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MODELING OF RHEOLOGICAL PROPERTIES OF DRILLING FLUIDS FOR ULTRA HIGH PRESSURE / HIGH TEMPERATURE (HPHT) OIL AND GAS WELLS

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ABSTRACT

Determination of mud properties at ultra HPHT deep wells has been a challenge in the Oil and Gas industry. Conventional mud designs and test equipment fell short of addressing inherent problems associated with these types of wells. This paper presents a novel approach in determining and modeling rheological properties of mud under this ultra high temperature and high pressure regime. Water based mud was formulated with special additives to enhance stability under such elevated temperature and pressure. Tests were conducted at 450, 460, 470, 480, 490 and 500°F as well as pressure of 9500, 9600, 9700, 9800, 9900 and 10000 psi. Using test results indicated that rheological property is a function of temperature, pressure and also the interaction effect of temperature and pressure respectively. Model coefficients were obtained using multiple regression analysis in visual basic.dot net software. The models which predicted the rheological properties with respect to temperature and pressure were developed. Results calculated from the model equations showed a good agreement with experimental values with less than 1% deviation. This will help predict rheological properties and rank the best of the models at high temperature and pressure thereby saving time and rigour associated with actual laboratory tests. Also, the generated mathematical equations for apparent viscosity, plastic viscosity, and yield point and gel strength will provide proactive step for practical drilling experience and for well planning.

Keywords: Apparent Viscosity, Plastic Viscosity, Yield Point, Gel strength, Temperature and Pressure.

INTRODUCTION

Most formations are at a very high temperature and pressure at a considerable high depth into the earth. Ultra HPHT wells are considered above 4000 metres (13300 ft) with temperature and pressure above 300 ^{O}F and 10,000 psi respectively Kirk (2001). Hence there is the need for a proper balance of this temperature and pressure to avoid oil and gas surge, kicks, formation damage and other hazards. Drilling a geothermal oil and gas well involves special problems like; high temperature, high pressure, high salinity, and formations of soft or fragmented rocks, making conventional chemical additives for drilling fluids quite unsuitable for use. Therefore advances and modifications in formulation or the development of entire new drilling-fluid materials is a matter of continuous research. Designing a fit-for-purpose drilling fluid for HPHT operation is one of the greatest technological Challenges facing the Oil and Gas industry today (Ibeh 2007). This has led to recent breakthrough, and many new techniques have been developed to profit from the abundance of oil and gas in an HPHT area. The demand for oil and gas is increasing by the day, to meet this demand, oil and gas need to be discovered in environments new to the petroleum industry. To do this, technologies used in conventional terrains need to be modified to adapt to this environments.

For HPHT wells, it is evident by the new set of drilling fluids designs and applications. Oil and gas production wells are now drilled more or less routinely in HPHT fields even though drilling is often more difficult, expensive, and dangerous than for any oil and gas well of equal depth for a normal temperature and pressure wells. A successful drilling of deep HPHT wells critically depends on the rheological properties of the drilling fluids designed for specific down hole conditions. Most times the rheological properties of drilling fluids under hole conditions may be very different from those measured at the surface conditions.

DEVELOPMENT IN HPHT DRILLING FLUIDS

Review of literatures showed that for non-HPHT wells, the effects of pressure and temperature on mud weight is minimal and can be ignored. However, for HPHT wells the effects of pressure and temperature on surface mud weight, the equivalent down-hole mud weight, and the equivalent circulating density (ECD) must be taken into consideration because of their relationship with rheological properties. Early investigation into the effects of temperature on the rheological properties of drilling fluids were performed by Bartlett in 1967 .The study showed significant decrease in viscosity (by half) of a particular ligno-sulfonate mud when its temperature was increased from 80^{O}F to 140^{o}F (Bartlett. 1967). Alderman et al.(1988) made measurements of the rheology of a range of water-based drilling fluids at temperature up to 266^{O}F and pressure up to 14,500 psig. The data was then used for a three-parameter Hershel-Bulkley yield / power –law model. However, in some cases a two-parameter equation gave a more acceptable fit (Casson 1959). In both models, it was observed that the behavior of the high-shear viscosity reflected the viscous nature of the continuous phase, a weak pressure dependence and exponential temperature dependence similar to that of water.

MODEL DESIGN

A number of rheological models, based on mathematical equations relating shear stress and shear rate in laminar flow conditions have been developed in order to predict fluid behavior at shear rates other than those actually tested. However most drilling fluids are too complex to allow a single set of equations to be used in determining their behavior under all conditions. Therefore the utilization of the appropriate rheological model together with shear stress / shear rate data obtained from a suitable instrument allows accurate determination of the fluid behavior under varying flow conditions found in the oilfield. This data then forms the basis for further calculations used to determine several important aspects related to the drilling fluid's performance. This model used a multiple regression analysis for a two factor factorial and investigated the relationship between the effects of HPHT on rheological properties. Data from the experimental rheologies were assembled and the regression analysis done, this can estimate the quantitative effect of temperature and pressure (Montgomery 1991). The statistical significant of the estimated relationship provided the degree of confidence, that is if the true relationship was close to the estimated relationship. The mathematical model described the relationship between a dependent variable (say-plastic viscosity) and its independent variables, (say-temperature and pressure). Montgomery et al (2003) stated that a regression model containing more than one regressor variables is called multiple regression and the dependent variable can be related to the regressor variables mathematically as;

$Y = \beta_0 + \beta_1 x + \beta_2 x_2 + \ldots. + \beta_k x_k + \varepsilon$……………………….(1)

Where the parameters:

x_1, x_2------------x_k , the regressors

$\beta j =$ 0, 1,…..,k are known as the regression coefficients.

Y is the dependent variable

Multiple regressions is also applicable to models with interaction effects like temperature and pressure. The interaction between the two variables can be represented by a cross-product in the model as:

$Y = \beta_0 + \beta_1 x_1 + \beta_2 x_2 + \beta_1\beta_2 x_1 x_2 + \varepsilon$…………………… (2)

Multiple regression actually is a technique that allows additional factors to enter the analysis separately so that the effect of each can be estimated(Montgomery et al.2003).

MATERIALS AND METHOD

The laboratory experiment were executed according to the factorial design concept. A series of test were performed to evaluate the performance of the drilling fluids relative to its rheological behaviors. A homogeneous mixture was obtained at 70 RPM for 5-10 minutes using the Hamilton constant speed mixer. The initial shear stress values were obtained using the Fann 35 viscometer. The Fann 35 viscometer is of the rotational coaxial-cylinder type used to measure directly six rotational speeds (600,300,200,100, 6 and 3 rpm.). The shear stress (scale reading) is determined as a function of the shear rate (from the rotational speed). The apparent viscosity(AV), plastic viscosity(PV), yield point(YP) and gel strength(GS) were mathematically deduced from the shear stress values corresponding to the shear rate., that is: AV=600rpm(value)/2, PV= 600rpm(value)-300rpm(value), YP=300rpm(value)-PV. The gel strength is a direct measurement from 3 rpm reading depending if it is 10 seconds or 10 minutes gel. The second phase of the testing used XHPHT Chandler viscometer, temperature and pressure were simultaneously increased and the fluid's plastic viscosity, yield point and gel strength determined at each increment. The Chandler model 7600 Ultra-High Pressure High Temperature viscometer(Chandler 2007) is a concentric cylinder viscometer that uses a rotor and bob geometry. All the test were conducted in line with standard ISO and API procedures for viscosity measurement at high temperature and pressure (API 1995, API 2007) .

RESULTS AND DISCUSSION

Table-1: XHPHT POLYMER SYSTEM

	A	**B**	**C**	**D**	**E**	**F**
Test temperature. (°F)	**450**	**460**	**470**	**480**	**490**	**500**
FLUID ADDITIVES: (Kg/m3)						
Driscal D: (HPHT fluid loss)	8	8	8	8	8	8
Caustic Soda : (alkalinity)	0.5	0.5	0.5	0.5	0.5	0.5
Sepiolite : (HPHT gel)	25	25	25	25	25	25
Thermatin : (HPHT fluid loss)	3	3	3	3	3	3
Safe Carb 10 : (weighting agent)	60	60	60	60	60	60
EMI-1048 : (HPHT thinner	1.5	1.5	1.5	1.5	1.5	1.5
Dristemp: (HPHT viscosifier)	6	6	6	6	6	6

Table 2: Experimental Result for Apparent Viscosity (AV) in centipoises, pressure in psi and temperature in deg. F

Pressure

Temp	450	460	470	480	490	500
9500	46/48.5	42.5/47.75	38/40.5	38/38.25	37.75/37.5	37/37
9600	46/49.25	45/48	43.75/45.5	43.5/44	41/41.75	39/40.5
9700	48/49.5	45.75/48.5	39.5/44.25	39.25/43	38.5/41	37.5/41
9800	48.75/50	46.5/49	44/46.75	43.75/44.5	4442.5	41/41
9900	48.5/51.75	47/49.5	44.75/48.5	44.5/48	44.5/46	41.5/42.5
10000	48.5/53	47.25/51	46/49	45/47.75	44.5/46.5	42/45

Table 3: Experimental Result for Plastic Viscosity (PV) in lbs/100 ft^2 , pressure in psi and temperature in deg. F

Pressure

Temp	**450**	**460**	**470**	**480**	**490**	**500**
9500	35/37	32/36.5	28/30	28/28	27.5/27.5	27/27
9600	35.5/38	35/37	34/35	34/34	32/32	30/31
9700	38/39	36/38	30/34	30/33	29.5/32	29/32
9800	39/40	37/39	35/37	35/35	35.5/34	33/33
9900	39.5/42	38/40	36/39.5	36/39	36.5/38	34/35
10000	40/44	39/43	38/41	37.5/40	37/39	35/38

Table 4: Experimental Result for Yield Point (YP) in Ibs/100 ft^2 ,pressure in psi and temperature in deg.F

Pressure

Temp	450	460	470	480	490	500
9500	22/23	21/22.5	20/21	20/20.5	20.5/20	20/20
9600	21/22.5	20/22	19.5/21	19/20	18/19.5	18/19
9700	20/21	19.5/21	19/20.5	18.5/20	18/18	17/16
9800	19.5/20	19/20	18/19.5	17.5/19	17/17	16/16
9900	18/19.5	18/19	17.5/18	1718	16/16	15/15
10000	17/18	16.5/16	/16	15/15.5	15/15	14/14

Table 5: Experimental Result for Gel Strength (GS) in Ibs/100 ft^2, pressure in psi, and temperature in deg.F

T

Pressure

Temp	450	460	470	480	490	500
9500	15.5/19	15/18	14/17	13/17	13/16.5	12/16.0
9600	15/18.5	14/17	13.5/17	12/16.5	12/16.0	11/15.0
9700	14/18	13.5/17.5	13/16.5	12/16.0	11.5/15	11/11.0
9800	13.5/17	13/16	12/15.0	11.5/15.5	11/14.0	10/13.0
9900	13/16	12.5/15	12/14.5	11/13.0	11/13.0	10/11.0
10000	12/14.0	11.5/13.0	11/12.5	10/11.5	10/11.0	9/10.0

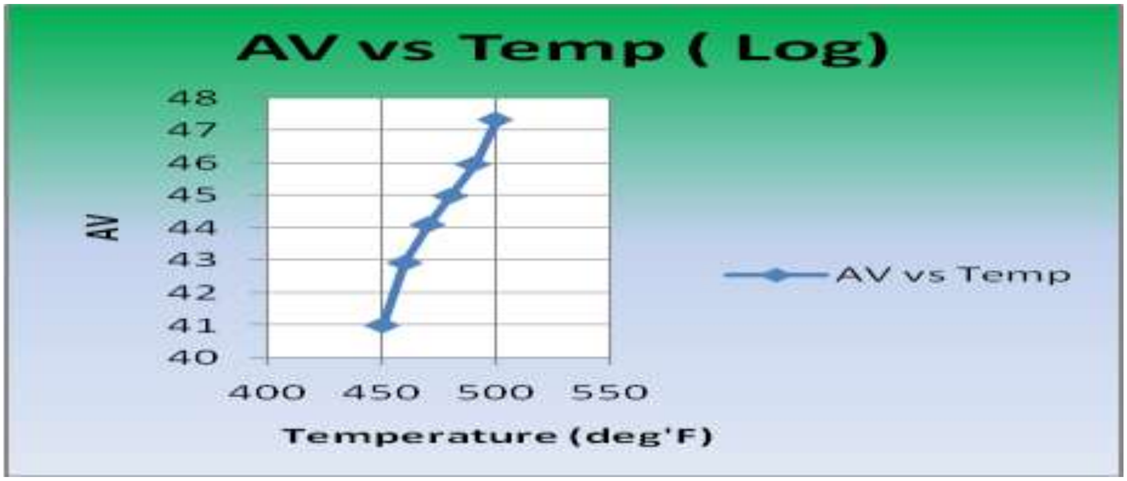

Figure 1: Effect of temperature on apparent viscosity from Logarithm model

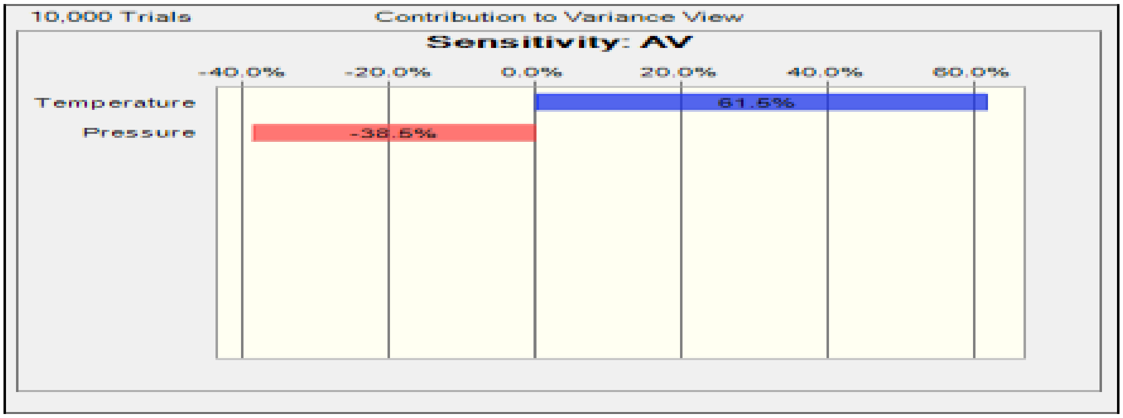

Figure 2: Comparison of sensitivity of Temperature and Pressure on apparent viscosity

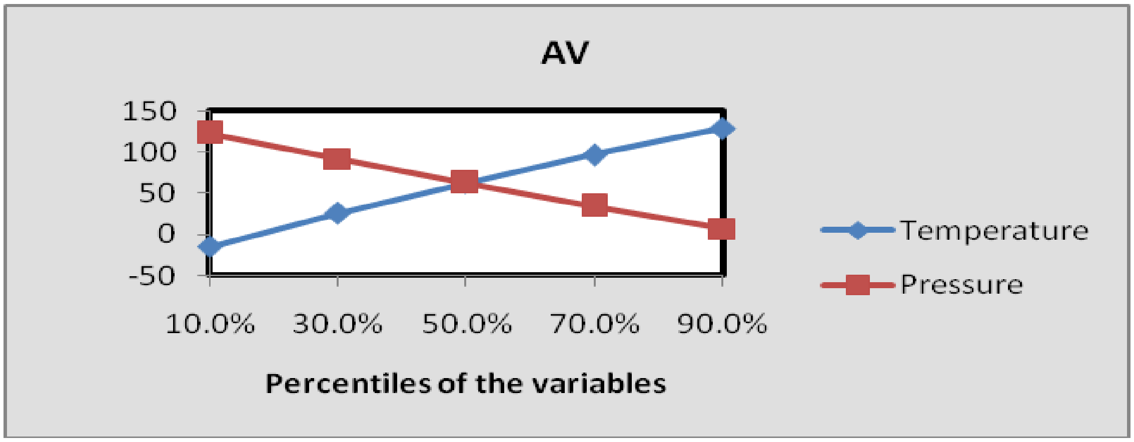

Figure 3: Percentage of the Temperature and Pressure responses for AV

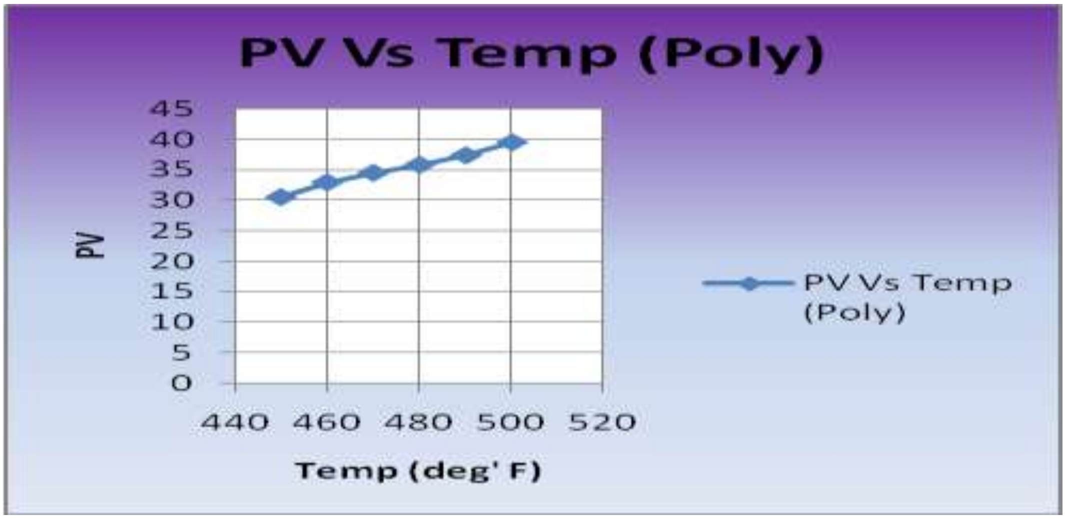

Figure 4: Effect of temperature on apparent viscosity from polynomial model

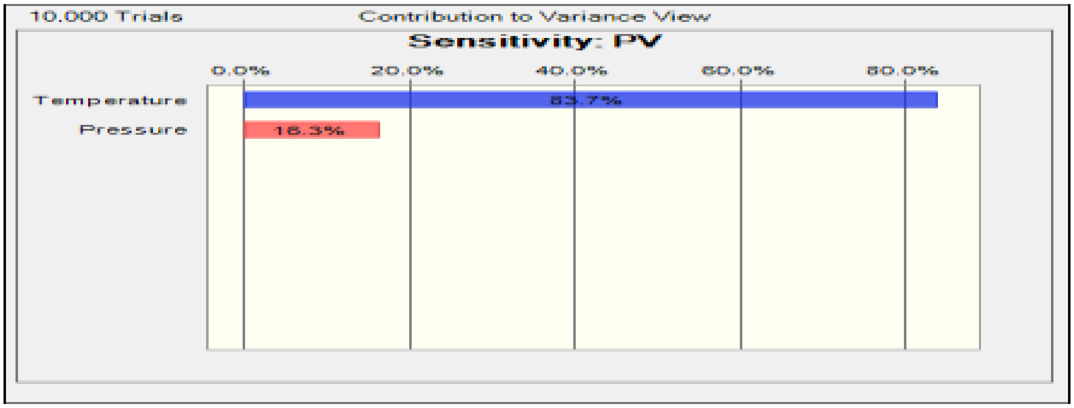

Figure 5: Comparison of sensitivity of Temperature and pressure on plastic viscosity

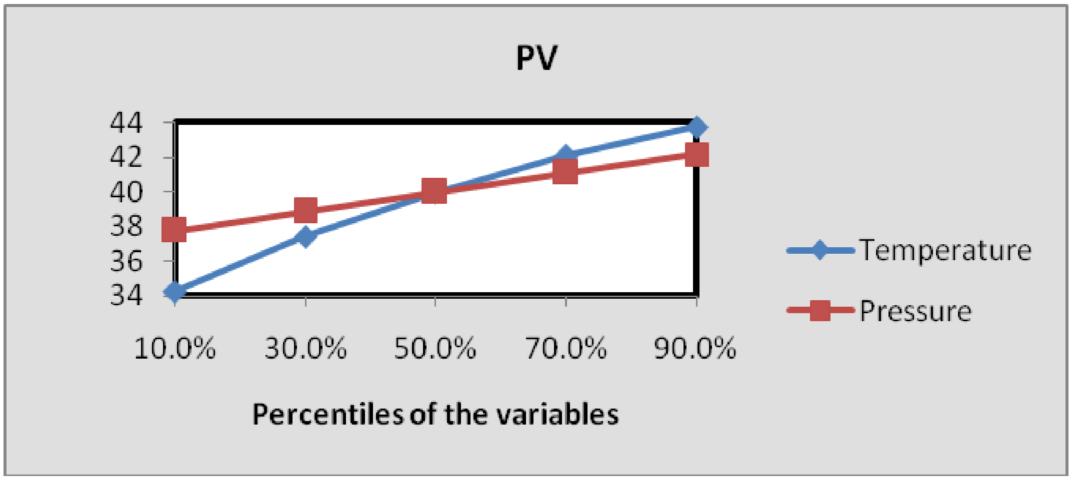

Figure 6: Percentage of the Temperature and Pressure responses for PV

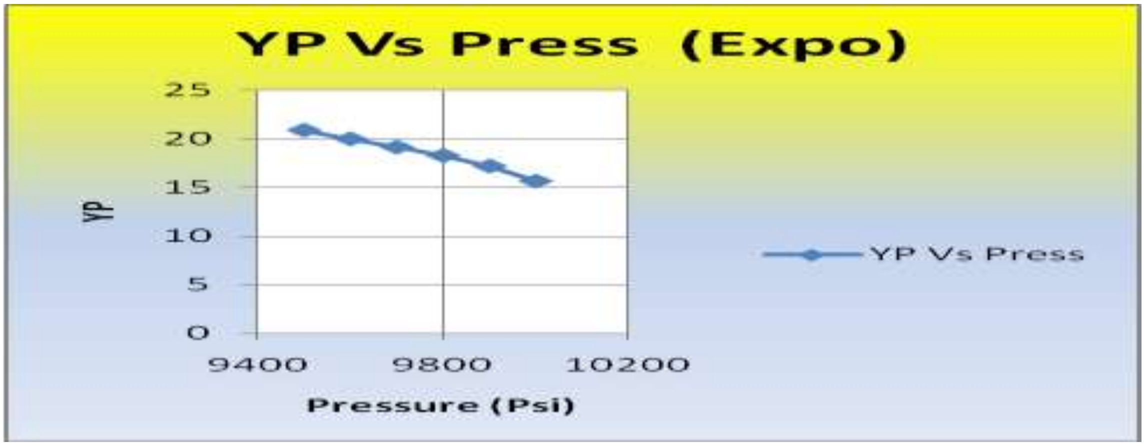

Figure 7: Effect of pressure on yield point from exponential model

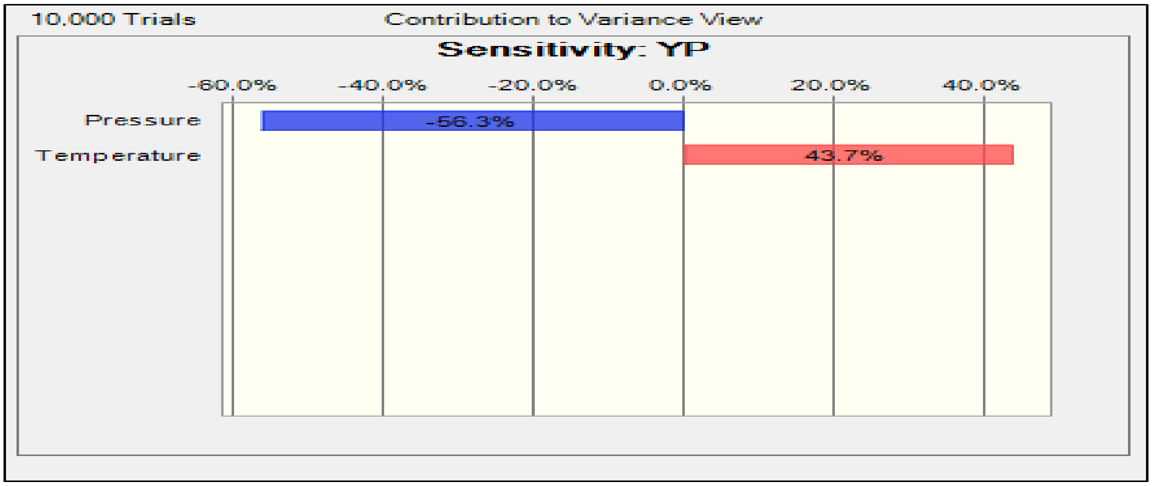

Figure 8: Comparison of sensitivity of Temperature and pressure on yield point

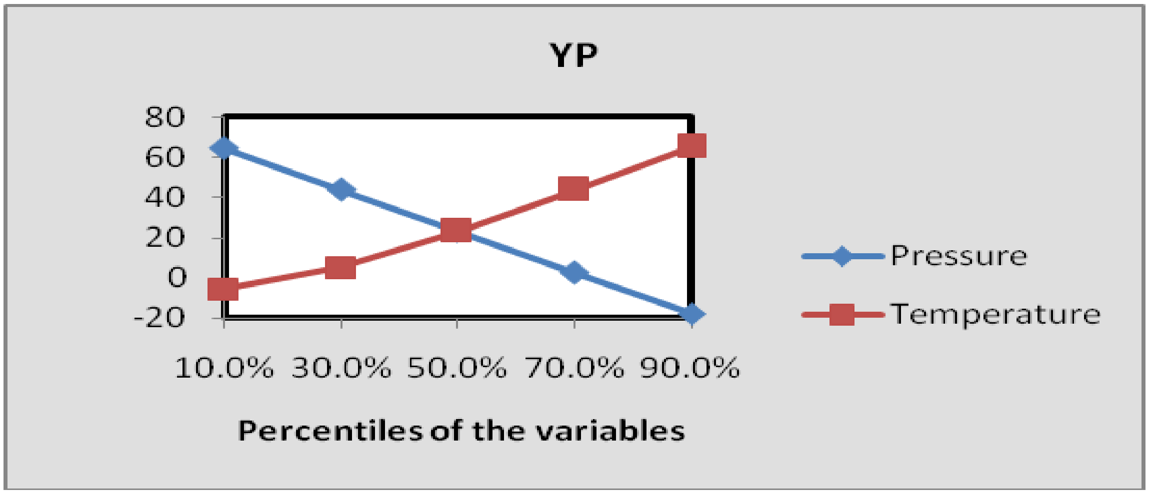

Figure 9: Percentage of the Temperature and Pressure responses for YP

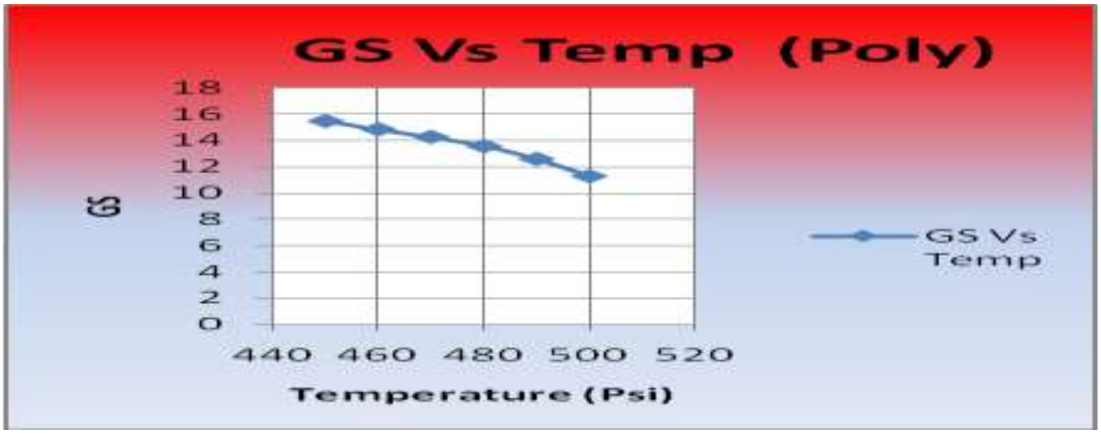

Figure 10: Effect of temperature on gel strength from polynomial model

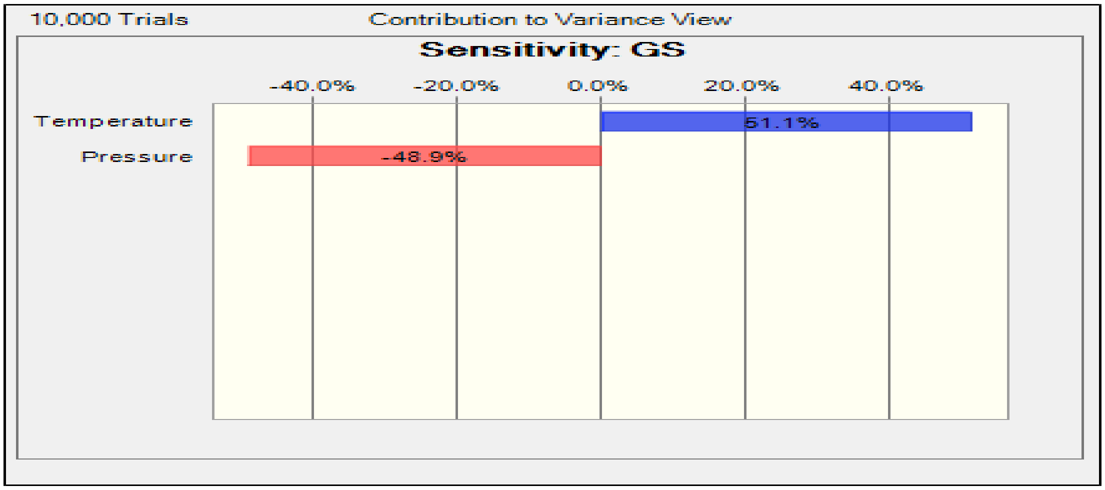

Figure 11: Comparison of sensitivity of Temperature and pressure on gel strength

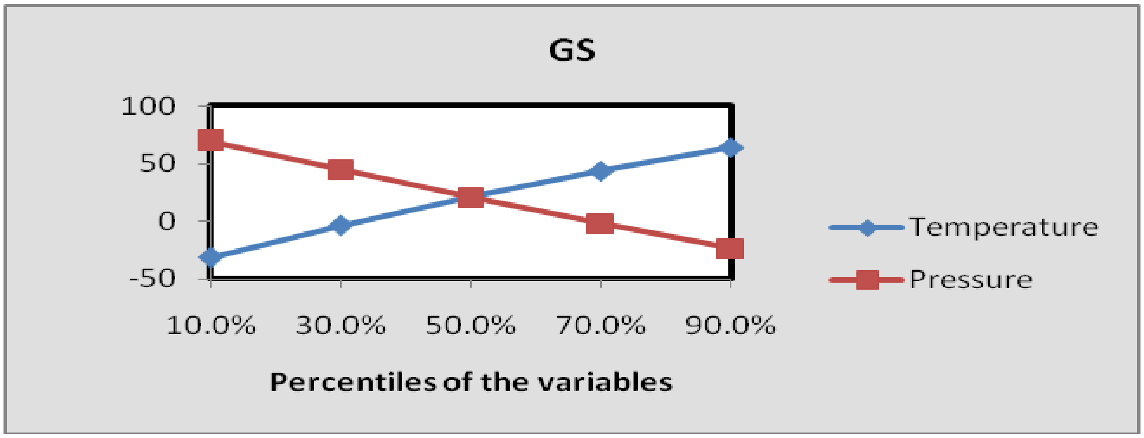

Figure 12: Percentage of the Temperature and Pressure responses for

DISCUSSION

Factorial designs are the most efficient way of investigating experiments that involved the study of the effects of two or more factor(Ibeh 2007). It allowed the effects of temperature to be estimated at several levels of pressure and verse versa, which gave valid results over a range of experimental conditions especially with the interaction effect(Montgomery 1991) Temperature and pressure were the two factors investigated in order to develop a methodology for testing drilling fluids using the automated Chandler model 7600 XHPHT viscometer and selected XHPHT drilling fluids chemical products . Also to statistically quantify the main and interaction effects of ultra-high temperature and pressure on the rheological properties of water based drilling fluids, through the Visual basic.dot net algorithm for statistical analysis and modeling to facilitate easy application. Table-1 shows the basic XHPHT chemical products, concentrations and functions different from the conventional water- based mud chemical products. Tables-(2-5) show two sets of experimental values for each corresponding temperature and pressure increasing simultaneously. Average values were computed by the software and used as an input data for the multiple regression modeling. The Figures- (1-12) shows the effect of temperature and pressure on rheological properties based on the sensitivity analysis from the model equations. Tests were conducted for 450, 460, 470, 480, 490 and 500 °F and all the rheological parameters monitored respectively in response to increase in pressure at 9500, 9600, 9700, 9800, 9900 and 10000 psi respectively. Attempt were made to develop model equation to predict the apparent viscosity, plastic viscosity, yield point and gel strength at different temperatures and pressures. In the model equations, (Algebraic, logarithmic, exponential and polynomial) were tested based on high multiple regression coefficient R^2 and adjusted R^2. The rheological properties (apparent viscosity , plastic viscosity , yield point and gel strength , were seen to vary with temperature and pressure as shown in the equations below, and can be predicted based on the equations as the best fit for the models using multiple regression coefficient and mean square error.

$$\mathbf{AV = 311809.470674 - 132387.62385\, Log(P) + 79618.71350\, Log(T) + 3629.1072451\, P^{2} T^{-3}} \ldots\ldots\ldots\ldots\text{-(3)}$$

$$\mathbf{PV = 20136.9987061 - 164.59627536\, P^{0.5} + 97540829046\, T^{-4} - 6494.80983116556\, P^{2}T^{-3}} \ldots\ldots\ldots\ldots(4)$$

$$\mathbf{YP = -18660.02193 + 117304959.14\, e^{(-p/1000)} + 58513.3388\, e^{(-T/1000)} + -27675.0918 P^{2} T^{-3}} \ldots\ldots\ldots\ldots(5)$$

$$\mathbf{GS = -2860.202 + 312056.44381\, P^{-0.5} + 2.26359\, T^{-6} - 4.91914*10^{18}\, P^{-2}\, T^{-3}} \ldots\ldots\ldots\ldots(6)$$

	R^2	**adjusted R^2**
AV =	0.9522	0.9997
PV =	0.9400	0.9996
YP =	0.9745	0.9999
GS =	0.9422	0.9997

Where AV is the apparent viscosity in cp, PV is the plastic viscosity in cp, YP is the yield point in Ibs/100 ft^2, GS is the gel strength in Ibs/100 ft^2, T is the temperature in ^{0}F , and P is the pressure in psi.

CONCLUSIONS

Values for rheological parameters are extremely useful in the drilling operations because they are applicable during well planning and also for the analysis of the performance of the circulating system for effective hydraulics and proper hole cleaning. Test results indicated that pressure and temperature can independently affect rheological parameters as well as its interaction as shown in the sensitivity analysis and the spider plots thereby confirming the trend obtained from the model results. The R^2 and the adjusted R^2 values obtained for the rheological parameters ranged between 94-97% and 98-99.99% respectively. Results calculated from the model equation showed good agreement with experimental values with less than 1% error. This will help predict rheological parameters at different temperatures and pressure thereby saving time and rigour associated with actual laboratory pilot test. Also, the advances made in this modeling have led to a better understanding and development techniques in determining effective mud viscosity/ density which is critical to the analysis of drilling and completion operations.

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