STUDY OF CONTINUOUS RHEOLOGICAL MEASUREMENTS IN DRILLING FLUIDS

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Abstract – Drilling an oil well involves using drilling fluids that perform cleaning and cooling functions, but that most importantly maintain the fluids of the geological formation contained by hydraulic pressure. A fundamental role in predicting the hydraulic pressure of the well consists of monitoring the fluid’s rheological behavior. This paper summarizes an ongoing effort to measure, by evaluating the performance of two online viscometers, drilling fluids' rheological behavior in real time. One online method proposes a modified Couette system. The other consists of a standard pipe viscometer with default modeling. The performances of the online devices were compared with an offline method – a Couette device commonly used in oilfields as a benchmark. For Newtonian fluids, agreement between the rheological behaviors was found for all instruments, validating the methodology proposed. For non-Newtonian fluids, there were divergences, which were investigated and their probable causes determined to be the following: homogeneity, slippage effects, and interaction in the fluid/gap interfaces. A case study demonstrated that these divergences were not significant during the prediction of hydraulic pressure, meaning that the methodology proposed has the potential to improve overall drilling performance.

Keywords: drilling fluid, online rheology, automation, continuous measurement.

INTRODUCTION

Drilling petroleum wells in ultra-deep water is an operation of great cost and risk. Due to the extreme pressure and temperature conditions, the operational window of hydraulic pressure control is too narrow for mistakes. This window represents the minimum and maximum pressures that can be applied to the system so as to avoid undesired flows towards the well, such as water or gas invasion originating from the rocks. The minimum pressure is known as porous pressure and the maximum is known as fracture pressure (Shaughnessy et al., 2007). To maintain the hydraulic pressure within the limits of the porous and fracture pressures, a common technique is the overbalanced technique. (In fact, the majority of Brazilian petroleum wells have been drilled in this manner.) In this technique, the operator pumps a drilling fluid throughout the well. To control the hydraulic pressure, it is necessary to characterize the rheological behavior of the fluid. Without such a parameter, it is impossible to predict hydraulic pressure and consequently maintain control.

In oilfields, operators carry out rheological measurements using offline viscometers that make use of manual procedures which date back more than 50 years. The evaluation of this process can be enhanced with online measurements. They can shorten distances between control centers and the field. Online measurements permit the predicting of hydraulic pressure almost instantly,
contributing to a more precise pressure control. In addition, constant monitoring allows problems to be detected earlier, permitting the operators to mitigate costly operational problems ahead of time (Oort and Brady, 2011).

Despite such benefits, works are scarce regarding online measurements of drilling fluids during flow. Their scarcity mainly arises because such fluids usually impose several operational difficulties during measurements (Apaleke et al., 2012, Gandelman et al., 2013).

Most drilling fluids are pseudo-plastic and have thixotropic effects. They tend to be dense because of a large amount of insoluble materials in suspension, are opaque, and can be water- or oil-based. The majority of standard offline viscometers and rheometers fail to characterize such fluids due to clogging, abrasion damage, bad homogeneity, or slippage effects. Considering the vast online technological market, few devices have been designed to monitor drilling fluids (Caenn and Chillingar, 1996).

Saasen et al. (2009) built a large-scale drilling fluid flow loop to measure several drilling fluid properties, including viscosity. The authors also used a Couette viscometer. Although many properties were investigated, there were no comparisons between online data with standard bench offline ones.

Broussard et al. (2010) developed their own density and viscosity meter; both measurements were done in the same apparatus. Unlike Saasen et al. (2009), the authors compared online measurements directly with offline ones obtained in standard bench devices. Their results showed agreement, as well as disagreement, during certain periods of trial. The main reasons which caused the deviation between online and offline data were not completely pointed out, but it was suggested that the differences may lie in geometry and drifting forces that existed in the online environment. Broussard et al. (2010) also used the Couette method for measuring the rheological behavior of drilling fluids.

Rondon et al. (2012) developed a prototype to be inserted into a drilling column to measure, from pressure drop readings, the rheological behavior of the fluid in real time in downhole conditions. Their online results were compared to standard benchmark devices, but only for polymeric solutions; drilling fluids have yet to be evaluated.

Carlsen et al. (2012) installed pressure sensors on a rig site, measuring gauge pressure and differential pressure at several different points during drilling operations. From hydraulic modeling, the author predicted the apparent viscosity from those pressure readings, all measurements were done at the surface. The online measurements were compared to standard bench devices and presented similar behavior found in Broussard’s work.

Vajargah and Oort (2015) proposed a method to determine rheology in real time from downhole measurements of pressure drop and temperature, considering the well as an annulus pipe viscometer. Their results were compared to offline data taken from an offline high-pressure high-temperature rheometer. Their paper does not extensively compare online and offline data.

The present work develops a Couette viscometer to continuously measure rheology on the surface, with no flow-rate limitation and up to pressures of 200 psi and 145°C. It also constructs a pipe viscometer for online comparison purposes. Online and offline data are also compared. In a case study, the pressure drop is calculated in real time using online data and compared with the data calculated from the offline device.

This paper stands out in demonstrating a newly developed device, optimized for drilling fluids, which needs no qualified personnel to operate, due to its high level of automation. The results demonstrate that the methodology proposed is of potential utility for any industry that may require hydraulic pressure control, rheological control or monitoring.

MATHEMATICAL MODELS REVIEW

Online/offline concentric cylinder viscometers (Couette viscometers)

A Couette viscometer calculates shear stress by measuring the drag force on the inner cylinder, transferred by the fluid contained in the gap. This force originates in the outer cylinder, which is rotated by a motor. The gap is the annulus space formed between the two concentric cylinders (inner and outer).

The shear stress for online or offline Couette viscometers, for Newtonian and non-Newtonian fluids, is calculated by (Barnes, 2000):

\[
\tau = \left( \frac{k}{2\pi r_1^2 H} \right) \theta
\]

where \( k \) is the elastic constant of the spring or torque sensor, \( r_1 \) is the inner cylinder radius, \( H \) is the height of the inner cylinder and \( \theta \) is the deflected angle of the torsion spring or sensor.

For Ostwald-de-Wale fluids, the shear rate for online/offline Couette viscometers (Barnes, 2000) is determined as follows:

\[
\dot{\gamma} = \Psi_n \left( \frac{2r_2^2}{r_2^2 - r_1^2} \right) \omega
\]
\[ \Psi_{(n)} = \left( \frac{\frac{2}{\beta^n}}{n, \beta^2} \right) \left[ \frac{\beta^2 - 1}{\frac{2}{\beta^n} - 1} \right] \]  \tag{3}

where \( \Psi_{(n)} \) is a dimensionless factor, \( r_2 \) is the radius of the outer cylinder, \( r_1 \) is the radius of the inner cylinder, \( \omega \) is the angular velocity of the rotating cylinder (outer one if the viscometer is a Couette system) and \( n \) is the behavior index of the fluid.

It can be seen in Eq. (2) that the shear rate for non-Newtonian fluids depends on the behavior index and ratio of the radii (the ratio is the gap of each instrument). Barnes (2000) showed that the behavior index can be calculated using the approximation:

\[ n = n' = \frac{\ln(\tau)}{\ln(\omega)} \]  \tag{5}

where data of \( \tau \) and \( \omega \) are determined experimentally.

**Online capillary or pipe viscometers**

For the laminar flow (Bird et al., 2001) of a fluid inside a straight circular pipe:

\[ \frac{-\partial P}{\partial z} = \frac{1}{r} \frac{\partial}{\partial r} \left( r \tau_{rz}(r) \right). \]  \tag{6}

Where \( P \) is the gauge pressure at position \( z \) (axial) and \( r \) (radial). From Equation (7), the shear stress is obtained by:

\[ \tau_{rz}(R) = \frac{\Delta P \cdot R}{2 \cdot L} \]  \tag{7}

and shear rate,

\[ \dot{\gamma}_R = \frac{4Q}{\pi R^3} \left[ \frac{3 + (1/n)}{4} \right] \]  \tag{8}

where \( \tau_{rz}(R) \) is the shear stress at the pipe wall, \( \Delta P \) is the pressure drop, \( R \) is the pipe internal radius and \( L \) is length, \( \dot{\gamma}_R \) is the shear rate at the pipe wall, and \( Q \) is the volumetric flow rate.

**MATERIALS AND METHODS**

**Flow loop**

The flow loop was built not only to develop the online equipment, but also to make and produce the necessary drilling fluids, whether oil-based or water-based. A brief description of the apparatus is found in Fig. 1:

- A 500-liter tank coupled with a high power and speed mixer;
- A 3-hppositive displacement pump that drives the fluid to the pipe lines;
- A centrifugal pump in parallel to flush the system during or after experiments;
- A heat exchanger to heat up or cool down the fluid;
- An online instrumentation to measure the desired fluid properties and control operational conditions such as flow rate, discharge pressure, pressure drop and temperature;
- To communicate with the equipment, hardware was used that was provided by National Instruments, along with the software LabVIEW®, with which the human-machine interface was constructed.

The online viscometers TT-100 and pipe can be identified in Fig. 1 by numbers 10 and 8, respectively. TT-100 performs both shear rate and shear stress measurements. The pipe viscometer generates shear stress by the pressure drop measured in the instrument numbered 8, and the shear rate is calculated by the determination of the volumetric flow rate, which is provided by the instrument numbered 7, a Coriolis mass flow meter.
Figure 1. Flow loop design.

1 = Stirred tanks with embedded PID control
2 = Helicoidally pump with embedded PID control
3 = Centrifugal pump with embedded ON/OFF control
4, 11 = Pressure meter
5 = Heater exchanger
6 = Temperature meter
7 = Volumetric flow meter
8, 9 = Differential pressure meter
10 = Online viscometer
12 = Online conductivity meter
13 = Online electrical stability meter
14 = Online density meter
15 = Level meter
16 = Rock fracture simulator
17 = Online meter of concentration of suspended solids
18 = Online meter for counting and measuring size of solids
m9 = Online meter of water in oil ratio
20 = Online filtration cell
21 = Computer host
22 = Router
23 = Remote terminal computer
24 = Remote terminal Tablets
Viscometers

Couette viscometer, online and offline

The Couette measurement system is present in TT-100, an online viscometer, and in FANN 35A, an offline viscometer. Figure 2 illustrates the mechanical parts of TT-100 (Brookfield manual, 1993).

![Figure 2. Viscometer BROOKFIELD, model TT-100, original motor.](image)

It can be observed in Fig. 2 that the gap for TT-100 is formed when the number 2 and 4 pieces are assembled. The original TT-100 comes with a DC motor with seven fixed velocities, manually controlled.

The objective was not only to determine rheological behavior, but to control the equipment remotely. So the original instrument was modified by replacing the DC motor with an AC brushless servomotor. These types of motors are controlled with a special vector inverter device, which allows full access to several motor parameters, such as speed, torque, and spin control. The motor replacement also permits capturing the velocity of the motor (RPM) in real time.

As a result of the online configuration, the operating principles of TT-100 are the same for any default Couette viscometer – with the exception of the fluid renewal inside the measurement chamber. If the fluid changes its rheological characteristics, TT-100 will report so as soon as this fluid arrives in the gap.

The offline instrument evaluates the shear stresses at six different shear rates. The velocities of the outer cylinder can be selected by manipulating simultaneously the speed selector along with the gear shift. The velocities are 3, 6, 100, 200, 300, and 600 RPM. The shear stresses, in each motor velocity, are calculated from the values of deflected angle, which can be read in the analogical display on top of the instrument.

Pipe viscometer

From experimental data of volumetric flow rate and pressure drop, it was possible to estimate the shear rate and shear stress, respectively, using the mathematical models illustrated above. Figure 3 shows the constructed viscometer in greater detail.

![Figure 3. Operational principles of pipe viscometer.](image)
Experimental design

Fluids and experimental procedure

To investigate rheology online, the study used three different fluids — one exhibiting Newtonian behavior and two exhibiting Non-Newtonian behavior. The Newtonian fluid was used to calibrate and validate the installed equipment. Because the fluid had fewer rheological complexities, it was expected that all viscometers would provide similar data. After validation, a polymeric solution was used to evaluate the performance of each viscometer against non-Newtonian fluid behavior. Finally, and of most interest, all instruments were tested with a water-based drilling fluid, typically used in drilling processes; the fluid has solids in suspension, in a medium concentration range (30 to 60 % in mass). Table 1 presents these fluids’ properties, such as composition and density.

Table 1. Evaluated fluids.

<table>
<thead>
<tr>
<th>Type</th>
<th>Viscosity</th>
<th>Composition</th>
<th>Density (g/cm³, 250C)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Newtonian</td>
<td>Constant</td>
<td>Glycerin 75%</td>
<td>~1,0</td>
</tr>
<tr>
<td>Non-Newtonian</td>
<td>Low range</td>
<td>CMC* solution 0,25% w/w</td>
<td>~1,0</td>
</tr>
<tr>
<td>Non-Newtonian</td>
<td>High range</td>
<td>CMC* solution 1% w/w</td>
<td>~1,0</td>
</tr>
<tr>
<td>Non-Newtonian</td>
<td>High range</td>
<td>Water based mud</td>
<td>~1,5</td>
</tr>
</tbody>
</table>

*CMC = Carboxyl Methyl Cellulose

The basic composition of the water-based mud was water, bentonite, barite, calcium carbonate, sodium hydroxide, xanthan gum, glutaraldehyde, and a rheological modifier.

The experimental procedure consisted of acquiring, at the same time, the rheological profile of the chosen fluid at the same temperature in all three instruments—TT-100, FANN 35A, and pipe viscometer.

Mathematical procedure

According to Billon (1996), many viscometers are sold to be used with Non-Newtonian fluids containing mathematical procedures only valid for Newtonian fluids to calculate apparent viscosity, shear rate and shear stress. The literature shows that the velocity gradients for non-Newtonian fluids formed in a gap or during tube flow are not as parabolic as for Newtonian fluids. The smaller the value of n, the more non-linear is the profile formed by the gradient velocity. Hence, the shear rate for non-Newtonian fluids, regardless of the geometry of the flow, depends directly on the behavior index and gap size. Ignoring these terms can lead to a miscalculation. As a result, an algorithm was built in a LabVIEW® environment to solve Eq. (2). The algorithm applies a linear fit to the logarithm of the income data of shear stress and motor speed. This algorithm can determine the slope of the line formed between those logarithms, which is $n'$ (Eq. (5)). This calculation allows the prompt determination of the dimensionless coefficient (Eq. (3)) necessary to calculate the shear rate of Ostwald-de-Waele fluids.

The linear fit is based on the iterative model (LabVIEW® instruction manual) represented by:

$$residual = \frac{1}{N} \sum_{i=0}^{N-1} w_i (\hat{y}_i - y_i)^2$$  \hspace{1cm} (9)

where $N$ is the number of data received, $w_i$ is the ith element of weight, $\hat{y}_i$ is the ith element of best linear fit and $y_i$ is the ith element of incoming data (dependent variable). This study considered the weight equal to 1 and the tolerance equal to 0.0001.

For the offline viscometer, the linear fit was done using a native algorithm from the software ORIGIN®, which is also based on the Least Square Method (LSM).

RESULTS AND DISCUSSION

Online rheology results

All evaluations were done at two different temperatures and in triplicate. The figures will only show the typical average result at lower temperature. Complete data can be observed in the tables.

Figure 4 presents the rheological behavior and its statistics for glycerin. The statistical information can be seen under the rheological profiles, respectively, according to the horizontal aligned axis.

The behavior of the plotted shear stress versus shear rate was, as expected, a straight line, characteristic of a Newtonian behavior. TT-100 presented some divergence above 750 s⁻¹. Besides that, all equipment presented similar data.

The measurement range of the pipe viscometer was limited by pump rotation and flow regime. Its inferior limit
was the minimum rotating speed of the pump, and the superior limit was the maximum flow rate to maintain the laminar regime.

One may also note the error bars, which represent the error propagation caused by sensor imprecision. Table 2 shows that all imprecisions accounted for this error propagation. The mathematical method used was the derivative one (Meyer, 1975).

In Fig. 4, it can be noted that the residual of TT-100 was larger than that of the pipe viscometer at the beginning of operation, despite being smaller until the end of the experiment. Thereby it is possible to infer that the incoming data (ln(τ) and ln(ω)) of TT-100 was more accurate than that of the pipe viscometer. This is acceptable because the pump vector inverter is not as precise as the servomotor vector inverters. Despite the larger residual at the beginning of the operation, TT-100 converged its slope faster than did the pipe viscometer.

To obtain the parameter µ of the Newtonian model, another linear fit was applied, but now using data of shear rate and shear stress. This fit was done using the software ORIGIN®, which received the exported data from LabVIEW®.

The obtained results of viscosity (µ) and the performance of the fit (R² - correlation coefficient) are presented in Table 3.

The results presented for n, in Table 3, permit the conclusion that the hypothesis of \(n = n'\) was acceptable.

To evaluate data for non-Newtonian fluid, a dilute solution of CMC was fabricated, approximately 0.25% in mass. Shown in Fig. 5 is the data obtained for this fluid.

It may be observed in Fig. 5 that the behavior of the...
Table 2. Imprecisions considered for error propagation.

<table>
<thead>
<tr>
<th>Instrument</th>
<th>Imprecise measure</th>
<th>dimension</th>
<th>range</th>
</tr>
</thead>
<tbody>
<tr>
<td>TT-100</td>
<td>Deflected angle</td>
<td>degree</td>
<td>± 1%</td>
</tr>
<tr>
<td></td>
<td>Motor velocity</td>
<td>RPM</td>
<td>± 1</td>
</tr>
<tr>
<td>FANN 35A</td>
<td>Deflected angle</td>
<td>degree</td>
<td>± 1</td>
</tr>
<tr>
<td>pipe</td>
<td>Pressure</td>
<td>Pa</td>
<td>± 1%</td>
</tr>
<tr>
<td></td>
<td>Flow rate</td>
<td>m³/s</td>
<td>± 1%</td>
</tr>
</tbody>
</table>

Table 3. Estimated μ for glycerin 50% and statistical results.

<table>
<thead>
<tr>
<th>Instrument</th>
<th>μ (cP)</th>
<th>R²</th>
<th>n</th>
<th>T (°C)</th>
</tr>
</thead>
<tbody>
<tr>
<td>TT-100</td>
<td>16.3 ± 5.5x10^-5</td>
<td>0.98</td>
<td>1</td>
<td>32</td>
</tr>
<tr>
<td>FANN 35A</td>
<td>15.8 ± 3.2x10^-4</td>
<td>0.99</td>
<td>1</td>
<td>32</td>
</tr>
<tr>
<td>pipe</td>
<td>15.5 ± 5.4x10^-5</td>
<td>0.98</td>
<td>1</td>
<td>32</td>
</tr>
<tr>
<td>TT-100</td>
<td>9.1 ± 5.2x10^-5</td>
<td>0.95</td>
<td>1</td>
<td>50</td>
</tr>
<tr>
<td>FANN 35A</td>
<td>8.6 ± 2.3x10^-4</td>
<td>0.99</td>
<td>1</td>
<td>50</td>
</tr>
<tr>
<td>pipe</td>
<td>8.2 ± 6.2x10^-5</td>
<td>0.94</td>
<td>1</td>
<td>50</td>
</tr>
</tbody>
</table>

Figure 5. Shear stress versus shear rate for dilute 0.25% CMC and its statistical results.
Table 4. Estimated K and n for dilute 0.25% CMC and statistics results.

<table>
<thead>
<tr>
<th>Instrument</th>
<th>K (10^-3)</th>
<th>n</th>
<th>n'avg</th>
<th>R²</th>
<th>T(°C)</th>
</tr>
</thead>
<tbody>
<tr>
<td>TT-100</td>
<td>0.10 ± 0.09</td>
<td>0.75 ± 2.99</td>
<td>0.69</td>
<td>0.99</td>
<td>30</td>
</tr>
<tr>
<td>FANN 35A</td>
<td>0.40 ± 2.70</td>
<td>0.52 ± 1.02</td>
<td>0.56</td>
<td>0.99</td>
<td>30</td>
</tr>
<tr>
<td>pipe</td>
<td>0.43 ± 1.80</td>
<td>0.52 ± 6.32</td>
<td>0.58</td>
<td>0.99</td>
<td>30</td>
</tr>
<tr>
<td>TT-100</td>
<td>0.03 ± 3.35</td>
<td>0.88 ± 1.62</td>
<td>0.78</td>
<td>0.99</td>
<td>50</td>
</tr>
<tr>
<td>FANN 35A</td>
<td>0.24 ± 1.80</td>
<td>0.56 ± 1.15</td>
<td>0.52</td>
<td>0.99</td>
<td>50</td>
</tr>
<tr>
<td>pipe</td>
<td>0.16 ± 1.13</td>
<td>0.60 ± 1.03</td>
<td>0.57</td>
<td>0.98</td>
<td>50</td>
</tr>
</tbody>
</table>
After 750 s$^{-1}$, the curve of TT-100 started to diverge, as was observed previously with low-viscosity range fluids. This was unexpected because the water-based mud is a high-range viscosity fluid. Although the divergence pattern is similar to the ones that occurred in previous experiments, the root of this divergence is distinct. The literature shows that the accuracy of Couette viscometers can be susceptible to fluids with suspended solids—the more homogeneous the fluid the more accurate the measurement.

It is also known that the slippage effect can impact viscometer readings when solids are suspended. The slippage effect reduces measurement precision because the velocity of the wall (spinning outer cylinder) and the velocity of the fluid at the wall are not entirely equal anymore. In summary, it was concluded that, when evaluating fluids with suspended solids, there are at least two concomitant different effects on Couette instruments: homogeneity and slippage.

For TT-100, the sample tended to be more homogeneous than FANN 35A due to the flowing of the drilling fluid inside the measuring chamber. This flow rate, on the other hand, caused the slippage effect to be more pronounced. The $\beta$ ratio (Eq. (4)) for TT-100 is 1.04 and for FANN 1.06. The narrower the gap, the more present the slippage effect, which decreases shear stress, consequently decreasing apparent viscosity. This may explain why FANN 35A
presented the highest values of shear stress and TT-100 the lowest (note that this impacts directly the value of the K parameter). In addition, the slippage effect was more pronounced at a lower shear rate, which explains why TT-100 tends, at high shear rates, to converge its rheological behavior to FANN 35A.

The rheological parameters presented in Table 6 demonstrate that the slope for TT-100 was not steady at a common average point; this may be attributable to the slippage effect.

Table 6. Estimated K and n for water-based drilling fluid and statistical results.

<table>
<thead>
<tr>
<th>Instrument</th>
<th>K</th>
<th>n</th>
<th>n’avg</th>
<th>R²</th>
<th>T (°C)</th>
</tr>
</thead>
<tbody>
<tr>
<td>TT-100</td>
<td>1.85 ± 3.51x10^-2</td>
<td>0.48 ± 2.90x10^-3</td>
<td>0.46</td>
<td>0.99</td>
<td>34</td>
</tr>
<tr>
<td>FANN 35A</td>
<td>4.20 ± 8.91x10^-2</td>
<td>0.37 ± 3.28x10^-3</td>
<td>0.38</td>
<td>0.99</td>
<td>34</td>
</tr>
<tr>
<td>pipe</td>
<td>3.55 ± 0.26</td>
<td>0.38 ± 1.11x10^-2</td>
<td>0.51</td>
<td>0.95</td>
<td>34</td>
</tr>
<tr>
<td>TT-100</td>
<td>1.34 ± 2.88x10^-2</td>
<td>0.50 ± 3.29x10^-3</td>
<td>0.48</td>
<td>0.99</td>
<td>50</td>
</tr>
<tr>
<td>FANN 35A</td>
<td>3.15 ± 0.18</td>
<td>0.39 ± 9.07x10^-3</td>
<td>0.40</td>
<td>0.99</td>
<td>50</td>
</tr>
<tr>
<td>pipe</td>
<td>2.60 ± 0.26</td>
<td>0.40 ± 1.55x10^-2</td>
<td>0.52</td>
<td>0.90</td>
<td>50</td>
</tr>
</tbody>
</table>

The best assumption for n’ = n was found using TT-100 and FANN 35A viscometers. The online linear fit for TT-100 at 50°C presented similar behavior compared to the previous one done at lower temperature.

Statistical analysis of the obtained results

The null hypothesis test is a statistical test which allows inferences over a determined data. Considering this study,
the null hypothesis is: changing devices does not influence the rheological parameters. To test this hypothesis, the STATISTICA software was used as computational tool. The mathematical approach used was the “Kruskal-Wallis ANOVA by Ranks”. Such method does not rely on data distribution parameters (normal distribution for instance), therefore it is adequate for unknown small samples, such as presented here. The results obtained after performing the statistical test can be observed in Table 7.

Table 7. Results obtained from Kruskal-Wallis statistical test.

<table>
<thead>
<tr>
<th>Variable</th>
<th>Coded variable</th>
<th>Significance (p-level)</th>
<th>Result over null hypothesis</th>
</tr>
</thead>
<tbody>
<tr>
<td>Device</td>
<td>TT100 / FANN</td>
<td>0.6907 0.5020</td>
<td>Accept Accept</td>
</tr>
<tr>
<td>Fluid</td>
<td>G/C1/C2/ WBM*</td>
<td>0.002 0.002</td>
<td>Reject Reject</td>
</tr>
</tbody>
</table>

* G – Glycerin, C1 – CMC at 0.25%, C2 – CMC at 1%, WBM – Water Based Mud

A 95% confidence interval was chosen; p-level limit was automatically created at 0.05. In Table 7, it can be seen that this parameter was 0.002 when computing the influence of the fluid over the parameters K and n. This means a probability of 99.998% that the null hypothesis is wrong, or a probability of 0.002% that the null hypothesis is right. Therefore, every p-level below 0.05 should reject the null hypothesis, as the opposite is true. In an overall analysis, considering still Table 7, the nature of the fluid presented statistical influence over the rheological parameters. On the other hand, changing devices did not. In conclusion, it can be inferred that the divergences found in the rheological parameters during the usage of different devices are not statistically relevant.

Investigation of the measured rheology on friction loss determination.

One of the major tasks during the drilling of petroleum wells is to determine the friction loss for pressure control. The rheological parameters influence this calculation directly. Thus to evaluate the impact of the different rheological behaviors obtained on the calculation of friction loss, a case study was conducted. Experimental data of pressure loss were collected for water-based mud and then compared with the calculated ones. The operational condition was at 50°C, in a straight pipe line with 30-cm length, 11.5-mm diameter, made of CPVC, with a flow rate of 0.26 m³/h (laminar regime). To calculate the pressure loss, the following was used,

\[ P_d = f \left( \frac{L}{D} \right) \left( \frac{\nu^2}{2} \right) \left( \frac{\rho}{10^5} \right) \]  

(10)

where

\[ f = \frac{64}{Re_{pl}} \]  

(11)

and

\[ Re_{pl} = \frac{D \nu \rho}{K \left( \frac{8 \nu}{D} \right)^{n-1} \left( \frac{3n + 1}{4n} \right)^n}. \]  

(12)

with \( P_d \) being the calculated pressure drop, \( L \) the length of the pipe, \( D \) the internal diameter, \( \nu \) the average velocity of the fluid, \( \rho \) the specific mass of the fluid, and \( K \) and \( n \) the power law parameters provided by the online and offline instruments. The results are shown in Table 8.

Table 8. Estimated pressure drop in a straight pipe line for a water-based drilling fluid, at 50°C, laminar regime.

<table>
<thead>
<tr>
<th>Instrument</th>
<th>( K )</th>
<th>( n )</th>
<th>( P_d ) (mBar) calculated</th>
<th>( P_d ) (mBar) experimental</th>
<th>Error</th>
</tr>
</thead>
<tbody>
<tr>
<td>TT-100</td>
<td>1.34</td>
<td>0.50</td>
<td>34.39</td>
<td>34.25</td>
<td>0.41%</td>
</tr>
<tr>
<td>FANN 35A</td>
<td>3.15</td>
<td>0.39</td>
<td>41.67</td>
<td>34.25</td>
<td>17.81%</td>
</tr>
<tr>
<td>pipe</td>
<td>2.60</td>
<td>0.40</td>
<td>36.54</td>
<td>34.25</td>
<td>6.27%</td>
</tr>
</tbody>
</table>

It can be seen that the viscometer that provided the smallest error (calculated value – experimental value) was TT-100, even with its deviance after 750 s⁻¹. The pipe viscometer provided a small error, and FANN 35A the highest one, although the steadiest curve. These results reinforce the notion that not always the best fit of rheological data generates the best prediction of pressure loss. In this case, the best prediction of pressure drop was given by the TT-100 rheological measurement.
CONCLUSIONS

Within a fluid loop, this work developed and installed two online viscometers to measure drilling fluid rheological behavior simulating a well-drilling operation. One was a modified Couette viscometer and the other a standard pipe viscometer. For validation, the study compared the performance of both instruments with FANN 35A, which is an offline viscometer that the petroleum industry commonly uses as benchmark.

For a Newtonian fluid, agreement was found in all instruments between data for viscosity, proving that the devices were properly calibrated and installed. For non-Newtonian fluids, there were divergences in the power-law parameters provided by each instrument, both for drilling fluid (with suspended solids) and polymeric solution. Similar results were observed in the previously cited literature. These divergences were investigated and the probable main causes were found to be the following: effects of homogeneity, slipperiness, and interactions in the fluid/gap interfaces. In addition, a case study was carried out that demonstrated that these divergences were not significant if the parameters were used for pressure drop calculations. As an overall conclusion, the methodology proposed can be used to obtain online measurements of drilling fluid rheological behavior as well as online prediction of friction loss. In consequence, this paper contributes significantly to overcome the initial steps toward a fully automated drilling operation.

ACKNOWLEDGEMENTS

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NOMENCLATURE

<table>
<thead>
<tr>
<th>Symbol</th>
<th>Description</th>
<th>Unit (SI)</th>
</tr>
</thead>
<tbody>
<tr>
<td>n</td>
<td>Behavior index</td>
<td>Dimensionless</td>
</tr>
<tr>
<td>n'</td>
<td>Pseudo behavior index</td>
<td>Dimensionless</td>
</tr>
<tr>
<td>P</td>
<td>Pressure</td>
<td>Pa</td>
</tr>
<tr>
<td>z</td>
<td>Orientation index (Cartesian)</td>
<td></td>
</tr>
<tr>
<td>x</td>
<td>Orientation index (Cartesian)</td>
<td></td>
</tr>
<tr>
<td>r</td>
<td>Tube or pipe position on radius</td>
<td>m</td>
</tr>
<tr>
<td>L</td>
<td>Tube or pipe length</td>
<td>m</td>
</tr>
<tr>
<td>v</td>
<td>Velocity of the fluid</td>
<td>m/s</td>
</tr>
<tr>
<td>(\bar{V})</td>
<td>Average velocity of the fluid</td>
<td>m/s</td>
</tr>
<tr>
<td>R</td>
<td>Tube or pipe radius</td>
<td>m</td>
</tr>
<tr>
<td>hd</td>
<td>Friction loss in a straight pipe line</td>
<td>m</td>
</tr>
<tr>
<td>Q</td>
<td>Volumetric flow rate</td>
<td>m³/s</td>
</tr>
<tr>
<td>f</td>
<td>Friction factor</td>
<td>Dimensionless</td>
</tr>
<tr>
<td>H</td>
<td>Height of the inner cylinder</td>
<td>m</td>
</tr>
<tr>
<td>D</td>
<td>Tube or pipe diameter</td>
<td>m</td>
</tr>
<tr>
<td>g</td>
<td>Gravity</td>
<td>m²/s</td>
</tr>
<tr>
<td>RePL</td>
<td>Reynolds for Power Law fluids</td>
<td></td>
</tr>
<tr>
<td>wi</td>
<td>(i^{th}) element of the array or matrix weight</td>
<td>Dimensionless</td>
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<td>(\hat{y}_i)</td>
<td>(i^{th}) element of the array or matrix of best fit</td>
<td>According to data</td>
</tr>
<tr>
<td>yi</td>
<td>(i^{th}) element of the array or matrix of observed values</td>
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<td>N</td>
<td>Size of the array or matrix</td>
<td>Dimensionless</td>
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