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Evaluation of Nanoparticles in Enhancing Drilling Fluid Properties

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Abstract—The dramatic increase of industrial demand for energy resources especially the petroleum products has drained the existing conventional reservoirs. Therefore, it is needed to explore and investigate the feasibility of producing petroleum from deep formations or unconventional reservoirs that are normally characterized by High Pressure/High Temperature (HPHT) environment which imposes more challenging drilling and production operations. This increment in the surrounding environmental conditions during the deep water drilling operations adversely affects the behavior of drilling fluid. Consequently, it may sometimes lead to unsafe or inefficient drilling operations. The potential application of nanoparticles in drilling fluid system has been explored. The focus of the research is to evaluate the effect of TiO_2 nanoparticles addition on the performance characteristics of drilling fluid in HPHT environments. Rheology, filtration and lubricity characteristics of drilling fluid were measured. The different concentrations of TiO_2 nanoparticles (0.05ppb, 0.1ppb, 0.5ppb and 1ppb) were applied for water-based mud and oil based mud, respectively. Results for water-based mud showed increase in yield point and plastic viscosity with the increase in nanoparticles concentrations. While, results of oil-based mud showed increasing of plastic viscosity and decreasing of yield point with the increase in nanoparticles concentrations for drilling fluid having thickening behavior under high temperatures and vice versa. Fluid loss during HPHT filtration showed significant reduction and thinner mud cake was obtained when nanoparticles concentrations are lower than (1g). There was reduction in friction coefficient of water-based mud with an average torque reduction of 24%. Similarly, improvement in oil-based mud lubricity characteristics was obtained for concentrations lower than 1g with an average torque reduction of 23%. As conclusion, low concentrations of TiO_2 nanoparticles enhanced the drilling fluid performance characteristics. It shows promising potential for further studies on other drilling operations considerations such as investigating different types and sizes of nanoparticles on drilling fluid as well as investigating the potential of replacing conventional drilling fluid additives with nano-scaled additives. Lastly, this research was a collaboration work with SCOMI OiltoolsSdn. Bhd. whereby all drilling fluid formulations were supplied by their R&D department, in addition to providing all the chemicals and facilities for various drilling fluid testing.

Index Terms—Drilling fluid, Filtration, Formation Damage, HPHT, Lubricity, Rheology, Synthetic-Based mud, TiO_2 Nanoparticles, Water-Based mud, Friction Factor.

1 Introduction

Within the few recent decades, the global energy demand has increased significantly which in turns require intensive search for more petroleum deposits around the world. The recent focus is developing new technologies that help producing petroleum from deep water formations or unconventional reservoirs characterized by High Pressure/High Temperature (HPHT) environment. These harsh environmental conditions urge the need for designing sophisticated drilling fluid formulations suitable for more challenging drilling operations. HPHT wells are defined as any well have bottom-hole pressure of 10,000psi and temperatures of 300^{o}F [1].Drilling operations have evolved remarkably to meet the new challenges encountered with complicated formations, from vertical, inclined, horizontal to sub-sea and deep-sea drilling [8]. According to Subhash *et al.* (2010) about 80% of total well cost is attributed to drilling operations. Drilling fluid may contribute 5% to 15% to drilling cost, but is the main cause for 100% of drilling problems [3]. Hence, it is essential for drilling operator and mud engineer to comprehend the changes in drilling fluid properties with varying conditions of the subsurface at the bottom of deep wells [2]. Basically, elevated temperatures and pressures with increasing well depth imposes technical problems in drilling fluid performance used in deep wells. Some of the technical problems that could be incurred by drilling fluid in deep drilling operations [8]:

- Stability of additives against high temperature.
- Control of rheology and filtration loss with high solid content.
- Narrow safe density window and poor stratum pressure-bearing capacity lead to borehole collapsing.
- Leakage of drilling fluid and stick-slip of drill bit.
- Weighting materials such as barite are subjected to degradation and breakdown of polymeric additives under HPHT conditions.

The urgent requirement of drilling fluid to function with wells having down-hole temperatures above 300^{o}F has increased beyond the conventional capabilities of biopolymers to create fluids with stable rheological properties [11]. When the drilling fluid undergoes high temperature, high pressure applications, it will likely to exhibit sagging comportment. Also, it shows synersis which is the phenomenon of liquid being expelled from the gel structure. Therefore, it is needed to formulate a HPHT drilling mud with the low

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shear rate viscosity and high anti-sagging capabilitie [6].

By the fact that nanoparticles constitutes are very small in sizes relative to other components of the mud system, they have the potential to act as effective lubricant additives. By virtue of the small size and shape of nanoparticles, they can enter the contact area between the surfaces easily. Also most of inorganic nanoparticles do not exhibit any affinity to oil and are not affected by the mud type. In-situ and ex-situ techniques for composing a wide variety of well dispersed nanoparticles in an invert emulsion as well as water-based drilling fluid have been explored. These methods greatly depend on high shearing, which produces finely dispersed water pools, in the case of invert emulsion drilling fluids, and the utilization of these water pools as nanoreactors to compose nanoparticles with sizes mainly below 100 nm. Once composed, these nanoparticles exhibit very high stability in the base drilling fluid and interact very efficaciously with the rest of the drilling fluid. Anterior experiments showed that these particles impeccably seal filter cakes by engendering crack-free, very smooth surfaces. These particles contribute to the formation of slippery layers between the borehole and the drill string leading to lowering overall the coefficient of friction and, subsequently, increment the extended reach of horizontal drilling [5].

Lately, a drilling fluid with promising future can be formulated with the help of the new nanotechnology. Many chemical materials can be manufactured with nano-scale particles that have the ability to enhance the rheological, thermal, mechanical, and optical properties of the drilling fluid upon using nano-additives [7]. The nanoparticles used in nano-based drilling fluid can exhibit superior characteristics to their base material and may provide features such as enhanced stability against sedimentation since the gravity force can be easily balanced with surface forces.

2 Methodology

The effect of TiO_2 (titania) nanoparticles have been explored in two types of drilling fluid namely water-based mud and synthetic (paraffin base oil) based mud. Therefore, the methodology chapter shall discuss WBM testing and SBM testing. All drilling fluids formulations, chemicals, testing equipment and facilities were provided by GRTC laboratories affiliated to SCOMI OiltoolsSdn. Bhd. and all the testing procedures were performed following SCOMI's laboratories protocol and API standards.

For water-based mud testing, the R&D department affiliated to GRTC laboratories provided KCl/PHPA (polymer) formulation to be used to investigate the effect of titania nanoparticles on its performance characteristics. This mud formulation is suitable for field applications and wells that have bottom-hole temperatures not greater than 250°F. However, after the addition of TiO_2 nanoparticles, the mud was also subjected to hot rolling at temperature reached 275°F, to investigate the possibility of temperature boosting capability of the added nanoparticles. Water-based mud testing included mainly the mud weight, rheology, pH, HPHT filtration and mud lubricity tests.

For Synthetic-based mud testing, two different mud formulations were provided by the R&D department of GRTC laboratories. The first SBM formulation is suitable for wells that drill into formations characterized by 300°F and the second formulation is suitable for drilling into formations characterized by 450°F. The tests conducted on SBM with such high and extremely high temperatures aimed to investigate the behavior of TiO_2 nanoparticles under such temperatures and its impact on the performance characteristics of SBM under severe conditions i.e. HPHT environments.

This paper will only discuss the main tests including mud rheology, lubricity and HPHT filtration.

2.1 Mixing the Base Mud

R&D department provided KCl/PHPA WBM formulation to be used as base mud for testing effect of different concentrations of titania nanoparticles on the performance characteristics of the drilling fluid. The WBM formulation is shown in Table 1.1

Table 2.1 KCl/PHPA WBM formulation

Product	Function	Base 1 bbl, g
Fresh water	Base fluid	290.95
SODA ASH	Treat calcium contamination	0.1
KCl	Source of potassium ions, to inhibit shale swelling and dispersion	30.00
HYDRO STAR NF	Fluid loss control and increase viscosity in WBM	2.00
Flowzan	Biopolymer-viscosifier	1.55
HYDRO CAP XP	PHPA systems provide maximum inhibition/encapsulation	1.50
HYDRO BUFF	Polymer extender for WBM	0.25
Caustic Soda	Control pH	0.10
Drill Bar 4.2	Weighting agent	136.04
Rev Dust	Simulate cuttings in mud	20.00
OX-SCAV	Polymer extender	1.00

R&D department provided Synthetic oil-based mud formulation to be used as base mud for testing effect of different concentrations of titania nanoparticles on the performance characteristics of the drilling fluid at 300°F and 450°F as shown in Table 2.2 and Table 2.3 respectively.

Table 2.2 SBM formulation suitable for temperatures reach 300°F

Products	Function	Base 1 bbl, g
Sarapar 147	Synthetic Paraffin Base oil	151.36
CONFI-MUL P	Primary emulsifier	5.00
CONFI-MUL S	Secondary emulsifier	7.00
CONFI GEL HT	Viscosifier	7.00
CONFI TROL HT	HPHT filtration control	8.00
Lime	Activate emulsion and control pH	8.00
fresh water	Internal phase	65.19
$CaCl_2$	Soluble weighting agent and Ca^{+2} inhibition	23.62
Drill Bar	Weighting agent	229.04

Table 2.3 SBM formulation suitable fortemperatures reach450°F

Products	Function	Base 1 bbl,g
Sarapar 147	Synthetic paraffin base oil	126.73
CONFI-MUL XHT	Primary emulsifier	15.00
CONFI-TEC XHT	Secondary emulsifier	1.50
CONFI GEL XHT	Viscosifier suitable for 450F	0.20
CONFI TROL XHT	Filtration control for HPHT	1.50
FLC 2000	Fluid loss control	8.00
Lime	Activate emulsion and control pH	15.00
fresh water	Internal phase	29.04
$CaCl_2$	Soluble weighting agent and Ca^{+2} inhibition	10.37
Drill Bar XP	Weighting agent	476.94
Rev Dust	Simulates well cuttings	30.00

Firstly, from the formulations given, all the chemicals necessary for mixing the water-based mud were collected from GRTC warehouse and any chemical taken was put inside a plastic container with proper labeling including product name, product ID and storage location in the warehouse. Also the amount taken was recorded in the warehouse data sheet. The prepared chemicals were placed inside one tray and were taken to R&D laboratories.

After chemical preparation, Silverson mixer is used for mixing five barrels of drilling fluid and a timer to indicate mixing duration. Each chemical was let to mix for appropriate duration to ensure dispersion of particles into the mud matrix. The mixing speed for Silverson mixer started with low rotation then gradually increased and lastly was set at 6000rpm with total mixing time for WBM is 45min and for SBM is 60min. After mixing the five barrels of mud, it was split into five separate mud cups so that each cup shall contain specific concentration of TiO_2 nanoparticles.

2.2 Preparing the Nano-Drilling Fluid

The five split mud cups were weighed using electronic balance to ensure that one barrel of mud cup have a total weight as specified in the mud formulation. Then 0.05g, 0.1g, 0.5g and 1g concentrations of TiO_2 nanoparticles were weighed using milligram electronic balance, petri dish, and spatula. Each concentration was added to a mud cup followed by proper labeling to indicate the content of the cup. After that, each mud cup was let to stir for 3-5min using Hamilton Beach mixer. The TiO_2 nanoparticles were purchased from Sigma-Aldrich and its properties are as follows:

Table 3.4 Characteristics of TiO_2 (titania) nanoparticles

Type	Anatase – nanopowder
Appearance	White powder
Particle size	< 25 nm
Surface area	45 – 55 m2/g
Purity	99.7 %
Trace metal analysis	< 4000 ppm
Formula weight	79.87 g/mol

2.3 Hot Rolling

This is the most important step in prior to any drilling fluid testing as it simulates the conditions under which the mud will be used. The mud sample is let to hot roll in a roller oven for 16hr. Rolling simulates the rotation motion of the drilling fluid along with drill pipe and drill bit, whereas the temperature of the oven represents the formation temperature being drilled. Mud samples are poured into ageing cells and pressurized to appropriate back pressure. For instance, hot rolling WBM at 250°F has to be pressurized to 100 psi, hot rolling SBM at 300°F has to be pressurized to 100 psi and SBM at 450°F has to be pressurized to 450 psi. Pressurizing the ageing cell is essential step to prevent the mud samples from boiling as it is being heated for continuous 16 hr. After the 16 hr., roller oven heater is turned off and the ageing cells are let to cool down at room temperature for half an hour, then the cells are taken out and placed into water bath for another half an hour. Heat resistant gloved were used for transferring the cells from the oven to the water bath.

3 Results

3.1 Effect of TiO_2 Nanoparticles on Water-Based Mud

3.1.1 Mud Rheology

Plastic Viscosity for 250°F WBM slightly decreases for concentrations less than 0.5 g, however, at concentrations greater than 0.5 g till 0.1 g, PV increases compared to base mud having zero titania concentration Similarity, plastic viscosity for 275°F WBM shows slight increase in PV with TiO_2 nanoparticles concentrations lower than 0.5 g, but for concentrations greater than 0.5 g, the increment in PV is slightly higher compared to base mud. As shown in Figure 3.1.

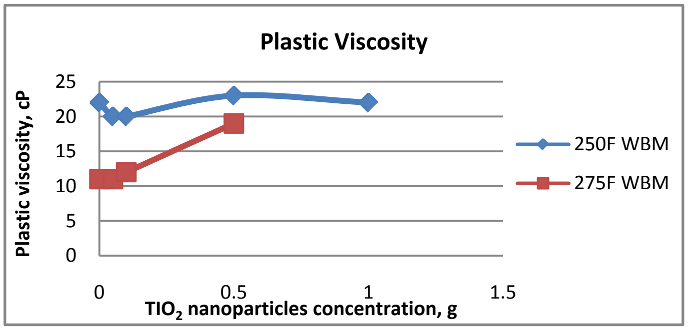

Fig 3.1 Effect of TiO_2 nanoparticles on PV of WBM

Figure 3.2, shows Yield Point for 250°F WBM is directly proportional with increased concentrations of TiO_2 nanoparticles till 0.5 g. For concentrations greater than 0.5 g, YP seems not affected much by the increment in titania nanoparticles concentrations. YP for 275°F WBM show that YP for this WBM (which was hot rolled at higher temperatures than it is designed to fit) have an opposing trend to the 250°F WBM. Whereby, YP decreases with increased concentrations of titania nanoparticles.

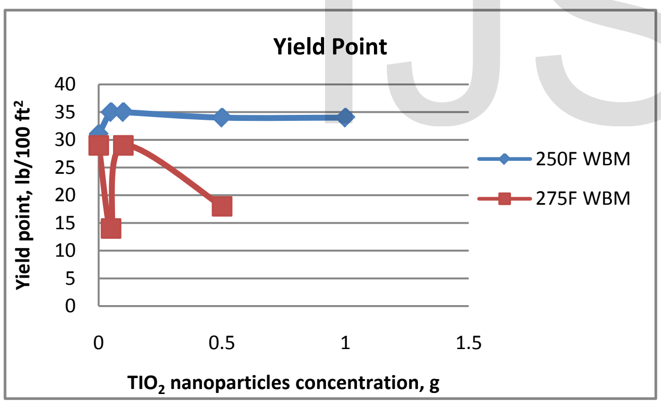

Fig 3.2 Effect of TiO_2 nanoparticles on YP of WBM

Gel strength results are shown in Figures 3.3 and 3.4, respectively.The gel strength of WBM for 10-sec and 10-min has a proportional relationship with increased concentrations of TiO_2 nanoparticles. Generally, gel strength and YP in the mud system are related in such a way that increment in gel strength is affected by increment in YP. The gel strength for 10-sec and 10-min of 275°F WBM decreased with increased concentrations of TiO_2 nanoparticles, similar to the trend of YP.

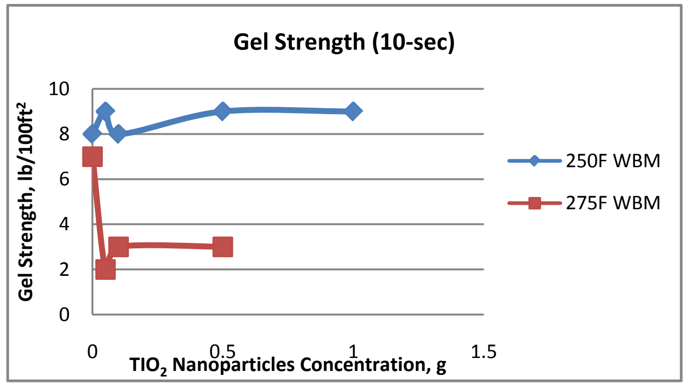

Fig 3.3 Effect of TiO_2 nanoparticles on 10-sec gel strength of WBM

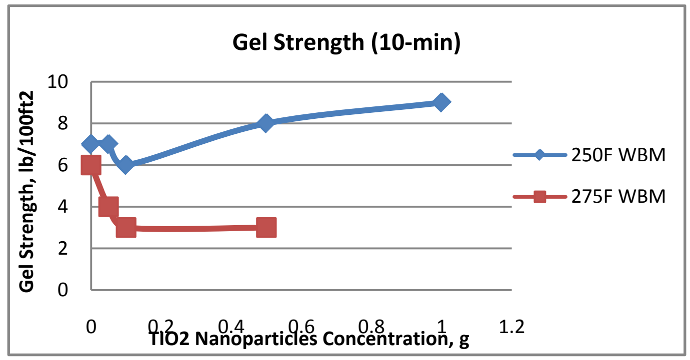

Fig 3.4 Effect of TiO_2 nanoparticles on 10-min gel strength of WBM

3.1.2 Mud Lubricity

Lubricity test results show significant reduction of friction coefficient with the addition of TiO_2 nanoparticles. In other words, nanoparticles improved the mud lubricity characteristics. The optimum concentration is 0.5 g which resulted in 34% torque reduction compared to base mud, increasing nanoparticle concentrations above that would rather increase the coefficient of friction. This optimum concentration is observed to be the same for both 250°F WBM and 275°F WBM, as shown in Figure 3.5.

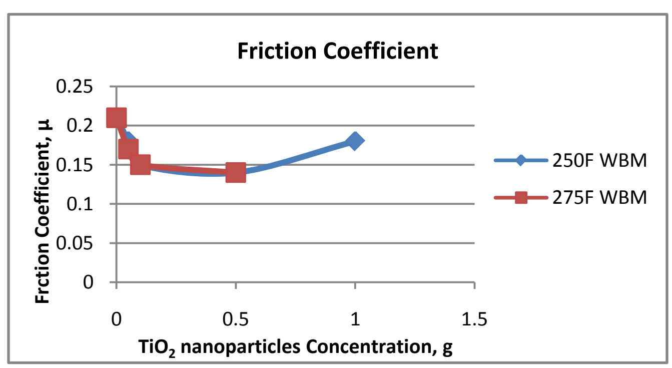

Fig 3.5 Effect of TiO_2 nanoparticles on friction coefficient of WBM

3.1.3 HPHT Filtration Test

Results show that the addition of TiO_2 nanoparticles to the mud system significantly enhanced the fluid loss rate over a period of 30 min especially with 0.1 g, which achieved 50% reduction in fluid loss compared to the base mud. However, increasing the concentrations above 0.5 g would rather increase the fluid loss. Furthermore, nanoparticles improved the filter cake characteristics by making it thinner and less permeable compared to the filter cake obtained from base mud. Results for HPHT filtration test of 275°F WBM were total loss of the mud for a period of time less than 10 min. The mud was too thin and completely filtrated through the filter paper. The filtrated thin mud flowed through the connected hoses and pipes of HPHT filtration apparatus and increased the pressure inside the pipelines due to differential pressure of 500 psi that was applied during the test. Results are shown in Figure 3.6.

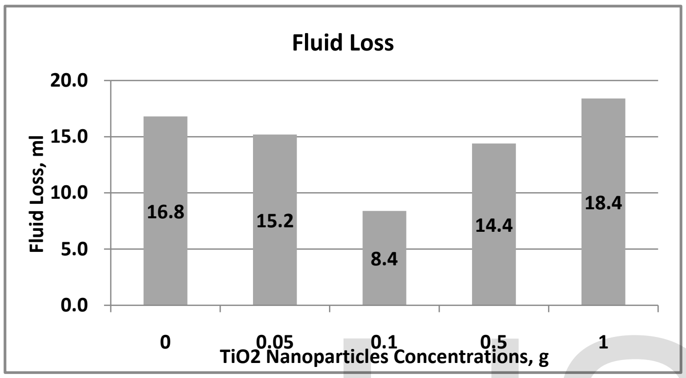

Fig 3.6 Effect of TiO_2 nanoparticles on fluid loss of 250°F WBM

3.2 Effect of TiO_2 Nanoparticles on Synthetic-Based Mud

3.2.1 Mud Rheology

Plastic Viscosity of 300°F SBM decreases with increased concentrations of TiO_2 nanoparticles, whereas plastic viscosity of 450°F SBM increases with increased concentrations of TiO_2 nanoparticles. Results are shown in Figure 3.7.

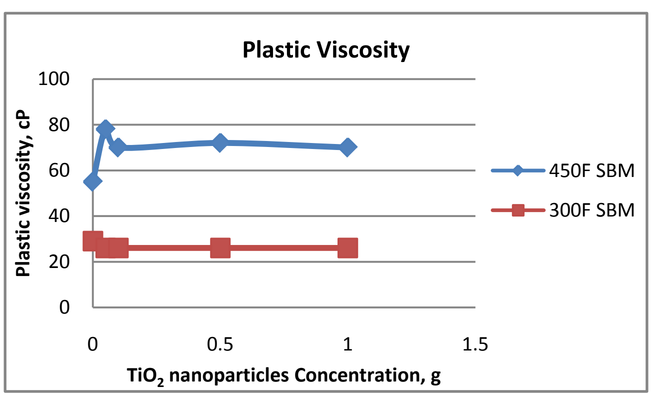

Fig 3.7 Effect of TiO_2 nanoparticles on PV of SBM

Results have shown on the following Figure 3.8 that yield point for 300°F SBM increases as titania concentration increases. On the other hand, yield point for 450°F SBM shows opposing behavior, where it decreases with increased concentrations of nanoparticles.

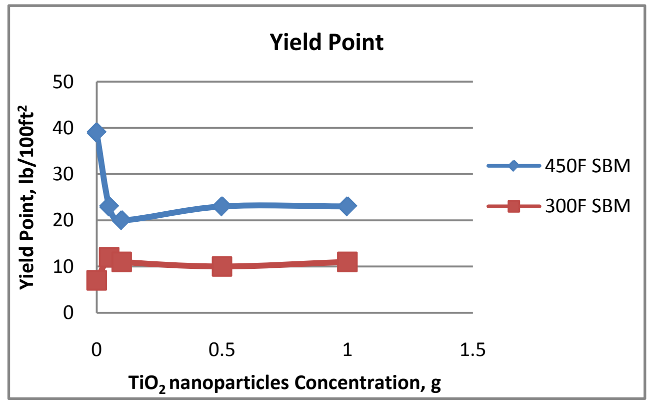

Fig 3.8Effect of TiO_2 nanoparticles on YP of SBM

The Figures 3.9 and 3.10 show the gel strength for 10-sec and 10-min for both 300°F SBM and 450°F SBM. Results show that increasing nanoparticles concentration increases the gel strength characteristics for both SBM formulations.

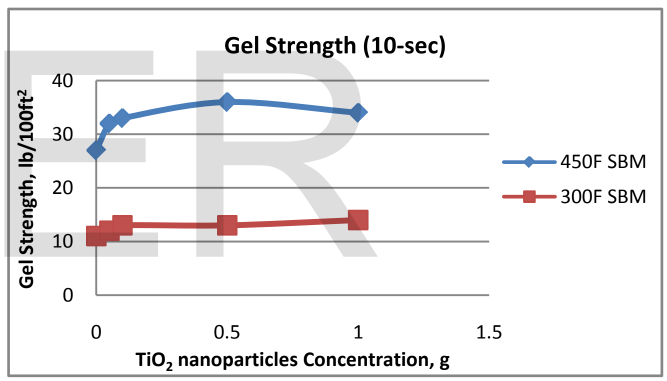

Fig 3.9 Effect of TiO_2 nanoparticles on 10-sec gel strength of SBM

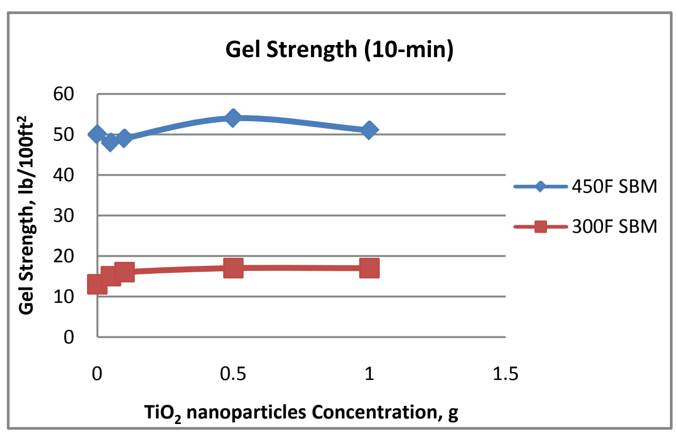

Fig 3.10Effect of TiO_2 nanoparticles on 10-min gel strength of SBM

3.2.2 Mud Lubricity

Results for mud lubricity of SBM system are shown in Figure 3.11. The base mud had 0.14 and 0.17 friction coefficient for 300°F and 450°F SBM respectively. The addition of nanoparticles greatly improved the mud lubricity by reducing the friction coefficient to 0.1 and 0.12 for 300°F and 450°F SBM respectively. The optimum concentration for both SBM formulations is 0.5 g which achieved the lowest friction with 28% torque reduction compared to base mud.

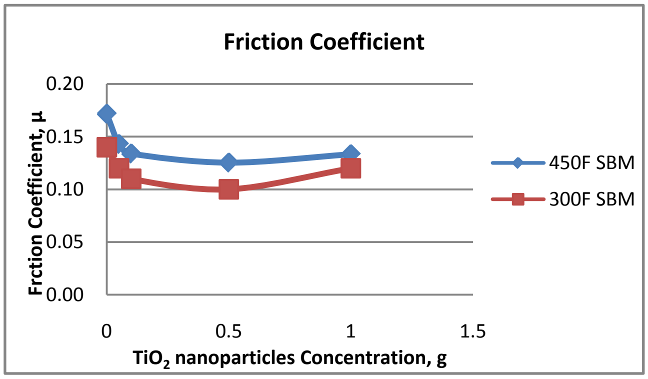

Fig 3.11 Effect of TiO_2 nanoparticles on friction coefficient of SBM

3.2.3 HPHT Filtration Test

HPHT filtration results are shown in Figure 3.12 and 3.13 which show results for fluid loss. The addition of titania nanoparticles has significantly reduced the mud filtrate collected over period of 30 min. The optimum concentration is 0.5 g which achieved the lowest fluid loss and resulted in 49% reduction in fluid loss for 300°F SBM and 86% reduction in fluid loss for 450°F SBM compared to base mud of each mud formulation. Increasing nanoparticles concentrations above 0.5 g would either increase the filtrate or obtain same amount of it which is considered a waste of chemical. Moreover, nanoparticles helped obtaining thinner and less permeable filter cake compared to the filter cake of the base mud at the same optimum concentration of 0.5 g.

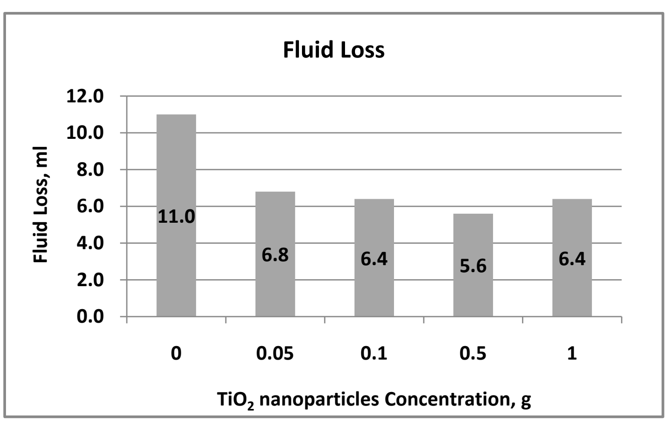

Fig 3.12 Effect of TiO_2 nanoparticles on fluid loss of 300°F 3BM

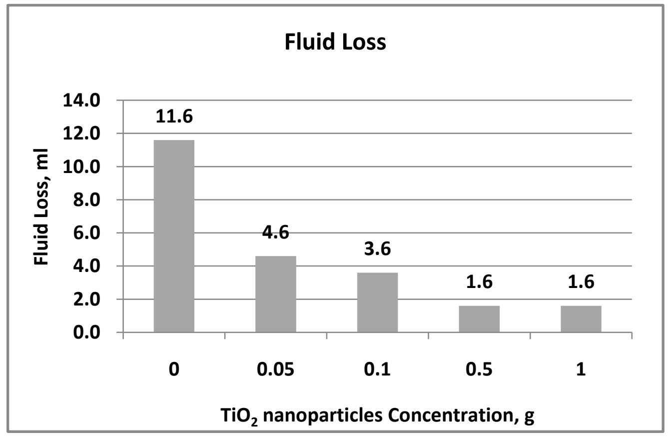

Fig 3.13 Effect of TiO_2 nanoparticles on fluid loss of 450°F WBM

4 Discussion

The addition on titania nanoparticles to water-based mud with 250°F hot rolling temperature slightly increased the mud viscosity due to the large surface area per volume property of nanoparticles which activate and promote more interactions between the nanoparticles, matrix and surrounding water-based mud. Also, the surface area may provide active sites for bonding with functional groups and hence, nanoparticles will bond with the mud, leading to increased viscosity for the mud. Although increased viscosity of the mud is not favorable in overall drilling operations especially in HPHT drilling, this increment is only few centipoises and still acceptable. Yield point also increased with the addition of nanoparticles to the water-based mud and this attributed to the fact that yield point is directly related to the amount of solid content of the mud. The third rheological parameter, gel strength, also increased with the addition of TiO_2 nanoparticles and this increment is attributed to the fact that gel strength occurs due to the presence of electrically charged particles which aggregate into a firm matrix under static conditions i.e. when mud circulation stops. The attractive forces between solid components of the mud and nanoparticles link together with the base mud within 10 seconds and/or 10 minutes forming gel structure and thus, increased gel effect.

In terms of impact of titania nanoparticles on the HPHT filtration properties of water-based mud, nanoparticles have significantly improved the fluid loss rate and filter cake thickness. From the results, it is observed that 0.1 g is the optimum concentration for TiO_2 nanoparticles to be added to the mud system which achieved 50% reduction in fluid loss compared to the base mud with thinner and less permeable filter cake [3]. Since all the mud components are at micro-sizes, the dispersed TiO_2 nanoparticles in the mud system act as bridging agent and seal the permeable filter cake at nano-scale producing firmer, crack free filter cake surface. Furthermore, titania nanoparticles has marked its efficiency by lowering the coefficient of friction for the water-based mud. From the results, it is shown that 0.5 g of TiO_2 nanoparticles in 350 ml (one barrel) of WBM has greatly improved the mud lubricity characteristics by achieving 34% torque reduction compared to the base mud. TiO_2 nanoparticles acted as solid lubricant for the mud that can smoothly slide between contacting surfaces and become a ball bearing material in the mud system. This phenomenon reduces the friction forces between the mud and the drill string as the mud being circulated throughout the wellbore which is very beneficial in reducing torque and drag problems encountered in deviated wells.

Nanoparticles have been proved failed to boost the temperature of failed water-based mud system. The formulation of KCl/PHPA WBM given by the R&D department affiliated to SCOMI Oiltools was suitable for field applications dealing with bottom-hole temperature of 250ºF, therefore is was expected that the mud will lose its rheological and filtration stability at temperatures greater than 250ºF. The whole WBM system failed at 275ºF and TiO_2 nanoparticles failed to sustain the mud performance and gave variation in rheological properties compared to the mud behavior at 250ºF. Early signs of rheological properties failure are detected from the thin mud structure that have very low dial readings from the viscometer at shear rates of 200, 100, 6 and 3 rpm as shown in annex A. and gel strength of the mud was insufficient and caused settling of weighting materials (sagging). Also, HPHT filtration test results were total mud loss in less than 10 minutes under 500 psi differential pressure applied. Therefore, in order to fully utilize the application of nanoparticles in drilling fluid, the mud system must be stable at the maximum temperature that the mud will experience at bottom-hole, to acquire optimum mud performance with little concentrations of nanoparticles that do not exceed 0.5 g in one barrel of mud.

Rheology test indicated slight decrease in viscosity with increased concentrations of TiO_2 nanoparticles for SBM formulation hot rolled at 300ºF, whereas viscosity slightly increased for SBM formulation hot rolled at 450ºF. It is deduce that the viscosity is directly affected by the behavior of mud formulation itself after being subjected to high temperatures. For instance, SBM formulation suitable for 300ºF has thinning behavior after hot rolling, while SBM formulation for 450ºF has thickening behavior. Therefore, the viscosity for 300ºF SBM decreases and viscosity for 450ºF increases even with the addition of different concentrations of TiO_2 nanoparticles. The further slight decrease in viscosity for 300ºF SBM is caused by repulsive forces occur between TiO_2 nanoparticles and solid particles exist within the mud matrix which reduces the viscosity as TiO_2 nanoparticles increases. On the other hand, the increase in mud viscosity of 450ºF SBM with increased concentrations of nanoparticles is due to linkage between nanoparticles with other mud components in the mud matrix. Yield point for 300ºF SBM increased and for 450ºF decreased with increased concentrations of TiO_2 nanoparticles. In HPHT drilling operations, it is favorable that plastic viscosity of drilling fluid would be as low as reasonably possible to minimize the effect Equivalent Circulation Density (ECD) which imposes extra increment in the mud viscosity as it is circulated throughout the wellbore due to annular friction against drilled formation. Moreover, yield point and gel strength is preferred to be relative low to prevent excessive gelation or high surge and swap pressure, but sufficient to prevent material sagging [9]. Since drilling fluids are non-Newtonian fluids and require initial stress to start flowing, YP causes sudden pressure change as the fluid starts moving or at about to stop and this pressure change cannot be avoided by any mechanical means. In addition, YP causes sudden change in surge and swap pressure when drilling string starts to move up/down during drilling or tripping regardless of how slow the pipe moves. Therefore, drilling fluid characterized by relatively low PV, YP and gel strength is more preferable in HPHT drilling operations.

HPHT filtration results were impressive for both SBM formulations and proved that TiO_2 nanoparticles works best under high and extra high temperatures. TiO_2 nanoparticles significantly reduced fluid loss by 49% for SBM at 300ºF and 86% for SBM at 450ºF using 0.5 g in one barrel of drilling fluid. Also, the addition of TiO_2 nanoparticles produced thinner and less permeable filter cake. These results suggest the possibility of using nanoparticles as fluid loss agents or nanofying conventional fluid loss control additives. Due to the very small size of nanoparticles they can fit in between other solids at micron sizes present in the mud matrix, and thus produce firmer, smoother and less permeable filter cake which ultimately reduces the loss of aqueous phase of the drilling fluid. Filtration is one of the most critical properties of the drilling fluid and reducing the tendency of losing the aqueous phase of the mud is a major concern in designing any mud formulation, because reducing the amount of fluid loss into drilled formation minimizes formation damage caused by invasion of drilling fluid filtrate. Furthermore, thinner and less permeable filter cake is favorable to minimize the risk of differential sticking problems caused by thick filter cake. Severe differential sticking problems imposes additional costly operations for retrieving stuck drill pipe, increases non-producing time by increasing duration of drilling operations and may eventually lead to well abandonment. Drilling fluid designed with minimal fluid loss rate aid in enhancing drilling operations by maintaining wellbore stability as the mud will preserve its aqueous phase, maintain proper mud weight and will not cause excessive buildup of solid deposits on the filter cake. Remarkably to address that the rate of penetration and well productivity are also enhanced with drilling fluid designed with optimum fluid loss control due to minimized formation damage and the likelihood of the differential sticking problems.

By nature oil-based drilling fluids are more lubricious than water-based drilling fluids. The addition of TiO_2 nanoparticles to synthetic oil-based mud further improved the mud lubricity characteristics and reduced the friction coefficient by 28% compared to base mud. Nanoparticles proved to enhance lubricity of drilling mud owing to their small size and shape which enable them to enter contact zones between surfaces. This phenomenon is very beneficial in many aspects such as, act as ball bearing particles that form slippery layers between borehole and drill string [3]. Simultaneously, these particles provide load-bearing surface between pipes, hence they will further lower torque and drag forces and therefore, increase extended well reach. Additionally, nanoparticles have less kinetic energy and abrasive action compared to larger particles and hence the wear/tear of down-hole equipment can be neglected [12].

5 Conclusion

This experimental research has explored the effect of different concentrations of TiO_2 nanoparticles on the performance characteristics of drilling fluid including water-based mud and synthetic-based mud. The research also covered examination of the performance of TiO_2 nanoparticles under severs environmental conditions namely HPHT conditions. The following points address the conclusion of this experimental research:

Nanoparticles in Water-based mud:

1. TiO_2 Nanoparticles increased the PV, YP and gel strength with increased concentrations of nanoparticles. However, this incremental in rheological properties is within desired range for optimum performance of drilling fluid under HPHT conditions.

2. TiO_2 nanoparticles significantly reduced the fluid loss rate and thinner filter cake is obtained with the addition of nanoparticles. The optimum concentration is 0.1g in one barrel of mud which lowered the fluid loss rate by 50% compared to base mud and achieved thinnest mud cake. The turnover concentration is 0.5g, above which higher fluid loss rate is obtained.

3. TiO_2 nanoparticles enhanced lubricity characteristics of the drilling fluid. The optimum concentration is 0.5 g in one barrel of mud which achieved lowest friction factor with 34% torque reduction compared to base mud.

4. TiO_2 nanoparticles cannot foster the performance of failed mud. When the mud loses its rheological stability and filtration properties, nanoparticles cannot perform effectively.

Nanoparticles in Synthetic-based mud:

1. Increased concentrations of TiO_2 nanoparticles increased PV and decreased YP for SBM that have thickening behavior under high temperatures and vice versa. The increment of PV and decrement of YP was not significant to adversely affect the rheological properties of SBM for optimum performance of drilling fluid at HPHT conditions.

2. Filtration properties were greatly enhanced with the addition of TiO_2 nanoparticles. At 300oF, TiO_2 nanoparticles reduced fluid loss rate by 49%, whilst at 450oF it reduced the fluidloss rate by 86%, also thinner mud cake is obtained compared to base mud. The optimum concentration is 0.5 g in one barrel of mud that achieved the lowest fluid loss rate, thinnest mud cake and it is also the turnover concentrations above which no significant improvement is observed.

3. SBM lubricity characteristics improved with the addition of TiO_2nanoparticles as they achieved 28% average torque reduction with 0.5 g in one barrel of mud compared to base mud.

Further conclusions, improved filtration properties of the drilling fluid aid to formation protection associated with lower filtrate and solid invasion. Minimized formation damage and enhanced productivity index can be achieved with low concentrations of nanoparticle. In addition, nanoparticles act as ball bearing solid lubricants that significantly reduce torque and drag problems and transfer the weight on bit which ultimately contribute to more efficient drilling operations especially in directional drilling and deviated wells.

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