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Designing Oil-based Drilling Fluids Based on Real-Time Downhole Rheology Estimation

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Abstract

Estimating real-time rheology of drilling fluids under downhole conditions is crucial for wellbore pressure management. The work investigates rheology of various oil-based drilling fluids (OBMs) with different additives, which enables modelling of the changes in rheology with respect to temperatures (T) and pressures (P) for a range of OBMs. Based on these 'T & P rheology' models, the downhole rheology of the fluid may be estimated in real-time and accordingly, the fluid design may be optimized during real-time operations.

The literature on OBMs has evolved over years. Based on the type of viscosifier-additives, OBMs may be classified into: clay-based, polymeric-viscosifier based, and HPHT-viscosifier based. Rheological data of the three categories of OBMs was obtained from literature for a range of mud-weights (10 and 20 lb_m/gal) and oil/water ratios (65:35 to 90:10). Based on the data, 'T & P rheology' models were developed which incorporated effect of chemistry of viscosifier additives on changes in downhole fluid-rheology. The 'T & P rheology' models were derived based on following principals: the temperature rheological-effect depends on chemistry/amount of viscosifier-additives in the fluid while the pressure rheological-effect depends on physical changes of bulk liquid properties.

The work would enable estimation of downhole rheology for different OBMs in real-time and accordingly, the fluid design may be optimized during real-time operations. Based on the work, wellbore pressures (and ECD) may be managed effectively during the real time drilling operations which would help in ROP maximization and avoidance of situations such as stuck-pipe, kick or lost circulation.

Introduction

At the latter half of the 20th century, Oil Based Muds (OBMs) have been into play to address the restrictions faced while using Water Based Muds (WBMs) especially to reactive shales (Wright 1954). Later over the years, OBMs have evolved with selective emulsifying agents with water as a dispersed phase for stable emulsions and also to prevent combustion hazard. For an OBM to be designed, the following are the typical components (Gates and Wallis, 1951; Lummus, 1954; Watkins, 1960):

- Base oil: diesel oil, paraffins, olefins.
- Emulsifiers: water/brine and tall oil derivatives.
- Weighting agents: solids like barite.
- Other additives: viscosifiers like organophilic, polymers; filtration control like modified lignite; oil-wetting agents like lecithin.

Organophilic clay based OBMs were the first generation OBMs. It was a transformation of hydrophilic clays to organophilic clays using the right type and amount of ammonium salts (Hauser 1950). It was otherwise known as Clay based OBMs. During this period, several oil-wells were drilled using organophilic OBMs in moderately high temperature and corrosive environments where WBMs were not deployable (Gray and Tschirley, 1975).

Nonetheless, the clay-based OBMs continued to have several limitations including:

- too thick fluid rheology at low temperatures.
- intensive gel structure causing pressure spikes during flow initiation.

About two decades ago, development of the second-generation of the OBMs was initiated (Burrows et al. 2004; Mowrey and Cameron 2006) that overcame the above barriers of the clay-based OBMs. These second-generation OBMs have been termed clay-free OBMs, as they did not consist of any organophilic clays. The viscosification was accomplished using polymeric viscosifiers. The clay-free OBMs proved really useful in deep-water wells owing to their average rheologies at low temperatures and also, in narrow-margin wells owing to their fragile gel structures (Knox et al. 2015). There was continuous enchantment in the clay-free OBM systems primarily based on work of numerous researchers in industry and academia. The prominent enhancements included addition of colloidal particles and high shear treatment to the fluid, and replacing the regular barite with micronized barite (Kageson-Loe et al. 2007; Zanten et al. 2012; McMillan et al. 2015).

However, at high-temperatures (> 200 °F), the barite sag and cuttings transport in challenging wells remained unresolved issues while the use of the clay-free OBMs (Kulkarni et al., 2016). The current development to address these issues was development of the third-generation of OBMs, termed as HP/HT OBMs. These HP/HT OBMs, with inclusion of colloidal particulates and novel polymeric viscosifiers, provided peculiar rheological behavior (Kulkarni et al. 2017). Consequently, improved fluid overall performance in HP/HT wells was observed (Strand et al. 2016; Mahrous et al. 2016).

Research Aim

Although the drilling activities operate continuously, drilling automation became a key theme in the oil industry. Figure 1 illustrates the drilling automation to be achieved in usage of drilling muds.

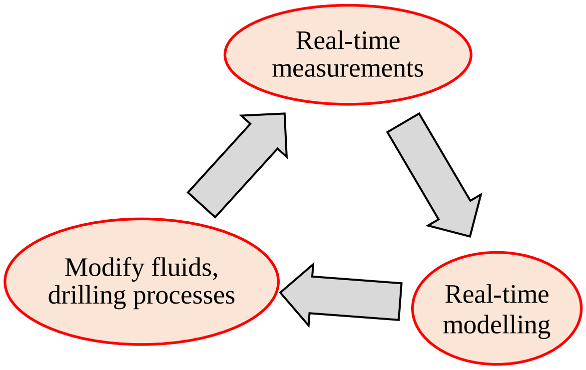

Fig. 1: Drilling Automation.

The loop of automation begins with real-time measurements of drilling fluids taken from surface equipment providing information regarding the properties of the fluids like density, rheology, composition, particle size distribution and in-line measurements can be measured from vibrations, LASER, optical, NMR, pressure sensors etc.

Based on the real-time measurements, real-time modelling originates for downhole parameters. Based on these parameters as well as from drilling and circulation history, fluid flow history, Transient Wellbore Pressure Management, ECD modelling, Stability, cuttings transport and particle-sedimentation can be predicted. With those predictions, drilling fluids can be altered for optimizing drilling processes and the whole loop begins, making the loop automated.

The current research is to establish relationships between the surface and downhole conditions especially for the rheological behaviour of the oil-based drilling mud. Figure 2 illustrates the research path established. The key area is to identify the proper model that suits the relation between surface and downhole with respect to changes in temperature and pressure.

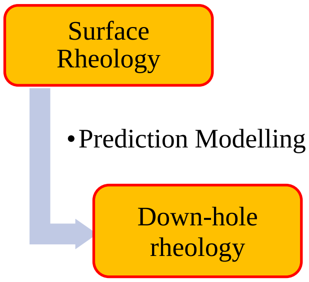

Fig. 2: Research path employed.

The approach for this path is two staged. Establish the high temperature rheology by generating temperature-sweeps for the 3 classes of OBMs based on the literature data. Then with the established relation of temperature rheology, generate pressure-sweeps for the same 3 classes of OBMs. Figure 3 illustrates the staged approach.

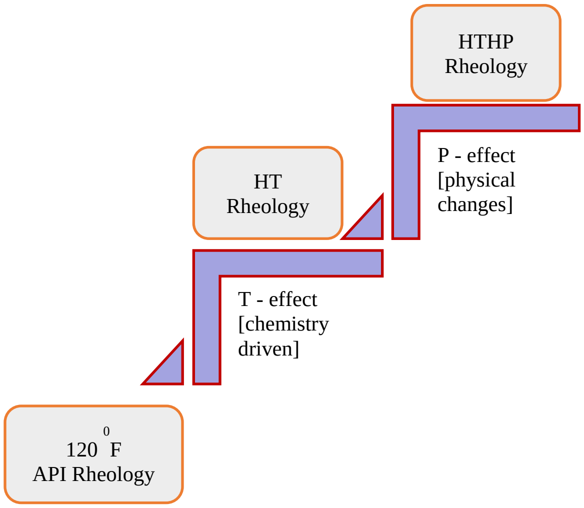

Fig. 3: Two staged approach used for Prediction Modelling.

Discussion

Significant data from literature based on rheological behaviour was observed and collected for the 3 classes of OBMs. The rheological data has been followed over a range of temperature, pressure and shear stress (T, P, τ) constraints in using the API recommended viscometer rotor/ bob (R_1/B_1) geometry. A 1.0 mm (approx.) gap is present between rotor and bob which is instrumental in measuring shear stress with respect to torsion spring rotation.

In the current work, the rheological data from literature is analysed to reconstruct temperature-sweep response of the OBMs. It is regarded that impact of pressure on fluid rheology is usually driven by the compressibility behaviour of base oil/emulsions. To the contrary, it is regarded that the effect of temperature on fluid rheology is especially impacted through the additives e.g. viscosifiers types/amount. Therefore, this paper focuses on reconstituting temperature-sweep response of these OBMs, distinguish their behaviours and from the pressure-sweep response of these OBMs, relate the effect of the compressibility.

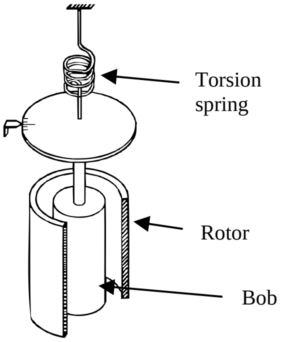

Fig. 4: Representative API viscometer geometry (Caenn et al., 2011).

The investigation of the rheological temperature-sweep of the three OBM systems has certainly proven that distinctive viscosifiers additives have specific impact on the fluid rheology. Figure 5 illustrates the distinct temperature-sweep rheology response of the three OBM systems at 2000 psi, 100 RPM. The figure demonstrates that the temperature-sweep rheological study could be used to signify the effect of viscosifiers.

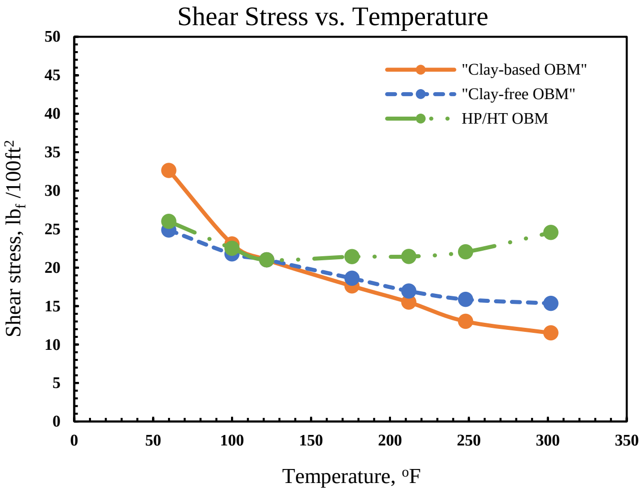

Fig. 5: Effect on shear stress with change in temperature for different viscosifier based OBMs (Burrows, 2004; Kulkarni, 2017; McMordie, 1975).

Clay-based OBMs' rheological response: The first generation of the invert-emulsion drilling fluids, consisted of organophilic clays as viscosifiers. The experimental data on characteristic rheological behaviour of these drilling fluids at a range of (T, P, τ) was obtained from McMordie et al. 1975. Figure 5 shows strong temperature thickening at cold temperatures (< 100 ºF) followed by thinning as the temperature increases at the studied RPM.

Clay-free OBMs' rheological response: The second generation of the OBMs, consisted of colloidal particles and polymeric viscosifiers instead of the organophilic clays. The experimental data on characteristic rheological behaviour of these drilling fluids at a range of (T, P, τ) was obtained from Burrows et al., 2004. Figure 5 shows that the occurrence of excessively thick rheology at cold temperatures was eliminated in the clay-free OBMs yet thinning remained as the temperature increases at the studied RPM.

HP/HT OBMs' rheological response: The third generation of the OBMs consisted of colloidal particles and a different set of polymeric viscosifiers. The experimental data on characteristic rheological behaviour of these drilling fluids at a range of (T, P, τ) was obtained from Kulkarni et al. 2017. Figure 5 shows that the HP/HT OBMs not only have moderate cold-temperature rheology but also possess very stable rheology at high temperatures (up to 325 ºF). Consequently, improved fluid performance in terms of barite sag and cuttings transport in several HP/HT and inclined wells was reported (Strand, 2016; Mahrous, 2016).

Model Generation

Numerous literatures have mentioned the prediction modelling of OBMs at high temperatures and high pressures, but most widely used model was based from McMordie et al. 1975 where shear stress response of the fluids at a given shear rate (or RPM) was incorporated in below equation 1.

$$\ln\left(\frac{\tau_{new}}{\tau_{ref}}\right) = A\left(P_{new} - P_{ref}\right) + B\left(\frac{1}{T_{new}} - \frac{1}{T_{ref}}\right) \quad (1)$$

where A and B are empirical parameters, P_{new}, P_{ref} represent the applied pressures on the fluid and T_{new}, T_{ref} represent the fluid temperature conditions.

With the responses observed from literature-based data in figure 5, the temperature model was developed using a power law model. Equation 2 describes the power law model developed relating shear stress with temperature.

$$\frac{\tau_{new}}{\tau_{ref}} = \left(\frac{T_{new}}{T_{ref}}\right)^{-x} \quad (2)$$

Following the 2-stage approach, the pressure-sweep model was developed from literature considering the phenomenon that pressurizing the OBM, the base oil/ emulsion in the OBM compresses. This leads to decrease in oil volume fraction in turn to increase in solid volume fraction. The change in volume fraction (density) is calculated using equation 3 from Zamora et al. 2012.

$$\rho_{oil\,/\,brine} = (a_1 + b_1P + c_1P^2) + (a_2 + b_2P + c_2P^2)T \quad (3)$$

Counting the change in solid volume fraction, the pressure-sweep model was developed from literature using classical fluid mechanics (Zarraga, 2000) as mentioned in equation 4. Equation 4 describes the relation between shear stress with solid volume fraction.

$$\frac{\tau_{new}}{\tau_{ref}} = \frac{1+(A\times\varphi_{new})+(B\times\varphi_{new}^2)}{1+(A\times\varphi_{ref})+(B\times\varphi_{ref}^2)} \quad (4)$$

Results

The literature-based data retrieved from Kulkarni et al. 2017 was analysed for high temperature rheology using the proposed models. For temperature-sweeps, the plots have been generated at different RPMs to substantiate the relation between RPM and temperature. Figures 6 to 9 illustrate the change of shear stress with temperature at different RPMs for same drilling fluids of 3 classes of viscosifiers.

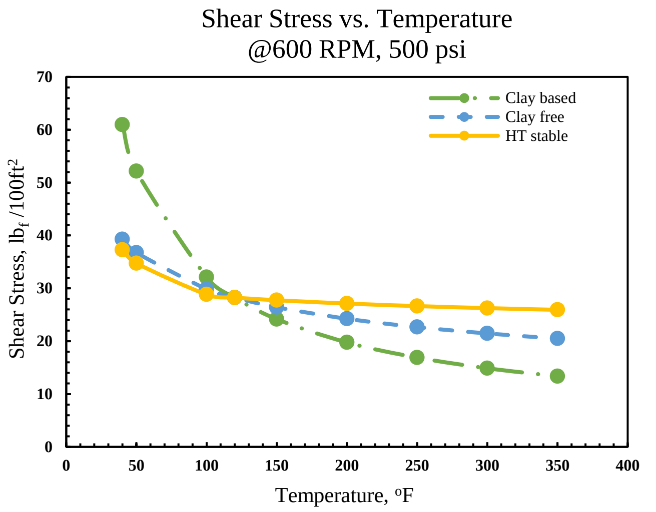

Fig. 6: Effect of temperature on shear stress at conditions 600 RPM, 500 psi.

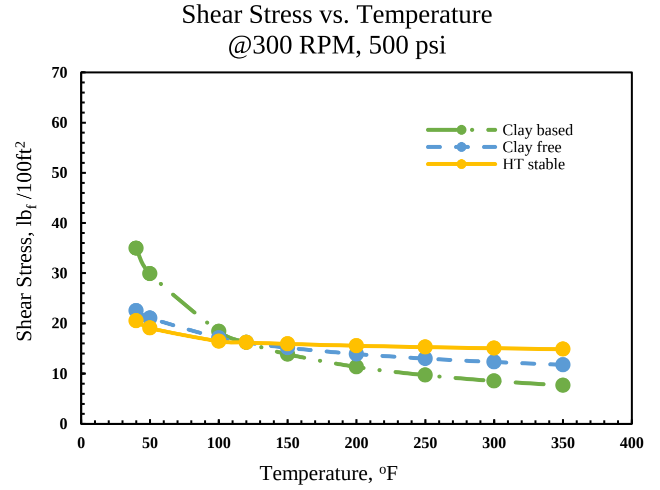

Fig. 7: Effect of temperature on shear stress at conditions 300 RPM, 500 psi.

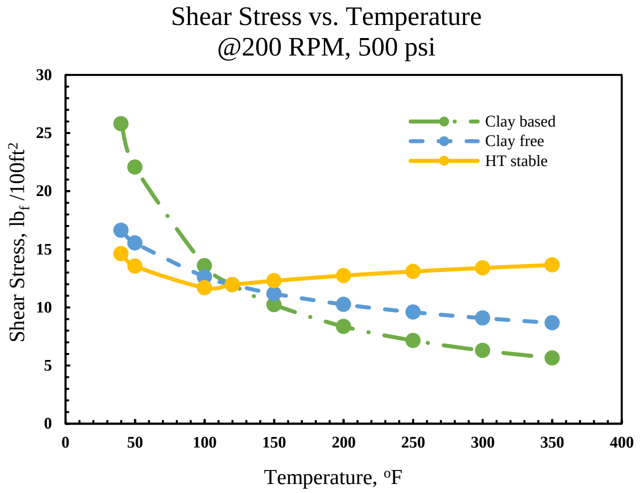

Fig. 8: Effect of temperature on shear stress at conditions 200 RPM, 500 psi.

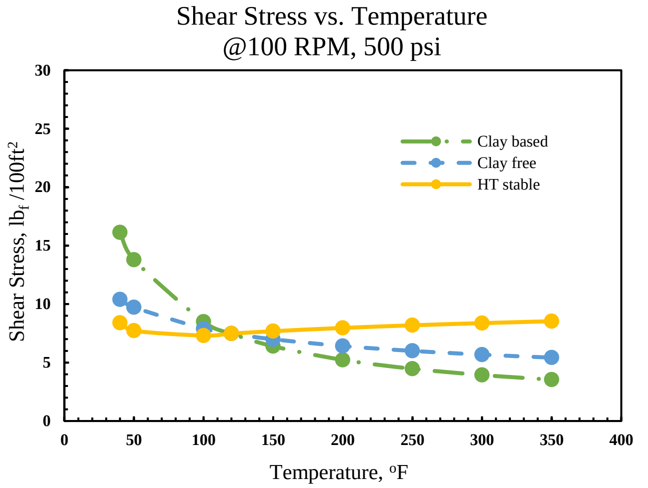

Fig. 9: Effect of temperature on shear stress at conditions 100 RPM, 500 psi.

Deduced from the plots (figures 6 – 9) observed, it is clear that the shear stress decreases as temperature increases and this relation majorly depends on

1. RPM at which the shear stress is measured.
2. The type/ amount of viscosifier used in the OBM.

The developed model for temperature-sweep demonstrates better results in comparison to McMordie model (McMordie et al., 1975), as the parameter A has to be evaluated for every combination of OBM (base oil/ emulsion + viscosifier) to be designed. Whereas the proposed model constitutes the base oil/ emulsion, the power *x* solely depends on RPM at which the shear stress is measured and the type/ amount of viscosifier used in the OBM.

Results generated from the temperature-sweeps have been analysed for high temperature high pressure rheology using proposed pressure-sweep model. For pressure-sweeps, the plots have been generated at different temperatures. Figure 10 illustrates illustrate the change of shear stress with pressure at different temperatures for same drilling fluids of 3 classes of viscosifiers.

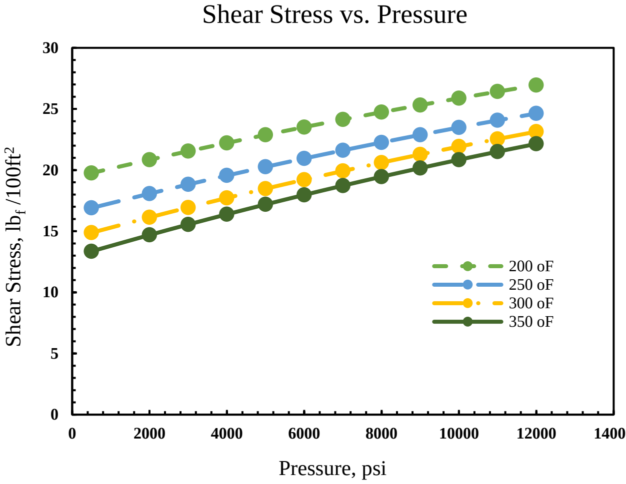

Fig. 10: Effect of pressure on shear stress.

Deduced from the plot (figure 10) observed, it is clear that the shear stress increases as pressure increases and this relation independent from

1. RPM at which the shear stress is measured.
2. The type/ amount of viscosifier used in the OBM.

Conclusions

With regards to the results noticed by using proposed models, it was observed that during:

- temperature-sweep investigation, different viscosifiers impact fluid rheology distinctly and the proposed temperature-rheology model constitutes base oil/ emulsion making the model to predict the viscosifier effect for the temperature change.
- pressure-sweep investigation, fluid compressibility is a key factor and the proposed pressure-rheology model constitutes type of viscosifier making the model to predict the solid volume fraction change effect on shear stress.

It is also observed that the average difference between modelled readings and literature data is ±2 dial readings for HTHP rheology.

Future Plan

The predicted temperature-rheology and pressure-rheology models were deduced from literature-based data. These models are to be validated using lab and field muds. These predicted models shall be modified with progress in experimental validation as well as utilization of Machine Learning models.

Nomenclature

Abbreviations

API = American Petroleum Institute
ECD = Equivalent Circulating Density
HPHT = High Pressure High Temperature
NMR = Nuclear Magnetic Resonance
OBM = Oil Based Mud/ Fluid
P = Pressure, psi.
RPM = Rotations/ Revolutions Per Minute, min^{-1}
T = Temperature, °F.
WBM = Water Based Mud/ Fluid

Alphabet

A = empirical constant, psi^{-1}
B = empirical constant, °F
a_1 = empirical constant, ppg
b_1 = empirical constant, ppg psi^{-1}
c_1 = empirical constant, ppg psi^{-2}
a_2 = empirical constant, ppg °F^{-1}
b_2 = empirical constant, ppg psi^{-1} °F^{-1}
c_2 = empirical constant, ppg psi^{-2} °F^{-1}

Greek symbols

τ = Shear stress, lb$_f$/100ft^2.
φ = Solid volume fraction (dimensionless)

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