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Table of contents

Table of Figures

Table of Tables

Explanations of symbols

μ	=	viscosity
SS	=	shear stress
SR	=	shear rate
τ	=	shear stress
K	=	consistency index
$\dot{\gamma}$	=	shear rate
n	=	exponent law index
Re	=	Reynolds number
ρ	=	density
V	=	velocity of the fluid
L	=	characteristic length scale of the flow
$V_{mud,start}$	=	original mud volume
$V_{mud,1}$	=	mud volume before ejection
$V_{mud,2}$	=	mud volume after ejection
V_{spacer}	=	spacer volume that's getting injected
p_1	=	desired mud ratio before ejection
p_2	=	desired mud ratio after spacer injection

Acknowledgments

I would like to begin by thanking my employer, Halliburton, who allows me to use their professional laboratory equipment and provides me with the space and assistance to carry out good, orderly, and high-quality test data. The people around me were committed to me and my project and always offered a helping hand if necessary. I would like to give an extra greeting to the mechanic, Derek Nilsen, who was available to develop, fix and modify equipment that was beyond my competence. It has been a pleasure and good learning experience. Thanks for all the good and funny conversations we had through this thesis.

Would also like to acknowledge my supervisors, Gunnar Lende and Arild Saasen, respectively from Halliburton and University of Stavanger, which have consistently provided me with guidance and assistance.

Abstract

When executing a drilling operation in a well, rheological properties are important to understand in order to have the most error- and problem-free drilling operation as possible. Drilling fluids such as mud, spacer and cement are used to achieve these error- and problem-free operations. Before using these fluids, tests are performed to get an understanding of their behavior both separately and together.

In this bachelor thesis the main focus is on oil-based mud and spacer, since these two fluids are relevant fluids for the tests relevant to this thesis. The goal is to find a new method that performs more efficient, cleaner and will give us meaningful results.

Two instruments have been restored and modified to perform these tests, that are compatibility and wettability. I will return to the definition and explanation of these at a later stage of the thesis. The development of these machines has been tested frequently to achieve the most meaningful and best results possible. A rheometer, Fann Model 286, and a wettability test apparatus, Fann Model C1001. Both from Fann Instrument Company is the two instruments that has been restored, modified and used.

The results from the development and tests will give us an idea and thought for how to improve and run tests smoothly. Also results that make sense in understanding of the rheological properties so that we can run drilling operations without problems.

Preface

The execution off compatibility and wettability tests is time consuming and extremely inefficient, especially working with oil-based muds. When I contacted Gunnar Lende regarding a potential bachelor's thesis, he had no doubts about where he saw potential for improvement in addition to exciting aspects of doing engineering work. It concerned the compatibility and wettability testing. If you are to carry out these two tests together, you can almost guarantee that two hours and 30 minutes will be spent in this area combined. Therefore, the aim is to find a new and more efficient method to run these tests.

I will present my conclusions and reflect on what I have learned during this six-month bachelor's thesis. It has been an exciting experience to work with new technology, particularly with technology that I have contributed to and believed in. Throughout this period, I have gained a vast amount of knowledge. This includes skills in utilizing tools to modify and develop new technology, as well as understanding the significance of oil-based mud and spacers and the importance of conducting compatibility and wettability tests prior to drilling operations.

Chapter 1 Introduction

During drilling, a rotating drill bit is used to break up the rock or soil, and drilling mud is used to cool, lubricate the bit, carry away the cuttings and provide pressure control. Spacer, which is a type of fluid that is used to separate the drilling mud from the cement, ensuring that the cement can be pumped cleanly and efficiently. This helps prevent contamination of the cement, which could compromise the integrity of the well. Cement is used to seal the casing in place and prevent the flow of fluids, such as water or gas, from surrounding formations. The cement is pumped into the annulus between the casing and the borehole wall, filling the space and forming a barrier. Overall, mud, spacer and cement are critical components in the drilling process, helping to ensure the integrity and longevity of the well.

In a formation where you perform a drilling operation, there are different types of geological conditions at different temperature and pressure conditions. It is therefore important to have a good understanding of how different types of liquids behave under these conditions and how they affect the geological formation. Furthermore, the geological conditions of a formation can also affect the type of drilling technique that is used. For example, if the formation is relatively soft and homogeneous, a rotary drilling technique may be sufficient. However, if the formation is harder or more complex, other drilling techniques such as directional drilling or hydraulic fracturing may be required. In addition, the properties of the formation can also impact the design of the wellbore, such as the angle and depth of the well. The geological conditions must also be considered during the completion process, such as choosing the appropriate type of completion technique or selecting the best location for the wellhead. In summary, a good understanding of the geological conditions of the formation is crucial in all stages of the drilling operation, from planning to completion, to ensure a safe and successful well.

The geological conditions of the formation being drilled are a crucial consideration when selecting and using drilling fluids. Different formations require different types of drilling fluids that are compatible with their specific geological conditions. Factors such as rock type, porosity, and permeability affect the performance of the drilling fluid and can impact the success of the drilling operation. For example, a formation with high porosity may require a low-density fluid to prevent damage to the formation, while a formation with low permeability may require a high viscosity fluid to improve hole cleaning. The selection of the appropriate drilling fluid also depends on the depth and temperature of the wellbore. It is essential to consider the geological conditions of the formation when selecting and using drilling fluids to ensure the success of the drilling operation.

Oil-based mud consists of a base oil, such as diesel or mineral oil, blended with various additives and solid materials, such as clays and weighting agents, to achieve the desired properties for efficient drilling. The specific composition of the drilling mud will depend on the geological conditions of the drilling site and the drilling objectives. For example, if the formation being drilled is highly porous, the mud may need to be weighted with heavier additives to prevent it from leaking into the formation. Conversely, if the formation is prone to collapse, the mud may need to be lighter to avoid further destabilizing the formation. Mud is constantly monitored and adjusted during the drilling process to ensure that it is performing optimally. Overall, mud plays a crucial role in the drilling process, helping to ensure that the well is drilled safely and efficiently.

Spacer fluid, also known as separation fluid, is a type of fluid that is used to separate the drilling mud from the cement slurry during the cementing process in a drilling operation. The contents of spacer fluid can vary depending on the specific requirements of the drilling operation, but typically it contains a blend of water, viscous polymers, surfactants and chemical washes. Purpose of the spacer fluid is to create a clean interface between the drilling mud and the cement, preventing contamination of the cement slurry and ensuring that it can be pumped effectively. The importance of spacer fluid cannot be overstated, as contamination of the cement slurry can compromise the integrity of the wellbore and lead to costly remediation efforts. Proper use of spacer fluid is critical to ensuring the long-term safety and productivity of the well.

When drilling with mud and pumping spacer and cement after drilling, it is important to know how they behave in a rheological point of view. Therefore, in a laboratory, there are experiments that are performed to get an understanding of how these fluids behave separately and also combined. Compatibility and wettability testing are critical in drilling and cementing operations because they help to ensure that the drilling fluid is compatible with the formation being drilled and can efficiently remove cuttings from the wellbore.

Compatibility is a test that are executed in a laboratory to check how compatible two fluids is. The compatibility of mud and spacer is crucial in drilling operations where multiple fluids are used. Compatibility testing of the mud and spacer is essential to ensure that they do not react chemically or physically with each other, leading to the formation of solids or other contaminants that can affect the performance of the drilling fluid. If the mud and spacer are not compatible, they can cause issues to the cementing operation. In addition, it could cause poor hole cleaning and increased risk of stuck pipe. The execution of the compatibility test is performed in various ways, such as analyzing the chemical and physical properties of each fluid and assessing their compatibility. Main focus for the liquids is on viscosity and water wetting abilities, as well as influence on thickening time and strength build-up. This ensures that the fluids are compatible, and the drilling operation can proceed successfully.

Wettability testing is an essential part of cementation operations involving drilling mud and spacer. The wettability of the mud and spacer affects the efficiency of the cementation process and can impact the quality of the wellbore. When drilling with mud and spacer together, it is crucial to ensure that they are compatible and that the mud can efficiently wet the formation. Attaining water wettability is crucial for the effective execution of cementing operations. Since cement cannot bond to surfaces that are oil-wet, it is essential to utilize a spacer fluid containing surfactants that can convert these surfaces into water-wet ones, thereby replacing the nonaqueous drilling fluid. When the spacer fluid is appropriately prepared, all surfaces are fully water-wetted prior to cementing, thereby reduce the risk of cement contamination and bonding issues while also ensuring a durable annular seal.

In Halliburton, these two tests are executed according to an API standard where technicians follow a strict procedure. API stands for American Petroleum Institute, which is a trade association that develops and publishes standards for the oil and gas industry. The API standards provide guidelines and best practices for various aspects of the industry, including exploration, production, refining, transportation, and marketing. The standards cover areas such as equipment design, safety, environmental protection, and performance requirements. For compatibility and wettability, the standard procedure can be read in the Appendix A and B attached to the thesis, or in the API 10B-2.

Chapter 2 Theoretical Review

1. Rheology

Rheology deals with the theory of the flow and deformation properties of materials, particularly important in the characterization of liquids. Within this subject there are many important parts that are necessary to understand the concept and use of liquids within the oil & gas industry. For instance, viscosity is an extremely important concept under the theory of rheology, and it is a measure of a fluid's resistance to movement (Helseth, 2021).

1.1 Newtonian & non-Newtonian

When working with liquids, they fall into two categories. Newtonian and non-Newtonian fluids. The word "Newtonian" originates from the physicist Isaac Newton, who first discovered the basic principles of viscosity.

1.1.1 Newtonian Fluid

Newtonian fluids refer to what one calls ideal theoretical fluids that can be described with simple models (Skjeggestad, 1989, p. 37). Newtonian fluids, such as water and oil, are simple and pure liquids that do not contain particles larger than molecules. Viscosity for ideal fluids is presented by the relation between shear rate (SR) and shear stress (SS). An important rule of thumb is that Newtonian fluids have constant viscosity, it is independent of the shear rate (SR). Formula be written as follows.

Viscosity for Newtonian Fluids
$$\mu = \frac{SS}{SR} \tag{1.1}$$

1.1.2 non-Newtonian Fluid

For non-Newtonian fluids, the behavior of viscosity is different in that it depends on the shear rate. Non-Newtonian fluids can be divided into three groups:

- Bingham Plastic fluids
- Pseudoplastic fluids
- Dilatant fluids

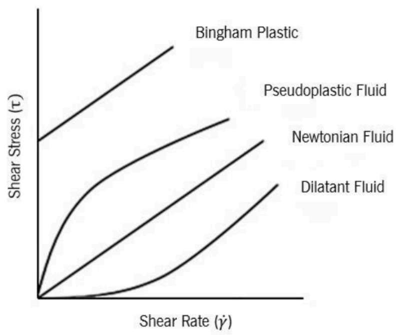

Figure 2.1 - Graphic illustration of non-Newtonian fluids behavior

Fluids containing *Bingham Plastic* properties are characterized by the presence of a yield point (YP) and are classified as shear-thinning liquids due to their viscosity decreasing as the shear rate (SR) increases. *Pseudoplastic fluids*, on the other hand, do not have a yield point (YP), but still exhibit shear-thinning behavior. *Dilatant fluids* are characterized by an increase in viscosity as the shear rate (SR) increases.

1.2 Rheological Models

Various mathematical rheological models have been developed to distinguish the behavior of fluids, both Newtonian and non-Newtonian, in order to establish a system for identification. These models possess unique characteristics that aid in determining fluid behavior.

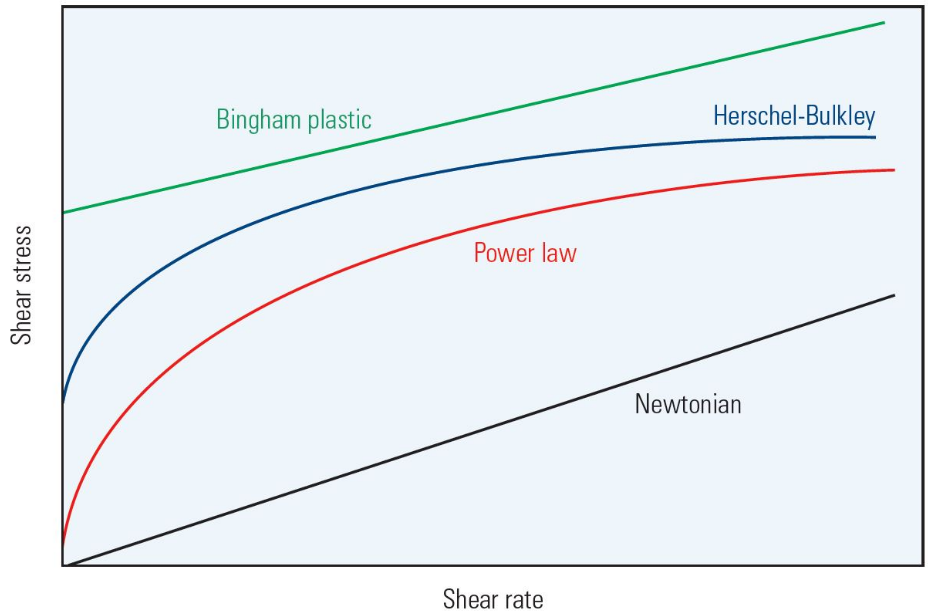

Figure 2.2 - Graphic illustration of Rheological models

1.2.1 Bingham Plastic model

Fluids that contain suspensions of solids and have a yield point (YP) are simplest described by the Bingham plastic model. This model is commonly used to characterize drilling muds. However, a disadvantage of using this model is that it is not appropriate for calculating viscosity and pressure loss. The Bingham plastic model is based on two measurements taken with a Fann viscometer, one at 600 rpm and another at 300 rpm. These measurements enable the calculation of various rheological properties associated with the fluid being tested.

1.2.2 Power Law model

When performing pressure control calculations and the shear rate is high, the Bingham plastic model may not be appropriate. Instead, the Power Law model can be used as a more suitable alternative. This model effectively describes the relationship between shear stress and shear rate for pseudoplastic fluids, making it ideal for modeling most types of drilling muds. The Power Law model offers several advantages over other rheological models. One such advantage is that it allows for the use of any shear rate, making it more flexible than other models. Additionally, the power law model provides an accurate description of a fluid's flow properties, particularly at low shear rates. The model is described by the following formula:

Power Law $$\tau = K(\dot{\gamma})^n \quad (1.2)$$

The Power Law formula is a useful tool for identifying the type of liquid being tested. A fluid is considered Newtonian if the value of n is equal to 1. If the value of n is less than 1, the fluid is considered pseudoplastic. On the other hand, if the value of n is greater than 1, the fluid is classified as a dilatant fluid. By utilizing the Power Law formula, it is possible to easily determine the type of liquid being tested based on its rheological properties. To determine the n-value, one can use this formula:

n-value $$n = \frac{log\frac{\tau_1}{\tau_2}}{log\frac{\dot{\gamma}_1}{\dot{\gamma}_2}} \quad (1.3)$$

1.2.3 Herschel-Bulkley model

The Herschel-Bulkley model is often considered the most suitable rheological model for describing measurement data. This model is able to accurately characterize a wide range of fluids, including those that exhibit non-Newtonian behavior, such as pseudoplastic or thixotropic fluids. As such, the Herschel-Bulkley model is a highly useful tool for predicting and understanding the flow properties of complex fluids. The model is described as follows:

Herschel-Bulkley $$\tau = \tau_y + K(\dot{\gamma})^n \quad (1.4)$$

The reason why the Herschel-Bulkley model is more appropriate than other models is the following. The Herschel-Bulkley model describes the material's reaction to stress by considering both elastic (temporary) and plastic (permanently) deformations. This model includes a yield-stress component, which represents the material's resistance to starting to flow, as well as a viscosity component, which describes how the material flows after the yield stress has been overcome. The Herschel-Bulkley model can therefore describe both Newtonian and non-Newtonian behavior. The lower the n-value, the more shear-thinning the liquid is. The calculation of the n-value here is different, and is as follows:

n-value $$n = \frac{log\frac{\tau_1-\tau_y}{\tau_2-\tau_y}}{log\frac{\dot{\gamma}_1}{\dot{\gamma}_2}} \quad (1.5)$$

2. Liquid flow

To work effectively with fluids and fluid flows, it is important to have a thorough understanding of the key terms and concepts associated with this field. Some of these concepts may include fluid dynamics, viscosity, flow rate, pressure, laminar flow, turbulent flow, Reynolds number, and Bernoulli's principle, among others. By familiarizing oneself with these fundamental concepts and terms, it is possible to gain a better understanding of the behavior of fluids and their flow properties, and to apply this knowledge to practical applications in a range of fields.

2.1 Laminar & Turbulent Flow

In 1883, the British physicist and engineer Osborne Reynolds conducted an experiment involving the flow of a liquid through a tube. Through his observations, Reynolds was able to distinguish two distinct categories of fluid flow, which are now known as laminar flow and turbulent flow. This groundbreaking experiment has since become a foundational concept in the field of fluid dynamics and has enabled scientists and engineers to better understand and predict the behavior of fluids under different conditions.

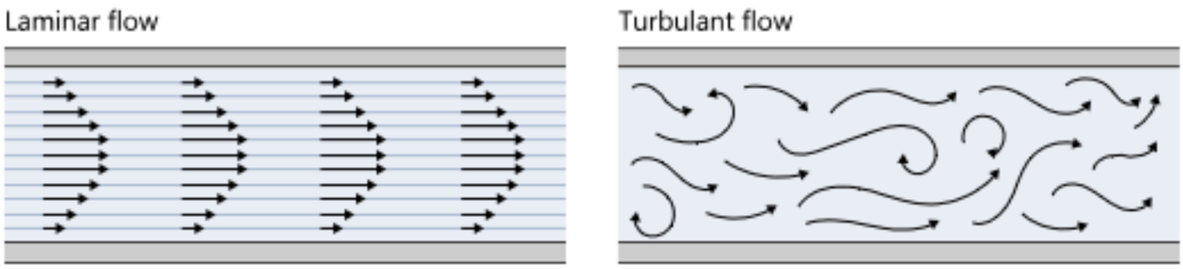

Figure 2.3 - Illustration of Laminar & Turbulent Flow

2.1.1 Laminar Flow

The first type is known as a laminar flow. The significance of these terms is that the fluid appears to move by the sliding of laminations of infinitesimal thickness relative to adjacent layers (Daugherty et al, 1989, p. 66). Laminar flow is characterized by smooth and orderly movement of the fluid particles in the flow, without any significant mixing or turbulence. In a laminar flow, the fluid particles move in parallel layers without crossing each other's paths, resulting in a well-defined flow pattern. This type of flow is usually observed at low velocities and with fluids of low viscosity, such as water or air at low velocities.

2.1.2 Turbulent Flow

Turbulent flow is a type of fluid flow characterized by chaotic and unpredictable motion of the fluid particles, with mixing and eddying of adjacent layers of fluid (Daugherty et al, 1989, p. 66). In a turbulent flow, the fluid particles move in irregular patterns, with vortices and swirls forming at different scales. Turbulent flow is usually observed at high velocities and with fluids of high viscosity, such as air or water at high velocities, or with fluids flowing over rough surfaces. Turbulent flow has higher levels of energy dissipation compared to laminar flow and is associated with higher levels of frictional losses and pressure drops.

2.1.3 Reynolds Number

The Reynolds number is a dimensionless quantity that can be used to predict whether a fluid flow will be laminar or turbulent. It is calculated by dividing the inertial forces of the flow by the viscous forces of the fluid and is given by the formula:

$$\text{Reynolds Number} \qquad Re = \frac{\rho V L}{\mu} \tag{2.1}$$

Where ρ is the density of the fluid, V is the velocity of the fluid, L is the characteristic length scale of the flow, and μ is the viscosity of the fluid. If the Reynolds number is less than about 2300, the flow is usually laminar, whereas if it is greater than about 4000, the flow is usually turbulent. In the intermediate range between 2300 and 4000, the flow may be transitional, and can exhibit characteristics of both laminar and turbulent flows. Therefore, the Reynolds number is a useful tool to predict the type of flow that will occur in different fluid systems, and to design and optimize fluid transport and engineering processes.

2.2 Flow regimes

Flow regimes are associated with different boundary conditions. Three flow regimes that are usually identified: steady state, pseudosteady state and transient state.

2.2.1 Steady State

A fluid flow in which the velocity, pressure, and other flow properties remain constant with respect to time. The flow is not changing with time, and it is in a state of equilibrium.

2.2.2 Pseudosteady State

A dynamic system that appears to be in a steady state but is actually undergoing continuous change. The system is changing over time, but the changes are happening so slowly that it appears to be in a steady state.

2.2.3 Transient State

A fluid flow in which the properties of the fluid are changing with respect to time. The flow is not in a state of equilibrium, and its properties are changing dynamically over time.

3. Drilling Fluids

Drilling fluids are an essential component of the oil and gas drilling process, and there are several different types used for different purposes. Mud, for example, is a type of drilling fluid that is used to cool and lubricate the drill bit, suspend cuttings, and provide pressure control. Spacer fluids, on the other hand, are used to clean the wellbore before cementing, and to prevent contamination between different types of cement. Finally, cement is used to seal the wellbore and provide structural support and requires careful formulation and placement to ensure a proper seal. Together, these different types of drilling fluids are critical to the safe and efficient completion of oil and gas wells.

3.1 Mud

3.1.1 Water Based Mud

Water-based drilling muds are comprised of water, salt, bentonite, and barite, along with chemicals that prevent the fluid from reacting with clay formations in the well (University of Stavanger, 2022, p. 68). These muds are suitable for drilling through most formations, although seawater is generally used in the top-hole sections.

The structure of the mud varies depending on the complexity required for drilling high temperature, high-pressure (HTHP) wells. Water-based drilling fluids typically contain a water phase, viscosity material, solid particles, and soluble chemicals. The water phase can be either fresh water or brine, with fresh water being suitable for spud mud in upper top-hole sections. Brine, on the other hand, inhibits hydration and swelling in clay formations.

Viscosity material, which maintains the desired viscosity in the mud, comprises clay and/or polymers. The drilling fluid also contains solid particles such as calcium carbonate, barite, or hematite, which increase the weight of the fluid and drill particles from the formation. Lost circulation material (LCM) is also included but only if there is a risk of losing the drilling fluid to the formation. Soluble chemicals like NaOH or KOH are added to regulate the pH.

3.1.2 Oil Based Mud

Oil-based drilling muds are composed of an oil base, typically augmented with water (usually 10-40% added), which is then mixed with salt. Emulsifiers are added to reinforce the emulsion and prevent the water droplets from separating during pumping. The water phase and emulsifiers provide the drilling mud with viscosity, specifically plastic viscosity (PV).

Oil humidifiers are included in the mixture to oil-coat solid particles such as clay and baryte, which facilitates mixing weight material into the oil/water emulsion. Inadequate oil humidifiers can cause solid particles to become water-saturated, sticking together and obstructing openings in shaker screens. Excessive oil humidifiers can decrease viscosity and result in solid particle precipitation.

Bentonite, used in oil-based drilling fluids, is chemically modified to ensure that it can be evenly dispersed in the oil/water phase. This process transforms the clay into an "organophilic" clay that can be dissolved in the oil phase, providing the desired viscosity and some filter loss control. Additional polymers are incorporated to achieve specific properties. The build-up of oil-based drilling mud is influenced by different pressures and temperatures. Higher temperatures decrease the viscosity of the oil, while greater pressures increase it. A combination of both can boost the density of oil-based drilling fluids.

3.1.3 Pros & Cons

Using oil-based drilling fluid has the advantage of reducing friction between the drill string and the casing or hole wall, which is particularly beneficial in long, horizontal sections. However, oil-based drilling fluid has some disadvantages. If the oil concentration in cuttings exceeds 10 grams per 1 kilogram of cuttings, it cannot be discharged, and must be transported ashore or injected into separate underground wells for proper handling. It is challenging to seal the well wall with oil-based drilling fluids in the event of loss circulation, as natural repair will not occur when the formation material swells.

On the other hand, water-based drilling fluids are preferred by authorities because they are considered less harmful to the health of drilling workers and the environment than oil-based drilling mud. However, water-based systems can cause undesirable reactions in some formation types, and drilling problems may occur more frequently, which can be avoided by using oil-based mud. From a cementing standpoint a water-based mud is much simpler to work with since the surfaces generally are water wet and hence surfactants are not necessary.

3.2 Spacer

Spacers are preflushes with carefully designed densities and rheological properties (Nelson & Guillot, 2006, p. 185). Viscosifiers are crucial for controlling rheological properties and suspending weighting agents. They can be classified into two types: water-soluble polymers and clays, with examples including xanthan gum, welan gum, and scleroglucan. Dispersants may be used for improving the compatibility of spacers with WBMs and cement slurries, and for dispersing the weighting agent in the spacer. Barite is commonly used as a weighting agent to achieve the desired spacer density, while surfactants possess both hydrophobic and hydrophilic properties that reduce surface tension and increase compatibility with oil-based muds, leaving the casing water-wet.

Spacers typically flow in laminar flow during mud displacement due to their high viscosity, but their composition can be optimized to decrease viscosity while maintaining stability for turbulent flow placement. Designing a spacer fluid with optimal rheological properties is a challenging task that depends on factors such as the concentration of viscosifying polymer and weighting agent, temperature, and base fluid.

Moreover, spacers play a critical role in maintaining the integrity of the wellbore during drilling operations. They are used to displace drilling fluids and prevent intermixing between the drilling fluid and the cement, which is essential for cementing operations. In addition, spacers can be used to clean the wellbore and remove any debris or residual fluids, providing a clean surface for cementing. The use of spacers is crucial in achieving a successful cement job, which is essential for zonal isolation, wellbore stability, and long-term well performance. Therefore, designing and implementing effective spacer fluids is a crucial step in the drilling and completion process.

3.3 Cement

Cement is a vital component in the oil and gas industry, serving as the primary material used to secure the wellbore and prevent fluid migration between the reservoir and the surface. The cementing process involves pumping a slurry of cement, water, and various additives down the wellbore to fill the annular space between the casing and the formation. Once in place, the cement is allowed to set and harden, providing a strong and low permeability barrier that ensures the integrity of the well.

The cementing process is critical to the success of drilling operations, as it provides a number of important functions. First and foremost, it serves as a mechanical barrier that prevents fluids from migrating between different zones in the wellbore. This is particularly important in situations where there are multiple formations with varying pressures or fluid types, as it helps to prevent contamination, cross-flow and seal the reservoir pressure. In addition to its mechanical properties, cement also provides thermal insulation and helps to stabilize the formation. By filling the annular space between the casing and the formation, it helps to prevent collapse and protect the wellbore from damage. It also acts as a heat sink, helping to regulate the temperature of the well and prevent thermal damage to the casing and other equipment.

Cementing is a complex process that requires careful planning and execution. Engineers must carefully design the cement slurry to meet the specific requirements of the well, considering factors such as formation characteristics, well geometry, and expected pressures and temperatures. They must also carefully monitor the cementing operation to ensure that the slurry is properly placed and that there are no voids or channels that could compromise the integrity of the well.

Overall, cementing is a critical component of the oil and gas industry, providing a strong and impermeable barrier that helps to maintain the integrity of the well. Through careful planning and execution, engineers are able to ensure that the cement is properly placed and that the well is protected from fluid migration, thermal damage, and other potential hazards. As such, it is an essential process that plays a vital role in the exploration and production of oil and gas resources.

Chapter 3 Equipment & Modifications

The performance of compatibility and wettability is currently carried out using two different methods and instruments, a rheometer (for example Fann Model 286) for compatibility and a wettability apparatus (for example Fann Model C1001) for the wettability test. To make it most efficient, we have modified and combined these two so that one can run the tests at the same time; and this the central point of this thesis.

1. Equipment

When performing test with drilling fluids, it is essential to have professional equipment and instruments to figure out if wanted rheological properties is maintained.

1.1 Rheometer Fann Model 286

The Fann Model 286 Variable-Speed Electronic Rheometer is a portable precision rotational viscometer designed for conveniently testing the rheological properties of drilling fluids using two modes of operation (Fann Instrument Company, 2007, p. 1). Firstly, we have the variable mode. Here one has the option of choosing rotational speed from 3 to 600 rpm. The second mode are set speeds from 100, 200, 300, 600 rpm. In addition, there is a gel function set at 3 rpm.

Figure 3.1 - Picture of Fann Rheometer Model 286 from Fann Instrument Company (2007, p. 1)

1.2 Wettability Test Apparatus Fann Model C1001

The Wettability Test Apparatus, Fann Model C1001 is designed to evaluate the apparent wettability of spacer fluids, preflush fluids, and spacer and surfactant fluid combinations (Fann Instrument Company, 2014, p. 5). Typically, oil-based fluids lack electrical conductivity for as long as the oil external emulsion is intact, whereas water-based spacers exhibit it. The degree of conductivity is influenced by the chemical composition of the fluid. The Fann Wettability Test Apparatus is capable of assessing both the surface-active and electrical characteristics of the fluid. The apparatus employs circuitry that gauges the electrical properties of the fluid and the electrode surfaces and generates a continuous reading that indicates the apparent wettability. This device enables laboratory chemists to evaluate oil-based drilling fluid and water-based spacer fluid mixtures under controlled conditions of shear rates and temperatures of up to 180°F (82°C). The data obtained from these tests can be utilized to create tailor-made surfactant and spacer fluid combinations, which can offer the best possible results in terms of performance, efficiency, and cost-effectiveness. An increase in conductivity indicates a transition from oil-external emulsion to water-external phase, as the spacer fluid has electric conductivity and contains surfactants that break the emulsion. This break of emulsion releases the water phase of the oil-based mud into the mixture, which substantially increases the conductivity as it typically is a CaCl2 brine.

Figure 3.2 - Picture of a Wettability Test Apparatus from Fann Instrument Company (2014, p. 1)

2. Modifications

From these two instruments there have been some modifications to enable us to run compatibility and wettability in one go. Here is a summary of what has been done. Essentially the wettability apparatus mixer part was not used.

2.1 Electrification of inner and outer axle down to bob and sleeve

In order for the current from the Wettability Apparatus to reach the liquid, we have led a power cable from the apparatus to the rheometer's inner axle and down to the rheometer's bob. Also, we have led a power cable from the outer axle down to the rheometer´s sleeve. From this we then can measure the conductivity between the bob and sleeve across the gap. Below you can see in Figure 3.3 the electrifications of the inner axle (left) and outer axle (right).

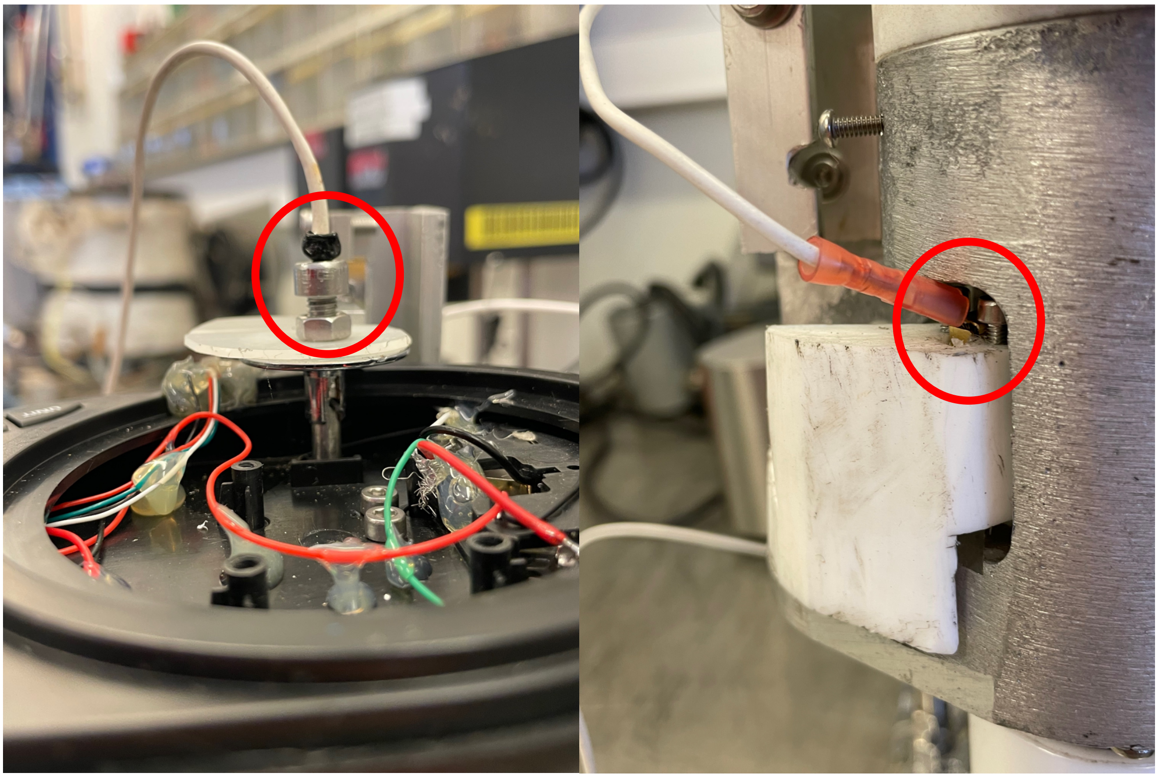

Figure 3.3 - Inner and outer axle electrifiation going through bob and sleeve

2.2 PTFE isolation

The rheometer is constructed from a conductive material, which raises safety concerns when working with electricity. To ensure the safety of the user, it is crucial to prevent any electrical current from flowing through the rheometer, which could result in dangerous and unfortunate circumstances. Consequently, we have installed PTFE to insulate the current and minimize potential hazards. PTFE, or *PolyTetraFluorEthylene*, is a synthetic fluor polymer of tetrafluoroethylene which is an excellent electrical insulator. Due to its exceptional electrical insulating properties and high melting point, PTFE is a common choice as an insulator for wiring and cables, particularly in computer applications. It is frequently utilized for this purpose (AFT Fluorotec, 2023). The PTFE isolation assures us that the current that is then sent from the wettability device only measures currents that pass through the liquid that we are testing. In Figure 3.4 the PTFE isolation is marked with red arrows.

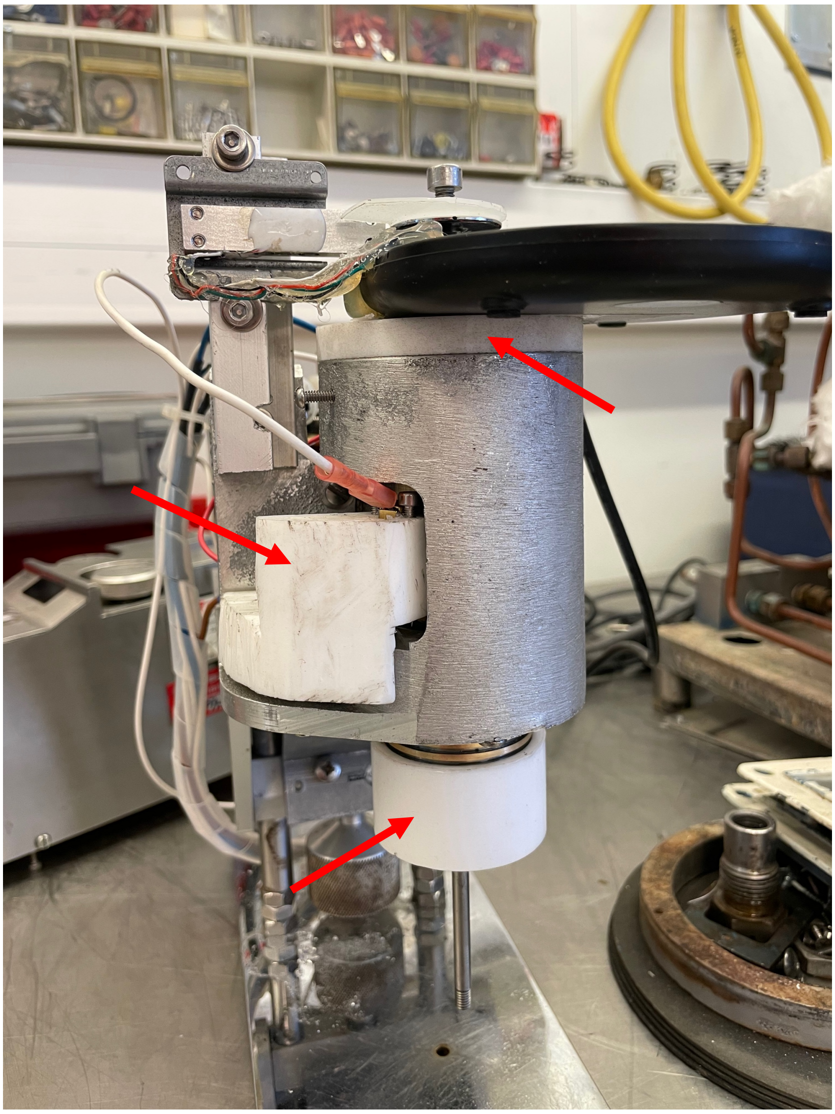

Figure 3.4 - PTFE isolations on the machine

2.3 “Limit switch”

The rheometer's tilt function allows the user to tilt the sleeve and bob in and out of the cup containing the test liquid. To ensure user safety, a "limit switch" has been incorporated into the rheometer to prevent electrical current from passing through the sleeve and bob when tilting the device. This feature enables users to handle the current-carrying components without the risk of electrical shock. When the rheometer is tilted downward to conduct conductivity measurements, the "limit switch" is activated, allowing the current to flow once more. The “Limit switch” is marked with a red circle in Figure 3.5.

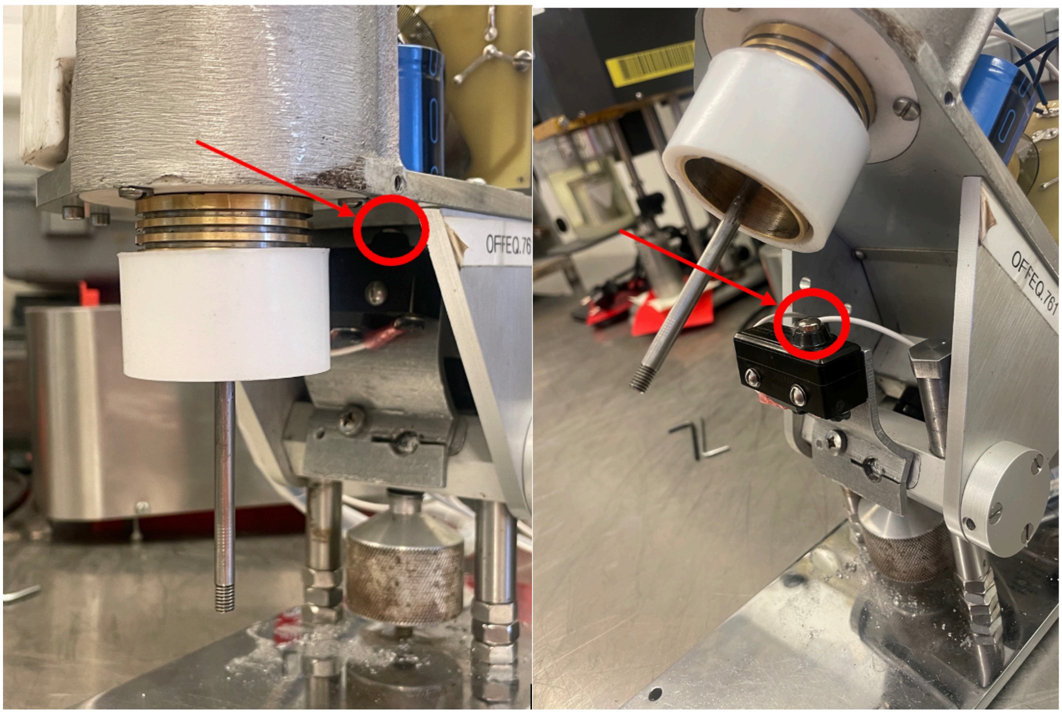

Figure 3.5 - "Limit switch" button placement

2.4 Conductivity measurements and bob modification

In a standard Wettability Apparatus, there is a fixed distance when measuring conductive current. We put a probe (Figure 3.6), which has a spacing of 11,16 mm between the poles, in the liquid and the probe measures conductivity.

Figure 3.6 - Standard Wettability probe

Using our modified machine, we conduct measurements with a set distance between the bob and sleeve. The sleeve has a radius at 18,25 mm and the bob have a radius at 17,25 mm. Therefore, we will have a distance between the sleeve and bob around 1,0 mm. To achieve optimal insulation of the conductive material, we designed our custom bob from PTFE. Extensive testing, which will be detailed later in the thesis, resulted in the final bob design. The initial bob had a radius of 17,25 mm and a length of 38,0 mm, which we used as a reference for the modifications. We used a lathe to turn down the material to create the final product, which appears as follows in Figure 3.7 & 3.8.

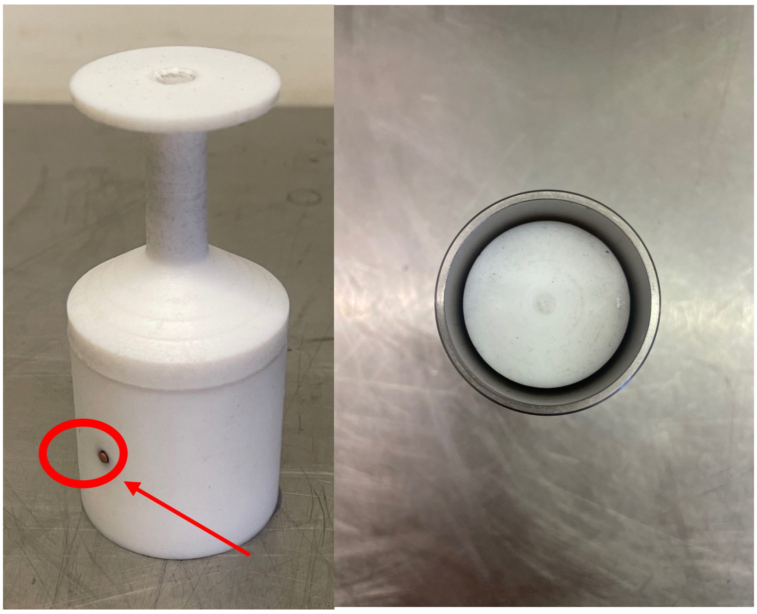

Figure 3.7 - Modified bob, where the red arrow points at the copper knob

We turned down the outside of an original bob to a circumference of 18,0 mm. Furthermore, we turned a corresponding outer side of a cylinder of PTFE down to the circumference and length of an original bob, which has a diameter of 34,5 and 38,0 mm respectively. Finally, we turned the inside of the modified PTFE bob so that the turned original bob would fit inside of our own PTFE bob. The inner turned original bob still conducts current, but how is it supposed to contact the liquid when it is isolated by the outer PTFE bob? We drilled a notch on the outside of the original bob and the inside of the PTFE bob, and drilled a small hole on the PTFE bob so that we could insert a copper wire (Figure 3.8) that protruded exactly with the outside of our modified bob, but which also came into contact with the original bob which was still conducting current.

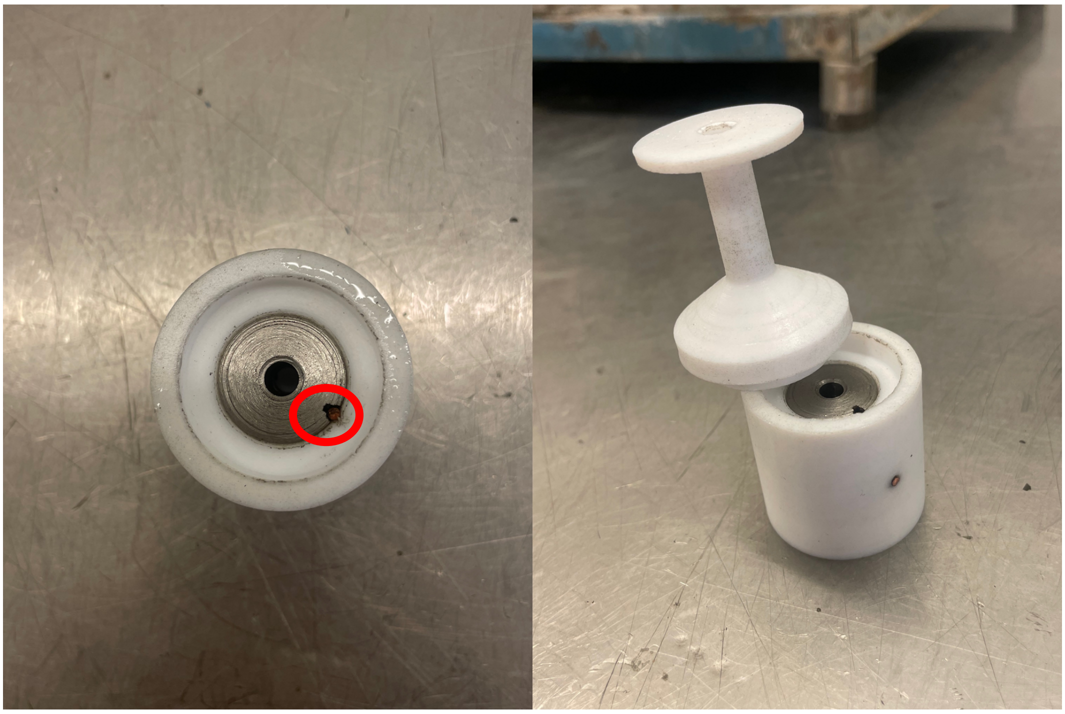

Figure 3.8 - Modified bob, where the inner copper wire is circled

2.5 PTFE modified propeller

Lastly, we explored the concept of incorporating an external propeller onto the sleeve to enhance fluid mixing. Consequently, we measured the outer dimensions of a sleeve and proceeded to drill and machine a PTFE outer propeller. The meaning behind it is that the fluid gets an opportunity to mix and condition itself, i.e., that the spacer and mud get to mix well together. The outcome of the propeller is illustrated in Figure 3.9.

Figure 3.9 – PTFE modified propeller

2.6 Rheology measurements

When using a regular rheometer, the readings are obtained from a dial reading, which has a range of values from 0 to 300 degrees (360 is one full revolution). However, this method of reading can lead to several uncertainties. The reading needle can fluctuate significantly, making it challenging for the user to determine the precise value. Moreover, the margin of error is 1.5, and if the reading falls between two values, such as 19 and 20, it can be difficult to ascertain the correct value, resulting in the user rounding up to the higher value. To address these issues, my supervisor, Gunnar Lende, proposed the idea of digital readings, which gave us the idea of using torque measurements instead of rotational displacement.

Initially, it was crucial to determine the maximum torque effect on a typical rheometer. Through a discussion with the mechanic, we established that the maximum impact was around 118 grams if the length of the arm was 17.25 mm. This was estimated by dividing 300 dial reading with a calibration factor, which is 2.54. To address this, he suggested installing a small KERN scale on the modified rheometer. KERN scale is a torque measurement used to read the shear stress values in grams. This scale has a maximum value of 150 grams and is therefore suitable for our needs. The scale is mounted onto the machine to provide viscosity measurement of the fluid as the sleeve rotates, creating friction with the bob. The bob will then rotate, causing the inner axle to rotate as well. At the top of this axle, there is a small disk connected, which will rotate and apply pressure force to a sensor, allowing us to measure the amount of weight in grams that the fluid is pressing on. The result of this can be shown in Figure 3.10.

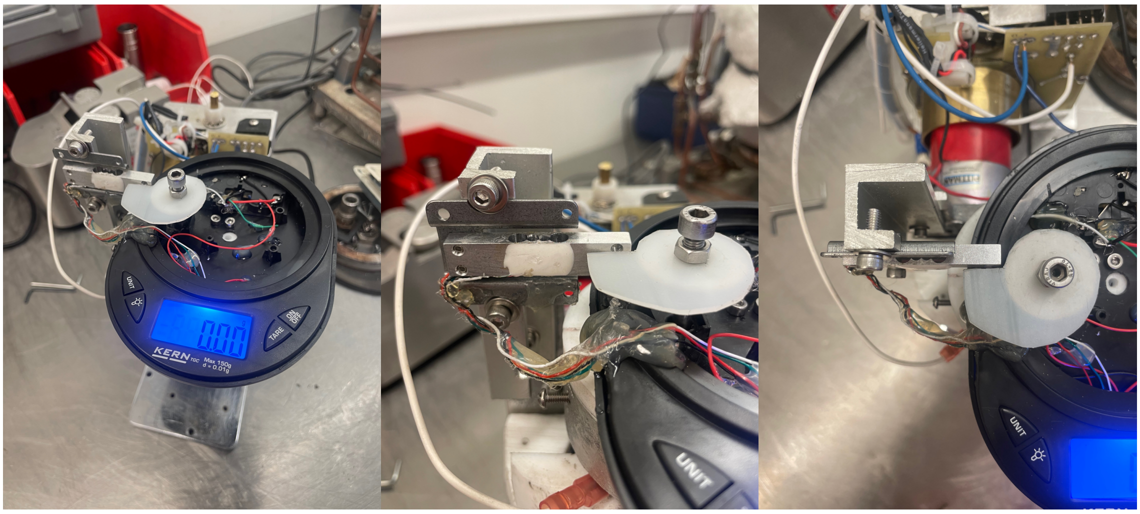

Figure 3.10 - KERN scale with the rotating disc

2.7 Modified Thermo-cup with quick coupling for injection

When carrying out compatibility and wettability, it will be necessary to take results of spacer and mud at different mixing ratios. In order to do this as simply as possible in an efficient way, we have drilled two holes on a Fann Thermo-Cup where we have screwed on two quick couplings for injecting and dispensing the two liquids (Figure 3.12).

Figure 3.11 - Picture of Thermo-cup from Fann Instrument Company (2007, p. 5)

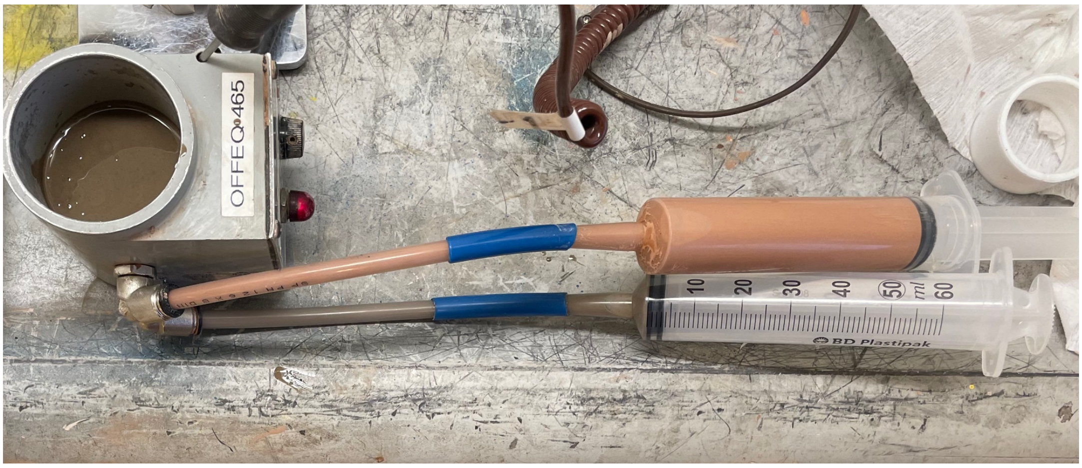

Figure 3.12 - Modified Thermo-cup with the syringes connected to it through tubes

3. Testing the machines functionalities

When you modify and test out an instrument, it is necessary and important to test it out so that you get the most optimal values that you are looking for. Therefore, multiple tests were run before we could carry out the actual test, so that the instrument was ready for use.

3.1 Sensitivity and bob test

When working with conductive electric current, there are several factors that affect the result. Initial tests showed that it was required to find the optimal balance between sensitivity and keeping the instrument reading on a reasonable scale.

Therefor there are some examples to change the conductivity sensitivity of the modified machine; Modifying the electrical circuit, changing the test methodology or reduce the electrically accessible contact surface. For us, the most obvious possibility to lower the sensitivity was to reduce the electrically accessible contact surface.

First of all, it was necessary to find out how sensitive the conductivity of the machine was. In the first instance, we checked how the standard wettability device reacted in pure fresh water and fresh water with different concentrations of salt. The set point value, the point that the wettability device must exceed in order to get maximum effect, was at a conductivity value of 1900. The salt-concentration in water was varied from 0.1 to 10 g/L. In Figure 3.13 one can see the outcome of the test.

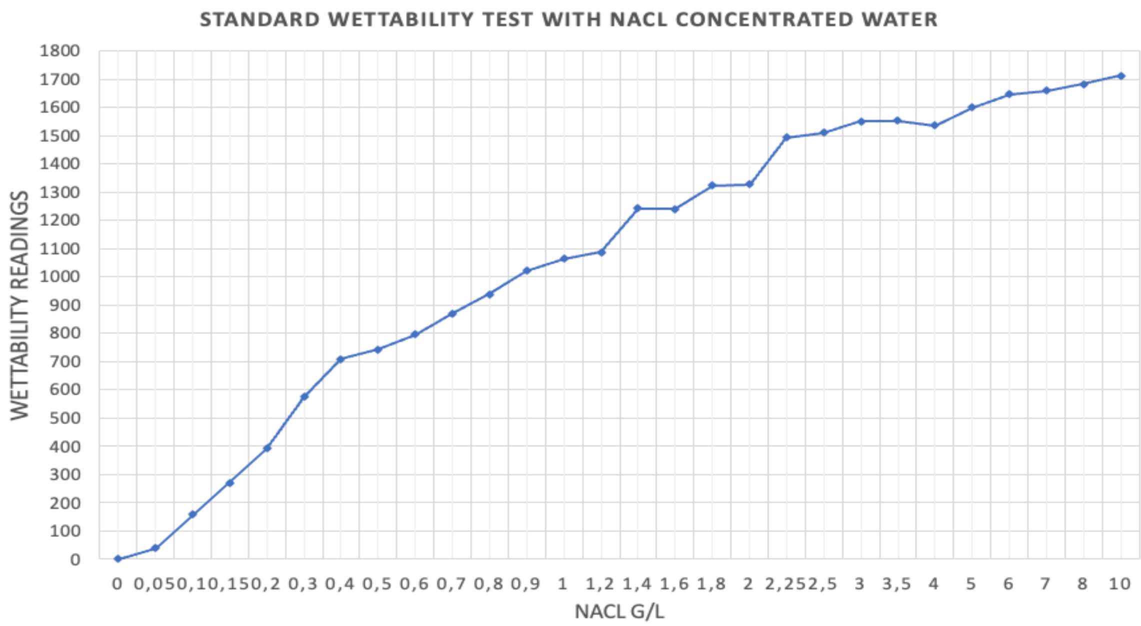

Figure 3.13 - Standard Wettability test with NaCl concentrated water

Furthermore, we measured the sensitivity of the modified machine. First and foremost, the plan was to use a Fann Yield Stress Adapter (FYSA) bob from Fann. This type of bob is primarily used in scenarios where there are large particles that can get stuck when using normal bobs. In addition, a normal type of bob has centrifugal forces that cause particles to migrate and stratify in the radial direction (Fann Instrument Company, 2009, p. 1).

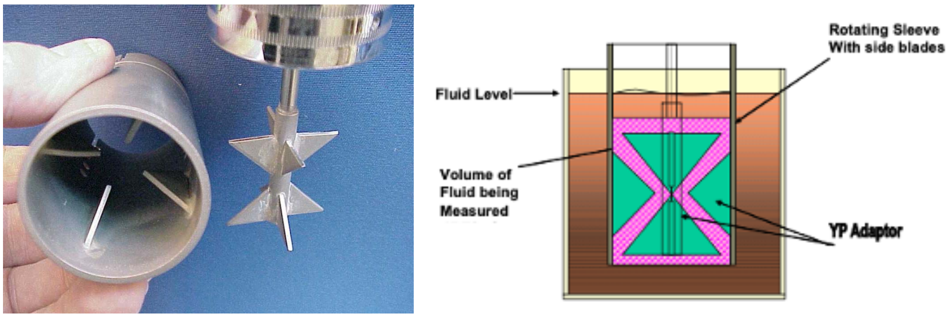

Figure 3.14 - Fann Yield Stress Adapter from Fann Instrument Company (2009, p. 1 & 2)

The electrical current was to be passed through the FYSA-bob and thus measure the conductivity between the bob and the outer sleeve. We did this by measuring conductivity with salt-concentrated water of 0.05, 2 and 10 g/L at different depths at which the bob was placed under the liquid. In addition, we measured deionized water and tap water against the same heights.

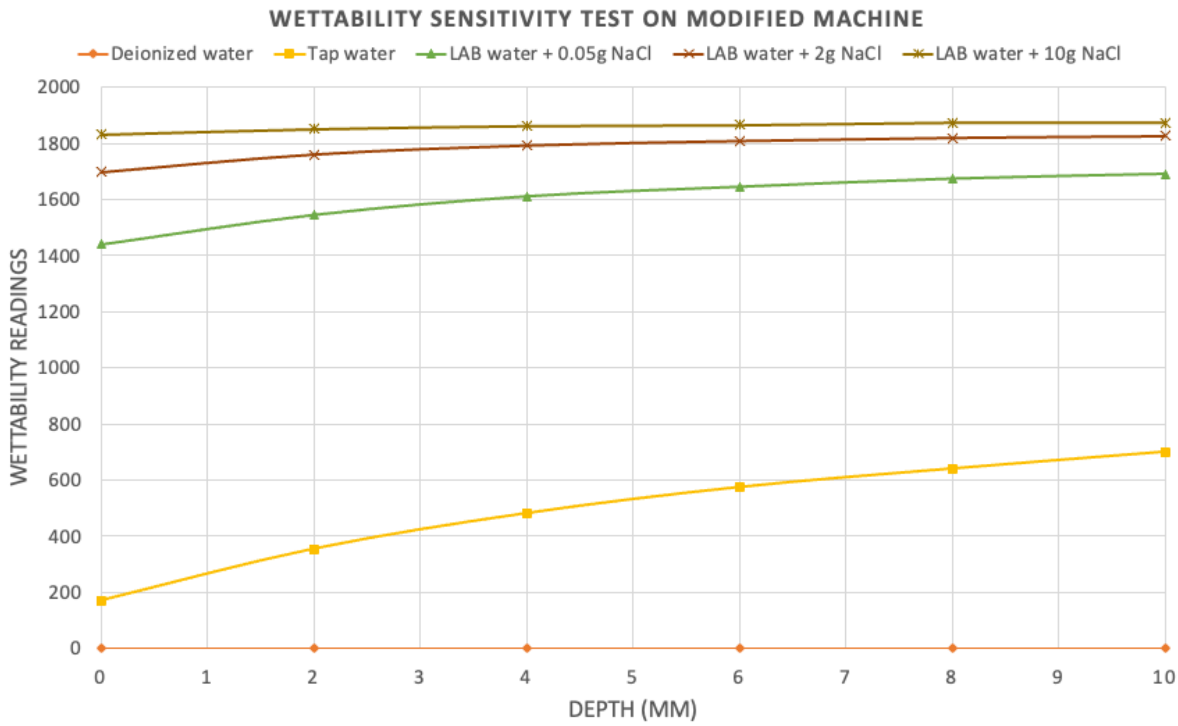

Figure 3.15 - Wettability sensitivity test on the modified machine

We realized at this point that we had to adjust and minimize the electrically accessible contact surface that is applied to the bob that was used. Thus, the mechanic came up with the idea of modifying a normal bob. In addition, the replacement to a normal bob would cause the rheology measurements to yield higher values, as the FYSA-bob has a smaller geometry.

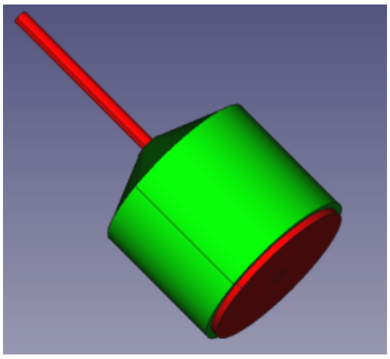

Figure 3.16 - Illustrated idea of the first version of the modified bob

We machined a normal bob and applied an outer PTFE insulation over it so that the geometry remained the same. That way we got a bob as shown in the figure above (Figure 3.16). But even with this type of bob we obtained high conductivity values. In the end, we came up with the idea of machining the bob all the way down so that we could PTFE insulate an entire bob and get a small copper knob to measure the conductivity, so that the electrically accessible contact surface was as small as possible. Thus, we finally arrived at the result which is shown in Figure 3.17.

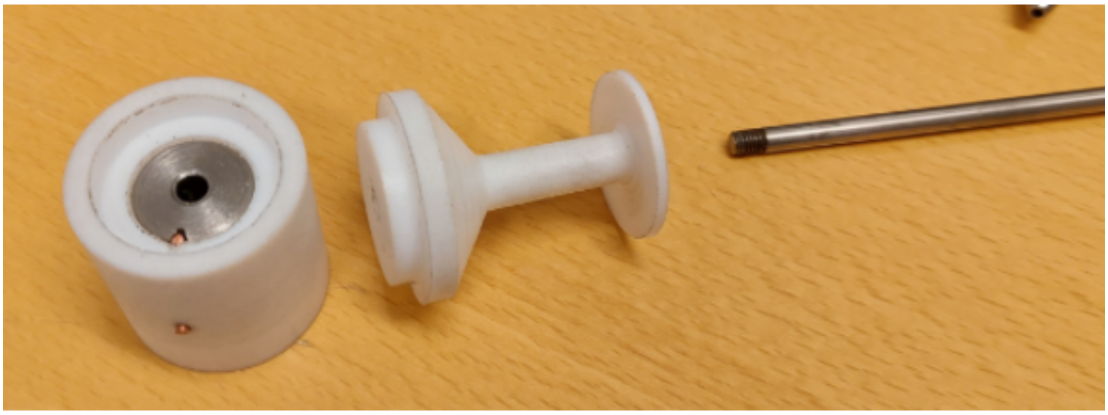

Figure 3.17 - Picture of the final product of the PTFE isolated modified bob

3.2 Rheology test

It is important to calibrate and test viscometers before use because inaccuracies or errors in the measurement results can cause the process control or quality control to be unreliable. This can result in incorrect analysis of the liquid or incorrect process control and can have serious consequences. By calibrating and testing viscometers, you ensure that they provide accurate and reliable measurements, and reduce the risk of errors in process control or quality control.

As mentioned earlier, the first thought was to use a FYSA-bob to measure rheology measurements. Therefore, we first ran a test to check the measurements of a FYSA-bob versus a standard bob. You can see from Figure 3.18 that when using FYSA, the values will be extremely small compared to a standard bob. The fluid used was a 200 cP calibration fluid. In addition, a comparison test was run with FYSA on a standard Fann35 model, and the results that were interesting here was that the rate of increase, which can be seen in Figure 3.19. If we put these values against each other, we see that they look roughly the same. Thus, we could at least conclude that the measurements from the modified machine returned something valuable.

When we then scrapped the idea using FYSA and switched to the PTFE-modified bob, it was necessary to compare this with a standard bob. We used a 100 cP calibration fluid and here we could see that the modified bob had approximately the same value as a standard bob on the modified machine and we thus concluded that after this test, as well as the conductivity test, we had found the best solution for the bob for both rheology and conductivity measurements. It should be noted that 600 rpm is considered irrelevant for cementing operations as so high shear rates are typically not encountered. The result of the comparison between the PTFE-modified bob and a standard bob is shown in Figure 3.20.

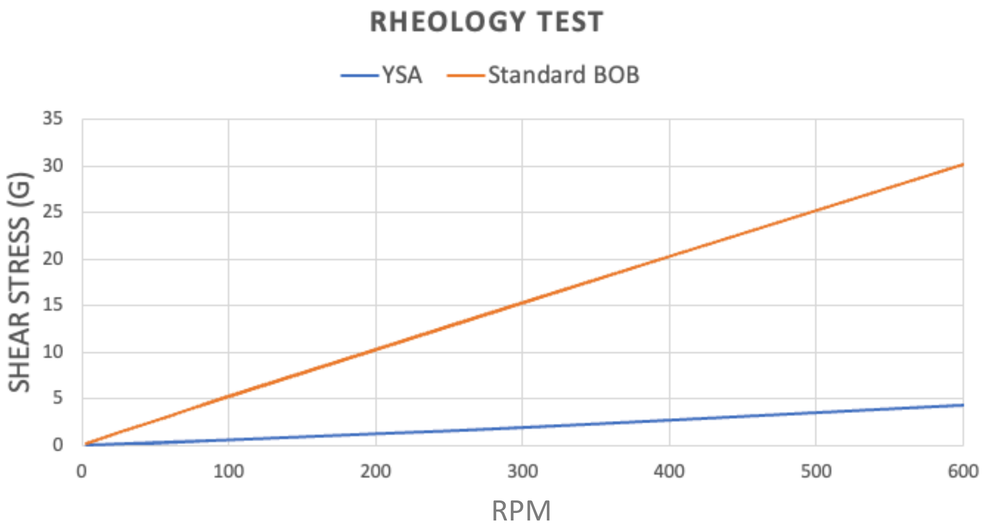

Figure 3. 18 - Rheology test on modified machine with FYSA and standard bob

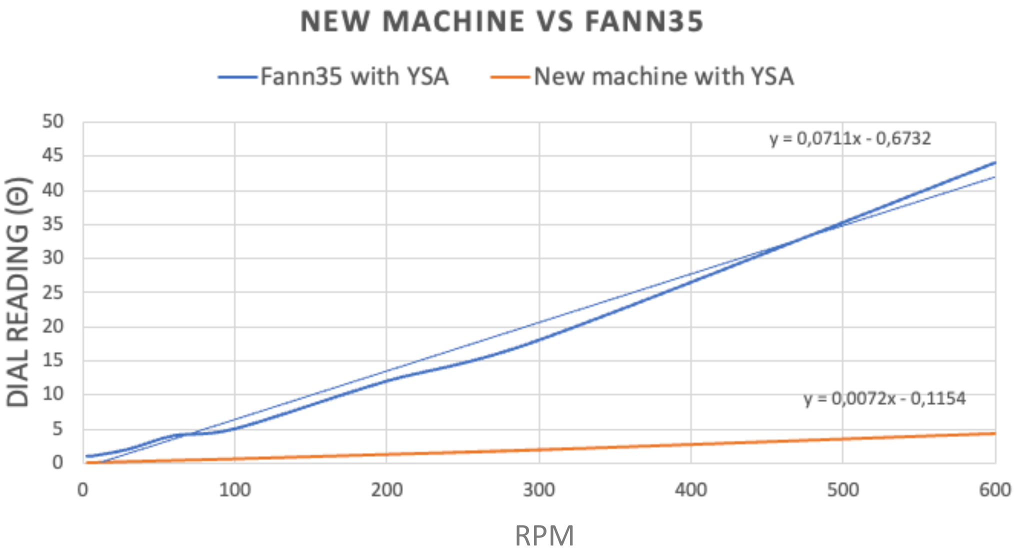

Figure 3.19 - Comparison of rheology values on Fann 35 and modified machine when using FYSA

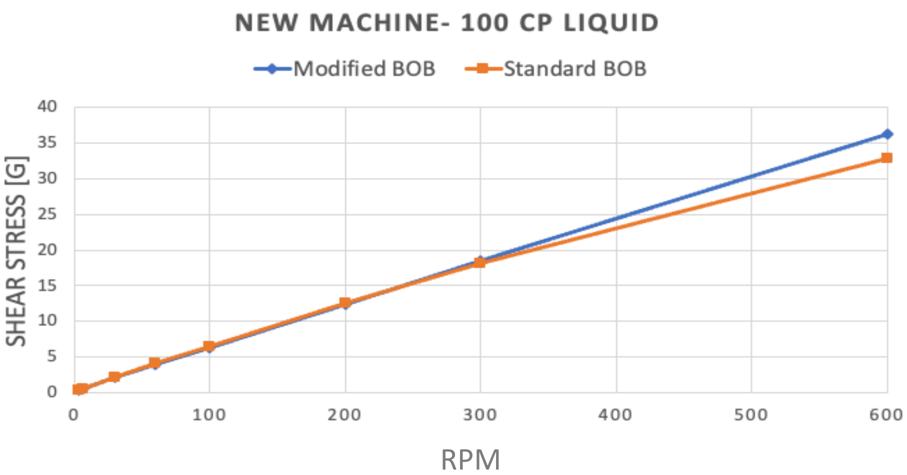

Figure 3.20 - Comparison of rheology vales on modified machine with standard bob and modified bob on a 100 cP liquid

Chapter 4 Experimental work, results and discussion

Mechanical testing is crucial to the success of a modified product, particularly for industrial and commercial use (Brown, 2023). This chapter aims to provide insight into the results obtained from the modified machine to test fluid compatibility and how the tests were conducted. This includes describing in detail any modifications made and potential sources of measurement errors.

1. Method

The experiment was conducted following the standard procedures (Appendix A & B) for compatibility and wettability testing, conducted at Halliburton. The procedures are detailed in Appendices A & B.

To conduct rheology measurements for compatibility, we tested various mud and spacer mixing ratios, which made it necessary to ensure that the modified machine could run measurements at these conditions. Additionally, we needed to include the mixing conditions required for the wettability test. The standard compatibility test involves mixing ratios of 100/0, 95/5, 75/25, and 50/50 (in percentage). The wettability test, on the other hand, requires mixing ratios of 100/0, 70/30, 60/40, 50/50, 40/60, and 30/70 (in percentage). As a result, we had to design a test that allowed us to test all mixing ratios and conduct both rheology and conductivity measurements. The resulting table is shown below in Table 4.1.

	100M/0S		*95M/5S*		*75M/25S*		*70M/30S*		*60M/40S*		*50M/50S*		*40M/60S*		*30M/70S*		*25M/75S*		*5M/95S*		*0M/100S*	
Ut/Inn	**0**		**7**		**27**		**9**		**19**		**22**		**26**		**33**		**22**		**104**		**130**	
	Compa	**Wetta**	**Compa**	**Wetta**	**Compa**	**Wetta**	**Compa**	**Wetta**	**Compa**	**Wetta**	**Compa**	**Wetta**	**Compa**	**Wetta**	**Compa**	**Wetta**	**Compa**	**Wetta**	**Compa**	**Wetta**	**Compa**	**Wetta**
300																						
200																						
100																						
60																						
30																						
6																						
3																						

Table 4.1 - Table overview for test to be run on modified machine. The second row is the amount of liquid replacement if the initial mud volume is 130 ml

The diferrence between the standard compatibility test and the modified machine test lies in how the mixing ratios are handled during testing. The conventional compatibility test involves extracting a certain amount of mud and spacer from each cell and transferring them to the other cell.

The modified method differs slightly from the old one. Instead of ejecting a quantity of mud and replacing it with the same quantity of spacer, the modified method involves ejecting mud and injecting an equivalent quantity of spacer. The initial replacement of fluids is straightforward - pure mud is replaced with pure spacer. However, subsequent transfers become more complex. When mud is ejected again, a small amount of spacer is also extracted due to the previous mixing of mud and spacer. To determine the approximate amount of spacer included in each mud ejection, the formula shown in Equation 4.1 is used.

$$V_{replacement} = V_{mud,start} \times \left(1 - \frac{\frac{V_{mud,2}}{V_{mud,start}}}{\frac{V_{mud,1}}{V_{mud,start}}}\right) \quad (4.1)$$

$$V_{mud,1} = V_{mud,start} \times \frac{p_1}{100} \quad (4.2)$$

$$V_{mud,2} = V_{mud,start} \times \frac{p_2}{100} \quad (4.3)$$

Replacing formula 4.2 and 4.3 inside of 4.1 and getting:

$$\textit{Liquid replacement} \quad V_{replacement} = V_{mud,start} \times \left(1 - \frac{\frac{p_2}{100}}{\frac{p_1}{100}}\right) \quad (4.4)$$

As an example, if we want to change the mixing ratio from 70% mud and 30% spacer to 60% mud and 40% spacer with an initial mud volume of 130 ml, we can input the values into the formula 4.4. The calculation shows that changing the mud percentage from p_1 = 70% to p_2 = 60% requires a liquid transfer of 18.57 ml, when $V_{mud,start}$ = 130 ml. However, it's challenging to eject exactly 18.57 ml using a syringe, so typically around 19 ml is ejected instead. To achieve the target mixture of 60% mud and 40% spacer, eject 19 ml from the 70% mud and 30% spacer mixture and replace it with 19 ml of pure spacer. For other mixing ratios, different quantities of the liquid will need to be transferred.

2. Procedure

When conducting an experiment, having a well-defined plan and a standard procedure is essential for several reasons. Firstly, it helps to ensure that the experiment is executed with precision and accuracy. Without a clear plan, the experiment may be haphazard and lead to unreliable results. Secondly, having a standard procedure allows for consistency in the experiment's execution. This is particularly important when multiple people are involved in the experiment, as it helps to ensure that all individuals carry out their assigned tasks in the same way. This consistency minimizes the potential for errors and increases the chances of obtaining valid and reproducible results.

Before explaining the procedure, it is necessary to acknowledge some key factors before testing and usage of the machine.

Before starting test: Prior to testing, shake the mud well and shear it in a Waring blender for 10 minutes. If the test requires a specific temperature, prepare the heater and thermos cup accordingly. Turn on the wettability apparatus and KERN scale and reset the latter to read 0 grams.

Operating the machine before testing: Position the plateau in such a way that the knobs underneath is attached to the thermos cup. Incline the bob and sleeve into the liquid and fine-tune using the screw beneath until the bob and sleeve are submerged below the liquid level.

Operating the machine with rheology readings: Begin with the left adjustment knobs at 300 rpm and proceed to measure rheology readings at each shear rate, down to 3 rpm, after achieving a stable reading. It is crucial to wait for the KERN scale to stabilize its shear stress value before taking measurements. Note that at 60, 30, 6, and 3 rpm, the left adjustment knob must be set to "Variable," while the right knob is manually adjusted to the desired rpm.

Operating the machine with conductivity readings: The modified device has two control buttons for conductivity measurements, F1 and F2. Pressing F1 resets the read values to zero and prepares the device for new readings. F2 is used to read the highest value measured in the liquid mixture. It is important to note that conductivity measurements are taken after the rheology measurements have been conducted. After noting down the shear stress value at a given shear rate, press F2 to read the highest conductivity value. Once recorded, F1must be pressed to reset the device for the next set of measurements.

After reviewing these procedures dealing with the use of the modified machine, one can proceed with the following test procedure:

1. Fill the thermos cup with 130 ml of sheared mud, being careful not to block the injection holes and tubes. The bottom of the tube should be filled with pure mud and the top with pure spacer prior to testing. Note that the tubes have a volume of 4 ml.

2. Begin by measuring shear stress readings at 300 rpm. After the measurement was conducted, press F2 on the wettability device to read the highest value. Record the value and press F1 to reset the device.

3. Continue measuring the ramp down curve until 3 rpm reading is recorded.

4. Once all values have been measured for a given mixing ratio, extract the desired amount of mud from the bottom syringe (Figure 4.2). Then, using the top syringe, inject the same amount of spacer back into the mixture.

5. Allow the new mixing ratio to condition and mix for 5 minutes before taking new measurements.

6. Once the new mixture ratio has conditioned for 5 minutes, press F1 on wettability apparatus, begin again at step 2, and continue with the same measurements.

7. When all planned mixing ratios have been measured, the test is complete. Clean all equipment used and report the results.

Compatibility and Wettability eject/inject table

Mud/Spacer [%]		*Eject [ml]* | *Inject [ml]*	*Conditioning time*
100/0 →	95/5	7	5 min
95/5 →	75/25	27	5 min
75/25 →	70/30	9	5 min
70/30 →	60/40	19	5 min
60/40 →	50/50	22	5 min
50/50 →	40/60	26	5 min
40/60 →	30/70	33	5 min
30/70 →	25/70	22	5 min
25/70 →	5/95	104	5 min

Table 4.2 - Table overview showing the quantity to be ejected and injected from the cup if the initial mud volume is 130 mL

3. Results

In this section, the results of verification experiments conducted on the modified machine is shown. While some sections will describe the outcomes, others will discuss why and how these results were obtained, towards the end. Since this is a new test with new measurement values and a new procedure and method, it is important to have results and refer to them. Thus, a standard compatibility and wettability test has been run which is done at the laboratory at Halliburton.

3.1 Reference test

The reference tests are as follows. The compatibility test (Figure 4.1) shows that the mud and the spacer are not very compatible, as the desired values for 50% mud and 50% spacer should lie between the graph with 100% mud and the graph with 0% mud, which it does at low shear rates, but after increasing shear rate the shear stress falls below the desired values. In the wettability test, you can see that the mud is broken by the spacer after 40% spacer has been added. The phrase "broken by the spacer" means that the mud has become water-wetted by the spacer, which causes the conductivity values to increase. Thus, it has begun to dissolve or lose its integrity. This result can be seen in the Figures 4. 1 & 4. 2 on the next page.

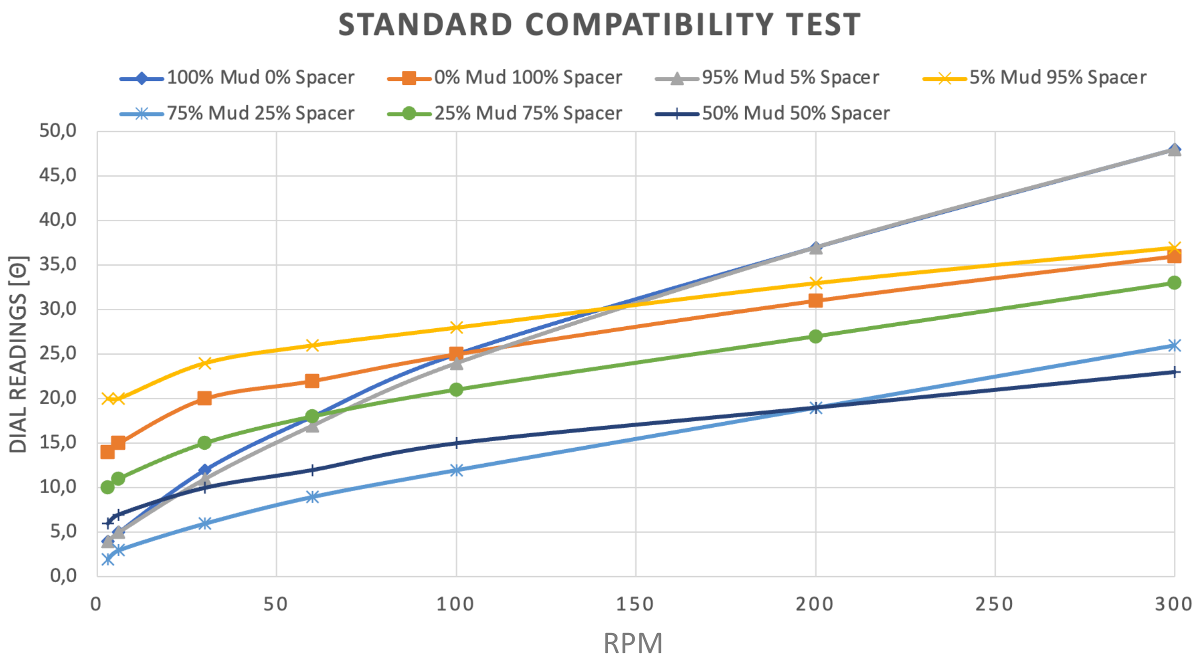

Figure 4.1 - Standard Compatibility test, reference test

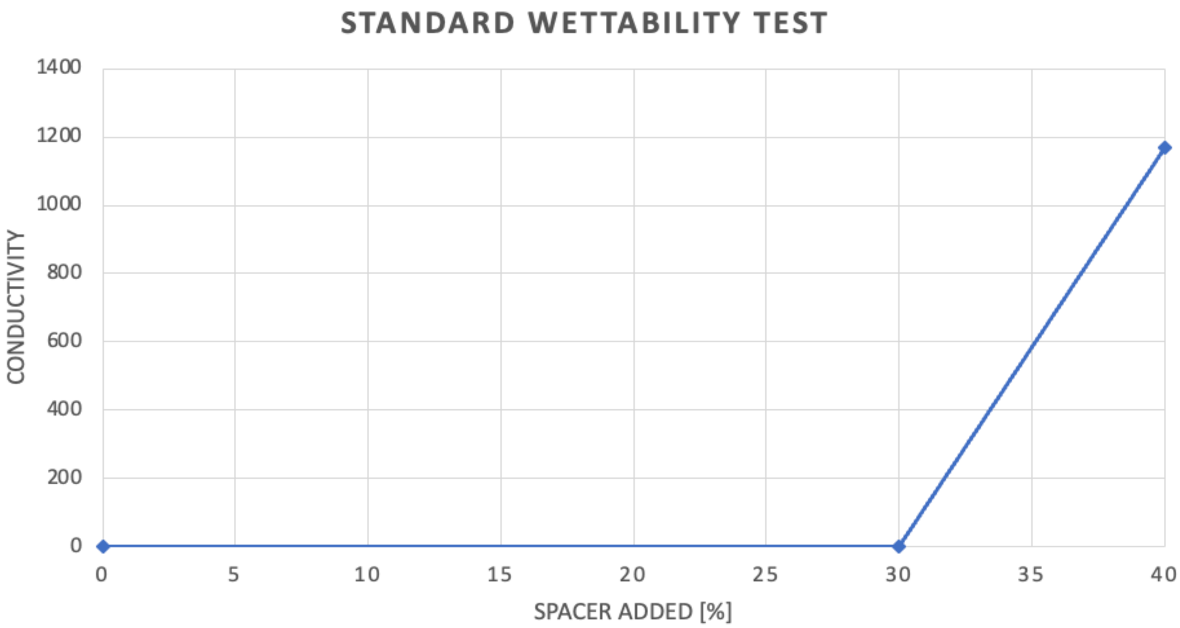

Figure 4.2 - Standard Wettability test, reference test

3.2 Experimental work

It is necessary to conduct a large number of tests to qualify modified technology. In order to obtain a sufficient number of results to compare, analyze and discuss. However, due to time constraints and the mechanic at Halliburton having to prioritize his own work, only six tests were conducted on the modified machine. Among these tests, three were performed with a PTFE propeller installed on the outside of the sleeve, and three were carried out without the propeller. The purpose of conducting tests with and without a propeller was to evaluate the behavior of the circulation and mixture of spacer and mud.

3.2.1 Comparison of rheological readings

First of all, comparison of rheological readings from reference readings against the values read on the modified machine will be shown (Figure 4.3). It is worth noting that rheology measurements obtained from the modified machine are given in grams. Therefore, it was crucial to determine how to convert these values to dial readings. We accomplished this by utilizing a calibration kit, which enabled us to obtain gram values on the KERN scale for specific weights applied to the modified machine. After applying 10, 20, 50, and 100 grams, we obtained corresponding gram values on the KERN scale of 4.71, 9.38, 23.02, and 44.92. These values were then divided by the gram values obtained using a normal Fann 35 for the same weights. Through this process, we arrived at an estimated gram-to-dial reading conversion factor of 5.52. Therefore, when a value in grams is obtained from the KERN scale, multiplying it by 5.52 will provide an estimated dial reading value.

In Figure 4.3 on the next page, we will see six different graphs where rheology measurements at the different mixing ratios are set against each other. Upon examining the graphs, it is evident that certain rheology measurements exhibit comparable values. For instance, when the mixture comprises 100% mud and 0% spacer, the values closely follow the lines, indicating a high degree of similarity. Similarly, when the mixture contains 95% mud and 5% spacer, the values show a striking resemblance. These observations suggest that the rheology measurements obtained from the modified machine are reasonably accurate. However, as the proportion of spacers in the mixture increases, the values tend to deviate more. This effect is particularly evident when using the propeller.

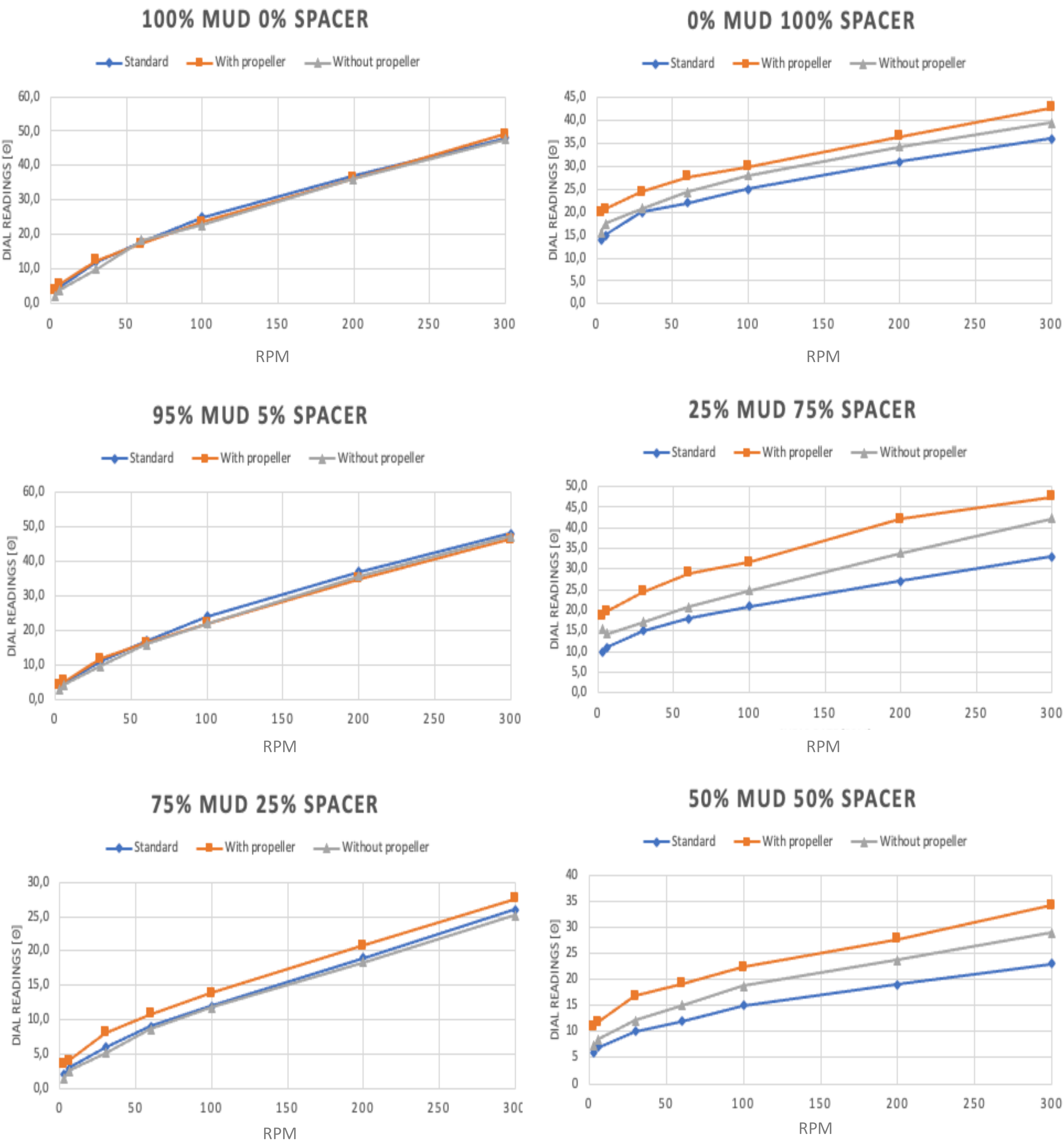

Figure 4.3 - Six different graphs comparing each mix ratio against the reference test

3.2.2 Comparison of Compatibility measurements with and without propeller

Initially, the plan was to solely rely on propellers for effective liquid circulation, without any conditioning in Howco, as typically done (Howco-conditioning is a mixing cell where liquid is preserved to maintain the desired conditions). However, doubts arose regarding the necessity of using a propeller. As previously stated, tests were conducted both with and without a propeller to evaluate whether the mixture of mud and spacer could be achieved more efficiently or equally well. In this section of the values obtained from tests conducted with and without a propeller are compared.

As mentioned earlier, a total of six tests were conducted, three with a propeller and three without. The values obtained from each test were added together and then averaged to create a graph. To elaborate further, the measurements obtained from the three tests that employed a propeller were 7.7, 7.9, and 7.7 grams at a rotation rate of 300 rpm. These values were averaged to obtain an average value of 7.8 grams. Multiplying this value by the gram-to-dial reading conversion factor of 5.52, we obtain an estimated average dial reading value of 42.8. This process was carried out for all measurements, and the resulting average values were plotted on two separate graphs: one with the use of a propeller and the other without.

The values depicted in the graphs at the next page appear to have a similar trend as that presented in the previous paragraph. A closer look at the values reveals that the rheology measurements for 75% mud exhibit the lowest values for all shear rates in both graphs. The remaining mud-spacer mixtures are comparable, with 70% mud showing the second lowest values, followed by 60% and 50% mud. The biggest leap occurs with the 40% mud mixture, where a significant increase in rheology measurements can be observed without a propeller, particularly after 100 rpm. Additionally, it is noteworthy that the values are generally higher when a propeller is used compared to when it is not. Further details on this observation can be found in the Appendix C & D.

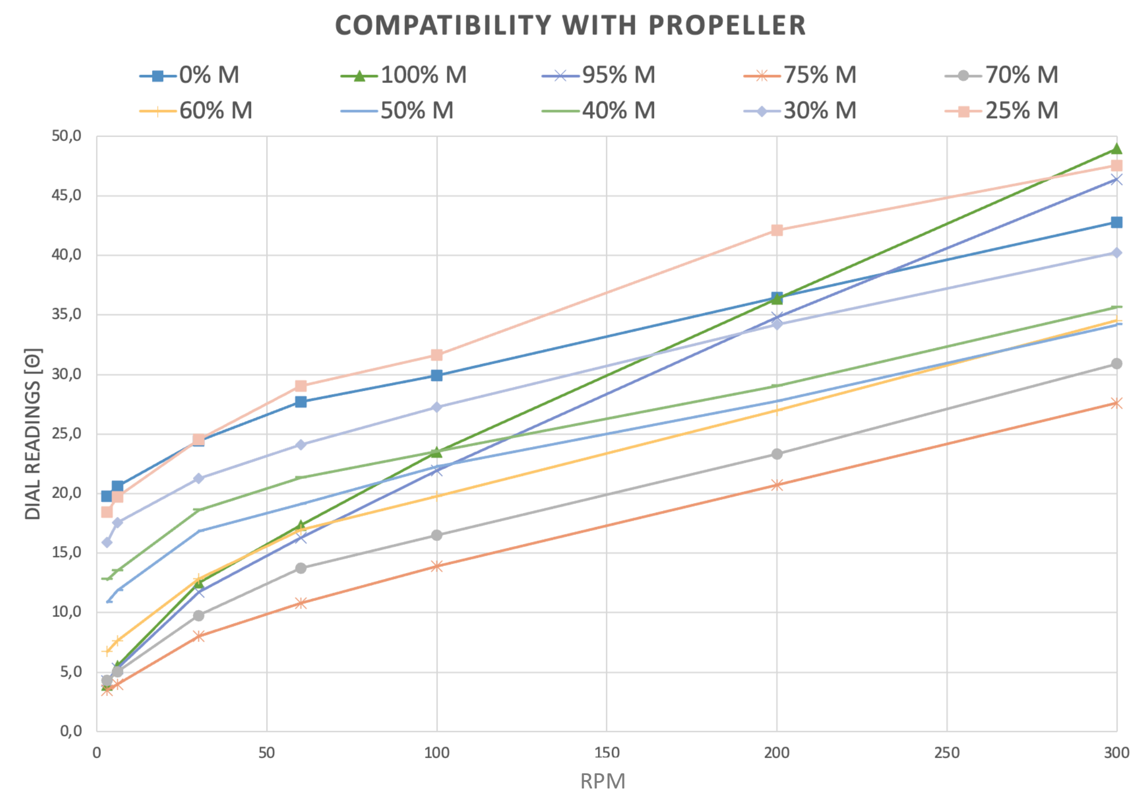

Figure 4.4 - Compatibility values with propeller

Figure 4.5 - Compatibility values without propeller

3.2.3 Comparison of Wettability measurements with and without propeller

As previously mentioned, when examining the wettability reference test, we observed a 40% improvement with the addition of a spacer. In that case, it is of course desirable that with wettability measurements on the modified machine, that we get the same value there. The measurements conducted with and without a propeller can be seen in the figures on the following page. Similar to the compatibility test, the results of the three tests conducted with and without a propeller have been averaged at each individual shear rate.

Let's consider something that creates an immediate impression. The first noticeable trend is the line at the top of the graph (Figure 4.6), where the mud mixture contains 60% spacer. This particular mixture produces the highest conductivity output. In Appendix E it can be observed that the addition of 40% spacer with the propeller yields the first significant results. However, the desired outcome is for the conductivity to exceed the setpoint values at 100% spacer, which the 40% spacer mixture does not achieve. With the propeller, the measurement at 40% spacer produces a conductivity value of 148, while 100% spacer exceeds 230. Upon discussing this with the mechanic, it was mentioned that although the conductivity does not surpass the setpoint value at 100% spacer, the values provide a slight indication that something is happening. Further measurements with the propeller approach the setpoint values that can be shown in Appendix E, Figure E.1.

When examining the results obtained without the propeller, it is evident that the conductivity values differ. In Appendix F, it can be observed that the first result for conductivity occurs at 50% spacer, which is not desirable when compared to the reference test conducted at 40% spacer (Figure 4.2). Furthermore, the values do not surpass the setpoint value. However, as previously mentioned, this provides an indication that something is happening. The reason why the conductivity effect does not occur before the addition of 50% spacer may be attributed to inadequate mixing and conditioning of the mud and spacer, unlike the mixture with the propeller.

It is worth considering whether the conductivity measurements are influenced by the shear rate. Although it is challenging to determine conclusively, Figures 4.6 and 4.7 provide some insights suggesting that this may be the case. When examining mixing ratios that surpass the set point, it becomes apparent that high conductivity values are observed at low shear rates, while these values decrease as the shear rate increases.

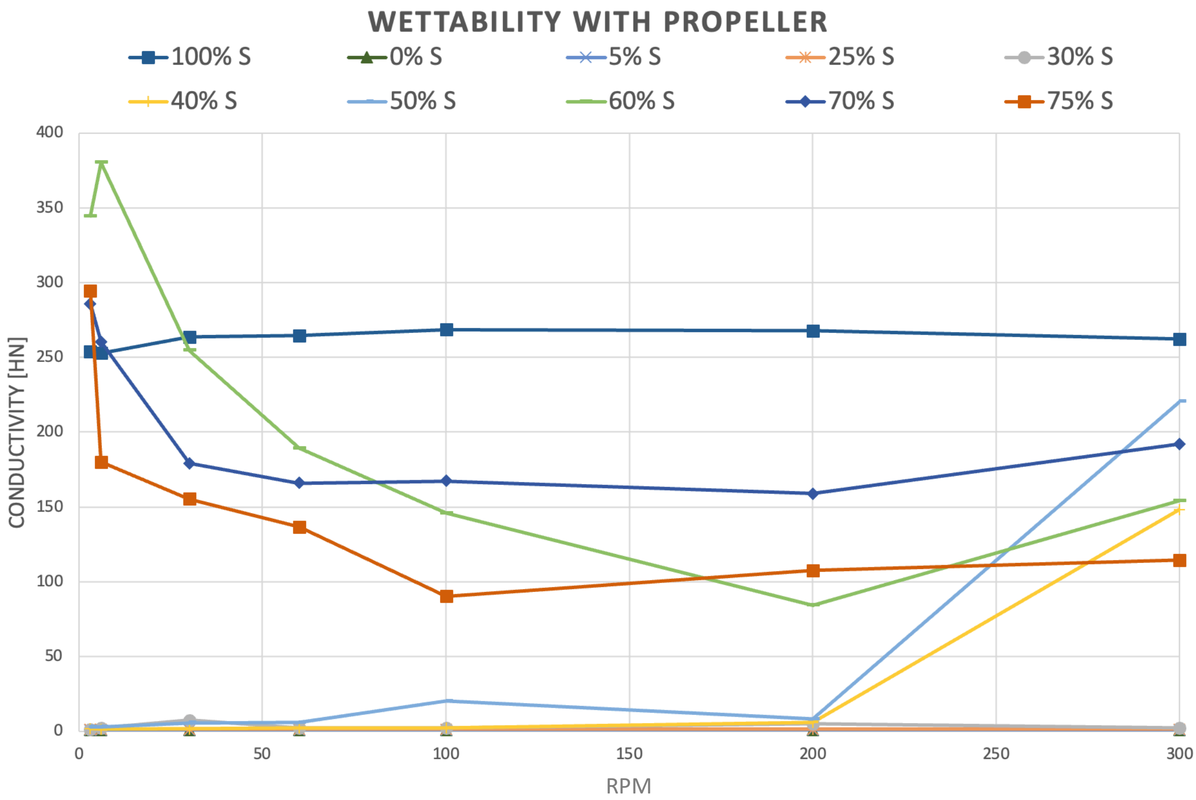

Figure 4.6 - Wettability values with propeller

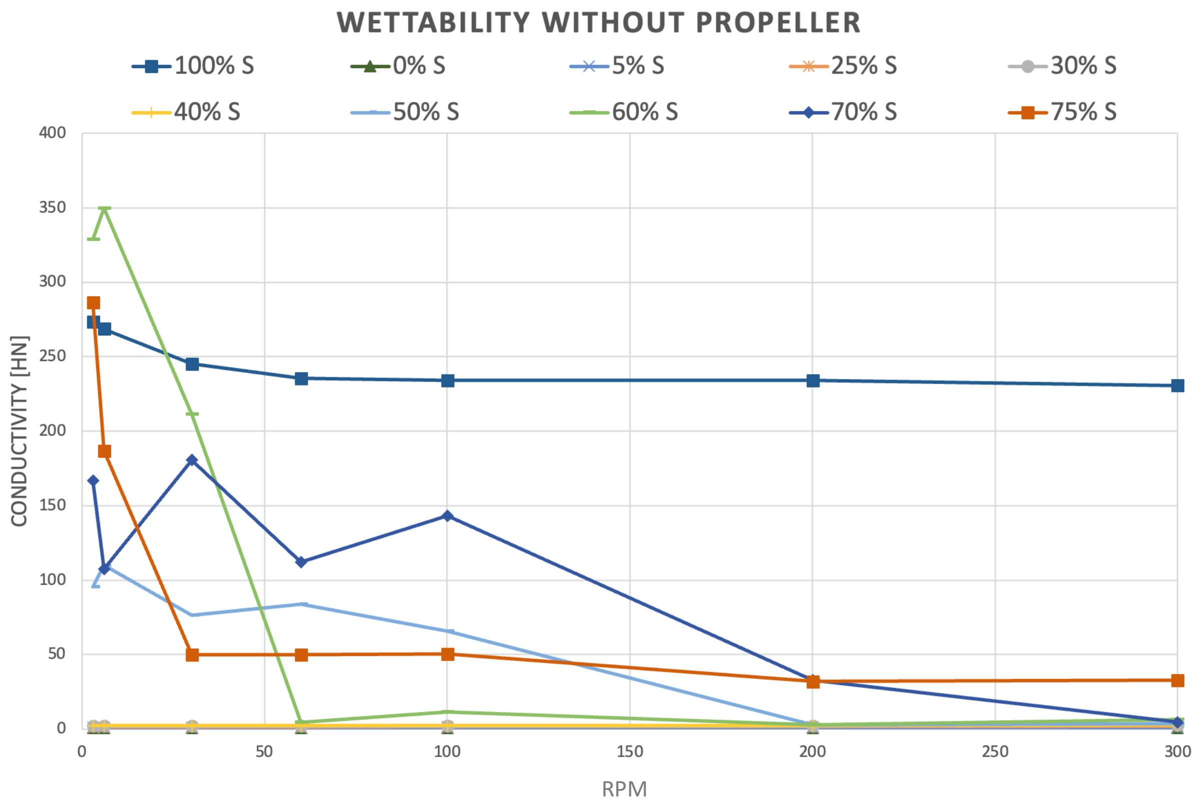

Figure 4.7 - Wettability values without propeller

3.2.4 Comparison of Wettability readings

Figure 4.8 presents a comparison between the standard wettability test and wettability measurements conducted with and without a propeller. The values obtained with and without the propeller correspond to the measurements taken at 3 rpm. This choice was made to align with the non-rotating liquid conditions of the standard test. Upon examining Figure 4.8, it becomes evident that the graph without a propeller exhibits significant deviations in relation to the amount of spacer added. Theoretically, as the amount of spacer increases, one would expect higher conductivity values. However, when focusing on the case with 70% spacer added, both the measurements with and without the propeller display a drop in values. Nonetheless, the drop in values is notably more pronounced in the case without the propeller.

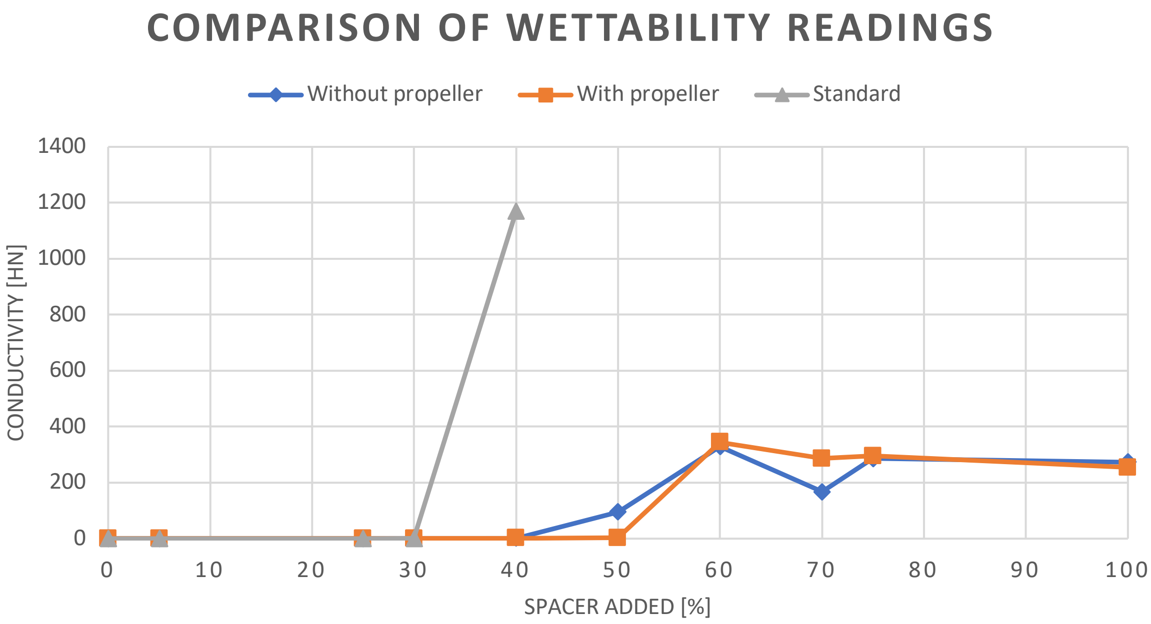

Figure 4.8 - Comparison of Wettability readings at low shear rates

4. Discussions

Discussing results and observations is important, particularly in this experiment where several factors are noteworthy. The first factor to consider is the rheology measurements. As previously mentioned, Figure 4.3 illustrates that the measurements obtained from the modified machine closely resemble those of the standard compatibility reference test. However, this is likely due to the settling of barite at the bottom of the cup in the modified machine. In a standard compatibility test, the mud and spacer mixture are poured into a cup from a Howco cell, which results in the barite settling at the bottom of the cell. Conversely, with the modified machine, the barite settling remains in the cup where the measurements are taken (Table I.1, Figure 1).

The second point to consider is the significance of liquid circulation. As shown in Appendix G (Table G.3 & G 4), using a propeller for circulation is crucial for the wettability test, as conductivity sell-off occurs earlier compared to tests conducted without a propeller. Moreover, it is noteworthy that after each test, the copper knob protruding from the bob designed to measure conductivity accumulated a type of black dust, which can be seen in Appendix I (Table I.1, Figure 3). Although it is unclear whether this affects conductivity measurements, it is a topic that could be discussed if the machine is to be implanted in the future. Further observations of the test can be shown in the figures in Appendix I.

According to Appendix H, the standard deviation of individual measurements is relatively small in the conducted tests. However, as previously mentioned, it is crucial to perform a significant number of experimental tests when introducing new technology. As a result, one cannot definitively claim that these figures are entirely accurate, but they do provide an indication of the potential of the modified machine.

Lastly, it is crucial to determine if the mixing ratios are accurate, i.e., if the correct amount of liquid has been expelled from the mixture. During the tests, handling the syringes was challenging as the liquids are relatively thick compared to the small opening at the tip of the syringe from which the liquid must be ejected. Additionally, small air bubbles were present, making it difficult to be completely certain if the right amount was ejected.

4.1 Source of error

- Unfortunately, it was not possible to run measurements on a mixture ratio of 5% mud and 95% spacer, as the liquid level came too far below the eject hole, which meant that I did not get the correct amount of mud out of the cup.

- With the variable speed of the modified machine, we had to set the desired speed at 60, 30, 6 and 3 rpm. In the case of around 6 rpm, it was extremely difficult to get exactly 6 rpm considering that the adjustment was very sensitive. Therefore, in some cases the set 6 rpm value could mean anything between 5 and 10 rpm.

5. Conclusion and lesson learned

The modified machine has significant potential to enhance the efficiency and productivity of compatibility and wettability testing. Typically for both standard compatibility and wettability tests, we spend combined approximately two and a half hours, with a significant amount of washing required, particularly during the test itself, creating significant time pressure. However, during the modified machine testing, it was spent an average of one hour and 15 minutes per test, and cleaning was only necessary at the end of the tests. It was more significant simpler and cleaner process with a greater sense of control throughout the test, particularly during the five-minute conditioning period. In contrast, during a standard compatibility test, one must use the five-minute conditioning period to clean equipment used, which is highly stressful, especially when using oil-based mud.

By considering compatibility values, we observe that the results obtained from the modified machine exhibit values that are indicative of meaningful measurements (Figure 4.3). However, regarding wettability, there remains some uncertainty. As mentioned earlier, it is still unclear whether the conductivity measurements are influenced by the shear rate. Therefore, conducting further research in this area would be of great interest. Hence, it is recommended that this becomes an intriguing experiment to explore in future studies.

Additionally, the modified machine is just a prototype, which implies that there are many opportunities to improve the machine and its ability to measure results. However, due to time constraints for submission, we were unable to make further improvements. Nonetheless, I am grateful for the opportunity to contribute with what I can to reach the point we have reached.

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Appendix A Standard Compatibility procedure

PPE - Minimum Safety Glasses, Shoes, Lab Coat, Gloves, thermal gloves for hot material, face mask for MUSOL, SEM-8. **NB!** Mix blades. **NOR HSE** Ref. WM-NO-HAL-HSE-0701

Before Making Slurry: Reserve calibrated rheometer, 2 x stainless beakers, timer, calibrated HOWCO (set to request temp),3ea 60ml syringes & cells. Obtain correct contamination fluid stated on request, **use ca. 420 mls** of this material. If MUD or 40% KHCO2 (potassium formate), shake well & then shear on Waring blender for 10 min prior to transferring to HOWCO cell for conditioning.

Make Spacer: If spacer is to be used, reserve overhead mixer, timer, large plastic beaker. Weigh chemicals. Weigh up water in a large plastic beaker & mix (low-med speed avoid turbulence ca. 400rpm). Slowly add Spacer material (may need to hydrate), NF-6 (e.g. RM-1NS, HALAD, chems) & mix 30mins. Use spatula to wipe any material from agitator blades & scrape bottom of beaker to ensure no lumps.

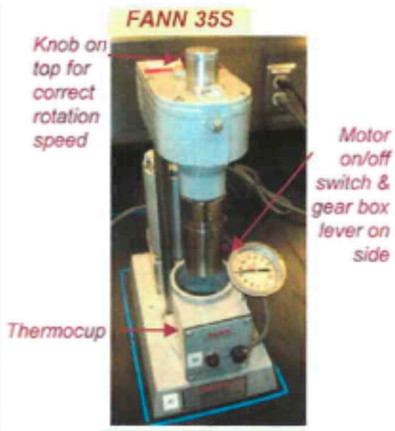
Slowly add Barite (if incl) & mix 10mins increasing mixing speed slowly without causing bubbles to form. Always last, add MUSOL & mix 2 mins. Add SEM-8 & mix 2 mins. Use **ca. 420mls spacer (material)** for test, bottle remaining material, label.

Run Test: As test is done quickly, do not use the Thermocup.
Operating Fann Model 35S - Motor MUST be «OFF» to move lever on side forward/back to change gears. Then, while motor* is ON, raise/lower knob on top of machine to put bob to correct rotation speed (rpm). *Adjust motor speed (Low/High) with switch on side.

1. Condition Spacer & sheared Mud at request temp (F)/*max176F* in separate cells for 30 min in HOWCO, set timer & label each to avoid confusion.
2. During conditioning clean dishes, mixers, etc.. Wash equipment as testing goes forward.
3. After conditioning, record start time.
4. Like Mix Rheology, but conditioned - Pour first 100% Spacer in a metal beaker ca. 3/4full:
   → Set onto rheometer base
   → Lower bob into slurry until slurry reaches guideline;
   → Record the viscosity readings in descending order to get step 1a&b data:
   300 – 200 – 100 – 60 – 30 – 6 – 3 (NB!: if 600 reading is required: get this reading last)
   → Wipe off bob
   → Repeat taking Fluid 2 100% viscosity readings
5. Take 20 mls of each beaker; put in opposite material's cells & cond for 5 mins (set timer)
6. When timer goes off, repeat above no. 4
7. For each step below adjust transfer amount; conditioning 5 mins; take readings, so forth:
   → Step 2a&b – record readings as above, then put 88mls of each beaker in opposite cell
   → Step 3a&b – record readings as above, then put 200mls of each beaker in a clean cell
   → Step 4 – Take final readings
8. Clean all dishes, equipment and wash bob.
9. Record Stop time.

STEP	Rheology Compatibility			
	% 2 Fluids (a&b) can be Spacer, MUD, cement, etc.	Cond time (min)	Add mls below to *opposite* HOWCO cell, condion 5 mins, then run rheos	
1a&b	100a	30	20ml	For 95/5 & 5/95 step 2 testing
	100b	30	20ml	
2a&b	95a/5b	5	88ml	For 75/25 & 25/75 step 3 testing
	5a/95b	5	88ml	
3a&b	75a/25b	5	200ml	*Into clean HOWCO cell* for final test 4
	25a/75b	5	200ml	
4	50a/50b	5	--	Test and finish

• Record Test Request temp (F). Set HOWCO at this temp (max 176F)
• Fluid 'a' is typically Spacer or Cement & Fluid 'b' is typically MUD



Appendix B Standard Wettability procedure

HSE **PPE -** Minimum Safety Glasses, Shoes, Lab Coat, Gloves, thermal gloves for hot material. **NB!** Mix blades, Pinch points. **NOR HSE** Ref. WM-NO-HAL-HSE-0701.docx

Before starting: Reserve Wettability apparatus in the hood, Waring blender, timer, calibrated HOWCO & cells (set to request temp) next to Wettability apparatus, 2-3 x 60ml syringes.

NB! Use **ca. 220mls** of the testing material. If MUD: shake well, then shear it on Waring blender for 10 min prior to transferring to HOWCO cell for conditioning.

Make Spacer: If required, mix up spacer fluid. Reserve overhead mixer, timer, large plastic beaker. Weigh up chemicals. Weigh up water in a large plastic beaker & mix (low-med speed avoid turbulence ca 400rpm). Slowly add Spacer, NF-6 (RM-1NS, HALAD, if using) & mix 30mins. Use spatula to wipe any material from agitator blades & scrape bottom of beaker to ensure no lumps. Slowly add Barite & mix 10mins increasing mixing speed slowly without causing bubbles to form. Always last, add Musol & mix 2 mins. Add SEM-8 & mix 2 mins. If Spacer already made, shake well prior to use.

Transfer ca. **420mls spacer** for test to HOWCO cell for conditioning. Bottle remaining material, label.

Run Test:

1. Condition Spacer & sheared Mud at request temp (F)/*max176F* in separate cells, label each to avoid confusion, for 30 min in HOWCO, set timer. ***NB!*** *warms quickly & can overshoot, so keep an eye on the temp. Lower set point as necessary.*
2. During conditioning clean dishes & fill Wettability metal beaker ca. ½ full with water. Set temp to request temp (F). Wash equipment as testing goes forward.
3. After conditioning, get 100% Spacer reading:
   → Remove Spacer cell, set thermocouple from Wettability apparatus into spacer to confirm temp ok.
   → Wipe probe, press «F2» button to zero out probe reading
   → Place probe carefully in spacer moving slightly back & forth, hold in «F1» button.
   → Record highest reading (see Wettability Program below) for «Setpoint».
   → Remove and wipe probe between each reading. Set Spacer cell back in HOWCO.
4. Remove water from Wettability apparatus beaker, wipe dry.
5. Pour Mud from cell into Wettability beaker, start mixing. *Contol heat to correct temp!*
   → Step 1 – When MUD is at desired temp add 85mls spacer to it mix till request temp; record reading as above for Spacer. (In between, cells to be back mixing in HOWCO for 5 mins. Set timer).
   → Step 2 – Add the next increment of spacer (see below table), mix to request temp, take reading.
   → Step 3 – Repeat spacer additions, heating to request temp and then taking readings until the reading is ɥAmp er > «Setpoint», i.e. the 100% Spacer reading. When it is, the test is finished.
   → Wash all dishes & equipment & report results info the request and iFacts.

STEP	Wettability Program			*Table*
	% Spacer/pre-flush fluid	Est. Spacer/pre-flush fluid (vol) ml	*Add* Spacer/pre-flush fluid (ml) in increments	Record ɥAmp at temp (F)
1	30	85	85	*Actual readings*
2	40	135	50	↓
3	50	200	65	
4	60	300	100	
5	70	470	170	
Setpoint: *Actual reading of 100% spacer at temp.*				

Appendix C Compatibility values with propeller

RPM	0% M	100% M	95% M	75% M	70% M	60% M	50% M	40% M	30% M	25% M
300	7,7	9,9	9,3	5,4	6,1	6,4	6,8	6,9	6,9	8,2
200	6,7	7,4	7,1	4,1	4,7	5,0	5,6	5,7	6,0	7,9
100	5,5	5,1	4,7	3,2	3,4	3,6	4,3	4,8	5,1	5,9
60	5,3	3,6	3,6	2,5	3,3	3,4	4,1	4,1	4,6	5,8
30	4,6	3,0	3,0	1,9	2,2	2,8	4,0	4,1	4,1	5,0
6	4,1	1,5	1,5	1,0	1,3	1,7	2,7	3,1	3,6	4,1
3	4,0	1,1	1,1	0,9	1,1	1,4	2,5	2,9	3,3	4,1

Table F1 - Compatibility readings for TEST 1 with propeller where % M = mud content in mixture

RPM	0% M	100% M	95% M	75% M	70% M	60% M	50% M	40% M	30% M	25% M
300	7,9	7,2	7,0	4,6	5,1	5,6	5,6	6,0	6,2	6,4
200	6,7	5,3	5,2	3,4	3,9	4,5	4,3	4,8	5,1	5,5
100	5,5	3,4	3,2	2,2	2,5	3,4	3,7	3,9	4,2	4,5
60	5,1	2,4	2,3	1,6	2,0	2,8	3,1	3,6	4,0	4,2
30	4,5	1,7	1,5	1,1	1,4	2,1	2,4	2,9	3,3	3,9
6	3,8	0,7	0,6	0,5	0,6	1,1	1,7	2,0	2,6	3,1
3	3,5	0,5	0,5	0,4	0,5	1,0	1,6	2,0	2,4	2,9

Table C.2 - Compatibility readings for TEST 2 with propeller where % M = mud content in mixture

RPM	0% M	100% M	95% M	75% M	70% M	60% M	50% M	40% M	30% M	25% M
300	7,7	9,6	8,9	5,0	5,7	6,8	6,2	6,5	8,8	11,2
200	6,4	7,1	6,7	3,8	4,1	5,2	5,2	5,3	7,4	9,5
100	5,3	4,3	4,1	2,2	3,0	3,8	4,2	4,2	5,6	6,7
60	4,7	3,4	3,0	1,9	2,2	3,0	3,2	3,9	4,5	5,8
30	4,2	2,2	1,9	1,3	1,7	2,2	2,7	3,1	4,1	4,4
6	3,3	0,8	0,8	0,7	0,8	1,4	2,1	2,2	3,4	3,5
3	3,2	0,6	0,7	0,6	0,8	1,3	1,8	2,1	2,9	3,1

Table C.3 - Compatibility readings for TEST 3 with propeller where % M = mud content in mixture

Appendix D Compatibility readings without propeller

RPM	0% M	100% M	95% M	75% M	70% M	60% M	50% M	40% M	30% M	25% M
300	7,4	9,2	8,5	4,6	4,7	6,1	5,4	7,0	7,3	7,2
200	6,5	7,1	6,5	3,5	3,7	4,5	4,4	5,6	5,5	6,1
100	5,4	4,4	4,2	2,3	2,5	3,2	3,7	4,2	4,1	4,6
60	4,5	3,5	3,2	1,8	2,1	2,5	3,1	3,9	3,8	4,2
30	4,2	2,2	2,1	1,3	1,6	2,0	2,5	3,2	3,1	3,7
6	3,6	1,0	1,1	0,8	1,0	1,4	2,0	2,6	2,3	2,9
3	3,2	0,7	0,9	0,6	0,8	1,0	1,6	2,3	2,6	4,2

Table D.1 - Compatibility readings for TEST 1 without propeller where % M = mud content in mixture

RPM	0% M	100% M	95% M	75% M	70% M	60% M	50% M	40% M	30% M	25% M
300	7,0	8,8	9,1	4,7	4,9	5,3	5,4	6,6	8,9	8,1
200	6,1	6,4	6,8	3,1	3,4	4,1	4,3	5,8	7,0	6,2
100	5,3	4,4	4,1	2,1	2,2	3,3	3,4	4,3	5,1	4,7
60	4,6	3,1	3,0	1,4	1,4	2,6	2,7	3,5	3,9	3,6
30	4,0	2,0	1,8	0,6	1,0	1,7	2,3	2,9	3,5	2,8
6	3,1	0,8	0,9	0,4	0,4	1,0	1,6	1,9	2,3	3,1
3	2,8	0,5	0,7	0,2	0,2	0,7	1,5	1,9	3,1	2,6

Table D.2 - Compatibility readings for TEST 2 without propeller where % M = mud content in mixture

RPM	0% M	100% M	95% M	75% M	70% M	60% M	50% M	40% M	30% M	25% M
300	7,0	7,9	8,0	4,4	4,7	4,4	4,9	7,7	7,2	7,7
200	6,0	6,1	6,1	3,4	3,7	3,7	4,2	6,0	6,0	6,1
100	4,6	3,6	3,6	2,0	2,3	2,7	3,1	3,9	4,1	4,2
60	4,1	3,4	2,4	1,5	1,7	2,2	2,4	2,9	3,5	3,5
30	3,1	1,3	1,3	0,9	1,1	1,6	1,8	2,3	2,7	2,8
6	2,8	0,3	0,3	0,2	0,3	0,8	1,0	1,6	1,8	1,8
3	2,5	0,0	0,0	0,0	0,2	0,6	0,9	1,4	1,6	1,7

Table D.3 - Compatibility readings for TEST 3 without propeller where % M = mud content in mixture

Appendix E Wettability readings with propeller

RPM	100% S	0% S	5% S	25% S	30% S	40% S	50% S	60% S	70% S	75% S
300	394	1	1	1	2	263	10	457	428	333
200	395	1	1	1	11	13	18	248	471	316
100	389	1	1	1	2	3	56	177	496	264
60	363	1	1	1	2	2	12	250	492	404
30	372	1	1	1	19	2	12	485	531	460
6	338	1	1	1	3	1	4	551	771	531
3	349	1	1	1	1	2	4	582	843	720

Table E.1 - Wettability readings for TEST 1 with propeller where % S = spacer added to the mixture

RPM	100% S	0% S	5% S	25% S	30% S	40% S	50% S	60% S	70% S	75% S
300	143	1	1	1	2	3	313	3	115	7
200	150	1	1	1	2	2	3	3	3	3
100	151	1	1	1	2	2	2	258	3	4
60	161	1	1	1	1	1	3	315	3	3
30	140	1	1	1	1	1	2	276	3	3
6	112	1	1	1	1	1	2	588	7	6
3	91	1	1	1	1	1	2	448	12	154

Table E.2 - Wettability readings for TEST 2 with propeller where % S = spacer added to the mixture

RPM	100% S	0% S	5% S	25% S	30% S	40% S	50% S	60% S	70% S	75% S
300	250	1	1	2	3	179	339	3	33	3
200	259	1	1	2	2	3	3	2	3	3
100	266	1	1	2	2	2	3	3	3	3
60	270	1	1	2	3	3	3	3	3	3
30	279	1	1	2	2	2	3	3	3	3
6	309	1	1	2	2	2	3	2	3	3
3	322	1	1	2	2	2	3	3	3	10

Table E.3 - Wettability readings for TEST 3 with propeller where % S = spacer added to the mixture

Appendix F Wettability readings without propeller

RPM	100% S	0% S	5% S	25% S	30% S	40% S	50% S	60% S	70% S	75% S
300	231	1	1	2	3	3	3	3	4	3
200	229	1	1	2	2	3	3	3	10	3
100	230	1	1	2	2	2	4	4	345	3
60	229	1	1	2	2	3	3	3	161	3
30	236	1	1	2	2	2	57	57	127	3
6	259	1	1	2	3	3	319	319	26	4
3	250	1	1	2	2	3	173	173	26	4

Table F.1 - Wettability readings for TEST 1 without propeller where % S = spacer added to the mixture

RPM	100% S	0% S	5% S	25% S	30% S	40% S	50% S	60% S	70% S	75% S
300	241	1	1	3	2	3	3	4	5	90
200	246	1	1	2	2	2	3	3	86	80
100	245	1	1	2	2	3	3	3	77	124
60	236	1	1	1	2	2	2	3	163	105
30	248	1	1	1	1	2	3	566	410	116
6	271	1	1	1	1	2	3	706	284	56
3	296	1	1	1	2	2	3	738	468	177

Table F.2 - Wettability readings for TEST 2 without propeller where % S = spacer added to the mixture

RPM	100% S	0% S	5% S	25% S	30% S	40% S	50% S	60% S	70% S	75% S
300	220	1	1	1	3	3	5	12	5	5
200	227	1	1	1	2	2	3	3	3	13
100	227	1	1	1	2	2	190	27	8	24
60	241	1	1	1	2	2	247	8	12	42
30	252	1	1	1	3	3	169	11	5	31
6	276	1	1	1	2	2	8	24	13	501
3	275	1	1	1	2	2	110	75	6	678

Table F.3 - Wettability readings for TEST 3 without propeller where % S = spacer added to the mixture

Appendix G Average Compatibility and Wettability readings

Average Compatibility readings with propeller (M = Mud)										
RPM	**0% M**	**100% M**	**95% M**	**75% M**	**70% M**	**60% M**	**50% M**	**40% M**	**30% M**	**25% M**
300	42,8	49,0	46,4	27,6	30,9	34,5	34,2	35,6	40,2	47,6
200	36,4	36,4	34,8	20,7	23,3	27,0	27,8	29,0	34,2	42,1
100	29,9	23,5	21,9	13,9	16,5	19,8	22,3	23,6	27,3	31,6
60	27,7	17,3	16,3	10,8	13,7	16,9	19,1	21,3	24,1	29,0
30	24,4	12,5	11,7	8,0	9,8	12,9	16,9	18,6	21,3	24,5
6	20,6	5,5	5,3	4,0	5,0	7,6	11,9	13,5	17,6	19,7
3	19,8	3,9	4,2	3,5	4,3	6,7	10,9	12,8	15,9	18,4

Table G.1 - Average Compatibility readings with propeller where % M = mud content in mixture

Average Compatibility readings without propeller (M = Mud)										
RPM	**0% M**	**100% M**	**95% M**	**75% M**	**70% M**	**60% M**	**50% M**	**40% M**	**30% M**	**25% M**
300	39,5	47,5	47,0	25,2	26,3	28,8	28,9	39,0	43,2	42,3
200	34,2	36,0	35,7	18,3	19,9	22,4	23,7	31,8	34,2	33,8
100	28,1	22,7	21,9	11,8	12,9	16,9	18,8	22,8	24,4	24,8
60	24,3	18,3	15,9	8,6	9,5	13,5	15,0	19,1	20,7	20,8
30	20,8	10,1	9,6	5,1	6,5	9,7	12,1	15,6	16,9	17,1
6	17,4	3,9	4,3	2,6	3,2	5,9	8,6	11,2	11,8	14,3
3	15,6	2,3	2,8	1,5	2,1	4,1	7,3	10,1	13,3	15,4

Table G.2 - Average Compatibility readings without propeller where % M = mud content in mixture

Average Wettability readings with propeller (S = Spacer) where 100% S is setpoint										
RPM	**100% S**	**0% S**	**5% S**	**25% S**	**30% S**	**40% S**	**50% S**	**60% S**	**70% S**	**75% S**
300	262	1	1	1	2	148	221	154	192	114
200	268	1	1	1	5	6	8	84	159	107
100	269	1	1	1	2	2	20	146	167	90
60	265	1	1	1	2	2	6	189	166	137
30	264	1	1	1	7	2	6	255	179	155
6	253	1	1	1	2	1	3	380	260	180
3	254	1	1	1	1	2	3	344	286	295

Table G.3 - Average Wettability readings with propeller where % S = spacer added to the mixture

Average Wettability readings without propeller (S = Spacer) where 100% S is setpoint										
RPM	**100% S**	**0% S**	**5% S**	**25% S**	**30% S**	**40% S**	**50% S**	**60% S**	**70% S**	**75% S**
300	231	1	1	2	3	3	4	6	5	33
200	234	1	1	2	2	2	3	3	33	32
100	234	1	1	2	2	2	66	11	143	50
60	235	1	1	1	2	2	84	5	112	50
30	245	1	1	1	2	2	76	211	181	50
6	269	1	1	1	2	2	110	350	108	187
3	274	1	1	1	2	2	95	329	167	286

Table G.4 - Average Wettability readings without propeller where % S = spacer added to the mixture

Appendix H Standard deviation of Rheology readings

Standard deviation with propeller										
RPM	**0% M**	**100% M**	**95% M**	**75% M**	**70% M**	**60% M**	**50% M**	**40% M**	**30% M**	**25% M**
300	0,1	1,5	1,2	0,4	0,5	0,6	0,6	0,5	1,4	2,4
200	0,1	1,1	1,0	0,4	0,4	0,4	0,7	0,5	1,2	2,0
100	0,1	0,8	0,8	0,6	0,5	0,2	0,3	0,5	0,7	1,1
60	0,3	0,7	0,7	0,5	0,7	0,3	0,5	0,3	0,3	0,9
30	0,2	0,6	0,7	0,4	0,4	0,4	0,8	0,7	0,5	0,5
6	0,4	0,5	0,5	0,3	0,4	0,3	0,5	0,6	0,5	0,5
3	0,4	0,3	0,3	0,2	0,3	0,2	0,4	0,5	0,4	0,7

Table H.1 - Standard deviation with propeller where % M = mud content in mixture

Standard deviation without propeller										
RPM	**0% M**	**100% M**	**95% M**	**75% M**	**70% M**	**60% M**	**50% M**	**40% M**	**30% M**	**25% M**
300	0,2	0,7	0,6	0,1	0,1	0,9	0,3	0,6	0,9	0,5
200	0,3	0,5	0,4	0,2	0,1	0,4	0,1	0,2	0,8	0,1
100	0,5	0,4	0,3	0,1	0,1	0,3	0,3	0,2	0,6	0,3
60	0,3	0,2	0,5	0,2	0,3	0,2	0,3	0,5	0,2	0,3
30	0,6	0,5	0,4	0,4	0,3	0,2	0,4	0,4	0,4	0,5
6	0,4	0,4	0,4	0,3	0,4	0,3	0,5	0,5	0,3	0,7
3	0,4	0,4	0,4	0,3	0,4	0,2	0,4	0,5	0,8	1,3

Table H.2 - Standard deviation without propeller where % M = mud content in mixture

Appendix I Noteworthy pictures from tests

Figure I 1 - Settling of Barite at the bottom of the sleeve	*Figure I 2 - Settling of Barite after end test in bottom of cup*
	
Figure I 3 - Black dust on copper knob on bob	*Figure I 4 - Picture of bob after finished test*
	

Table I.1 - Pictures of equipment after test