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The Effect of High Pressures and High Temperatures on the Properties of Water Based Drilling Fluids

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Abstract

Tremendous amounts of hydrocarbons are located in deeper formations where higher pressures and temperatures are experienced. Designing a proper drilling fluid that can tolerate such high-pressure, high-temperature (HP/HT) conditions is a challenging task. The work presented in this paper is focused on investigating the rheological behavior of water-based drilling fluids with different properties at extremely high pressure and temperature conditions using a state-of-the-art viscometer capable of measuring drilling fluids properties up to 600 °F and 40,000 psig. The results of this study show that the viscosity, yield point and gel strength decrease exponentially with increasing temperature until the mud samples fail. This behavior is the result of the thermal degradation of the solid, polymers, and other components of the mud samples. Increase in intermolecular distances due to high temperature will lower the resistance of the fluid to flow and, hence, its viscosity, yield point, and gel strength will decrease. Moreover, conducting this study led to the conclusion that viscosity, yield point, and gel strength increase linearly as the pressure increases. Pressure's effect on these parameters, however, is more apparent at lower temperatures. Ultimately, the study concluded that the mud samples that were used, which are standard industrial types, failed at a temperature of 250 ^{o}F and that the combined effect of temperature and pressure on mud's rheology is complex.

Key words: Drilling fluids; HPHT; Rheology; Water based mud

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INTRODUCTION

It is evident that significant amounts of oil and gas lie within deep formations. Temperature and pressure, however, increase with depth and, therefore, producing from such zones involves several challenges to petroleum engineers in terms of drilling, completion, and production. Among these challenges is the alteration of the rheological properties of drilling fluid[1].

Understanding the rheological characteristics of the drilling fluids under elevated pressures and temperatures is essential for the drilling engineers. The general practice has been to measure a fluid's flow characteristics under ambient surface conditions and extrapolate these measurements to downhole conditions. This requires a reliable model of how the rheology of the fluid changes with the variations in temperature, pressure and shear history which it experiences during circulation inside the wellbore[1].

Despite considerable experimental studies over the years, there is relatively little systematic understanding of how the flow behavior changes with downhole conditions. The rheology of the fluid is influenced by many factors including temperature, pressure, shear history, composition and the electrochemical character of the components and of the continuous fluid phase[1].

This work focuses on investigating the rheological behavior of water-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 psig. Understanding the effect of these two factors, high temperature and pressure, is crucial for the purpose of designing an acceptable drilling fluid that can function properly in such environment.

Although oil based mud is usually a preferred choice for HPHT drilling due its inherent high thermal stability, there are several limitations that made developing HPHT water based mud a necessity. First, using oil based muds is prohibited in many places around the world (e. g., Europe) due to environmental reasons. Also, high gas solubility in oil based muds increases the risk of getting kicks and, hence, requires more cautious control procedures. For these reasons, formulating a water based mud capable of enduring HPHT conditions became inevitable.

Therefore, there have been few endeavors to investigate the behavior of water based fluids under HPHT conditions over the last few decades. Taking a quick look at the literature available on this issue, however, we can see that for all the previous studies, the testing temperature did not exceed 500 ^{o}F and the testing pressure were usually less than 20000 psi and hence the importance of the study presented in this paper as it tested water based mud for temperature and pressure ranges that have never been applied before (temperature up to 550 ^{o}F and pressure up to 35,000 psi).

1. MATERIALS AND METHODOLOGY

Chandler Model 7600 Ultra-HPHT Viscometer, a concentric cylinders viscometer, is used as the main viscometery device in this study, as shown in Figure 1. This system uses a rotor and bob geometry for rheology parameters measurement and its precision and applicability is widely approved for applications in petroleum industry. This equipment meets ISO and API standards for viscosity measurement of completion fluids under HPHT conditions[2].

To determine the conditions under which water based drilling fluids of certain compositions fail and find out the effect of high temperature and high pressure on the rheological properties of water based mud, two water based mud samples were chosen to carry out a matrix of experiments. These samples were actual drilling fluids used by industry for drilling at large depths where pressure and temperature are relatively high. Table 1 lists the properties of these two samples.

The first step in the experimental work was to create a matrix of experiments to be performed. This matrix is shown in Table 2. The experiments were first performed on an 8.6 ppg water based mud for a range of pressures and temperatures. In order to find the effect of specific variables, temperature and pressure, namely, the pressure was kept constant in each experiment while the temperature was ranged from room temperature to 500 ^{o}F in 50 ^{o}F intervals. This allowed the analysis of the effect of temperature on viscosity of water based muds under HPHT conditions. Then, pressure was raised and kept constant with the same temperature steps. During these experiments, fluid's plastic viscosity, yield point, and 10-sec gel strengths were determined at each step.

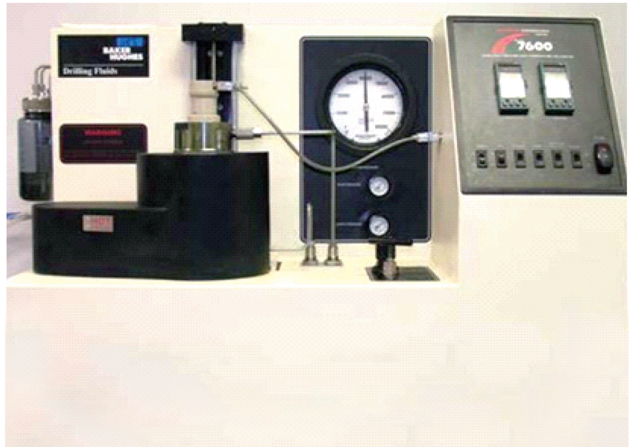

Figure 1
Chandler Model 7600 HPHT Viscometer

Table 1
Properties of the Two Mud Samples Used in the Study

Mud properties		
Properties	**Mud sample 1**	**Mud sample 2**
Sample From	ACTIVE	OUT
Time Sample Taken	19:00	23:00
Flowing temp (F)	144	120
Depth (ft)	10392	9018
TVD (ft)	6250	6411
Mud weight (ppg)	8.6	9.9
Funnel Viscosity (sec/qt)	38	38
Temp. for PV (F)	120	120
Plastic Viscosity (cp)	5	8
Yield Point (lbf/100 ft^2)	15	14
Gel Strength (10 sec)(lbf/100 ft^2)	4	4
Gel Strength (10 min)(lbf/100 ft^2)	5	5
Gel Strength (30 min)(lbf/100 ft^2)	6	6
API Filtrate (ml/30 min)	4.6	3.8
Cake Thickness API (1/32 in)	0.5	1
Solids Content (%)	2.5	10
Oil Content (%)	1	0
Water Content (%)	96.5	90
Sand Content (%)	0.1	
MBT Capacity (lb/bbl)	0.5	0.1
pH	9.2	9.7
Mud Alkalanity (Pm)(ml N50 H_2SO_4)	0.44	0.6
Filitrate Alkalanity (Pf)(ml N50 H_2SO_4)	0.19	0.15
Filtrate Alkalanity (Mf)(ml N50 H_2SO_4)	0.74	0.3
Calcium (mg/L)	720	480
Chlorides (mg/L)	9000	160000
Total Hardness (mg/L)	860	650
Excess lime (lb/bbl)	0.01	0.11
K^+ (mg/L)		
Make up water Chlorides (mg/L)	7000	8000
Solids adjusted for salt (%)	1.64	-0.71
SO_3 (ppm)	10	150

Table 2
Experimental Matrix

Run #	Mud sample used	Pressure (psi)	Temperature range (°F)
1	8.6 ppg	5000	70-500
2	8.6 ppg	15000	70-500
3	8.6 ppg	25000	70-500
4	8.6 ppg	35000	70-500
5	9.9 ppg	15000	70-500

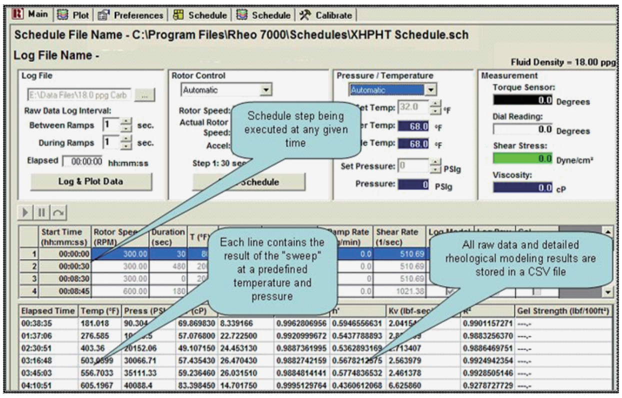

Figure 2
Scheduled Program for Experiments Run

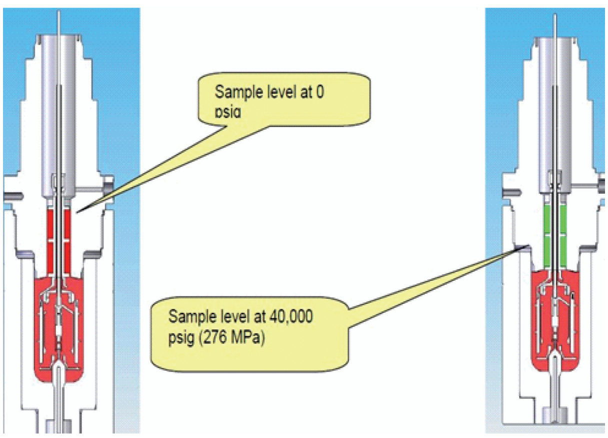

Figure 3
Pressurizing Process for Chandler Model 7600 HPHT Viscometer

The experiment matrix, which involved varying the temperature and pressure, showed the impact of changing these two parameters on viscosity profile. In addition, an experiment was conducted for the 9.9 ppg mud while keeping the same pressure value and temperature profile for the purpose of comparison with the results from the 8.6 ppg mud sample. This experiment showed the effect of mud density on viscosity profile for water based muds. During all of these experiments, 10-second gel strength readings were recorded and plots were generated. Moreover, a scheduled program was used to control the steps of each experiment as shown in Figure 2.

The experiments were conducted following the experimental design shown in Table 2. During these experiments, dial reading, yield point, and 10-sec gel strengths were determined at each step. Figure 3 shows the pressurizing process for Chandler Model 7600 HPHT Viscometer.

2. RESULTS AND DISCUSSION

According to the results obtained from the experiments, the role of high temperature and high pressure condition on different properties of drilling fluid is discussed below.

2.1 Plastic Viscosity

Plastic Viscosity (PV) is the slope of the shear stress versus shear rate line above the yield point. Based on its definition, plastic viscosity represents the viscosity of the mud when extrapolated to infinite shear rate. Figure 4 show that plastic viscosity decreases with the increase in temperature. An increase in temperature significantly reduces the plastic viscosity of the mud sample to very low values (less than 1 cp). This reduction is independent of pressure. It is shown that Mud Sample # 1 loses its resistance to flow at temperatures above 350 °F.

Also, Figure 4 shows that the increase in pressure increases the value of plastic viscosity. Compared to the effect of changing the temperature, however, the effect of changing pressure values was not as pronounced. Nonetheless, the effect of pressure on plastic viscosity was more apparent at temperatures lower than 250 °F.

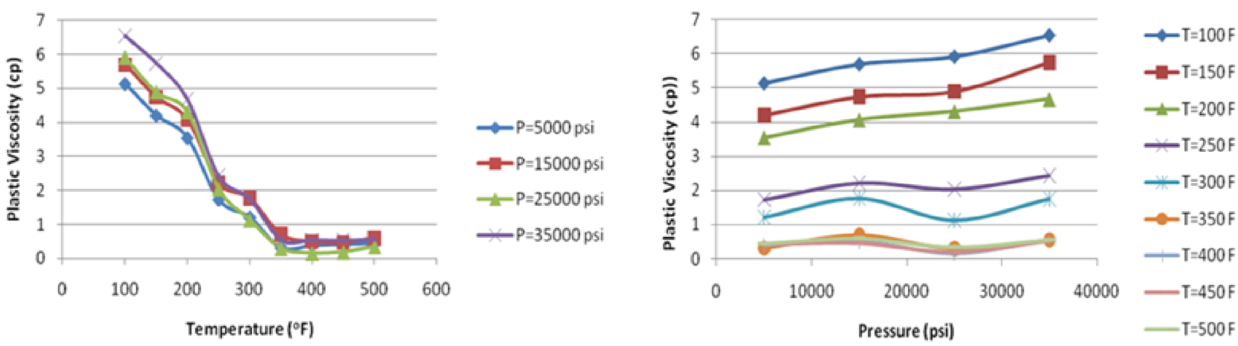

Figure 4
Plastic Viscosity Versus Temperature (Left) and Plastic Viscosity Versus Pressure (Right)

2.2 Viscosity

Figure 5 compares the viscosity values at different rotor speeds and for two models, Bingham Plastic and Power Law. The graphs show that the lower the shear rate, the higher the viscosity for both models. In addition, these graphs show patterns of viscosity with temperature and pressure similar to those shown in plastic viscosity graphs. Viscosity was decreasing with increasing temperature until a temperature value of 350 °F after which the viscosity plateaued at minimal values for all the different rotor speeds for both models. Similarly, increasing pressure resulted in higher viscosity values; especially at lower temperatures (lower than 250 °F). Again, the effect of pressure on viscosity was not as pronounced as the effect of temperature.

2.3 Yield Point (YP)

Figure 6 shows that the yield point for Mud Sample # 1 was generally decreasing with temperature until a temperature of 250 °F at which the yield point dropped to a minimal value. For temperatures higher than 250 °F, the curve for yield point plateaued with slight increment. Moreover, Figure 6, shows that increasing the pressure values results in higher yield point until the pressure reached a value of 15000 psi after which there was drop in the yield point at a pressure value of 25000 psi followed by a plateau in the case of high temperatures, or a significant increase in the case of low temperature. In other words, the effect of pressure is more apparent at lower temperatures.

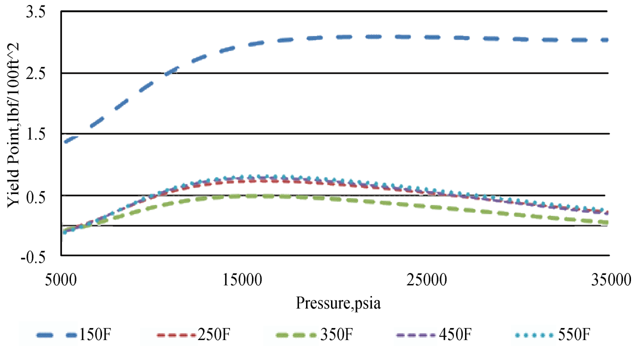

Figure 6
Yield Point Values Versus Pressure for Different Temperatures at 600 RPM, 8.6 ppg Mud

2.4 Gel Strength (10-sec)

Figure 7 shows the effect of varying temperature and pressure on 10-sec gel strengths of Mud Sample # 1. This figure shows that gel strength was decreasing with increasing temperature until a temperature of 250 °F after which there was a general increase in gel strength.

Moreover, this figure shows that increasing the pressure reduces the gel strength until a pressure of 25000 psi after which there was an increase in the value of the gel strength. The effect of pressure, however, was more apparent at lower temperatures (below 250 °F).

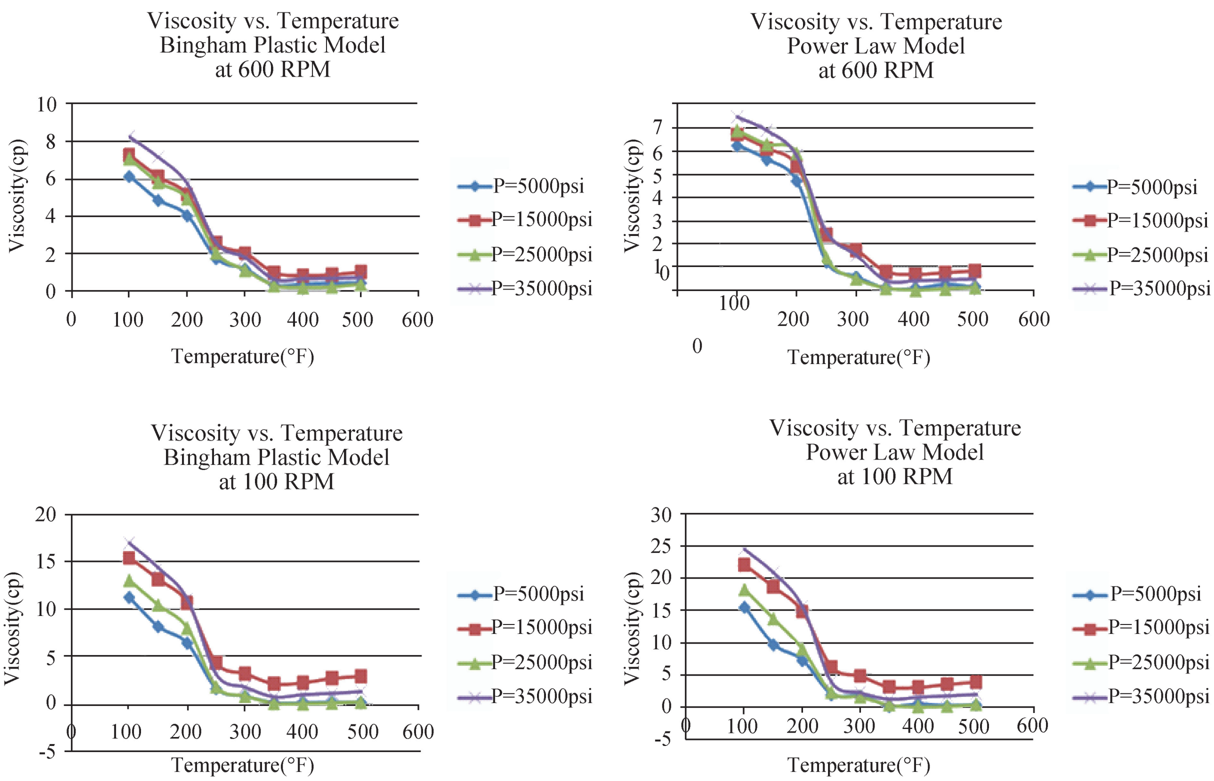

Figure 5
Viscosity vs. Temperature for Different Pressures for 600 and 100 RPM for Bingham Plastic and Power Law Models

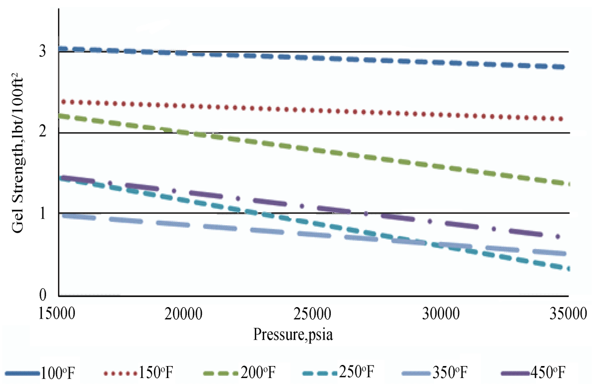

Figure 7
Gel Strength (10-sec) Values Versus Pressure for Different Temperatures, 8.6 ppg Mud

2.5 Comparing the Rheology of the Two Mud Samples

Figure 8 compares the Yield Point (YP) and Plastic Viscosity (PV) for Mud Samples # 1 and # 2 for varying temperatures and pressures. This figure shows that the yield point for the lower density mud (8.6 ppg) was slightly higher until a temperature of 300 °F after which the difference between the two muds' yield points was growing greater. Viscosity, on the other hand, was higher for the heavier mud sample (9.9 ppg) until a temperature of 400 °F after which the viscosity for both samples was very low and approximately similar.

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. On the other hand, high pressures result in compressing the mud's molecules. This explains the increase of the viscosity, yield point and gel strength at higher pressure values[3]. Technically, it seems that both mud samples failed at temperature of 250 °F as all the curves of viscosity, yield point, and gel strength have undergone abrupt changes in behavior at this point.

2.6 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 to convey drilling cuts. Figure 9 shows the variation in rheological profile with respect to time of the experiment for the 8.6 ppg mud. This figure shows that the dial reading changes with temperature and pressure. The real line represents the dial reading of the drilling fluid. The dot-dashed and dashed lines respectively show the temperature of the sample being tested and applied pressure. Dial readings (real 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 indicates that the rheological profile was gradually decreasing as temperature increased. This suggests that the mud sample was thermally degrading until a temperature of 250 °F after which erratic readings of dial readings that were inconsistent with the rheological profile were observed. This suggests that this mud sample failed at this specific temperature.

2.7 Data Fitting

Viscosity data obtained from the experiments were fitted using Herschel-Bulkley model. This model provides a more realistic mathematical description of viscosity than the Power Law model which ignores the yield stress of the mud. The formula for the Herschel-Bulkley Model is:

$$\tau = \tau_o + k\gamma^n$$

Where k is the consistency index (equivalent to viscosity), τ_o is the yield stress, and n is the model index.

The data were fitted for all the tested temperature and pressures. For instance, Figure 10 shows the curves for different temperatures at constant pressure of 5000 psi with Herschel-Bulkley fit whereas Figure 11 shows the same curves and fit but at different pressure of 35000 psi for the same 8.6 ppg mud sample.

These two figures indicate that the experimental data closely match Herschel-Bulkley fit especially at higher pressure (Figure 11) which reduces the impact of high temperature on the mud viscosity. Figure 10 shows that the fit is lost at temperature of 250 °F and above which is an indication of the mud failure.

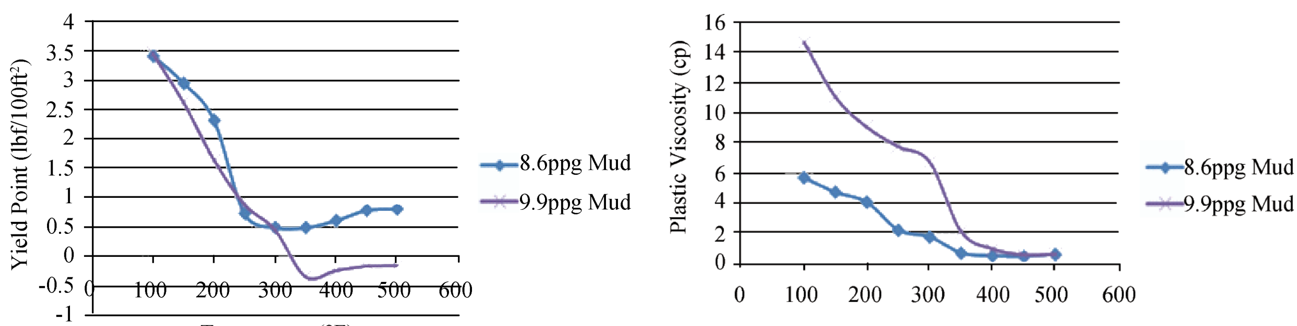

Figure 8
A Comparison of the Yield Point (Left) and the Plastic Viscosity (Right) for the Two Mud Samples at Different Temperatures

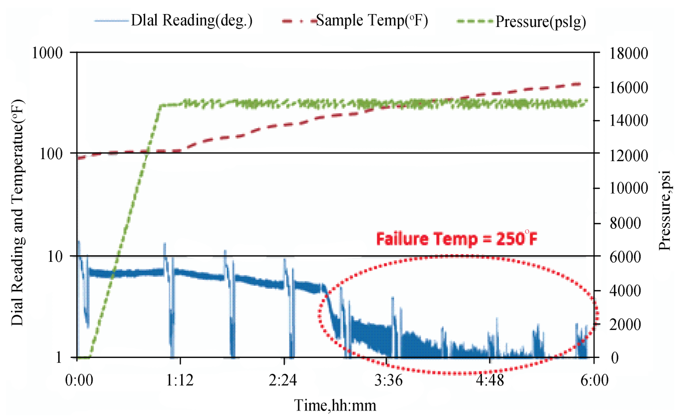

Figure 9
Failure Temperature Calculation Based on Rheology Tests for 8.6 ppg Water Based Mud

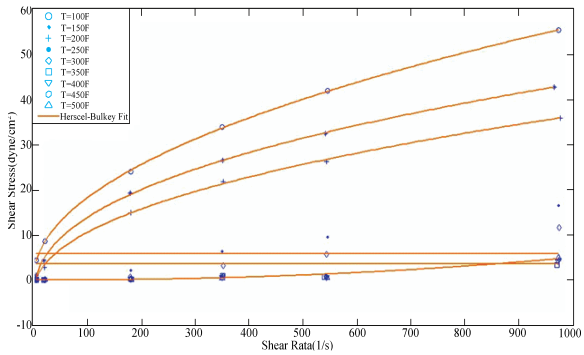

Figure 10
Shear Stress vs. Shear Rate for Three Different Temperatures with Data Fitting According to Herschel-Bulkley Relationship at 5000 psi (8.6 Mud Sample)

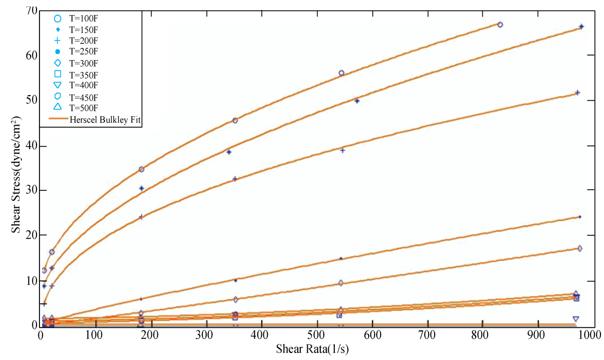

Figure 11
Shear Stress vs. Shear Rate for Three Different Temperatures with Data Fitting According to Herschel Bulkley Relationship at 35000 psi (8.6 ppg Mud Sample)

CONCLUSIONS

In this study, the effect of high temperature and high pressure on the rheological properties of water based mud was investigated. Furthermore, the conditions under which water based mud of certain composition fails were determined. These mud samples, 8.6 ppg and 9.9 ppg density, were provided by one of the companies operating in Qatar. Based on the results of the tests performed, the following conclusions were made:

(1) Increase in pressure results in higher yield point until the pressure reaches a value of 15,000 psi after which the yield point drops. The effect of pressure on yield point is more apparent at lower temperatures.

(2) Plastic viscosity of mud decreases with the increase in temperature.

(3) Compared to the effect of changing the temperature, the effect of changing pressure is less pronounced. The effect of pressure on plastic viscosity is more apparent at temperatures less than 250 °F.

(4) Increasing pressure results in higher viscosity values, especially at low temperature values (lower than 250 °F). Viscosity decreases with increasing temperature until a temperature value of 350 °F after which the viscosity plateaus at minimal values for all different rotor speeds. The effect of pressure on viscosity is not as predominant as the effect of the temperature.

(5) Gel strength decreases with increasing temperature until a temperature of 250 °F after which there is a general increase in gel strength. Increasing the pressure reduces the gel strength until a pressure of 25,000 psi after which the value of the gel strength increases. The effect of pressure is more apparent at lower temperatures (below 250 °F).

(6) The yield point for lower density muds is higher until a temperature of 300 °F. Viscosity is higher for heavier mud samples until a temperature of 400 °F after which the difference between different mud weights is reduced. Gel strength is generally higher for lower density mud. The mud samples failed at temperature of 250 °F.

(7) Temperature and pressure can have complex effect on mud's rheology.
(8) Herschel-Bulkley model provides a good mathematical description of the viscosity of water based muds especially at temperatures lower than the failure temperature of the mud.

It is important to note that these conclusions were drawn from the observations made from conducting this study and hence they are pertinent to the specific mud samples used in the study. Muds with different formulations and weights might show slightly different responses to changing temperature and pressure but the general behavior of the mud is expected to roughly be analogous.

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