Petroleum xxx (xxxx) xxx–xxx

Contents lists available at ScienceDirect

Petroleum

journal homepage: http://www.keaipublishing.com/en/journals/petroleum

A nano-particle based approach to improve filtration control of water based muds under high pressure high temperature conditions

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HIGHLIGHTS

- A new mud design using nano particles was presented to improve the drilling efficiency.
- A surface modification approach might be needed to improve the filtration control.
- Stability of the colloidal solution must be measured to achieve the best results.
- Nano Glass Flakes (NGFs) are cheap and stable particles under HPHT conditions.

ARTICLE INFO

Keywords:
Nano glass flakes
Filtration loss
Rheology
HPHT
Dispersion

ABSTRACT

There have been many attempts to improve the filtration control of water based muds under High Pressure High Temperature (HPHT) condition using a cost effective approach. Nano particles are perhaps the best option considering their successful applications reported in many studies. However, they are often expensive and pose unfavourably changes on the rheology of the muds. In this paper, an attempt was made to show the application of Nano Glass Flakes (NGFs) as a cheap but effective nano particle to control the filtration of water based muds under HPHT conditions. Performing a series of rheology, filtration and conductivity tests on the mud samples with unmodified NGFs revealed that this nano particle increases the mud rheology, yield point and gel strength of the mud with a slight impact on the filtration loss. However, by modifying the surface charges of NGFs with a cationic surfactant, filtration loss was significantly reduced without any severe impacts on the mud rheology. Considering the conductivity of the mud which increases by adding the modified NGF, this nano particle might be a good choice to improve the overall performance of water based muds under HPHT conditions.

1. Introduction

There have been many studies to improve the filtration control and rheology of Water Based Muds (WBMs) under High Pressure High Temperature (HPHT) Conditions. This is mainly due to the disintegration of clay bentonite and polymers such as Polyanionic-Cellulose (PAC) used to control the rheology and the loss of mud filtrate into high permeable formations [1,2]. Although thermal extenders[1] have been proposed and used under these circumstances to improve the stability of the colloidal solution, the disintegration issue has not been totally resolved yet.

Many of the studies carried out in recent years attempted to show the applications of nano particles in improving the filtration control of WBMs. For instance [3], studied the effect of nanoparticles on the filtration and rheological properties of WBMs. Their study showed that nano particles do not have a signification impact on the filtration loss, but thickness of the mud cake becomes thinner once nanoparticles are used which is essential to reduce the likelihood of differential sticking

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Peer review under responsibility of Southwest Petroleum University.

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[1] A class of polymers used to prevent bentonite disintegrations and unfavourable changes of mud rheology.

https://doi.org/10.1016/j.petlm.2018.10.006
Received 17 May 2018; Received in revised form 19 August 2018; Accepted 26 October 2018

Please cite this article as: Guan, O.S., Petroleum, https://doi.org/10.1016/j.petlm.2018.10.006

Table 1
Chemical composition of NGFs used for the purpose of this study.

SiO_2 (%)	K_2O (%)	B_2O_3 (%)	ZnO (%)	Na_2O (%)	MgO (%)	CaO (%)	Al_2O_3 (%)	TiO_2 (%)
64–70	0–3	2–5	8–13	1–4	1–4	3–7	3–6	0–3

[4]. added the xanthan gum-based polymer, viscoelastic surfactants, conventional fluid loss (polymer-based) additives and nanosilica into WBMs. They reported that the mud cake formed after modification is thin and the filtration loss is reduced, but the percentage of reduction was not reported. They also used a high concentration (i.e., 10%, 20% and 30% wt. %) of nanosilica in the mud which does not seem to be an economically feasible choice [5]. studied the impact of iron oxide (Fe_2O_3) nanoparticles on the rheological and filtration properties of WBMs under HPHT conditions. They claimed that iron oxide nanoparticles, embedded randomly in the pore space of bentonite clay, can enhance the gel strength of the mud. Their mud design, however, was not capable of reducing the filtration loss [6]. studied changes in the thickness of the filter cake and rheological properties of WBMs once modified by silicon nanoparticles. They indicated that the rheological properties of the WBM treated with the nanoparticles remains the same, but the thickness of the mud cake decreases by 34% [7]. synthesised nanoparticles with the dimension of 30 nm, and compared their impacts on the filtration properties of Oil Based Muds (OBMs). The results obtained indicated that the filtration loss under the Low Pressure Low Temperature (LPLT) condition for the in-house prepared nanoparticles was reduced by 70%. The thickness of the filter cake did not change but the rheological properties of the OBM remains almost the same once nanoparticles were added [8]. synthesised iron-based nanoparticle and calcium-based nanoparticle to study their effects on the filtration loss of OBMs. They also added graphite as a Loss Circulation Material (LCM) into the OBM with different concentrations. The filtration test showed that the filtration loss decreases significantly when 1% wt. iron-based nanoparticles are used. The calcium-based nanoparticles also reduced the filtration loss, but its effect was not as much high as that of the iron-based nanoparticles [9]. conducted a series of experiments to investigate the effect of multi-walled carbon nanotubes (MWCNTs) on the rheological and filtration properties of WBMs and Synthetic Based Muds (SBMs). They pointed out that the lowest filtration loss is achieved by adding 0.01 ppb MWCNTs. However, the filtration loss of SBMs with MWCNTs did not changes once MWCNTs was added but the rheological properties increased [10]. studied the effect of iron-oxide nanoparticles on the rheological properties and filtration control of WBMs. They indicated that unlike the Low Pressure Low Temperature condition, the filtration loss decreases under HPHT conditions by 28% once nano particles are added [11]. studied the effect of nanosilica and highlighted the negative impacts of nanosilica on the rheological properties such as Yield Point (YP) and gel strength. It was also revealed that nanosilica within the range of 0.1%–0.3% wt. has the greatest impact on the mud properties with a huge sensitivity to the variation of pH [12]. conducted a series of experiment to improve the cutting carrying capacity of WBMs by adding nanosilica. They emphasised that by adding nanosilica, the rheological properties of WBMs such as YP decreases, which reduces the cutting carrying capacity of the fluid. They used alkylbenzyldimethylammonium chloride (ABDACl) as a cationic surfactant to modify the surface charge of nanosilica and successfully improved the YP and Plastic Viscosity (PV) of the drilling fluid. It was also shown that filtration loss can be reduced and a thinner mud cake can be produced once nanosilica is modified. Having said that, it seems that the challenge of developing a functionally viable, physically stable and long lasting nano based fluids has not been totally resolved yet.

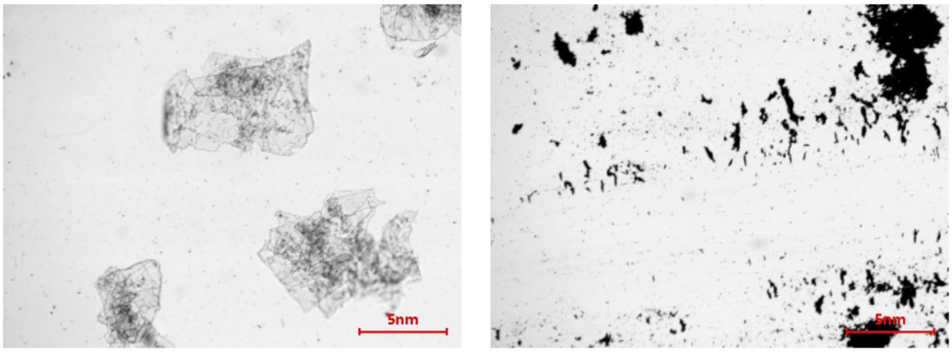
The aim of this paper is to design a nano based fluid using Nano Glass Flakes (NGFs), as a cheap but efficient particles which can improve the filtration control of WBMs without posing any significant impacts on the mud rheology. A series of rheology, filtration loss and conductivity tests were carried out to show how NGFs can be properly embedded in the structure of WBMs to improve the filtration control.

2. Materials and methods

2.1. *Nano Glass Flakes*

Nano glass flakes (NGFs), used for the purpose of this study, were transparent broken window pane pieces in 100 nm with a nominal thickness of 1 μm donated by Glassflakes limited, England. They were produced by heating silicon dioxide (SiO_2) under an extremely high temperature condition, say 1700 °C. Table 1 gives the chemical compositions of NGFs used for the purpose of this study.

NGFs are considered as one of the most favourable nanomaterials for reinforcement and coating of materials due to their salient physical, mechanical and chemical characteristics. They have a density of 2.60 g/cm^3 with the softening and melting temperature of 688 °C and 950 °C respectively. They are also a very strong material with a compressive and shear strength of 1983 kg/cm^2 and 1985 kg/cm^2 respectively. Besides, NGFs are highly resistant to abrasion and considered as an ideal barrier against corrosive attack caused by chemical interactions [13]. Considering these characteristics and their cheap price, NGFs could be a very good choice to improve the filtration control of WBMs under HPHT conditions. Fig. 1 shows the NGFs dispersed in deionized water and used for the purpose of this study.



(a)

(b)

Fig. 1. Nano Glass Flakes (NGFs) before dispersion in deionized water under two different scales.

2.1.1. Surface charge of NGFs

Having known the surface charges of bentonite under different pH from the study of [12]; a series of tests were conducted to measure the surface charge of NGFs before and after modification by a surfactant. This would help to determine the colloidal stability of dispersed particles in the designed mud. For the purpose of this study, the Malvern Zetasizer Nano-ZS of Malvern instrument was used to measure the surface Zeta potential of solutions. During the test, 5 mg/L NGFs solution with and without surfactant was prepared, stirred with Silverson homogenizer for 10 min while the pH was varied between 1.0 and 10.0 by adding 0.1 M HCl and 0.1 M NaOH to the solution.

2.1.2. Modification of NGFs

For the modification of surface charges, which might be needed to have a better interaction between NGFs and colloidal particles in the drilling mud, a cationic surfactant, known as Hexadecyltrimethylammonium bromide (CTAB) was used. Cationic surfactants contain cationic functional group at their heads, which is positively charged. They have a better surface wettability, pH resistance, emulsifying and solubilisation ability [14]. They are also regarded as a readily biodegradable material [15]. According to [16]; adsorption of surfactants on the surface of a charged particle can modify the charge distribution, and alter the interactions between particles. Therefore, a suitable surfactant can improve the rheological and filtration properties of WBMs.

However, the Critical Micelle Concentration (CMC) of CTAB should be determined before adding it into any solutions. The CMC test is essential to determine the saturation limit of surfactants in water. If this saturation exceeds certain limits, surfactant's monomers start to aggregate which are called micelle (see Fig. 2). These micelles, if formed by any means, may unfavourably change the properties of solutions such as conductivity, surface tension, osmotic pressure and absorption [17].

The CMC test was carried out by measuring the conductivity of CTAB solution using Seven Multi Conductivity and pH meters. The concentration of CTAB mixed with 50 ml deionized water was varied from 0.5 wt % to 8.0 wt %. It should be noted that the surfactant will alter the surface activity and as such foam are formed on the surface of the solution. Thus, the samples were sealed and kept aside to have the foam broken before any measurements. The dip cell was rinsed and cleaned with distilled water before any new measurements to remove the impurities left from the previous recording. The conductivity of the solution was then recorded to evaluate the CMC of CTAB.

2.2. Mud samples

2.2.1. Reference Mud

WBMs prepared for the purpose of this study composed of 15 g bentonite and 350 ml deionized water. Bentonite and water were mixed using the FANN Multimixer 9B and the mixture was blended for 10 min at a constant rate of 11,500 RPM to ensure that the drilling fluid is very well mixed and the coagulation of bentonite is prevented. Tables 2 and 3 respectively give the chemical components and the list of apparatuses used for the mud sample preparations and zeta potential measurements.

2.2.2. Mud with unmodified NGFs

The WBMs with the unmodified NGFs were prepared by adding two different concentrations, of nano particles (i.e., 0.5 wt%, and 1.0 wt%) into 350 ml deionized water, as reported in Table 3. These two concentrations were chosen mainly because any concentrations below 0.5 wt% did not have any sufficient impacts on the filtration loss while adding NGFs more than 1 wt % was not cost effective. NaOH was also added to modify the pH and bring it to 10 for a better stability of the colloidal solution. The mixture was stirred by Silverson Homogenizer under a constant speed of 2000 RPM for 10 min, followed by sonication using LSP-500 Laboratory Scale Ultrasonic Liquid Processor for another 15 min to ensure that the nano particles are well dispersed. The dispersed solution was then immediately mixed with bentonite, and blended with FANN Multimixer 9B for another 10 min at a rate of 11,500 RPM.

2.2.3. Mud with modified NGFs

As it was mentioned earlier, CTAB was chosen as the surfactant for the modification of NGFs' surface charges. Thus, different concentrations of CTAB was added into the NGFs solution with a pH of 10 but it was found that 0.25 wt% is sufficient to modify the surface charges of NGFs as per the zeta potential measurements. The mixture was stirred by using Silverson Homogenizer under a constant rotational speed of 2000 RPM for 10 min, followed by sonication for another 15 min to create a well dispersed solution. The solutions were then mixed with bentonite to prevent the formation of foam, and blended with FANN 9B Multimixer for another 10 min at a rate of 11,500 RPM. Table 4 summarizes the mud samples prepared for the purpose of this study.

2.3. Mud rheology

The rheology of the mud samples was measured using FANN Model 35 Viscometer at different speeds as per the API standard recommended practices for WBMs [18]. The dial reading obtained were then recorded and used for further assessment of the rheological and thixotropic properties.

Bingham plastic and Power law mathematical models are commonly used to determine the rheological parameters of WBMs, among which the Bingham plastic is the one widely employed by the industry. In the Bingham plastic, a plastic viscosity and yield point are determined for the mud samples while the power law is represented by the consistency index (k) and behaviour index (n). The parameter k is linked to the apparent viscosity and n shows the degree of the non-Newtonian

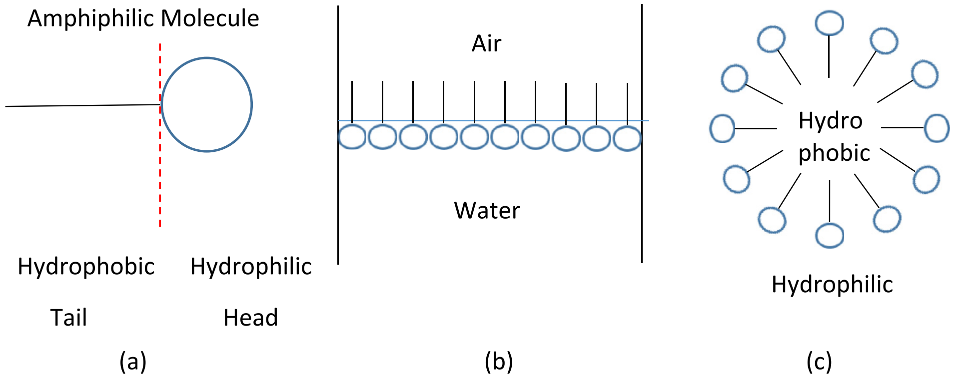


Fig. 2. Mechanisms of micelle formation: a) structure of amphiphilic surfactants, b) surface saturated with amphiphilic surfactants and c) structure of micelle.

Table 2
Chemical components used for the mud sample preparation.

Components	Purity	Brand	Purpose
Deionized Water	–	–	Mud Sample Preparation
Bentonite	80–95%	Mi SWACO	Viscosifier
Sodium Hydroxide (NaOH)	99%	Merck	pH modifier
Hydrochloric Acid (HCl)	37%	Merck	pH modifier
100 nm Nano Glass Flakes (NGFs)	99%	Glass Flake Ltd.	Potential filtration loss additive
Hexadecyltrimethylammonium bromide (CTAB)	> 95%	Merck	Surface charge modifier

Table 3
List of apparatuses used for the purpose of this study.

Equipment	Purpose
FANN Multimixer 9B	To blend the bentonite with the solution to prepare the mud samples.
Silverson Homogenizer	To stir the mixture of NGFs with distilled water to prevent flocculation of NGFs.
LSP-500 Laboratory Scale Ultrasonic Liquid Processor	To sonicate the NGFs solution to create a well dispersed solution.
Malvern Zetasizer Nano ZS	To measure the zeta potential of the NGFs of the NGFs solution.
Multi Conductivity Meter	To measure the conductivity of the solution for CMC test
FANN Viscometer 35SA	To examine the rheological properties of the mud samples
Series 300	To determine the filtrate volume, and thickness of the mud cake
FANN HPHT Filter Press 175CT	To measure the filtrate volume, and thickness of mud cake formed

Table 4
Mud samples and respective abbreviated names.

Sample	Abbreviated Name
15 g Bentonite +350 ml deionized water	R
15 g Bentonite +350 ml deionized water +0.5 wt% NGFs	NGFs – 0.5%
15 g Bentonite +350 ml deionized water +1.0 wt% NGFs	NGFs – 1.0%
15 g Bentonite +350 ml deionized water +0.5 wt% NGFs +0.25 wt% CTAB	MNGFs – 0.5%
15 g Bentonite +350 ml deionized water +1.0 wt% NGFs +0.25 wt% CTAB	MNGFs – 1.0%

behaviour. Both of these two mathematical models were used for the purpose of this study.

2.4. Filtration loss

2.4.1. LPLT condition

For the Low Pressure Low Temperature (LPLT) filtration tests, FANN Series 300 LPLT Filter Press was used under the room temperature of 77 °F and the pressure of 100psi, by following the API recommended practices. A 25 ml graduated cylinder was placed under the LPLT filter press for 30 min to collect the filtrate volume. The filtrate volume was recorded every 30 s for the first 5 min, every 2.5 min for the second 5 min, and every 5 min for the last 20 min. The thickness of the mud cake formed on the filter paper was also measured at the end of the test.

2.4.2. HPHT condition

For the HPHT tests, FANN Model 175CT HPHT Filter Press was used. The pressure of the regulator was set to be 600 psi with the back pressure of 100 psi, and the temperature of 250 °F. The tests were conducted for 30 min by following the API standard for WBMs. The thickness of the mud cake was then measured for further analysis. Fig. 3 shows a flowchart with the steps taken in this study to evaluate the designed muds.

2.4.3. Mud cake permeability

Permeability of the filter cake obtained from the LPLT and HPHT tests was determined by following the Darcy's law which is expressed as:

$$\frac{dV}{dt} = \frac{KA\Delta P}{\mu h} \tag{1}$$

where dV/dt is the rate of filtration, A is the cross-sectional area, K is the permeability, ΔP is the differential pressure, μ is the viscosity and h is the filter cake thickness addressed as:

$$h = \frac{V_f}{A(\frac{f_{sc}}{f_{sm}} - 1)}, \tag{2}$$

where

$$V_f = A\sqrt{\frac{2K\Delta P}{\mu}(\frac{f_{sc}}{f_{sm}} - 1)} \times \sqrt{t}. \tag{3}$$

In the above equations, f_{sc} is the volume fraction of solids in the filter cake, f_{sm} is the volume fraction of solids in the drilling fluid and t is the duration of the filtration test in minutes. It should be noted that the filter area of the filter cake for LPLT and HPHT was 39.37 in^2 and 19.63 in^2 respectively.

3. Results and discussions

3.1. Zeta potential and surface charges

Particles dispersed in a solution often have different surface charges which may cause unfavourable interactions in aqueous systems. Zeta potentials apparatus is able to determine the electrostatic surface charges of different particles dispersed in a solution [19] and reveals the stability of the colloidal solution. In fact, the larger the absolute value of zeta potential is, the higher the electrostatically stability and the more stable the particle dispersion in the solution would be. The zeta potential was measured using the Malvern Zetasizer Nano ZS apparatus with the results shown in Fig. 4.

Looking at Fig. 4, it seems that the unmodified NGFs have a negative surface charges under any pH conditions. In fact, the results indicate the maximum zeta potential of −40.2 mV somewhere between the pH of 9–10. This would be the most stable situation for the solutions with NGFs where sufficient hydroxyl groups are present for interacting with other colloidal particles. However, bentonite clay is known to have a negative surface charges [20,12]; and as such the repulsive force between clays and NGFs might affect the performance of the drilling mud in terms of rheology and filtration loss. Thus, the surface charge modification of NGFs might be required to prevent such undesired changes. However, before modification, the CMC test was done to determine how much CTAB can be added to the solution. The results obtained are

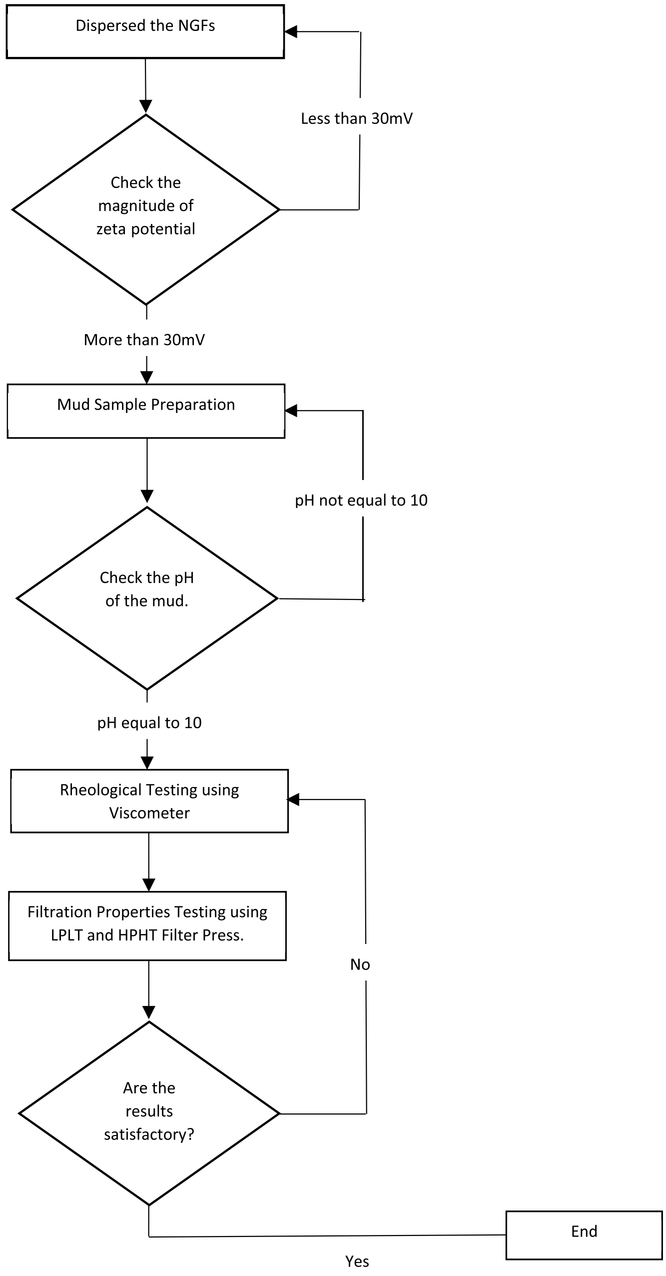


Fig. 3. Flowchart of the mud designs used for the purpose of this study.

shown in the right side of Fig. 4.

From Fig. 4, it was noted that as the concentration of CTAB increases, the conductivity of the solution increases due to the increases of Centrimonium ions. However, once the concentration of CTAB reaches 5.0 wt%, the rate of increase in the conductivity decreases which might be due to the saturation of water with Centrimonium ions. Hence, the monomers started to aggregate and formed micelles. Therefore, the CMC of the CTAB solution was set to be 5.0 wt%.

Knowing the CMC of CTAB, attempts were made to modify the surface charges of NGFs by adding 0.25 wt% CTAB to the solution. The results obtained from the zeta potential measurements indicated that this amount of CTAB is sufficient enough to completely change the surface charges of NGFs (see Fig. 4 left). The mechanism by which the surface charge of NGF was modified by CTAB is shown in Fig. 5.

As it is shown in this Figure, the CTAB molecules are initially dissociated into Centrimonium ions, which are positively charged. Due to the attraction between negatively surface charge of NGFs and the positive charge of Centrimonium ions, ionic interactions occur by formation of an organic chain of CTAB array which decreases the surface energy of NGFs. As a result, the steric (i.e., the arrangement of atoms in the molecule) among NGFs changes, NGFs appears in the mono-dispersed state, and the stability of the solution improves [2].

3.2. Mud rheology

The rheology of the mud is determined to evaluate the behaviour of drilling fluids during circulation, and plays an important role in the penetration rate, borehole cleaning and its stability. The results obtained from the rheological measurements of the mud samples containing modified and unmodified NGFs are given in Table 5.

As it seen in this Table, as the concentration of NGFs in the drilling fluid increases, the yield point and plastic viscosity increases. Generally, in any colloidal stable dispersion systems, the particles usually exert repulsive forces against each other [21]. Due to the high zeta potential exhibited by the NGFs, the repulsive forces between NGFs and bentonite are strong, preventing the free flow of particles in the drilling fluid, which ultimately increases the plastic viscosity. The elongated shape of NGFs which randomly orients the particles in the drilling fluid may further prohibit the flow of the particles in the drilling fluid (See Fig. 6). The increases in the yield point is also linked to the strong repulsion force between the negatively charged NGFs and the negatively charged bentonite particles [10]. indicated that the strong electrostatic repulsion between negatively charged particles prevents coagulation and hence a strong clay platelet network is formed in the drilling fluid system which increases the viscosity and the yield point.

However, the results obtained from adding the modified NGFs to the drilling fluids, which are given in Table 5, revealed that modifying the

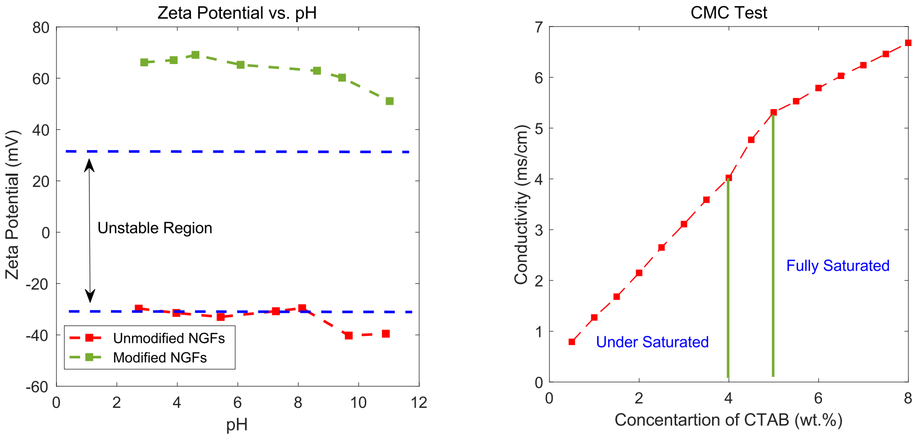


Fig. 4. Zeta potentials of modified and unmodified NGFs (left) and conductivity of the solution against the concentration of CTAB in the CMC tests (right).

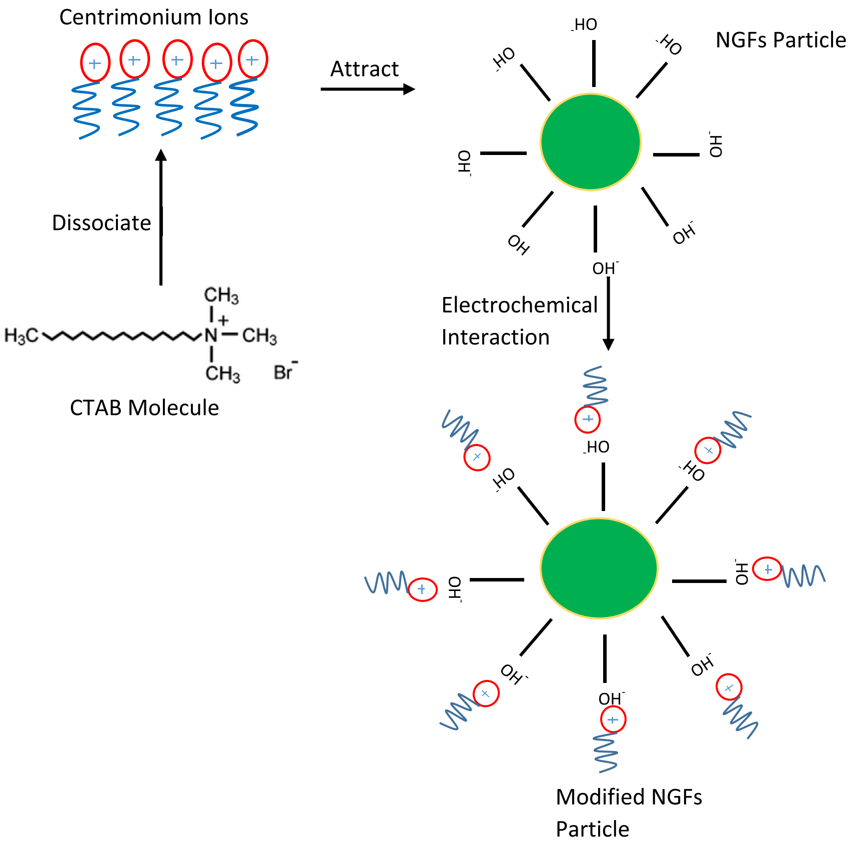


Fig. 5. Mechanism of modification of NGFs surface charges.

Table 5
Rheological properties of different mud samples.

Samples	Bingham Plastic		Power Law		Gel Strength	
	YP (Pa)	PV (cP)	K	n	10s (Pa)	10 m (Pa)
R	2.6	4.3	0.51	0.2981	0.47	2.87
NGFs - 0.5%	7.5	4.8	2.08	0.48	0.47	8.6
NGFs - 1.0%	11.7	7.5	1.9	0.3752	1.9	11.01
MNGFs - 0.5%	2.3	3.2	0.088	0.6577	0.38	2.87
MNGFs - 1.0%	3.2	3.4	0.1948	0.5619	0.38	33.5

NGFs using CTAB helps the mud to maintain its plastic viscosity and the yield point. This is mainly due to the interaction between positively charged modified NGFs and negatively charged bentonite, which forms particles with a bigger size inside the mud as shown in Fig. 6. Thus, the bigger the particles size is, the lower the viscosity would be. Fig. 7 compares the rheological models of different mud designs.

Gel strength is another important property of WBMs which allows the suspension of cuttings when the pump is off for tripping or work-over operations. In fact, it is crucial for a drilling fluid to have the ability to transport cuttings during circulation and support the cuttings suspension once the circulation stops [22]. stated that the gel strength of the drilling fluid should fall in the range of 6–10 lb/100 ft^2. The results obtained from the gel strength measurements after 10 s and 10 min are given in Table 5.

It appears that all the muds provide a same gel strength after 10 s except the one with 10 wt % NGFs. It was also observed that the gel strength of all the mud samples after 10 min is higher than that of the reference set. However, the gel strength of the unmodified muds is significantly above the desired range. Considering the fact that progressive gel development may not be favourable during tripping, due to the high pump pressure which is required to start the circulation, the unmodified mud may not be a good choice for drilling as far as the rheology and gel strength are concerned.

3.3. *Filtration loss*

Filtration loss measurements were carried out on the mud samples under both LPLT and HPHT conditions. The filtrate volume, mud cake thickness and permeability were then measured after running the tests for 30 min. The results obtained for LPLT condition is reported in Table 6 and Fig. 8.

As it is given in Table 6 and Fig. 8, it seems that addition of the unmodified NGFs slightly increase the filtration loss but the filtration control improves once the concentration of modified NGFs increases in the mud. This decrease in the filtrate volume is due to the electrostatic repulsion between the negatively charged NGFs and bentonite, which prevent the coagulation of particles, while maintaining the fluid in a well dispersed system at the same time. Due to the pressure applying on the mud cake, the dispersed non-coagulated structure of particles in the mud cake is compaction and as such the porosity and the permeability of the mud cake reduce [10].

On the other hand, the filtrate volume is significantly reduced once modified NGFs is added to the mud and the percentage of reduction increases as the concentration of modified NGFs increases. This reduction might be related to the electrostatic attraction between face-to-face (modified NGFs and bentonite) and edge-to-face (positive edge bentonite-negative face bentonite). This attraction traps the modified NGFs between the clay particles and forms a solid structure so called heterocoagulated formation which holds the fluid within the structure and reduces in the filtrate volume. In fact, the interaction between two particles that have different characteristics such as charges, sizes or chemical compositions, will results in the formation of cluster, followed by the gel-like structure, which is often termed as heterocoagulation [23].

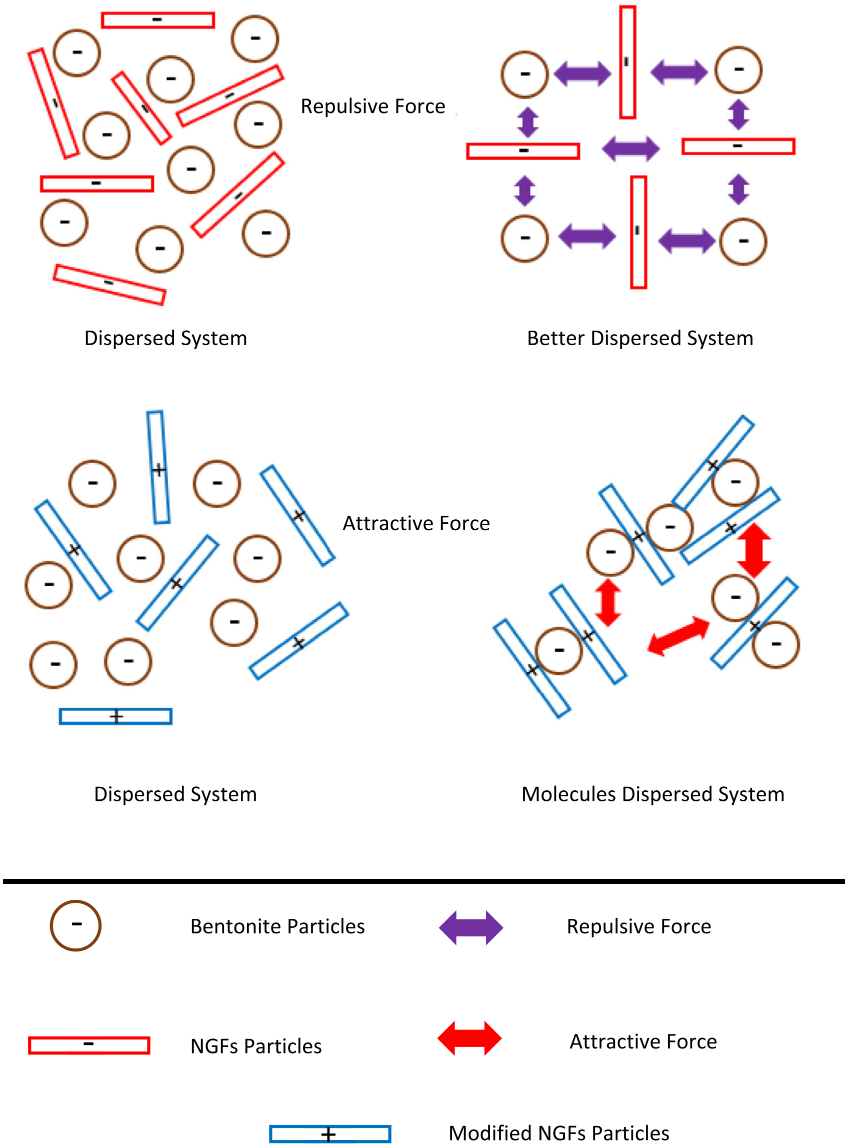


Fig. 6. Interaction between NGFs and bentonite and bottom (top) and Interaction between modified NGFs and bentonite (bottom).

It worth to mention that the decreases in the mud cake thickness (2/32 inches) shown in Fig. 8 minimizes the chance of differential pipe sticking during drilling which is perhaps another advantageous of modifying nano particles before adding them to WBMs. Table 7 and Fig. 9 provide the details of the results obtained from HPHT filtration tests.

Looking at Table 7 and Fig. 9, the filtrate volume of the mud samples reduces as the concentration of modified NGFs increases due to the strong and rigid heterocoagulated formation in the mud cake. In fact, as the concentration of modified NGFs increases, there are more nano size particles available to seal the nano pore throat of clays, and as such the permeability of the mud cake reduces, and the filtration control improves. This points out the fact that the mud designed in this study can withstand the downhole HPHT conditions and provide a good filtration control. The unmodified NGFs, however, showed a similar behaviour as that of the LPLT condition and initial increased the filtrate volume but decreased it eventually.

It should be noted that the mud cake development rate for all the mud samples upon addition of NGFs are faster than that of the reference set. In fact, the filtrate volume of the reference set in the earlier phase of the filtration test is higher than the filtrate volume of the other mud samples (see Fig. 9). This indicates the fact that addition of NGFs and modified NGFs into the drilling fluids might help to increase the mud cake development rate.

3.4. Electrical conductivity

Given the extreme conditions of HPHT wells, a series of experiment must be done to ensure that additives used to design the drilling fluids are compatible with the bentonite clay and electrical conductivity of the mud is not unfavourable changed. It should be recalled that the electrical conductivity of the mud must be maintained to ensure that the measurements made through the logging programme can be properly made without any interruption [24]. As a matter of fact, if the drilling fluid cannot provide a good conductivity, good electrical penetration into the formation is prevented, resulting in poor signals or an unfavourable signal-to noise ratio for image and wireline log data recording. In this study, to measure the electrical conductivity of the mud samples, Seven Multi Conductivity Meter were used and the results obtained were reported in Table 8.

Looking at Table 8, it seems that NGFs are chemically stable particles, and there is no sign of any interruption in the conductivity of the mud samples being tested. Instead, upon modification, NGFs can improve the performance of the drilling fluid in terms of electrical

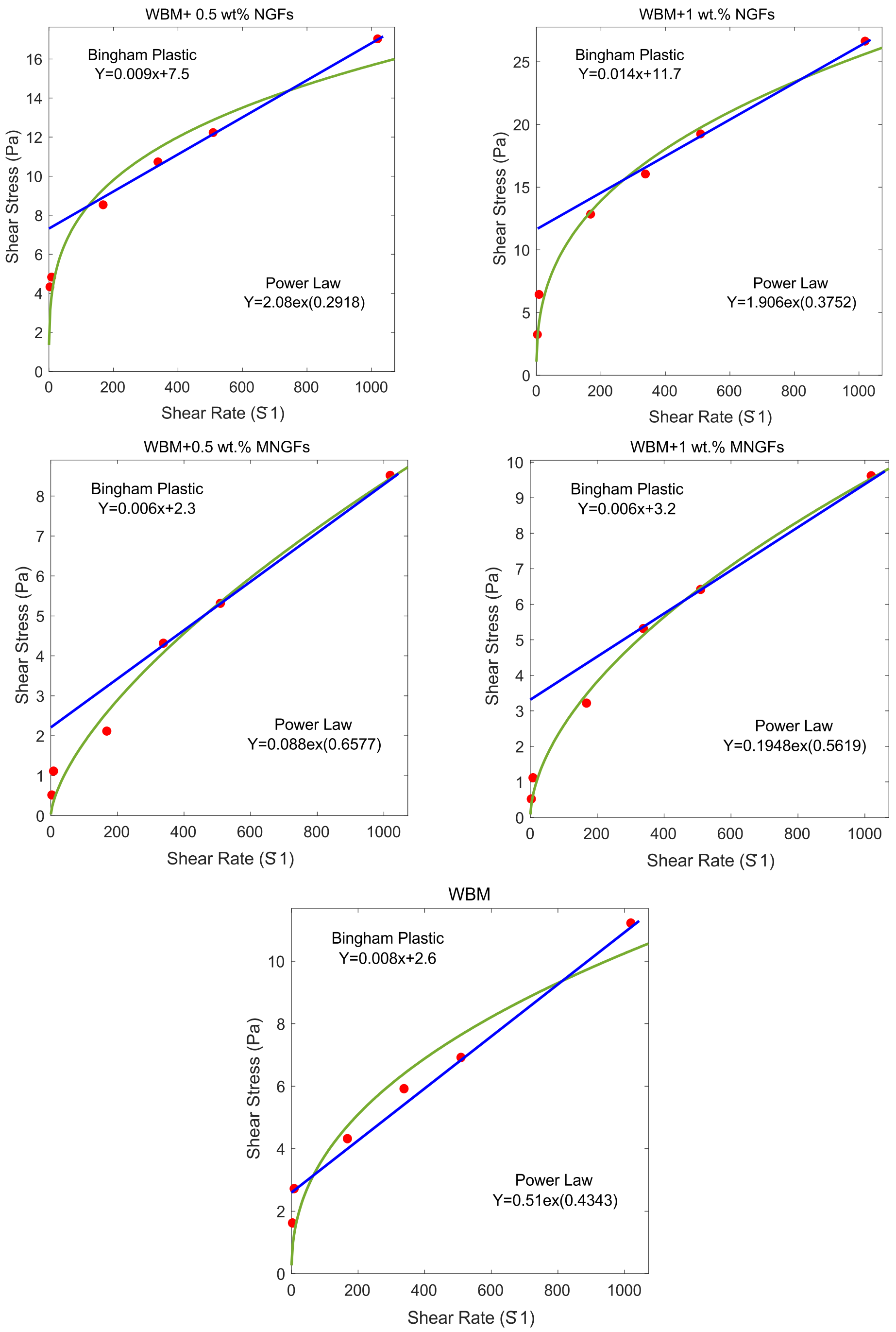


Fig. 7. The rheological model of the reference, modified and unmodified WBMs.

Table 6
Filtration control related properties of modified and unmodified mud under LPLT condition.

Sample	Filtrate Volume (ml)	Changes respect to reference mud (or unmodified NGFs Mud) (%)	Mud Cake Thickness (/32in)	Mud Cake Permeability (x10^4 mD)
R	22.0	–	3	5.72
NGFs - 0.5%	22.5	+ 2.27	3	5.58
NGFs - 1.0%	20.3	− 7.72	3	5.27
MNGFs - 0.5%	14.8	− 32.95 (− 34.2)	2	2.56
MNGFs - 1.0%	11.0	− 50.00 (− 52.17)	2	1.91

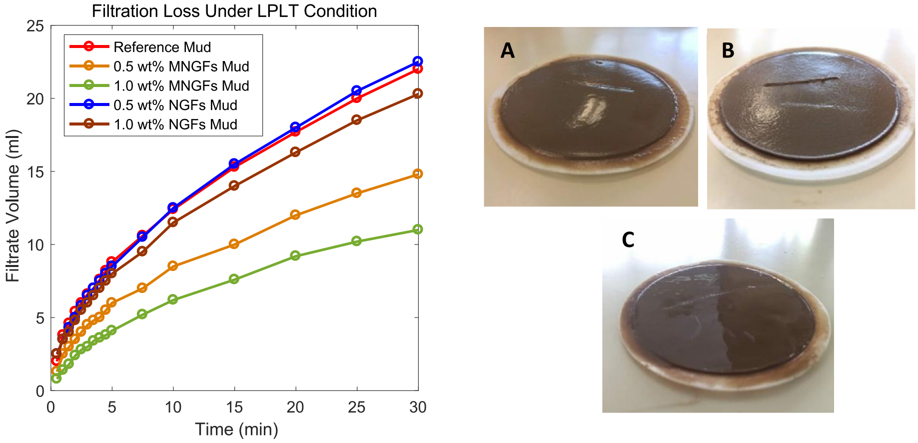


Fig. 8. Cumulative filtrate volumes of the mud samples with modified and unmodified NGFs under the LPLT condition (left) and the mud cakes obtained: A) Unmodified NGFs based mud, B) Modified NGFs based mud, C) Reference Mud.

Table 7
Filtration control related properties of modified and unmodified mud under HPHT condition.

Sample	Filtrate Volume (ml)	Changes respect to reference mud (or unmodified NGFs Mud) (%)	Mud Cake Thickness (/32in)	Mud Cake Permeability (x10^4 mD)
R	21	–	6	4.38
NGFs - 0.5%	23.00	−9.52	6	4.80
NGFs - 1.0%	19.50	7.14	6	4.07
MNGFs - 0.5%	16.50	21.43 (−30.4)	4	1.95
MNGFs - 1.0%	12.00	42.86 (−36.8)	4	1.67

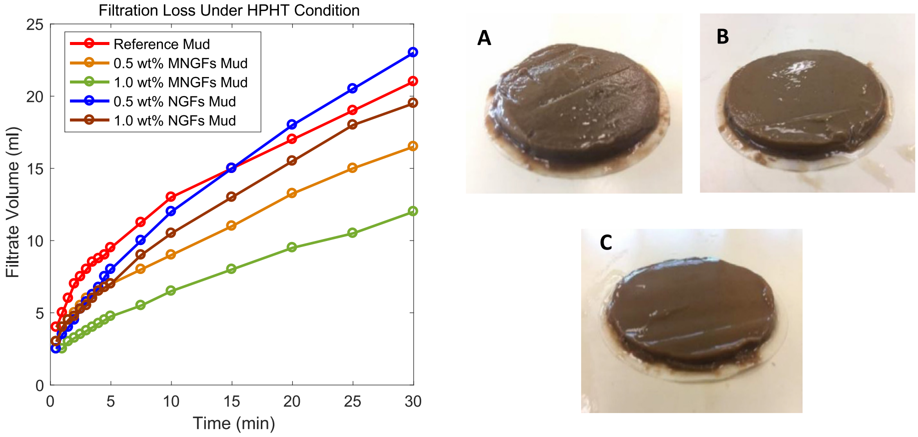


Fig. 9. Cumulative filtrate volumes of the mud samples with modified and unmodified NGFs under HPHT conditions (right) and the mud cakes obtained: A) Mud with the unmodified NGFs, B) Mud with the modified NGFs, C) Reference Mud.

Table 8
Electrical conductivity of mud samples designed in this study.

Samples	Electrical Conductivity (mS/cm)
R	2.72
NGFs - 0.5%	3
NGFs - 1.0%	2.85
MNGFs - 0.5%	4.05
MNGFs - 1.0%	3.93

conductivity and be a great asset to enhance the efficiency of drilling operation with increasing the pentation rate and life of the bit used.

4. Conclusions

In this paper, NGFs as a cheap and thermally stable nano particles were used to improve the filtration properties of WBM by conducting a series of rheological, filtration loss and conductivity tests. The results obtained indicated that adding NGFs without modification increases the yield point, plastic viscosity and the gel strength of the drilling fluids, which may not be desired. On the other hand, the yield point, plastic viscosity and gel strength decrease once modified NGFs are used. The results of the filtration loss tests indicated that the modification of NGFs using CTAB helps to create a strong and rigid structure network formed by the ionic interaction which reduces the filtration loss of the mud samples under LPLT and HPHT conditions. The thickness and permeability of the mud cakes were also decreased upon adding the modified NGFs. The good thermal properties of NGFs and improvement of mud conductivity was another good characteristic which improves the electrical conductivity and drilling efficiency.

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