Novel Nanoparticles-Containing Drilling Fluids to Mitigate Circulation Loss

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ABSTRACT

Mechanism of particle based wellbores strengthening was investigated and modeled through an extensive series of core fracturing and particle plugging tests. The potential impact of nanofluids in mitigating circulation loss issues was studied using filtration experiments. Novel drilling fluids containing iron (III) hydroxide nanoparticles (NPs) were formulated using a blend of custom prepared NPs with drilling fluids supplied by a company and their filtration properties were evaluated. Iron (III) hydroxide NPs were prepared by aqueous reactions involving iron (III) chloride and NaOH. The product particles were identified by X-ray powder diffraction (XRD) and their particle size distribution was determined by Transmission Electron Microscopy (TEM). Preliminary API test results showed that fluid loss from invert emulsion drilling fluid decreased significantly at relatively very low content of NPs, compared with literature. At the concentration of NPs considered, no changes in the drilling fluid density or pH could be seen.

Keywords: Circulation loss, wellbore strengthening, nanoparticles (NPs), invert emulsion

INTRODUCTION

Drilling operations are conventionally performed using the rotation of a string of pipes and bottom-hole assembly. The required torque and weight for penetration of rock is provided by the rotary table at the surface or the downhole motors. Figure 1 illustrates the components of a oil well drilling system. One of the major processes in drilling operations, known as circulation system, includes the injection of a fluid through the drill string and regaining it at the surface. Drilling fluid is in charge of several prominent functions such as providing borehole stability, transferring cuttings to the surface, lubricating and cooling the drilling bit, and isolating the formation fluids [1]. Drilling fluid is treated at the surface to remove the cuttings, gas, sands and silts and is re-injected in the hole as the pre-specified properties are obtained.

Circulation loss is one of the major drilling issues which may occur during the operation due to numerous factors. The problem can happen in any stage of the operation in various levels of intensity. Since the rock is not a uniform media and contains many types of discontinuities, fluids may enter the formation voids due to the positive pressure gradient. The intensity of the problem is a function of drilling fluid rheology and additives, geometry of the

opening, and operational parameters. Circulation loss usually occurs in loose gravels and sands, induced and natural fractures and sometimes in vugular and cavernous formations [2]. Loose sands and gravels are encountered in shallow depths leading to a limited fluid loss known as seepage loss via the inter-granular space. The rest of the "thief zones", however may introduce more severe consequences to the operation such as wellbore collapse, gas or water kicks, stuck pipes or bit and even blowout if the remedial measures are not taken. Circulation loss usually starts in the order of 1.59 m^3/hr (10 bbl per hour) and may increase over the time. Roughly, circulation loss is classified as seepage loss, moderate loss, severe loss and total loss based on its intensity in terms of volume of the fluid loss per hour. While most of the lost circulation zones are specific to certain types of lithology, induced fractures can initiate in all rock types as a result of execc pressure in the wellbore. The critical pressure at which the fracture opens up and the fluid stars to invade the formation is considered as the upper limit of the downhole pressure in the wellbore. The lower limit is defined by formation pressure or collapse gradient of the rock.

1 Mud pumps
2 Swivel
3 Kelly
4 Drill bit
5 Drill pipe
6 Annular space
7 Cuttings
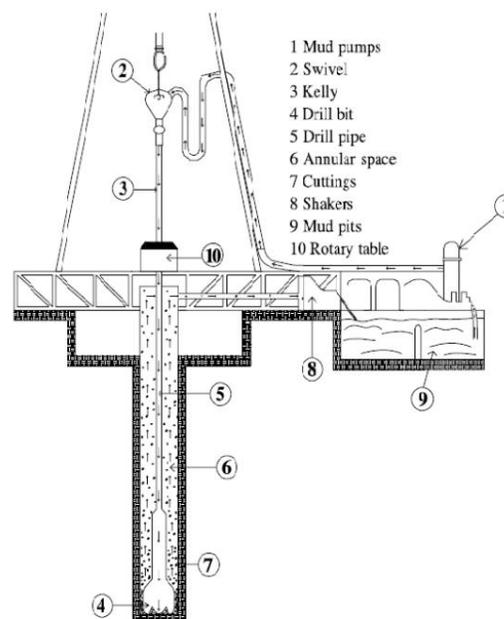8 Shakers
9 Mud pits
10 Rotary table

Figure 1: Schematic of a drilling rig [3]

Pressure increase in the wellbore gives rise to the tangential (hoop) stress around the wellbore and induced fractures occur when the tensile stress exceeds the toleration of the rock. However, the drilling fluid does not

start to flow to the opening immediately. The pressure level at which the fluid invades the formation through a tensile fracture, known as circulation loss gradient is a function of several parameters related to rock, fluid and the operation. Field and laboratory experiences have proven the importance of the drilling fluid and its additives on increasing the circulation loss pressure leading to more stable borehole [4,5]. This is of significant importance for drilling operators and extensive studies have been conducted to investigate this impact.

The maximum pressure a wellbore can tolerate before losing the contained drilling fluid is called the Wellbore Pressure Containment (WPC). The process of increasing the WPC by adding engineered material to the drilling fluid has been recently named as wellbore strengthening. Wellbore strengthening is achieved via application of Lost Circulation Materials (LCMs) in the drilling fluid. In this paper, a brief description of the proposed mechanism is presented. In addition to major volumetric circulation loss the permanent filtration through the porous media around the well causes wellbore stability issues in water sensitive shales. Besides, the filtration process increases the pore pressure around the well and decreases the fracture gradient. It is very important to build a firm filter cake around the borehole in shale formations to prevent shale swelling. LCM with diameters in the range of 0.1-100 μm may play an important role when the cause of fluid loss occurs in the 0.1 μm-1 mm porous formation. In practice, the size of pore opening in shales that may cause fluid loss varies in the range of 10 nm-0.1 micron where nanoparticles (NPs) as a loss circulation material could fulfill the specific requirements by virtue of their size domain, hydrodynamic properties and interaction potential with the formation [6,7].

As significant fluid loss happens in the wellbore via larger opening geometries, NPs can fill the gaps between larger LCMs and assist in increasing the stability of the sealing.

WELLBORE STRENGTHENING

Pressure in the borehole is the most important parameter in wellbore stability control. Excessive pressure results in tensile fracturing of the rick and significant fluid loss followed by sudden pressure drop in the wellbore and possible kick. Therefore it is essential to estimate the fracture gradient accurately and maintain a safe mud weight in the well. However an exact estimation of the fracturing gradient is not always possible due to the random nature of the rock properties and the dynamic operational condition.

The drilling procedure disturbs the stress state around the wellbore leading to a tangential stress higher than the initial stress of the region. As the pressure in the wellbore increases, the tangential stress decreases and turns into a tensile stress pulling the grains apart. Once this tensile stress reaches the maximum strength of the rock, tensile fracture initiates at the wellbore [8]. This mechanism is also

used intentionally for reservoir stimulation purposes. It has been understood through several studies that drilling fluid effects the pressure level at which the fluid starts to enter the formation [4,5]. Therefore designing engineered fluids has become of interest of most operators to increase the circulation loss pressure and complete the drilling process with minimal drilling fluid loss.

Morita et al. suggested the Lost Prevention Material (LPM) screen-out process as a mechanism of wellbore strengthening [9]. In another major study, Whitfill and Hemphill found the plugging process to govern the strengthening mechanism [10]. Stress caging, is another suggested mechanism for wellbore strengthening which highlights the importance of particles in keeping the fractures open to increase the hoop stress around the borehole [11]. Researchers in the University of Stavanger shed light on the importance of particle properties and developed an elasto-plastic model which emphasized on the significance of the compressive strength and angle of internal friction of the sealing. They suggested that the particles forma bridge over the fracture which can stand higher levels of pressure in the wellbore [4,5].

In the first phase of the experiments in the present work, several types of LCMs in different concentrations and particle size distributions were tested in core fracturing and particle plugging experimental setups. Details of the results are described elsewhere and here, only a brief description is presented [12]. It was well understood that the particle size distribution of LCMs, their concentration, their resiliency modulus, fracture geometry as well as the friction coefficient of the fracture surface are the influential parameters in the wellbores strengthening process. Once the fracture initiates the rock splits at the point of maximum tensile stress and the LCMs form a sealing in the fracture immediately as a result of filtration and overbalance. Figure 2 illustrates the proposed mechanism for wellbore strengthening. A wide range of particle size distribution facilitates a firmer and more resilient plug so that the wellbore becomes more resistance to pressure in the borehole. Equation 1 estimates the wellbore pressure containment increase due to presence of the plug over the fracture.

$$\Delta P = 2\mu_f M \frac{U_r}{D_f} \qquad (1)$$

Where μ_f is the friction coefficient of the fracture surface, M is the fracture depth, U_r is the resiliency modulus of the plug, D_f is the fracture width and ΔP is the wellbore pressure containment increase.

The importance of low permeability and low porosity sealing in the tensile fractures led to proposing the application of nanoparticles in drilling fluids. The main advantage of nanoparticles lies within their high mechanical strength and small size which guarantee a highly stable plug with minimum permeability. The below described

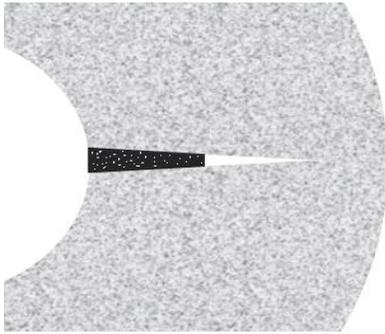experiments are the first part of the nanoparticle testing as a potential remedy to for fluid loss.

Figure 2: Schematic illustration of plugging mechanism during wellbore strengthening process

EXPERIMENTAL

Iron (III) hydroxide NPs were prepared by aqueous reaction between iron (III) chloride and NaOH at specified temperature and rate of mixing as per the following reaction.

$$FeCl_3 \text{ (aq)} + 3NaOH \text{ (aq)} \longrightarrow Fe(OH)_3 \text{ (s)} + 3\ NaCl \text{ (aq)}$$
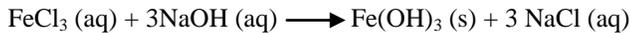
The product $Fe(OH)_3$ NPs were collected and their identity was confirmed using XRD and their particle size distribution was determined using TEM. The recovered particles were mixed overnight with the invert emulsion drilling fluid as shown in Figure 3.
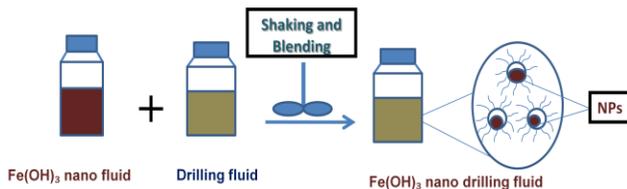

Figure 3: Novel nano drilling fluid preparation

Invert emulsion drilling fluid (Oil:Water (V/V) = 90:10) without NPs and LCM (Gilsonite) and commercial invert emulsion drilling fluid having same proportion of oil and water with 14% w/w LCM (Gilsonite) only were considered as a baseline drilling fluid for comparative evaluation of API filtration property. Invert emulsion drilling fluid with 0.74% w/w NPs and 14% w/w LCM together were considered as our nanofluid of study. The API (30-min test) filtration properties of the drilling fluid were determined using standard FANN filter press. pH measurements were done by pH paper (0-14). Iron (III) chloride (laboratory grade, Fisher Scientific, Toronto, ON, Canada) and sodium hydroxide Powder (AlfaAesar, Toronto, ON, Canada) were used as the precursor salt and

precipitating agent respectively. All chemicals were used without further purification. Invert emulsion drilling fluids were collected from Calgary based drilling fluids company. To identify the iron (III) hydroxide NPs, formed colloidal suspension was first centrifuged at 5000 rpm to recover the nanoparticles, then washed several times with deionized water and finally left them to dry at room temperature. X-ray spectra were collected using Ultima III Multipurpose Diffraction System (Rigaku Corp.,TX) with Cu Kα radiation operating at 40 KV and 44 mA. JADE software was used to identify the structure. Photographs of the nanoparticles were collected from different locations on the copper grid using a Phillips Tecni TEM (voltage of 200KV) equipped with a slow-scan camera. Particles sizes were measured using ImageJ software.

RESULTS AND DISCUSSION

The amount of nanoparticles added in formulating of invert emulsion based nano drilling fluid system was 0.74% w/w. Even with a small amount of nanoparticles addition, the invert emulsion drilling fluid became stable, no agglomeration and phase changes occurred in the w/o emulsion and became liquid when it was shaken. Therefore no other additives were required to mix. Evaluation of different concentration of iron hydroxide nanoparticles in drilling fluid lead us to define the optimum range for a stable NPs based fluid formulation. Typical samples prepared this way showed that even after several weeks, finally formulated nano drilling fluid remained stable. This behavior is attributed to the fact that both the Van der Waals attractive and electrostatic repulsive forces exist in the emulsion fluid system and nanoparticles are tightly held in the water pools surrounded by the surfactant layers. Nanoparicles that grow or agglomerate to sizes beyond the stabilization capacity of invert emulsion fluid might settle under gravity. The X-ray diffraction was performed on the NPs collected after their first preparation in bulk water. Figure 2a clearly indicates the diffraction pattern of the sample very much likely to match with iron (III) hydroxide representatives and the peak maximum around $2\theta = 35°$ which can be attributed to the presence of aggregates dispersed in an amorphous phase. It is to be noted that iron (III) hydroxide can transform into α-Fe_2O_3 and β-FeOOH as well as α-FeOOH due to the reaction conditions [13]. Figure 2b shows the TEM photographs of the NPs. After analysis using ImageJ software the average mean particles size was measured at 28 nm. The effectiveness of the nanoparticles in fluid loss prevention can be clearly seen from Table 1.The API fluid loss of the samples indicated a decreasing trend in fluid loss over a period of 30-min as around 9% for the drilling fluid with 14% w/w LCM and 70% when used LCM and NPs together. The reported literature values for the loss reduction was found less than 40% even after addition of 30 wt% of NPs [674]. Figure 5 (a-c) shows the mud cake formation before and after addition of NPs. The NPs (figure 4c) deposit a fine thin

layer of particles and looks like reddish brown seems that iron (III) hydroxide are deposited on the cake surface. The mud densities 0.93 ± 0.2 g/cm^3 were found almost constant in all samples. The addition of NPs did not increase the mud weight. A pH level 12.5 was found in all samples; even NPs addition did not change the pH of the drilling fluid samples.
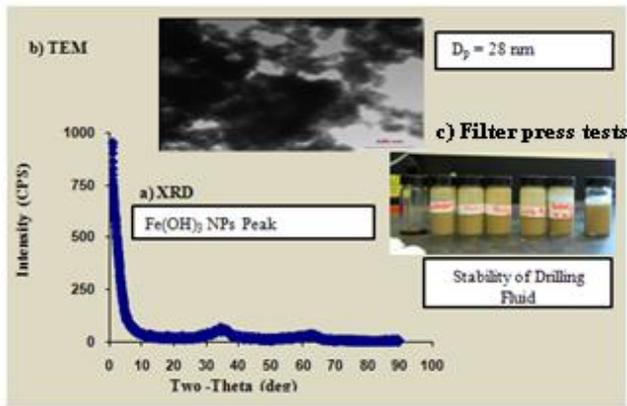

Figure 4: NPs Characterization by a) XRD, b) TEM and stability observation of drilling fluid

Table 1: API Fluid loss test at 25°C and 100 Psi

Time (min)	Fluid Loss (mL)		
	DF	DF+14% w/w LCM	DF+14% w/w LCM+ 0.74 % w/w NPs
7.5	2.0 ± 0.2	1.4 ± 0.2	0.2 ± 0.2
30	3.96 ± 0.2	3.6 ± 0.1	1.1 ± 0.1

Figure 5 : Filter cakes of a) DF, b) DF with LCM, c) DF with LCM and NPs

CONCLUSION

The incorporation of custom prepared NPs in invert emulsion fluid system reduces the fluid loss substantially due to the nano particles itself and nano induced aggregates. Nanoparticles are though to be able to fill the gaps between rock grains as well as larger LCMs to provide more a resistant seal over the openings. The future of this study will clarify the impact of nanofluids on core fracturing and particle plugging tests.

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