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DEVELOPMENT OF ON-LINE SENSORS FOR AUTOMATED MEASUREMENT OF DRILLING FLUID PROPERTIES

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Abstract

The high costs associated with drilling operations, especially in offshore environments, make it necessary to optimize each step of the job. The drilling mud plays a critical role in the drilling operation, as it is responsible for several functions (solids transport, wellbore mechanical stability, signal sensor transmission, etc.). Besides that, the attention given to the control of drilling mud properties has not changed much from the last 50 years. Downhole and surface online measurements for several drilling parameters are available for anticipated diagnostics of operational problems. Drilling automation is already a reality (automated pipe handling, controlled tripping operations, etc.), but the drilling mud properties continues to be measured manually. The drilling mud sample has to be collected, transported, treated and analyzed to only then the measured property is reported.
This work aims to present the development and result of experiments performed at a large scale drilling fluid loop, aiming the evaluation of commercial and built in property sensors. The following properties were determined: rheological parameters, mud weight, water-oil content, emulsion electrical stability (for oil based muds), fluid conductivity (for water based muds) and particle size distribution.
The use of neural networks (Multi-Layer Perceptron type) allows the connection of the on-line equipment results to increase the reliability of mud properties determination. Comparisons with the results obtained from laboratory equipment were performed to train the neural networks as well validate the developed techniques.

Introduction

Automation in drilling operations is being pushed by several segments of industry. Real time downhole sensors are available in most offshore operations enabling the use of real time diagnostic systems to anticipate operational problems.
Drilling fluids data collection, however, did not change in the past decades. Information depends on manual testing, usually performed by a technician a few times a day. This methodology certainly does not help to capture the effects of an expected problem in the fluid properties till a new analysis is provided. Additionally, this procedure does not include the proper characterization of temperature and pressure effects on mud properties. (Gandelman *et al*., 2013)
Some efforts to enable online drilling fluid properties measurements are listed in the literature, as follows.

Saasen *et al.*, 2008, detail an experimental work carried on an automated drilling flow loop in which many on line data were obtained. Some of the sensors were developed or customized by the authors while others were acquired through vendors. The authors showed to be able to measure rheology, electrical stability, fluid loss, density, hydrogen sulfide concentration, pH and particles content and size distribution. The authors conclude that simple viscometers based on vibration pins or ultrasound attenuation would not be able to measure properly the viscosity at the desired shear rate range. In order to achieve this goal, the authors propose a Couette viscometer built by Brookfield Incorporation. This device was customized to allow full automation and control. Electrical stability required a dedicated development. Density measurements were performed by Coriolis devices. An off line device to determine the suspended solids concentration, using x-ray technique, and compared the results with the API methodology, obtained by the retort kit device. This was the main starting point for the development of the present work.

Broussard *et al.*, 2010, presented a field study of the recent scenario on automation of drilling fluid properties. It was discussed and presented field data focusing on the strengths and limitations of the instruments. Their work also contributed with an insight of the reality of the integration of those instruments to the routine of a drilling rig. The authors pointed out the actual capabilities of the drilling service companies on actually delivering this real time data. The authors prepared a sensor package where density and viscosity were measured in real time, using an oscillating u-tube technology and a Couette viscometer, respectively. They also compared the data obtained in real time with the compatible one obtained off line, on the standard instrumentation. Both measurements agree to a certain level of tolerance. The authors conclude that many efforts are still to be undertaken in order to turn this technology completely viable in the oil field, however.

Miller *et al.,* 2011, presented real time data of density of viscosity acquired during the drilling of a well. The authors pointed that on line data is an improvement on the drilling monitor process, and instrument package is an advantage when the technology is operated and maintained by the oil rig service crew and not by dedicated engineers.

In real rig conditions, in many cases, it is possible to use automation sensors and tools to predict costly problems. Usually those problems are preceded by symptoms which can be accurately measured and qualified. Quoting Van Oort *et al.,* 2011:
"Costly drilling problems do not occur without warning. They manifest themselves over time through recognizable symptoms and patterns. Recent testing of an automated cased-based reasoning (CBR) system to predict twist-off and stuck-pipe events has shown that these precursors can be accurately identified far in advance of the problem."

Following the track of the previous references, and learning from them, the present work shows results of different online measurement strategies for mud properties, such as density, electrical stability, electrical conductivity, rheology and the concentration of total solids suspended. The experimental work was carried on a dedicated flow loop which enabled to install, test and modify commercial sensors, and also to evaluate dedicated customized ones.

Rheology measurements were obtained by a modified Brookfield process viscometer. Density was determined by a Coriolis device commercialized by Metroval. Electrical conductivity measurements were provided by Stratos Pro 4, while a prototype was developed for electrical stability. Total solids concentration was measured by an acoustic sensor provided by Rhosonics.

Methodology

Automated flow loop plant

A dedicated flow loop was set to test the sensors acquired or designed. The design of the plant allowed producing drilling fluids under constant real time monitoring. This configuration permitted to evaluate the sensors under a wide range of different operational conditions, providing more opportunities to conclude about their performance.

This unit is composed by several pipe lines, two pumps, three tanks, proper instrumentation and a supervisory system. The unit is capable of mixing water and oil based fluids in volumes up to 500 liters. As basic features, the unit controls and monitors temperature, pressure and volumetric flow rates.

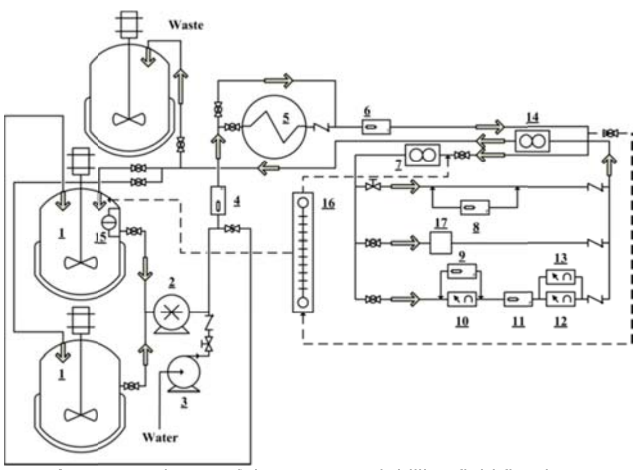

Figure 1. Scheme of the automated drilling fluid flow loop.

The legend of Figure 1 is presented in Table 1.

Table 1. Description of the equipment present in the dedicated flow loop.

Number	Device
1	Stirring Tank
2	Positive displacement pump
3	Centrifugal pump
4, 11	Pressure transducer
5	Heat Exchanger
6	Main temperature meter
7	Volumetric flow meter
8, 9	Differential pressure meter
10	Process viscometer
12	Electrical conductivity meter
13	Electrical stability meter
14	Density meter
15	Level meter
16	Fracture simulator prototype

Rheology

The original process viscometer from Brookfield is Couette type equipment, designed to operate at six different shear rates, previously calculated to be the same ones existent in FANN 35A viscometer. The original gear box only allows manual change of speed; therefore to control remotely the shear rate and having it as a variable in the supervisory, it was necessary to customize the device by changing its original engine. Figure 2 presents the scheme of the original viscometer.

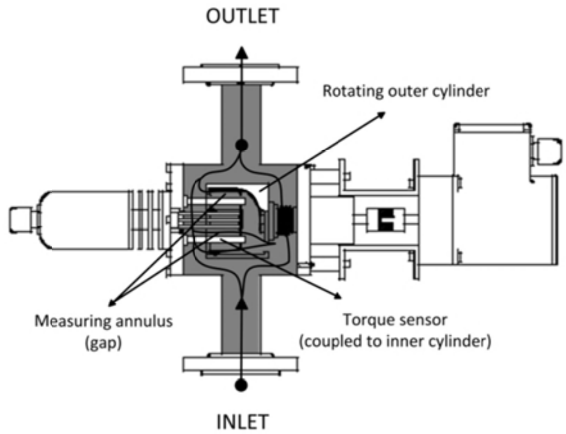

Figure 2. Process viscometer model TT-100 in its original state.

The fluid from process occupies the measurement chamber driven by pressure forces. At any moment, as desired by the user, the outer cylinder is driven to spin, causing the deflection of the inner cylinder due to drag forces. The system allows axial flow, and consequently, fluid renewal inside the gap. The torque applied in the inner cylinder is transformed into an electrical signal, which is interpreted as shear stress by the supervisory system (Brookfield instruction manual, 1993).

With the customized engine, the automation system gains control over the motor speed. The feedback on this speed is an electrical signal which is interpreted as shear rate. Therefore, it is possible to evaluate shear stresses over a wide range of shear rates. As a consequence, it is possible to determine the fluid rheological parameters in real time.

This set up also allows the user to program the viscometer to operate under a desired schedule. It is possible, for example, to program the viscometer to verify if the fluid gelation properties.

The operational condition limits of the device are 1 to 15 bar (14.7 to 220.5 psi) of total pressure, temperature up to 160^{0}C (256°F) and volumetric flow rate between 1 and 3 m^3/h (4.4 to 13.2 US gpm). The major limitation of the viscometer is the size of the solids suspended. The solids must present maximum diameter of 1mm.

Density

Based on Coriolis forces, the density meter from Metroval measures not only density but also mass flow rate. With these two measurements it is possible to determine the volumetric flow rate of the line, even if the fluid is non-Newtonian. Inside the device there is an omega tube, which is coupled to several coils. Depending on the vibrational state of this tube, an electrical signal is generated by the coils, which is interpreted into density and mass flow rate. The limitation of the equipment is also the size of particles, 1mm of diameter at maximum, and the flow must be free of gas or air bubbles. Other manufacturers provide similar devices.

Electrical Conductivity and Stability of Emulsions

A dedicated sensor was designed and built to determine the electrical stability of an emulsion following the same technical designs from the off line standard device (Fann 25D). The electrical stability indicates, qualitatively, the nonpolar level of the fluid, and quantitatively, the voltage required to transpose an electrical current of 61 micro amps between probes. Technically, the higher the voltage is the higher is the non-polarity of the fluid. (Fann instruction manual, 2009).

The prototype mechanism is the following: a specific signal is generated by the supervisory; this signal is sent to be amplified. The amplified signal is sent to the immersed probe in the flow line, and as the voltage and current arises, the prototype informs back to the supervisory, by analogical signal, the values of each one in real time.

The prototype constructed is flexible to modulate and change various aspects of the signal, such as form, frequency, amplitude, rate of voltage increase etc. This allows the user to explore the effects of the different types of electrical signals on the final value of voltage.

A process electrical conductivity meter was installed in parallel to provide more information about the emulsion state of the fluid. If there is only one phase (oil), the sensor should read zero. Tests incorporating water into the oil based fluid showed that when the emulsion is broken the conductivity meter exits zero and exponentially arises.

Suspended solids concentration

Many techniques have been studied over the years to determine such variable. The most relevant are based on x-ray and acoustic (Motz *et al.,* 1998 and Saasen *et al.,* 2008). An acoustic device that is capable of determining the ultrasound attenuation and sound speed existent between two parallel probes was installed in the system. These probes are designed to allow the measurements when flow occurs between them. It is possible to correlate the sound properties with the quantity of solids suspended if all other properties of the solid and fluid are known (Koltzova *et al.,* 2001).
The ultrasound attenuation depends on many aspects of the system, mainly the amount of solids suspended, the fluid viscosity and on air or foam dispersed on the liquid phase. Because of that, the first requirement to use this technique is that the liquid phase must be absent of foam or air. Usually this type of measurement is widely employed when the fluid is Newtonian, where the viscosity does not change over shear rate (McClements, 2006).

Thus, some improvement in the instrument must be done to have accurate measurements of solids suspended. On top of that, many others additives are used in drilling mud which were not predicted by the factory calibration.

Results and Discussion

Rheology

A Newtonian fluid was initially tested to verify the calibration of the process viscometer (TT-100). Figure 3 presents the comparison of rheology results between TT-100 and Fann 35A viscometer for glycerin, at 32^0C. Similarly, a CMC solution was selected to verify the equipment behavior with a non-Newtonian system.

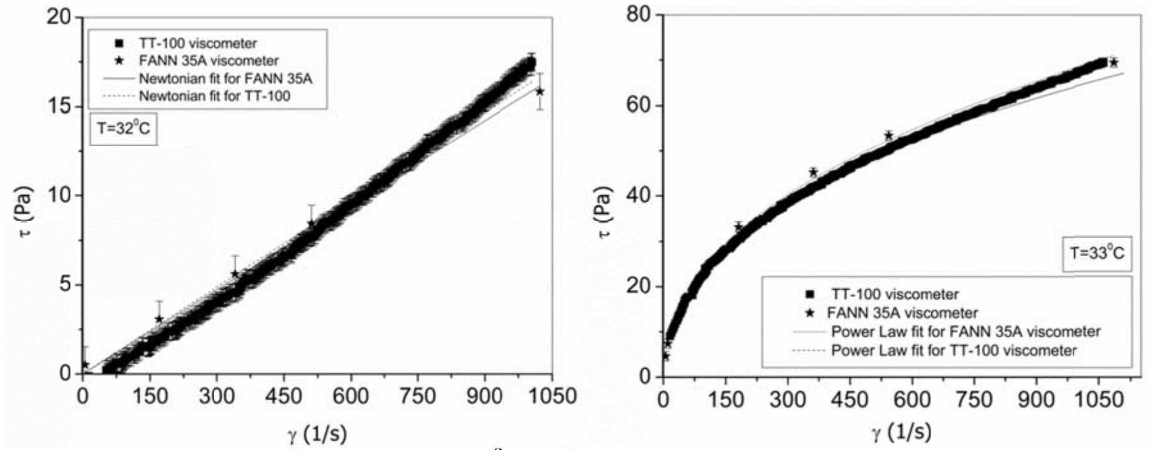

Figure 3. Rheological profile of glycerin, at 32°C, to the left, and CMC rheological profile, at 33°C, to the right.

It is observed in Figure 3, in the left graph, that both instruments provided a linear relation between shear rate and shear stress, classifying the glycerin is a Newtonian fluid, as expected. The vertical bars are the experimental uncertainties based on the accuracy of each sensor. In the right graph, it can be observed a nonlinear relation between shear rate and shear stress. The characteristics of this curve classify the CMC solution as a pseudo plastic fluid, as expected (Morrison, 2001). Both measurements agree statically for the two fluids, as stated by the curve fitting proposed by Table 2 and Table 3 (Newtonian model for glycerin and power law model for CMC solution).

Table 2. Curve fitting for glycerin, at 32°C.

Device	μ (cP)	R2
TT-100	$16.3 \pm 5.5.10^{-5}$	0.98
FANN 35A	$15.8 \pm 3.2.10^{-4}$	0.99

Table 3. Curve fitting for CMC solution, at 33°C.

Device	*K*	*n*	R^2
TT-100	$2.72 \pm 9.97.10^{-3}$	$0.46 \pm 5.63.10^{-4}$	0.99
FANN 35A	3.24 ± 0.52	$0.44 \pm 2.46.10^{-2}$	0.99

The possible main cause of the divergences observed may be the size of the gap of each instrument. The larger the gap is the larger is the error due to numerical approximation during the calculus of shear rate for non-Newtonian fluids (Billon, 1996).

Figure 4, to the left, presents the rheological profile obtained with water based drilling fluid, and to the right is shown the rheological of a non-aqueous drilling fluid, respectively. The first was prepared in the lab while the second was provided by a fluid company. Table 4 and Table 5 display the curve fitting results for both muds.

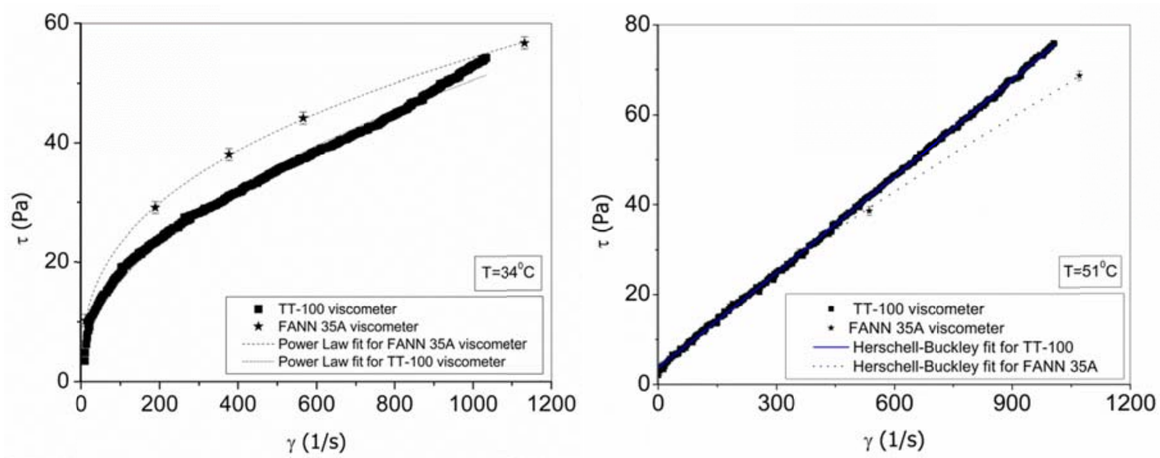

Figure 4. To the left is the rheological profile of a water based mud, at 34°C, to the right is the rheological profile of a non-aqueous drilling fluid, at 51°C.

Table 4. Curve fitting for water based mud, at 34°C.

Device	*K*	*n*	R^2
TT-100	$1.85 \pm 3.51.10^{-2}$	$0.48 \pm 2.90.10^{-3}$	0.99
FANN 35A	$4.20 \pm 8.91.10^{-2}$	$0.37 \pm 3.28.10^{-3}$	0.99

Table 5. Curve fitting for non-aqueous drilling fluid, at 51°C.

Device	*K*	*n*	R^2
TT-100	$0.07 \pm 1.16.10^{-3}$	$1.00 \pm 2.44.10^{-3}$	0.99
FANN 35A	0.17 ± 0.02	0.85 ± 0.02	0.99

Some divergence was found in both cases. For the water based mud, the probable causes for this divergence may be pointed as the gap size effect associated with the slippery effect. This last one is present when solids are suspended inside the gap. Slippery cause errors during measurements since the velocity of the fluid at the wall of the inner cylinder may fluctuate, especially with fluids which present lower lubricity, as water based (Barnes, 2000). During the measurement of the synthetic based fluid, it can be seen that after 500 s^{-1} the curve started to deviate from the off line one. Because the oil based fluid has higher lubricity when compared to water based fluids, the behavior during measurement found in the right graph of Figure 4 is the opposite found in the left graph of the same Figure. In the left TT-100 tends to underestimate the shear stress, when compared to FANN measurements, and in the right one, it overestimates.
A comparison between gelation properties obtained by both methods is not direct since the spring constant for both elements differ in 930 times and, consequently, the sensibility for the analysis is different.

Density

A comparison between the density values obtained with the online Coriolis densimeter and the conventional mud balance was performed for both water based and synthetic muds. The water based mud test included a weighting phase (by adding barite to the system) and heating, as demonstrated in the left graph on Figure 5, followed by a dilution procedure, as demonstrated in the right graph of the same Figure.

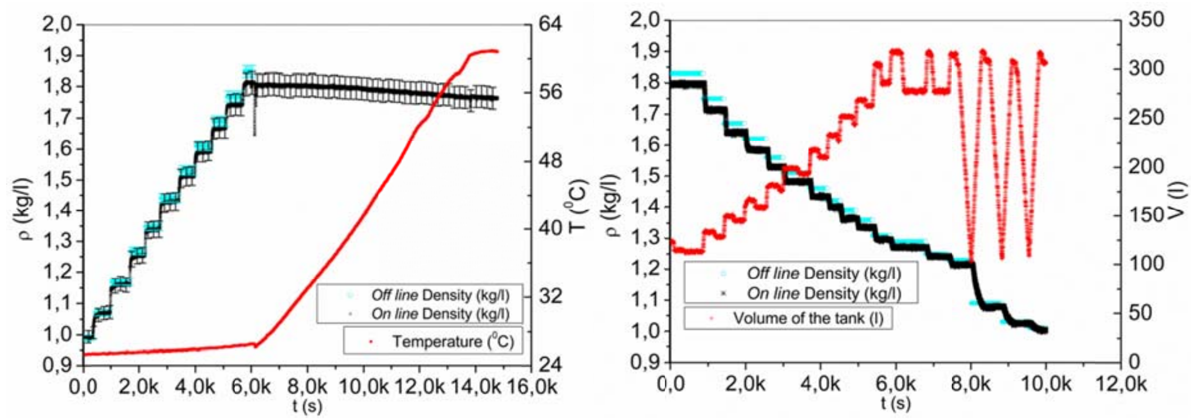

Figure 5. Densification and heating of water based mud, to the left, and dilution test to the right.

In Figure 5 each step upwards means that barite was added to the tank. The discontinued horizontal points, in blue are the off line measurements, while the high frequency ones the on line measurements. The other high frequency data (in red) is the temperature of the test. Since the off line instrument does not provide temperature control, this measurement was only performed in the on line device. The vertical bars are the experimental error (if off line) or the device accurateness (if on line). Results indicate that the results obtained by the on line device statistically agree with the conventional methods. The online device was able to capture density increase due to barite addition and density decrease due to heating and dilution.
Figure 6 shows a similar comparison for a synthetic base system. It was not possible to evaluate the density meter at the same range used in the previous test due to safety issues (pump pressure limitations). Results also show agreement between the results obtained from both equipment.

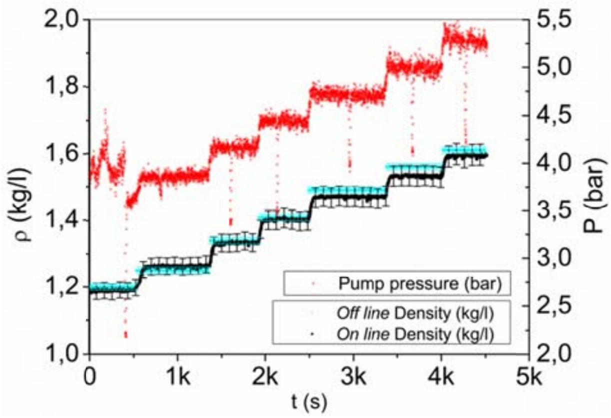

Figure 6. Densification and pressure buildup of synthetic based mud.

Emulsion stability

Drilling with inverse emulsions is frequently convenient and their stability is a requirement to maintain designed properties, especially rheology (Pal, 1993, Fingas and Fieldhouse, 2003). Batch tests were performed to compare the FANN 23D data with the ones performed by the developed prototype. Three different emulsion samples with different oil/water ratios were tested: 50/50 (Figure 7), 40/60 (Figure 8) and 30/70 (Figure 9).
In the figures, the voltage and amperage are shown in the left and right vertical axis, respectively. As the voltage increases the current maintains its value at low levels until it rapidly increases exponentially. At this point, the electrical barrier provided by the oil phase is broken and the polar part of the system, in this case water, is exposed. The current generated is directly proportional to the voltage applied and inversely proportional to the electrical resistance. Each fluid has its own voltage reference, which is the voltage peak when the current reaches 61 µA (Fann instruction manual, 2009).

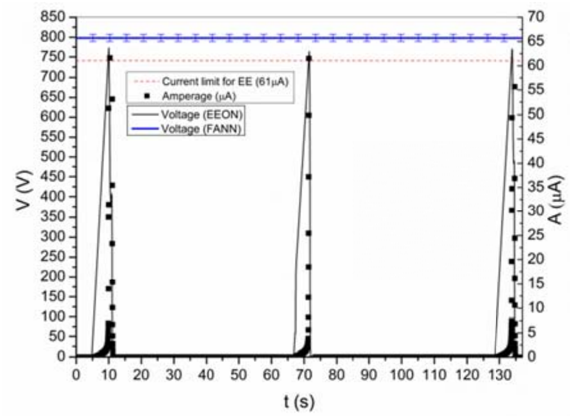

Figure 7. Electrical stability test, sample 50/50.

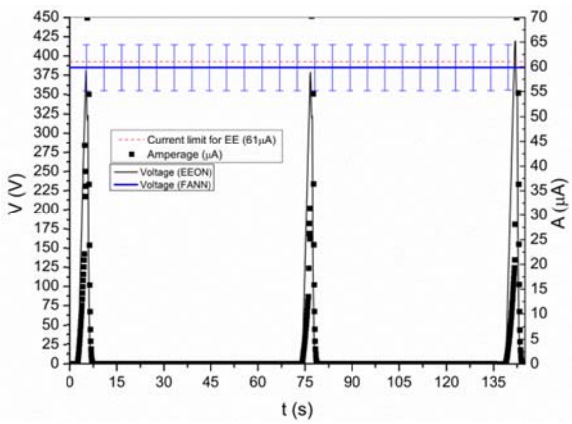

Figure 8. Electrical stability test, sample 40/60.

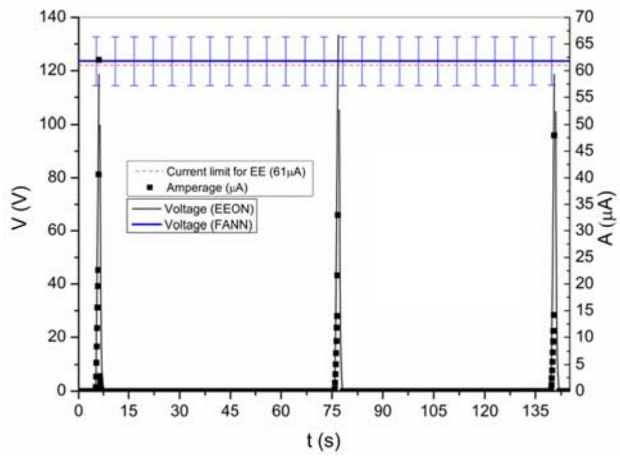

Figure 9. Electrical stability test, sample 30/70.

The on line voltage (EEON – Electrical Stability online) is represented by the continuous line while the conventional data (FANN) are represented by the continuous blue horizontal one. The points are the on line electrical current which was monitored synchronously to the voltage measurements. The red dots at 61 µA mark the current limit of the test, as specified by API.

In Figure 7, the off line measurement of electrical stability was around 800V. This value is in fact the average value of several replicates, and the standard deviation is shown by the vertical bars on top of the line. It can be observed that the on line data are slightly lower than the conventional measurement (775V).

As the ratio of water increases, the electrical stability decreases, as expected. Such statement can be confirmed observing Figure 8 and Figure 9. In both cases the voltage peaks for both instruments are statistically the same.

An additional experiment was done in the dedicated flow loop where synthetic based oil was submitted to pumping. Water invasion and oil addiction was performed to simulate drilling common routines. The state of the emulsion and the rheology were monitored only on line. Due to an intentional excess of water invasion, the fluid suffered an emulsion breakage and results were observed. The following Figures detail the test conditions.

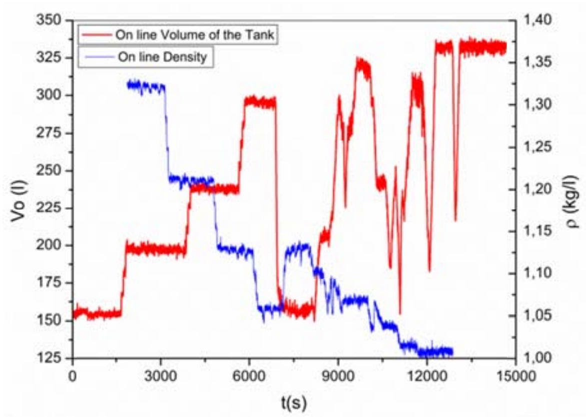

Figure 10. Tank volume and density.

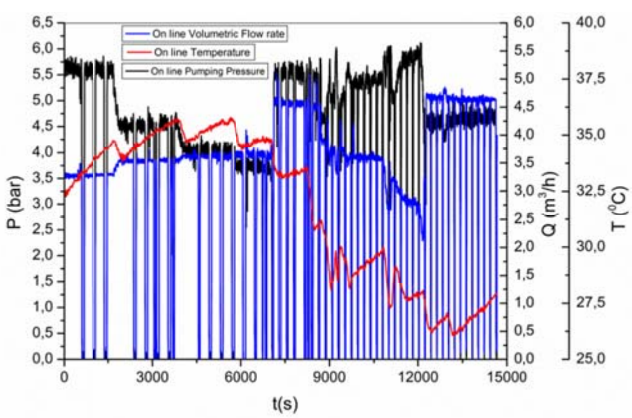

Figure 11. Flow rate, pressure and temperature.

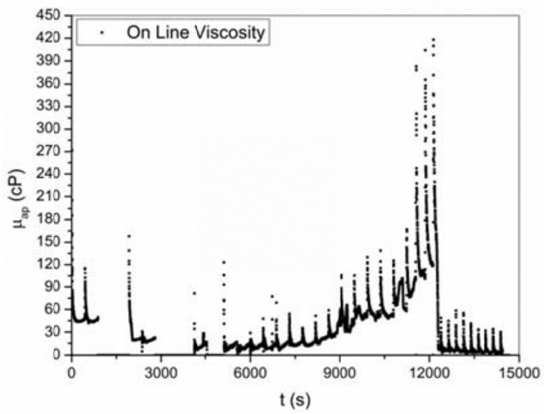

Figure 12. Apparent viscosity.

Test procedure started with addition of pure oil to the mud system, which immediately caused an increase in the tank volume and decrease in the density of the fluid (Figure 10). Every time the tank capacity was reached (~325 liters); purges were done to allow the continuation of the test. After the first purge, proximately at 7500 seconds of test, water was added, until the tank is full again. This step was repeated until the emulsion was broken. Figure 11 shows the pressure, flow rate and temperature of the whole system. The constant drop to zero on pressure and flow rate is because the electrical stability test must be performed at a static condition (as API describes). Therefore every time a test was performed; previously the pump was automatic turned off. Relative velocity between the probe and sample may interfere in the results (Saasen, 2009).

Still in Figure 11, it can be seen that flow rate was kept at a minimum level in order to maintain a renewal of the fluid inside the electrical stability and conductivity measuring chamber, when the test was not active.

When oil was being added, the apparent viscosity decreased, as can be observed in Figure 12. When water was being added, there was a significant increase on the apparent viscosity, causing the pressure to rise. This behavior is expected and it was described in more details by Russel *et. al.,* 1989, *apud* Sanfeld and Steinchein, 2008. At the end of the test, when the emulsion was broken, there was an abrupt decrease on the apparent viscosity, which caused a decrease on pressure. This is also expected because at this point there was no emulsion anymore, the system became a two-phase (oil and water) flow and the typical viscosities of both phases are lower than the viscosity of the previously state.

In the same Figure the temperature profile indicates that every time a perturbation occurred the system was cooled. The heating process was caused by natural friction, no heater was used.

Figure 13 shows the general electrical monitoring of the emulsion state during the described test.

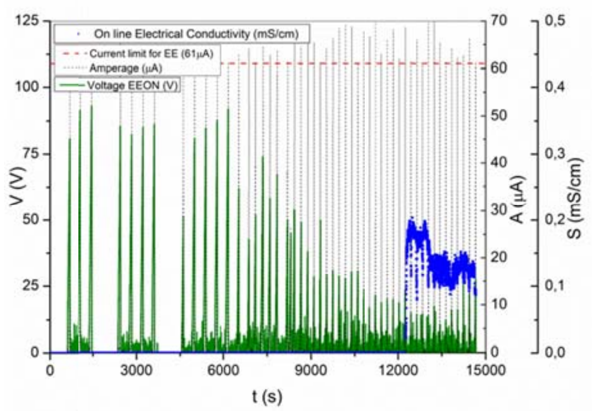

Figure 13. General electrical behavior of the system.

The olive lines are the voltage picks as the black ones are the current picks. The blue dots are the on line data of electrical conductivity.

According to Figure 10, oil was added until approximately 6000s. Observing Figure 13, it is possible to conclude that oil alone does not change the electrical stability of the system significantly, but the addition of water after that immediately starts to decrease the voltage picks. As water entered the system, the voltage picks kept decreasing. It was observed in all Figures that proximately at 12000s the system changed its state drastically due to the breakage of the emulsion; this is confirmed by looking at the same moment in Figure 13. Not only the voltage picks are less than 25V but the electrical conductivity deviates from 0. When the emulsion was stable, the conductivity meter marked 0.

Therefore, the electrical stability meter is a tool that can indicates the state of the emulsion while there is one phase only, and the conductivity meter can be used as an auxiliary tool that detects the breakage of it (phase separation).

Solids concentration

Ultrasonic attenuation and sound speed depend not only on the quantity of the solids suspended, but also on the quantity of solids dissolved, like salts and mainly on rheology. Therefore, to determine the total solids suspended it was acquired not only the ultrasound attenuation and sound speed, but also apparent viscosity at 1021 s^{-1} and density. These auxiliary measurements help the software made to discern when an increase of attenuation is due to the increase of viscosity or solids. In example, if an increase on attenuation is due to the entrance of solids into the system the density should also increase, and some increase may be observed on viscosity. On other hand, if an increase on the attenuation is observed due to the addition of polymers, the density may change slightly or not even change but viscosity will significantly increase. The sound speed is also important since it helps the system to discern when the density is rising due to solids suspended or solids dissolved.

Dedicated software takes care of data processing and provides suspended solids concentration. The mathematical methodology to relate those variables was based on an artificial neural network, trained from the cumulated experimental results over the past few years.

During the network training, concentration of the suspended solids was the target variable, and density, viscosity, ultrasound attenuation and sound speed were the independent variables. The next Figures demonstrate some of the typical results which composed the network training data.

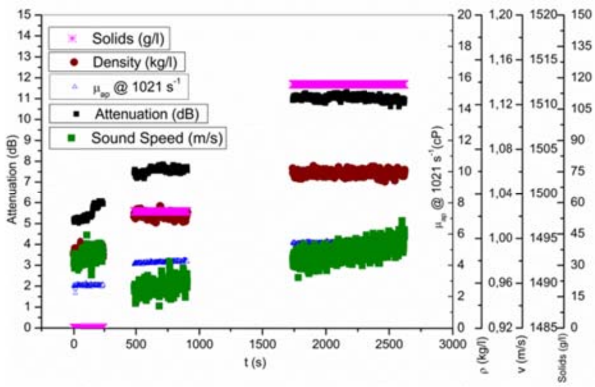

Figure 14. Typical system behavior during preparation of a water based mud type 1.

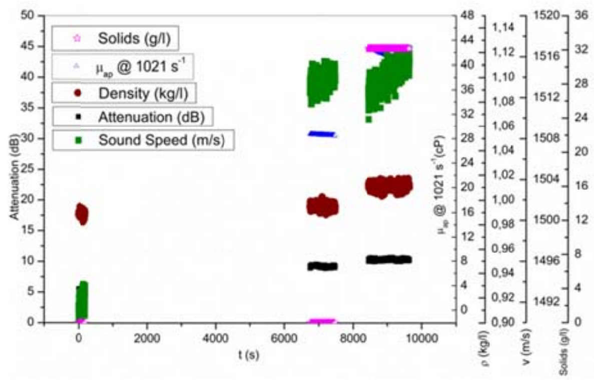

Figure 15. Typical system behavior during preparation of a water based mud type 2.

Figure 14 illustrates the process of preparation of a water based system, starting from industrial water. Initial configurations of the other variables were: viscosity 2 cP at 1021 s^{-1}, density 1.00 kg/l, sound speed 1495 m/s, attenuation at 5.5 dB and concentration of solids is zero g/l. When the first kind of solid was added to the system, the concentration raised to proximately 60 g/l (off line measurement), the attenuation raised to 8 dB, the apparent viscosity raised to 5.5 cP, density was up to 1.02 kg/l and sound speed decreased to 1490 m/s. When we added the second kind of solid the system changes again.

In this manner, the software started to "learn" how the system behaves according to each addiction or perturbation implemented. The empty spaces between the measurements are the transient stages, and do not matter to the network training since the experimental concentration of solids in this period is unknown.

Figure 15 illustrates the fabrication of a second type of water drilling fluid, now starting with water and a small quantity of polymer. Due to the very small quantities applied (less than 1%); density practically did not change; only viscosity did. Therefore the concentration of solids was zero in the beginning and during the polymer dissolution. The attenuation increased from 5 to 10 dB. Since the polymer goes to the dissolved phase, the sound speed also changes significantly. After 7000s weighting material were added to the tank and the system reacted accordingly.

Another typical result is demonstrated in Figure 16. In this test we stared the system with the water based mud type 2 and added solids to it continuously. This test simulated a geological solid invasion.

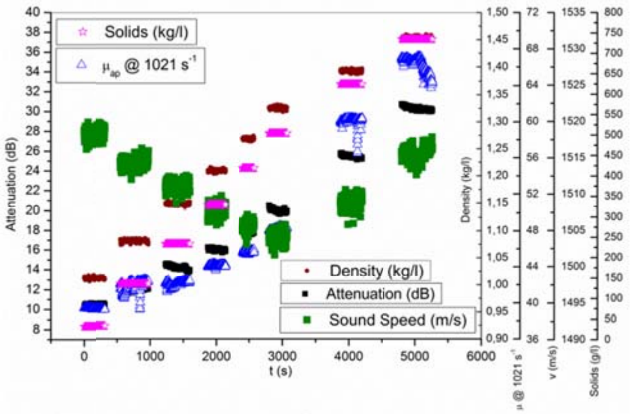

Figure 16. Solids incorporation in water based mud type 2.

Mud 2 was designed as a low solids system and after a certain time several different types of insoluble solids were incorporated.

Immediately after the addiction of the first type of solid, all properties increased except for the sound speed, the addiction of this solid was repeated couple of times. Following, a heavy solid (type 2) was added into the system, increasing significantly the density and slightly the viscosity. At this point the sound speed kept decreasing as attenuation and concentration increased. After several additions of this heavy solid, an incorporation of carbonate solids was simulated, this started at 3000s. The system kept the same tendency except for the sound speed, which started to increase instead of decreasing. This change on the sound speed velocity proves that some of the carbonate salts are being diluted into the fluid.

All those results in addition with much more data were used to train the neural network. Figure 17 illustrates the general performance of the prediction capacity of the architecture made.

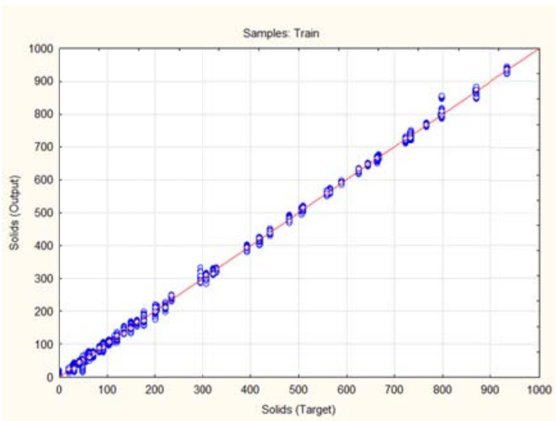

Figure 17. Concentration of solids suspended predicted by the artificial neural network (Output) against experimental one (Target).

The points presented in Figure 17 are 20% of the total input data. In other words, 80% was used during training and 20% were used for validation. Validation points are not used during training and their performance indicates the predictive capacity of the network. To accomplish such performance we used MLP architecture, 50 neurons, exponential function in the inner layer and identity function in the outer layer.

Final remarks

Pilot scale evaluation of on line rheology, density, electrical stability and conductivity and solids concentration of drilling fluids showed reasonable agreement with conventional measurements.

Based on it, online sensors seem to be adequate for field use, supporting automatic problem detection projects and, in the future, drilling automation. Next steps include the evaluation of additional sensors and a field test.

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