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The Rheological Properties of Oil-Based Mud Under High Pressure and High Temperature Conditions

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Abstract
Designing a proper drilling fluid that can function properly under the conditions of High-Pressure, High-Temperature (HP/HT) operations is very challenging. Among these challenges is the alteration of the rheological properties of drilling fluid due to the high temperature and high pressure (Ibeh et. al, 2007). This work investigates the rheological behavior of oil-based drilling fluids with different properties at Ultra-HP/HT conditions using a state-of-the-art viscometer capable of measuring drilling fluids properties up to 600°F and 40,000 psi. For this purpose, two actual oil based mud samples used by industry with the same mud weight (12.5 ppg) were chosen to carry out a matrix of experiments. The results of this study led to concluding that the viscosity, yield point and gel strength decrease with increasing temperature (until the mud sample fails, for oil-based mud with regular formulation). This behavior is the result of the thermal degradation of the solid, polymers, and other components of the mud samples and the expansion of the molecular distances which will lower the resistance of the fluid to flow and, hence, its viscosity, yield point, and gel strength. Moreover, it is concluded that the viscosity and yield point increase as the pressure increases. Pressure's effect on these parameters, however, is more apparent at low temperature (below failure point, for oil-based mud with regular formulation).

Key words: High pressure high temperature; Oil-based mud; Rheology; Rheological properties

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INTRODUCTION

In addition to depletion of easy to access, shallow reservoirs, oil prices growth in the previous decade, made the production from deep formations economically defensible. Technical issues along with attempts to produce such reservoirs mainly attributed to the fact that temperature and pressure directly increase with an increase in depth (Ibeh, 2007). Technically, accurate knowledge and precise prediction of drilling fluids behavior at high pressure/high temperature drilling conditions is one of the most important issues in drilling in deep reservoirs which would lead to a safe and efficient operation (Bland *et al.*, 2006).

For a drilling engineer it is essential to understand the changes in rheological properties brought about by varying subsurface conditions particularly in deep oil reservoirs. In order to allocate the most suitable type of mud for drilling under HTHP conditions, a complete understanding of the variations in rheological properties with temperature and pressure must be present. This requires the presence of a model to simulate those variations, more specifically in regards to factors such as viscosity.

There is very little experimental data available that pertains to understanding the flow behavior and rheological changes with downhole conditions. In this study parameters such as temperature, pressure, shear history, composition and the electrochemical character of the components and of the continuous fluid phase where considered for their effect on rheology.

In order to contribute to the advancement of knowledge upon properties of oil-based muds under Ultra-HTHP conditions a methodology for investigation and testing was implemented on a number of samples of said drilling fluid. This study was conducted by using state-of-the-art viscometer capable of accurate measurements for drilling fluids properties up to 600°F and 40,000 psig.

In terms of practical applicability of such a research, cases such as the Elgin and Franklin fields in the North Sea demonstrate the wide-reaching consequences of testing under Ultra-HTHP conditions. In these particular fields pressures reach 16,300 psig and temperatures around 400°F at reservoir conditions. This results in substantial emphasis on the importance of mud weights thus outlining the significance of conducting research on their viscosities in these conditions (Wang *et al.,* 2000).

Another case where extreme drilling conditions are encountered is BP-Amoco rig, off the coast of Louisiana, drilled 22,000 feet deep at conditions of 16,000 psi and 380°F. Drilling muds used for such conditions must be investigated prior to their application in the field owing to the major implications of the latter failing due to operating conditions (Shaughnessy *et al.,* 2000).

Another obvious application of this study is in designing an appropriate drilling fluid for drilling Geothermal wells.

In essence, this study seeks to analyze and comprehend the effect of high temperature and high pressures on the rheological properties of drilling fluids, more specifically oil-based muds. This would allow the design of appropriate mixtures which can operate successfully under such conditions.

1. MATERIALS AND METHODS

This study was based on implementing the *Chandler Model 7600 Ultra-HPHT Viscometer* which is a concentric cylinder viscometer that uses a rotor and bob geometry widely accepted in petroleum industry. This equipment meets ISO and API standards for viscosity measurement of completion fluids under HPHT (High Pressure High Temperature) conditions (Gusler *et al.,* 2007). The Maximum Temperature and pressure applied to the mud system are of 600^{o}F and 40,000 psig. The minimum Shear Stress of 20 dyne/cm^2 and Maximum Shear Stress of 1533 dyne/cm^2 can be recorded by this device. The range of viscosity measurement is Minimum Viscosity of 2 cp at 600 RPM and Maximum Viscosity of 300 cp at 300 RPM. The shear rate ranges from 1.7- to 1022 sec^{-1} (1 to 600 RPM with B1/R1). Figure 1 shows the Model 7600 HPHT Viscometer.

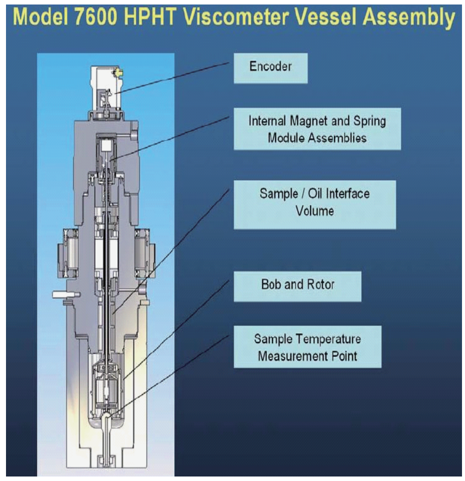

Figure 1
Model 7600 HPHT Viscometer Used in This Work

Before starting the experiments on oil based muds, the matrix in Table 1 was created which includes the experiments that were performed. First experiments on an oil based mud sample, that is designed to withstand HPHT conditions (HPHT mud) for a range of pressures and temperatures, were performed and then another set of experiments with a regular oil based mud was carried out. In order to find the effect of specific variables, temperature and pressure in this case, one parameter was kept constant and the others were changed. It was decided that the pressure is to be kept constant in each experiment while the temperature was changed from room temperature (70^{o}F) to 550^{o}F in 50^{o}F steps. This allowed analysis to reveal the effect of temperature on viscosity of oil based muds under HPHT conditions. Then, pressure is raised and kept constant with the same temperature steps.

Table 1
Experiments' Matrix

Run #	Mud Sample Used	Pressure (psi)	Temperature Range (F)
1	HPHT	5000	70-550
2	HPHT	10000	70-550
3	HPHT	15000	70-550
4	HPHT	20000	70-550
5	HPHT	25000	70-550
6	HPHT	30000	70-550
7	HPHT	35000	70-550
8	Regular	5000	70-550
9	Regular	10000	70-550
10	Regular	15000	70-550
11	Regular	20000	70-550
12	Regular	25000	70-550
13	Regular	30000	70-550
14	Regular	35000	70-550

Having a matrix of experiments while temperature and pressure were variables showed the impact of pressure and temperature changes on viscosity profile. A sample output of the experiments matrix software used.

The mud samples that were used were both oil based muds provided by one of the companies operating in Qatar. The mud weight of both mud samples were 12 ppg. One of the mud samples had been designed to withstand high temperatures and pressures while the other sample was an oil-based mud with regular formulation.

The properties and the specifications of the two mud samples used in this study, HPHT Sample and the Regular Oil-based Mud Sample are shown in Table 2.

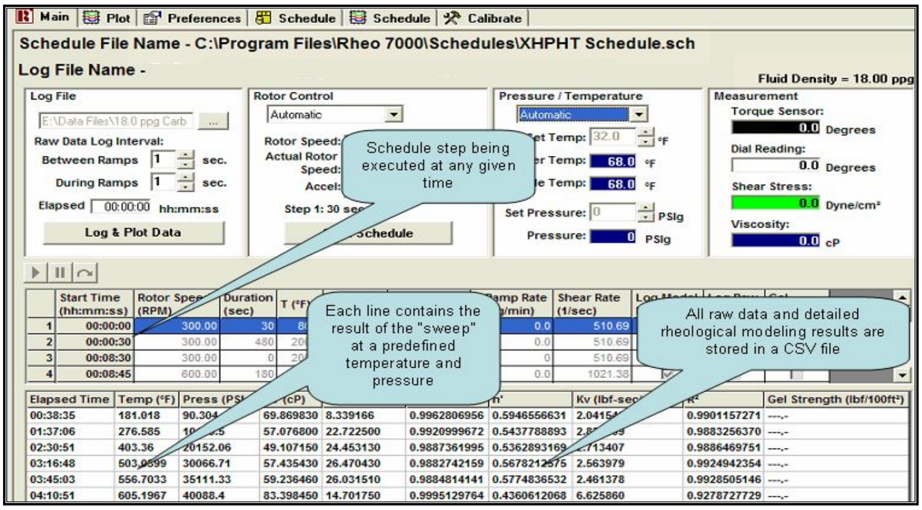

Figure 2
Scheduled Program for Experiments Run

Table 2
Properties of the Two Mud Samples Used in This Study

Sample Type	Fluid Formulation		Mud Properties	
	LVT-200, bbl	0.502	Heat Age Temp, F	150
	Versagel HT, ppb	5.0	Heat Aging Hours	16
	Lime, ppb	10.0	Static/Rolling	R
	Mul XT, ppb	25.0	Mud Weight, ppg	12.5
	Surewet, ppb	5.0	Rheo Temp, F	150
	Water, bbl	0.165	600 RPM	55
	$CaCl_2$, ppb	20.57	300 RPM	34
	CC-555, ppb	1.0	200 RPM	25
HPHT OBM (High Pressure High Temperature Oil-Based Mud)	Barite, ppb	126.66	100 RPM	17
	Micromax, ppb	95.0	6 RPM	6
	SafeCarb 10, ppb	20.0	3 RPM	5
	One-Trol HT, ppb	15.0	PV, cps	21
			YP, lbs/100 ft^2	13
			10 Sec. Gel	7
			10 Min. Gel	7
			E.S., Vts @ 120 F	734
			Synl/Water Ratio	75/25

To be continued

Continued

Sample Type	Fluid Formulation		Mud Properties	
Regular OBM (Regular Oil-Based Mud)	LVT-200, bbl	155.47	Mud Weight, ppg	12.5
	Versagel HT, ppb	5.0	OWR	75/25
	Lime, ppb	8.0	Rheo Temp, F	150
	VersaMul, ppb	9.0	600 RPM	76
	VersaCoat HF, ppb	3.0	300 RPM	51
	Water, bbl	63.64	200 RPM	42
	$CaCl_2$, ppb	22.37	100 RPM	31
	VersaTrol, ppb	6.0	6 RPM	17
	VersaMod, ppb	0.25	3 RPM	16
	M-I Bar, ppb	251.91	PV, cps	25
			YP, lbs/100 ft^2	26
			10 Sec. Gel	23
			10 Min. Gel	33
			E.S., Vts @ 120 F	718

***Courtesy of MI-Swaco**

The experiments were conducted following the experimental design shown in Table 1. During these experiments, dial reading, yield point, 10-sec, and 10-min gel strengths were determined. The working procedure can be summarized by the following steps:

Initializing and setting-up the viscometer: In this step the operator must make sure that pressure and temperature conditions are at ambient conditions. The torque encoder is set to zero.

Loading fluid samples: Before using the samples the fluid samples are mixed, and 175 ml of mud samples are used in the experiments.

Reassembling the vessels: The O-rings and metal ring are placed and an extra 25 ml of mud sample is injected through a syringe port.

Starting the schedule: The heater is turned on to do a pre-determined schedule. After the experiment is finished, and temperature is below 150°F, the pressure is ramped down

Manually releasing the remaining pressure in the pressure lines.

2. RESULTS AND DISCUSSION

Basically, when dealing with drilling mud at high temperature and high pressure, different parameters are influencing the rheology and dynamic behaviors. In brief, the following effects are involved in interpretation of the rheology graphs,

i **Physical Effects:** A temperature rise will lead to an increase in random motions of the molecules which lead to reduction in viscosity. Meanwhile, high pressure conditions increases fluid viscosity. In oil based mud systems the sensitivity of mud to pressure is more than that of water based muds, due to compressibility of oil.

ii **Electrochemical Effects**: The balance between the inter particle attractive and repulsive forces can be altered by changes in salt content of the mud. The solubility of salts are mainly, dependent to pressure and temperature. The imbalance between the intermolecular forces can also lead to flocculation of the particles in mud.

iii **Chemical Effects:** Reactions with clay minerals are intensified at higher temperatures, which can result in changes in rheology of the drilling fluid (Ibeh, 2008).

The results of the tests performed using the two mud samples were used to generate graphs that helped make the following observations about the rheology of the mud samples under the ultra-high pressure/temperature conditions:

2.1 Viscosity

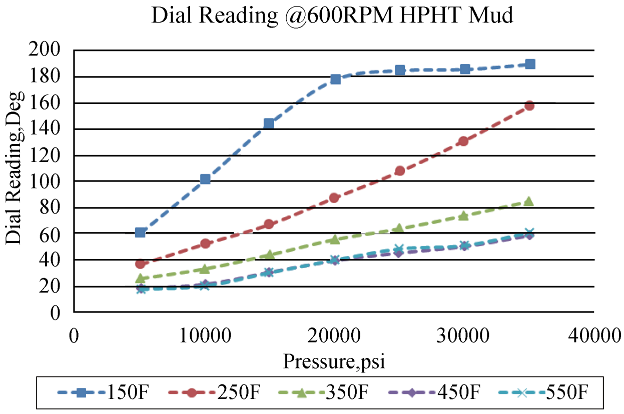

Figure 3
Dial Reading Values Versus Pressure for Different Temperatures at 600 RPM, HPHT Mud

Figure 3 shows the dial reading values for the HPHT mud versus pressure for different temperatures at 600RPM. The plot shows that the viscosity of this sample increased as pressure increased (directly proportional) and decreased as temperature increased (inversely proportional). The trend for increment with pressure was almost exponential.

Viscosity, however, undergoes higher increment with pressure at lower temperatures. The plot, however, shows no indications that the mud sample has failed mainly because of its unique formulation that makes endure HPHT conditions.

Figure 4, on the other hand, shows that the viscosity of the second mud sample (Regular OBM) was also increasing as pressure increased and decreasing as temperature increased. This plot, however, shows an abrupt increase and an inconsistent trend in viscosity at temperatures of 450°F and above. This is an indication that this mud sample has failed under that range of temperatures as it is not designed to withstand ultra-high temperatures and pressures (Lee *et al.*, 2012).

In addition, both Figure 3 and Figure 4 show that the effect of pressure on viscosity was not as predominant as the effect of the temperature.

2.2 Yield Point

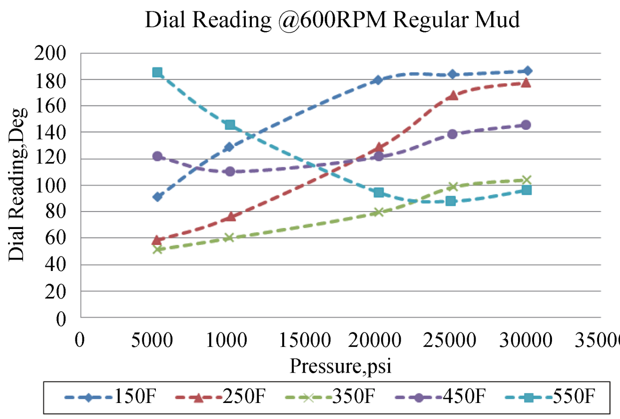

Figure 4
Dial Reading Values Versus Pressure for Different Temperatures at 600 RPM, Regular Mud

Yield Point (YP) is a parameter of the Bingham plastic model. It is the yield stress extrapolated to a shear rate of zero. A Bingham plastic fluid plots as a straight line on a shear rate (x-axis) versus shear stress (y-axis) plot, in which Yield Point is the zero-shear-rate intercept. Plastic Viscosity (PV) is the slope of this line. Yield Point is calculated from 300 and 600 RPM viscometer dial readings by subtracting PV from the 300 RPM dial reading. Yield Point is used to evaluate the ability of a mud to lift cuttings out of the annulus. A high Yield Point implies a non-Newtonian fluid, one that carries cuttings better than a fluid of similar density but lower Yield Point. Yield Point is lowered by adding deflocculant to a clay-based mud and increased by adding freshly dispersed clay or a flocculant, such as lime.

For a Bingham Plastic fluid, stress can be applied but it will not flow until a certain value, the yield stress, is reached. Beyond this point the flow rate increases steadily with increasing shear stress. This is roughly the way in which Bingham presented his observation, in an experimental study of paints. These properties allow a Bingham plastic to have a textured surface with peaks and ridges instead of a featureless surface like a Newtonian fluid.

Figures 5 and 6 show the yield point values for the mud samples with pressure for different temperatures at 600 RPM. Figure 5 shows the yield point for the HPHT Oil Based Mud sample. Similar to viscosity, yield point's plot shows that it was higher for low temperatures and vice versa. Also, it indicates that there is a significant increase in yield point values with pressure when the temperature is low whereas the increment was small for higher temperatures.

Figure 6, on the other hand, shows that yield point for the regular OBM sample also increases as pressure increased and decreases as temperature increased. At temperatures of 450°F and above, however, the behavior of the fluid abruptly changes and becomes inconsistent with the rest of the data which also indicates the failure of this mud.

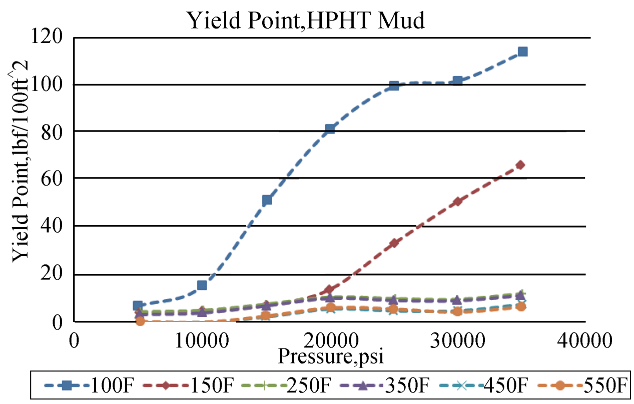

Figure 5
Yield Point Values Versus Pressure for Different Temperatures, for the HPHT Mud

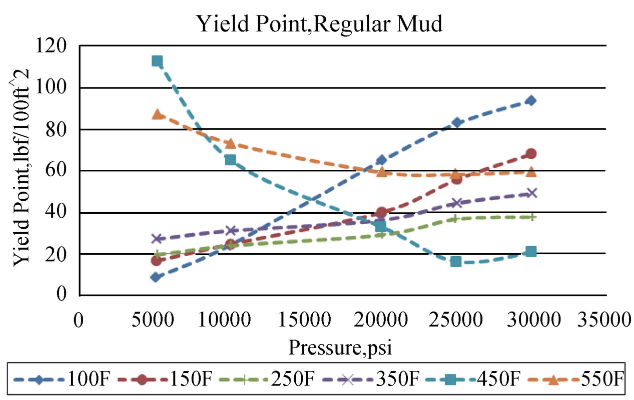

Figure 6
Yield Point Values Versus Pressure for Different Temperatures, for the Regular Mud

2.3 Gel Strength (10-sec & 10-min)

Gel Strength is the shear stress measured at low shear rate after a mud has set quiescently for a period of time (10-seconds and 10-minutes in the standard API procedure, although measurements after 30-minutes or 16-hours may also be made).

Figures 7 and 8 show that the 10-sec and 10-min gel strength for the HPHT OBM sample was increasing as pressure increased but decreasing as temperature increased. Increment of gel strength with pressure was higher at lower temperature.

Figure 9 and Figure 10 show the 10-sec and 10-min gel strength for the regular OBM sample. The trend of gel strength with pressure in for this sample was not very apparent but we could roughly say that the gel strength was increasing as a whole as pressure increased for temperatures at 400°F (failure temperature) and below while this trend is completely different and inconsistent for the 500°F curve.

This behavior of the different rheological properties of the mud samples under high temperature is the result of the thermal degradation of the solid, polymers, and other components of the mud samples and the expansion of the molecules which will lower the resistance of the fluid to flow and, hence, its viscosity, yield point, and gel strength. High pressure, on the other hand, results in compressing of the molecules of the mud and this explains the increase of the viscosity and yield point at higher pressure values.

Finally, from the above observations, it can be concluded that HPHT mud sample did not fail and endured the conditions that it was designed to withstand. The regular mud sample, however, was also resilient to the HPHT conditions but ultimately failed at temperature of 400°F as all the viscosity, yield point, and gel strength curves have undergone abrupt changes in behavior at this point.

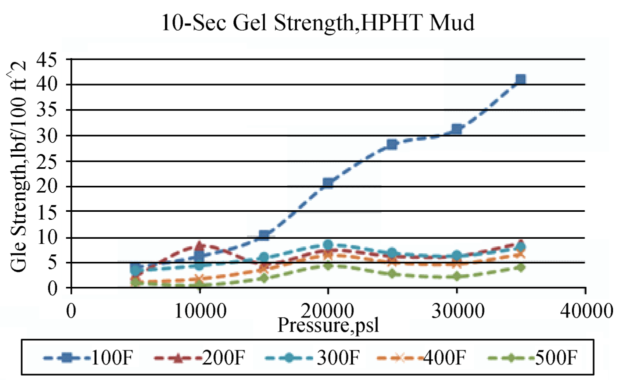

Figure 7
10-sec Gel Strength Values Versus Pressure for Different Temperatures, HPHT Mud

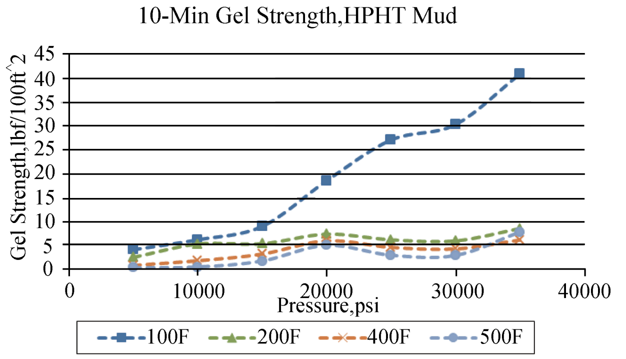

Figure 8
10-min Gel Strength Values Versus Pressure for Different Temperatures, HPHT Mud

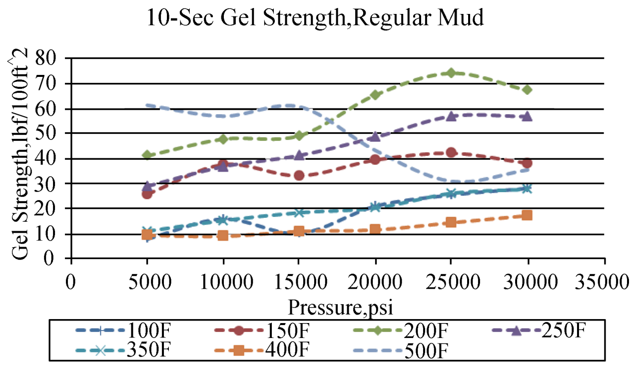

Figure 9
10-sec Gel Strength Values Versus Pressure for Different Temperatures, Regular Mud

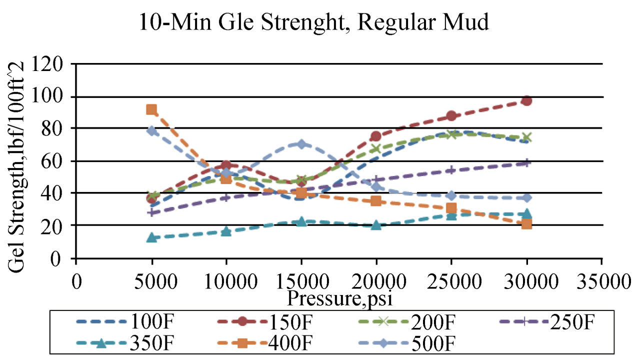

Figure 10
10-min Gel Strength Values Versus Pressure for Different Temperatures, Regular Mud

2.4 Failure Temperature

Failure temperature at a specified pressure is the temperature at which the viscosity of the drilling fluid will reduce dramatically and drilling fluid loses its ability in conveyance of the drilling cuts. Figure 11 shows the variation in rheological profile with the time of the experiment of the Regular OBM (upper plot) and HPHT OBM (lower plot) based on dial readings changes with temperature and pressure. The active line represents the dial reading of the drilling fluid. The dot-dashed line and dotted line are respectively showing the temperature of the sample being tested and applied pressure. Dial readings (active line) are shown in repeated cycles of different RPM values (600, 300, 200, 100, 6 and 3 RPM) with higher RPM values corresponding to longer spikes.

The plot for the Regular OBM (upper plot) shows that the rheological profile (represented by dial reading) was gradually decreasing as a whole as temperature increased which suggests that the mud sample was thermally degrading until a temperature of 420°F at which erratic readings of dial reading that is inconsistent with the rheological profile were observed. This suggests that this conventional oil-based sample failed at this specific temperature.

Under similar conditions, however, the plot for the HPHT OBM (lower plot) shows a consistent rheological profile throughout the whole experiment. Temperature was increased to maximum testing value (>550°F) yet no erratic changes were observed. This sample, due to its special formulation, endured the testing conditions and did not fail although it has undergone thermal degradation as the consistently decreasing rheological profile suggests.

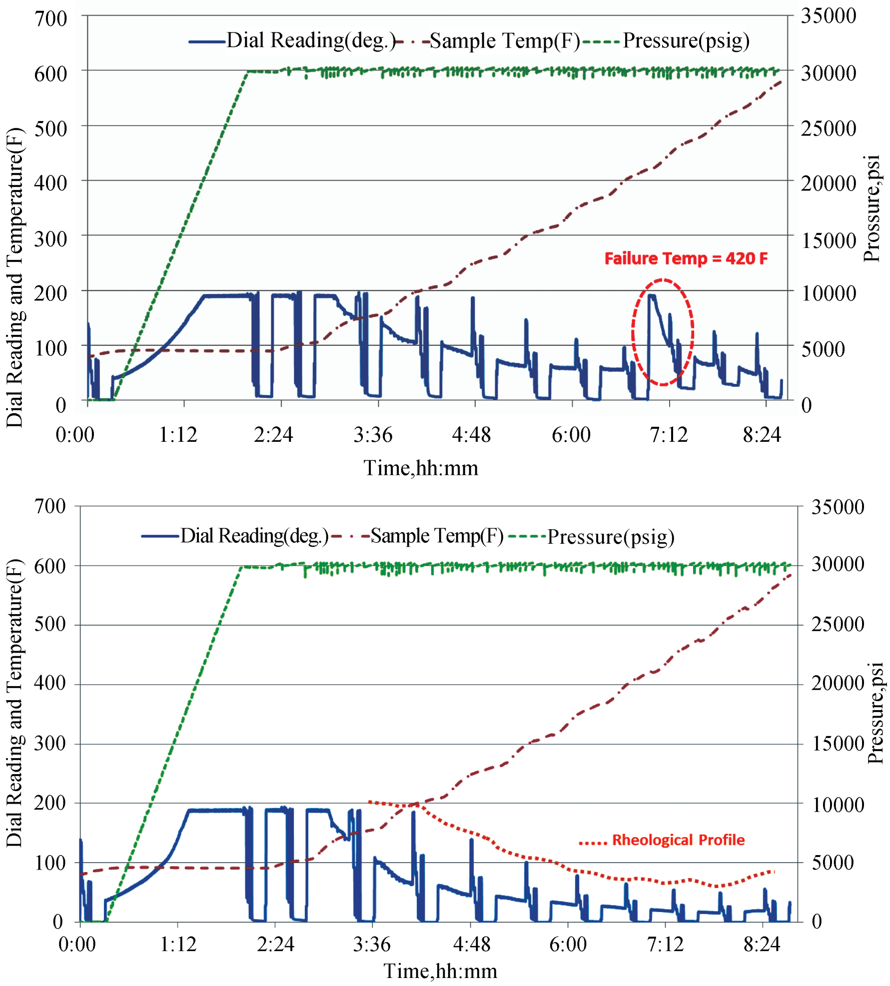

Figure 11
Failure Temperature Calculation Based on Rheology Tests for the Regular Mud (Upper) and HPHT Mud (Lower)

2.5 Data Fitting and Modeling

Herschel-Bulkley relationship was used to mathematically describe the viscosity of the two mud samples that were tested. This model is more realistic than the Power Law model as it takes into consideration yield stress as its formula shows:

$$\tau = \tau_o + ky^n \qquad (1)$$

Where k is equivalent to mud's viscosity.

For the HPHT mud samples and at fixed pressures of 5000 psi (Figure 12) and 35000 psi (Figure 13), the experimental data were fitted, for three different temperatures (100, 300, and 500 F), using Herschel-Bulkley model and an excellent fit was obtained in both cases.

The same procedure was done for the experimental data of the Regular Oil-Based Mud sample (Figure 14 and 15). The mud sample here, however, fails at temperatures above 400 °F and that causes the inconsistency in the trends of the data at different temperatures.

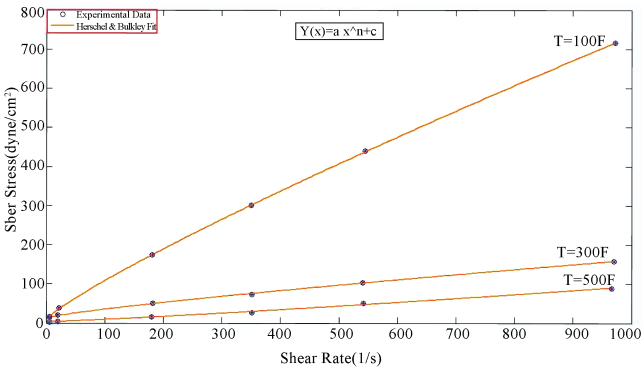

Figure 12
Shear Stress vs. Shear Rate for Three Different Temperatures with Data Fitting According to Herschel-Bulkley Relationship at 5000 psi (HPHT Oil-Based Mud sample)

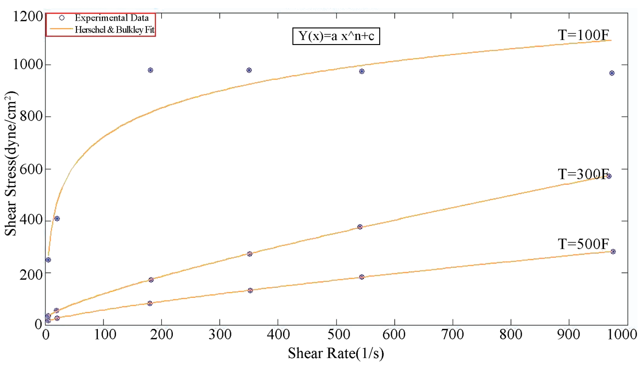

Figure 13
Shear Stress vs. Shear Rate for Three Different Temperatures with Data Fitting According to Herschel-Bulkley Relationship at 35000 psi (HPHT Oil-Based Mud Sample)

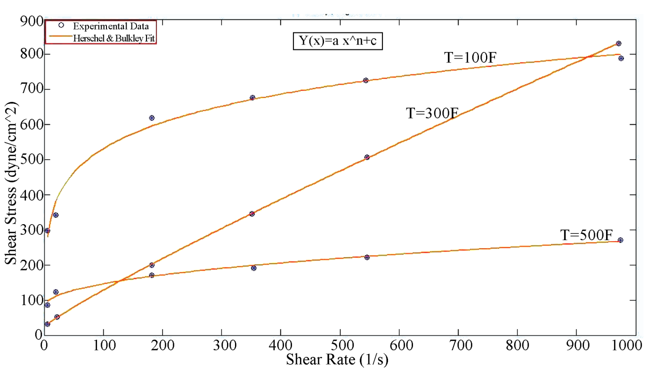

Figure 14
Shear Stress vs. Shear Rate for Three Different Temperatures with Data Fitting According to Herschel-Bulkley Relationship at 5000 psi (Regular Oil-Based Mud Sample)

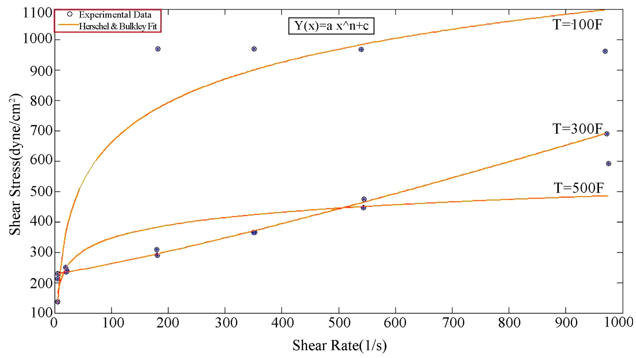

Figure 15
Shear Stress vs. Shear Rate for Three Different Temperatures with Data Fitting According to Herschel-Bulkley Relationship at 35000 psi (Regular Oil-Based Mud Sample)

2.6 Pressure & Temperature Dependence of Viscosity

In order to provide a mathematical description for viscosity dependence on pressure, Dial Readings at different RPMs and at fixed temperatures were graphed against pressure for the two mud samples that were tested (Figure 16, 17, and 18). An exponential function in the form (2) was used to generate a fitting for the experimental data and a very good match was obtained especially at lower temperature (250°F) for both mud samples (Figure 16,17, and 18). This further confirms the directly proportional relationship between viscosity and pressure (Lee *et al.*, 2012).

$$\mu = a*e^{(b*P)} \quad (2)$$

Where a and b are constants and P is the pressure.

Temperature dependence of viscosity was also examined and the Dial Readings at different RPM's and at two different pressures (5000 and 35000 psi) were graphed against temperature for both mud samples (Figure 19, 20, 21, and 22). For the HPHT OBM sample, trends in the experimental data were apparent and an exponential function of the form (3) generated a very close fitting to the experimental data (see Figures 1 and 2). This further confirm the inverse relationship between viscosity and temperature For the Regular OBM samples, it was hard to obtain a data fit because the sample fails at temperatures above 400°F (see Figures 3 and 4).

$$\mu = a*e^{(b/T)} \quad (3)$$

Where a and b are constants and T is the Temperature.

It is also worth noting that the exponential models that were used to fit the experimental data of the two mud samples are close to Arrhenius equation of temperature dependence of viscosity (Lee *et al.*, 2012).

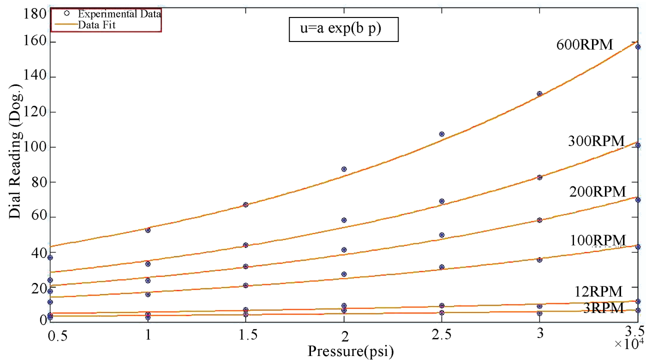

Figure 16
Viscosity (Dial Reading) as an Exponential Function of Pressure at 250°F and for Different RPM Values (HPHT OBM)

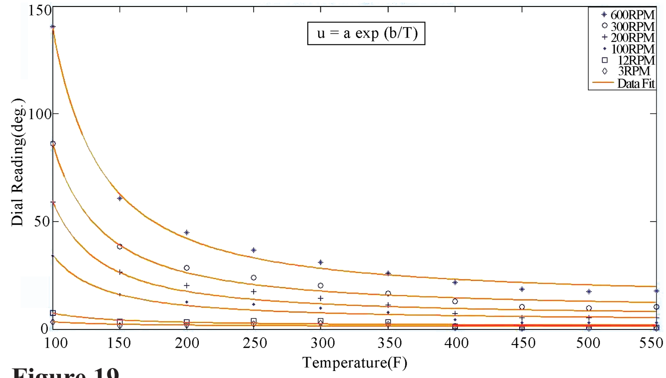

Figure 19
Viscosity (Dial Reading) as an Exponential Function of Temperature (1/T) at 5000 psi and for Different RPM Values (HPHT OBM)

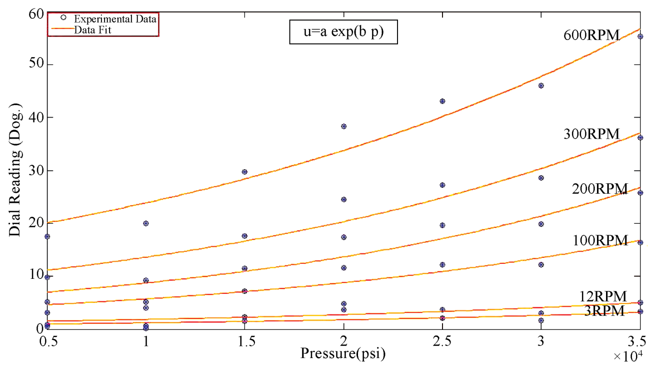

Figure 17
Viscosity (Dial Reading) as an Exponential Function of Pressure at 500°F and for Different RPM Values (HPHT OBM)

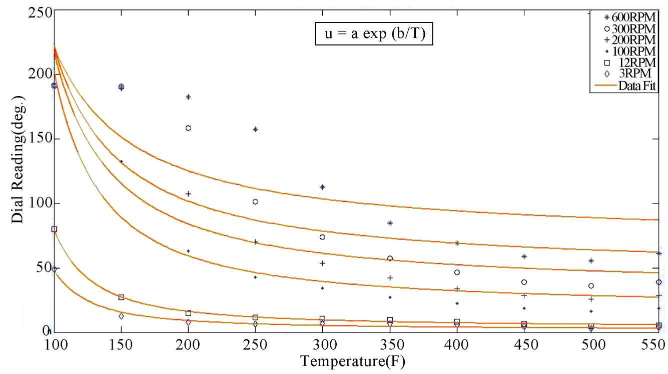

Figure 20
Viscosity (Dial Reading) as an Exponential Function of Temperature (1/T) at Fixed 35000 psi and for Different RPM Values (HPHT OBM)

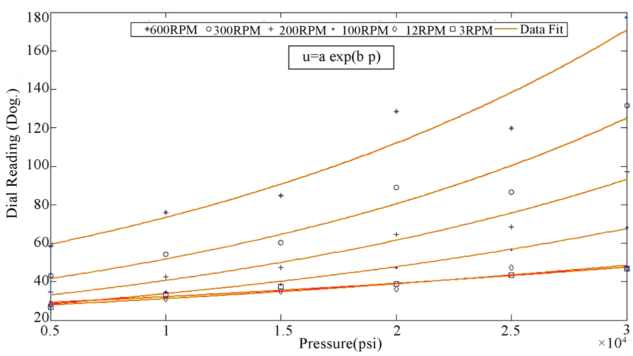

Figure 18
Viscosity (Dial Reading) as an Exponential Function of Pressure at 250°F and for Different RPM Values (Regular OBM)

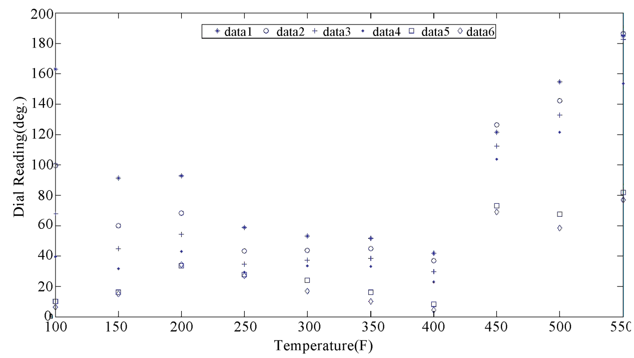

Figure 21
Dial Reading vs. Temperature for Regular OBM at 5000 psi Showing that the Trend is Lost at Temperatures Above 400 F at Which is the Failure Temperature of This Sample

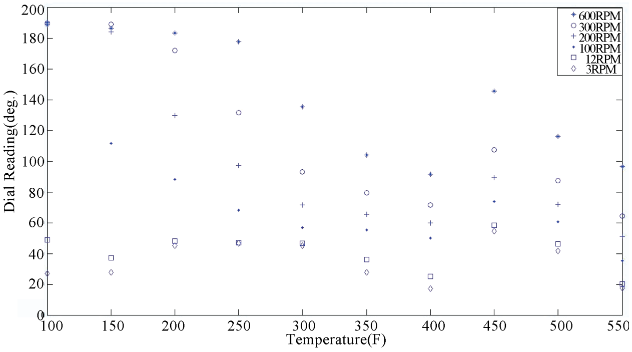

Figure 22
Dial Reading vs. Temperature for Regular OBM at 35000 psi Showing that the Trend is Lost at Temperatures Above 400 F at Which is the Failure Temperature of This Sample

CONCLUSIONS

Based on rheology tests at high pressure and high temperature conditions on two drilling muds used for drilling operations in Qatar the following conclusions are drawn:

Viscosity, yield point, and gel strength have inversely proportional relationship with temperature.

Increasing the pressure results in higher viscosity and yield point when the temperature is lower than the failure point.

The effect of pressure on mud's rheology is not as predominate as temperature's effect.

The oil based mud sample with regular formulation failed at temperature of 400^{o}F.

The oil based mud sample designed to withstand HPHT conditions did not fail.

The combined effect of temperature and pressure on oil based mud's rheology is complex.

The temperature and pressure dependence of viscosity follow the exponential model.

Herschel-Bulkley model provides excellent match to the experimental data and can be used to predict the rheological behaviour of the HPHT mud sample.

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