AADE-20-FTCE-111

Field Operations Results and Experience with Inline Drilling Fluid Property Measurement

S. Zafar Kamal Ph.D., Richard Frazier, Doanh B. Ho, Lauren Miller, OFI Testing Equipment, Inc.;
Paul Scott ConocoPhillips E&P Co.;
Pradipto K. Bhattacharya Ph.D., Rheology Solutions

Abstract

Drilling fluids are key to ensuring safe drilling operations and the quality of wells during construction and completion. As such, drilling fluid properties are critical control parameters of the drilling and completions process. Moreover, digital advances in drilling, e.g., remote operations centers, automation, real-time hydraulics, and optimization, depend on frequent measurement of physical and compositional properties of drilling fluids. Traditionally, these properties have been measured by manual field sampling and testing. These manual measurements lag recent advances in drilling efficiencies. Manual testing results in delayed “measurement to response time”, is susceptible to bias, inconsistencies, and inadvertent human errors.

In this paper, we share our recent experience in capturing key drilling fluid properties; mud weight, apparent viscosity, rheology profile, and emulsion stability without human intervention. We believe that this is a unique and possibly first of its kind endeavor where a combination of in-situ and ex-situ measurements of drilling fluid rheology have been made in the field. With this effort we have continuously collected data at a frequency relevant to critical operations and needs for predictive modeling. Our results are based on a live pilot, at multiple, multi-well pads, unconventional drilling operations in the United States. This system is physically integrated with the mud system, and electronically integrated with the rig data acquisition system. Data is made available to rig operations and to remote location(s) for surveillance, reporting and modeling. We will share our experience in validating data quality, establishing frequency of data collection as relevant to different measurements, and integration with modeling and predictive systems. We will conclude with lessons learned, future scalability and an open systems concept in support of operators, oil field services, OEMs and other entities in the drilling fluid ecosystem.

Introduction

We illustrate continuous measurement of drilling fluid (mud) properties by utilizing available and proven technology – deployed as an open and scalable solution. This is done through a real-world implementation of a continuous monitoring system on an active land drilling rig deployed on multiple multi-well pads, over a six-month period. We start by describing the deployed system, sharing data and results, providing a discussion of inline and near line measurement of the rheological profile. This paper is concluded by sharing lessons learned and thoughts on future developments.

Drilling mud has several key roles during the drilling and completion of oil and gas wells, e.g., circulate cuttings from the well as drilling progresses, maintain wellbore control/stability, and provide information about the formation. The integrity of the wellbore, as it is drilled, stabilized and completed is highly dependent on the management of mud flow and its properties. Flow is maintained via velocity and pressure with pumps and flow control equipment. While drilling mud properties change over time and are dependent on the formulation of the mud, physical and chemical interaction of the mud with the formation, pressure, temperature, flow rate, bit speed, weight on bit, suspended and carried solids, etc.

Mud properties must be monitored as drilling progresses to target depth and adapted as required by the drilling program as well as the changing wellbore characteristics. In addition to being critical to the safety and efficiency of the operation, mud properties provide information about the formation. With this knowledge, problems can be anticipated, and changes are made to the drilling program, such as, drill speed and weight on bit. With better and more frequent understanding of mud properties, the following benefits may be realized:

- **Safety** – Improve reaction time, accuracy in well control and maintaining well integrity
- **NPT** (nonproductive time) - Reduction in lost time with better awareness
- **Cost Reduction** – Less use of materials, mud engineer time and other services
- **Reduce time to target** – Maintain optimal ROP (rate of penetration)

Prominent examples of applications for real-time and inline drilling fluid property measurements are; real-time hydraulics to monitor hole cleaning and ECDs (equivalent circulating density) to reduce NPT, MPD (managed pressure drilling) hydraulics to determine backpressure, detection of fluid problems (contamination, barite sag, kicks/water flows), reduce manual processes & workloads, optimize drilling fluid treatments, and data feed into drilling automation.

Improvements to the physical process of drilling, e.g., repeatable operations and high functioning rigs, are resulting in faster ROP (rate of penetration) and shorter time to TD (total depth) while going to greater depths and longer laterals. This speed has made traditional means of measuring drilling fluid properties less meaningful.

The capability described in this paper is applicable to all types of drilling fluids and rig types. It is also applicable to fluids used for fracking, completion and EOR (enhanced oil recovery). In this paper we focus on continuous measurement of Non-Aqueous Fluid (NAF) properties while drilling. NAFs are typically more expensive than water-based muds, they are reused and recycled via reconditioning to the extent possible. Our focus is on measuring mud properties while drilling so that this information can be used to monitor fluid properties and observe changes in density, rheology, and emulsion stability. For this pilot the objective was to feed this data into the rig data information system where it would be used for simple real time calculations for predicting hole cleaning efficiency and ECD at total depth (TD) and at a problematic weak sandstone that is prone to lost circulation. This data is then available to be viewed through the rig data information system by the Driller and other personnel at the wellsite as well as remotely via the internet or smart phone apps.

Drilling muds contain several components which are designed to carry out key functions during drilling; weighting agents, emulsifiers and wetting agents, viscosifiers, filtration control additives, and an internal brine phase. Furthermore, drilling fluid rheology measurements are key inputs to hydraulic models utilized to predict ECD, annulus pressure(s), hole cleaning efficiency, and other parameters critical to maintaining a safe and stable wellbore, while optimizing drilling operations. It is therefore critical that the mud properties are measured in a timely and accurate manner to ensure operational integrity while changes or exceptions are identified quickly leading to corrective actions and optimal performance.

Drilling mud density and viscosity have traditionally been measured via manually collecting a mud sample and measurements with a mud balance and Marsh Funnel at the mud pits. Typically, mud samples are taken to the rig-site mud laboratory to measure detailed physical and chemical properties, e.g., with a direct indicating rotational viscometer, filtration cell, electrical stability meter, retort and chemical titrations. Taking a sample to the rig-site laboratory presents several potential issues, for instance, the latency in sampling to measurement, representativeness of the sample, and the speed and frequency in which these measurements can be made. Typically, the drilling fluid is only tested in this manner twice a day.

From a latency perspective, recent improvements to the drilling process have resulted in significant reduction of drilling time, e.g., higher rates of penetration (ROP) are enabling reaching total depth (TD) in seven to ten days on a >17,000 feet wellbore with >10,000 feet of lateral section. These rates of drilling have far surpassed traditional measurement capability, e.g., in the time a sample is drawn, taken to the lab and measurements reported the bit may have drilled hundreds of feet from when the sample was drawn. The need for continuous and for frequent measurements is critical.

OFITE Automated Solutions (OAS)

The OAS system was placed in a safe area, just outside the designated Zone 1, adjacent to the mud pits. The drilling mud samples are drawn into the system on a continuous real-time basis downstream from the shakers. For hole cleaning and ECD calculations it is the rheology of the fluid in the annulus that is important. This contrasts with the suction pit data that is most frequently reported by the mud engineer, after the mud has been diluted and conditioned. OAS consists of sampling and instrumentation subsystems as outlined in Figure 1 and described below.

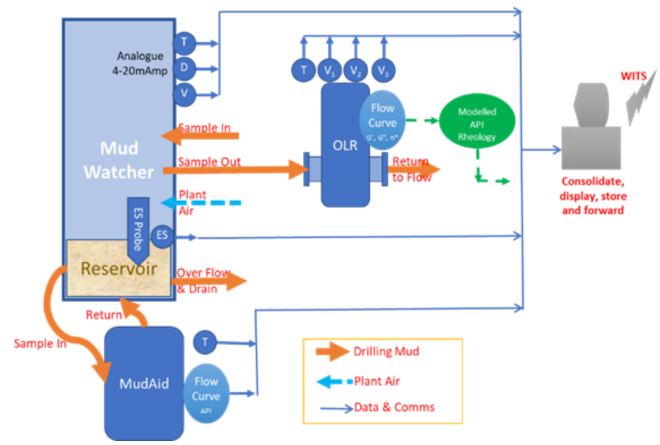

Figure 1 – OFI Automated Solutions (OAS)

As shown in Figure 1, the Mud Watcher™ (MW) unit is the main sample management subsystem. It continuously draws a sample into the system by connecting to the mud flow sampling point with a standard 1" stainless steel Camlock™ (Cam and Groove) connection. It measures density, relative viscosity, and temperature continuously. Early results from the MW were presented by its designer Mr. Ross Colquhoun (Miller, 2011).

The outflow line from the MW routes the drilling mud to the OLR™ (OnLine Rheometer) which then returns the mud to the same tank where the sample was drawn. The OLR measures viscoelastic properties near real time.

The Mud Aid™ (MA) is located adjacent to the Mud Watcher to enable a direct draw of the sample from the MW internal reservoir into the MA measurement system. It then returns the sample back the MW reservoir. It measures conventional rotational mud viscometer shear stress values periodically, and in time should replace the need for manual rotation viscometer measurements by the mud engineer, potentially reducing that workload by several hours a day.

An automated ES (Emulsion Stability) meter is installed within the MW at the MW internal reservoir.

On the OAS, data is consolidated to a data aggregator. It enables the transfer of data for local monitoring, integration into the rig data information system, and/or for transfer to remote drilling monitoring systems and databases via a standard WITS™ (Well Information Transfer Standard) interface. This data and the real time calculated hole cleaning and ECD values can be monitored by anyone on the rig or remotely.

Figure 2 – Rigsite location for the OAS

OAS was deployed at multiple drilling sites over a 6-month period. Since the start of the pilot, it has been used at four different pads, monitored over 18 wells and over 200,000 feet of NAF section drilling

Measurement Frequency for Data Gathering

Measurements from each system, units of measurement, and minimum frequency (cycle-time) for each measurement is listed in Table 1. Please note that actual recording, reporting or uploading from the system would depend on the user application and data upload capability or capacity of the receiving system.

Table 1 – Measurement Units and Minimum Frequency

Instrument Measurement	Output Units	Measurement Frequency
MW – Temperature	°C	Real-time
MW – Density	Kg/m³	Real-time
MW – Dynamic Viscosity	CentiPoise (Cp)	Real-time
OLR – Temperature	°C	3 mins
OLR – Visc (@ Shear 1)	CentiPoise	3 mins
OLR – Visc (@ Shear 2)	CentiPoise	3 mins
OLR – Visc (@ Shear 2)	CentiPoise	3 mins
OLR – G' Flow Curve	Pascals vs. Hz	3 mins
OLR – G" Flow Curve	Pascals vs. Hz	3 mins
OLR – Visc Flow Curve	Cp vs. Hz	3 mins
MA – Temperature	°C	15 minutes
MA –R3 to R600	CentiPoise	15 minutes
MA –PV, YP, n and K	App units	15 minutes
ES Meter	Volts	5 Minutes

Value in Real-Time Data Collection

In the following, basic data collected is presented and discussed. The most important takeaway from the data collected is that the OAS allows changes to be observed that would not be identified by routine manual measurements. These include early detection of fluid and wellbore problems such as contamination, fluid instability, or density and viscosity out of desired ranges. To further this point, selected data sets are presented below.

First, three sets of data are correlated to drilling progression by total depth on the lateral section of the well.

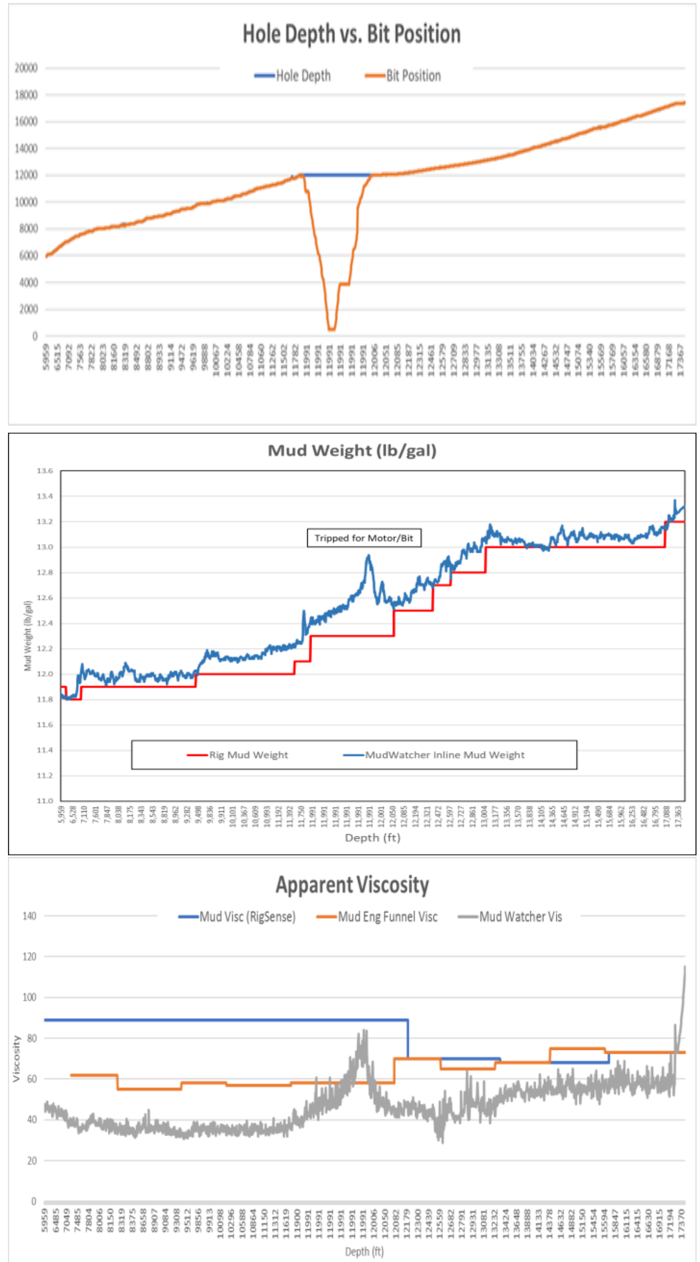

Figure 3 – Bit Position, Mud Weight, and Apparent Viscosity by Depth

Mud Weight is measured continuously by the MW as listed on Table 1. The correlation of the Mud Weight to manual mud balance measurements has been consistent and matches very well. Our data shows changes in mud condition went undetected by the periodic manual measurements. The apparent viscosity matches very well with the manual funnel viscosity trend. In both cases the instruments can capture a much more realistic trend of what happens between manual measurements. In the data above, a bit and motor trip was made at approx. 11900 ft. During and just after this process changes in Mud Weight and apparent viscosity were better captured by the OAS instruments.

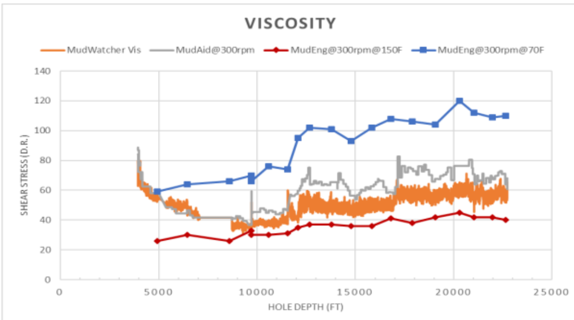

Figure 4 – Apparent Viscosity Comparison

As shown in Figure 4, apparent viscosity measurement follows the 300 RPM viscosity trend of the API Couette Viscometer, the offset can be explained by the changing shear conditions as well as the frequency of measurement (MA is hourly, vs. the continuous readings from the MW).

We were also able to trend and update Plastic Viscosity (PV) and Yield Point (YP) as shown in Figure 5a and 5b below.

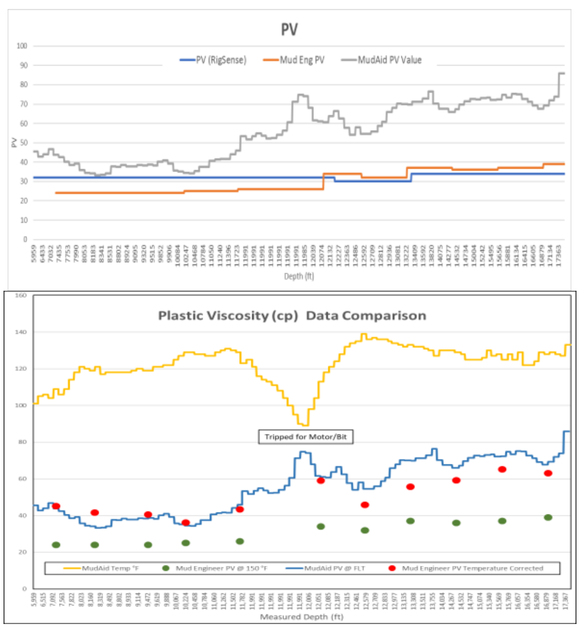

Figure 5a – Plastic Viscosity (PV) trend and correlation

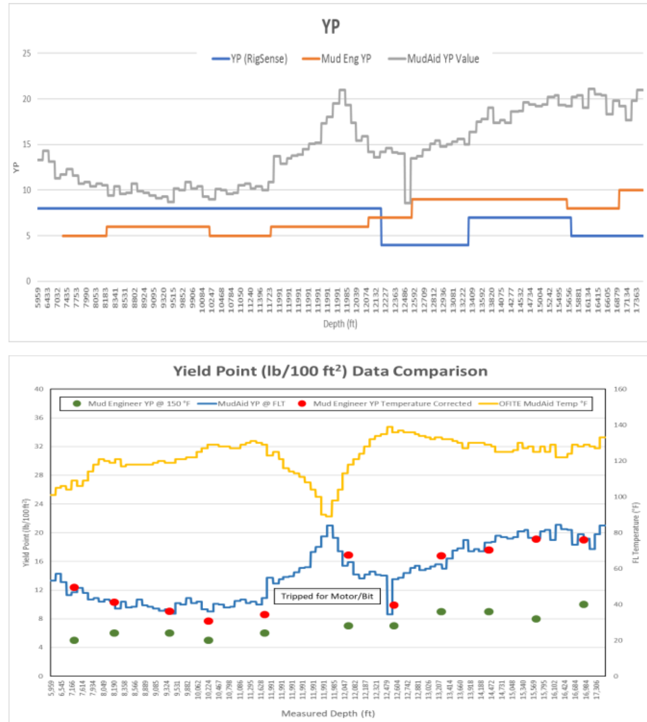

Figure 5b – Yield Point (YP) trend and correlation

Further by studying the temperature dependency of PV and YP as shown in Figure 6, we were able to "correct" PV and YP values as shown in the lower part of Figure 5a and 5b. This modelled correction shows an excellent correlation of the automated data collection and lays the foundation for future heating/cooling of the sample in the OAS such that temperature coefficients could be measured automatically and frequently.

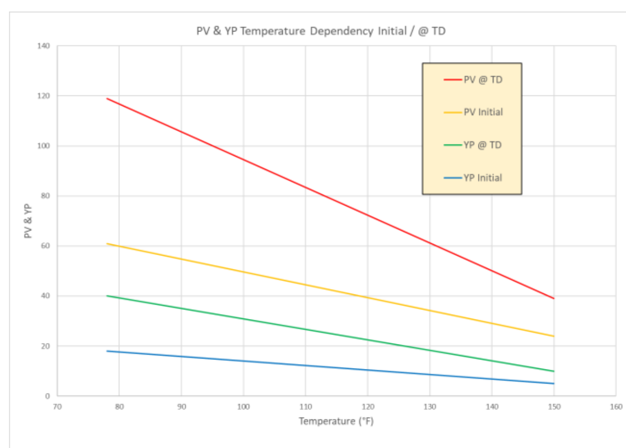

Figure 5 – PV & YP Temperature Dependency Initial to @ TD

Harsh Environment Considerations

Throughout the pilot different situations occurred, both expected and unexpected, everything from natural elements, to power outages and changing drilling mud conditions.

Mitigating these situations and maintaining a consistent flow regime in order to continually provide reliable data required agility and quick response. Points to consider such as sampling, safety redundancy, data and system start up, settling and temperature are shared below.

Sampling

One of the most, if not the most, critical element to any device used for measuring a fluid in or near line is how the sample is collected and processed. In this case the MW was the primary system responsible for sample handling. Located downstream of the shakers, below the mud pits, the MW would pump a mud sample into its own reservoir which then would be cycled through with a secondary pumping system in a pressure-controlled environment which allows for consistent laminar flow. Since the MW can maintain the fluid level of its reservoir, the MA (positioned next to the Mud Watcher) has easy access to draw from the same. Essentially allowing for two different measurements of the same sample. The third device, the OLR was plumbed into the return flow line from the MW back to mud pit. Since this is on the return from the MW, the sample conditions benefit from the same continuous laminar flow allowing a consistent mud sample flowing through the OLR.

Safety redundancy

To prepare for the unknown, we focused on “prevention and containment”. The location of the OAS below the mud pits was one of the first areas of concern. With hoses drawing the sample from above, the unit had to manage constant head pressure due to gravity. In order to prevent the reservoir from overflowing, two safety features were added. An air actuated safety valve activated via float valve in the reservoir and a separate overflow tank with a second set of float valves and secondary pump system. In the case of increased flow into the reservoir, an overflow pipe relieves the excess into a secondary tank. Once this overflow tank reaches a set level, the secondary pump kicks on to send mud back to pit. Further to mitigate loss of air or power electronic solenoids actuators were installed to automatically close safety valves. Additional manual valves and check valves were installed for emergency shutoffs and isolation for maintenance.

Data and System startup

In order to protect/continually keep connection and maintain data collection, a UPC was included in the design to maintain the computer and DAQ system for short stints of power outages. All three instruments communicate through one data aggregator and then out to rig system. In the case the connection was interrupted with the rig system, the local computer is capable of recording data locally. This ensures continuous records throughout any power cycles or outages of the rig data information system. All three instruments are capable of self-startup and are easily brought back online in the case of power outages.

Settling and Temperatures

One of the primary purposes of drilling fluids is to carry drill solids and barite. This being the case, there is the potential for settling of particles throughout the drilling process and naturally these devices are not immune. We have configured this system such that settling during normal operations does not impact measurement quality or flow. We check for, and remove, any settled material during planned periodic maintenance and are continuing to engineer improvements to minimize potential settling and the need for maintenance.

In addition to particles and settling, drilling mud also is exposed to a wide range of temperature variations. Throughout the drilling process the mud temperatures varied in ranges from 80F to 165F. Depth and atmospheric conditions impacted the temperature of the mud. During the beginning of the pilot OAS saw ambient air temperatures as high as 110F and as low as the mid 20F’s. Temperature had little to no effect on the operation or functionality of the instruments or data.

Better and Faster Rheological Measurements

Automation is only as good as the measurement capability in relevant time. The greater need for automation in the drilling industry must be supported by instruments that can provide real-time / near-real-time measurements of physical and chemical properties of fluids.

The influence of rheology in the context of efficient drilling operations has long been appreciated for monitoring hole cleaning and ECD. However, the changing practices have made it difficult for manual mud testing techniques to cater to the demand of immediacy, as discussed above. Recent availability of instruments that provide information about physical and chemical properties of materials “in-situ” and in “real-time” can provide rapid feedback on the changes that occur on microscopic level where chemistry dominates. On the continuum end, technologies like wired-drilled pipe provide rapid feedback on flow (Saasen, 2009) (Stock, 2012) parameters and pressure gradients. These technologies, along with an increasingly automated mudlogging workflows have taken the ROP metrics achievable today beyond traditional measurement techniques. Workflows associated with drilling fluid property measurement and specially rheology measurements have, however, remained tediously primitive.

By following the rheology of the mud, adjustments to the chemistry can be made so that fluid properties can be maintained at an optimal level. This has always been done – but today, it must be done quicker and better. Therefore, new approaches to rheology measurements and interpretation are needed that provide rapid feedback so that the information can be acted on at the appropriate time. Various research initiatives and other work has been done to measure drilling fluid properties inline or near line. A key contribution towards this is the work done by Ross Colquhoun (Miller, 2011), where a truly industrial, Zone 1 enabled instrument was utilized on multiple rigs to measure density and apparent viscosity. Efforts in this area have been limited by the complexity of instruments that prevent field deployment at scale. For instance: (Stock, 2012) where particle size distribution (PSD), ES and 3D rheology were measured using X-ray florescence and other technologies; (Saasen, 2009) where a combination of technologies like

Raman Spectroscopy was combined with PSD and ES measurements; Or, (Dotson, 2017) where promising modeling has been accomplished using yard and limited field data but not yet made available for field deployment. Similarly, in (Sercan Gul, 2019) yard and field tests were summarized in the use of a pipe rheometer.

The solution presented here, utilized instruments already deployed in O&G and other industries, to enable measurements of rheological parameter "in-situ" in robust and repeated field deployment. These instruments make the process of measurements safe, automated and quick. Further, measurements can be integrated with computer models. Measurements are made in "native" conditions that the liquid experiences in the pipeline, allowing for a better understanding of the actual conditions of the process than was previously possible from laboratory measurements. For instance, some liquids segregate into liquid-rich and solid-rich regions during pipe-flow. While "in-situ" measurements, such as the OLR can perform, might be able to pick up this inhomogeneity, it is difficult to recognize these in laboratory measurements, where the sampled liquid is directly or indirectly pre-processed to homogeneity before measurement.

In the following sections, we provide context for rheological measurements as a precursor for discussing our results for real-time measurement of the full rheological profile we achieved with the OAS

Background to Rheology and Viscoelastic Property Measurement

As mentioned above drilling fluids are complex material that consist of a base liquid and several additives. The combination of these constituents provides certain microstructural peculiarities to the liquids that allow them to respond in a non-linear manner when a deformation is imposed on them. A striking example of this behavior is "shear-thinning" - which allows the resistance to flow (viscosity) to decrease as the strength of flow (shear rate) increases. In contrast, in a purely molecular liquid (like water), the viscosity is independent of the rate of shear and presents the same value at all flow strengths in the laminar flow. The extent to which the non-linear characteristics of the liquid manifests depends intimately on how the flow-field organizes the microstructure. If the flow is very strong (turbulent) much of the non-linear characteristics (like shear-thinning) fails to manifest immediately. Therefore, in determining the rheology of the liquids, an understanding of the nexus between the flow-field and the microstructure is of paramount importance before an assessment of the material parameters like viscosity can be made.

There are primarily three flow regimes: laminar, turbulent, and a transitional regime where the flow-field transitions between laminar and turbulent. The art and science of rheology is primarily applicable to the laminar regime. In this regime liquid planes slide over one another (like a deck of cards resting on a table and pushed at the top) and, in the process, deforms the microstructure to various degrees of order, which in turn influences the non-linear response of the liquid. Rheological techniques characterize how these ordered states influences the deformation and flow of matter. It is important to note that the special arrangements discussed above guarantees that the flow is laminar when being pumped between the instruments. This provides a robust ground for trusting the data that arises from the measurements.

Rheological measurements also come in various flavors. These, in general, can be divided into two broad categories: linear rheology; where the stress resulting from an applied deformation (strain) is a "linear" function of the strain, and non-linear rheology; where the stress and strain have a non-linear relationship. In complex liquids, linear behavior is noticed at small strains, and non-linear behavior at larger strains. In principle, if careful experimental practices are employed, each technique of experimental rheology should be able to provide information on both linear and non-linear rheology. However, as the subject has matured, some techniques are preferred for linear rheology and others for non-linear rheology. For instance, oscillatory flow, at small strain amplitudes are preferred for linear rheology while steady shear flow (like in the concentric cylinder Couette cell) can be used to characterize the non-linear rheology of the liquids.

The OAS provides a unique opportunity to obtain both types of information at the near real-time. While the OLR provides in-situ "near linear" behavior using oscillatory flow technique (which is somewhat new to the industry), the MA provides the familiar Couette cell based non-linear rheology measurements in an automated manner. The "in-situ", "real-time" aspects of these measurements make them extremely desirable for the high-speed drilling operations. To our knowledge this is a first of its kind in the industry.

Discussion of Real-Time Rheology

The importance of characterization of both the linear and non-linear rheology is in fact recognized by the industry, with the current standard of API 13D (API - Amercian Petroleum Institute, 2017) referring to linear rheology on several occasions. Most structured liquids, including drilling muds, possess a solid-like (elastic) and a liquid-like (viscous) character. Their linear rheology is measured using the oscillatory flow mode, where the sample is held between two plates that are "jiggled" back and forth or up and down at very small amplitudes (such that the microstructure is deformed mildly but not destroyed by the flow), and at one or more frequency(ies), to uniquely characterize the liquid. The elastic and viscous properties of the liquid are characterized by the storage modulus (G') and the loss modulus (G'') respectively and their relative importance varies with the frequency of deformation. The OLR has been developed over a number of years to measure G' and G'' in a reliable way and the details of these developments and their physical underpinnings are available elsewhere (D. Konigsberg et al., 2013), (D. Bell, 2006) and (Phan-Thien, 1980).

These properties can be measured in a laboratory Couette rheometer. In Figure 7a, a comparison between G' and G'' measured on a water-based drilling fluid by a laboratory rheometer and by the OLR is presented. While the OLR measures at higher frequencies, the measurements made in the lab seems to monotonically segue into the OLR measurements. In effect the OLR measurements extends the laboratory measurements to higher frequencies. It can also be observed for Figure 7a that the moduli cross each other twice; once at low frequencies and once at a higher frequency. The inverse of the crossover frequencies can be used to estimate time scales over which the microstructural order reorganizes in the liquids at various strength of deformation, e.g., defining the viscoelastic region to approximate carrying capacity of the fluid.

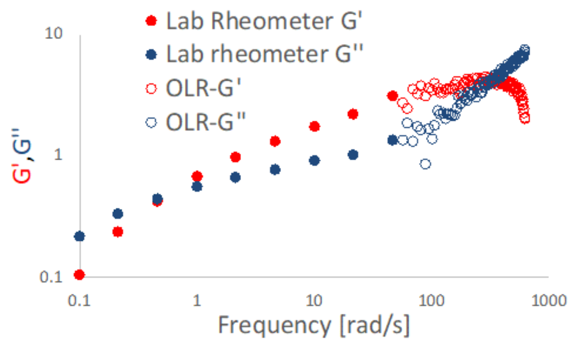

Figure 7a - Laboratory based tests of linear rheology performed by a laboratory rheometer and the OLR on a prototypical water-based drilling mud.

The reorganization processes are ultimately related to the underlying chemistry and thus the linear rheology can be used for the understanding of how the chemical details ultimately renormalizes and influences macroscopic (flow) properties. In some sense the understanding of linear behavior is more fundamental because linear rheology is intimately related to the chemistry of the system and complements, chemistry, spectroscopic and scattering techniques that are used to characterize the molecular structure and organization of matter. Also, all non-linear behavior emerges out of and should converge to the linear behavior when the strains become large or small respectively. Techniques exist (although complicated) that allow prediction of non-linear rheology from linear measurements. We show one example in Figure 7b where we compare the shear rheology of a water-based mud measured on a Couette Cell viscometer (symbols) to those obtained from OLR measurements (line).

It must be borne in mind that the data representing the line is converted from the oscillatory (linear) measurements made by the OLR (like the unfilled symbols in Figure 7a and extended to the ranges covered by the Couette Cell viscometer. It can be observed from the Figure 7b that good agreement can be obtained between the Couette Cell viscometer measurements and the OLR output, which implies that all other calculated values like PV, YP, LSYP etc. will have an equivalent close correspondence with those measured by the Couette Cell viscometer. We use this approach later during field trials, to extract PV and YP values from OLR measurements.

In Figure 7b, we present laboratory-based tests of linear rheology performed by a laboratory rheometer and the OLR on a prototypical water-based drilling mud. The shear-stress vs. shear-rate profile of a water-based drilling mud measured by an API-approved Couette-Cell viscometer (symbols) matches the predicted OLR measurements (line).

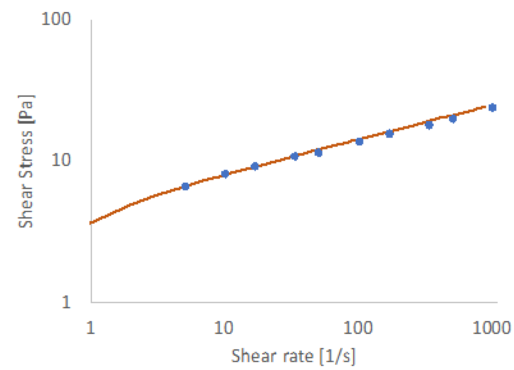

Figure 7b - Comparison between the shear-stress vs shear-rate profile of a water-based drilling mud measured by an API-approved Couette-Cell viscometer (symbols) and the those predicted from OLR measurements (line).

In the following we furnish and discuss some of the real time data available from a recent field trial. As mentioned, the OAS houses three main units: the MW that conditions the fluids for measurement purposes, the OLR that performs oscillatory flow for measuring linear rheology, and the MA, that is an online version of Couette Cell viscometer used to measure the familiar non-linear rheology in laboratories. Each instrument in the OAS measures the temperature of the liquid passing through it. In Figure 8 below we show the temperature trend recorded at each equipment as the trial progressed.

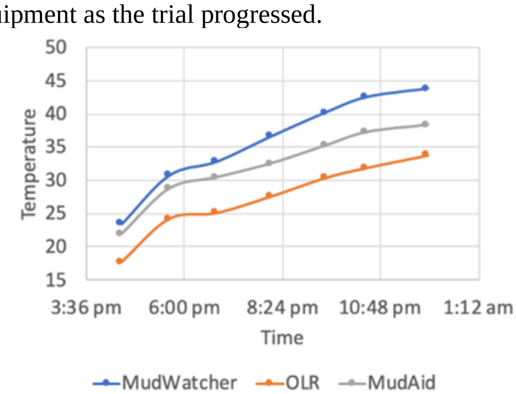

Figure 8 – The variation of temperature of the recirculating drilling mud as measured by the three rheology related instruments on OAS.

The current OAS works at ambient temperature, resulting in an unavoidable variation in the individual temperature at the instruments preventing a direct quantitative comparison between the rheological measurements of MA and OLR (since viscosity is a strong function of the temperature). However, some “qualitative” comparison of the trends can still be made, and these are discussed below.

In Figure 9a and 9b we show the PV values recorded by MA and the OLR respectively. We have also included the temperature profiles recorded by the instruments to reinforce the fact the measurements were made at different temperature values, and therefore only trends can be compared in a qualitative sense. As mentioned above in context of Figure 7b, an algorithm was used to extrapolate the measured linear rheology to non-linear domain, to obtain an estimate of PV from the OLR data. These limitations notwithstanding, it can be concluded from studying Figures 9a and 9b that the evolution of both the temperature profile and the OLR PV values closely resemble those observed for the case of the MA measurements, with a sharp initial drop in magnitude followed by a region of marginal decay, over the time-scales where comparable data are available.

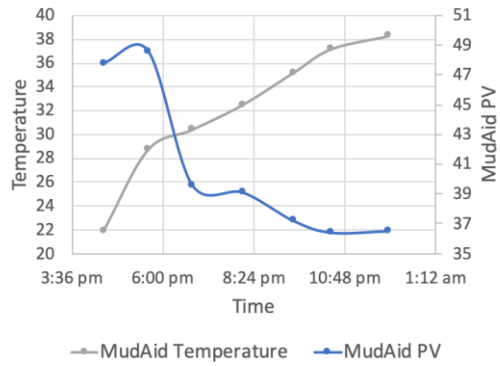

Figure 9a - The evolution of the temperature and drilling mud PV measured on MA.

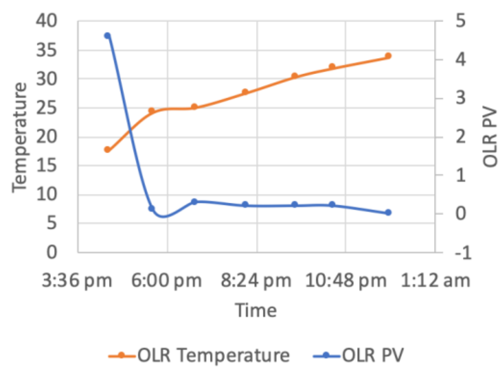

Figure 9b - The evolution of the temperature and drilling mud PV is estimated from OLR measurements.

In Figures 10a and 10b, the YP values are compared. The correspondence is less obvious in the initial stages where a distinct peak exists in the MA YP values, which is absent in the OLR YP. Nevertheless, both YP values decay at different rates over the rest of the time frame, which makes the trends qualitatively similar. Once again, we reiterate that both the PV, and the YP values that are reported by the OLR are obtained indirectly (via a mathematical model) – with a starting point in a set of data that is fundamentally different to those that for the MA PV and YP. In that sense the observed similarity is perhaps remarkable despite the obvious anomalies and limitations. Further work however is needed to make the correspondence more robust.

The OAS demonstrably provides information spanning both ends of the rheological spectrum. The OLR, and the MA measurements together bridge the gap between the chemistry, and hydraulics as the drilling progresses. While, operating the OLR, and the MA in tandem would provide the operator a distinct advantage, both from an operational and a scientific standpoint, it has been demonstrated that the OLR itself can serve the dual purpose, albeit in a limited sense, if it becomes necessary.

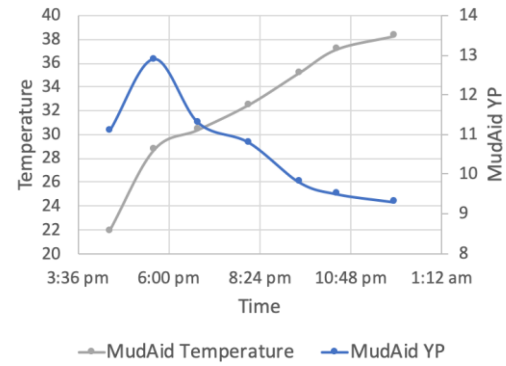

Figure 10a - The evolution of the temperature and drilling mud YP measured on MA.

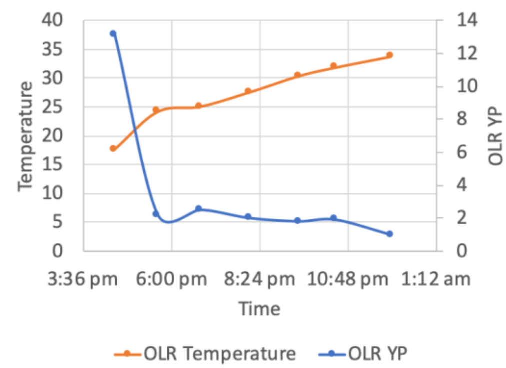

Figure 10b - The evolution of the temperature and drilling mud YP is estimated from OLR measurements.

Conclusions

The two primary purposes of the extended field pilot were to determine if the deployed technology is capable of reliably providing accurate data, without human intervention for extended periods of time, and is robust enough to handle continually changing rig-site conditions through the drilling process.

First, the data collected both by field engineers compared to the instrumentation have proven that these automated measurement technologies do provide repeatable quality results. And, that these measurements can be reliably taken without human intervention. Analyzed data showed that viscosity changes more with temperature than anticipated or as manually measured. The mud weight showed a similar effect, however more in line with conventional thinking. In regards to future application, this data is available for direct integration with an active hydraulics or drilling automation model that could, for instance, help manage the ECD in a trip cycle when the mud is typically cooler and viscosity has not yet been stabilized. Temperature correction coefficients change more than anticipated indicating the need for multiple temperature measurements.

Second, due to the timing of the pilot which started in August and continued through the fall and winter months, proved the technologies can handle a wide range of environmental conditions. These conditions included extreme heat through the summer months to freezing temperatures along with rain, humidity, etc. In addition to the environment, the drilling fluid conditions experience continuous changes that the technologies must deal with. These changes include temperature, solids content, density, viscosity, etc. While slight modifications and improvements to sample handling, containment, and flow regimes were made, overall technologies proved they were field suitable.

In conclusion, our experience shows robust and reliable technology can be deployed to gain valuable and timely information throughout the drilling process. We also show that such a system can be open, not limited to integration with certain systems, and can be operated by rig personnel. This capability is designed to empower Drillers, Service Providers and Operators leading to improved decision making through visualization and simulation.

Acknowledgments

The authors would like to acknowledge contributions and help from the larger team: OFITE technicians Terry Braun, Ebram Azer, and Rick Jones; ConocoPhillips rig-site staff Bill Lawton and Benny “Bull” York ; ConocoPhillips office-based members James Chen, Kristine Midtgarden, DJ Summers, and Justin Garner; NOV rig-site support Ramone Lopez and Juan Chapa; NOV data acquisition team; NOV office staff Victor Hernandez, Mark Crabbe, and Eric Scott; Consulting Mud engineers Terry Thibodeau and Mark Symns.

References

1. API - Amercian Petroleum Institute. (2017). *API 13D - Rheology and Hydraulics of Oil-Well Drilling Fluids.* Washington, D.C.: API - Amercian Petroleum Institute.
2. D. Bell, e. a. (2006). Rheologica acta. *Rheologica acta, Vol. 46(1), 111.*
3. D. Konigsberg et al., ,. (2013). Applied Rheology. *Vol. 23, 35688*.
4. Dotson, A. M. (2017). Improvements in Automated Continuous Measurement of Drilling Fluid Properties. *Society of Petroleum Engineers. doi:10.2118/188022-MS*.
5. Miller, A. M. (2011). The Continuous Measurement and Recording of Drilling Fluid Density & Viscosity. *Society of Petroleum Engineers. doi:10.2118/140324-MS*.
6. Phan-Thien, N. (1980). *The Journal of the Australian Mathematical Society, Series B. Applied Mathematics, Vol.22(01), 22*.
7. Saasen, A. O.-L. (2009). Automatic Measurement of Drilling Fluid and Drill-Cuttings Properties. *Society of Petroleum Engineers. doi:10.2118/112687-PA*.
8. Sercan Gul, E. v. (2019). Automated Surface Measurements of Drilling Fluid Properties: Field Application in the Permian Basin. *URTeC: 964*.
9. Stock, T. R. (2012). The Development and Successful Application of an Automated Real-Time Drilling Fluids Measurement System. *Society of Petroleum Engineers. doi:10.2118/150439-MS*.