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Flow properties of water-based drilling fluids

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Preface

This report is the final product of the TPG4910 Drilling Engineering, Specialization Project at the Norwegian University of Science and Technology (NTNU), at the Department of Petroleum Engineering and Applied Geophysics. The thesis is prepared in cooperation with NTNU, Det norske oljeselskap ASA and SINTEF. I hereby declare that this thesis is written by me, Aleksander Kristensen, and all sources used are stated in the bibliography.

I want to thank Pål Skalle for being my supervisor, in addition to Jan David Ytrehus, Torbjørn Vrålstad and Arild Saasen. I also want to direct a special thanks to Det norske oljeselskap for giving me the opportunity of writing this thesis in cooperation with them. The excellent people employed at Det norske have always been willing to discuss and help me with all my questions, and for that I am truly grateful. Prime working facilities and the best work environment also helped a lot.

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Finally, I want to sincerely thank my proofreading team(Morten M, Morten S and Marte). Without their help, support and encouragement this report would have been substantially worse.

Abstract

The objective of this master thesis was to investigate the flow properties of water based drilling fluids, utilizing measurements in both the micro and macro scale. The research was performed on two realistic drilling fluids by the use of a viscometer, a rheometer and a realistic flow loop, where the latter represents the macro scale. The research outcome could possibly improve the understanding of flow behavior in wellbores, and remove uncertainties associated with annular friction.

The two fluids utilized in the research was made up with the goal of having equal rheological qualities, when measured with a Fann 35 viscometer. A more thorough examination of the two fluid's rheology was then executed by using a Anton Paar MCR302 rheometer. The macroscopic properties was researched employing a flow loop, capable of simulating realistic wellbore conditions.

The main outcome of this thesis is that even though two fluids appear to have the same rheoligical properties when measured on simple equipment, their fundamental different microscopic structure will exhibit variations when the fluids are utilized in real applications.

Due to problems encountered when mixing the fluids, as well as problems with one of the fluids itself, not all intended experiments were conducted. The experiments should be replicated with an emphasis on temperature control, avoiding bubbles and foam, and be conducted within a shorter time period.

Sammendrag

Nye regler ved NTNU fra 2012 krever at sammendrag er skrevet både på norsk og engelsk.

Målet med denne masteroppgaven var å undersøke strømningsegenskapene til vannbaserte borevæsker ved å bruke målinger gjort i både stor og liten skala. Undersøkelsen ble gjort med to realistiske borevæsker ved bruk av instrumenter som et viscometer, et rheometer og en realistisk strømningssløyfe som representerte storskala. Konklusjonen til denne oppgave er ment å kunne forbedre vår forståelse av hvordan strømningen i borehull seg, og dermed distansere oss fra usikkerheter assosiert med friksjon i ringrommet.

De to væskene som ble brukt i denne undersøkelsen ble laget med et mål om ha tilsvarende rheologiske kvaliteter under målinger med et Fann 35 viscometer. En grundigere undersøkelse av de to væskers rheologi ble senere utfrt ved bruk av et Anton Paar MCR302 rheometer. De makroskopiske verdiene ble undersø-kt ved hjelp av en strømningssløyfe, som var i stand til å simulere realistiske vilkår for borehull.

Hovedkonklusjonen fra denne tesen er at selv om to væsker tilsynelatende har de samme rheologiske egenskaper når de blir målt med enkelt utstyr, så vil deres forskjellige mikroskopiske struktur påvise variasjoner når de blir brukt i ekte situasjoner.

Grunnet problemer som oppsto når våskene ble mikset, og problemer med en av væskene, så ble ikke alle eksperimentene utfrt som planlagt. Eksperimentene burde bli gjentatt med vektlegging p temperaturkontroll, forhindring av bobbler og skum, og prve å bli ferdigstilt innen et kortere tidsvindu.

Contents

List of Figures

List of Tables

Chapter 1

Introduction

With the recent years high oil prices, oil fields previously believed not economically viable have become more interesting for energy corporations. Both marginal fields, where the hydrocarbon content is low or unsure, and technically challenging fields are now of interest. Especially deep offshore prospects are challenging due to the narrow margin of the pore pressure and the fracture pressure. The ability to drill such wells without problems, depends on the ability to precisely predict the friction pressure loss caused by the drilling fluid flow in the system. Making wrong predictions and acting upon their presumptions could lead to serious drilling incidents like kicks, drilling fluid loss and in final consequence a hydrocarbon leakage leading to a blow out. This could result in serious damage to equipment, workers and the environment, exemplified by the Macondo accident (C. Moomjian Jr., 2013).

Flow regimes under drilling operations vary from the simple laminar pipe flow, to the more unstable annulus flow. Several studies report that the flow regimes are determined by several parameters such as type of fluid, well bore geometry, well bore size, rotation of the drill string, eccentricity of the inner pipe (drill string) and more. More experiments and studies should be conducted in order to fill the knowledge gaps of how the drilling fluid behavior really is in the wellbore.

Two drilling fluids with seemingly identical values will be the basis for the research. This thesis will examine rheological differences in two types of water based drilling fluids, namely so-called Bentonite based and Potassium Chloride based. An examination of different additives commonly used will also be conducted. A finer examination of the fluids will be conducted, before a medium-scale flow loop will be used for observation of the flow properties. A comparison will be then made and discussed, also focusing on solids transportation and their influence on pressure drop. The results of the study could be useful for hydraulic program optimization and well control, especially in wells drilled with managed pressure drilling (MPD) techniques, and long wells - extended reach drilling (ERD).

Chapter 2

Fundamental theory

In order to fully understand the background and importance of this thesis' research some basic information is needed. Many of the basic concepts will be familiar for people working in the oil industry, but some parts, e.g. rheology, may not be that well-known.

2.1 Rheology

2.1.1 Basics of Rheology

Rheology is defined as the science of deformation and flow of matter (Darby, 1976). As a theoretical subject, rheology is a branch of physics and physical chemistry; commonly classified as a branch of fluid mechanics (Darby, 1976). Rheology itself has been acknowledged as a separate scientific branch since the mid 1920's (Mezger, 2011).

All real materials will deform to some extent when subjected to stress. If the material is an ideal liquid it may "deform continuously" or flow, when a force is applied. For ideal solids the deformation will be elastic. The relationship between the applied force and the resulting deformation is a unique function of each specific material. For fluids, i.e. liquids and gases, this function is known as a rheological property of the material.

In all fluid flows there are different sub-layers of fluid that move with different velocities. If the flow in a circular pipe is laminar, the fluid flow rate adjacent to the pipe wall will be zero, while the flow will be at the maximum velocity in the center of the pipe (Bourgoyne Jr. et al., 1986). This phenomena, named the velocity profile, implies that the molecules are moving relative to each other when in motion. The relative movement and rotation of molecules are caused by internal friction forces, leading to a certain flow resistance. Consider a two-dimensional (2D) system of two parallel plates with a fluid between the plates, where one of the plates is stationary and the other is moving in one direction parallel to the first. The fluid will then be sheared due to the friction acting between the plate and the fluid. Figure 2.1.1 illustrates how the plate causes the fluid to be sheared.

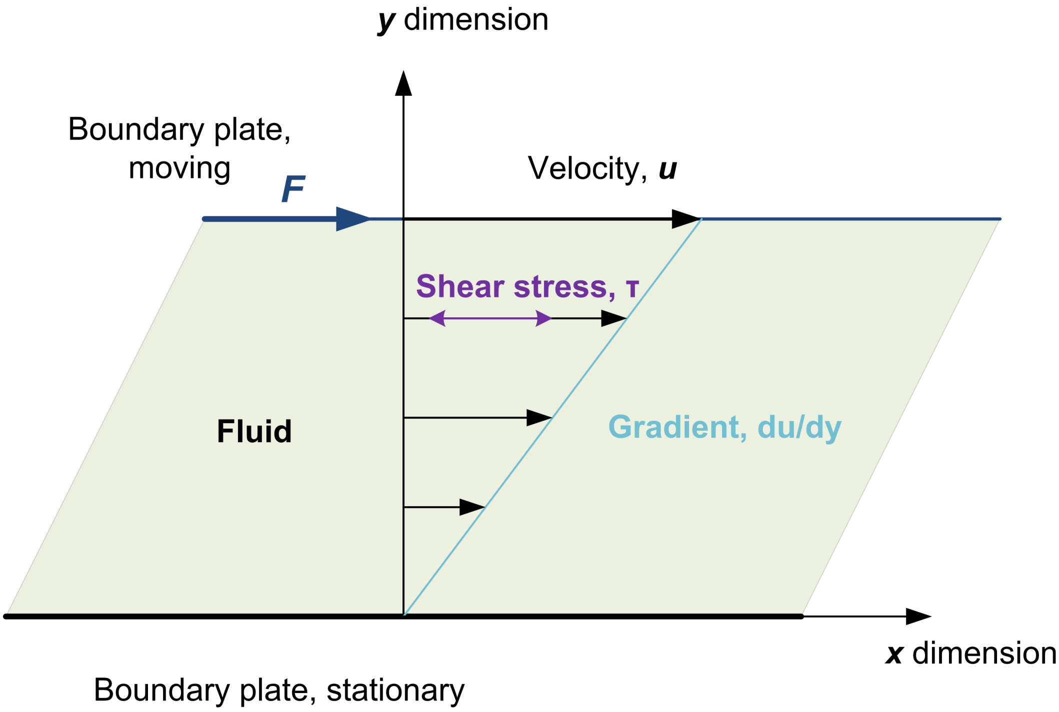

Figure 2.1.1: Flow between two parallel plates illustrating shear stress, free after Mezger (2011).

The upper plate in Figure 2.1.1 is moved by a force F, and the plate acts on the fluid with an area A. The displacement of that plate results in relative movement of all elements of the material in the x-direction, resulting in deformation and fluid *flow*. Assume that the displacement of a given element is dx at the location dy, the shear strain is given by

$$\gamma = \frac{dx}{dy} \tag{2.1.1}$$

Shear stress

The shear stress exerted on the fluid is defined as the relationship between force F and area the force acts upon A

$$\tau = \frac{F}{A} \tag{2.1.2}$$

The relationship between shear strain and shear stress defines shear dependent viscosity of the material. If the material is a fluid, a constant force on the upper plate will result in a constant velocity $\boldsymbol{u}$. The deformation, or flow, can be described by the time rate change of shear strain, also referred to as the shear rate (Darby, 1976).

Shear rate

Given the velocity $\boldsymbol{du}$ at the position $\boldsymbol{dy}$ the shear rate is

$$\dot{\gamma} = \frac{d\gamma}{dt} = \frac{d}{dt}\left(\frac{dx}{dy}\right) = \frac{1}{dy}\frac{d}{dt}(dx) = \frac{du}{dy} \tag{2.1.3}$$

The shear rate is the same as the velocity gradient illustrated in figure Figure 2.1.1. In other words, it is the rate of which the shear is applied on the fluid. All shear dependent fluids will change viscosity when exposed to different shear rates.

Viscosity

Viscosity is the representation of the internal resistance to deformation, a fluid shows under stress. In everyday language one usually refers the viscosity to *"how thick"* the fluid is, meaning the "thicker" the fluid is the greater the internal friction is. Viscosity is the most elementary property dealt with in rheology (Sandvold, 2012).

For some fluids the viscosity can be expressed through a coefficient, but for most fluids it is more a factor dependent on other properties. These properties can be, but not limited to, temperature, pressure, shear rate, on how the fluid has been treated before, and under which regimes the shear has influenced the fluid. For more on Newtonian fluids and other fluid types, see section 2.2 .

In order to properly predict how a fluid will act, it is important to have knowledge on how fluids change under different external conditions. The SI unit for viscosity is Pas, while in the industry centiPoise (cP) is also used. A centiPoise is equivalent to 1 mPas. Water at 20°C has the viscosity of 1.002 centiPoise and thus serves as a useful reference.

Viscosity is defined by the American Petroleum Institute (API), as the ratio of shear stress to shear rate (American Petroleum Institute, 2010).

$$\mu = \frac{\tau}{\dot{\gamma}} \tag{2.1.4}$$

Other scientific communities define viscosity as:

$$\eta = \frac{\tau}{\dot{\gamma}} \tag{2.1.5}$$

and uses $\eta = \mu$, if η is only shear dependent.

The viscosity of fluids is dependent on the temperature. For Newtonian fluids the viscosity generally decreases when the temperature is increased. As mentioned earlier the pressure will also influence viscosity. With isotropic pressure increase, the fluid's viscosity will grow exponentially. When performing measurements and analysis in a laboratory, a change in absolute pressure the magnitude of one bar, will have a negligible effect on the viscosity (Sandvold, 2012). On the other hand, a change in temperature will have a significant effect on the measurements, and should subsequent be recorded. Preferably temperature changes should be avoided, when measuring viscosity. In a real situation, i.e. in a real well, the fluid will experience a range of different temperatures and pressures, both in significant orders. Therefore it is important to have a basic understanding on how drilling fluids behaves under various external conditions.

Extensional viscosity

Not all fluid flow is determined by shear stress. Tensile flow are natural occurring, and the internal friction of the two flow types are not the same for such applications as for shear dependent flow. Extensional viscosity is the term with the notion η_E, for the internal resistance of such flows. For ideally viscous fluids, when the values of tensile strain rate $\dot{\varepsilon}$ and shear rate $\dot{\gamma}$ are the same, the following relationship is valid:

$$\eta_E(\dot{\varepsilon}) = 3\eta(\dot{\gamma}) \tag{2.1.6}$$

For applications where the tensile strain rate is greater than the shear rate, the Trouton ratio expresses the relationship (Mezger, 2011):

$$TR = \eta_E(\dot{\varepsilon})/\eta(\dot{\gamma}) \tag{2.1.7}$$

2.1.2 Time-Dependent Behavior

Some fluids have a viscosity behavior depending on time or what kind of shear stress they have previously been exposed to, sometimes called the shear history. These should not be confused with Pseudoplastic (shear-thinning) and Dilatant (shear-thickening) fluids, although their names are somewhat similar. Figure 2.1.2 illustrates the concepts of time-dependent fluids.

Thixotropy

Thixotropic fluids are showing signs that the viscosity is reduced when the shear force is constant for some time, i.e. the fluid flows easier with time under static shear stress. They develop a solid state structure when at rest or with decreasing shear rate, like a gel. The gel structure strength depends on the time at rest and when sheared. The gel will begin to break as shear is initiated, and will ultimately break completely when exposed higher and prolonged shear. A fluid could be described by a simple rheological model, i.e. Bingham Plastic or Power Law, and simultaneously be thixotropic (Amoco Production Company, 1994). Examples of thixotropic fluids are mayonnaise, paints and inks, and also some drilling fluids.

Rheopectic

Rheopectic fluids are less common than fluids with thixotropic behavior. They show a time-dependent increase in viscosity, meaning that the longer they undergo shear stress the thicker they will be, i.e. the higher viscosity they will have.

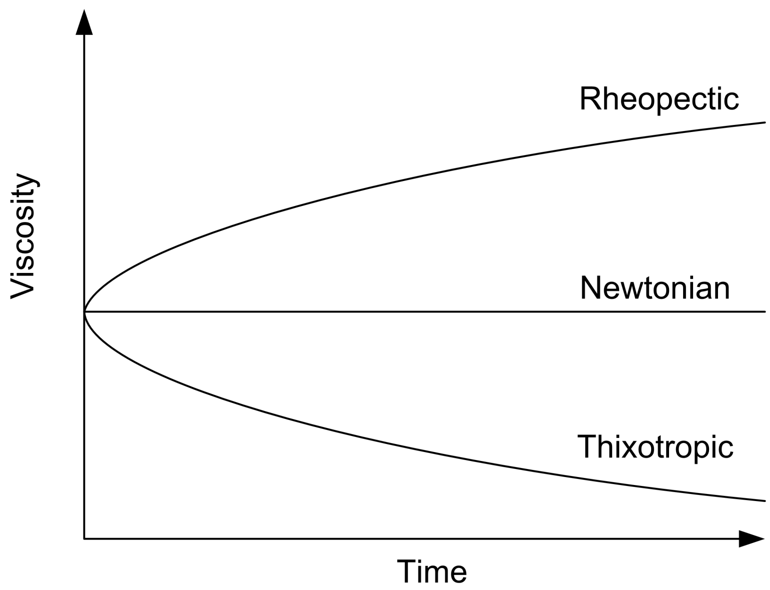

Figure 2.1.2: This graph illustrates fluids with and without time-dependent viscosity under static shear condition.

2.2 Rheological models

Fluids are classified by their rheological behavior American Petroleum Institute (2010). All fluids are classified as either Newtonian or Non-Newtonian, the clearest distinction between different types of fluids. Figure 2.2.1 illustrates a graphical representation on how different fluids react, when exposed to increased shear rate.

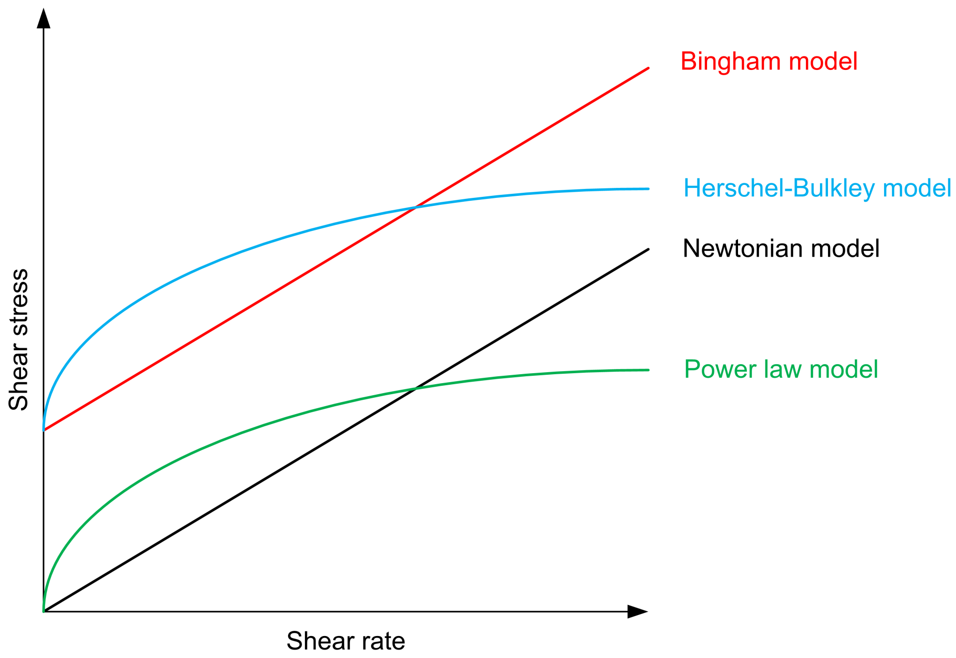

Figure 2.2.1: Plot showing the most used rheological models in the drilling industry for different fluids. Free after Skalle (2012)

2.2.1 Newtonian

The Newtonian fluid model is valid for fluids that does not change properties during time or shear stress variations, i.e. time independent and consistent. Newtonian fluids have a linear proportional relationship between the shear stress τ and the shear rate $\dot{\gamma}$, where μ is the constant of proportionality. In mathematical terms this means:

$$\tau = \mu\dot{\gamma} \tag{2.2.1}$$

This constant is the *viscosity* of the fluid (Bourgoyne Jr. et al., 1986).
The viscosity is not a real constant, i.e. constant regardless of which system

it is measured in, but dependent upon temperature and pressure. In relation to Figure 2.1.1 this means that if the force F is doubled, the plate velocity u will also double. Pure water is the typical example of a Newtonian fluid. Other material examples are glycerin and light oils. A single measurement will provide the viscosity of the fluid, regardless of the shear force, for the specific pressure and temperature.

2.2.2 Bingham Plastic

The Bingham plastic model, also known as the Yield Point (YP) model or simply the Bingham model, describes a fluid with a yield stress component and a Newtonian component. The fluids that fit this model require a certain amount of shear stress before flowing. After exceeding the critical stress value, the fluid yields and will thereafter behave as a Newtonian fluid with increasing shear stress. Everyday examples of Bingham fluids are mayonnaise and ketchup. This model also include fluids that hold solids suspended (Sandvold, 2012).

Common drilling fluids often tend to *gel* during longer periods of standstill. The fluid then forms a solid state, i.e. the fluid is not 100 % liquid any more, thus more rigid. This gelling requires a certain shear stress to be overcome, and this is the yield point of the fluid. The model is therefore used when describing some drilling fluids.
The definition is:

$$\tau = \tau_y + \mu_{pl}\dot{\gamma} \tag{2.2.2}$$

Where τ_y is the yield stress and μ_{pl} is the plastic viscosity.

2.2.3 Power Law

Power law fluids are defined as:

$$\tau = K\dot{\gamma}^n \tag{2.2.3}$$

Where K is the consistency index and n is the power law index. There are two basic forms of power law fluids, depending on the value of the coefficients in the power law equation (Equation 2.2.3), K and n .

Pseudoplastic

Pseudoplastic fluids are shear thinning, meaning they will have less viscosity with higher shear rates. For pseudoplastic fluids the flow behavior index is below one, $n < 1$. Shear thinning behavior is found in polymers and polymer solutions, among them many drilling fluids. A pseudoplastic fluid is displayed in Figure 2.2.1.

Dilatant

Dilatant fluids are shear thickening, and less common than shear thinning fluids in nature. Dilatant fluids increase their viscosity exponentially when the shear force is increased, i.e. the flow behavior index is greater than one, $n > 1$. The best known example of a dilatant, made famous by various Hollywood movies, is a mixture of sand, clay and water, also known as quicksand. From the movies we know that the harder a person stuck in quicksand struggles, the less is the effort worth. That means the viscosity will increase with movement (shear), thus making the movement more difficult.

2.2.4 Herschel-Bulkley

The Herschel-Bulkley model is also called the Yield Power Law (YPL) model, since it takes both a yield point and a power law development into account. Effectively it is a combination of the Bingham and power law fluid models.

$$\tau = \tau_y + K\dot{\gamma}^n \tag{2.2.4}$$

The Herschel-Bulkley model is often used to describe oil-well drilling fluids, since it considers both a yield point and power law development with increasing shear rate. The yield point factor is due to gelling.

2.2.5 Other models

Rheology models are used in many other industries than the drilling industry, and hence other rheology models are developed to better fit the viscoelastic fluids in use. Rheology models are made for predictions, due to the fact that is would be very time consuming, or impossible, to measure fluid properties under all possible conditions. Other models not commonly seen in the drilling industry, are among other:

Casson

$$\sqrt{\tau} = \sqrt{\tau_y} + \sqrt{\mu\dot{\gamma}} \tag{2.2.5}$$

Collins-Graces

$$\tau = (\tau_y + K\dot{\gamma})\left(1 - e^{-\beta\dot{\gamma}}\right) \tag{2.2.6}$$

Robertson-Stiff

$$\tau = K\left(\dot{\gamma}_y + \dot{\gamma}\right)^n \tag{2.2.7}$$

2.2.6 Rheological Modeling in the Drilling Industry

The Herschel-Bulkley model is the most commonly used model for drilling fluids in the oil industry today. The fluids used for drilling oil and gas wells will experience a wide range of different shear rates, and the YPL model has been found to be a simple and applicable model when considering the whole range of different shear rates (American Petroleum Institute, 2010). Knowledge on drilling fluid rheology is important for the following applications, all of them of importance for the drilling process (American Petroleum Institute, 2010):

- Calculating frictional pressure loss in annuli and pipes.
- Estimating equivalent circulating density (ECD) of the fluid under downhole conditions.
- Determining flow regimes in the annulus.
- Estimating hole-cleaning efficiency.
- Estimating surge and swab pressures.
- Optimization of the circulating system for improved drilling efficiency.

2.3 Viscoelasticity

According to Mezger (2011) the behavior of "all real materials are based on the combination of both a viscous and an elastic portion and therefore it is called viscoelastic". The extremities of reactions to shear behavior are flow of ideally viscous liquids and deformation of ideally elastic solids. Mezger (2011) suggests that this is rarely the case. Viscoelastic materials are showing both viscous and elastic behavior at the same time.

Viscoelastic fluid behavior can be explained by two parameters, the storage modulus G' and the loss modulus G''. These parameters are measured in shear, and the relationship is the relationship of stress and strain. The storage modulus represents the elastic part of the material behavior. This modulus is a measure of the deformation energy which is stored by the material. If the energy is 100% stored, the material will reclaim it's original structure, thus be a ideal elastic solid. The loss modulus G'' is the measure of loss of deformation energy during the shear process.

2.3.1 Amplitude Sweep Test

Amplitude sweeps are tests done in oscillation, with increasing amplitude for a constant frequency. Amplitude sweeps are done in order to find the linear viscoelastic (LVE) range. Within the LVE range fluids will act according to Hooke's law, meaning they will generally act elastic (Mezger, 2011).

The amplitude sweep measures the storage and loss moduli, G' and G'' respectively. If the storage modulus is greater than the loss modulus, the fluid has characteristics like a solid or gel. The elastic part dominates the viscous one, and the fluid displays a certain rigidity. Some matters, such as lotions and coatings, exhibit flow behavior at medium and high shear rates, but $G' > G''$ within the LVE range. They have a gel-like consistency at low shear rates, and even if they only have a weak gel structure, stability and firmness are expected (Mezger, 2011). Figure 2.3.1 illustrates a fluid exhibiting such properties. Stable dispersions, such as some water based drilling fluids, are examples of this behavior.

If the loss modulus G'' is greater than the storage modulus G', viscous behavior dominates the elastic part. At rest, and within the LVE range, these materials are not stable and will be flowing with time, since they are in fact flowing in the entire measuring range. Examples of matters displaying such behavior are bitumen and the Earth's mantle, although flowing with

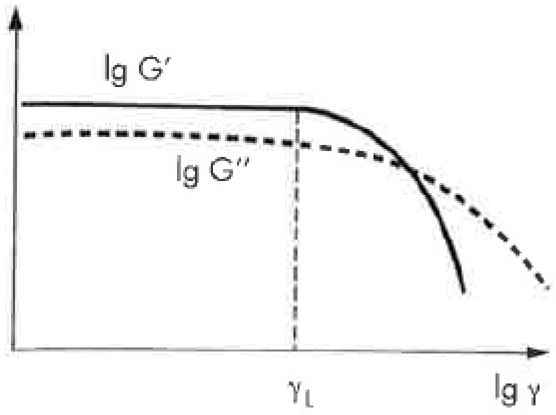

Figure 2.3.1: A strain amplitude sweep of a fluid having gel-like character in the LVE range (Mezger, 2011).

extremely low velocities. Sometimes the flow velocity could be so low that the material is mistaken for a solid. Old fashioned one-layered window glass are sometimes thicker in the bottom, indicating a very slow flow.

When the value of storage and loss moduli cross, the material starts to flow. In the scientific community this value, $G' = G''$ is known as the flow point of the fluid. In the drilling industry the value is named yield point. Yield point in a rheoligical sense, is the point when the LVE plateau begins to deviate. The rhelogical yield point is hence the limit of the LVE range. In order to avoid confusion it should be stated what kind of yield point is intended, since there is a difference. For the rest of report flow point will be referred to as yield point, since this definition is the drilling industry standard.

2.3.2 Frequency Sweep Test

Frequency sweeps are oscillatory tests performed with a constant amplitude within the LVE range, while variating the frequency. The purpose of frequency sweeps are for examining time-dependent deformation, since frequency is the inverse of time. Long term behavior is simulated by low frequencies (slow motion), and short term by swift motion (high frequencies). A typical value of 1 rad/s is Only frequency sweeps done in the LVE range are useful, so an amplitude sweep has to be carried out first. The viscoelastic property of long term dispersion storage stability can be evaluated with frequency sweeps. In other words, how long a drilling fluid with suspended particles may be uniform and stable under static conditions (no circulation).

2.4 Annulus Wellbore Hydraulics

When researching drilling fluids and their behavior it is not beneficial to only describe the rheological side of things. Fluid mechanics should also be part of such research.

2.4.1 Fluid Mechanics

Fluid mechanics is the study of the forces involved in both still and flowing fluids.

Reynolds number

Reynold introduced a dimensionless number in order to compare fluid flow independent of which medium surrounded them and other variables. The Reynolds number is the ratio of inertial forces to viscous forces in fluid flow (American Petroleum Institute, 2010). The ratio is dimensionless and defined for circular pipes as:

$$Re = \frac{dV\rho}{\mu} \tag{2.4.1}$$

Where d is the diameter of the flow channel, V is the average flow velocity, ρ the density of the fluid and μ the fluid viscosity. For other circumstances the equation will be different, or compensated by choosing a different value for d.

Taylor number

G.I. Taylor (1923) introduced a dimensionless number that characterizes the importance of inertial forces relative to viscous forces in a fluid rotating around an axis. The physical meaning of the Taylor number is comparable to the Reynolds number (Saasen, 2013), they are both a ratio between viscous and inertial forces. The definition for the Taylor number for the flow between two concentric cylinders is:

$$Ta = \frac{\Omega^2 \rho^2 R_1 (R_2 - R_1)^3}{\mu^2} \tag{2.4.2}$$

Where Ω is the characteristic angular velocity, ρ the density of the fluid, μ the viscosity, R_1 the external radius of the inner cylinder, and R_2 the internal radius of the external cylinder.

2.4.2 Flow Regimes

Fluid flow in circular pipes can behave in different ways. Most common fluids are transported in circular pipes. This is because pipes can withstand a large difference in pressure between the inside and outside of the pipe, without being significantly distorted (Çengel and Cimbala, 2010).

The theory behind fluid flow is commonly well understood, yet only fully developed laminar flow is theoretically obtained. Therefore flow with other characteristics, like turbulent flow, must rely on experimental and empirical relations. The borderlines between laminar, transitional and turbulent flow regimes are set by the Reynolds number of the flow. For laminar flow, the viscous forces dominate, while for turbulent flow the inertial forces play the bigger role American Petroleum Institute (2010).

All fluid flow inside a pipe has the velocity profile of *zero* at the pipe wall due to no-slip condition to a maximum at the center of the pipe.

Laminar

Laminar flows are relatively easy to describe both mathematically, physically, and graphically. Laminar flow is characterized by smooth streamlines and a highly ordered motion. In general they have low Reynold number values, and can therefore be described as slow flowing. For circular pipes the flow regime is generally laminar if the Reynold number is under 2300 (Çengel and Cimbala, 2010). The pressure required to move fluid under laminar conditions increases when velocity or viscosity is increased. The velocity profile of a laminar flow is quite easy to depict. In pipes, the cross section along the pipe, the velocity profile will be parabolic.

Turbulent Flow

Turbulent flows are characterized by velocity fluctuations for a single element particle and a highly disordered motion. The reason behind these fluctuations is rapid mixing between the fluid particles from adjacent layers. This leads to a momentum transfer between fluid particles, and thereby increasing the friction force on the pipe wall (Çengel and Cimbala, 2010). Since the friction is higher for turbulent flow than laminar, a higher pressure drop is needed for turbulent flows, which in reality often means artificial power (pumping).

Fluids flowing in circular pipes will act turbulent if the Reynold number is higher than approximately 4000. For other geometries other boundary values are valid. It is quite complicated to model the flow under such conditions, due to the irregular and unstable nature of turbulence.

Transitional Flow

The transition from laminar to turbulent flow does not happen suddenly. It occurs over some regions where the flow fluctuates between laminar and turbulent. It is therefore described as a separate regime. The transition is controlled by the relative importance of viscous forces and inertial forces on the flow, that is the Reynolds number.

Chapter 3

Oilwell Drilling Fluids

3.1 Role of Drilling Fluid

The drilling fluid plays an integral part of all drilling operations, and should be optimized according to different parameters to achieve the best results and industrial effectiveness. The main tasks for the drilling fluids are:

- Hole cleaning. Getting the crushed material out from the well. It is important that the hole is properly cleaned with regards to completing the well.
- Controlling formation pressure (being a barrier). See Drilling window for more on this.
- Buoyancy. Keeping the drillstring submersed reduces the effective weight of the drill string on the hook load. This also reduces fatigue and costs (need less high strength steel in the top of the drillstring).
- Lubrication. Smoothening operation for the bit and also the drillstring in long deviated/horizontal wells.
- Cooling. Keeping the drill bit cool, in order to keep change the mechanical properties of the bit.
- Provide power to the bit. Hydraulic power is transmitted so that the can cones rotate. Only valid for roller-cone bits. For PDC bits the hydraulic power is used for jetting the crushed rock away from the bit teeth.
- Keeping the wellbore stable with regards to chemical reactions. Shale can be a problem.
- Signal transfer. For real time measurements and logging, the drilling fluid itself is used as the transfer medium for pressure waves.
- Costs. Drilling fluids are an expensive part of the operations, and should be handled with care to avoid excessive spending.

- Environment. Additives are used in drilling fluids, and some of them are not eco-friendly to the marine environment.

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3.1.1 Rheology measurements

There are different methods and equipment for measuring the rheological properties of a fluid. In the drilling business the most common way is by using a Fann 35 Viscometer. A viscometer is a rotational type of rheometer and can only perform measurements under one flow condition (one shear rate at one specific temperature).

Fann 35 Viscometer

A Fann 35 viscometer has six different settings, speeds/shear rates, in order to measure the viscosity of the fluid. Since there are only six shear rates, a model is applied to the measurements, making extrapolations possible. This gives an idea on how the fluid behavior will be under changing circumstances.

The standard approach for calculating the Bingham model coefficients in SI units, as explained by Skalle (2012):

- After the stress dial readings are converted to SI units and a correction factor of 1.06 are added, the plastic viscosity (μ_{pl}) is defined as:

$$\mu_{pl} = \frac{\tau_{600} - \tau_{300}}{\dot{\gamma_{600}} - \dot{\gamma_{300}}} \tag{3.1.1}$$

- Where the subscripts indicate rotation speed in RPM. The yield point is found by rearranging Equation 2.2.2:

$$\tau_y = \tau_{600} - \mu_{pl}\dot{\gamma_{600}} \tag{3.1.2}$$

Funnel viscosity

Funnel viscosity is commonly measured by a Marsh funnel, and is a timed rate of flow for a specified fluid volume. It is a quick reference that is routinely made on a drilling fluid system in the drilling industry (Amoco Production Company, 1994). However, instead of measuring shear rate to shear strain, it measures Extensional viscosity. This type of viscosity are found around tool joints in a real well.

Rheometer

A rheometer is an advanced instrument, capable of measuring elasticity, liquidity, viscosity and stability. The Anton Paar MCR 302 is capable of performing measurements in the scale from nano Newtonmeter to similar shear rates as fluid experience flowing through the nozzles in drill bits. Rheometers are able to take measurements in both oscillation and rotation mode, consequently giving them a wide range of measuring capability.

3.2 Oil Well Drilling Physics

A short introduction to the physics involved in oilwell drilling, in order to understand the outcome of the research in this assignment.

3.2.1 Drilling window

The drilling window is a nickname for the pressure gradient margin between the fracture pressure gradient and the pore fluid pressure gradient. All drilling fluids must be between these two values at a given depth, in order drill under normal circumstances.
The general formula for the weight of the drilling fluid column, i.e. the hydrostatic pressure of the fluid in the well, is:

$$p = \rho g h \tag{3.2.1}$$

The drilling industry usually replaces the h with D (vertical depth), in order to have positive values all the time. The equation becomes:

$$p = \rho g D \tag{3.2.2}$$

Depth is usually measured in reference to the drilling deck, or the rotary kelly bushing as its called. This could be several meters above both sea level, sea bottom and land level. Rearranging the equation in terms of density gives:

$$\rho = \frac{p}{gD} \tag{3.2.3}$$

In other words, the drilling fluid needs to have a density greater than the density corresponding to the pore pressure of the rock drilled. The drilling fluid can not be too dense either, since this may fracture the formation. It is within these margins conventional drilling maybe be conducted a safe manner.

3.2.2 ECD and ESD

The pressure the well bore and the formation experience is not only dependent on the weight of the drilling fluid column, but also the fluid flow. When there is flow inside a pipe, in our case a well bore, friction will be present. This friction represents an extra factor contributing to the well pressure. The fluid needs extra pressure to overcome the friction (which is dependent on the flow), in order to flow back to the surface. The friction the fluid experiences in the annulus represents extra weight in the bottom of the fluid column, thereby an effective increase in the fluid's density will occur. This can be expressed as:

$$ECD = \rho + \frac{\Delta p_{ann.fric.} + \Delta p_{cutt.} + \Delta p_{swab} + \Delta p_{rotation} + \Delta p_{accel.}}{gD} \tag{3.2.4}$$

where $\Delta p_{ann.fric.}$ is the annular friction pressure induced by circulation, $\Delta p_{cutt.}$ is the pressure change due to cuttings in the fluid, Δp_{swab} is the pressure experienced when moving the drillstring up/down the borehole, $\Delta p_{rotation}$ the pressure impact of rotating the drillstring, and $\Delta p_{accel.}$ the pressure change due to acceleration of the drilling fluid. Equivalent static density (ESD) is the density a drilling fluid has in standstill, i.e. ρ in Equation 3.2.4.

3.2.3 Fluid velocity

The average bulk fluid velocity is inversely proportional to the cross-section area of the fluid conduit. For this assignment the fluid velocity inside the drill pipe is not relevant, and hence not taken into account. It is only the annual fluid velocity that is important with regards to hole cleaning. The average velocity in a pipe the following:

$$V = \frac{Q}{A} = \frac{Q}{\frac{\pi}{4}d^2} \tag{3.2.5}$$

For an annulus with a pipe inside, the average annular velocity is:

$$V_a = \frac{4Q}{\pi d_{hyd}^2} \tag{3.2.6}$$

Where Q is the bulk volume flow and d_{hyd} is the hydraulic diameter. The concept of hydraulic diameter is to relate fluid behavior in an annulus to that of one in a circular pipe (American Petroleum Institute, 2010). There are multiple ways of expressing annular hydraulic diameter. The most commonly used is the cross section area of the borehole subtracted the cross section area of the drillstring, according to American Petroleum Institute (2010). This gives:

$$d_{hyd} = d_h - d_p \tag{3.2.7}$$

Where d_h is the hole diameter and d_p is the pipe diameter.

3.2.4 Drillstring eccentricity

In long wells, especially inclined wells, the drill pipe will not always be in the center of the wellbore or casing, in fact most of the time this will not be the case. This is because of the geometry of the well, combined with the stiffness of the steel used in the drill string. In the medium inclined section, i.e. well angle between 30-60°, the drillstring will be on the high side of the wellbore. In these high inclined and horizontal sections, the string will be on the low side of the wellbore. Figure 3.2.1 and Figure 3.3.1 illustrates this effect. The eccentricity will accordingly affect both the flow and the velocity distribution, hence the cuttings removal process.

For comparative reasons the eccentricity e is defined as the displacement of the radii divided by the difference in radii (American Petroleum Institute, 2010). The values are consequently 1 for a fully eccentric annulus and 0 for perfect concentric annulus.

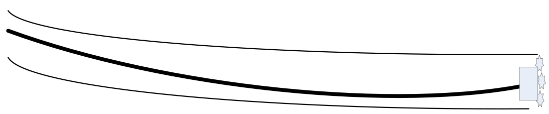


Figure 3.2.1: An illustration on how the drill string eccentricity occurs in high-inclined and horizontal wellbore sections.

3.3 Cuttings Transportation

When drilling wells, the rock surface is crushed by the teeth of the drilling bit. In order to continue drilling the crushed rock must immediately be removed from under the bit. The broken rock pieces, called cuttings, is removed by flushing drilling fluid from nozzles in the bit at high velocity. This procedure is where the drilling fluid experiences the highest shear forces in the drilling fluid circulation system. Typically about 50% of the pressure loss takes place through the nozzles (Skalle, 2012). This pressure loss is intentional, in order to create the high velocities needed for flushing the rock away from under the bit. The number of nozzles and the orifice size of these are optimized for different sections and different applications to best comply with the formations expected and the planned rate of penetration. (ROP). The hydraulic energy from the fluid traveling out of the nozzles is in relation with the drilling rate. The higher the energy, the higher the ROP may be. This is found in several studies (Skalle, 2012). The process of removing drilled rock is called hole cleaning.

The rock must then be transported from the bottom of the well to the top (and out of it). This requires a certain lift force and velocity in the fluid, in order to keep the particles suspended. The particle size will vary from $2\mu m$ to $5cm$ in diameter, depending on the bit, the ROP, rotational force and speed (RPM) and the drilled formations integrity. Larges pieces can fall out of the well bore, if the formation is not strong enough. Such pieces are different than ordinary crushed rock, and subsequently called cavings. Regular crushed rock is called cuttings.

Removal of drilled cuttings from the wellbore is essential for the drilling operation. A failure in the transport process can lead to a number of problems, such as:

- Stuck pipe, when going forward and especially backwards.
- Pack off. Increased pressure in the drilling fluid pumps.
- Lost circulation. Too much cuttings in the well will increase the weight of the column and can lead to fracturing.
- Poor cement jobs. The cement sticks to the cuttings and not the wall.
- Low rate of penetration (ROP), leading to high costs.
- Solids contamination will alter the fluid properties with regard to density, viscosity and gelling effect.
- Problem getting completion equipment where it should be. Horizontal sections, where dunes and high beds will hinder liners and sand screens.

3.3.1 Cuttings From Under the Bit

When the drilling fluid travels through the nozzles of the bit it experiences the highest shear rate in the circulation loop. The fluid has a high velocity on purpose, in order to get a hydraulic effect and thus flush the cuttings away.

3.3.2 Cuttings in the Annulus

According to (Salvesen, 2013) almost all drilling fluids in use these days have a shear thinning profile, so that the higher the velocity the lower the viscosity will be. For low velocities the fluid will have high viscosity. This is important for covering all sections of the well, i.e. from riser (low velocity) to through the nozzles (very high velocity). Increasing the flow rate will always improve the hole cleaning, for all sections of the well. The reason why not having the pumps on full capacity all the time is that the ECD will limit too high. For long, deviated wells there will be a too big discrepancy between the ESD and the ECD, which will reduce the wellbore stability. Also, with the pump rate at maximum, hydraulic erosion on the wellbore wall may be problematic.

Vertical well

The cuttings must be transported out of the wellbore, in order for drilling to commence. In a vertical well, or slightly inclined well, i.e. the well inclination is below 30°, this is normally not a problem. The cuttings are effectively suspended by the forces in the drilling fluid. The annular fluid velocity is in most cases larger than the slip velocity of the cutting particles (American Petroleum Institute, 2010). Hence a net upward velocity will act on the cuttings and they are thereby transported out of the wellbore.

Medium inclined, 30-60°

In the build-up sections of modern wells is where most problems occur (Salvesen, 2013). Boycott discovered in the 1920s that blood would settle faster in inclined test tubes than in vertical tubes. This is also the case for cuttings in medium-inclined wellbores. The distance from the flow area to the lower side of the wellbore, in a vertical cross section of the inclined wellbore, is relative small compared to a vertical wellbore. The particles will therefore settle faster. In these well sections the particle will not travel further down the well, but rather lay as a layer of cuttings atop the borehole wall. With time many particles will settle. Particles on the borehole wall will travel downwards slower, partly because being close to the wall and thereby not being in the main flow channels, and partly since they have to roll down to overcome the wall friction. When the weight of the cuttings no longer could be suspended of the repose angle, an avalanche will be activated. This may also happen when tripping (no circulation) or when there is a stop in the circulation. String rotation does not help as much due to the geometry of the well section, since the string will be on the top side of the well bore. See Figure 3.3.1 for an illustration of this.

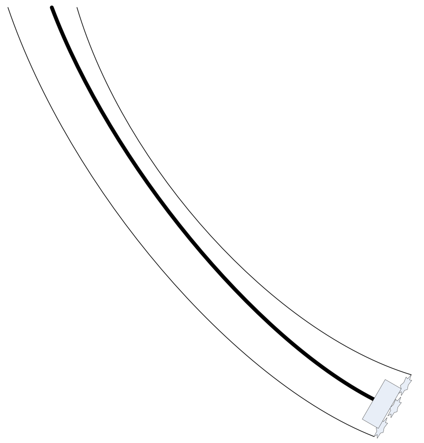


Figure 3.3.1: An illustration of how the drill string eccentricity is in medium inclined wellbore sections.

High inclined and horizontal sections, >60°

In high-inclination and horizontal wells, hole cleaning is normally something that is given much attention. Due to the nature of these sections, that is the small distance from the center to the bottom of the well (typically 4.25-3.5 inches), particles will settle on the lower side of the wellbore. The vertical component of the drilling fluid velocity is significantly reduced in high inclination sections, and thereby the decreases the capability of suspending cuttings in the drilling fluid. Once the particles hit the borehole bottom they have small chances of re-entering the fluid. The local fluid velocities are insufficient near the wall (Skalle, 2012). As a consequence of this, cutting beds are created with time.

These cuttings are often transported as beds/dunes much like sand dunes in the desert, or as a continuous moving bed. Rotation will interrupt the formation of stable cuttings beds and improve hole cleaning in horizontal sections. In Figure 3.2.1 a drillstring is laying on the low side of the wellbore. If rotating is initiated the particle settling process will be interrupted, and the particles already settled could be reintroduced to the flow.

3.4 Drilling Fluid Composition

As in most businesses, the oil industry extensively uses abbreviations and nicknames for different parts and equipment. Drilling fluid is typically called "mud", hence we have the expressions oil based mud (OBM) and water based mud (WBM).

Current industry practice and terminology, adopted by the American Petroleum Institute (API) and the International Association of Drilling Contractors (IADC), categorizes nine different fluid systems (Company, 2008). Of the nine, seven are water based, one is oil based and the last category is for air/mist/foam/gas drilling.

3.4.1 WBM

Water based drilling fluids are the most used type of drilling fluid (Amoco Production Company, 1994). They are generally relative easy to build, inexpensive to maintain and can be changed to overcome most drilling challenges.
The seven different water based systems are:

- Non-dispersed.
- Dispersed.
- Calcium treated.
- Polymer.
- Low solids.
- Saturated salt.

Bentonite

Bentonite is a generic name for some impure clays, mostly consisting of the mineral montmorillonite. The reason why clays and especially bentonite are used in the drilling industry today, are the rheological properties a mixture of bentonite and water gives. Relative small amounts of bentonite will be suspended in the water, giving the fluid shear thinning (pseudoplastic) properties. This effect helps the formation of drilling fluid cake at the borehole wall, and also gives some viscoelastic features. A kind of gel state will observed when not being exposed to forces other than gravity for some time, i.e. no circulation.

KCl

Potassium Chloride based drilling fluids are used for inhibition effects. Shale inhibition is by some considered to be the most imporntant factor for preventing hole problems, when drilling with water based fluids (Løklingholm, 2002). KCl will exchange ions with the shale, and thereby alter the complex structure. Since shale is not one material, but a umbrella conception, the reaction of different shales upon KCL is not uniform. And also for reducing swelling of shales.

3.4.2 OBM

Oil based drilling fluids are both used and built different than WBMs. They have a base oil and water droplets emulsified within. OBM are used when you expect shale/clay parts of the well to be troublesome. They have significant less water content than WBM, so hydration of the shale sections will be minimal. Another advantage with OBMs are when drilling the reservoir sections, due to reduced skin in the permeable zone. Oil based drilling fluids is also applicable when drilling highly deviated or horizontal wells due to their high natural degree of lubricity.

A major disadvantage for oil drilling fluids are that they have to be clean onshore. All the drilling fluid and the cuttings must be collected and shipped to a cleaning facility. They are a environmental hazard, and extra care must be given when dealing with OBM. Extra cost, time and particularly space must be allocated when oil based drilling fluids will be used.

3.4.3 Additives

Additives are added to drilling fluid system in order to enhance some qualities, and some other additives are added to reduce negative effects. According to World Petroleum Magazine there are more than 3000 known additives for drilling fluids (Skalle, 2012). Listing them all would be pointless since many are similar, i.e. that they enhance/gives the same properties/qualities, and some are outdated. The magazine World Oil categorizes the different types of additives, where the classifications are generally accepted by the IADC Subcommittee on Drilling Fluids (Company, 2008).

- Calcium Reducers.
- Corrosion inhibitors.
- Defoamers.

- Emulsifiers.
- Filtrate reducers.
- Flocculants.
- Foaming agents.
- Hydrate suppressants.
- Lost circulation materials.
- Lubricants/pipe-freeing agents.
- Shale control inhibitors.
- Temperature stability agents.
- Thinners/dispersants.
- Viscosifiers.
- Weighting materials.

Some of the additives are only used in OBM and air/gas systems, such as emulsifiers and foaming agents respectively.

Additives applicable for this research

Barite is the most commonly used material to increase the fluid density. The drilling fluid need to be as dense as the pressure present in the borehole wall was before it was drilled, in order to function as a proper barrier.

Xantham Gum is a common viscosifying agent, due to high resistance against mechanical degradation.

Soda ash, or bicarbonate, is a buffer used for maintaining the proper pH-level in drilling fluids. Materials are well protected against corrosion if they are in the right pH range.
Defoamers are used to reduce and preferably eradicate foam and bubbles formed in the drilling fluid.

Chapter 4

Research Background

Relevant current research for this research.

4.1 Pressure loss

The pressure needed for pumping the fluid with sufficient velocity has some limitating factors. The highest amount of resistance, i.e. friction, is experienced before the fluid exits the nozzles in the drill bit. This is due to the narrow geometry inside the drill pipe and the necessity of extremely narrow nozzle openings. These factors are uninteresting in this research, since the steel strength is not a limitation and it is only the velocity/pressure/flow of the drilling fluid beyond the nozzles which contributes to hole cleaning. What we are interested in are the impact on the annular friction loss by:

- Presence of cuttings.
- Drillstring rotation effect.
- Fluid properties.
- Eccentricity effect.

4.1.1 Cuttings Concentration

The presence of cuttings in flow will increase the frictional pressure loss. In high-inclined and horizontal well sections the cuttings will be settled in beds and thereby reduce the flow area, as well as increase the skin friction according to Saasen (2013). When the cuttings are reintroduced into the flow, energy is spent on accelerating the particle and generating particle rotation. The particle will then collide with the wall and dissipate the energy. Hence are cuttings concentration contributing to increased frictional pressure losses.

The cuttings particle size and the magnitude of the annulus gap compared to the particles will effect the pressure loss.

4.1.2 Drillstring Eccentricity

The annulus of a realistic wellbore is highly unlikely fully concentric, due to the dimensions of things. The drillstring length is far greater than the gaps between the borehole wall or casing, and keeping it 100 % centralized the whole time, while rotating and passing through different well sections with different geometries, is nearly impossible. Thereby flow instabilities will be present, due to the wobbling of the drillstring (transversal motion) and a non-uniform flow pattern. The wobbling may create vortices and thereby disturb the flow stability leading to turbulence and higher pressure loss. Figure 4.1.1 depicts different lateral motion a drillstring may provide during rotation.

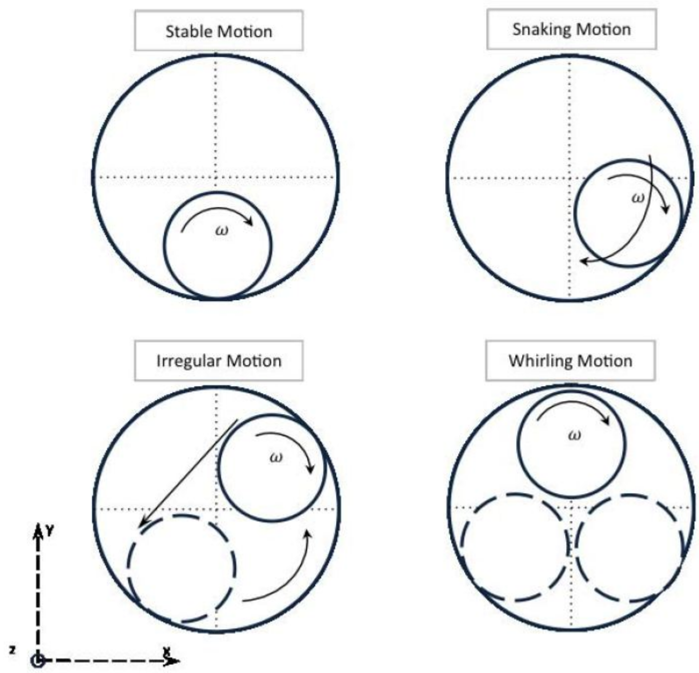


Figure 4.1.1: Whirling motion caused by drillstring rotation (Erge et al., 2013)

4.1.3 Drillstring Rotation

The effect on pressure loss by rotation of the drillstring is something that is yet to be fully understood. Several different studies shows different results, varying from a positive (increase) contribution to the pressure loss to a negative(decrease). Unlike the effect made by tool joints, the contribution from rotation is possible to take away during circulation. The tool joints can not be changed while the string is inside the hole, but it is possible to avoid rotating the string. This was extensively done in the eighties (Salvesen, 2013), when drilling inclined wells. The BHA had a bent housing connected to the drill bit and downhole motor. Then they drilled for some time without rotating, before they turned the drillstring a certain number of degrees on the topside, in order to get the desired inclination or azimuth change. This slide and turn method of drilling caused a lot of hole cleaning problems, especially when pulling back out of the hole. Nowadays, with rotary steerable motors, this is not so much a problem. Put the pressure difference between rotation and no rotation should still be examined more closely, for long slim-hole conditions with regard to ECD.

There has been some research on the pressure loss effect of drillpipe rotation, but the conclusions are not uniform. The effect on frictional pressure loss in annuli is mainly influenced by fluid properties, i.e. rheology and density, fluid flow regime, eccentricity and diameter ratio (Ahmed and Miska, 2008).

Chapter 5

Experimental Studies

Various experimental methods were used to examine the drilling fluids. A Fann Viscometer, a Anton Paar MCR302 rheometer and a medium sized flow-loop were used, where the latter was the most important for the research. Two different drilling fluids were used during the investigation. One based on bentonite, and the other based on potassium chloride. Pressure drop was measured in the flow loop experiments, in order to determine annular friction variances caused by fluid properties and inner string rotations. Rheological measurements were conducted with a rotational viscometer and rheometer capable of both rotation and oscillation. The rheological measurements gives a basis for prediction on how fluids would act, in different flow conditions, and are thus important for modeling fluid flow.

5.1 Test Matrix

In order to properly examine the flow properties of water based drilling fluids, some parameters have to be variated so the a range of results become available. Table 5.1 summarizes the parameters of the flow loop testing.

Table 5.1: Test matrix for the experiments conducted in the flow loop.

Experimental Test Matrix		
Variable	Variations	Comment
Fluid type	2	
Flow rate	4	
Rotation speed		
Cuttings size	1	
Parallels	2	Repetition for better accuracy.

The total number of flow loop experiments were thus $2 * 4 * 2 * 1 * 2 = 32$.

5.2 Fluids

Two different water based drilling fluids were examined and used in the flow loop.

5.2.1 Bentonite Type

In order to get the fluid properly mixed, two batches were prepared separately in a mixing tank with circulation before transported to the main system. The main system is the flow loop with its tank. This sort of heavy drilling fluid was too much for the mixing pump and it had to be replaced. Batch number one was therefore not circulated the whole time, but stood still for about two weeks time. This may have influenced the results of the Bentonite experiments, due to precipitation of heavy particles which was later not reabsorbed.

Table 5.2: The weight share of the ingredients the Bentonite fluid contained.

Bentonite fluid	
Additive	**Share [Weight %]**
Barite	37.50
Water	59.62
Soda Ash	0.77
Xantham Gum	0.15
Bentonite	1.96
Sum	100

5.2.2 KCl Type

The Potassium Chloride based drilling fluid was built with the intension of having the same Fann viscometer values and density as the Bentonite type. A trial-and-error method was used to acquire the similar quality as the Bentonite drilling fluid. Initially the KCl fluid was modeled as the example fluid made by Sintef Bergen (Torsvik, 2013). See Appendix C for the mix they used.

5.2.3 Difference between the ingredients and additives. 0

Table 5.3: The weight share of the ingredients the Potassium Chloride fluid contained.

Potassium Chloride fluid	
Additive	**Share [Weight %]**
Barite	40.27
Water	56.09
Soda Ash	0.14
Xantham Gum	0.28
KCl	2.58
EMI 1705	0.17
DEFOAM AL	0.48
Sum	100

5.3 Apparatus

5.3.1 Fann Viscometer 35

Please see 3.1.1 for more details on the Fann 35 Viscometer. Inaccurate measurements, but simple, robust and time saving.

5.3.2 Anton Paar Rheometer

Modular Compact Rheometer. Highly advanced. Measured the rheology of the fluids, including stability of solid state (i.e. gelling or not) and if the dispersions will prove to be stable, i.e. no precipitation.

5.3.3 Flow Loop

The flow rig used in this research is the same as was used by Taghipour et al. (2013). The flow loop is designed for carrying out experiments under various conditions, such as:

- Annular flow geometry
- Eccentric inner pipe position
- Free lateral movement
- Non-Newtonian fluid rheology
- Realistic particle properties
- Realistic borehole wall materials

The flow rig consisted of the following main components:

- Horizontal test section
- Fluid pump
- Sand injector unit
- Sand collector unit
- Sensor units
- Connection hoses

The horizontal test section is 12 meter, with a cylindrical geometry housing. In the middle of the section, a transparent part is located in order to conduct visual observations. The wellbore condition was made up by replaceable hollow cylinders of concrete, with an inner diameter of $D_o = 100$ mm. The simulated drillstring was a steel rod with external diameter $D_i = 50$ mm. The drillstring was connected to a motor at one end by a flexible joint, thus allowing free lateral (whirling) motion. The drillstring was fully eccentric.

The sensor connected to the flow rig included an electromagnetic flow meter, temperature gauge, torque cell, and differential pressure (DP) transducers, all of them connected to a logging system. One DP cell measured the differential pressure between ports located at 3 m and 7 m from the test section inlet. Another DP cell measured the pressure drop between 7 m and 8 m from the inlet, and was mostly used to check for deviations in fully developed fluid flow. The sand injector unit controlled the cuttings rate. A gamma densitometer was later installed on the rig, with the purpose of measuring sand bed level. A photography of the test section, outlet hosing and drillstring motor can be seen in Figure 5.3.1.

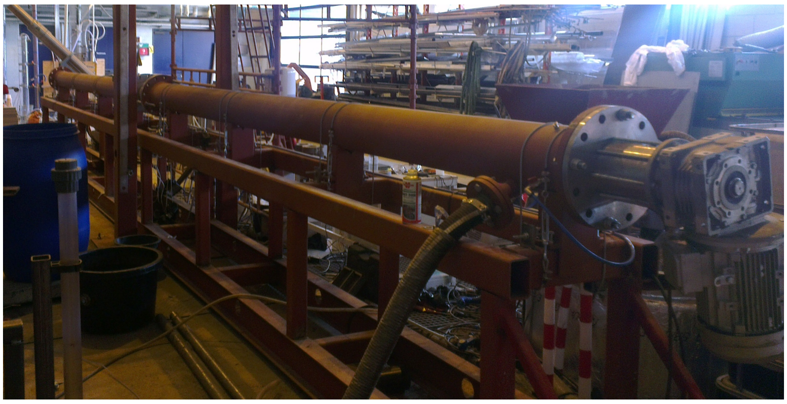


Figure 5.3.1: Test section as seen from outlet end, with drillstring motor and outlet hosing.

5.4 Test Procedure

5.4.1 Fann 35 Viscometer

The measurements performed on the Fann 35 viscometer started by recording the dial value for the 600 RPM speed, then the 300 RPM reading. The gel values were obtained by first shearing the fluid for two minutes with 600 RPM, then waiting for 10 seconds or 10 minutes accordingly. After the time of standstill, the highest dial reading observed when introducing 3 RPM rotation was recorded.

5.4.2 Anton Paar MCR 302 Rheometer

The Anton Paar MCR 302 Rheometer is delivered with a computer software, which control the rheometer. This reduces manual operations to filling, emptying, and cleaning the rheometer equipment utilized. All measurements are recorded in the software and no manual calculation is needed. A bob-and-cup configuration was used for all rheometer experiments. The software recommended limits and parameters for amplitude and frequency sweeps.

5.4.3 Flow Loop

Several tests at different flow rates in the annulus were performed, accordingly to the test matrix presented in Table 5.1.
The sand used in the experiments consisted of 99.5% SiO_2 and had a median diameter of $\sim 1.3mm$. The sand rate was 43 gram/s, corresponding to a realistic field condition ROP of 8 m/hour (Taghipour et al., 2013). Eccentricity of the simulated drillstring was 1.0, i.e. it lay on the bottom of the test section. All experimental work was performed at ambient pressure and temperatures. Summarized, the flow loop test were performed as following:

- Flush DP housing cells.
- Initiate circulation of the lowest velocity of interest, 0.3 m/s. Ramp up the velocity in steps, in order to record stable values. The velocities chosen were 0.54 m/s, 0.75 m/s, and 1.00 m/s, in addition to 0.3 m/s.
- When stable measurements at 1 m/s was achieved, drillstring rotation at 150 RPM was initiated.
- The velocity was decreased in steps, after stable DP measurements were recorded.
- For the tests that included sand injection, the injection started at the lowest velocity. After stable DP values, and presumably stable sand levels, velocity was increased.

- The test that included both sand injection and drillstring rotation was initiated at the lowest velocity, with sand and rotation initiation at the same time. After stable values weer achieved, flow rate was increased.
- When performing tests with sand injection, the sand collector unit had do be emptied after a series.
- Offset pressure values were recorded for dynamic and static 0 m/s flow, with open and closed circulation valve.

5.5 Experimental Challenges

As often happens when experimental research is conducted, unknown hiccups may occur. The research presented in this thesis did not go without some problems with the fluids.

5.5.1 Bentonite Fluid

The Bentonite fluid was initially mixed in an interim tank, with a submersible pump as the driving force behind the mixing. As more components were gradually added, it became clear that the submersible pump could not deliver sufficient energy to achieve a uniform fluid. Lumps occurred without the pump managing to break them down. With time the heavy particles settled on the bottom of the interim tank. The fluid was transferred to the flow loop tank, but due to heavy particles laying on the bottom like a sludge, 100% of the content did not transfer. The fluid that was transferred, was then treated with more of the same ingredients in order to get the rheological and density qualities wanted. Subsequently the content share ratio of the Bentonite fluid is unclear.

5.5.2 Potassium Chloride Fluid

Having learned from the challenges with the Bentonite fluid, the intake to the mixing of the KCl fluid was different. The first compounds in the mix was water and Xantham gum, in order to have a more viscous liquid before introducing heavier particles. The idea was that the increased viscosity would be beneficial for holding the heavy particles suspended. The submersible pump was replaced with two new ones, and operated in a sufficient matter.

After transferring the fluid to the flow loop system, circulation was engaged. It should be mentioned that there was some residue fluid from the Bentonite experiments left in the tank, but the amount was considered to be insignificant. The Potassium Chloride fluid was then put in circulation, in an effort to get the mix properly sheared. In order to obtain the same density and rheological properties as the Bentonite fluid, a mix-and-test method was utilized. Barite was added to achieve a density equal to the other fluid. Then a share corresponding to the original portion of the mix, of the other dry compounds was added while the fluid was flowing in the loop. Fann viscometer and density measurements were performed, and the KCl fluid treated accordingly.

When the actual flow loop testing was to begin, foaming was experienced. The foaming eventually became a large problem, introducing bubbles in the flow. The bubbles could be heard at the inlet and outlet of the test section. Bubbles in the flow reduced the pump's effectiveness, in such an extent that the pump power had to be increased to maintain a constant flow rate. The flow rate itself was measured by the flow meter, and it is likely that the measurements were inaccurate. The amount of bubbles present in the flow would affect the effective cross section where the flow meter is measured upon. The bubbles caused problems when changing flow rate, and stable velocities were not achieved. Bubbles would probably also affect the rheology of the fluid, so measures had to be taken in order to get reasonable results.

Manually optimizing pump power proved an insufficient method of mitigating the bubble problem. Defoaming agent EMI 1705 was added, with the amount corresponding to 0.17% of the total content. The effect of EMI 1705 was not observable. A drilling fluids engineer from MI Swaco inspected the rig and proposed improvements in order to prevent bubbles. Some parts of the fluid tank system was rebuilt, also with a non-observable effect. A stronger defoaming agent, with the commercial name DEFOAM AL, was added with good results. Bubbles could not be heard at the inlet and outlet of the test section, and foam was not being created in the fluid tank. A Fann viscosity measurement was performed on the fluid, without it seemingly being affected by the defoamer.

After the problem with presence of bubbles in the flow was contained, due to a weekend interference, not all tests could be completed straight away. When reinitiating the circulation, signs of foaming and bubbles in the flow were prominent. Substantial amounts of foam in the tank, and an audible amount of bubbles at the inlet and outlet was observed. The Potassium Chloride fluid seemed to consume the effect of the heavy defoamer with time, as it had with the light defoaming agent. The experiments resumed without the previously experienced problems with unstable flow rate. Some defoamer was added, in order to make sure no more problems would be encountered.

Chapter 6

Results and Analysis

The results obtained during the experimental investigations are presented in three groups, one group for each measurement system.

6.1 Fann Viscometer Measurements

In annulus and riser drilling fluids experience shear rate in the order of 10-500 s^{-1} (Amoco Production Company, 1994), thus making research on drilling fluids most applicable in this region of shear rates.

Fann measurements were taken while the mixing of the drilling occurred, in order to obtain the desired quality. The tables in Appendix B provides insight as to how the drilling fluids evolved during the project period. The final results obtained from the Fann viscometer measurements were are presented in Table 6.1.

Table 6.1: The final Fann viscosity measurements of Bentonite and KCl fluids.

Fluid sample	600 [RPM]	300 [RPM]	10s gel	10min gel	Density [SG]
Bentonite	45	31	7	13	1.36
KCl	47	33	8	11	1.37

The calibration and geometry of Fann viscometers require that the readings are corrected with a factor of 1.06, in order to be valid values of shear stress (in $lbf/100ft^2$)(Skalle, 2012). The measurements obtained corrected and converted to SI units are shown in Table 6.2:

Table 6.2: The Fann viscometer measurements of Bentonite and KCl fluids.

Fluid system	RPM	$\dot{\gamma}$ $[s^-1]$	τ [Pa]	μ [mPas]
Bentonite	600	1022	22.84	22.35
	300	511	15.83	30.80
KCl	600	1022	23.85	23.34
	300	511	16.75	32.78

Using the standard oilfield approach for Bingham fluids, as described in section 3.1.1, the results presented in Table 6.3 were obtained.

Table 6.3: Bingham model coefficients done by standard approach and including correction factor.

Fluid sample	μ_{pl} [mPas]	τ_y [Pa]
Bentonite	13.91	8.63
KCl	13.91	9.64

A flow curve with the Fann viscometer measurements corresponding to Table 6.2 is presented in Figure 6.1.1:

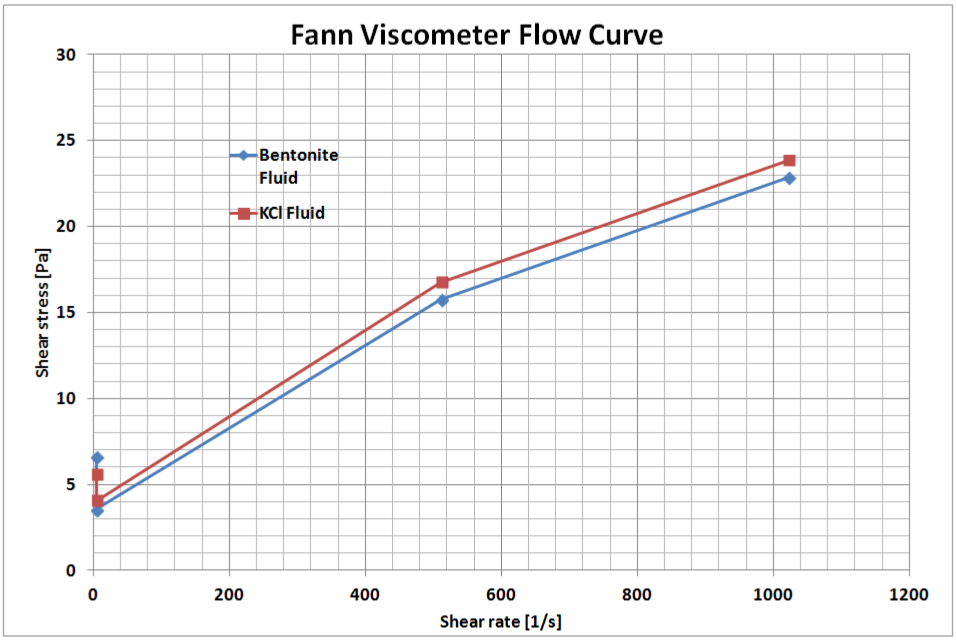


Figure 6.1.1: Flow curve based on Fann viscometer measurements, including 3 RPM points recorded after 10 s and 10 min.

6.2 Anton Paar MCR 302 Rheometer

A more thorough examintion of the two fluid was performed in a Anton Paar MCR 302 rheometer. The results from the Anton Paar rheometer are as following. The temperature was controlled at 22,00 °for all the rheometer tests. To avoid too many similar graphical presentations, only the results most important for the conclusion are presented here. Other results are found in the appendices.

6.2.1 Amplitude Sweep Test

Amplitude sweep tests were done to both fluid types. The Bentonite fluid amplitude sweeps were performed with strain ranging from 0,01-100 %, while the KCl fluid sweeps ranged from $0,01 - 500\%$. The KCl fluid had a greater range of strain, due to the crossing point ($G' = G''$) was not within the standard strain range. The angular frequency was 10 rad/s for both sweeps, which is a standard value for fluids with suspended particles. The amplitude sweeps are presented in Figure 6.2.1 .

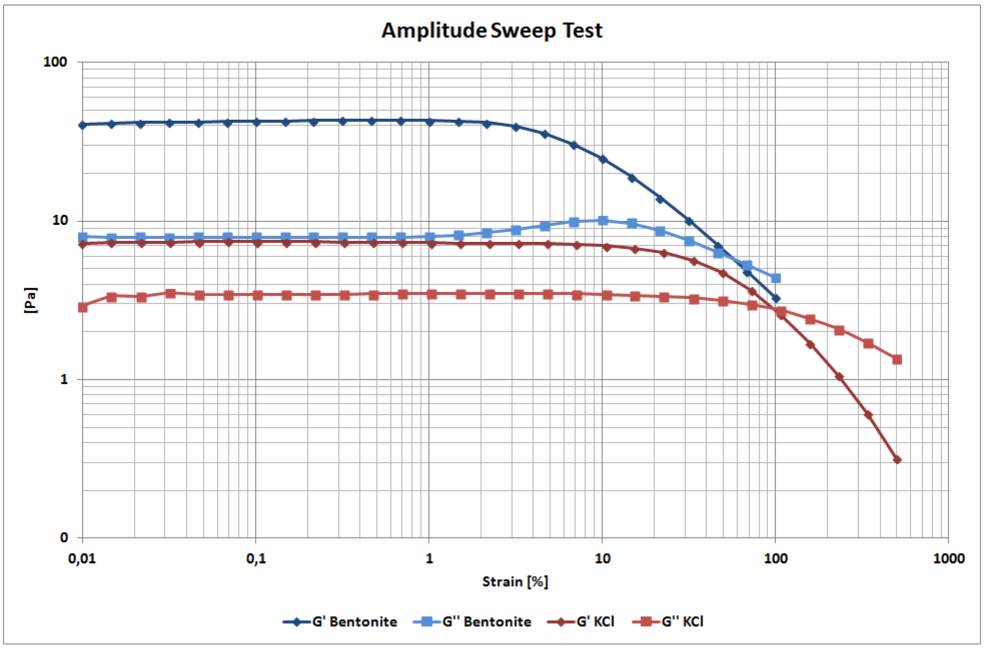


Figure 6.2.1: Amplitude sweep results for both the KCl and the Bentonite fluid samples.

The plot of storage and loss moduli for the drilling fluids, proves there exist a LVE range in both fluids. The limit of the LVE range was approximately 1%

for the Bentonite fluid and 5% strain for the KCl fluid. Both samples had a higher value of G' compared to G'' within the LVE range, proving gel like behavior. The elastic portion dominates the viscous one, indicating a certain stability in low shear range.

The computer software connected with the Anton Paar rheometer performed calculations for yield point, i.e. the point where the storage modulus (G') and loss modulus (G'') cross. The yield points calculated as described in Table 6.4.

Table 6.4: Yield points as calculated by Anton Paar Software, for Bentonite and KCl fluid samples.

Fluid	**Yield point(τ_y) [Pa]**
Bentonite	4.669
KCl	3.851

The calculated yield point values, done by the Bingham model, are significantly higher than the Anton Paar software calculated. In the Bingham approach compared to rheometer calculations a yield point increase of 84.8 % for the Bentonite fluid, and 150.4 % for the KCl fluid was observed.

6.2.2 Frequency Sweep Test

Based on the results from the amplitude sweep tests, frequency sweeps were conducted on both fluids samples with amplitudes within the LVE range. Calculations made by the Anton Paar software, based on the amplitude sweep, recommended values of constant amplitudes for the frequency sweeps. For the Bentonite fluid, this value was 0.219 Pa, while for the KCl fluid it was 0.0807 Pa. This corresponds to strain of 0.5 % and 1 %, respectively. The frequencies were ramped down from 10 rad/s to 0.1 rad/s. The results of the frequency sweep are shown in Figure 6.2.2.

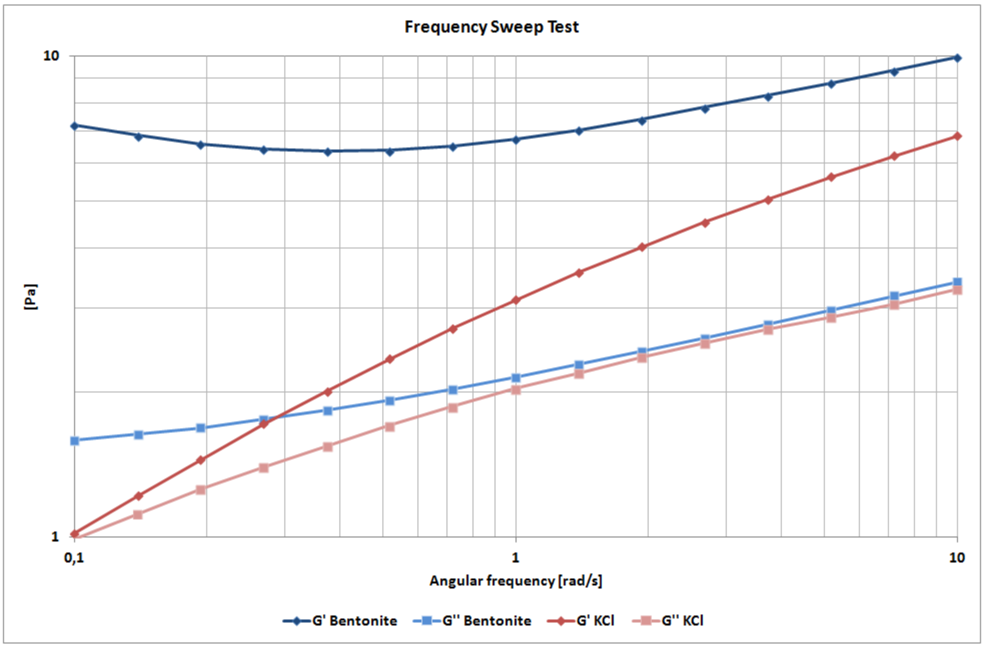


Figure 6.2.2: Frequency sweep results for both the KCl and the Bentonite fluid samples.

As seen in Figure 6.2.2 the results are quite different for the Bentonite and the KCl. For both fluids, the value of G' was greater than G'' through the whole range of frequencies. This means that the elastic response dominated viscous response. The values are not the most important part in this test, however the trends of the curves are. For the Bentonite sample, the storage modulus G' shows an increase in the low angular frequencies, while the KCl experiences a decline. Frequencies below 1 rad/s indicate how the fluid behavior functions in the long term, and the results suggest a difference between the Bentonite and the KCl in long term behavior. For the fluids in this research it appears like the Bentonite is more stable than the Potassium Chloride.

The Bentonite fluid's response to the frequency sweep indicates that the fluid consisted of cross-linked molecules. This suggests a gel-like state and stability at rest (Mezger, 2011). For the Potassium Chloride it seems as the curves for G' and G'' will cross for frequencies some point below 0.1 rad/s, if the curves are extrapolated. This indicate that the molecules in the fluid are unlinked, thus displaying the same behavior as of viscoelastic liquid at rest (Mezger, 2011).

6.2.3 Flow Curve

A flow curve is a graph depicting how a fluid's shear stress correspond to an inflicted shear rate. This is done by a rotational measurement. For the rheometer this means ramping up shear rates from 0 to the maximum shear rate of interest. In this research the shear rate was increased from 0 to 2000 s^{-1}.

The flow curve test basically measures the same as a Fann viscometer, that is how the shear stress relates to shear rate. The flow curve in Figure 6.2.3 shows the Bentonite and KCl fluids reaction in shear stress when the shear rate is increased. The graph is excluding measurements with shear rates above 1100, because shear rates above 1100 are not expected to occur in annular sections of real wellbores.

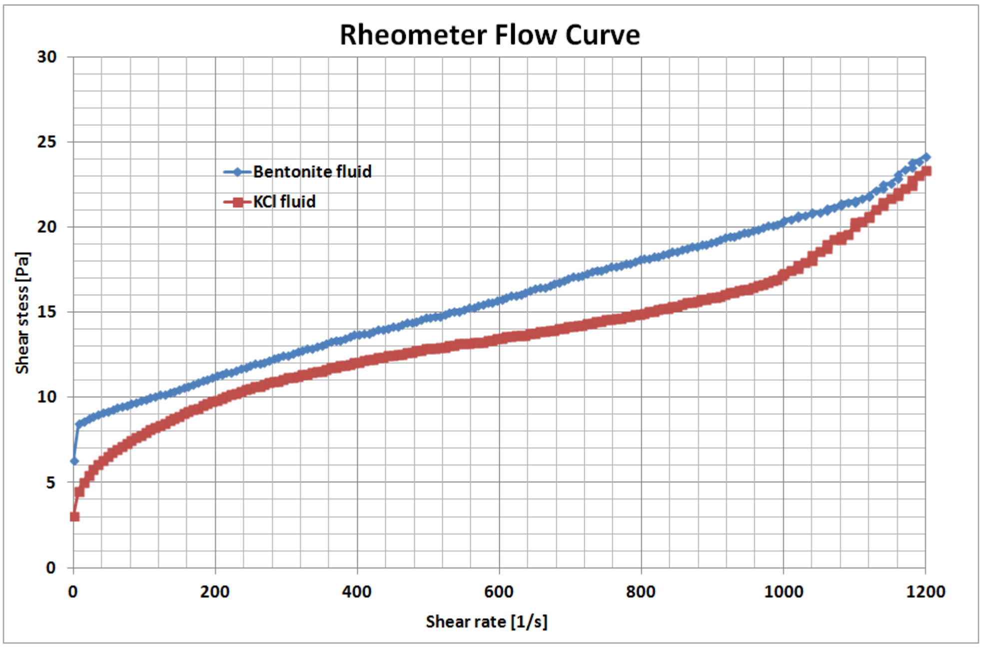


Figure 6.2.3: Flow curve for both the KCl and the Bentonite fluid samples, measured in the Anton Paar rheometer.

Apparently the slope is increasing for the KCl fluid from approximately 980 s^{-1} , and from approximately 1100 s^{-1} for the Bentonite fluid. This could indicate turbulence in the system (rheometer).

If the flow curves from the Fann viscometer and the Anton Paar rheometer are depicted in the same figure, differences are easier to observe. Figure 6.2.4

has both flow curves in one plot.

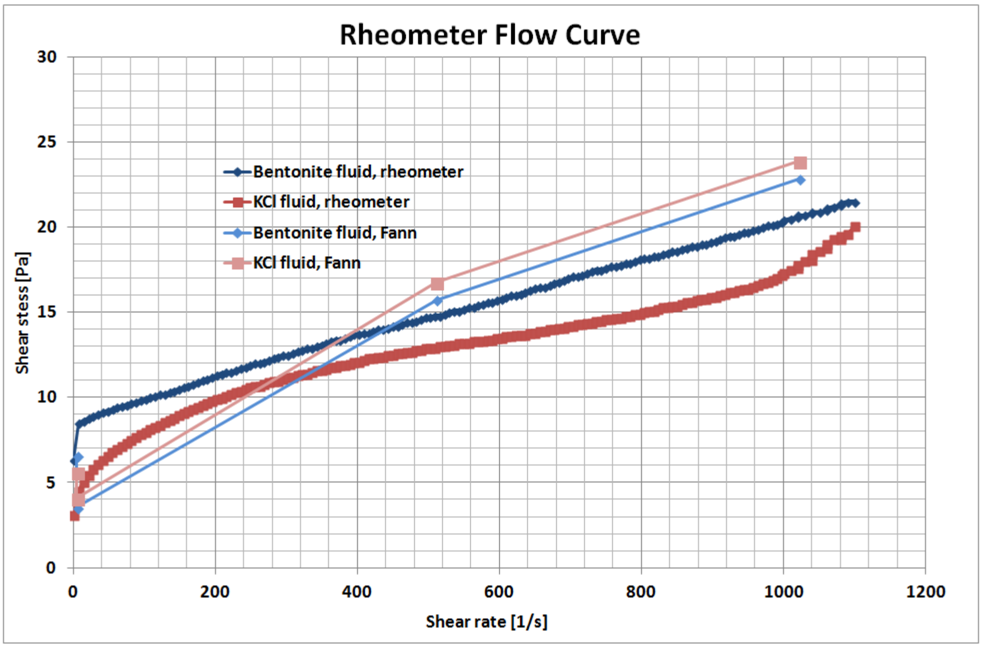


Figure 6.2.4: Flow curves based on rheometer and Fann viscometer tests. The Fann measurement included the 10s and 10min gel, which were conducted at 3 RPM.

The measurements performed on the Fann viscometer have generally higher values than the results from the rheomoter. The low end rheology, i.e. the lowest part of the shear rate range, do not have the resolution required for accurately describing what the fluid experiences. The fluids were at rest prior to rheometer testing, but for the Fann measurements the fluid was extracted from the flow loop circulation. The "10s gel" and "10min gel" values recorded at 3 RPM, or 5.1 s^{-1}, are like affected by the shear history and probably not fully recovered, i.e showing some thixotropic effect.

6.2.4 Viscosity Curve

If we reverse the values in the flow curve we could produce a viscosity curve, to illustrate effective viscosity reaction to different shear rates. The effective viscosity is the viscosity at a given shear rate, i.e. $\mu_{eff} = \frac{\tau}{\dot{\gamma}}$. Based on the results from the Anton Paar rheometer flow curve, combined with results from the Fann viscometer, Figure 6.2.5 is created. As the viscosity is inverse of shear stress, the curves are the inverse of Figure 6.1.1.

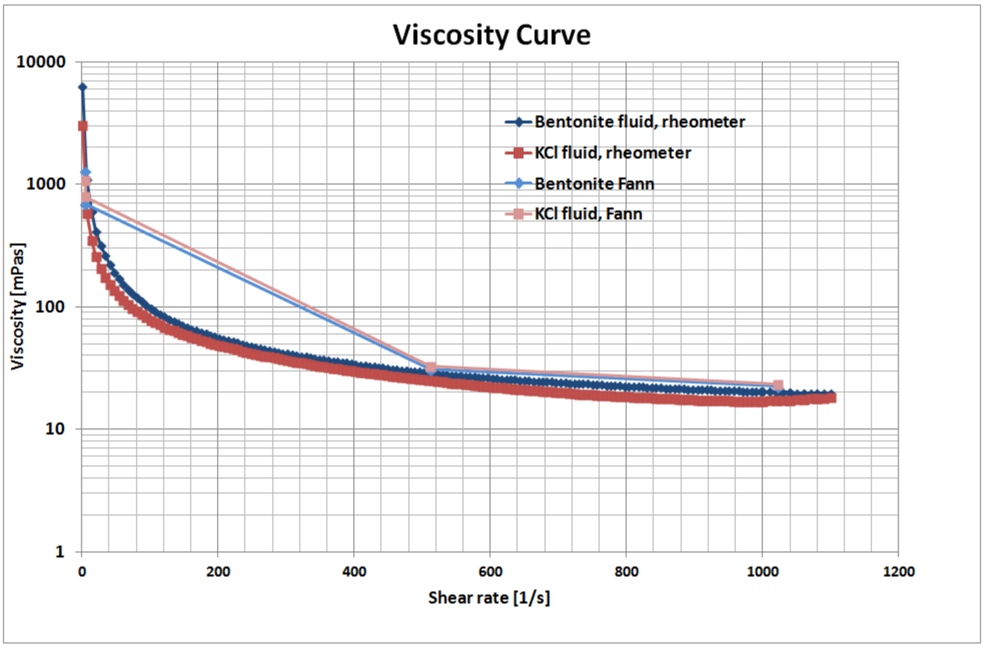


Figure 6.2.5: Viscosity curve for both the KCl and the Bentonite fluid samples, based on measurements from the Anton Paar MCR 302 rheometer and the Fann viscometer.

As for the shear stress to shear rate curve, the viscosity flow curve is not uniform. In the rheometer measurements the KCl fluid has the lowest viscosities, while the opposite is the case for the Fann measurements.

6.3 Flow Loop

After the problems experienced were overcome, positive results were obtained in the flow loop experiments. All flow loop test series were repeated once, then averaged prior to graphical presentation. This was done in order to reduce uncertainties. No measurements were significantly out of range, so all recorded measurements are presumed to be correct. Testing with the lowest obtainable rotational speed, 15 RPM, were also performed and recorded. The fluid flowed at a rate of 0.54 m/s, and sand injection was present.

6.3.1 Bentonite Fluid

All results from the flow loop experiment with Bentonite fluid are presented in Figure 6.3.1.

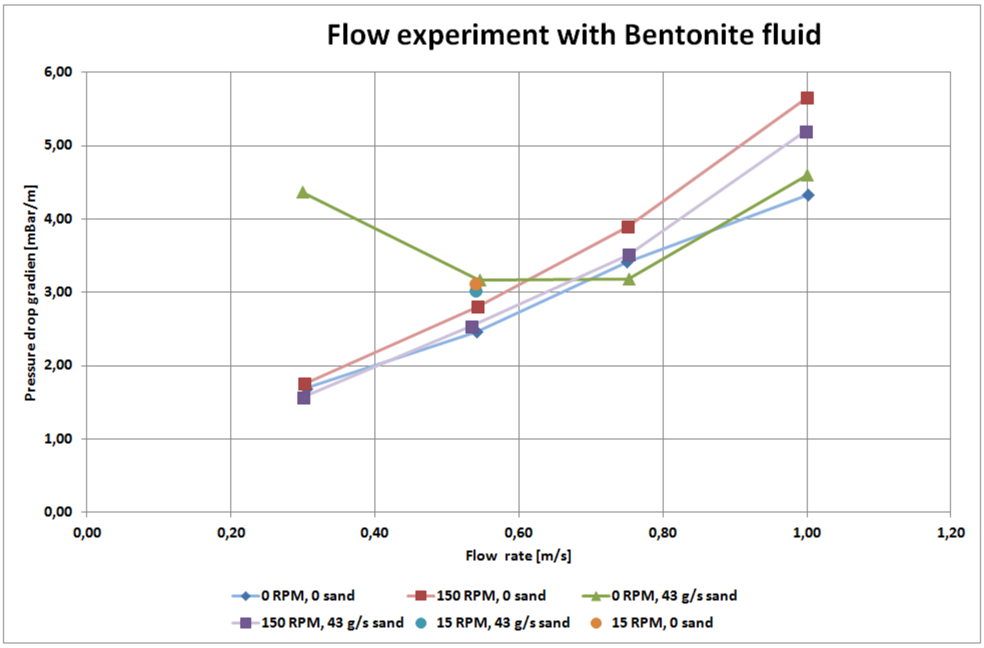


Figure 6.3.1: The pressure drop gradient for the Bentonite fluid with variable flow rate, sand injection and rotation speed.

6.3.2 Potassium Chloride Fluid

The KCl testing was more troublesome, but in the end positive results was obtained, presented in Figure 6.3.2. Overall the differential pressures measured with the KCl fluid was greater than for the Bentonite.

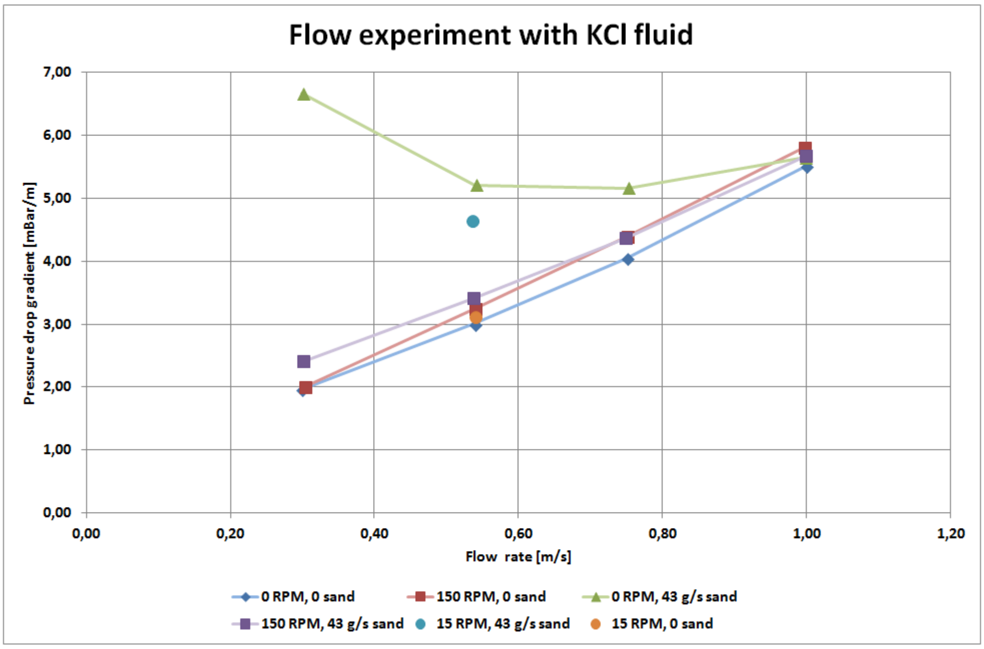


Figure 6.3.2: The pressure drop gradient for the KCl fluid with variable flow rate, sand injection and rotation speed.

6.3.3 Comparison

The difference in pressure drop when rotation is introduced is generally larger for the Bentonite drilling fluid than for the KCl drilling fluid. An increase in pressure drop gradient of 30.5 % when the flow rate is 1 m/s is seen for the Bentonite, while the KCl experienced a 5.4 % increase in pressure drop gradient. As seen in Figure 6.3.3 the trend for the Bentonite fluid is that the higher the flow rate is, the greater impact of rotation. This is not valid for the KCl fluid however. For KCl the greatest difference in pressure drop gradient when introducing rotation is the middle flow rates, 0.54 m/s and 0.75 m/s. Turning on rotation when the flow rate was 1 m/s resulted in a 5.4 % increase in pressure drop.

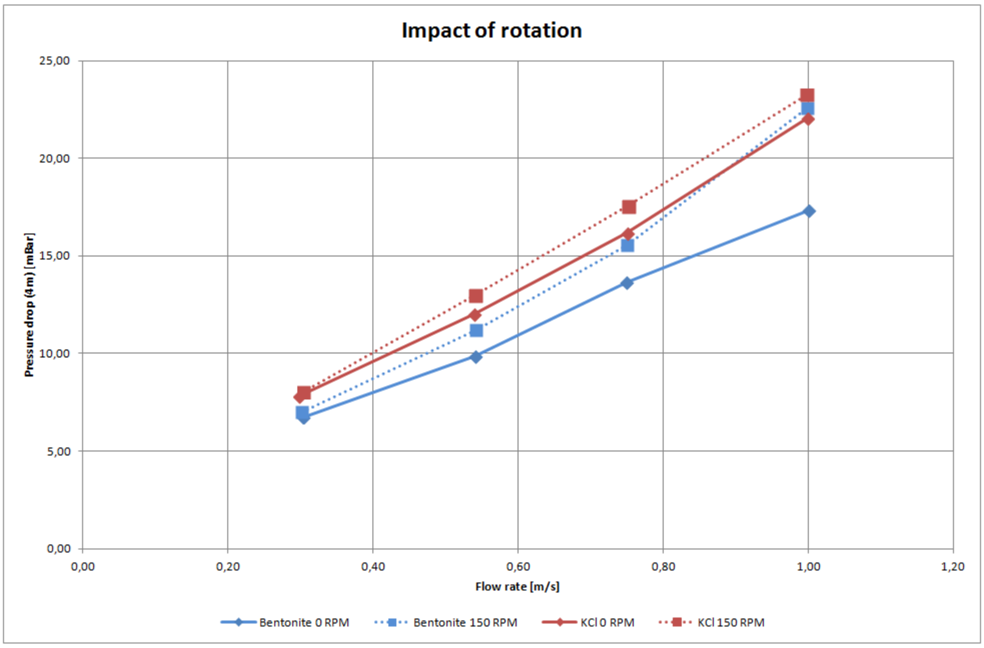


Figure 6.3.3: The pressure drop over 4 meters for the KCl fluid, for all flow rates and rotation speed.

A comparison between fluids for the testing with sand injection (and sand beds) when introducing rotation can observed in Figure 6.3.4. Discrepancies between the two drilling fluids are clearly observable. Again the Bentonite displays an increasing impact of rotation when increasing flow rate, while for the KCl the trend is not as clear.

The Bentonite fluid increases it's pressure drop by 12.8 % , the KCl fluid 0.5 % in a flow rate of 1 m/s. For flow of 0.3 m/s the Bentonite pressure drop is decreased by 64.2 % while the KCl experienced a decrease of 63.9 %.

6.3.4 Hole Cleaning

Both the Bentonite and the Potassium Chloride drilling fluid proved to be opaque, thus making visual observations of sand bed level not possible. The gamma densitometer used also proved to be inapplicable. This is because the combination of outer housing (made of steel), concrete circular wellbore and steel drillstring offered too much resistance for the radioactive source. Therefore no direct measurement of hole cleaning performances for the different drilling fluids were conducted.

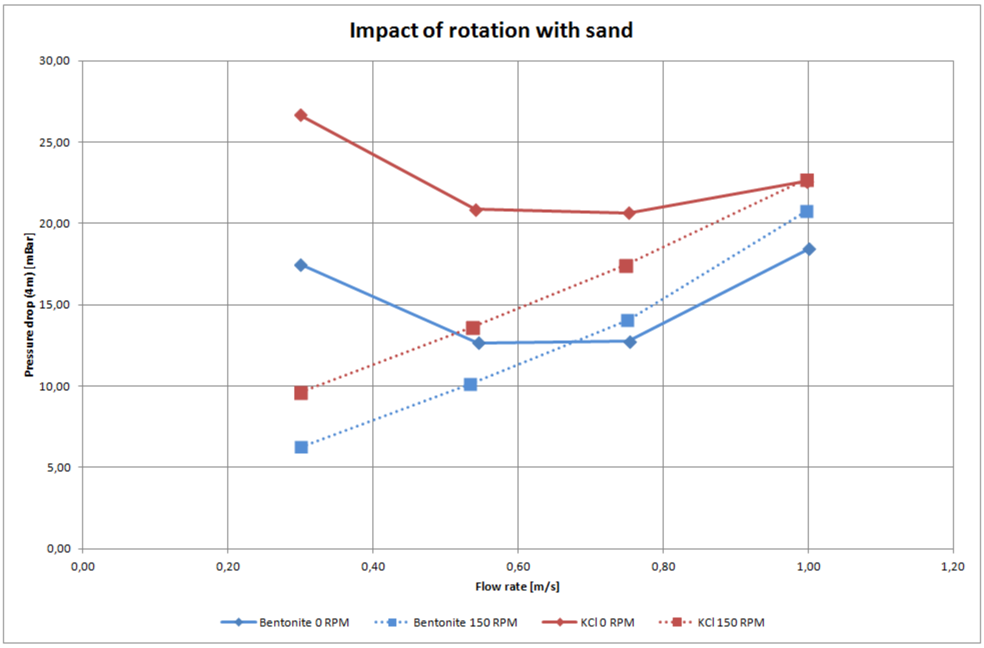


Figure 6.3.4: The pressure drop over 4 meters pipe length for both fluids, for all flow rates and rotation speed with sand injection.

The drilling fluids impact on hole cleaning performances could best be observed in Figure 6.3.4. It is not a direct measurement on sand bed level, or hole cleaning capabilities, but it grants some indication on hole cleaning. The two fluid's effect on hole cleaning are not fundementally different. Both fluids exhibits a similiar trend as observed in Figure 6.3.4, but there is some discrepancies.

6.4 Calculations

6.4.1 Reynold's Number

By using regression analysis on both fluids in Figure 6.2.3, coefficients for estimating the Reynold's number were found. See Figure 6.4.1 for match of regression equations and the coefficients. The Bentonite fluid is best fitted with a linear regression equation, which corresponds to the Bingham model. The KCl fluid's best match was a power law equation. The R^2 is an indication on how well the regression equation fit the curve it is suppose to replicate.

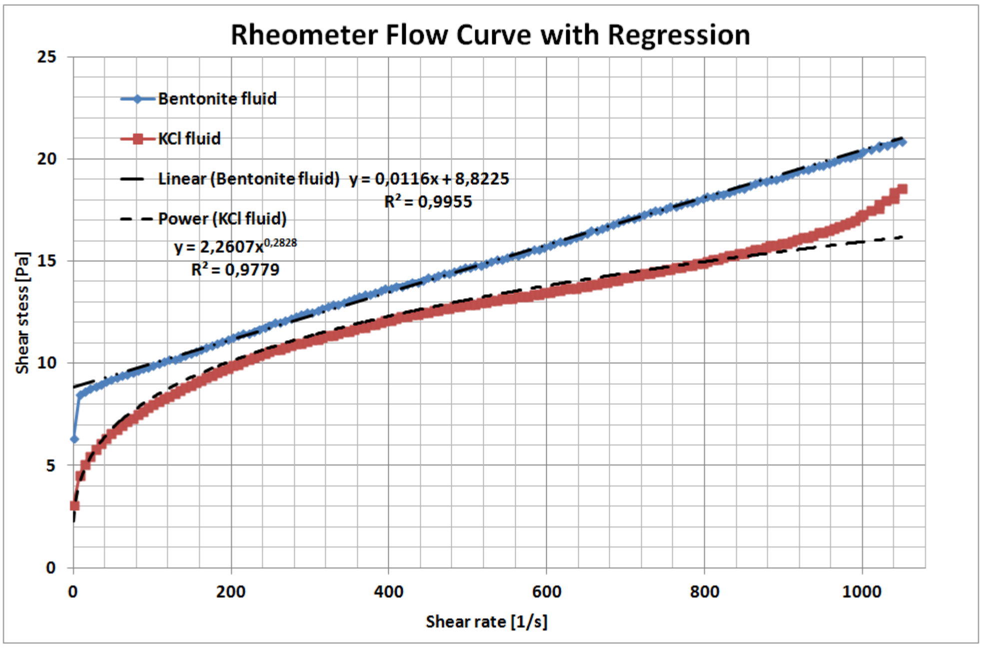


Figure 6.4.1: Regression analysis performed on the rheometer flow curve.

The generalized Reynold's number for power-law fluids can be expressed as (Taghipour et al., 2013):

$$Re_{PL} = \frac{\rho V \left(D_o - D_i\right)}{\mu_{eff}} \tag{6.4.1}$$

where the effective (average) fluid viscosity is

$$\mu_{eff} = K \left(\frac{12V}{(D_o - D_i)} \frac{2n+1}{3n} \right)^{n-1} \tag{6.4.2}$$

when assuming that the friction factor dependence on Reynold's number in laminar flow is the same as for Newtonian fluids. For simplicity the Reynold's numbers calculated ignore the effect of yield stress values. For the Bentonite fluid the Bingham model was the best fit, and the n parameter is set to 1, thus the expression is valid for Bingham fluids as well. From Figure 6.4.2 it appears that both fluids are turbulent for flow rates above approximately 0.65 m/s, when assuming a turbulence limit of $Re > 4000$ as is the case with circular pipes (Çengel and Cimbala, 2010).

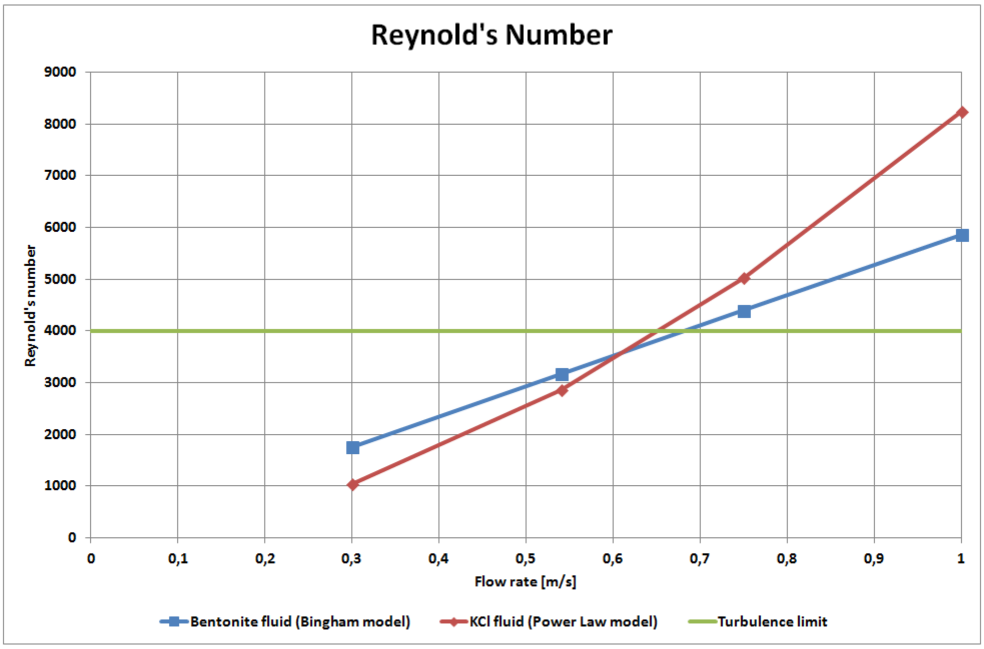
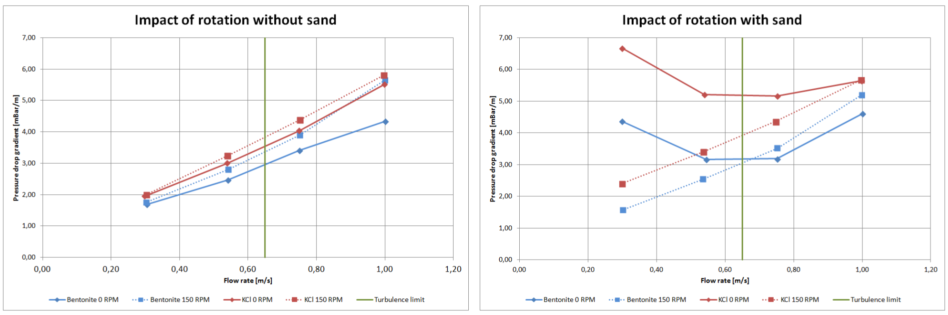


Figure 6.4.2: Reynold's number calculated for Bentonite and KCl drilling fluid, using Bingham and Power Law models respectively.



(a) Predicted turbulence limit plotted with rotation impact pressure gradients.

(b) Predicted turbulence limit plotted with rotation impact on sand injecting pressure gradients.

Figure 6.4.3: Classification of flow regimes for test with and without sand injection.

Chapter 7

Discussion

Chapter 7 contains a technical discussion (7.1 and 7.2), weaknesses of present report, and ending with suggestions of future improvements.

7.1 Viscometer versus Rheometer

The discrepancies in yield point values are significant. The Bingham approach clearly does not give the same value as the rheometer. For the Bentonite sample, an increase of 80.4% in yield point is calculated, compared to the rheometer. The difference for the KCl fluid is even greater, 150%. This indicates that yield point values should be measured in a rheometer, since estimation values give too high results. The discrepancies are explainable through the fact that Fann measurements are only taking 6 shear rates into account. Then interpolation and extrapolations are made. The further away from the measuring points you are, the more uncertain the resulting values will be.

A Marsh Funnel was considered and found not applicable for this research, and was therefore not used in this thesis. It gives an apparent viscosity (one parameter model), but it varies versus fluid height.

Rheometer Results

The results from the frequency sweep presented in Figure 6.2.2 indicated intermolecular linking in the Bentonite fluid, while indicating no linking in the KCl fluid. Bentonite, as mentioned in section 3.4.1, is a generic name for a mixture of minerals, which all have a sheet structure (Skalle, 2012). These sheets will create bonds between the plate edges, comparable to a house of cards (Torsvik, 2013). The bonds are caused by attractive and repulsive forces, which affect properties like viscosity and yield point (Skalle, 2012).

The Potassium Chloride was built by adding a higher amount of Xantham gum. Polymers, such as Xantham gum, form long chains of molecules, like a thread. The threads will disperse if charged (repulsive forces from same charge), but may wind into balls if the charge is neutralized by a certain degree of salinity. As Xantham gum is anionic by nature (Vanzan Xanthan Gum, 2013), i.e. negatively charged, and the KCl fluid consisted of 2.6 weight percentage KCl, this is expected to happen. The network structure provided from this phenomena was not enough for making a stable gel structure.

Differences in network structure could explain why the KCl fluid experienced foaming. It is believed that the loosely network created by the polymer is more capable of incorporating bubbles of air (Torsvik, 2013). The Bentonite "card house" network is stronger, and therefore bubbles and foam were not a problem.

The difference in measured viscosity are peculiar. While the results from the Fann viscometer indicated that the KCl fluid was more viscous, the results from the rheometer test indicated that the KCl liquid was less viscous than the Bentonite. The recorded measurements did not agree upon which drilling fluid that was more viscous.

There was likely differences in the measuring conditions, with respect to atmospheric pressure, sample temperature and drilling fluid age. The possible change in atmospheric pressure considered negligible and would unlikely affect the rheological properties of the fluids. Temperature variations are considered to be in the significant scale. The highest recorded temperature of drilling fluid in flow loop circulation was 26.6℃. Other flow loop tests had temperatures close to 22.1℃. The flow loop rig was located in an airy workshop, so ambient temperature down to 16℃may have been present during the test period. Fann viscometer measurements may then have been conducted in a approximately temperature range of 10℃. This is believed to have an insignificant impact on viscosity measurements performed with the Fann viscometer. As a comparison. a change of 10℃in water at 20℃, would have an impact of $20 - 30\%$.

When the two drilling fluids were tested in the rheometer, there existed an age difference Between the Bentonite and the KCl fluid. This could have affected the outcome in a unknown degree. The Bentonite fluid was mixed approximately one month before the KCl fluid. The Bentonite fluid was kept in a container for about three weeks after flow loop experiments, prior to the rheometer measurements. The KCl fluid experienced a standstill period of five days. This difference in age and standstill time may have influenced the results from the rheometer.

7.2 Operational Issues

Flow Condition

Based on the calculations and predictions made in Figure 6.4.2 both fluids are in a turbulent flow regime when the fluid velocity is above 0.65 m/s. No clear distinction of flow regime is observed in Figure 6.4.3. The predictions of turbulence limit are not accurate, and a significant degree of uncertainty must be expected. This is due to the fact that the estimation of the hydraulic diameter is precisely that, an estimation, and when introducing sand beds and particles in the flow the uncertainty is increased. The turbulence limit is expected at Reynold's number of 4000. This value is for circular pipes, and not necessarily valid for circular pipes with a fully eccentric inner pipe.

Impact of Sand Injection

When sand was injected into the flow, some phenomena were observed. After some time circulating with sand at the lowest flow rate, a stable sand layer/bed was created. When increasing the flow rate from $0.3m/s$ to $0.54m/s$ a decrease in pressure drop gradient was observed. This is contradictory to what one normally would expect happen when increasing the flow rate; the pressure drop should increase as well. The explanation of this is as follows: When the flow rate is increased, more pressure acts upon the sand bed, thereby removes some of it. When removing the sand bed the cross section area for the flow increases, and as a result the pressure loss decreases.

Impact of Rotation

The rotation of the simulated drillstring enhanced the hole cleaning performance, as expected. For the KCl fluid a mere 0.5 % increase in pressure drop gradient with a flow rate of 1 m/s was observed, when sand was injected. The Bentonite drilling fluid increased it's differential pressure by 12.8 % on the other hand. This could be explained by the different rheologies of the two fluids. As seen in Figure 6.2.3 the KCl fluid seems to be in a turbulent flow regime at lower shear rates than the Bentonite fluid. This would affect cuttings transportation and differential pressure in the flow loop. Assume the KCl fluid reached turbulence at lower shear rates, which corresponds to flow rate in the flow loop; this will aid hole cleaning since turbulent flows exhibit a higher shear at the wall and will improve erosion.

Hole Cleaning Performance

It is hard to know the exact effect the different drilling fluids had upon hole cleaning performances, due to opaque drilling fluids and a too weak gamma densitometer. But some conclusion may be derived from the differential pressure measurements done during sand injection. The KCl type fluid had a smaller positive change in pressure drop gradient than the Bentonite type, when increasing flow rate from 0.75 m/s to 1 m/s. This indicates that the Bentonite fluid could not carry away the particles as effectively as the KCl. The sand bed level was probably higher, causing a smaller cross section volume for the flow to pass. This means that the local velocity increases, and thereby the pressure as well.

As seen in Figure 6.3.4 the pressure gradient for the Bentonite fluid increased more than the KCl fluid, when rotation was introduced .

7.3 Limitations and Weaknesses

Fluids

Mixing

The Bentonite fluid was premixed in a mixing tank before it was transferred to the main system. Some days after the mix was made, it appeared as if the fluid was not properly mixed and non-uniform. Lumps, containing heavy particles, were found when the mixing tank was drained. In the end, it is difficult to accurate point out how much of the heavy particles were left in the mixing tank and if some of the other ingredients were part of the lumps/solids. This makes it more difficult to replicate the experiments and results.

Temperature effects

Since the fluids were left in the tank of the flow loop overnight and over weekends after being built, some evaporation surely existed. The fluid main tank was not a closed system, and evaporation is challenging to exclude. The effect of evaporation could increase the fluid density, as seen in the KCl fluid, and higher shear stress values on the Fann viscometer. It is difficult to quantify the evaporation, but it should not be excluded. The tests were performed in room temperature, and supposedly the tank held a temperature of 22 °. However, circulation increased the temperature, due to friction. The testing was subsequently performed with a variance of temperatures, and this may have affected the viscosity, hence the pressure loss and flow regime.

Temperature affecting the viscosity may explain why the measurements from the Fann viscometer and the Anton Paar rheometer did not agree on which liquid was more viscous. The rheometer tests were conducted in a fixed-temperature environment, which was not the case for the Fann measurements. This testing was executed in room temperature over a timespan of one month, thereby reducing the probability of having the exact temperature constant. The fluid which was tested in the Fann viscometer, was extracted from the flow loop during circulation. A temperature difference in the circulation drilling fluid of approximately 4 °was observed during flow loop test. Since no temperatures were recorded when performing measurements on the Fann viscometer, there could be a sufficient discrepancy in temperature to explain this contradictory observation.

Anther possible explanation of this observation could be aging of the viscosifier. The Bentonite fluid sample that was extracted for rheometer measurement purposes, was without circulation for around three weeks. A sample volume was collected in a closed container, and left for three weeks before commencing testing with the rheometer. The degradation of Xantham gum is known to happen, and is commonly managed by adding biocide. The adding of biocide was not done for either the Bentonite fluid or the Potassium Chloride fluid. Thus, aging effects on the drilling fluids can not be excluded.

Bubbles

For the KCl drilling fluid the problem with foam and bubbles in the flow could mean that values for flow rate, pressure drop and rheological measurements were incorrect. It is hard to predict how bubbles will appear in a cross section, but generally they will either be on top of the flow, like e separate layer, or they could be dispersed in the flow. If the case of dispersed bubbles is assumed correct, cuttings holding capacity will be altered for the KCl flow. It is hard to quantify such alterations, but it would be foolish not to take them into account.

Rheology Measurement Errors

Fann

Fann viscometer tests were not conducted with a calibrated viscometer. This does not mean that all test results are wrong, but it could definitely prove to change the final outcome. According to Schaeffer (2013), Fann viscometers are solid equipment, which can handle rough use and still deliver accurate results. With regard to this, the results from the Fann measurements are assumed to be correct.

The measurements with the Fann viscometer was done in room temperature, assumed to be constant at 22°. Room temperature is not a valid scientific temperature, and this could affect the measurements. The Fann viscometer measurements were only recorded with three of six speed settings. Recording measurements for the full range would reduce the uncertainty.

Rheometer

The rheometer tests were conducted in a temperature controlled environment, thus the results should be correct. The value of 22°was chosen. Since the Fann measurements were not conducted under the same temperature, there might be a difference and the flow curve results may have proven to be non-comparable.

The greatest possible source of error in the rheometer testing values, is that the tests were conducted some time after the fluid sample was extracted from the flow loop system and the drilling fluid was made. This is especially important for the Bentonite fluid, which was examined in the rheometer nearly one month after it was circulated in the flow loop. It also took 3-4 weeks from the drilling fluid was completed to the time it was circulated and results recorded. The aging of viscosifiers, in our fluids the Xantham gum, is a known industry problem, and this could very well make a significant impact on rheometer measurements.

The KCl drilling fluid did not suffer the same inactivity time before being tested in the rheometer, but also for that drilling fluid a delay of approximately one week had passed.

Calculation Errors

Offset Values for Flow Loop Experiments

All pressure data presented in this report has been corrected for offset values. Calibration of the pressure sensors in the flow loop was conducted by recording the pressure during zero dynamic flow rate. The pump software was given orders to deliver 0.0 m/s flow. In automatic mode, the pump still delivers some flow, although very low values. The interpretation of this is that the test section is filled with fluid. Another method of choosing reference points is simply by draining the test section and then record the values. The former method was chosen since the values for the fluids were closer than for the drained section, thus making them easier to compare. These offsets could be measured or chosen incorrectly.

The offsets values affects the pressure measurements in a simple, arithmetic (+/-) way. The pressure difference in percentage values could therefore be untrue, but the graphical presentation will still be correct. These offset uncertainties will also affect the comparison of Bentonite and Potassium Chloride fluids, in absolute numbers. The difference in rheological properties measured with the rheometer indicates that there is a difference in fluid behavior, and hence there should be differences for the flow loop results as well.

Reynold's Number

In order to calculate Reynold's number, and thereby decide under which flow regime the tests were conducted, a value for viscosity is needed. As the fluids used in this research are non-Newtonian, the effective viscosity will not be constant. This implies that the Reynold's number depend on the value of viscosity. And since the viscosity for non-Newtonian fluids depend upon shear rate, inaccuracies may occur.

As seen in Figure 6.2.5 the viscosity drops with increasing shear rate. It is challenging to predict the shear rate of the flow loop, but it is assumed the lowest values for viscosities are valid. As mentioned earlier, the viscosity increases with shear rates higher than approximately 950. This phenomena is attributed to turbulence in the rheometer cup, and not necessarily the case in the flow loop.

Hole Cleaning

In order to really know how fluid properties and drillstring rotation affect cuttings transportation sand beds for horizontal sections, an optical examination would be preferred. Neither of the two drilling fluids were lucid, and thereby making it challenging to know how much sand was present in the test section. A gamma-densitometer was installed, only to be removed shortly after, due to low signal strength. The sand bed level had to be estimated on the basis of differential pressure measurements, thus the uncertainty is insignificant.

Wear of Concrete

The concrete blocks used inside the outer pipe could have eroded to some degree by the rotation of the inner string. This would make the flow area larger, thus reducing friction pressure. This may have influenced the results and made the flow pattern more complex, by not being fully circular.

7.4 Potential Improvements and Further Work

Further work with different rotation speeds, with an oil based drilling and with the test section inclined, is recommended. Higher flow rates should also be applied if possible and with larger sand particles replicating drilled cuttings. Experiments with higher fluid velocity would give knowledge on how cuttings transportation is in a real wellbore, with real fluid flow rates. Experiments with larger particles would give insight in realistic borehole fluid flow containing realistic cuttings. Test conducted with other fluids will likely give different results, and therefore it would be beneficial to have a wide array of realistic drilling fluids available for research purposes.

The research presented in this report should be replicated in order to confirm the findings. A replicated test would remove the uncertainties regarding what the real share of ingredients in the fluids were. In new tests, acoustic or ultrasound measuring systems should be installed on the transparent part of the flow loop test section. This would aid the knowledge on cuttings transport in real wellbores, since the sand level content could be more accurately monitored.

Chapter 8

Conclusion

When no cuttings are present, rotation of a fully eccentric drillstring in a horizontal section will increase the annular pressure drop. If cuttings are present the rotation will aid hole cleaning. This is valid for all flow rates regardless of drilling fluid type, with and without cuttings in the wellbore. Sand bed content are determined by flow rate, rotation and fluid properties. Additionally observations are split into three groups:

- Cuttings behavior
  - Water based drilling fluids that have close to equal properties when measured by simple equipment, may give different results when used in a realistic flow loop.
  - Microscopic structure of drilling fluids affects properties measured in full scale.
- Experimental issues
  - Gamma densitometers are unfit for measuring sand bed levels in the flow loop used.
  - Realistic drilling fluids are optimized for drilling purposes, not for experimental use. KCl based drilling fluids easily produces foam, especially when the fluid splashes.
  - No direct examination of sand bed level in the flow loop was performed, due to the opaque characteristics of realistic drilling fluids.

- Suggestions for future experiments
  - Further experimental research should be conducted in the test rig utilized, with both water based and oil based drilling fluids, in order to determine different cuttings transportation capability of different drilling fluid systems.
  - More measurements performed with Fann viscometer, utilizing the whole range of speed setting, should be performed.
  - Future testing of rheoligical properties, with Fann viscometer and Anton Paar rheometer, should be performed shortly after samples are collected.

Bibliography

Ahmed, R. and Miska, S. (2008). Experimental study and modeling of yield power-law fluid flow in annuli with drillpipe rotation. SPE 112604. IADC/SPE. Presented at the SPE/AIADC Drilling Conference held in Orlando, Florida, USA 4-6 March.

American Petroleum Institute (2010). *Rheology and Hydraulics of Oil-well Fluids, API Recommended Practice 13D*, sixth edition.

Amoco Production Company (1994). *Drilling Fluids Manual*, 6 edition.

Bourgoyne Jr., A. T., Millheim, K. K., Chenevert, M. E., and Young Jr., F. S. (1986). *Applied Drilling Engineering*, volume 2. Society of Pretoleum Engineers.

C. Moomjian Jr. (2013). Macondo litigation and its impact on the offshore industry.

Çengel, Y. A. and Cimbala, J. M. (2010). *FLUID MECHANICS Fundamentals and Applications*, volume 2. McGraw-Hill.

Company, G. P. (2008). Drilling, completion and workover fluids. Special Supplement to World Oil June edition.

Darby, R. (1976). *VISCOELASTIC FLUIDS An Introduction to Their Properties and Behavior*, volume 9. Marcel Dekker.

Erge, O., Miska, S. Z., Takach, N., Ozbayoglu, M. E., Yu, M., May, R., and Saasen, A. (2013). Effct of drillstring deflection and rotary speed on annular frictional pressure losses. Presented at the ASME 2013 32nd International Conference on Ocean, Offshore and Artic Engineering, Nantes, France, June 9-14 June 2013.

Løklingholm, G. (2002). The drilling fluid inhibition properties effect on hole quality - a well survey.

Mezger, T. G. (2011). *The Rheology Handbook*. European Coatings Tech Files, 3rd revised edition.

Saasen, A. (2013). Annular friction losses during drilling - the effect of drillstring rotation.

Salvesen, S. E. (2013). Hole cleaning in deviated wells. University lecture held at NTNU, in the subject TPG4220 - Drilling Fluid.

Sandvold, I. (2012). Gel evolution of oil based drilling fluids. Master's thesis, NTNU.

Skalle, P. (2012). *Drilling Fluid Engineering*. Ventus Publishing ApS, third edition.

Taghipour, A., Ytrehus, J. D., Reyes, A., Skalle, P., Abdollahi, J., Lund, B., Saasen, A., and Melchiorsen, J. C. (2013). Experimental study of hydraulics and cuttings transport in circular and non-circular wellbores.

Taylor, G. I. (1923). Stability of a viscous liquid contained between two rotating cylinders. 223:pp. 289--343.

Torsvik, A. (2013). Personal Email Correspondanse.

Vanzan Xanthan Gum (2013). `http://www.rtvanderbilt.com/vanzan.pdf`. Retrieved June 28, 2013.

Appendix A

Drilling Fluid Contents

A.Torsvik (2013) made sample fluids which were intended on having the same Fann 35 Viscometer and density properties. The recipe were upscaled for use in the flow loop.

A.1 Bentonite Fluid

Table A.1: Weight ratio Bentonite example fluid.

Material	Weight ratio
Bentonitt	0.018313953
Soda Ash	0.00872093
Xanthan Gum	0.00130814
Fresh Water	0.638081395
Barite	0.333575581
Sum	1

A.2 KCl Fluid

Table A.2: Weight ratio KCL example fluid.

Material	Weight ratio
KCl	0.044928523
Soda Ash	0.00136147
Xanthan Gum	0.002722941
Fresh Water	0.63308373
Barite	0.317903336
Sum	1

Appendix B

Fann Measurements History

During the project several Fann viscometer measurements were performed. Table B.1 and Table B.2 gives the rheological history measured with the Fann viscometer.

Table B.1: Bentonite shear stress history.

Date	Hour	600 RPM	300 RPM	10s gel	10min gel	Density (SG)
10th May	-	45	33	8	11	-
13th May	09:00	38	27	6	-	-
	15:30	40	28	7	11	-
16th May	15:10	42	29	7	12	1.36
23rd May	09:35	45	31	7	13	1.36

Table B.2: KCL shear stress history.

Date	Hour	600 RPM	300 RPM	10s gel	10min gel	Density (SG)
3rd Jun	14:20	45	32	8	11	1.35
	14:50	44	32	10	11	-
4th Jun	11:30	45	32	8	11	1.36
17th Jun	10:30	47	33	8	11	1.37

Appendix C

Sintef Measurements

SINTEF Bergen (Torsvik, 2013) got the following results using a Fann 35 Viscometer for testing a Bentonite fluid, with the same portion of chemicals used as in Table A.1.

Table C.1: The viscosity measurements made by Torsvik (2013) for the Bentonite fluid

Viscosity $[lb/100ft^2]$			
600 RPM	300 RPM	10 s gel	10 min gel
76	54	16	17

With the density:

Table C.2: Density of the test fluid made by Torsvik (2013)

Density $[\frac{g}{cm^3}]$	Temperature [°C]
1.37614	21.51