Experimental Study of Rheological Properties of Model Drilling Fluids

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ABSTRACT

We report the design, use and characterization of a model drilling fluid used in a series of laboratory flow loop experiments with hydraulic transportation of sand. The experiments are part of a project with the purpose of studying noncircular wellbore geometries for drilling applications, and in particular helical grooves.

The main objective of the work reported here was to design, characterize and tune a model drilling fluid for a series of flow loop experiments. The fluid should have realistic properties relative to field applications, while also being practical for the specific flow loop experiments. The characterization and tuning should ensure consistent experimental conditions with respect to rheological properties using different batches of chemicals, different fluid batches and during the experiments.

The main tool used for fluid characterization was the Fann viscometer, which is a de facto standard method for rheology characterization in the oil industry.

A water-based drilling fluid using laponite and Xanthan polymer was designed, and the fluid characterization allowed us to detect changes in fluid rheological properties due to aging and experimental use. Further, we were able to adjust the formulation to maintain the rheological properties with different chemical batches.

Transient flow loop experiments with presheared and rested fluid respectively showed some differences which could be due to gelling effects. Further experiments are needed to conclude on this.

INTRODUCTION

Oil well drilling fluids are complex fluids which are designed to serve several purposes; maintaining integrity of the formation, cooling and lubrication of the drill bit, as well as transportation of the rock particles (cuttings) which are cut loose by the bit. The challenge of the latter has increased with the introduction of long inclined and horizontal well. Modelling and simulation of this transport problem is an equally challenging problem as it should account for

- Non-Newtonian fluid rheology
- Annular flow geometry
- Eccentric pipe position
- Pipe rotation
- Lateral pipe movement
- Particle-laden fluid

Most of the literature on this topic, both experimental and theoretical, take into account only a subset of these conditions. In particular the lateral pipe movement is often overlooked in this context. In the experimental setup of the present work all of these characteristics are considered.

The effect of non-Newtonian viscosity on cuttings transport properties was summarized by Nazari et al.[1].

Typically, the drilling fluid viscosities are characterized by a yield strength τ_y, a flow behaviour index n, and a plastic viscosity (or consistency index) K. The Herschel-Bulkley model is

$$\tau = \tau_y + K\dot{\gamma}^n \quad (1)$$

where the case n = 1 reduces to the Bingham model and the case $\tau_y = 0$ to the power-law model.

Escudier et al.[2] reported experiments with Newtonian and non-Newtonian fluids in a concentric annulus. One of the fluid systems was made from 1.5% Laponite and 0.05 % CMC in water. The Herschel-Bulkley model parameters were $\tau_y = 1$ Pa, $n = 0.41$ and $K = 0.988$ Pa*s^n.

An unconventional non-circular wellbore design has recently been developed[3]. The main idea of this design is to create a wellbore with spiral-shaped grooves along the borehole wall in order to enhance cuttings transport and reduce mechanical friction between drillstring and wellbore.

The idea of using pipe geometries which encourage swirl in order to enhance particle transport in fluids is more than 100 years old, as described by Raylor et al.[4]. In a more recent SPE paper Surendra et al.[5] discuss the use of swirl flow in oil and gas production systems and present results from CFD simulations. The work presented in this paper is the first to apply this principle to drilling applications, accounting for annular flow geometry and non-Newtonian fluids.

We have previously tested this principle in a flow loop with circular and non-circular wellbores produced from plastic and using fresh water as flowing medium and with quartz sand representing the cuttings. Hydraulic pressure losses and sand bed height were recorded during both steady state and transient conditions. Results showed that the non-circular geometry performed favourably compared to the circular geometry.

The paper is organized as follows. We first describe the design of the model drilling fluid.

Next we briefly describe the experimental setup and present some flow loop results.

We then discuss the fluid management conducted during and in parallel with the experiments. This involved fluid characterization as well as tuning by adjusting the composition to maintain the desired rheological properties.

We conclude by discussing the choice of fluids, their rheological properties with respect to the objectives of the project, as well as the methods used for fluids characterization.

EXPERIMENTAL

Drilling Fluid Design

The objective of the drilling fluid design was to obtain a formulation of a water based fluid with distinct non-Newtonian properties, including yield strength, shear thinning, and thixotropy. Due to the particle separator unit of the flow loop, the yield strength of the fluid should not too large such that particles become suspended in still fluid. The fluid should also be transparent for visual observation and video recording.

It was therefore decided to use a synthetic clay (laponite) in combination with a Xanthan gum biopolymer.

Laponite is a layered silicate colloid (lithium magnesium sodium silicate) consisting of extremely small platelets of 1 nm thickness and 25 nm diameter. It is used as a rheology modifier and will impart thixotropic, shear sensitive viscosity and improve stability and syneresis control. The rheological properties of Laponite suspensions are influenced greatly by solvent ionic strength and shear history[6].

Hydrated laponite produces a completely transparent fluid due to the small clay particle size. The laponite particles will further counteract the drag reducing effect of the polymer.

Xanthan gum was chosen for the polymer due to its high resistance to mechanical degradation. It has lower resistance to biological degradation, but this can be compensated by adding a biocide.

A defoamer was added to some of the fluid batches used, in order to minimize the concentration of air bubbles.

Fresh water from the municipal supply was used. The water quality was not analysed for this project. However, according to information from Trondheim kommune[7], the water is soft (hardness = 3 dH), pH = 8.1 with electrical conductivity = 12.1 mS/m.

The chemicals added to the water were thus

- Laponite RD (synthetic clay powder)
- Duotec NS (Xanthan gum powder)
- Soda Ash (powder)
- SafeCide (liquid biocide)
- Defoamer

Soda Ash was added for pH stabilization, and has a significant impact on the rheological properties of laponite.

Laponite RD produced by Rockwood Additives was purchased from Andreas Jennow A/S, whereas the other chemicals were provided free of charge courtesy of MI-Swaco.

The concentrations chosen for the active rheological components (laponite and Xanthan gum) were determined from a compromise between the field-realistic drilling fluid rheology, and the practical aspects of operating the loop, mainly in terms of sand handling and separation.

Figure **1** below illustrates the optical properties of water with laponite only (left), and with some polymer added (right). Sand articles used in the experiments at the bottom of 3 cm liquid layer.

Figure 1. Optical properties of water + 5g/l Laponite RD (Figure 1a, left) and with 5 g/l Laponite + 0.25 g/l Xanthan Gum (Figure 1b, right).

Based on recommendations and preliminary Fann viscometer tests conducted by MI-Swaco, we initially decided to use the following default formulation for the flow loop experiments:
0.46 % Laponite RD
0.1% Duotec NS
0.1% Soda Ash
0.025% SafeCide
where all percentages are by weight.

Fluid Characterization

Fluid samples were prepared and characterized using a Fann Viscometer Model 35SA. A Fann viscometer is a Couette coaxial cylinder rotational viscometer, and is a de-facto standard rheometer used in the oil industry. The test fluid is contained in the annular space (shear gap) between an outer cylinder and a bob.

Samples of drilling fluid were analyzed during the flow loop experiments to characterize the rheological properties.

The primary purpose of this characterization was to ensure consistent experimental conditions during flow loop experiments with circular and non-circular wellbore geometries. The main tool for characterization was the Fann viscometer measurements and consequently consistency was determined in terms of the Fann viscometer readings. The fluid characterization is necessary for several reasons:

a) The chemical composition of the Xanthan gum (Duotec NS) viscosifier used in fluid batches in latter experiments (in year 2012) differed from the composition used in experiments in 2011.

b) differences in concentrations between fluid batches due to inaccuracies and human errors during fluid preparations

c) fluid aging

d) fluid contamination

Flow Loop

The experimental flow loop has a 12 m long test section with an annular flow geometry with a steel pipe inside a wellbore consisting of replaceable concrete wellbore sections confined within a steel housing, with a transparent section in the middle.

The test section is inclinable and experiments were conducted with horizontal and 30° inclination.

Process equipment included fluid pump and sand injection and separation units. A motor connected to the steel pipe allowed this to rotate freely inside as a real drill pipe. Pressures (absolute and differential) as well as flow rate and temperature were measured and logged.

The fluid is pumped from a main tank together with sand which is injected from a dry sand feeder, through the test section and returned to the same tank. The fluid is recirculated, whereas the sand is separated out in a basket and disposed of.

In order to test and compare circular and non-circular flow geometries, two sets of concrete pipes have been produced, each consisting of short segments for easy assembly and disassembly. The non-circular geometry is constructed with a spiral shaped pattern in the inner wall as shown in Figure **2**. Both geometries have a drift diameter (diameter of largest inscribed circle) of 10 cm, and the inner rod has a diameter of 5 cm.

The sand injected with the fluid (see Figure **1**) is Dansand nr. 3 (0.9-1.6 mm diameter) from Dansand A/S. This is a nearly pure natural quartz sand from a marine deposition. The sand size range was chosen as a fairly realistic cuttings size range.

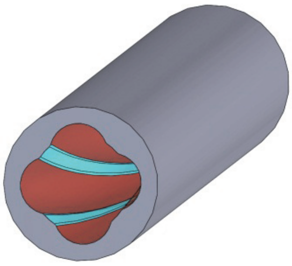

Figure 2. Noncircular wellbore geometry used in flow loop experiments.

Fluid Preparation

Laponite was mixed with water only, as recommended, and allowed to hydrate for at least 12 hours, at weight concentration of 5.5%. This produced a clear gel. The hydrated laponite was then diluted with more water.

The other chemicals were then mixed separately with some water to produce a high concentration viscosifier mixture which was then added to the diluted laponite.

RESULTS

Fluid Characterization

Figure 3 shows measured Fann data from initial fluid batch and manually matched model data. Fann viscosimeter readings showed that the Xanthan gum polymer used for experiments in 2012 gave higher viscosity than was obtained in experiments conducted in 2011. Consequently, the target fluid composition was changed relative to the original composition as shown in Table **1** and in Fig. 4.

Table 1. Mass fractions of Laponite and Xanthan used in different formulations.

	Mass fraction	
Formulation	Laponite	Xanthan
1	0.0040	0.00051
2	0.0038	0.00074
3	0.0038	0.00081
4	0.0042	0.00088
5	0.0041	0.00096

Fluid contamination was mainly caused by erosion of sand particles and of the concrete wellbore walls.

The general trend observed was an increase in the Fann viscometer readings (i.e. shear stress) versus time. This increase is due to a combination of pure aging and deterioration due to fluid wear and contamination with particles. However, as seen in Figure **5**, this process is very nonlinear.

We observed that the fluid became contaminated with fine particles as more experiments are conducted. This could be a more important factor than aging in terms of changed rheology. Thus, the Fann readings of the used fluid in Figure **5** shows larger values than the aged fluid in Figure **6**.

The latter figure shows the pure effect of aging of a single fluid sample.

Samples taken from the flow loop at different times but measured at the same time show significant differences due to use, see Figure **7**. This will be a combination of the stress loading of the fluid (e.g. in the pump) and contamination by particles.

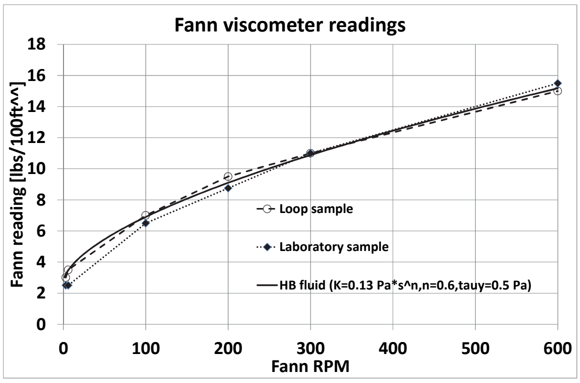

Figure 3. Fann viscometer data from laboratory and loop samples using default formulation, and matched Herschel-Bulkley model.

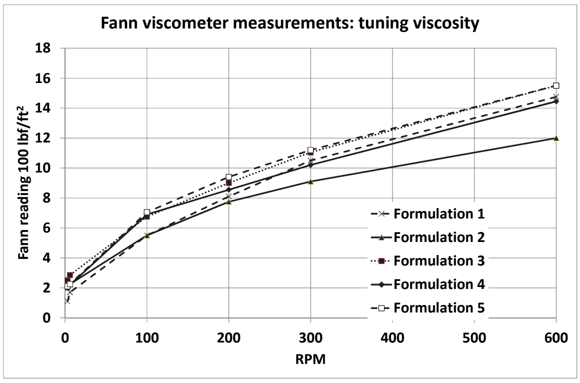

Figure 4. Fann viscometer measurements of different formulations, measured with new fluid.

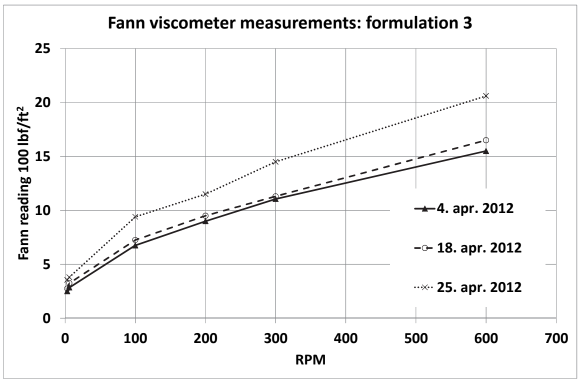

Figure 5. Fann viscometer reading of three fluid samples from loop fluid; taken when new (4.apr.2012), during the experiments (18.apr.2012) and after the final experiment (25.apr.2012).

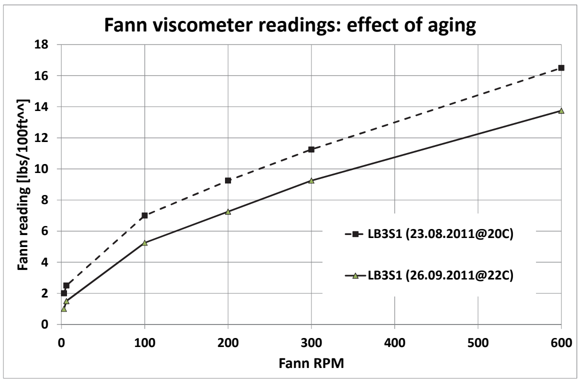

Figure 6. Fann viscometer reading of fluid sample at two different times.

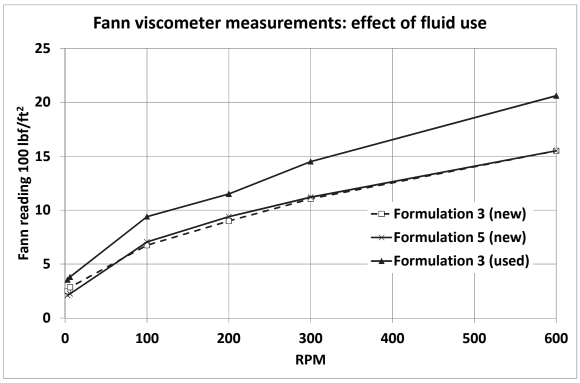

Figure 7. Fann viscometer reading showing effect of use of formulation 3.

We can relate the difference in Fann viscometer readings to a corresponding difference in flow loop measurements. A flow loop experiment conducted for the circular geometry and with horizontal test section, using fluid formulation 3 (see Table **1**) was repeated using fluid formulation 5. These formulations have similar Fann viscometer characteristics when new, but experiment 1 was conducted with formulation 3 (used), see Figure **7**. The measured pressure drop in the test section for these two experiments is shown in Figure **8**. The difference seen can be explained qualitatively by the difference in Fann viscometer characteristics.

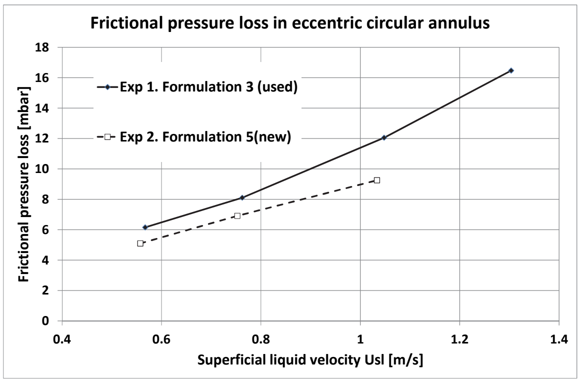

Figure 8. Repeated flow loop experiment, showing effect of different fluid properties due to use.

In addition to the fluid characterization reported above, measuring the steady state shear stress response to a given strain rate, we also noticed a distinct thixotropic effect during the Fann viscometer measurements. Typically we observed that the Fann viscometer readings at the highest shear rate (600 RPM) would decrease by 10-20 % over a period of ca 5 minutes when starting with a nonsheared fluid. The Fann viscometer results reported above are generally for a sheared fluid.

Other methods of fluid characterization

We also characterized the fluid using a Marsh funnel viscometer and using an Anotn Paar rheometer. The former is a very simple device for oil field use, measuring the time required for a given amount of fluid to drain through a funnel. The geometric shape may make this a useful tool for measuring fluids with a significant extensional viscosity. For the fluids used here the viscosity was so low, however, that the measurement was dominated by the pure inviscid hydrodynamic effects.

Two samples of formulation 3, measured at the same time, but taken at different times and thus exposed to different use, were characterized using an Anton Paar rheometer. The steady state viscosity measurements confirmed qualitatively the aging effects observed in the Fann viscometer measurements.

Flow Loop Results

We here present results showing the effect of drillpipe rotation on frictional pressure losses during steady state flow with 60 g/s sand in inclined pipe. The sand mass rate is so large that a sand bed is formed. Pressure loss is measured over a 4 m long distance in the test section.

Notice that without drillstring rotation, there is a minimum in the pressure drop versus flow rate.

This minimum can be explained as follows. At very low flow rates there is a thick sand bed and thus a small effective flow area which creates a large flow resistance. As the flow rate increases, more

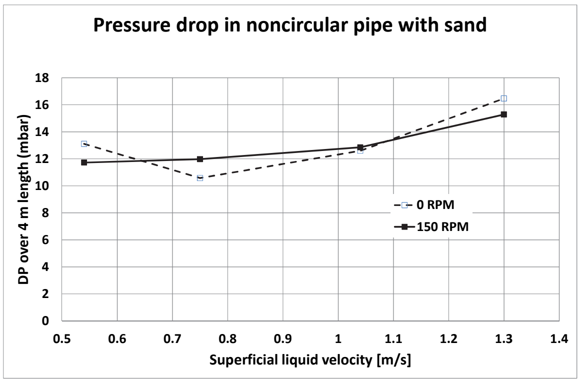

Figure 9. Effect of string rotation on frictional pressure loss in sand-laden liquid flow with noncircular wellbore geometry.

sand is being entrained from the bed into the flow. The flow area increases and the pressure drop decreases. As the sand bed vanishes the flow area cannot increase anymore, and the pressure drop increases due to increased wall shear stress. The location and magnitude of this minimum depends on operational parameters such as drillstring rotation which affects the effective Reynolds number, but also on the viscosity of the fluid. At a high rotational drillstring speed, the effect described above is completely masked.

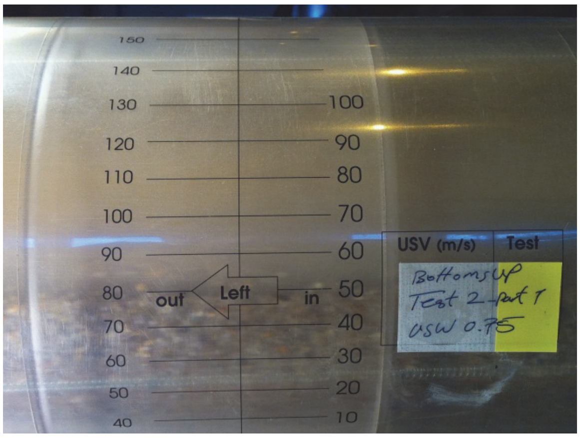

Figure 10. Initial sand bed before cleanout operation.

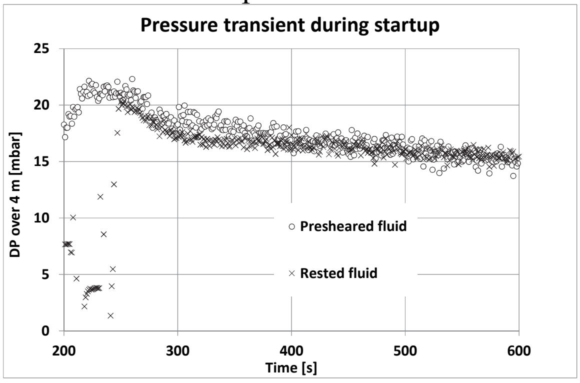

Figure 11. Measured differential pressure versus time during sand cleanout operation: comparing tests with presheared and rested fluid.

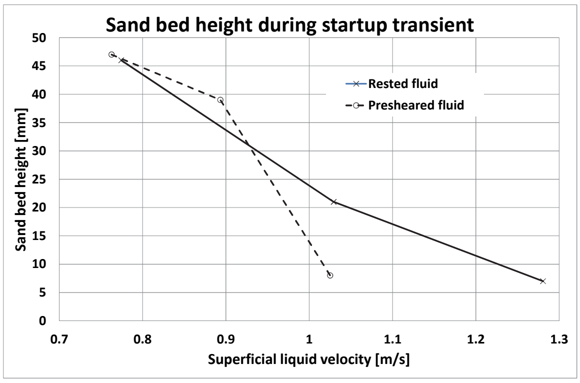

Figure 12. Measured sand bed height versus flow rate during sand cleanout operation: comparing tests with presheared and rested fluid.

We have noticed a small gelling tendency of the fluid when left to rest for some time. To check whether this could have any impact on hydraulics and sand cleanout capacity we conducted a pair of cleanout tests with circular wellbore in horizontal position. We first prepared a sand bed in the test section by injecting sand with fluid, see Figure **10**. Then we allowed the sand bed and fluid to rest overnight. We then turned on pumping with a preset flow rate $U_{sl} = 0.75$ m/s without sand injection. A gradual reduction in the pressure gradient in the test section will be seen as the bed is eroded until a new steady state bed height is reached. This flow rate is not sufficient to clean the test section. We then cleaned the test section, prepared a sand bed again and repeated the cleanout test without allowing the fluid to rest. The resulting pressure transients over a 4 m length in the test section are shown in Figure **11**.

We do not observe any significant differences in the pressure transients. However, there is a difference in the transient sand bed height. This could be due to gelling effects. However, further experiments are needed to confirm this.

DISCUSSION

We have used the Fann viscometer as our primary tool for characterizing the rheological properties of the drilling fluid used, to ensure and, if necessary, tune the fluid formulation. The Fann viscometer readings are found to be quite repeatable, and differences can be explained by aging and use of fluid. We also have some data showing sensitivity of flow loop results to rheological properties as measured with the Fann viscometer. Thus, it appears that the Fann viscometer is a suitable tool for the characterization of the fluid used here, as the Fann viscometer exposes the fluid to a pure shear strain rate. This will be quite representative to the situation in an annulus as in the present experiments, with a combined cylindrical Couette and Poiseuille flow. The steel rod used in the present experiments does not have any tool joints with increased diameter. A real drillstring with tool joints may cause extensional viscosity effects and time dependent effects to be more important.

CONCLUSION

We have used a Fann viscometer for characterizing a model drilling fluid for flow loop experiments with a drillpipe inside.

We find that the Fann viscometer can be used to measure the most relevant rheological properties of the fluid used in the present experiments with a non-Newtonian model drilling fluid.

Some effects of fluid history on sand transport properties were found. These could be due to fluid gelling effects. However, further studies are recommended to investigate this.

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