Drilling fluid rheology at challenging drilling conditions – an experimental study using a 1000 bar pressure cell

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ABSTRACT

Wells are frequently explored in deeper and more challenging areas, leading to more extreme well conditions. In this work we have used an MCR rheometer with a 1000 bar pressure cell to study drilling fluid viscosity at HPHT conditions and the effect of dissolved gas in an oil based drilling fluid.

INTRODUCTION

Drilling operations are becoming more and more challenging as fields are explored in areas of extreme temperatures and pressures. These new drilling conditions challenge the composition of the drilling fluids. In general, oil based drilling fluids (OBDF) perform better at HPHT conditions due to a more stable viscosity profile, higher thermal tolerance, and shale inhibition properties[1, 2]. Also the considerable range in downhole pressure must be taken into account in evaluating drilling fluid rheology, since pressure will influence viscosity, gel strength and yield point[1]. According to international standards, the flow behaviour of drilling fluids is measured at 27 or 50 °C and at atmospheric pressure[3, 4]. In order to verify the validity of extrapolation to downhole HPHT conditions, better knowledge about the rheology of drilling fluids under HPHT conditions is required.

By using the Anton Paar 1000 bar pressure cell (Pr1000) we have studied one OBDF at temperatures ranging from ambient to 150 °C and at pressures from atmospheric to 1000 bar. Using the Pr1000 cell one can successfully measure viscosity down to about 35 mPas[5]. Drilling fluids are shear-thinning, temperature-dependent fluids, often of low viscosity at drilling conditions. This challenges the experimental outline when analysing OBDFs in Pr1000.

In this report we show the effect of temperature, pressure and gas absorption on OBDF rheology at HPHT conditions. The various parameters tested will all influence the drilling fluid performance by altering the fluid viscosity. Also the performance of the Pr1000 cell will be evaluated and discussed.

MATERIALS AND METHODS

Fluid composition and fluid handling:

In this study we have analysed one OBDF (mixed and delivered by M-I Swaco, Bergen, Norway) based on a refined deepwater base oil. The OBDF is an emulsion formulated with calcium chloride brine. The oil/water ratio in the liquid phase is 80/20. The main weighting material is barite and the fluid density is 1.6 g/cm^3. The fluid also contains viscosifiers, fluid loss material and pH additive. Before sample filling, the OBDF was mixed in a Waring blender LB20ES at 6000 rpm for 10 min to homogenize the

fluid. The density was measured on an Anton Paar DMA 4500 to ensure that the fluid did not show any sign of barite sag or liquid evaporation.

Experimental equipment:

In this study we have used an Anton Paar MCR 102 rheometer with a concentric cylinder CC27 (gap size 1.14 mm), hereafter denoted AP/CC27 (atmospheric pressure), and a 1000 bar pressure cell with two measuring bobs: CC26 (gap size 2 mm) and CC29 (gap size 0.5 mm), hereafter denoted Pr1000/CC26 and Pr1000/CC29, respectively.

The Pr1000 cell is designed in such a way that the sample has to be transferred from a pressurizing unit entering the bottom of the pressure cell in the rheometer. In our experimental setup[6] the sample is loaded in a piston cylinder (Leutert sample cylinder type 600 light, operating conditions: 1000 bar / 200 °C, hereafter referred to as the sample cylinder) which is connected to the rheometer through a 2.4 m long 1/8" tubing section incorporating several high pressure valves. At the hydraulic end of the piston cylinder, a Teledyne ISCO pump, model 65D, is connected. The pump enables transfer of the sample from the sample cylinder to the rheometer and functions as the pressurizing unit for the Pr1000 cell. The sample cylinder is also connected to a second piston cylinder acting as a gas reservoir. This gas cylinder is connected to a second Teledyne ISCO pump, which allows the addition of gas at controlled mass fraction to the sample. Prior to transferring a sample with dissolved gas, the pressure cell and the connecting tubing are evacuated down to < 0.45 mbar.

After the fluid was transferred from the sample cylinder to the rheometer, it was let to rest 2 hours for structure regeneration before measurements. The length of the resting time was determined after having tested the repeatability of the flow profile using various resting times ranging from 0 – 2 hours.

Rheological measurements:

Measurements were recorded and analysed in Rheoplus. We used the Excel-based Rheoplus Profile Generator and Estimator from Anton Paar to calculate measuring point duration and recommended settings. The amplitude sweep was done with an angular frequency of 10 rad/s. The thixotropy test was run as a step test consisting of three intervals: oscillatory rest interval (amplitude gamma: 0.1 %, angular frequency: 10 rad/s), rotational shear interval (shear rate: 3000 s-1, 0.1 s) and oscillatory regeneration interval (amplitude gamma: 0.1 %, angular frequency: 10 rad/s). Flow curves were run with controlled shear rates (intervals as given in the figures). Flow curves analysed at atmospheric conditions were run with measuring point duration of 2 s, while all other measurements in the Pr1000 cell were run with 0.3 min measuring point duration.

RESULTS

Shear history and structural properties at rest

We wanted to study how shear from the sample transfer between the sample cylinder and the rheometer influenced the structural character of the fluid. In Fig. 1 we show an amplitude sweep of the OBDF shortly after transfer from the sample cylinder and a similar sweep in which the OBDF was applied directly into the pressure cell by carefully pouring the fluid through the top nut. (The last method is not recommended as it may lead to displacement of bearings.) In the first case, where the fluid is pumped through 2.4 m of tubing, the shear stress on the fluid is significantly higher than for the second

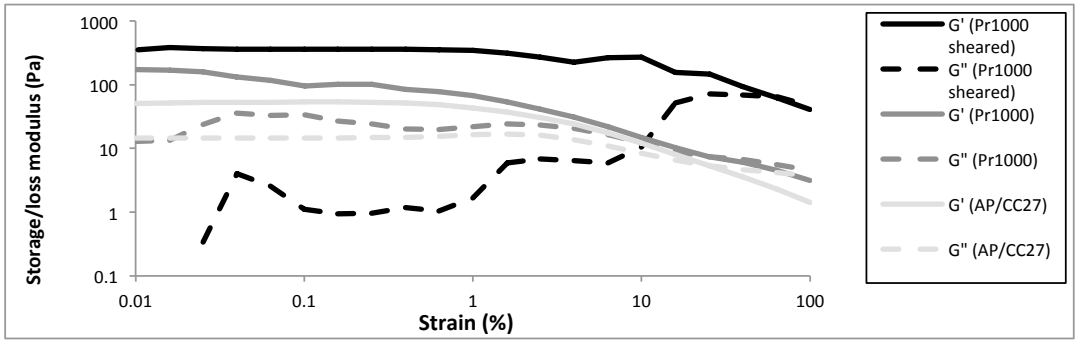

Figure 1. Amplitude sweep of storage modulus G" (solid lines) and loss modulus G' (dashed lines) at ambient conditions. Colour codes: Sheared sample transferred from sample cylinder: Black, "non-sheared" sample directly loaded in Pr1000: Dark grey, "non-sheared" sample in AP/CC27: Light grey.

case. In Fig. 1 the storage and loss modulus of the sample which was transferred from the sample cylinder, are shifted to higher and lower values, respectively, clearly showing that this sample has a shear-history. Interestingly, this sample has a stronger, more stable structure and a higher flow point than the sample that was loaded directly in the pressure cell. The shear effect on structural stability is in line with the shear-induced structural strength discussed below (Fig. 2).

When comparing the two first curves with a similar sweep done in AP/CC27, the curve of the "non-sheared" sample in Pr1000 corresponds better to the AP/CC27 measurements than the "sheared" sample. Also the flow points of these two "non-sheared" samples are more similar. However, the pressure cell measurements are more irregular, especially in the low strain area.

Shear-induced structural change

The fluid was analysed for its time-dependent behaviour. The OBDF shows a thixotropic behaviour with 100 % regeneration within 6.5 min (see Fig. 2). However, as the fluid is subjected to low oscillation over time, the fluid gains a higher structural strength, probably due to increased emulsion stability.

Flow behaviour of the OBDF in various measuring systems.

We compared measurements done using the pressure cell with those using AP/CC27 at atmospheric pressure and room temperature. The flow (Fig. 3) and viscosity (Fig. 4) curves show that measurements done with the pressure cell diverge from that done in AP/CC27. The viscosity for the selected OBDF is on average 12-15 % lower when measured in the pressure cell compared to AP/CC27. A certain deviation is expected, since the Pr1000 cell does not have the same accuracy as the AP/CC27.

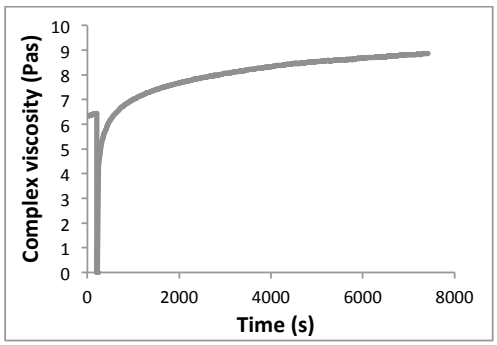

Figure 2. Thixotropy test showing the complex viscosity profile of the OBDF. Measurement was done in AP/CC27 at room temperature.

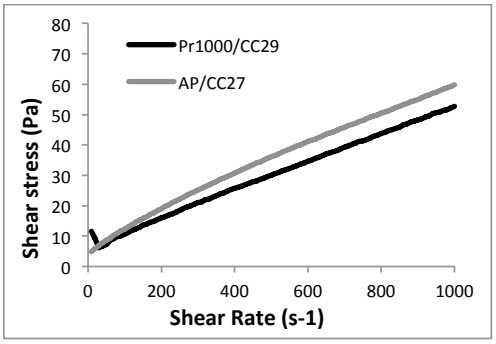

Figure 3. Flow curve of OBDF measured in the Pr1000/CC29 and in AP/CC27. Measurements were done at ambient conditions.

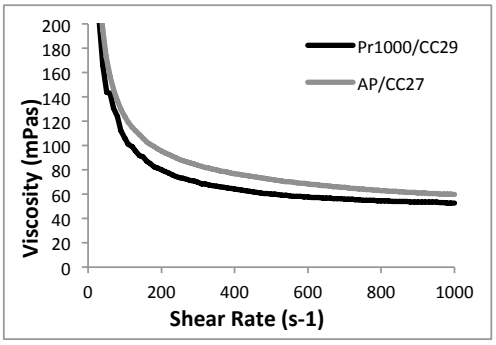

Figure 4. Viscosity curve of OBDF measured in Pr1000/CC29 and in AP/CC27. Measurements were done at ambient conditions.

The effect of temperature on the OBDF viscosity

As with most fluids, the viscosity of the OBDF decreases with temperature. By raising the temperature by 20 °C we here see a nearly 30 mPas decrease in viscosity, see Fig. 5. In the high shear region the fluid shows turbulent flow as indicated by the increased viscosity. To avoid this effect it might have been advisable to measure with a smaller gap.

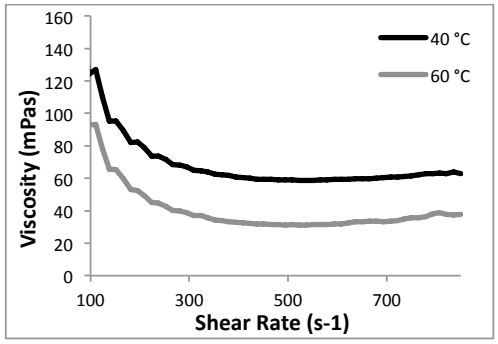

Figure 5. The effect of temperature on the OBDF viscosity measured in Pr1000/CC26 at 5 bar.

The effect of pressure on OBDF viscosity

Pressure is known to increase the viscosity of drilling fluids. We have measured viscosity of the OBDF at various temperatures and pressures. As shown in Fig. 6, the viscosity increases with about 7 mPas when raising the pressure from 5 (grey curve) to 160 bar (black curve) at 60 °C. Such data are important to take into account when planning drilling operations, enabling correct calculation of the viscosity dependent pressure profile.

Increasing the pressure may also enable improved measurement accuracy of low viscous samples. 5 % methane was dissolved in the OBDF and viscosity measured at 400 bar (Fig. 7, black curve). At these conditions the sample viscosity is far below the minimum recommended viscosity for the Pr1000 cell (35 mPas[5]), and the torque values are below or close to the intrinsic friction of the cell (data not shown). This indicates that the data are less reliable, however, trends in the data may still be of significance. By increasing the pressure to 640 bar (Fig. 7, grey curve), the viscosity increases with 10-25 mPas over the shear rates analysed. Measuring at high pressure enables more accurate viscosity measurements of this gas/OBDF mixture.

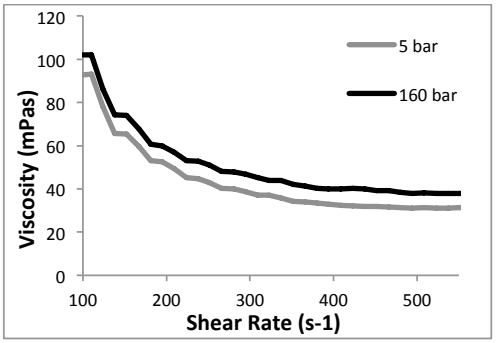

Figure 6. The effect of pressure on OBDF measured in Pr1000/CC26 at 60 °C.

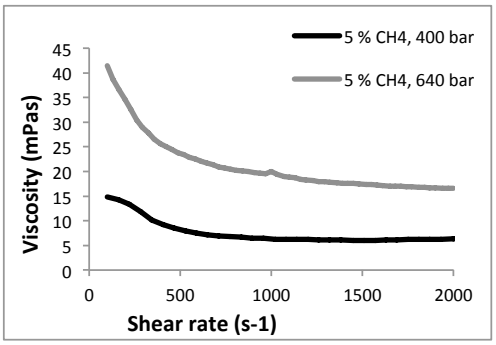

Figure 7. The effect of pressure on OBDF with gas measured in Pr1000/CC29 at 40 °C.

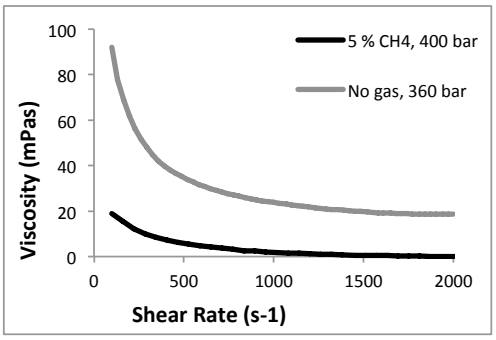

Figure 8. The effect of 5 % gas absorption in OBDF measured in Pr1000/CC29 at 100 °C. Sample with gas was measured at 12 bars above bubble point.

The effect of gas on OBDF viscosity

The fluid was saturated with 5 % methane and viscosity was measured on the mixture at single phase conditions. As shown in Fig. 8, gas absorption in OBDF significantly lowers the fluid viscosity, accounting for a viscosity decrease of 20-76 mPas at shear rates 100-2000 s-1 for the mixture analysed.

DISCUSSION

In this study we have used the Pr1000 cell to measure viscosity of an oil based drilling fluid with and without dissolved gas at various measuring conditions. As expected, the fluid shows temperature- and pressure-dependent viscosity. The OBDF is shear-thinning and shows a shear-induced structural change, which is likely due to increased emulsion stability. Performing oscillatory tests using the Pr1000 cell are difficult in the low strain area[7], because the inertia of the bob is much higher than for the conventional atmospheric setup. This leads to less reliable results for amplitude sweeps and other oscillatory tests. However, trends may still be displayed correctly.

The OBDF used in this study has particles of up to 75 µm. The measurement gap should preferably be 10 times the particle size in order to obtain gap-independent results[8]. However, as demonstrated in Fig. 5, a large gap may lead to turbulence if the fluid viscosity is low. The pressure cell has two measuring bobs, CC26 which has a gap size of 2 mm and CC29 with a gap size of 0.5 mm, both of which have been used in this study. By choosing the CC26 with a gap size >10 times the particle size of our OBDF, turbulent shear flow conditions is more easily encountered for this low viscous fluid. However, by reducing the gap size to 6.7 times the particle size we experience less problems with turbulence and we can also measure at higher shear rates.

The main limitation of the pressure cell is the high intrinsic friction which limits the use of this measuring device for low viscous fluids. Some other limitations of Pr1000 have been identified and are suggested for improvements:

1) The pressure cell comes with two pressure heads, one for temperatures below 100 °C and one for temperatures above 100 °C. The high pressure gasket for temperatures above 100 °C is not leak tight at lower temperatures. Consequently, samples with gas cannot be measured at temperatures above and below 100 °C in the same run, without changing sample and pressure head. At the same time, our experience is that the O-ring for temperatures below 100 °C is not resistant to OBDF with high gas content at high pressures.

2) Sample filling and cleaning is very time consuming, and cleaning can only be done by demounting the pressure cell. Changing sample in the pressure cell is therefore not straightforward, and reuse of sample often has to be considered. Sample handling prior to measurements are therefore not uniform, contributing to the variation in measurements.

3) Correct mounting of the bob in the pressure cell is difficult to verify by visual inspection. It is crucial that the bob is correctly installed, otherwise axes will be bent and measurements will be incorrect.

CONCLUSIONS

In this work we have used the Anton Paar 1000 bar pressure cell to study viscosity of drilling fluids at HPHT conditions and the effect of dissolved gas in the drilling fluid. This type of results add valuable knowledge about drilling fluid rheology under extreme conditions and can be used in computational models for improved calculation of the bottom hole pressure and the prediction of gas absorption in the drilling fluid.

We have compared measurements done in the pressure cell with measurements done in an open concentric cylinder at similar conditions. We here show that some variation can be seen between the two measuring geometries, indicating both handling and measuring uncertainties.

When analysing samples with dissolved gas, measurements have to be done at a pressure above the bubble point to ensure that the multi-component fluid is at single phase conditions. We find that the 1000 bar pressure cell is a good tool for measuring samples at HPHT conditions including the possibility to add gas.

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