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INVESTIGATION OF THE EFFECT OF YTTRIUM OXIDE (Y_2O_3) NANOPARTICLE ON THE RHEOLOGICAL PROPERTIES OF WATER BASED MUD UNDER HIGH PRESSURE HIGH TEMPERATURE (HPHT) ENVIRONMENT

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ABSTRACT

Be informed that plastic viscosity (PV), yield point (YP) and gel strength of Water Based Mud (WBM) system decrease exponentially with increasing temperature until a mud system fails owing to the thermal degradation of the solid, polymers and other components of the mud sample at High Pressure-High Temperature conditions (HPHT). Hence, it then becomes imperative for continuous research into a thermally stable nanoparticle that can annul this abysmal effect and produce a Water Based mud system that can be applied to wells with HPHT conditions without the fear of impending failure. In this research, six samples of water based mud were prepared with varying amount of Yttrium oxide nanoparticle concentrations as well as a controlled sample without a nanoparticle.

Results showed that a thermally stable rheological properties was achieved by an optimum nanoparticle concentration of 2.50g at temperature of 300^{O}F and pressure of 10,000psi with only 13.33%, 9.67%, 13.33% and 15.63 % reduction in PV, YP,10seconds and 10minutes gel strength respectively. Whereas, a water based mud system without nanoparticle has an ignominious reduction of 88.10%, 77.6%, 75% and 70% reduction in PV, YP,10seconds and 10minutes gel strength respectively under the same temperature of 300^{O}F and pressure of 10,00psi which indicates an outright failure of the mud sample to carry cuttings.

Key words: Water based mud (WBM), Yttrium oxide, Nanoparticle, Rheological properties, HPHT.

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1. INTRODUCTION

Drilling mud systems are typically designed to carry the rock cuttings excavated by the drill bit up to the surface, suspend drill cuttings, weighting materials and additives under a wide range of conditions and prevent influx of formation fluid into the well bore. There are several different types of drilling fluids, based on both their composition and use that can perform the above mentioned functions but with varying degrees of efficiency and well conditions. These fluids are Water Based Mud (WBM), Oil Based Mud (OBM) and Synthetic Based Mud (SBM).

The four key factors that inform our decisions about the type of drilling fluid selected for a specific well are: cost, technical performance, anticipated well and formation conditions and environmental impact. Selecting the correct type of fluid for the specific conditions is an important part of successful drilling operations.

However, it is comparatively easy to formulate a mud with suitable properties but it is much more difficult to maintain those properties while drilling because of dispersion of drilled solids into the mud, adsorption of treating agents by drilled solids and contamination by formation fluids [1]

Environmental and economical considerations have led to the increasing use of Water Based Drilling fluids (WBMs) in applications where Oil Based Fluids (OBMs) have previously been preferred including high temperature high pressure (HTHP) wells [2]

However, drilling high temperature high pressure (HTHP) wells pose some technical problems which have been highlighted by [3] to include additive instability against high temperature, control of rheology and filtration loss with high solid content, borehole collapsing owing to narrow safe density window and poor stratum pressure bearing capacity, degradation of weighting materials such as barite and breaking down of polymeric additives under HPHT conditions.

Similarly, at HTHP conditions, the drilling fluids are likely to experience gelation, degradation of weighting materials and the breakdown of polymeric additives which act as viscosifiers, surfactants and fluid loss additives [4-5].

Hence, the urgent requirement of drilling fluid to function with High Temperature-High pressure wells has increased beyond the conventional capabilities of biopolymers to create fluids with stable rheological properties [6].

A nano-based drilling fluid is a fluid that has a nanoparticle size ranging between1-100 nanometers in size with surrounding interfacial layer [7].

Nanoparticles are applied in drilling muds to confront the challenges of high temperature and pressure of deeper formation owing to thermal degradation of mud components at high temperature in order to minimize fluid loss and help in well bore stability, remove toxic gases such as Hydrogen Sulphide (H_2S) and to prevent inflow of formation fluid into the wellbore [8].

2. MATERIALS AND METHOD

2.1. Rheological Parameters under Investigation

Rheology is the science of deformation and flow of matter. It is concerned with how fluid behave under varying conditions of temperature, pressure and shear rate.

Fluid Viscosity (μ): The *viscosity of a fluid* (μ) is defined as the degree of resistance to flow offered by the fluid. It is quantified as the ratio of the shear stress (τ) to that of the shear rate (γ).

$$\mu = \frac{\tau}{\gamma} \tag{1}$$

The unit of viscosity is Newton seconds/m^2 or Pascal seconds or poise (dyne.s/cm^2).

Shear Stress (τ): This is defined as the force required to sustain the movement of a particular type of fluid flowing through an area.

Mathematically,

$$shear\ stress\ (\tau) = \frac{force}{area} \tag{2}$$

The unit is N/m^2, Pascal or Dynes/cm^2.

Shear rate γ :This is defined as the rate of change of velocity when one layer of fluid passes over an adjacent layer divided by the distance between them. It is expressed in sec^{-1} (reciprocal seconds). It can be converted to sec^{-1} by using the equation 3

$$\gamma = 1.703\theta \tag{3}$$

Where θ is dial speed in Revolution Per Minute (RPM)

Plastic Viscosity: Plastic Viscosity is a measure of resistance of drilling mud to flow caused primarily by the mechanical friction between the suspended solid particles, the solid particles and the liquid phase. It is the viscosity a fluid would have at a very high shear rate. Plastic viscosity is sensitive to the concentration of solid and therefore indicates dilution requirement. Plastic viscosity of a fluid is defined as the difference between the 600rpm and the 300rpm viscometer dial readings and it is usually expressed in centipoise (cp) or milliPascal seconds (mPa.s).

Plastic Viscosity is expressed as:

$$PV = \theta_{600} - \theta_{300} \tag{4}$$

The unit is cp.

The plastic viscosity depends primarily on the following factors:

Solids concentration.

Size and shape of the solid particles that is present in the mud.

Viscosity of the fluid phase.

Presence of some long chain polymers.

Oil-to-Water or Synthetic-to- Water ratio in Invert-Emulsion fluids,

Type of emulsifiers in invert emulsion fluids.

Yield Point: Yield point is a measure of the electro-chemical or attractive forces between particles in a fluid under flow conditions. It is the resistance to initial flow or the stress required in order to move a fluid. These forces are a result of negative and positive charges located on or near the particle surfaces. Yield point is sensitive to the electrochemical environment and hence indicates the need for chemical treatment of mud. The yield point will decrease as the attractive forces are reduced by chemical treatment. Reduction of yield point will also decrease the apparent viscosity. It is expressed in pounds per 100 square feet (*lbl*100ft^2). Mathematically, it is defined as the difference between the 300rpm dial reading and the plastic viscosity.

Yield point can be expressed Mathematically as:

$$\text{Yp} = \theta_{300} - PV \tag{5}$$

Unit of yield point is lb/100ft^2

Gel Strength: This is the shear stress of a drilling mud measured at low shear rates after the drilling mud has been static for some period of time. It is the shearing stress necessary to initiate a finite rate of shear. While the yield point and the plastic viscosity are both related to properties of the mud when it is moving, the gel strength measures a property of the mud when it stops moving. Drilling fluids are thixotropic. This means that when they are not moving they tend to form a gelled structure. When the pump is started, the gel is broken and the mud becomes liquid again. These measurements are normally taken and reported as initial gel strength (zero quiescent time) and final gel strength (ten quiescent time The gel strength is one of the important drilling fluid properties because it demonstrates the ability of the drilling mud to suspend drill solid and weighting material when circulation is ceased. Two forms of gel strengths were of interest, the 10 seconds and 10 Minutes gel strengths. The 10 seconds gel strength is the maximum dial deflection observed when the cup is rotated by hand immediately after flow has ceased. The gel values were measured and recorded in pounds per 100ft^2 (lb/l 00ft^2).

Flow Behaviour Index (n): This is an indicator of the tendency of a fluid to shear thin and it is dimensionless. When n < 1, the fluid is shear thinning and when n > 1, the fluid is shear thickening [9].

$$n = 3.32 \log\left(\frac{\theta_{600}}{\theta_{300}}\right) \tag{6}$$

Consistency Index Factor (K): This is defined as the viscosity index of the fluid system and the unit is lb/100ft^2

$$k = \frac{\tau}{\gamma^n} = \frac{\theta_{600}}{1022^n} \tag{7}$$

2.2. Yttrium Oxide (Y_2O_3) Nano Particle

Yttrium oxide nanoparticle is an air stable, solid substance with a characteristic whitish appearance. Its physical properties are shown in Table 1 below and a transmission electron microscope image (TEM) shown in figure1.

Table 1 Physical Properties and Particulate Nature of Yttrium Oxide (Y_2O_3) Nano particle.

Form	Nano powder
Appearance	White powder
Structure	Spherical
Particle size	20-30 nm
Density	5.01 $g/_{cm^3}$ at 25^{O}C
Melting point	2410 ^{O}C
Molecular Weight	225.81$g/_{mol}$
Purity	$\geq$ 99.9%

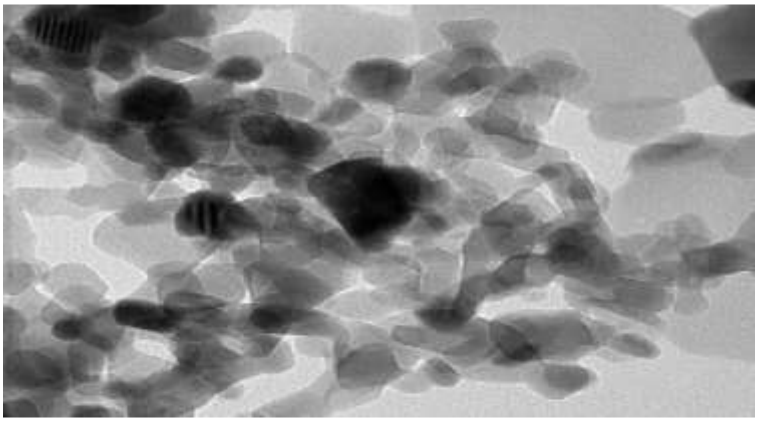

Figure 1 TEM Image of Yttrium Oxide Nanoparticle.

2.3. Experimental Design and Mud Formulation

The following Mud samples were prepared in the course of the experiment based on the mud composition and components presented in Table 2.

Sample A : Control sample of WBM with Zero Nanoparticle

Sample B :WBM sample with 0.5g Yttrium Oxide (Y_2O_3) Nanoparticle

Sample C : WBM sample with 1.00g Yttrium Oxide (Y_2O_3) Nanoparticle

Sample D : WBM sample with 1.50g Yttrium Oxide (Y_2O_3) Nanoparticle

Sample E : WBM sample with 2.00g Yttrium Oxide (Y_2O_3) Nanoparticle

Sample F : WBM sample with 2.50g Yttrium Oxide (Y_2O_3) Nanoparticle

Sample G : WBM sample with 3.00g Yttrium Oxide (Y_2O_3) Nanoparticle

Table 2 Formulation of a Bentonite Water Based Drilling Mud

Component	Function	Quantity
Water (ml)	Base fluid that dissolves other additives.	350
Bentonite(g)	An organophilic clay used for increasing viscosity	22.50
Caustic Soda (g)	For PH Control	0.60
Soda Ash (g)	For treating possible Calcium Contamination	0.60
Bio Polymer (g)	Viscosity Control Agent	2.50
Potassium Chloride (KCl) (g)	Inhibition of Shale Swelling	25
Carboxyl Methyl Cellulose (CMC) (g)	Fluid Loss Additive	2.00
Barite (g)	Weighting Agent	160

2.4. Rheological Properties Determination at Ambient Conditions.

The rheological properties of all the mud samples were determined at temperature of 75^OF by using an 8 speed rotational viscometer shown in Figure 2. It must be noted that the Muds were hot-rolled for Ten Hours and allowed to cool before embarking on any test.

Experimental Procedure for Determining Mud Samples Viscosity from 8 Speed Viscometer

- The aged mud samples were agitated for 30 Minutes by using the multi mixer to prevent sagging of mud components
- The agitated mud sample was poured into the mud cup and placed on the viscometer platform under the sleeve ensuring the pins at the bottom of the cup fit into the holes in the base plate.
- The knurled knob between the rear support post were turned to raise or lower the platform until the rotor sleeve is immersed in the mud sample up to the scribed line.
- The mud samples were initially stirred for two minutes and then the control knob was turned to the desired rotor speed.
- The dial reading was allowed to stabilize and the reading recorded.
- The above steps were carried out for rotor speeds of 600rpm, 300rpm, 200rpm, 100rpm, 60rpm, 30rpm, 6rpm and 3 rpm.
- The process was repeated for other mud samples at 75^OF with different Nano particle Concentrations.

Figure 2 8- Speed Rotational Viscometer

Experimental Procedure for gel strength determination

- The mud sample was stirred at 600rpm for about 30 seconds.

  The control knob was then turned to the stop position
- The mud sample was allowed to remain static for some time (10 seconds) and then the control knob was set at a low rotor speed (Gel).

- The maximum dial deflection was read and recorded as the 10 seconds gel.

  Also, the mud sample was allowed to remain static period of 10 minutes to obtain the 10mminutes gel strength
- The whole process was repeated for all the formulated mud samples at ambient conditions.

2.5. Rheological Properties Determination at HPHT Condition

The Rheological Properties of the mud samples were obtained at constant pressure of 10,000psi and Varying temperature of 120,180,250 and 300 ^{O}F by using Chandler Model 7600 HTHP Viscometer shown in Figure 3 below. This Viscometer is designed for determining the rheology of drilling fluids while subjected to varying well conditions in accordance with. International Standard Organization (ISO) and American Petroleum Institute (API) standards. The viscometer has a rotational speed varying from 0-900 rpm with upper limit of pressure and temperature of 40,000psig and 600^{O}F respectively. It also has an automatic 10 second and 10 Minutes gel strength measurement.

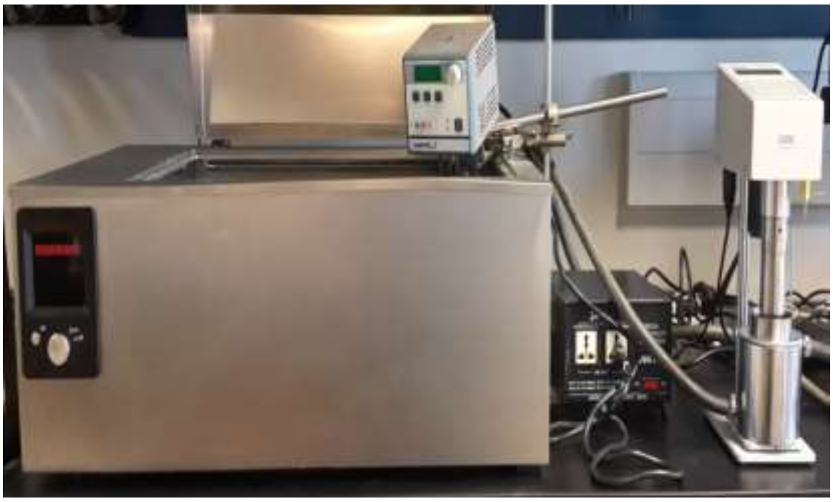

Figure 3 Chandler (Model 7600) HPHT Viscometer.

3. RESULTS AND DISCUSSION

3.1. Plastic Viscosity Variation with Nanoparticle Concentration and Temperature

The plastic Viscosity (Pv) increased slightly as the Nanoparticle concentration increases but decreases as the temperature increases as shown in Table 3-9 and Figure 4. This increase in Pv with nanoparticle concentration enhances the ability of the drilling fluid to carry the rock cuttings to the surface, especially in larger hole sizes where the annular velocity developed by the pump is relatively low [10] and it can be attributed to an increase in the percent by volume of solids, a reduction in the size of the solid particles, a change in the shape of the particles or a combination of these. Plastic viscosity increases because as the nanoparticles are dispersed in the WBM, water absorbs into it and become agglomerated. Similar results have been obtained by [11] on the effect of NanoFe_2O_3 on plastic viscosity of water based mud. A drastic reduction of 88.10% in PV of WBM with Zero amount of Nanoparticle (Sample A) was observed at temperature of 300^{O}F and pressure of 10,000psi as shown in Figure 4. This too little plastic viscosity will allow cuttings to fall out of the slurry and be deposited behind the drill head and consequently result in drilling failure. However, with addition of nanoparticle concentrations of 2.50g and 3.00g, a PV reduction of 13.33% at High temperature of 300^{O}F and pressure of 10,000psi was achieved.

A very high PV can be reduced by addition of water (dilution) or by the mechanical separation of excess solids because too high viscosity increases pump pressure and limit flow properties that in turn will reduce penetration rates.

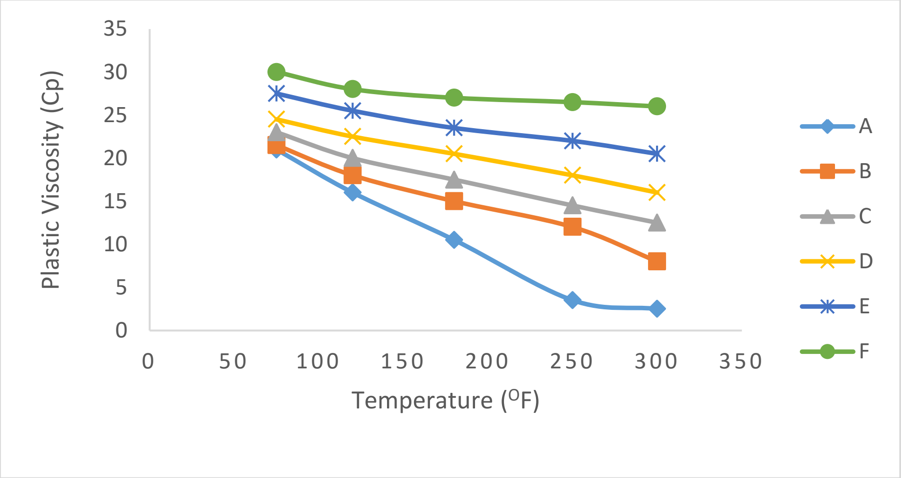

Figure 4 Plastic Viscosity Variation with Nanoparticle Concentration and Temperature of Water Based Mud.

3.2. Yield Point Variation with Nanoparticle Concentration and Temperature

Figure 5 shows the Variation of Yield point (YP) with Yttrium Oxide Nanoparticle concentration and temperature. Generally, the yield point increased as the nanoparticle concentration increases but decreases as the temperature increases. These variations in Yield point are due to changes in the surface properties of the fluid solids, volume concentration of the solids, and electrical environment of these solids (concentration and types of ions in the fluid phase of the fluid) as nanoparticles concentration increases and temperature decreases. [12] also observed that the yield point of WBM increased on the addition of multi-walled carbon nanotube(MWCNT) and Graphene Nano platelet (GNP).

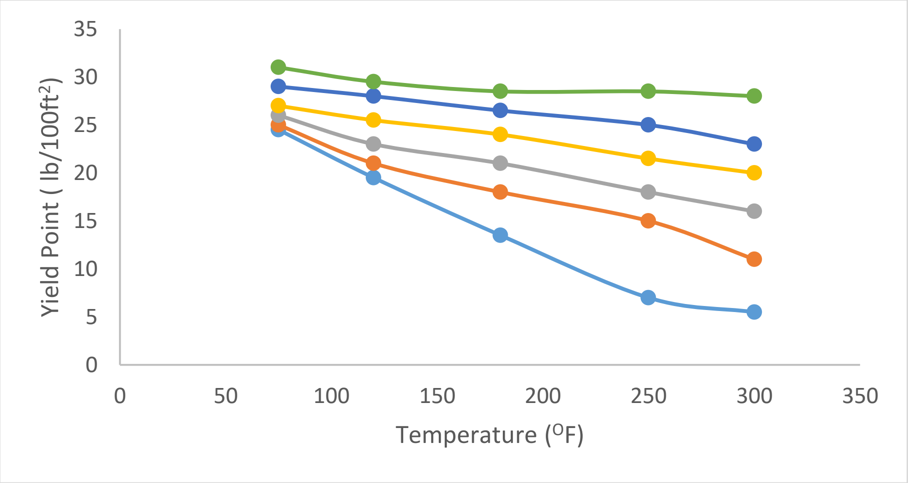

Figure 5 Yield Point Variation with Nanoparticle Concentration and Temperature of Water Based Mud.

An abysmal reduction of 77.60% in YP of WBM with Zero amount of Nanoparticle (Sample A) was observed at temperature of 300^{O}F and pressure of 10,000psi as shown in Figure 5. This reduction would adversely affect the dynamic suspension of drilling cuttings and efficient cleaning of the well bore while drilling [13]. However, the WBM becomes thermally stable with the addition of 2.50g and 3.00g of Yttrium Oxide nanoparticle resulting in only 9.67% reduction in the Yield point at the same HPHT conditions as deduced from Table 8 and 9 respectively.

3.3. Gel Strength Variation with Nanoparticle Concentration and Temperature

The Gel strength variations with nanoparticles concentration and temperature is presented in Figure 6 and 7 for the Ten seconds and Ten Minutes gel respectively.

The gel strength also increases with increase in nanoparticle concentration but decreases with temperature. Deductions from Table 3 and Figures 6 and 7 show that a reduction of 75% and 70% in 10s and 10minutes gel strength respectively was recorded by WBM with Zero amount of Nanoparticle (Sample A) at temperature of 300^{O}F and pressure of 10,000psi. These ridiculously low gel strengths will impair the ability of the mud to suspend barite and drill cuttings when circulation is stopped. But with nanoparticle concentration of 2.50 g, the gel strength becomes relatively stable under this HPHT conditions.

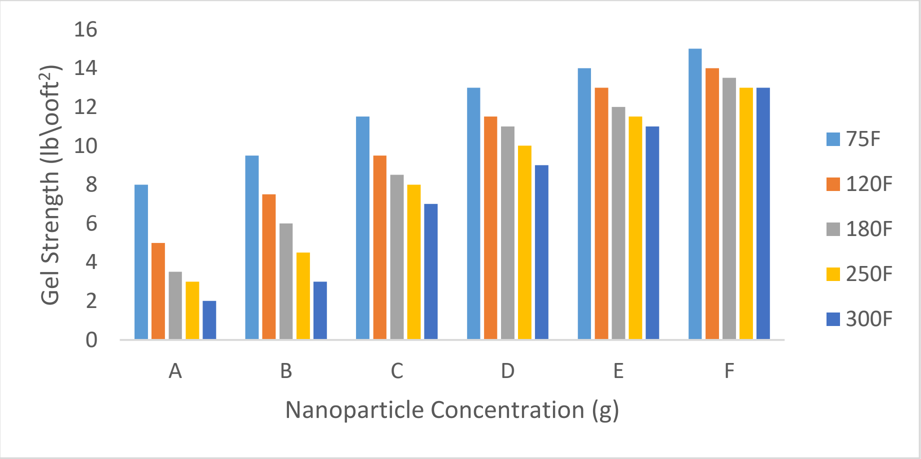

Figure 6 10 Seconds Gel Strength Variation with Nanoparticle Concentration and Temperature of Water Based Mud.

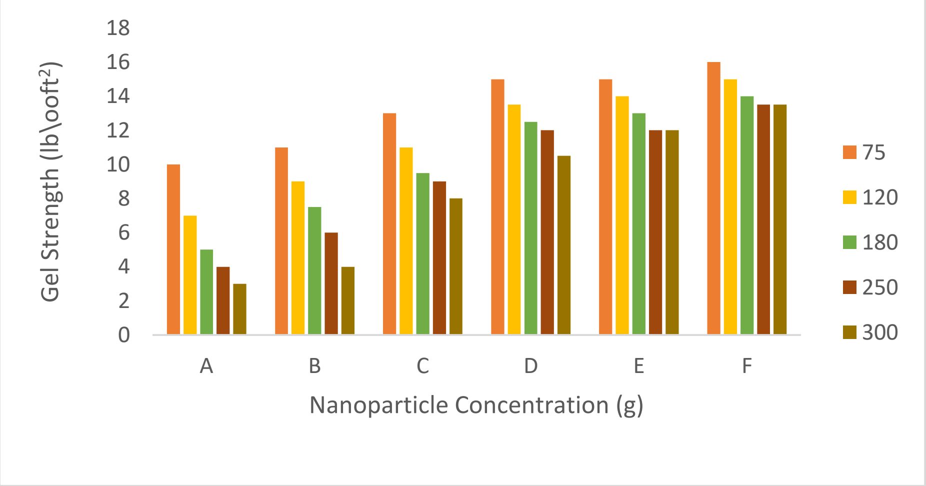

Figure 7 10 Minutes Gel Strength Variation with Nanoparticle Concentration and Temperature of Water Based Mud.

3.4. Flow Behavior Index (n) and Consistency Factor (K) Variation with Nanoparticle Concentration and Temperature

The flow behavior index indicates the tendency of a fluid to shear thin under varying conditions of temperature, pressure and stress [14]. Analysis of shear stress results showed that as nanoparticle concentration increases, the fluid becomes more shear thickening because n and k increases as shown in Figures 8 and 9. But under HPHT conditions of 10,000psi and 300^{O}F, the viscosity of the water based mud sample without nanoparticle (Sample A), significantly decreased and thus the mud system experienced a high shear thinning behavior at these high temperature and pressure. However, the fluid system becomes thermally stable as the nanoparticle concentration increases up to an optimum concentration of 2.50g.

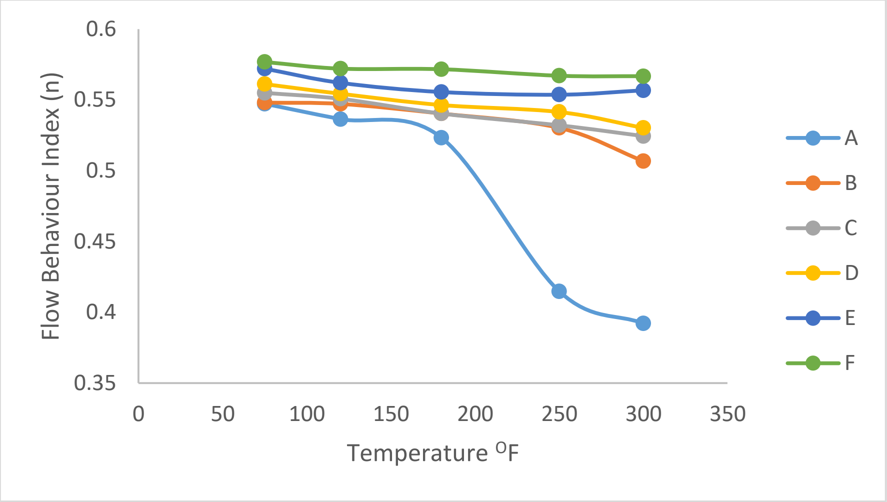

Figure 8 Flow Behavior Index Variation with Nanoparticle Concentration and Temperature of Water Based Mud

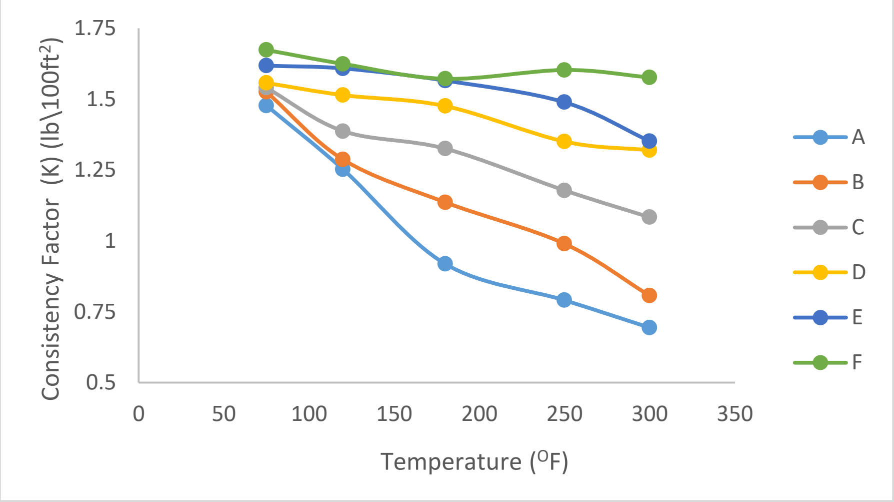

Figure 9 Consistency Factor Variation with Nanoparticle Concentration and Temperature of Water Based Mud.

3.5. Shear Stress Variation with Nanoparticle Concentration and Temperature

The shear stress increases with Nanoparticle Concentration and decreases with temperature as shown in Figures 10-15.

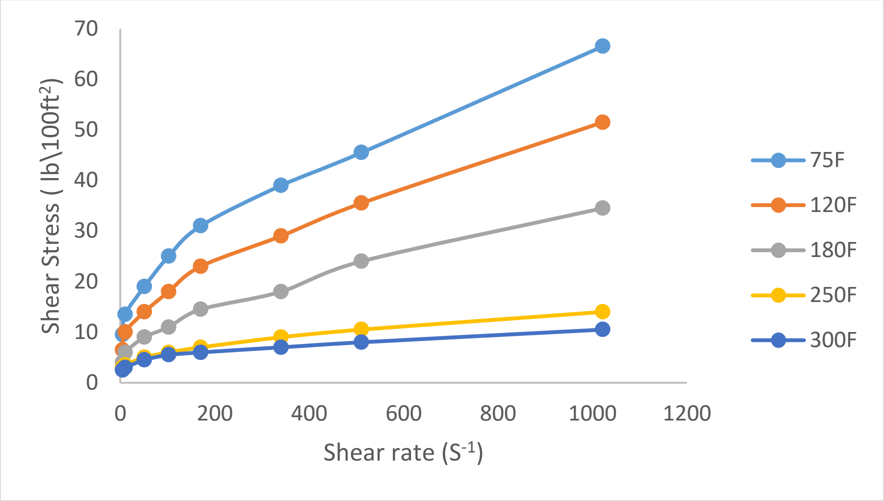

Figure 10 Shear Stress Versus Shear Rate Variation with Temperature for Sample A

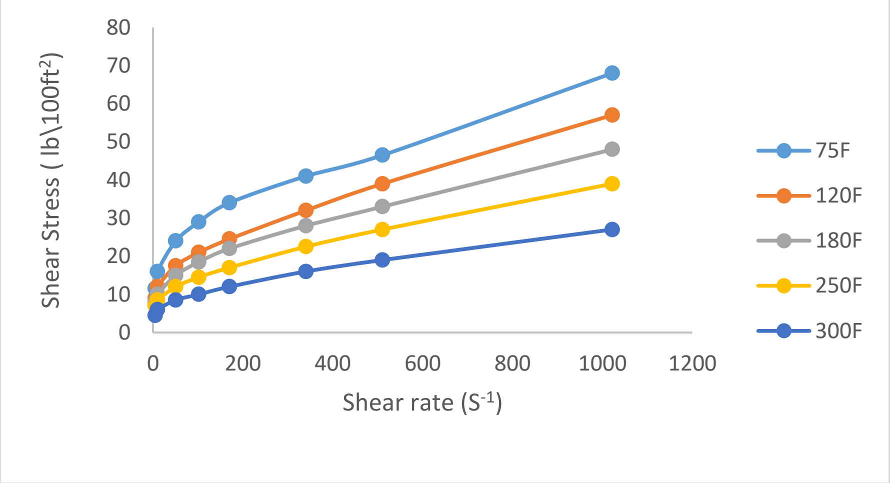

Figure 11 Shear Stress Versus Shear Rate Variation with Temperature for Sample B

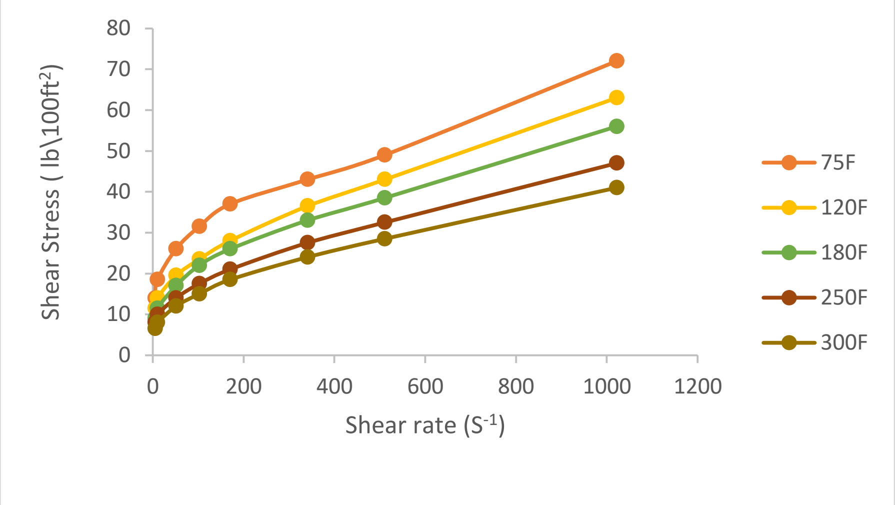

Figure 12 Shear Stress Versus Shear Rate Variation with Temperature for Sample C

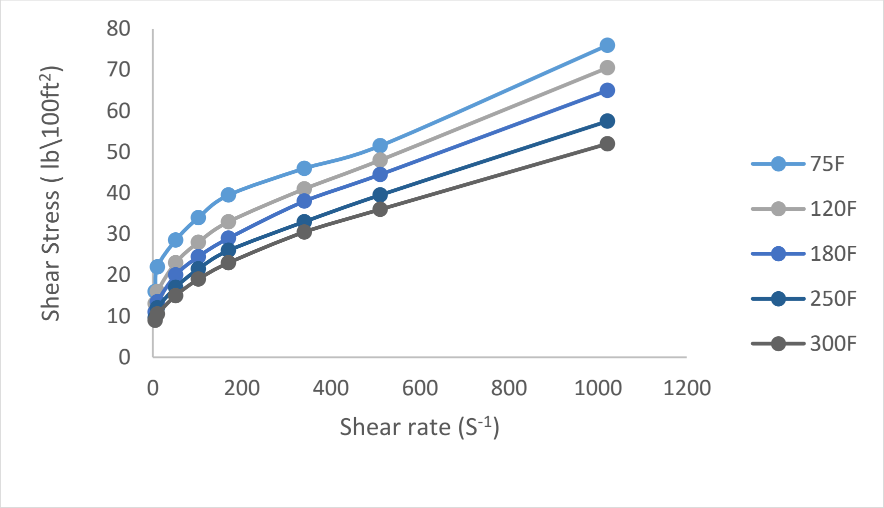

Figure 13 Shear Stress Versus Shear Rate Variation with Temperature for Sample D

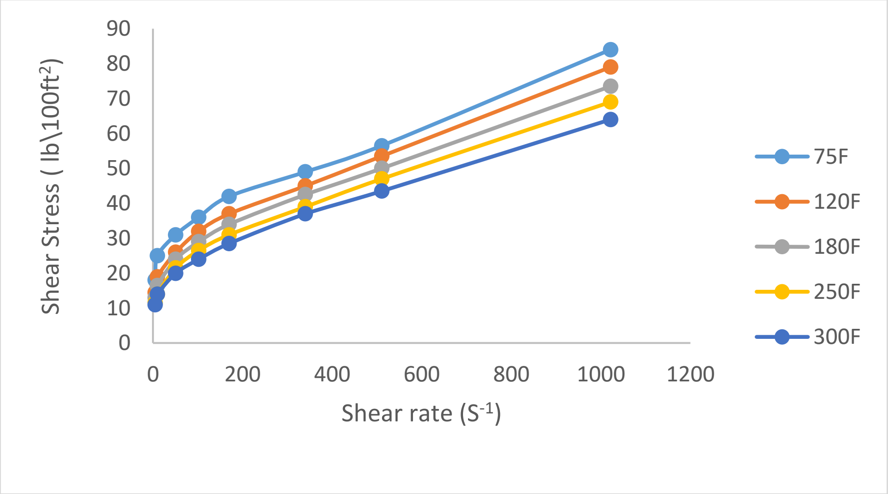

Figure 14 Shear Stress Versus Shear Rate Variation with Temperature for Sample E

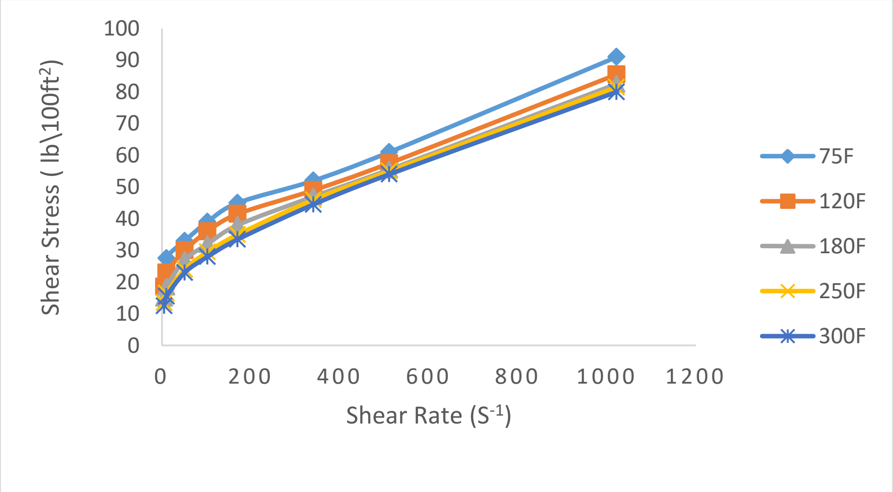

Figure 15 Shear Stress Versus Shear Rate Variation with Temperature for Sample F

Table 3 Rheological Properties of SAMPLE A in $\left[{}^{lb}/_{100ft^2}\right]$

Temperature Shear rate(s^{-1})	**75^{O}F**	**120 ^{O}F**	**180^{O}F**	**250^{O}F**	**300^{O}F**
1022	66.50	51.50	34.50	14	10.50
511	45.50	35.50	24	10.50	8
PV	21	16	10.50	3.5	2.5
YP	24.50	19.50	13.50	7	5.5
Gel (10s)	8	5	3.5	3	2
Gel (10min)	10	7	5	4	3

Table 4 Rheological Properties of SAMPLE B in $\left[{}^{lb}/_{100ft^2}\right]$

Temperature Shear rate(s^{-1})	**75^{O}F**	**120 ^{O}F**	**180^{O}F**	**250^{O}F**	**300^{O}F**
1022	68	57	48	39	27
511	46.50	39	33	27	19
PV	21.5	18	15	12	8
YP	25	21	18	15	11
Gel (10s)	9.5	7.5	6	4.5	3
Gel (10min)	11	9	7.5	6	4

Table 5 Rheological Properties of SAMPLE C in $\left[{}^{lb}/_{100ft^2}\right]$

Temperature Shear rate(s^{-1})	**75^{O}F**	**120 ^{O}F**	**180^{O}F**	**250^{O}F**	**300^{O}F**
1022	72	63	56	47	41
511	49	43	38.50	32.50	28.50
PV	23	20	17.50	14.50	12.5
YP	26	23	21	18	16
Gel (10s)	11.50	9.5	8.50	8	7
Gel (10min)	13	11	9.5	9	8

Table 6 Rheological Properties of SAMPLE D in $\left[{}^{lb}/_{100ft^2}\right]$

Temperature Shear rate(s^{-1})	**75^{O}F**	**120 ^{O}F**	**180^{O}F**	**250^{O}F**	**300^{O}F**
1022	76	70.50	65	57.50	52
511	51.50	48	44.50	39.50	36
PV	24.5	22.50	20.50	18	16
YP	27	25.50	24	21.50	20
Gel (10s)	13	11.50	11	10	9
Gel (10min)	15	13.5	12.5	12	10.50

Table 7 Rheological Properties of SAMPLE E in $\left[{}^{lb}/_{100ft^2}\right]$

Temperature Shear rate(s^{-1})	**75^{O}F**	**120 ^{O}F**	**180^{O}F**	**250^{O}F**	**300^{O}F**
1022	84	79	73.50	69	64
511	56.50	53.50	50	47	43.50
PV	27.50	25.50	23.50	22	20.50
YP	29	28	26.50	25	23
Gel (10s)	14	13	12	11.50	11
Gel (10min)	15	14	13	12	12

Table 8 Rheological Properties of SAMPLE F in $\left[{}^{lb}/_{100ft^2}\right]$

Temperature Shear rate(s^{-1})	**75^{O}F**	**120 ^{O}F**	**180^{O}F**	**250^{O}F**	**300^{O}F**
1022	91	85.50	82.50	81.50	80
511	61	57.50	55.50	55	54
PV	30	28	27	26.50	26
YP	31	29.5	28.50	28.50	28
Gel (10s)	15	14	13.5	13	13
Gel (10min)	16	15	14	13.5	13.5

Table 9 Rheological Properties of SAMPLE G in $\left[{}^{lb}/_{100ft^2}\right]$

Temperature Shear rate(s^{-1})	**75^{O}F**	**120 ^{O}F**	**180^{O}F**	**250^{O}F**	**300^{O}F**
1022	91	85.50	82.50	81.50	80
511	61	57.50	55.50	55	54
PV	30	28	27	26.50	26
YP	31	29.5	28.50	28.50	28
Gel (10s)	15	14	13.5	13	13
Gel (10min)	16	15	14	13.5	13.5

4. CONCLUSIONS

The following inferences can be drawn based on the experimental investigation of the effect of Yttrium Oxide Nanoparticles on the Rheological properties of Water based mud.

- Plastic Viscosity (PV), Yield point (YP) and Gel Strength increases as nanoparticle concentration increases but the increment is within the acceptable range for the optimum performance of water based mud under HPHT conditions
- An optimum Yttrium nanoparticle concentration of 2.50g can help to maintain highly thermally stable rheological properties under HPHT conditions of 300^{O}F and pressure of 10,000psi with only 13.33%, 9.67%, 13.33% and 15.63 % reduction in PV, YP,10seconds and 10minutes gel strength respectively. Whereas, a water based mud system without nanoparticle has an ignominious reduction of 88.10%, 77.6%, 75% and 70% reduction in PV, YP,10seconds and 10minutes gel strength respectively under the same temperature of 300^{O}F and pressure of 10,00psi which indicates an outright failure of the mud sample to carry cuttings.
- Yttrium nanoparticles help to maintain a relatively stable rate of change of viscosity with the rate of change of shear producing a drilling fluid system that is neither too shear thickening nor too shear thinning at very high temperature and pressure. Whereas, a water Based Mud

system with Zero % yttrium oxide Nanoparticle produced a very high shear thinning fluid that cannot suspend and release cuttings.

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