Improving Drilling Fluid Properties at High Pressure Conditions Using Selected Nanomaterials

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Abstract. Drilling fluids with conventional lubricants (including solid and liquid lubricants) will produce lubricant film between drill string and wellbore/casing, but this film will not be strong enough to protect the bit bearing surfaces subjected to high load conditions during the drilling operations, resulting in shortening the life of drill bit. In this research, the possibility of using nanomaterials as extreme pressure lubricants was investigated by adding different concentrations (0.02, 0.05 and 0.1) wt. % of TiO₂ nanoparticles (NPs) and Cu NP into water-based mud. The lubricating film strength of water-based mud samples under extreme pressure conditions were measured using Extreme Pressure (EP) and Lubricity Tester. With the purpose of getting the best performance from extreme pressure lubricants, the effect of nanomaterials on rheological (including plastic viscosity, yield point, apparent viscosity, and gel strength) and filtration (including filtrate loss volume and mud cake thickness) properties were measured. TiO₂ NPs and Cu NP showed a good enhancement in lubricating film strength under extreme pressure conditions. The maximum value of lubricating film strength increasing percentage (69.6%) was obtained using TiO₂ NPs with concentration of 0.1 wt. %.

1. Introduction

One of the significant functions of drilling fluid is lubricating the bits and drill string. They fail more rapidly if it was not lubricating effect of drilling fluid, where the bits are subjected to heavy weight load which increase the bearing and tooth wear of roller cone bits. Also during drilling extended and horizontal wells the torque and drag between the drill string and wellbore increase due to high friction which leads to reduction in the equipment life and decrease in the well length [1]. Oil and synthetic base muds lubricate better than most water base muds, but lubricants can be added to water base muds to improve them. Two main properties are important to choose the lubricant materials; they are coefficient of friction (COF) and extreme pressure (EP). The extreme pressure property of lubricant concerns with the strength of the film produced by the lubricant where the metal surfaces are in contact with each other under high pressure. Most of lubricant losses their hydrodynamic lubricant at high pressure load. The extreme pressure lubricant provides a strong protection film of metals that are subjected to high pressure load. It is not necessary that lubricant materials that have low coefficient of friction can have a strong lubrication film[2].
In recent years nonmaterials have been used in all fields of petroleum industry and drilling process was one of them. Adding nanomaterials to drilling fluid in order to improve lubricity, improve rheological properties, improve fluid loss, improve BHA’s life, and improve thermal stability of drilling fluid. Some researchers [3],[4],[5] and [6] used nano-additive to enhance the rheological, filtration and coefficient of friction reduction properties of drilling fluid. Jahns [7] used alumina, titania, and silica nanoparticles to improve water base mud, he found that titania, and silica nanoparticles reduced friction factor effectively, while alumina nanoparticles had a limited friction reduction. Taha [8] added (1-5) vol% of nanographene to water base mud, he gained a 50% torque reduction in high temperature-high pressure (HTHP) water-based mud by using 4% - 5% by volume of the nonmaterial. In Krishna work [9], a boron-based a nonmaterial was added to water based mud, a 80% torque reduction in 10 lb/gal water-based mud and 52% torque reduction in 13.5 lb/gal water-based mud were obtained by using 5% by volume of the product. [10] and [11] used chemically and mechanically generated barite nanoparticles at different concentrations to enhance the lubrication properties of water base mud. Al2O3, Fe3O4, and SiO2 nanoparticles with KH550 coating effect on water based mud lubricity have been studied by [12]. He found that lubricity was improved with the addition of SiO2 nanoparticle with and without coating, performing of SiO2 nanoparticle with KH550 coating was better than SiO2 nanoparticle without coating. [13] used Cu, XC polymer, barite, and lignite nanoparticles. She gained good reduction in COF for both water-based mud and KCl polymer mud. The maximum value of COF reduction percentage (more than 60%) was obtained by adding 4 gm XC Polymer to KCl polymer mud. [1] investigated the usage of adding multi-walled carbon nanotubes (MWCNT) and graphene-nanplatelets (GnP) to water base mud in order to reduce coefficient of friction. Their results showed that the addition of 0.01 ppb of MWCNT and 0.2 ppb of GNP gave torque lubricity reduction between 35 to 59%.

In spite of the above workers, studying the combined effect of nanomaterials on both of lubricity coefficient and extreme pressure has not been done yet. Hence, the main objective of this research is to investigate the possibility of using nanomaterial as lubricant materials and study the stability of the thin film formed between the two metal surfaces under extreme pressure conditions.

2. Experimental Work
2.1 Materials
Commercial bentonite (supplied by Oren Hydrocarbons Middle East Inc.) was used in the preparation of water-based mud. The nanomaterials that had been used in this study were Copper NP* (supplied by Nanjing Nano Technology Co., Ltd.) with (10-30) nm particle size and purity of 99.99% and Titanium dioxide NP of 25 nm particle size and 99.98% purity (supplied by Cheng Du Micxy Chemical Co., Ltd.)

2.2 Procedure of Experiments
2.2.1 Clay Characterization Analysis:
Bentonite was quantitatively and qualitatively analyzed using XRF-1800 Sequential X-ray Fluorescence Spectrometer and XRD-6100/7000 X-ray Diffractometer respectively. While Particle-size distributions of bentonite was measured using a Malvern Mastersizer 2000 particle size analyzer, these analyses were carried out in Geological Survey/Central Laboratories Department.

2.2.2 Drilling Fluid Preparation:
To prepare the blank sample of water-based mud (according to API Specification 13A, 2010), the bentonite is mixed with fresh water using Hamilton Beach Mixer for 10 minutes and then the suspension is aged in a sealed container for 16 hours to ensure good hydration of bentonite. It is important to mention that the blank sample of water-based mud didn’t have any other chemicals, just water and bentonite, in its formulation. This is in order to investigate the effect of nanomaterials on the drilling fluid properties without the side effect of chemicals. Then nanomaterials with concentrations of 0.02, 0.05, 0.1 wt% were added to water-based mud and mixed for 10 minutes using Hamilton
Beach Mixer then the samples were continued to mix using Ultrasonic Bath for 10 minutes to ensure a good dispersion of nanomaterials.

2.2.3 Measurements and Instruments:
The lubricating quality of water-based mud with and without nanomaterials had been measured by using OFITE EP and Lubricity Tester. The standard lubricity coefficient test is run at 60 rpm with 150 in-lb of force (the equivalent of approximately 600 psi pressure of the intermediate fluid) is applied to two hardened steel surfaces, a rotating ring and a stationary block. Before any test, the apparatus was calibrated with distilled water so as to calculate the value of correction factor (CF) using the following equation:

\[ CF = \frac{34}{\text{Meter Reading}} \]  

(1)

The lubricity coefficient (LC) of water-based mud was calculated manually using the data obtained from apparatus as follows:

\[ LC = CF \times \frac{\text{Meter Reading}}{100} \]

(2)

Where:
CF = Correction Factor
LC = Lubricity Coefficient

The film strength of water-based mud under extreme pressure conditions (extreme pressure test was run at a high shear rate, 1,000 RPM, and torque ranging from 150 to 270 inch-pounds) was calculated manually using the data obtained from apparatus as follows:

\[ P = \frac{T}{1.5 \times L \times W} \]

(3)

Where:
P = Film Strength (psi)
T = Torque Meter Dial Reading (in-lb)
W = Scar Width (inches)
L = Scar Length (inches)

The rheological properties of water-based mud with and without nanomaterials had been measured using OFITE Hand Crank Rheometers as follows:
The rheological properties including plastic viscosity (PV), yield point (YP), and apparent viscosity (AV) were calculated manually using the data obtained from the rheometer as follows:

\[ PV = \phi_{600} - \phi_{300} \]

(4)

\[ YP = \phi_{300} - PV \]

(5)

\[ AV = \frac{\phi_{600}}{2} \]

(6)

Where:
PV = Plastic Viscosity (cP)
\( \phi_{600} = \) Dial Reading at 600 RPM
\( \phi_{300} = \) Dial Reading at 300 RPM
YP = Yield Point (lb/100 ft²)
AV = Apparent Viscosity (cP)

Also the gel strength was measured from the rheometer. Filtrate volume and mud cake thickness were measured using OFITE Low-Pressure Filter Press with Dead Weight Hydraulic Assembly.
3. Results and Discussion

3.1 Clay Characterization

The X-Ray fluorescence (XRF) and the X-Ray diffraction (XRD) analyses of bentonite that was used in the preparation of water-based mud are shown in Tables 1 and 2 and figure 1. The analyses show that the major component of bentonite is montmorillonite and a high percentage of Silicon Oxide (SiO2) along with Aluminum Oxide (Al2O3), as well as a low percentage of Potassium Oxide (K2O).

Table 1. XRF Analysis of Bentonite.

| Component | Quantity | Component | Quantity |
|-----------|----------|-----------|----------|
| SiO2 %    | 49.98    | SO3 %     | 0.16     |
| Fe2O3 %   | 10       | LOI %     | 8.49     |
| Al2O3 %   | 17.5     | P2O5 %    | 0.62     |
| CaO %     | 4.4      | Na2O %    | 2.24     |
| MgO %     | 4.9      | K2O %     | 0.12     |

LOI: Loss On Ignition

Table 2. XRD Analysis of Bentonite.

| Minerals               |
|------------------------|
| Major                  |
| Montmorillonite, Quartz|
| Minor                  |
| Palygorskite, Calcite  |

Figure 1. XRD Analysis of Bentonite.
The particle size distribution of bentonite is within average size of 238 nm, as shown in Figure 2.

![Particle Size Distribution of Bentonite](image)

**Figure 2.** Particle Size Distribution of Bentonite.

3.2 **EPLubricating Quality Measurement:**

Effect of TiO2 NP and Cu NP addition to water-based mud with different concentrations on EP film strength is illustrated in Table 3 and shown in Figures 3&4.

| weight % | Lubricity coefficient | Lubricity Reduction % | Film Strength | Film Strength Increasing % |
|----------|-----------------------|-----------------------|---------------|----------------------------|
| Blank    | 0.532                 | /                     | 2373.6        | /                          |
| TiO2 NPs |                      |                       |               |                            |
| 0.02     | 0.483                 | 9.21                  | 3371.6        | 42                         |
| 0.05     | 0.513                 | 6                     | 3491.13       | 47                         |
| 0.1      | 0.491                 | 7.7                   | 4025.7        | 69.6                       |
| Cu NP    |                      |                       |               |                            |
| 0.02     | 0.5                   | 5.4                   | 3326.94       | 40.16                      |
| 0.05     | 0.503                 | 5.45                  | 3306.87       | 39.3                       |
| 0.1      | 0.482                 | 9.39                  | 3748.43       | 57.92                      |

The addition of both TiO2 NP and Cu NP to water-based mud caused a significant increase in lubricating film strength at extreme pressure conditions, the greatest increase (69.6%) was observed by adding TiO2 NP at concentration of 0.1 wt%. However, the effect of these additives on the reduction of coefficient values is so slight and insignificant. Also, they increase slowly with increasing the concentrations of nanomaterials.

According to the layered shape of montmonolite of bentonite, the nanoparticles move towards the surface of these layers due to some physical forces (vanderwalls and coulombic), and this will make a change in the surface of bentonite. Indeed, due to the high temperature produced from the friction at the point of rubbing contact, a chemical reaction occurs leading to form a film on the surface of metal. However, this film is thin and this can be concluded from the low effect of nanoparticles on lubricity coefficient. Increasing the weight of nanomaterials showed a regular effect on these values. In spite of that, the strength of this film at extreme pressure increased with the addition of nanomatierals addition and its weight values.
Figure 3. Effect of Nanomaterial's Concentration on EP Film Strength of Water Based Mud.

Figure 4. Effect of Nanomaterial's Concentration on EP Film Strength Increasing Percentage of Water Based Mud.
3.3 Rheological Properties:
The rheological properties of water-based mud with different concentrations of both TiO2 NP and Cu NP are illustrated in Table 4 and shown in Figures 5 to 8.

| weight % | PV, cP | YP, lb/100 ft² | AV, cP | Gel Strength, lb/100 ft² |
|----------|--------|----------------|--------|--------------------------|
|          |        |                |        | 10 sec                   | 10 min |
| Blank    | 9      | 27             | 22.5   | 12                       | 15     |
| TiO2 NPs |        |                |        |                          |        |
| 0.02     | 11     | 28             | 25     | 13                       | 19     |
| 0.05     | 12     | 28             | 26     | 20                       | 22     |
| 0.1      | 10     | 30             | 25     | 20                       | 20     |
| Cu NP    |        |                |        |                          |        |
| 0.02     | 10     | 28             | 24     | 15                       | 20     |
| 0.05     | 11     | 27             | 24.5   | 17                       | 20     |
| 0.1      | 12     | 30             | 27     | 20                       | 20     |

As mentioned above, adding nanomaterials can affect on the surface of bentonite that lead to change in the drilling fluid properties. Indeed, these nanomaterials have large surface area per volume causing an increase in the interaction between the particles. A slight increase in plastic viscosity, yield point and apparent viscosity are shown in figures 5 to 7. Also, a slight increase in gel strength values with an increase in nanoparticle concentration as a result of the increasing inattraction forces and electrostatic force[14][15] and [16].

Figure 5. Effect of Nanomaterial's Concentration on Plastic Viscosity of Water Based Mud.
Figure 6. Effect of Nanomaterial's Concentration on Yield Point of Water Based Mud.

Figure 7. Effect of Nanomaterial's Concentration on Apparent Viscosity of Water Based Mud.
3.4 Filtration Properties:

The filtration properties of water-based mud with different concentrations of TiO2 NP and Cu NP are illustrated in Table 5 and shown in Figures 9 and 10.

Adding TiO2 NP to water-based mud caused a slight decrease in filtrate volume, and approximately had no effect on mud cake thickness. While the addition of Cu NP caused an increase in mud cake thickness at concentrations of 0.05 and 0.1 wt%, and had no effect on filtrate volume.

Nanomaterials may cause a decrease in filtrate loss volume, this may be explained due to the ability of nanomaterials to seal the nanopore throats of the wellbore formation and prevent water infiltration [17] and [18].

Table 5. Filtration Properties of Water Based Mud with Different Concentrations of Nanomaterials.

| Weight, % | Filtrate Volume, ml | Mud Cake Thickness |
|-----------|---------------------|--------------------|
| Blank     | 10                  | 0.2                |
| TiO2 NPs  |                     |                    |
| 0.02      | 8.8                 | 0.23               |
| 0.05      | 9.6                 | 0.28               |
| 0.1       | 8.8                 | 0.25               |
| Cu NP     |                     |                    |
| 0.02      | 10                  | 0.17               |
| 0.05      | 10                  | 0.35               |
| 0.1       | 10                  | 0.3                |
Figure 9. Effect of Nanomaterial's Concentration on Filtrate Volume Loss of Water Based Mud.

Figure 10. Effect of Nanomaterial's Concentration on Mud Cake Thickness of Water Based Mud.

4. Conclusions

1. Both TiO2 NP and Cu NP caused a significant increase in lubricating film strength at extreme pressure conditions.
2. TiO2 NP provide better effect on lubricating film strength
3. Slight decrement of lubricity coefficient upon adding various concentrations of TiO2 NP and Cu NP
4. Adding TiO2 NP and Cu NP causes a slight change in rheological and filtration properties.
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