drill pipe rotation are controlled from the control panel by using a computer. National Instrument data logger and LabVIEW 2013 a data acquisition software are used to data logging and storage, real time data display, process monitoring and etc. The annular pressure, flow rates, injection and collection tanks weight, rate of penetration (ROP), inner pipe rotation speed (pipe RPM) and differential pressures were measured by the system.

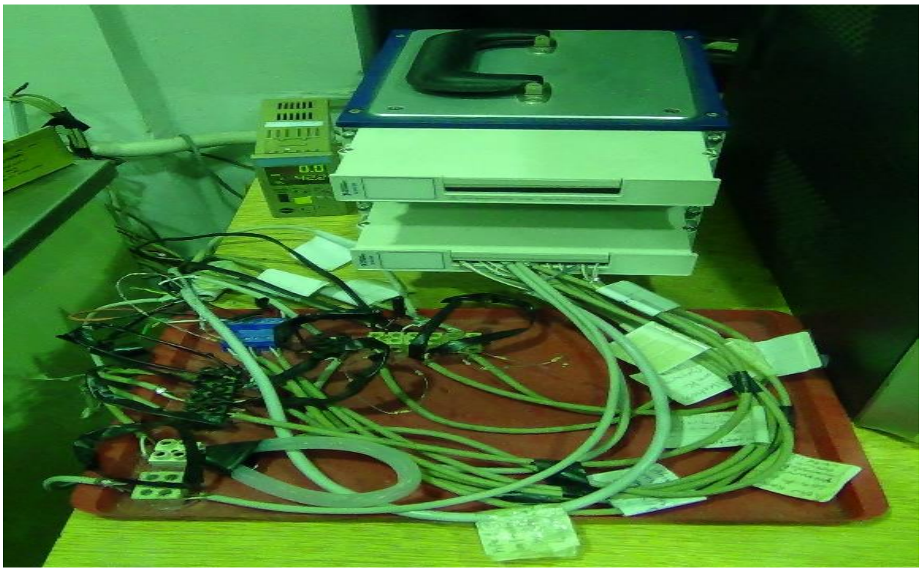

Figure 3. 16 Data logger and Acquisition System (National Instrument NI SCXI-100)

Regular calibration checks were carried out on all of the instruments in order to ensure the accuracy of logged data. Table 3. 1 Capacity and Brand Name of Experimental Components presents the capacity and brand name of each component in the experimental setup.

Table 3. 1 Capacity and Brand Name of Experimental Components

Component	Brand Name	Capacity	Error Range
Centrifugal Pump	DOMAK	1.136 m3/min	-
Liquid Tank		2100 liter	-
Magnetic Liq. Flow Meter	TOSHIBA	1.136 m3/min	± 5 %
Volumetric Gas Flow Meter	COLE PARMER INST. CO.	0-1000 lit/min at 25 psi	± 15 %
Electro Pneumatic Control Valves	SAMSON		-
Digital Differential Pressure Transducer	HONEY WELL INST. CO.	0-14 psi	± 1 %
Load Cell	ESIT ELECTRONIC LTD	0-5000 kg	± 5 KG
High-Accuracy Gauge Transmitter	COLE PARMER INST. CO.	0-30 psi, 0-60 psi	± 5 %
Air Compressor	TAMSAN	3000 lit/min at 6 atm	-
Air Dryer	OMI	700 lit/min at 6 atm	-

3.2. Installation of Data Acquisition System

Before starting this study, an older version of NI-DAQ and LabVIEW software were used in METU-PETE Cuttings transport flow loop which was out of date and also was not running properly. So it has been decided to use NI-DAQ and LabVIEW 2013 as software in order to improve accuracy of the obtained data. National Instrument SCXI-1000 chassis was used as hardware. The installation procedure is presented as follow:

- Install Application Software NI-DAQmx
- Install NI-DAQ 2013
- Re-install the Devices, Accessories and cables
- Confirm the Devices are recognized
- Run Test Panels
- Take an NI-DAQmx Measurement
- Install LabVIEW 2013
- Construct an NI-DAQmx task and Test the task
- Graph Data from DAQ Device
- Edit the NI-DAQmx task
- Add the output measurement devices to the modulo channels.
- Modify the existing back and front panels of LabVIEW (see figure 3. 17).

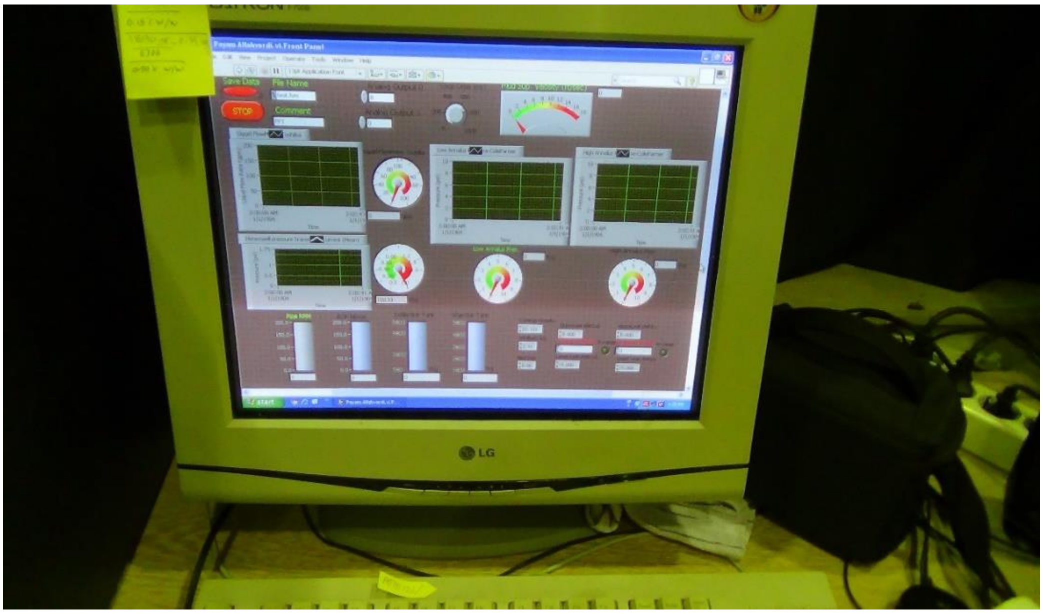

Figure 3. 17 Front Panel of LabVIEW Designed by R. Ettehadi and Modified by the researcher

3.3. Materials Used in the Experiments

The drag reducing fluid was prepared by using a commercially available polymer, partially hydrolyzed poly-acrylamide (PHPA). Physical properties of polymer is listed in Table 3. 2.

Table 3. 2 Selected PHPA Properties

Polymer	
Poly Bore (PHPA)	Very High Molecule Weight
Appearance	White Granular
Bulk Density	52 lb/ft^3
pH (0.25 % solution)	8.5-9
Package (Bucket)	14 lb (6.35 Kg)

Figure 3. 18 Poly-Bore PHPA

The cuttings are made of industrial sand. The physical properties of the cuttings are shown in Table 3. 3. Particle size distribution of the sand particles is shown in figure 3. 19.

Table 3. 3 Physical Properties of Sand Particles

Cuttings type	Particle diameter (D50), mm	Cutting Density, lb/gal
Industrial Sand	2.75	23.050

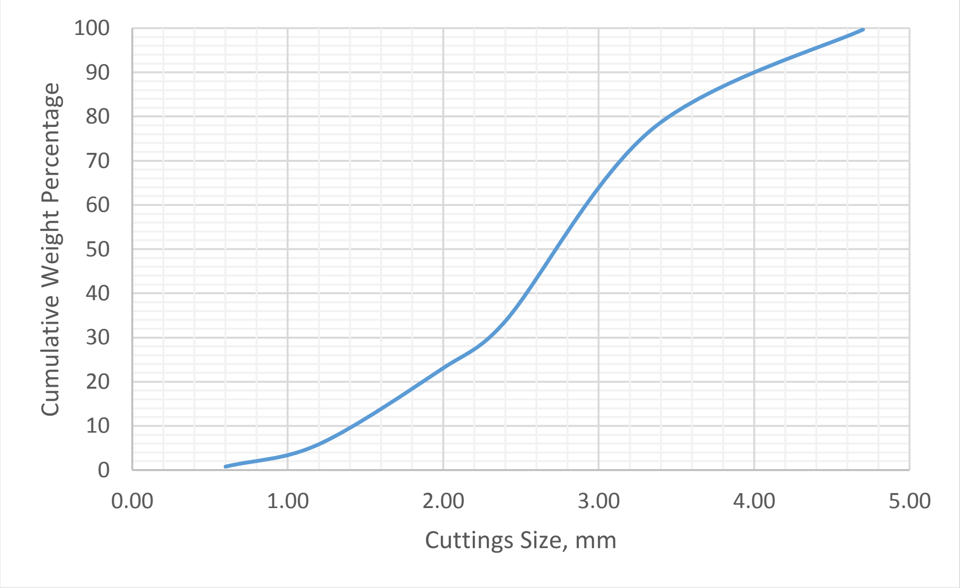

Figure 3. 19 Particle Size Distribution of Cuttings

3.4. Test Procedure and Data Acquisition

All experiments were conducted under atmospheric pressure and ambient temperature conditions. The inner pipe was not rotated during the experiments (i.e. simulating slide drilling conditions). After bringing the lab facility to a fully operational condition, before starting the experiments, all the measurement equipment and data acquisition system were calibrated to ensure that the logged data were within acceptable accuracy. During the experiments the accuracy of all the measuring data was maintained by regular calibrations. At first, single phase water flow experiment were conducted in order to validate the proper operation of experimental setup and data acquisition system. During all the experiments, differential pressure loss, annulus pressure, flow rate and ROP data have been logged and recorded.

3.4.1. Single Phase (Liquid) Flow

The experiments were conducted in horizontal concentric annulus without drill pipe rotation. The standard procedure adapted was as follows: Using a centrifugal pump, the prepared liquid was pumped at a constant flow rate. Once the flow rate was stabilized, data acquisition system was activated to record the flow rate, annulus pressure and pressure drop data. The detailed test procedure for single phase liquid flow is as follows:

1. Prepare the liquid (water or polymer) in the main mud tank.
2. Check the differential pressure transducer lines for being full of water in order to avoid contamination.
3. Start running data acquisition system.
4. Check the flow line.
5. Start air compressor to support air for pneumatic control valves.
6. Start the pump.

7. Set liquid flow rate to desired value by adjusting opening of the control valve.
8. Wait until flow rate is stabilized.
9. Start recording data.
10. Stop recording data.
11. Change the flow rate to a new desired value.
12. Repeat steps 8 to 11 until data is collected for all desired flow rates.
13. Stop mud pump.
14. Stop compressor.

3.4.2. Two Phase (Cuttings-Liquid) Flow

Using a centrifugal pump, the prepared liquid was pumped at a constant flow rate. Once the flow rate was stabilized, cuttings were injected into the flow loop. After cuttings and liquid flow rate were stabilized and the flow reached steady state condition, the data acquisition was started. Simultaneously, digital camera recorded all steps of the experiments to determine the cuttings bed height and identify the flow pattern. The detailed test procedure for two phase cuttings-liquid flow is as follow:

1. Prepare the liquid (water or polymer) in the mixing tank.
2. Check the differential pressure transducer lines for being full of water in order to avoid any (air/solid) contamination.
3. Start running data acquisition system.
4. Check the flow line.
5. Start air compressor to support air for pneumatic control valves.
6. Start the pump.
7. Set liquid flow rate to desired value by opening/closing the control valve.
8. Wait until flow rate is stabilized.

9. Start injecting cuttings into test section at a desired ROP.
10. Start Camera to record the flow in the test section.
11. Wait until cuttings injection rate is stabilized.
12. Start recording data.
13. Stop recording data.
14. Stop the camera.
15. Change the cuttings injection rate to a new desired value.
16. Repeat steps 10 to 14 until all required data are collected.
17. Stop the pump.
18. Stop the air compressor.
19. Repeat steps 1 to 18 for a different liquid flow rate.

3.5. Sensitivity Analysis of the Experimental Data

In order to be sure of the accuracy of the data a series of error analyses were carried out in measurement of different variables. The mass flow meter measure the flow rate by a Micro-motion system with an accuracy of 1 %.

For differential pressure transducers (Honey Well Differential Pressure Transducer), the accuracy is about ± 0.25 % of the full scale according to the catalogs. Due to fluid flow fluctuations, the measured values showed ± 0.9 % error (or less).

To be sure of reliability of the data recorded during the experiments, measurement tools were re-calibrated every two weeks. Figure 3. 20 shows the calibration tool of the pressure transmitters and differential pressure transducers.

Figure 3. 20 Calibration Tool

Most of experiments was repeated in order to ensure the repeatability and accuracy of the recorded data. Figure 3. 21 presents a data series of repeated tests which proves the repeatability of the experiments.

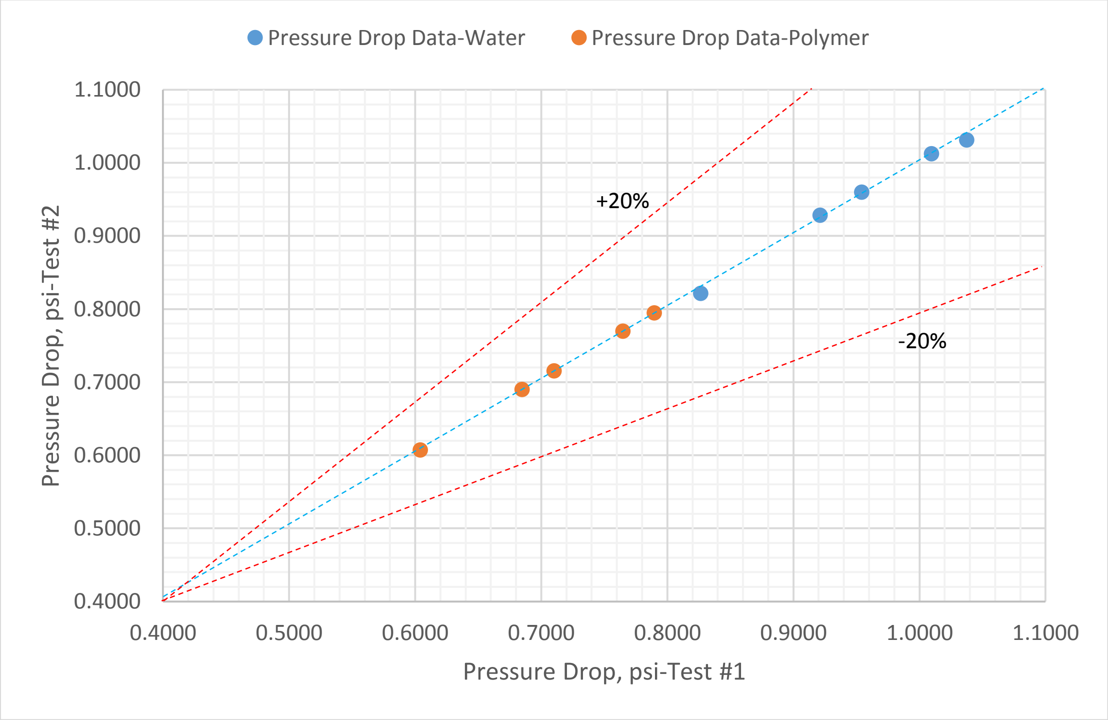

Figure 3. 21 Repeatability of the Tests

Chapter IV

AN EXPERIMENTAL STUDY OF DRAG REDUCING FLUID FLOW IN HORIZONTAL CONCENTRIC ANNULI

A comparative study of water versus drag reducing fluid flow in horizontal concentric annuli has been conducted and the results are presented in Chapter IV. This chapter starts with description of how the polymer fluid is prepared, followed by the presentation of the results of the tests conducted for rheological characterization of drag reducing fluids, and finally, finishes up by presenting the results of the full scale flow experiments conducted using horizontal annuli where the frictional drop for drag reducing fluid flow and water were measured and compared.

4.1. Polymeric Fluid Preparation

Procedure recommended by Wyatt et al. [55] has been followed for polymer solution preparation. Initially, a concentrated solution of polymer was prepared by adding it very slowly to the mixing tank filled with water (≈ 950 liter). The solution was allowed to rest for 15 hours and then the solution was diluted to the final desired concentration (wt/wt) (≈ 1680 liter). A high molecular weight partially hydrolyzed polyacrylamide (PHPA) provided by MAPEK was used as drag reducer agent in this study. Physical properties of the PHPA polymer are listed in Table 3. 2.

4.1.1. Rheological Characterization of Drag Reducing Fluids

Rheological measurements were conducted at controlled shear stress using Fann 6 speed rotational viscometer. Plot of shear rate and shear stress measurements showed that the fluid rheological behavior is well described by Power Law model (see figure 4. 1):

$$\tau = K\gamma^{n} \tag{Eq. 4.1}$$

where:

τ : shear stress, $lb/100ft^2$;

K : consistency index, $lb - sec^n/100ft^2$

n : flow behavior index;

γ : shear rate, $1/sec$.

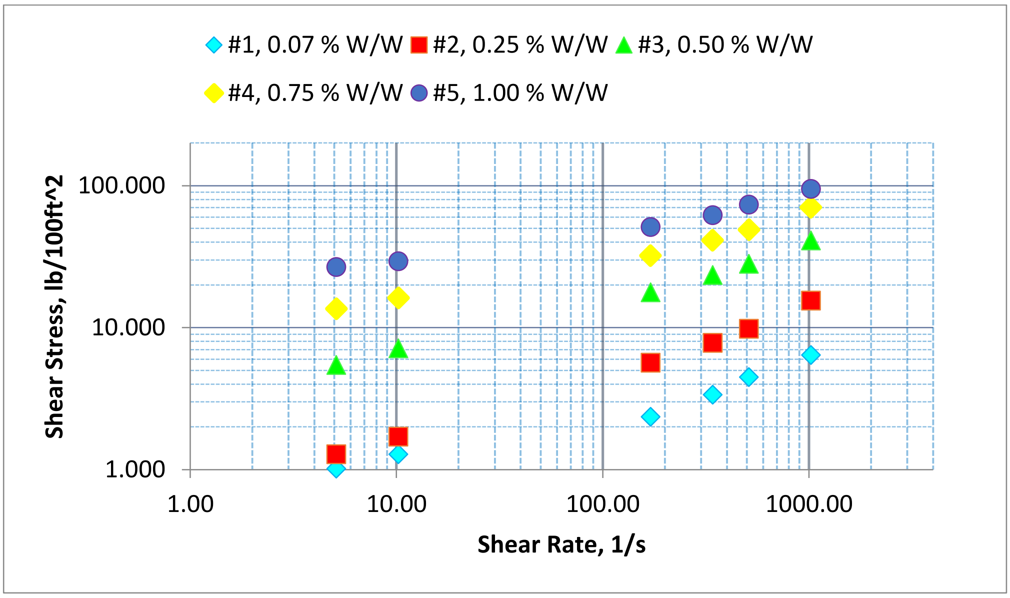

Figure 4. 1 Rheological characteristics of fluids with different polymer concentrations

Summary of rheological model parameters (n, K) of the drag reducing fluids prepared using different polymer concentrations are given in Table 4. 1:

Table 4. 1 Rheological model parameters of fluids with different polymer concentrations-using API standard equations

Polymer concentration, %W/W	K [lb.s^n/100ft^2]	n
0.25	0.601	0.42
0.50	2.943	0.34
0.75	8.496	0.25
1.00	18.448	0.19

Table 4. 2 Rheological model parameters of fluids with different polymer concentrations-using curve fitting of experimental data points

Polymer concentration, % W/W	K [lb.s^n/100ft^2]	n	R^2
0.25	0.5892	0.45	0.99
0.50	2.9722	0.36	0.99
0.75	8.0923	0.29	0.98
1.00	17.386	0.23	0.98

API standard equations for calculating k and n values for annular flow are listed by equation 4.2 and 4.3:

$$n = 0.0657 * \log({}^{\theta_{100}}/_{\theta_3}) \quad \text{(Eq. 4.2)}$$

$$K = \theta_{100}/170.3^{n} \quad \text{(Eq. 4.3)}$$

where:

K : consistency index, $lb - sec^{n}/100ft^{2}$;

n : flow behavior index;

θ_{100}: viscometer reading at 100 rpm, Fann degree;

θ_3: viscometer reading at 3 rpm, Fann degree.

4.2. Drag Reduction Experiments

The effectiveness of the drag reducing agents are compared by the percentage of drag reduction (DR) at defined by Eq. 4.4:

$$DR = \frac{\Delta P_s - \Delta P_p}{\Delta P_s} * 100 \quad \text{(Eq. 4.4)}$$

where:

DR : Drag reduction, %;

ΔP_s : Pressure drop due to flow of water, psi;

ΔP_p : Pressure drop due to flow of polymeric fluid, psi.

An example of frictional pressure loss data measured for single phase flow of water and drag reducing fluid are shown in Figure 4. 2.

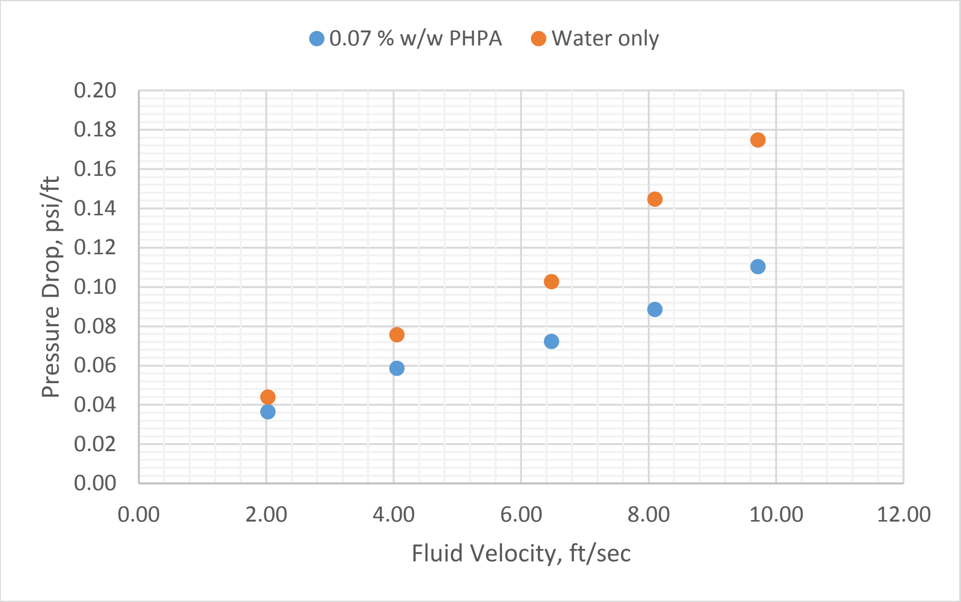

Figure 4. 2 Frictional pressure drop for single phase flow of water and drag reducing fluid

As shown in Figure 4. 2, with the increasing fluid velocity much lower frictional pressure losses were observed for drag reducing polymer fluid flow than that of water flow.

Amount of drag reduction varies depending on the type of polymer, polymer concentration, and the fluid velocity (i.e., level of turbulence intensity, or Reynolds number) [12]. Screening experiments, therefore, were conducted to determine the polymer concentration which gives the highest drag reduction, and the effect of fluid velocity on the drag reduction.

Two different blend of PHPA polymers were tested at first to see which one will provide more drag reduction (see Figure 4. 3). As shown in Figure 4. 3, Poly-Bore PHPA reduced frictional pressure losses more than the other type (EZ-Mud). So the Poly-Bore PHPA was selected to continue with the rest of the screening experiments.

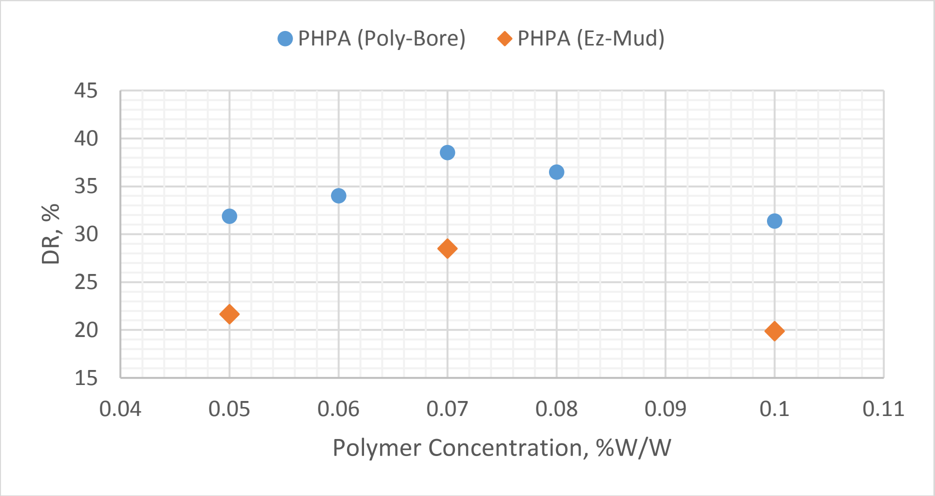

Figure 4. 3 Drag Reduction vs. Polymer Concentration (100 gpm, 66400 Solvent Reynolds Number)

Data presented in Figure 4. 3 also indicates that highest drag reduction was obtained at polymer concentration of 0.07 % wt/wt. At this polymer concentration 38 % drag reduction was observed while the fluid flow rate was 100 gall/min (Solvent Reynolds Number: 66400).

Figure 4.4 presents the drag reduction due to flow of polymer fluid at different flow rates and different polymer concentration. As shown in this figure the polymer concentration giving the most reduction in frictional pressure drops remains the same at different flow rates.

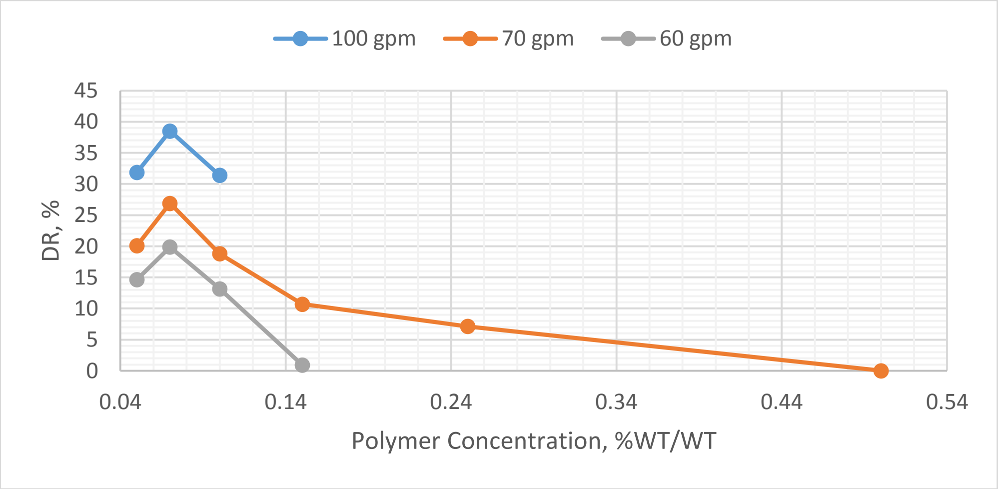

Figure 4. 4 Polymer Concentration vs. Drag Reduction at Different Flow rates (Solvent Reynolds Number: 66400, 46500 and 39800)

Effect of fluid velocity (i.e., turbulent intensity, Reynolds number) on the amount of drag reduction is shown in Figure 4. 4 obtained by using 0.07 % wt/wt of PHPA fluid. With the increasing fluid velocity (i.e. increasing Reynolds number), more drag reduction was obtained.

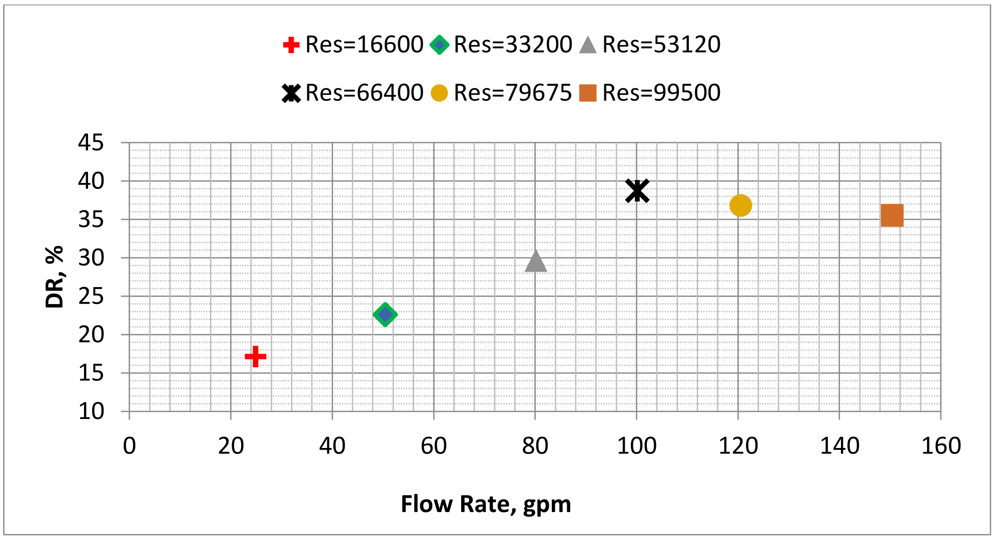

Figure 4. 5 Drag Reduction vs. Flow Rate (0.07 % wt/wt PHPA concentration)

However, as shown in figure 4. 5, drag reduction start to decrease above certain flow rates (100 gpm, Res=66400). This can be due to shear degradation of the polymer molecules at higher flow rates [55]. Hoyt [56] also reported that by increasing the flow rate drag reduction increases until a critical wall shear stress is reached where the rate of polymer degradation becomes so high and the effectiveness of the drag reducing polymer reduces after that point.

The summary of the results from drag reduction experiments for 70 gpm flow rate are given in Table 4. 3:

Table 4. 3 Drag Reduction Experiments Results

Polymer Concentration, % wt/wt	Solvent Reynolds Number	Drag Reduction, %
0.05	46500	20
0.07	46500	27
0.10	46500	19
0.15	46500	11
0.25	46500	7
0.50	46500	0

4.3. Friction Factor Calculation

In order to determine friction factor accurately for single phase fluid flow in annuli, firstly Reynolds number were calculated using the equation 4.5:

$$N_{Re} = \frac{928\,\rho \bar{v} d_{hyd}}{\mu} \qquad \text{(Eq. 4.5)}$$

where:

ρ : water density, lb/gal;

$\bar{v}$: fluid average velocity, ft/sec;

d_{hyd} : hydraulic diameter of annulus, in;

μ : fluid viscosity, cp.

Jones and Leung [57] presented a correlation which has been commonly accepted as one of the most accurate correlation for calculating friction factor (Eq. 4.6) in flow through the concentric annulus. They used *modified Reynolds number* and *laminar equivalent diameter* instead of Reynolds number and hydraulic diameter.

$$\frac{1}{\sqrt{f}} = 2.0 \log_{10} Re^{*}\sqrt{f} - 0.8 \qquad \text{(Eq. 4.6)}$$

where:

f : Fanning friction factor;

Re^{*} : Modified Reynolds number.

$$Re^{*} = \frac{\rho v d_L}{\mu} \qquad \text{(Eq. 4.7)}$$

$$d_L = d\emptyset^{*}(a) \qquad \text{(Eq. 4.8)}$$

$$\emptyset^{*}(a) = \frac{1}{(1-a)^2}\left[1 + a^2 - \frac{1-a^2}{\ln\frac{1}{a}}\right] \qquad \text{(Eq. 4.9)}$$

where:

d_L : Laminar equivalent diameter;

$\emptyset^{*}(a)$: shape function;

a : radius ratio.

Figure 4. 6 present comparison of the pressure drop calculated using Jones correlations versus observed pressure drop in the test section. The calculated pressure drop values were within +/- 20% of measured values.

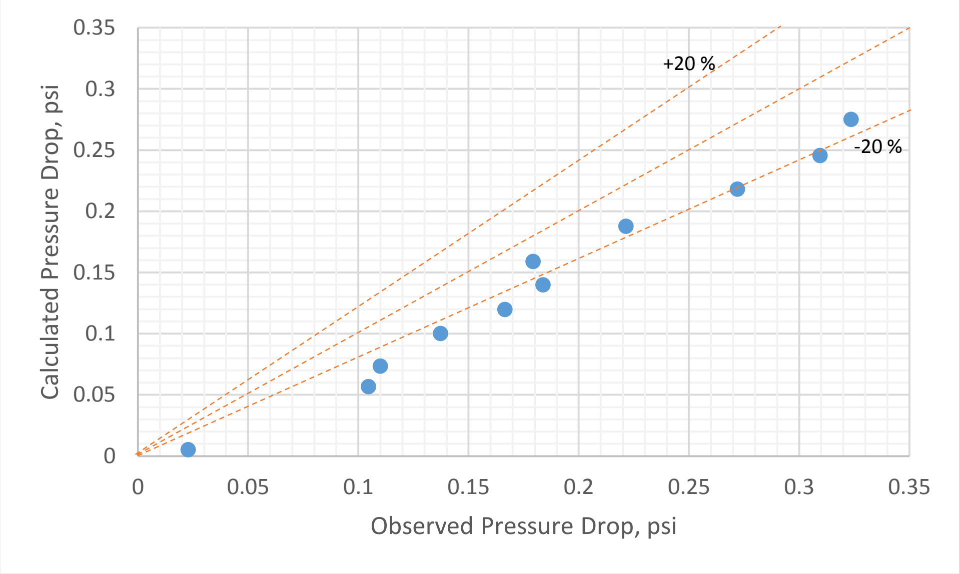

Figure 4. 6 Comparison between Experimental Data obtained from current study and calculated pressure drop using Jones correlations

Colebrook [58] presented an empirical correlation for determination of friction factor for fully developed turbulent fluid flow in circular rough pipes which is given by:

$$\frac{1}{\sqrt{f}} = -4\log_{10}(0.269\,\epsilon/d + \frac{1.255}{N_{Re}\sqrt{f}}) \qquad \text{(Eq. 4.10)}$$

where:

f : fanning friction factor;

ϵ/d : relative roughness of the pipe;

N_{Re} : Reynolds number.

Figure 4. 7 presents the comparison of the measured pressure drop values versus the pressure drop calculated using Colebrook correlation. Calculated pressure drop values from Colebrook correlation match the experimental results with a closer margin of error than that of Jones correlation in this case.

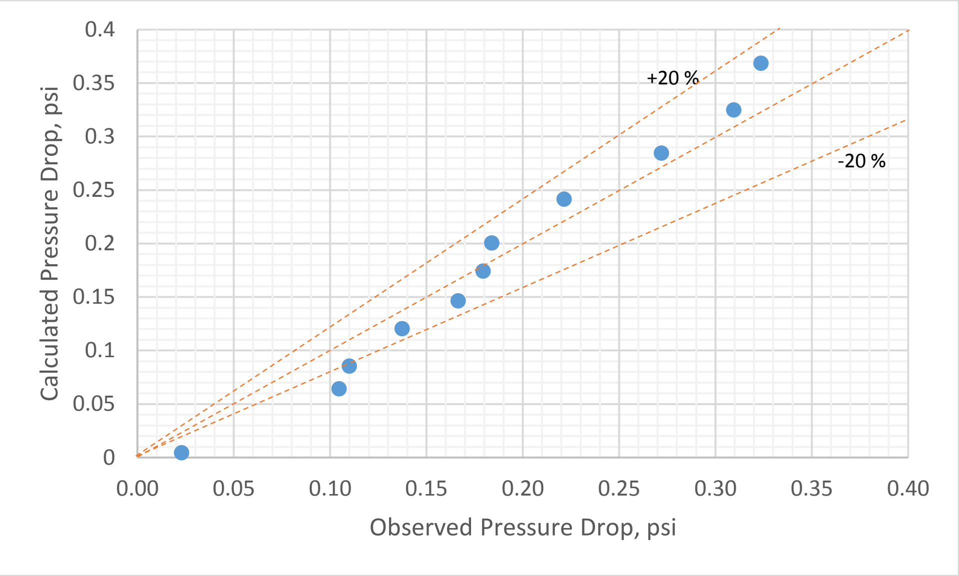

Figure 4. 7 Comparison between Experimental Data obtained from current study and calculated pressure drop using Colebrook correlations

Figure 4. 8 and 4. 9 present fanning friction factor versus Reynolds numbers of the fluid flow for water and polymer fluid respectively. In these figures experimental data are compared with the ones obtained from Jones and Colebrook correlations. For polymer the experimental data are compared with Virk's ultimate asymptote. As figure 4. 9 shows the experimental friction factors are higher than the Virk's Ultimate asymptote which is because these are not for maximum drag reduction condition presented by Virk et al. [59].

Virk et al. [59] conducted a theoretical analyses and defined the theoretical maximum of drag reduction (Virk's asymptote). They found the maximum drag reduction condition is reached when the wall boundary layer reaches to the center line of the fluid flow field.

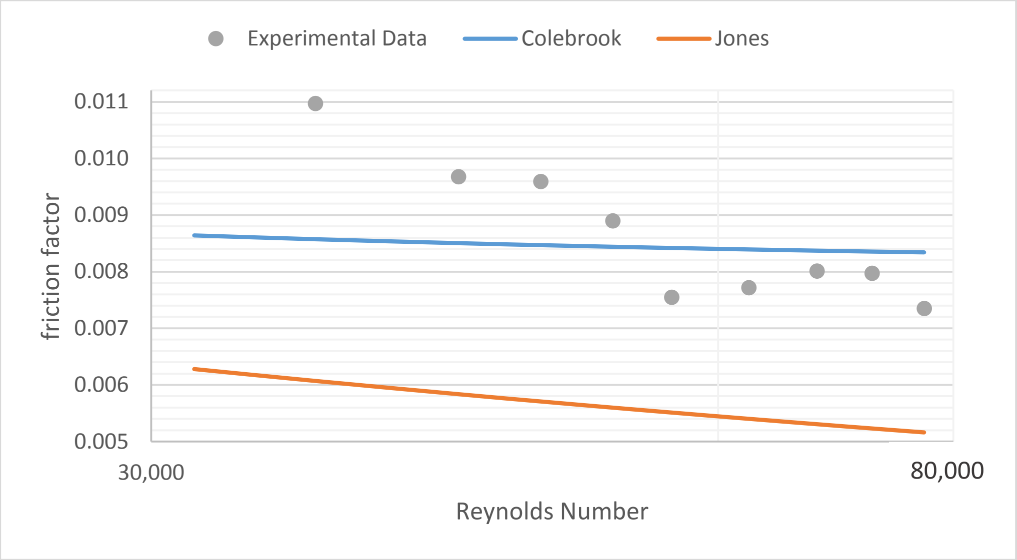

Figure 4. 8 Friction Factor vs. Reynolds Number (Water flow)

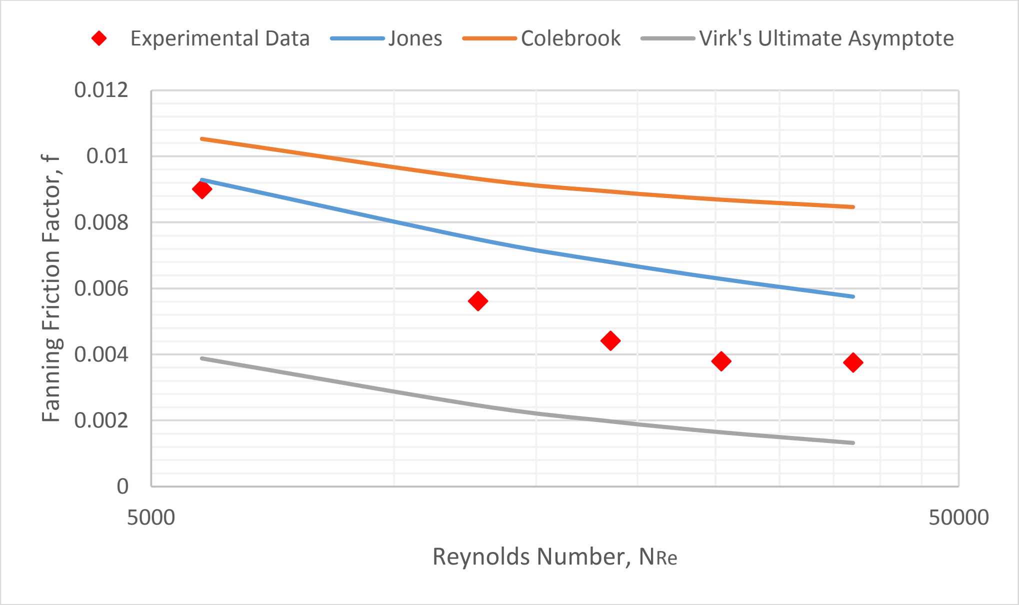

Figure 4. 9 Friction Factor vs. Reynolds Number (Polymer Flow)

The relationship between friction factor and Reynolds number for theoretical maximum drag reduction case (Virk's Asymptote) is given by Eq. 4.11.

$$f = 0.59 * N_{Re}^{-0.58} \qquad \text{(Eq. 4.11)}$$

The recommended range for above equation is Reynolds number between 4000 to 40,000 according to Virk et al. [59].

For polymer fluid flow the experimental data are also compared with Virk’s ultimate asymptote. As shown in figure 4.9 the experimental friction factors are higher than of the ones obtained from the Virk’s Ultimate asymptote [59] indicating that maximum drag reduction has not been reached under our experimental conditions.

Chapter V

EXPERIMENTAL PROGRAM OF CUTTINGS TRANSPORTATION

In this chapter, results of cuttings transport experiments with water and drag reducing fluid are reported. Cuttings transport efficiency of water and drag reducing fluid in horizontal concentric annuli is compared.

5.1.Experimental Procedure

A schematic view of the flow loop shown in figure 5. 1 should be referred to follow the description of the experimental procedure. The first task for conducting the cuttings transport experiments was to prepare the flow loop. Initially, cuttings are stored in the collection tank (#1). In order to inject the cuttings into the flow loop, solids have to be moved from cuttings collection tank (#1) to the cuttings injection tank (#2). The arrows on the blue line in figure 5. 1 shows the cuttings transportation path from collection tank to the injection tank. The liquid tank (#3) is filled up with water at room temperature. Then using the centrifugal pump (#4) the water is pumped at high flow rate (> 120 gpm) to the collection tank through the blue line shown in figure 5. 1. Due to the Bernoulli Effect created by the fluid flow under the collection tank (#1), the cuttings are sucked into the pipeline and are carried to the injection tank (#2). After carrying most of the cuttings to the injection tank (#2) some residual cuttings are still left in the collection tank which cannot be carried by this method. So another pipe line (#5) is connected to the top of the collection tank (#1) to allow flow of water through the collection tank (#1) in order to move all the cuttings down to the flow line to injection tank (#2).

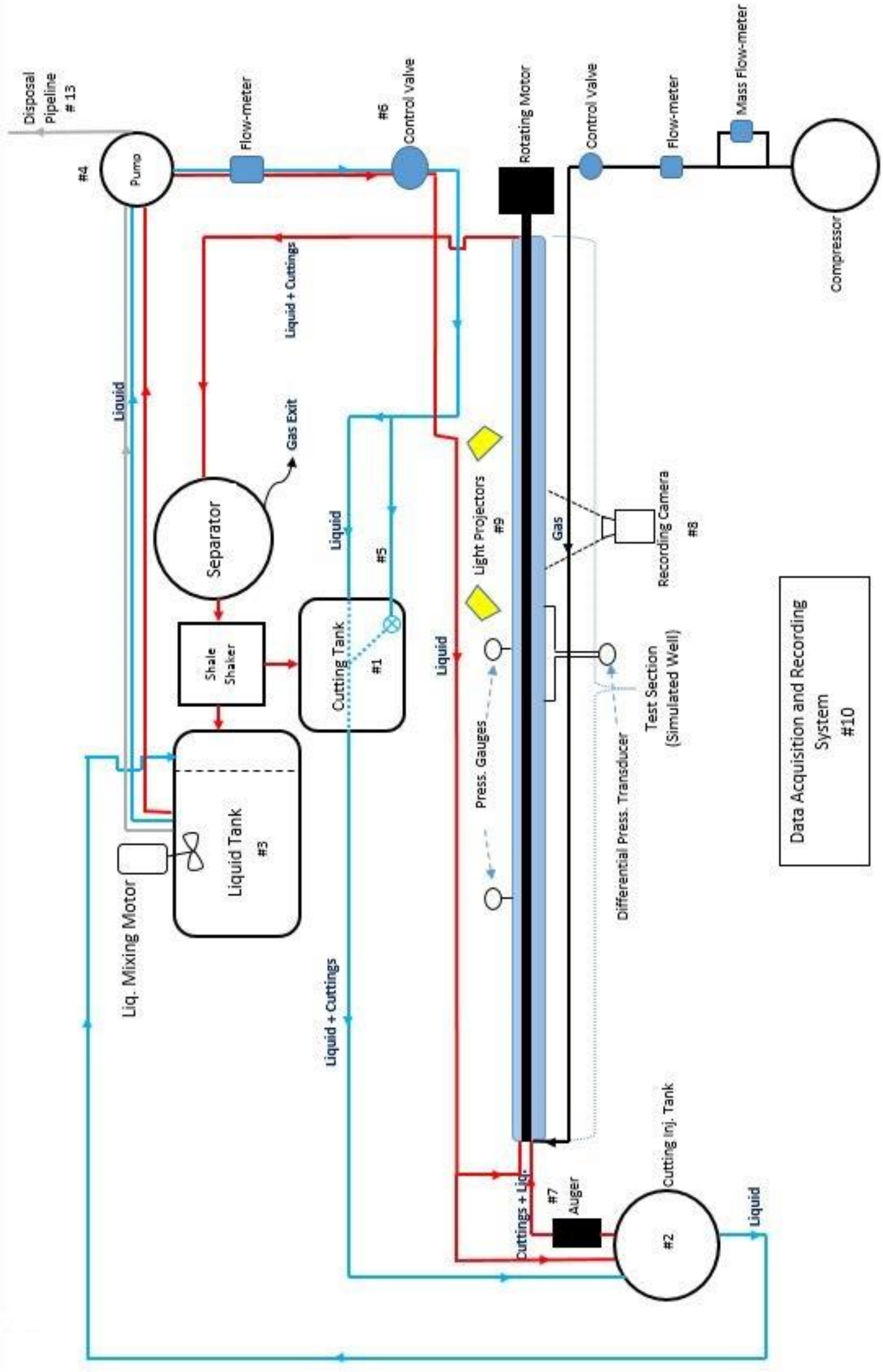

Figure 5. 1 Schematic of Experimental Set-Up

Once the cuttings are ready to be injected to the test section, test fluid (water or polymeric fluid) is prepared in the liquid tank (#3). First the fluid is pumped to the test section through the red line shown in the figure 5. 1. After the desired flow rate is reached (controlled by pneumatic control valve-#6) at steady state condition, the cutting are injected to the system at a controlled rate by means of speed controllable auger (#7) and simultaneously, the camera (#8) is started to record the particle movements and bed establishment. Once the two phase solid-liquid flow reaches steady state condition (i.e., constant cuttings bed height) the data acquisition system was started to record the data. Drilling fluid flow rate, frictional pressure drop, cuttings bed height are measured in addition to visual recording of the test section. Figure 5. 2 shows a picture of the cuttings bed at 60 gpm flow rate and 95 ft/hr rate of penetration using polymeric fluid as a test fluid.

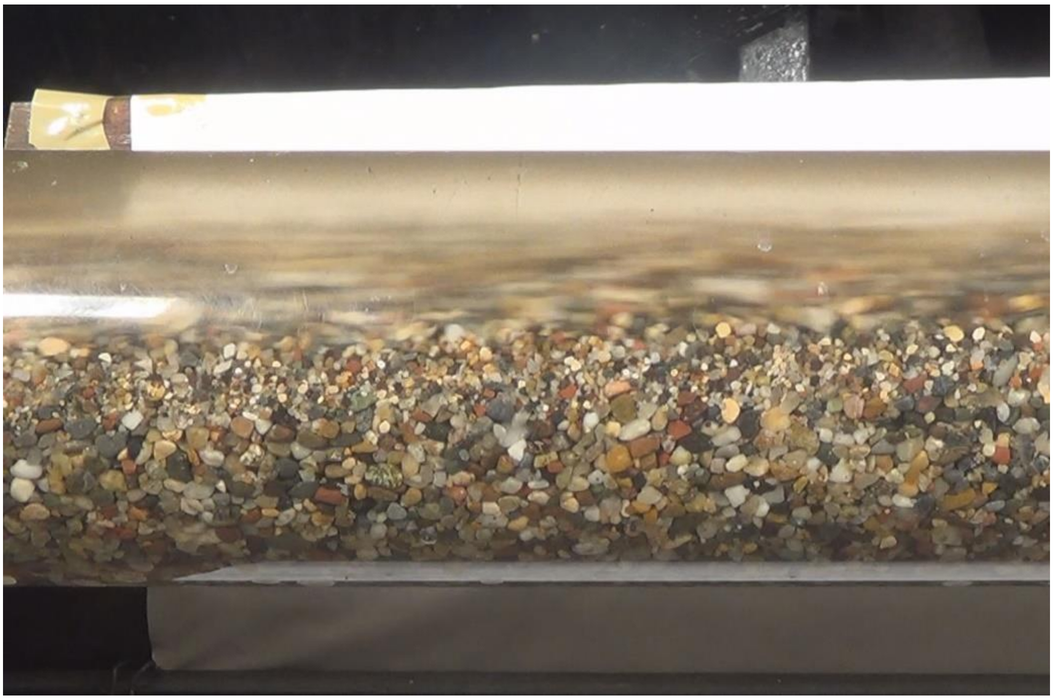

Figure 5. 2 Cuttings stationary bed (Res=39800, ROP=95 ft/hr, Test fluid: PHPA)

The fluid coming out of the test section goes in to the separator (#11) as shown in figure 5. 1 and then poured onto the shale shaker (#12). At this stage liquid and solid phases are separated and poured into liquid tank (#3) and cuttings collection tank (#1) respectively. After sufficient data is recorded data acquisition system (#10) is stopped recording data, then the camera (#8) and auger (#7) is turned off. After that fluid is circulated at high flow rates in order to clean the test section and then the circulated liquid is disposed using newly added pipeline (#13).

These stages are repeated for every experiments in order to record data at different flow rates, rates of penetration and fluid type.

5.1.1. Cuttings Bed Height Calculation

Cuttings bed height deposit is translated into annular area occupied by cuttings (Cuttings Area) and used for assessing cuttings transport efficiency of water and drag reducing fluids

Nomenclature used for cuttings bed height calculation is shown in Figure 5. 3. A ruler was attached around the outer pipe to measure the perimeter of the cuttings bed (red line shown in the Figure 5. 3, S_1). Then this measured line was converted to cuttings bed height by using the equations 5.1 to 5.6:

$$\alpha = \frac{180}{\pi * R_{out}} * S_1 \qquad \text{(Eq. 5.1)}$$

$$h' = R_{out} * (1 - \cos\alpha) \qquad \text{(Eq. 5.2)}$$

$$h = h' - (R_{out} - R_{in}) \qquad \text{(Eq. 5.3)}$$

$$A' = ({}^{2\alpha}/_{360})\pi r^2 \qquad \text{(Eq. 5.4)}$$

$$A = A' - [(r - h) * \sqrt{r^2 - (r - h)^2}] \qquad \text{(Eq. 5.5)}$$

$$CA = (A/A_{ann}) * 100 \qquad \text{(Eq. 5.6)}$$

where:

S_1: measured perimeter, cm;

R_{out} : Outer diameter of the casing, cm;

R_{in} : Inner diameter of the casing, cm;

h : Cuttings bed height, cm;

A : Cuttings Deposition Area, cm^2;

A_{ann} : Annular Cross-sectional Area, cm^2;

CA : Cuttings Bed Deposition Area Percentage, %.

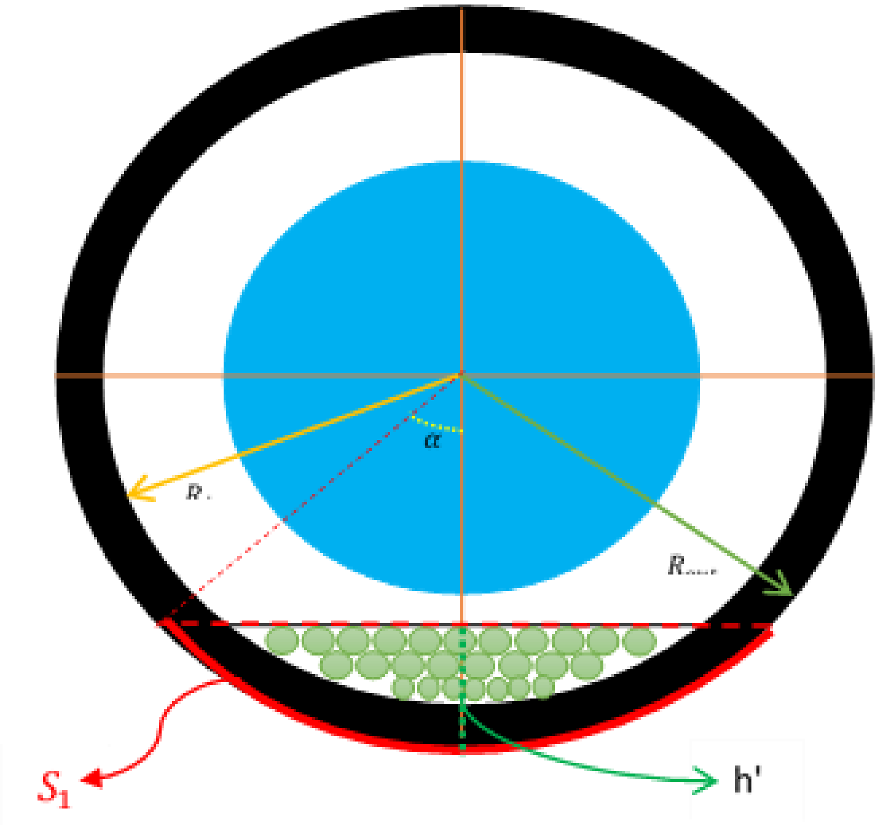

Figure 5. 3 Cuttings bed schematic diagram

5.2. Effect of Drilling Fluid Flow Rate on the Cuttings Area

Figure 5. 4 and Figure 5. 5 shows the area of annulus occupied by cuttings (cuttings area) versus fluid superficial velocity for water and drag reducing fluid.

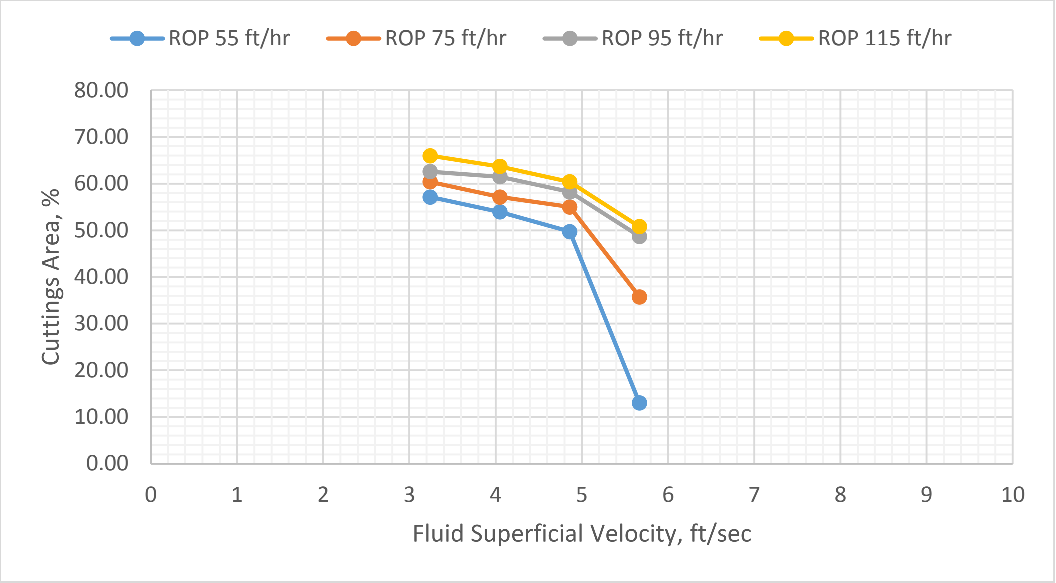

Figure 5. 4 Cuttings area vs. water superficial velocity at different rates of penetration.

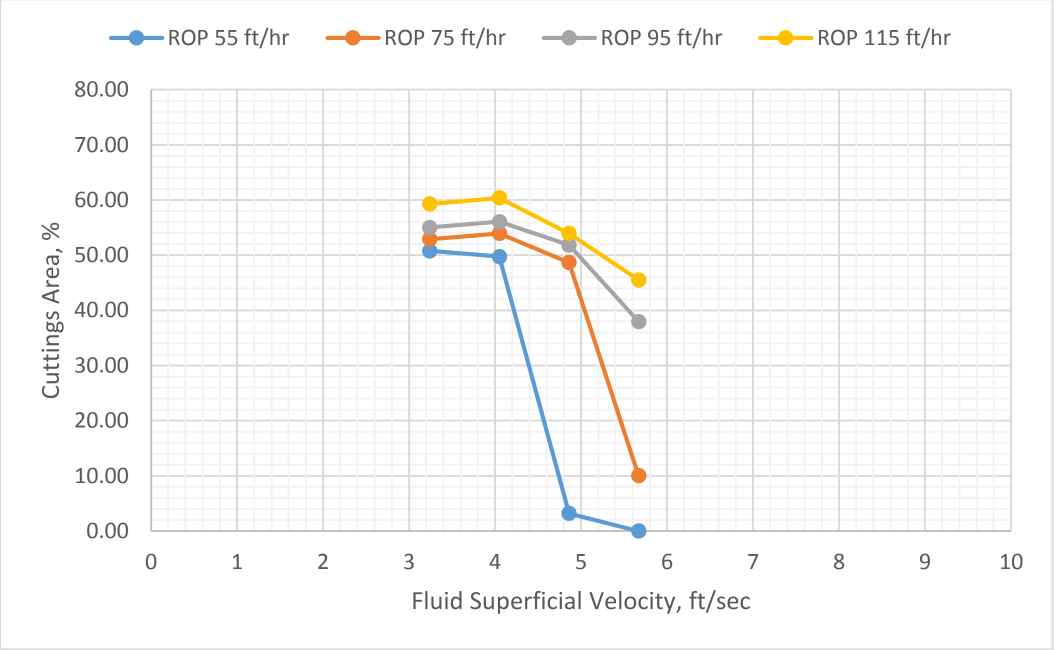

Figure 5. 5 Cuttings area vs. drag reducing fluid (0.07 % wt/wt polymer concentration) superficial velocity at different rates of penetration

As Figure 5. 4 and Figure 5. 5 show cuttings area decrease with increasing fluid superficial velocity. This happens due to increase of the turbulence of the flow with increasing the fluid flow rate which is a key factor in hole cleaning. Figure 5. 6 shows the rate of percent reduction in cuttings area with the increasing water flow rate at different drilling rates. As shown in Figure 5. 6 rate of cuttings bed area reduction becomes more dominant at higher fluid velocities.

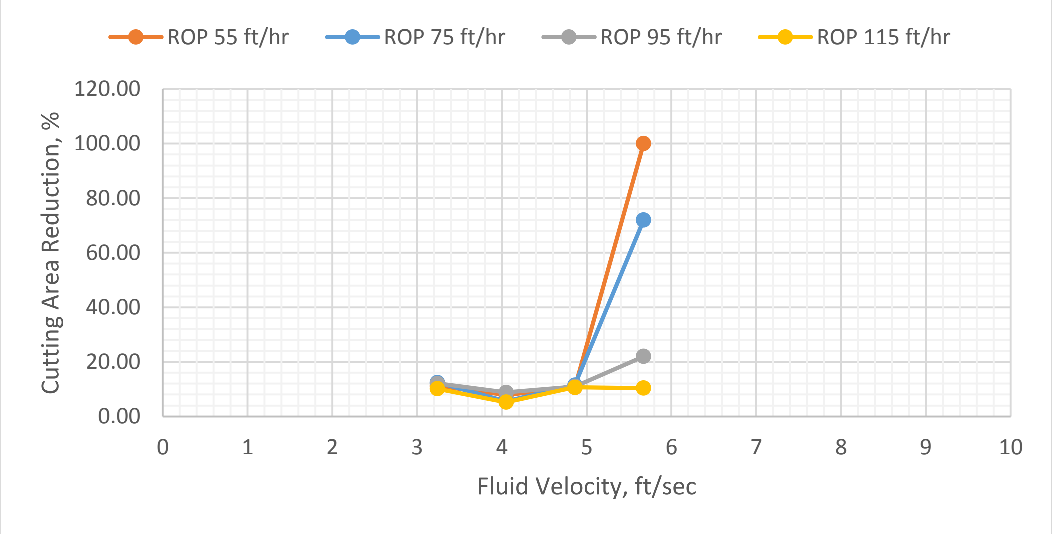

Figure 5. 6 Cuttings area reduction vs. fluid superficial velocity at different drilling rates (0.07 % wt/wt polymer concentration)

Figure 5. 7 shows the effect of fluid superficial velocity, on drag reduction effectiveness. Increasing fluid velocity enhances the drag reduction effectiveness at all drilling rates, which was also observed by previous studies as well [4], [12], [59], [1].

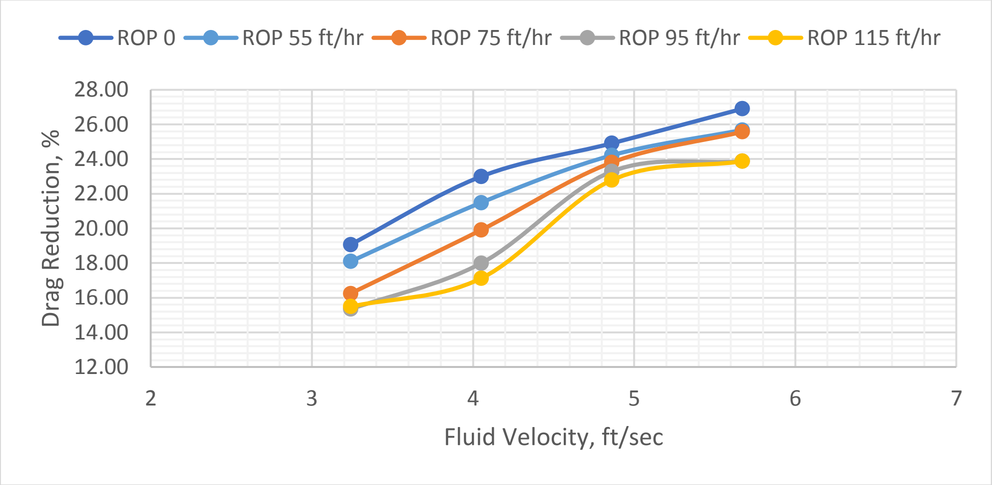

Figure 5. 7 Drag reduction vs. fluid velocity at different drilling rates (0.07 % wt/wt polymer concentration)

Figure 5. 8 summarizes the effect of polymer concentration of the drilling fluid on the cuttings area. It indicates that using the drilling fluid yielding the highest drag reduction (with 0.07 % wt/wt polymer

concentration) also resulted in the lowest cuttings bed height in the horizontal annuli. In other words, the drilling fluid causing the maximum drag reduction also resulted the most efficient cuttings transport.

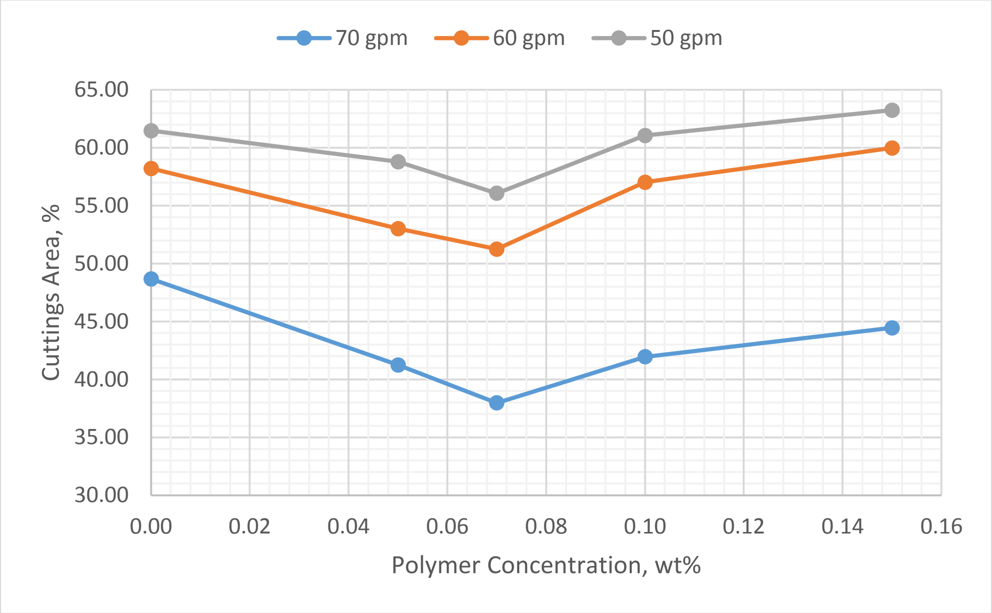

Figure 5. 8 Cuttings area vs. polymer concentration at three different flow rates and 95 ft/hr rate of penetration

5.3. Frictional Pressure Drop Due to Flow of Water and Drag Reducing Fluid with cuttings

Figure 5. 9 and Figure 5. 10 shows the pressure drop data versus fluid superficial velocity obtained for both water and drag reducing fluid (0.07 % wt/wt polymer concentration) flow respectively, with cuttings at different rate of penetration (changing from 0 to 115 ft per hour).

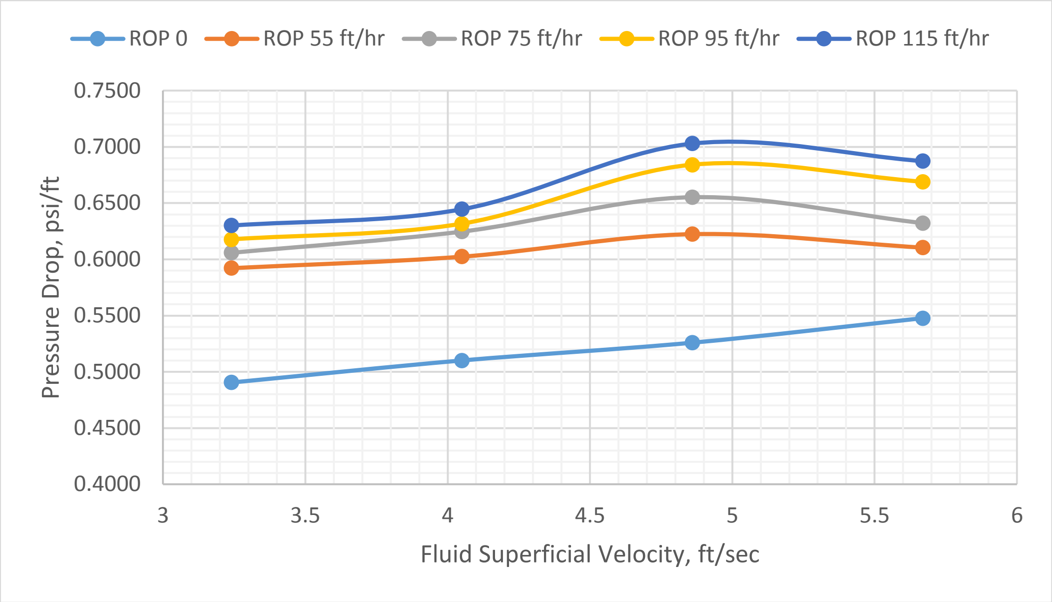

Figure 5. 9 Pressure drop vs. water superficial velocity at different rates of penetration

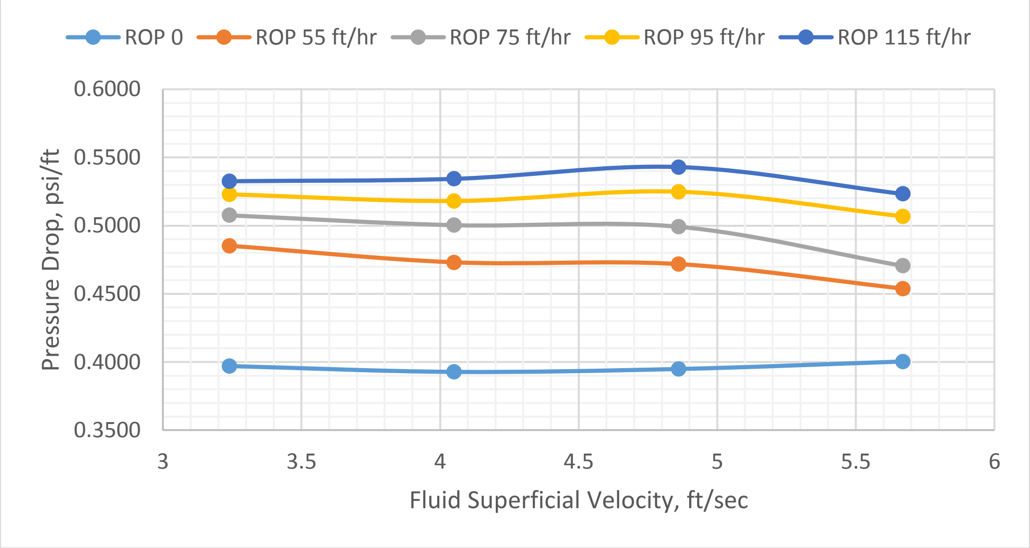

Figure 5. 10 Pressure drop vs. drag reducing fluid (0.07 % wt/wt polymer concentration) superficial velocity at different rates of penetration

As Figure 5. 9 and Figure 5. 10 indicate pressure drop increase with the increasing fluid velocity; but after some points, it starts to decrease due to the reduction in the cuttings area (i.e. increasing area open for flow).

Figures 5. 11 to 5. 15 show the comparison of frictional pressure drop versus fluid superficial velocity at different rates of penetrations for water and drag reducing fluid. Figure 5. 11 is when no cuttings were injected into test section. It is shown that with increasing the fluid velocity pressure drop increases monotonically. But when cuttings are injected (5. 12 to 5. 15) frictional pressure losses increases with increasing flow rate only up to a certain point. Beyond this point, with further increase in fluid velocity, cuttings bed start to move and cuttings depositional height decreases and then the area open for fluid flow is increased; therefore, a decrease in pressure losses is seen. Same trend is seen for cuttings transport both with water and polymer fluid. However, for polymer fluid case, the slope of the pressure drop line is lower than that of water.

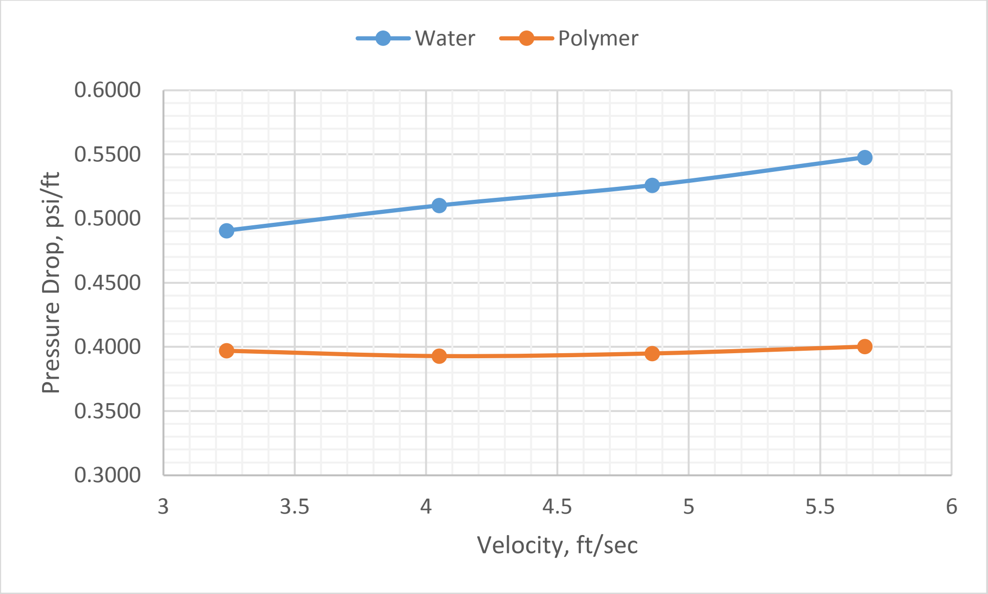

Figure 5. 11 Frictional pressure drop vs. Fluid superficial velocity for single phase fluid flow (no cuttings)

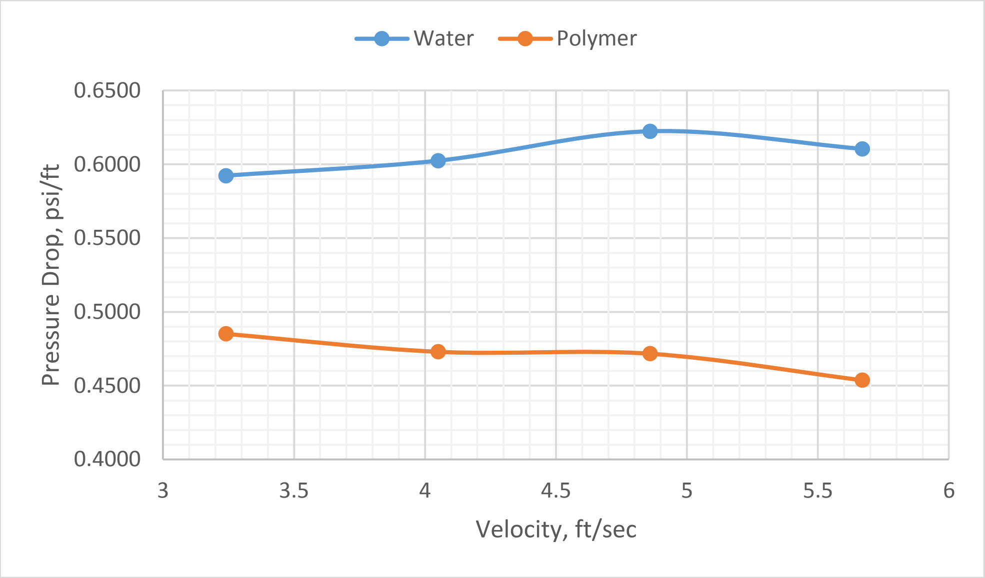

Figure 5. 12 Frictional pressure drop vs. fluid superficial velocity for 55 ft/hr rate of penetration

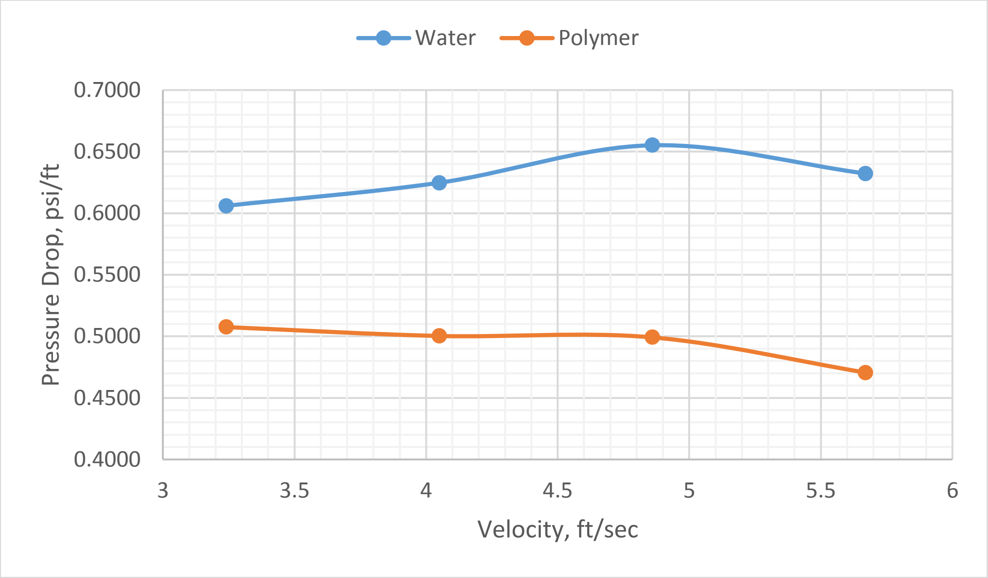

Figure 5. 13 Frictional pressure drop vs. fluid superficial velocity for 75 ft/hr rate of penetration

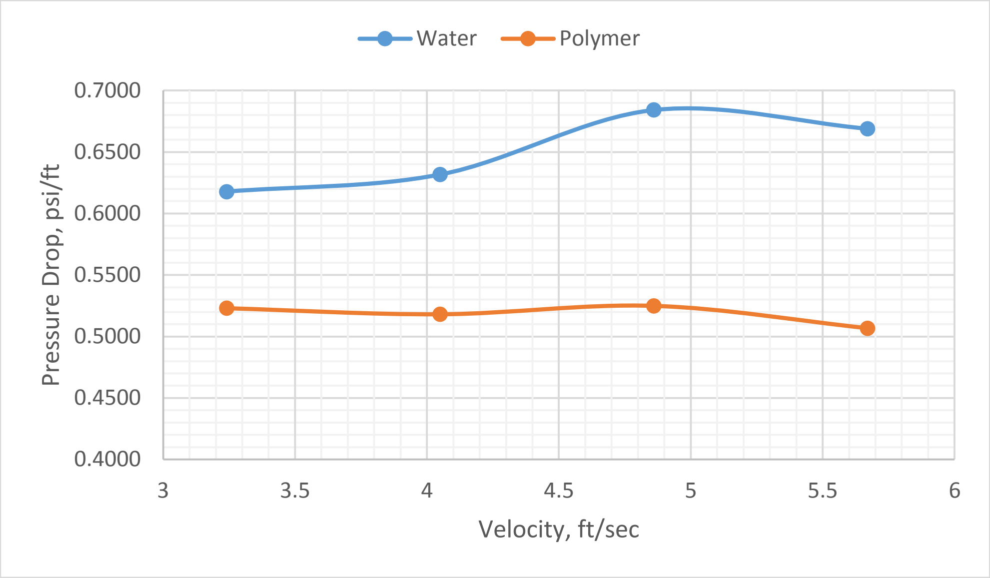

Figure 5. 14 Frictional pressure drop vs. fluid superficial velocity for 95 ft/hr rate of penetration

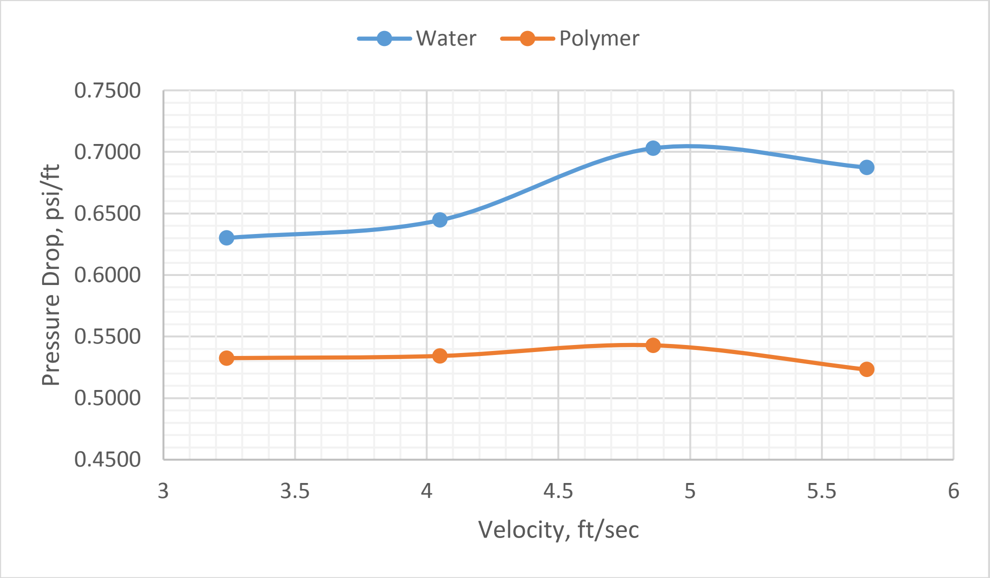

Figure 5. 15 Frictional pressure drop vs. fluid superficial velocity for 115 ft/hr rate of penetration

5.4. Effect of Drilling Fluid Rheological Characteristics on the Cuttings Area

In order to investigate the drilling fluid rheology effect on cuttings transportation, water and polymeric fluids prepared with different polymer concentrations were used. Figure 5. 16 shows the shear stress versus shear rate characteristics of polymer fluids. Figure 5. 17 shows how the viscosity of polymer fluids change with shear rate.

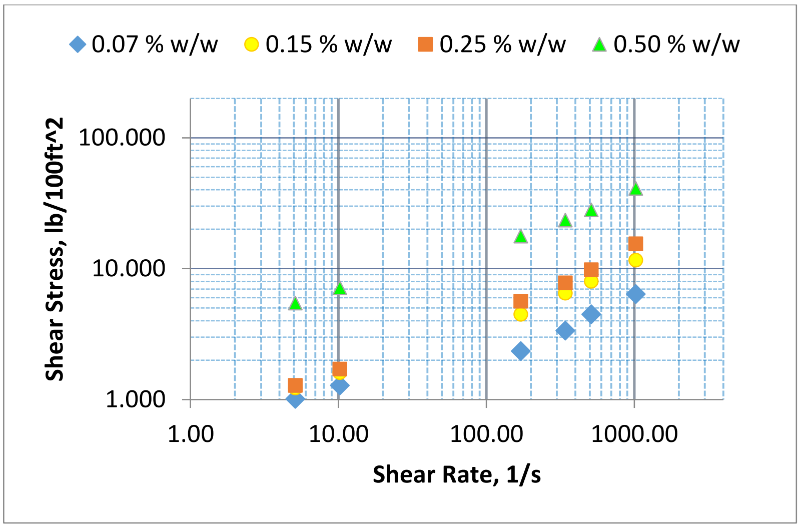

Figure 5. 16 Rheological properties of the high concentration polymer fluids

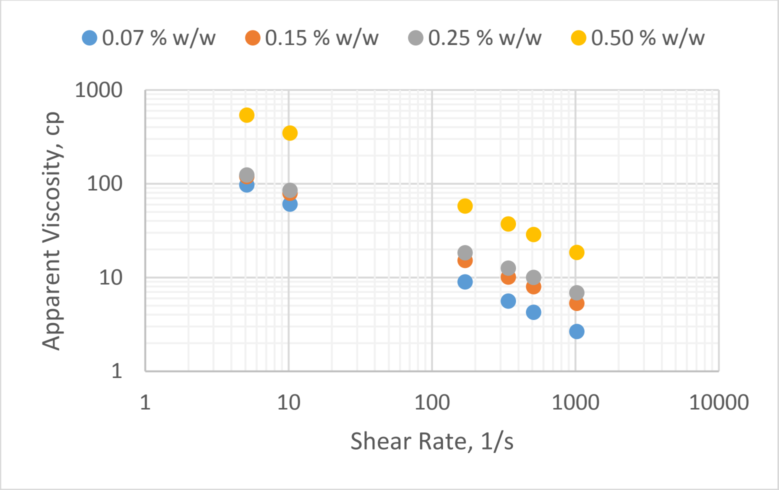

Figure 5. 17 Apparent Viscosity of the high concentration polymer fluids

As shown in Figure 5. 17 apparent viscosity increases with increasing the polymer concentration. Effect of drilling fluid viscosity on the cuttings transport efficiency is shown in figure 5. 18 at different drilling rates.

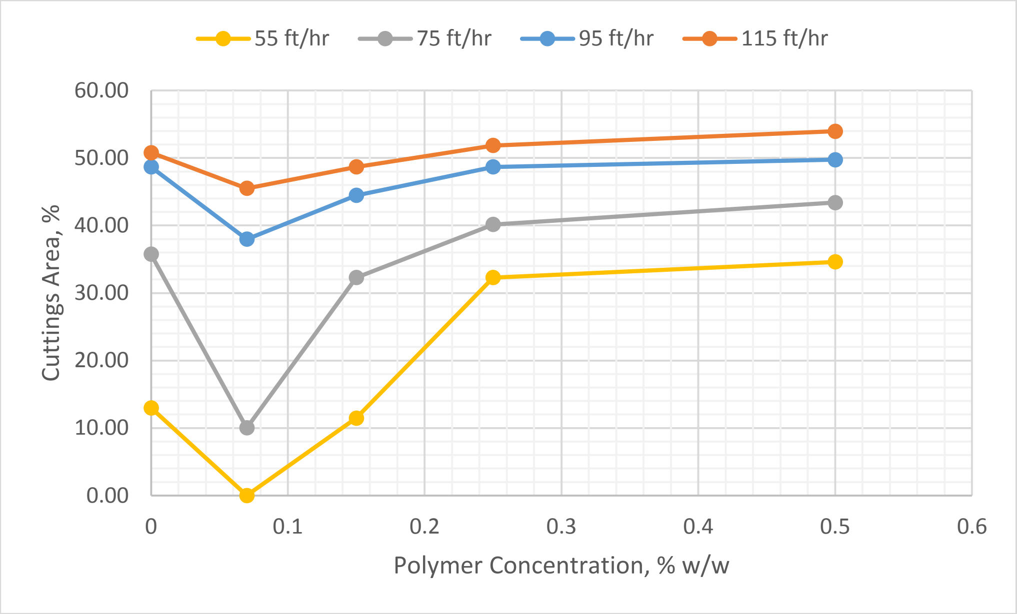

Figure 5. 18 Cuttings Area vs. Polymer Concentration at different rates of penetration

As shown in figure 5. 18, at some critical polymer concentration (0.07% wt/wt, where fluid shows highest drag reduction effect), cuttings transportation is better comparing to water as a drilling fluid. Also as the polymer concentration is increased higher than a critical level (i.e. 0.07% wt/wt corresponding to maximum drag reduction effect) cuttings carrying capacity of drilling fluids decreases. In other words, increasing the viscosity above some critical level has adverse effect in terms of cutting transport efficiency of the fluid.

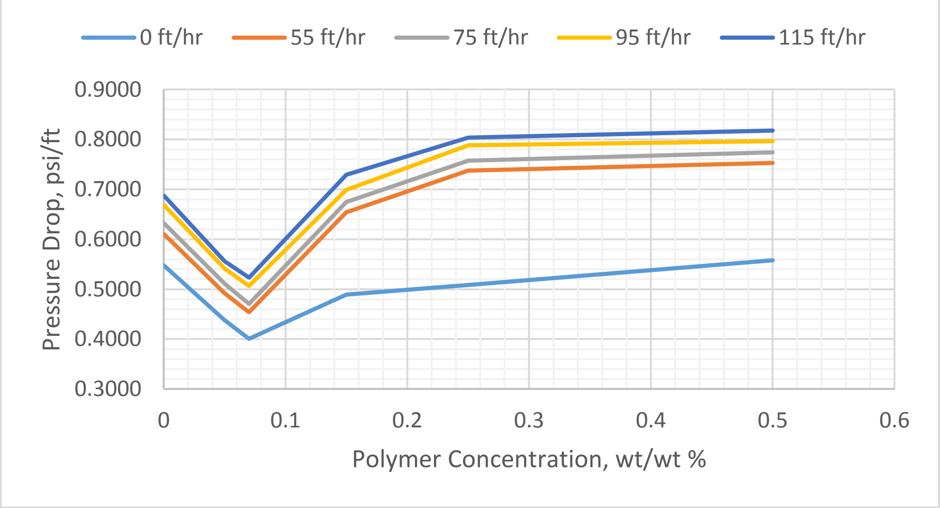

Figure 5. 19 Pressure drop vs. polymer concentration at different rates of penetration

Figure 5. 19 presents results for pressure drop versus polymer concentration at different rates of penetrations. Similar to trends shown in figure 5. 18, results in figure 5. 19 also indicate that minimum pressure losses occurred when using optimum PHPA concentartion (0.07 % wt/wt) for all drilling rates.

Figure 5. 20 presents data of cuttings area versus drilling rate for different polymer concentrations. The experiments showed that with increasing the drilling rate (cuttings injection rate) for all polymer concentrations, cuttings accumulation in the well bore increases as well. It is also seen that minimum cuttings accumulation (most efficient transportation of the cuttings) occurred when using polymer fluid with optimum polymer concentration (0.07 % wt/wt).

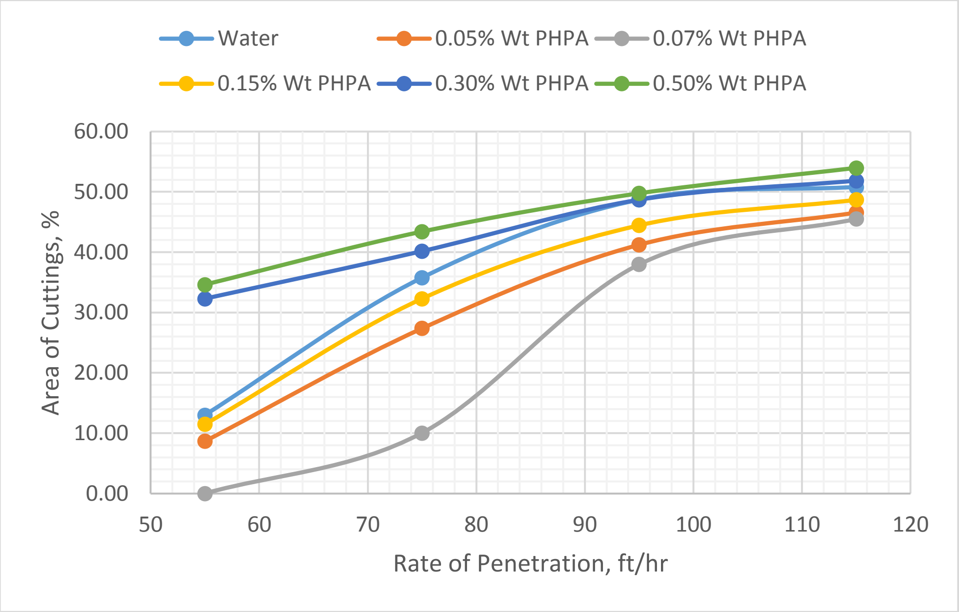

Figure 5. 20 Cuttings Area vs. Rate of penetration for different polymer concentrations (Res=47,000)

Chapter VI

CONCLUSIONS AND RECOMMENDED FUTURE WORK

In this chapter, summary of the most important findings and conclusions of this research are presented. Recommendations for future work is also presented in this chapter.

6.1. Drag Reduction phenomena in Horizontal Concentric Annuli

The main findings of the research from experimental study of the drag reduction phenomena in horizontal concentric annuli are as follows:

- Different PHPA concentrations varied from 0.05 % wt/wt to 0.12 % wt/wt was tested. Based on maximum pressure drop reduction, drag reduction, was found to be the minimum at polymer concentration of 0.07 % wt/wt.
- Drag reduction is increased with increasing the fluid velocity (Reynolds number). But after some point drag reduction start to decrease with increasing the Reynolds number due to polymer molecule degradation (breaking of the heavy weight polymer molecules into smaller molecules). Solvent Reynolds number varied from 9,500 to 100,000 and maximum drag reduction was found to be about 38 % at 66,400 solvent Reynolds number.
- It can be concluded that by adding drag reducing agent to drilling fluids frictional pressure drop in the borehole can be is decreased; so the fluid can be pumped at higher flow rate which is desirable.

6.1.1. Cuttings Transport Performance of Water versus Drag Reducing Fluids

The main findings of this research from experimentally study of cuttings transport performance of water versus drag reducing fluids are as follows:

- Experiments showed that a direct relation exists between cuttings area and rate of penetration. Increasing the injection rate of cuttings (increasing ROP) resulted in more cutting accumulation in the wellbore for both water and drag reducing fluid for all flow rates.
- Cuttings area is decreased with the increasing fluid velocity for both water and drag reducing fluid.
- Increasing cuttings area (or cuttings accumulation) in the annuli results in more frictional pressure losses.
- The optimum value of the polymer concentration (0.07 % wt/wt) resulted in lowest cuttings area in the annuli.
- Increasing the fluid viscosity may not be an effective solution for cuttings transportation problem at high flow rates.

6.2. Future Work

Followings are recommended for future work:

- ✓ Investigate the effect of other parameters on cuttings transport such as drill pipe rotation, solids properties, hole inclination, temperature.
- ✓ Investigate the cuttings transportation with multi-phase drag reducing fluid (Drag reducing fluid-Gas-Solids).
- ✓ Simulate the cuttings transport using CFD coding and develop numerical model.

- ✓ More accurate and successful results can be obtained using image analysis technique by means of two or three high speed camera recording of the experiments from different directions.

REFERENCES

[1] C. Ercan and M. E. Ozbayoglu, ""PHPA" as a Frictional Pressure Loss Reducer and Its Pressure Loss Estimation," in *SPE/IADC Middle East Drilling Technology Conference and Exhibition*, Manama, Bahrain, 2009.

[2] G. Jiimaa, Cuttings Transport Models and Parametric Studies in Vertical and Devieated Wells, Stavager, Norway: University of Stavanger, 2013.

[3] S. N. Shah, A. Kamel and Zhou, "Drag Reducing Characteristics in Straight and Coiled Tubing-An Experimental Study," *Journal of Petroleum Science and Engineering,* no. 53, pp. 179-188, 2006.

[4] B. A. Toms, "Some Observation on the Flow of Linear Polymer Solutions Through Straight Tubes at Large Reynolds Numbers," Amesterdam, Netherland, North Holland Publication Company, 1948, pp. 135-141.

[5] J. G. Savings, "Drag Reduction Characteristics of Solution of Macromolecules in Turbulent Pipe Flow," in *AlChE meeting*, Houston, Texas, USA, 1963.

[6] J. L. Lumley, "Drag Reduction By Additives," in *Annual Reviews of Fluid Mechanics*, vol. 1, Palo Alto, Calif, 1969.

[7] J. W. Hoyt, "A Turbulent Flow Rheometer," in *Symposium on Rheology*, New York, 1965.

[8] J. L. Lumley, "Drag Reduction in Turbrlent Flow by Polymer Additives," *Journal of Polymer Science-Macromolecular Reviews,* pp. 263-290, 1973.

[9] J. H. Hand and M. C. Williams, *Journal of Applied Polymer Science,* vol. 13, pp. 249-503, 1969.

[10] J. H. Hand and M. C. Williams, *Nature,* vol. 70, pp. 227-369, 1970.

[11] T. J. Black, "Viscous Drag Reduction Examined in the Light of a New Model of Wall Turbulence," in *Viscous Drag Reduction*, New York, Plenum Press, 1969, pp. 383-407.

[12] P. S. Virk, "Drag Reduction Fundamentals," *AlChe Journal,* vol. 21, pp. 625-656, 1975.

[13] A. Abubakar, T. Al-Wahaibi, Y. Al-Wahaibi, A. R. Al-Hashmi and A. Al-Ajmi, "Roles of Drag Reducing Polymers in Single and Multi-Phase Flows," *Chemical Engineering Research and Design,* vol. 92, pp. 2153-2181, 2014.

[14] G. V. Nesyn, V. N. Manzhai, Y. V. Suleimanova, V. S. Stankevich and K. B. Konovalov, "Polymer Drag Reducing Agents for Transportation of Hydrocarbon Liquids: Mechanism of Action, Estimation of Efficiency, and Features of Production," *Polymer Science,* vol. 54, pp. 61-67, 2012.

[15] H. R. Crawford and G. T. Pruitt, "Drag Reduction of Dilute Polymer Solutions," in *Symposium on Non-Newtonian Fluid Mechanics, 5th Annual Meeting A.I.Ch.E.,* Houston, Texas, USA, 1963.

[16] A. G. Fabula, "The Toms Phenomenon in the Turbulent Flow of Very Dilute Polymer Solutions," in *4th International Congress on Rheology,* Providence, R.I., 1963.

[17] P. K. Ptasinski, F. T. M. Nieuwstadt and B. H. A. A. H. M. A. Van Den Brule, "Experiments in Turbulent Pipe Flow with Polymer Additives at Maximum Drag Reduction," *Turbulance and Combustion,* vol. 66, pp. 159-182, 2001.

[18] F. E. Rodriguez Corredor, M. Bizhani and E. Kuru, "Experimental Investigation of Drag Reducing Fluid Flow in Annular Geometry Using Particle Image Velocimetry Technique," *Journal of Fluids Engineering,* vol. 137, pp. 1-16, 2015.

[19] W. Interthal and H. Wilski, "Drag Reduction experiments with very Large Pipes," *Colloid and Polymer Science,* vol. 263, pp. 217-229, 1985.

[20] H. R. Karami and D. Mowla, "Investigation of the effects of various parameters on pressure drop reduction in Crude Oil Pipelines by Drag Reducing Agents," *Journal of Non-Newtonian Fluid Mechanics,* Vols. 177-178, pp. 37-45, 2012.

[21] P. S. Virk, "Drag Reduction in Rough Pipes," *Journal of Fluid Mechanics,* vol. 45, no. 2, pp. 225-246, 1971.

[22] T. R. Sifferman and R. A. Greenkorn, "Drag Reduction in Three Distinctly Different Fluid Systems," *Society of Petroleum Engineers Journal,* pp. 663-669, 1981.

[23] C. E. Williams JR. and G. H. Bruce, "Carrying Capacity of Drilling Muds," in *Petroleum Transactions, AIME*, New Orleans, LA, USA, 1951, pp. 111-120.

[24] M. E. Charles, "Transport of Solids by Pipeline," in *1st International Conference on the Hydraulic Transport of Solids in Pipes*, Coventry, United Kingdom, 1970.

[25] K. C. Wilson, "Co-ordinates for the Limit of Deposition in Pipeline Flow," in *3rd International Conference on the Hydraulic Transport of Solids in Pipes*, Golden, Colorado, USA, 1974.

[26] K. C. Wilson, "A Unified Physically-Based Analysis of Solid-Liquid Pipeline Flow," in *4th International Conference on the Hydraulic Transport of Solids in Pipes*, Golden, Colorado, USA, 1976.

[27] K. C. Wilson, "Bed Load Transport at High Shear Stress," *Journal of Hydr. Div.*, vol. 113, pp. 97-103, 1987.

[28] Y. Televantos, C. Shook, A. Carleton and M. Streat, "Flow of Slurries of Coarse Particles at High Solids Concentrations," *The Canadian Journal of Chemical Engineering*, vol. 57, pp. 255-262, 1979.

[29] A. W. Iyoho, Drilled Cuttings Transport by Non-Newtonian Drilling Fluids Through Inclined Eccentric Annuli, Tulsa, Oklahoma, USA: University of Tulsa, 1980.

[30] S. O. Okranji, "Mud Cuttings Transport Study in Directional Well Drilling," University of Tulsa, Tulsa, Oklahoma, USA, 1981.

[31] P. H. Tormen, A. W. Iyoho and J. J. Azar, "Experimental Study of Cuttings Transport in Directional Wells," *SPE Drilling Engineering*, pp. 43-56, 1986.

[32] P. Doron, D. Grancia and D. Barnea, "Slurry Flow in Horizontal Pipes-Experimental and Modeling," *International Journal of Multiphase Flow*, vol. 13, pp. 535-547, 1987.

[33] W. J. Meano, Experimental Study of Shale Cuttings Transport in an Inclined Annulus Using Mineral Oil-Base Mud, Tulsa, Oklahoma, USA: University of Tulsa, 1987.

[34] A. S. Bin-Haddah, Development of Models for Drill Cuttings Trasnport in Inclined Wells Based on Deposition Critical Velocity Concept, Tulsa, Oklahoma, USA: University of Tulsa, 1988.

[35] N. P. Brown, P. A. Bern and A. Weaver, "Cleaning Deviated Holes: New Experimental and Theoretical Studies," in *SPE/IADC Drilling Conference*, New Orleans, Louisiana, USA, 1989.

[36] T. R. Sifferman and T. E. Becker, "Hole Cleaning in Full-Scale Inclined Wellbores," in *SPE 65th Annual Technical Conference*, New Orleans, Louisiana, USA, 1990.

[37] J. T. Ford, J. M. Peden, E. G. Oyeneyin and R. Zarrough, "Experimental Investigation of Drilled Cuttings Transport in Inclined Boreholes," in *SPE 65th Annual Technical Conference*, New Orleans, Luisiana, USA, 1990.

[38] A. L. Martins and C. Santana, "Evaluation of Cuttings Transport in Horizontal and Near Horizontal Wells-A Dimensionless Approach," in *SPE 2nd Latin American Petroleum Engineering Conference*, Caracas, Venezuela, 1992.

[39] T. Hemphill, "Research Solving Problems in Cuttings Transport," *The American Oil & Gas Reporter*, pp. 32-37, 1992.

[40] T. R. Sifferman and T. E. Becker, "Hole Cleaning in Full Scale Inclined Wellbores," *SPE Drilling Engineering*, 1992.

[41] P. Doron and D. Barnea, "A Three-Layer Model for Solid-Liquid Flow in Horizontal Pipes," *International Journal of Multiphase Flow,* vol. 19, pp. 1029-1043, 1993.

[42] A. Saasen, "Hole Cleaning During Deviated Drilling-The Effect of Pump Rate and Rheology," in *SPE European Petroleum Conference*, Hague, Netherland, 1998.

[43] S. Walker and J. Li, "The Effect of Particle Size, Fluid Rheology, and Pipe Eccentricity on Cuttings Transport," in *SPE/ICoTA Coiled Tubing Rountable*, Houston, Texas, USA, 2000.

[44] A. Saasen and G. Lonklingholm, "The Effect of Drilling Fluid Rheological Properties on Hole Cleaning," in *IADC/SPE Drilling Conference*, Dallas, Texas, USA, 2002.

[45] I. Kjosnes, G. Loklingholm, A. Saasen, A. Syrstad and K. A. Solvang, "Successful Water Based Drilling Fluid Design for Optimizing Hole Cleaning and Hole Stability," in *SPE/IADC Middle East Drilling Technology Conference and Exhibition*, Abu Dhabi, UAE, 2003.

[46] J. Li and G. Wilde, "Effect of Particle Density and Size on Solids Transport and Hole Cleaning With Coiled Tubing," in *SPE/ICoTA*

Coiled Tubing Conference and Exhibition, Woodlands, Texas, USA, 2005.

[47] M. E. Ozbayoglu, A. Saasen, M. Sorgun and K. Svanes, "Estimating Critical Velocity to Prevent Bed Development for Horizontal-Inclined Wellbores," in *SPE/IADC Middle East Drilling and Technology Conference*, Cairo, Egypt, 2007.

[48] H. I. Bilgesu, N. Mishra and S. Ameri, "Understanding the Effect of Drilling Parameters on Hole Cleaning in Horizontal and Deviated Wellbores Using Computationnal Fluid Dynamics," in *Eastern Regional Meeting*, Lexington, Kentucky, USA, 2007.

[49] M. Yu, E. Takach, D. R. Nakamura and S. M. M., "An Experimental Study of Hole Cleaning Under Simulated Downhole Conditions," in *SPE Annual Technical Conference and Exhibition*, Anaheim, California, USA, 2007.

[50] Y. Li, N. Bjorndalen and E. Kuru, "Numerical Modeling of Cuttings Transport in Horizontal Wells Using Conventional Drilling Fluids," *Journal of Canadian Petroleum Conference*, vol. 46, 2007.

[51] M. Duan, S. Miska, M. Yu, N. Takach and R. Ahmed, "Critical Conditions for Effective Sand-Sized Solids Transport in Horizontal and High Angle Wells," in *The Production And Operations Symposium*, Oklahoma City, Oklahoma, USA, 2007.

[52] M. Duan, S. Miska, M. Yu, N. Takach and A. Ramadan, "Transport of Small Cuttings in Extended-Reach Drilling," *SPE Drilling & Completion*, vol. 23, pp. 258-265, 2008.

[53] A. Piroozan, I. Ismail, Z. Yaacob, P. Babakhani and A. Shamsul I. I., "Impact of Drilling Fluid Viscosity, Velocity and Hole inclination on Cuttings Transport in Horizontal and Highly Deviated Wells," *Journal of Petrol Explor Prod Technol*, pp. 149-156, 2012.

[54] L. J. and B. Luft, "Overview of Solids Transport Studies and Applications in Oil and Gas Industry-Experimental Work," in *SPE Russian Oil and Gas Exploration and Production Technical Conference and Exhibition*, Moscow, Russia, 2014.

[55] N. B. Wyatt, C. M. Gunther and M. W. Liberatore, "Drag Reduction Effectiveness of Dilute and Entahgled Xanthan in Turbulent Pipe Flow," *Journal of Non-Newtownian Fluid Mechanics, ELSEVIER*, vol. 166, pp. 25-31, 2010.

[56] J. W. Hoyt, "Drag Reduction by Polymers and Surfactants, Viscous Drag Reduction in Boundry Layers," 1989.

[57] O. C. Jones Jr. and J. C. M. Leung, "An Improvment in the Calculation of Turbulent Friction in Smooth Concentric Annuli," *Journal of Fluids Engineering,* vol. 103, pp. 615-623, 1981.

[58] C. F. Colebrook, "Turbulent Flow in Pipes with Practical Reference to the Transition Region between the Smooth and Rough Pipe Laws," *Journal of Inst. Civil Engineers,* 1938.

[59] P. S. Virk, H. S. Mickley and K. A. Smith, "The Ultimate Asymptote and Mean Flow Structure in Toms' Phenomenon," *Journal of Applied Mechanics,* pp. 488-493, 1970.

[60] F. E. Rodriguez-Corredor, M. Bizhani and E. Kuru, "An Experimental Study of The Effect of Drag Reducing Additives on The Structure of Turbulence in Concentric Annular Pipe Flow Using Particle Image Velocimetry Technique," in *ASME International Mechanical Engineering Congress & Exhibition (IMECE)*, San Diego, California, USA, 2013.

[61] P. H. Tormen, A. W. Iyoho and J. J. Azar, "Experimental Study of Cuttings Transport In Directional Wells," *SPE Drilling Engineering,* pp. 43-56, 1986.

[62] T. J. Larsen, A. A. Pilevari and J. J. Azar, "Development of a New Cuttings-Transport Model For High-Angle Wellbores Including Horizontal Wells," *SPE Drilling & Completion,* pp. 129-135, 1997.

[63] H. Cho, S. N. Shah and S. O. Osisanya, "A Three-Segment Hydraulic Model for Cuttings Transport in Horizontal and Deviated Wells," in *SPE/Petroleum Society of CIM International Conference on Horizontal Well Technology*, Calgary, Alberta, Canada, 2000.

[64] I. Kjosnes, G. Loklingholm, A. Saasen, S. O. Syrstad, A. Agle and K. A. Solvang, "Successsful Water Based Drilling Fluid Design for Optimizing Hole Cleanig and Hole Stability," in *SPE/IADC Middle East Drilling Technology Conference & Exhibition,* Abu Dhabi, UAE, 2003.

[65] J. Li and B. Luft, "Overview of Solids Transport Studies and Applications in Oil and Gas Industry-Experimental Work," in *SPE Russian Oil and Gas Exhibition and Petroleum Technical Conference and Exhibition*, Moscow, Russia, 2014.

[66] F. E. Rodriguez Corredor, M. Bijhani and E. Kuru, "A Comparative Study of Hole Cleaning Performance - Water Versus Drag Reducing

Fluid," in *33th International Conference on Ocean, Offshore and Arctic Engineering*, San Francisco, California, USA, 2014.

[67] J. Li and S. Walker, "Sensitivity Analysis of Hole Cleanin Parameters in Directional Wells," *SPE Journal*, vol. 6, 2001.

[68] M. E. Ozbayoglu, A. Saasen, M. Sorgun and K. Svanes, "Effect of Pipe Rotation on Hole Cleaning dor Water-Based Drilling Fluids in Horizontal and Deviated Wells," in *IADC/SPE Asia Pacific Drilling Technology Conference and Exhibition*, Jakarta, Indonesia, 2008.