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Optimization of nano-silica in enhancing the properties of synthetic based drilling fluids for tight gas reservoir conditions

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Abstract. The nano-silica in drilling fluids is commonly used to improve the performance of drilling fluids, mainly water and oil based muds. Tight gas reservoirs are experienced a myriad of problems during drilling. One of the problems is the gas influx into the wellbore because of the abnormal pore pressure, fluid loss due to the fracture pressure and pore pressure is very narrow margin, stuck down hole equipment in the wellbore due to high differential pressure between hydrostatic pressure and pore pressure. Another problem is related to drilling mud and cement. However, not much studies have been done on the effect of nano-silica in invert-emulsion drilling fluids. This research paper focuses on how nano-silica influences the performance of invert-emulsion/synthetic based mud in tight gas reservoirs at harsh operation conditions, high pressure high temperature (HPHT). Synthetic based mud has been selected as an ideal drilling fluid to be used in HPHT tight gas reservoirs due to its superior qualities. In order to objectify this study, numerous experiments sets have been carried out in which different concentrations of nano-silica with respect to the fluid loss agent have been added to the synthetic based mud and the resultant performance is carefully studied in order to determine the optimum concentration of nano-silica that will elicit the best performance from synthetic based drilling fluids. The obtained results showed that a maximum concentration of about 40% provides the best performance Nano-silica has also improved the rheological properties of SBM by reducing the plastic viscosity and yield points.

1. Introduction

To keep up with the increased global demand of energy, companies have changed focus to unconventional and deep water reservoirs which are poised to contain a majority of the worlds undiscovered hydrocarbon resources [1]. When compare today with a decade ago, the amount of potential reservoirs has increased by 50% owing to the rise in technological advancements in the exploration and production of oil and gas.

Many authors have labelled unconventional reservoirs as high temperature, high pressure reservoirs (HPHT) due to their pressure and temperature conditions which have made it a challenge to extract hydrocarbon resources from them. They are defined as those reservoirs that have a bottom-hole temperature of more than 10,000 psi and a temperature of more than 300ºF. Drilling for oil and gas is challenging in such conditions due to the problems that arise during drilling [2]. The rate of penetration rapidly decreases when the drill string penetrates HPHT zones as compared to when drilling through

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conventional zones which do not pose much problems and most of the problems that arise can be easily dealt with using various technological techniques that have been developed in the oil and gas industry [3,4].

Tight gas reservoirs are categorized as HPHT reservoirs and have large volumes of gas with high productivity potential. They are known to have small pores, high capillary pressure ad strong water wettability [5]. Drilling into tight gas reservoirs has caused problems such as the gas influx into the wellbore because of the abnormal pore pressure, fluid loss due to the fracture pressure and pore pressure is very narrow margin, stuck down hole equipment in the wellbore due to high differential pressure between hydrostatic pressure and pore pressure.

Another issue that arises is that of formation testing in which inaccurate data is gotten due to challenges such as filtrate invasion and weak mud cake build up within the wellbore wall [6]. The data gotten from formation pressure testing is vital in the determination of the approximate reservoir estimates which is important in determining the productivity of the well and whether it is economical to produce from it [7]. A majority of the problems laid out arise during drilling, stimulation, production and completion as they all involve use of drilling fluids and therefore in order to mitigate the issues, a proper enhanced drilling fluid is needed.

Drilling fluids are used in almost every process in the drilling process ranging from exploration, appraisal, production and even during shutting of the well. It is also the only material that comes into contact with all parts of the wellbore and well system [8]. Drilling technology in itself accounts for more than $4/5^{ths}$ of the total amount of money used in the development of a well and is therefore a technology that can be optimized to further cut down the costs that would have been realised when drilling through tight gas formations [9].

Focusing on high pressure high temperature wells, the type of drilling fluid that is preferred is synthetic based mud because it contained much better quality parameters when compared to its predecessors: oil based mud and water based mud. Synthetic based mud has proven successful in directional, extended reach, horizontal, and extreme extended reach drilling. However, as much as synthetic based mud (SBM) has superior qualities, it has its limitations when it comes to drilling HPHT zones. The high temperature experienced causes the chemical components in the SBM formulation to degrade when it is exposed to those conditions for an extended period of time. The characteristics of 10,000 psi and 300^{o}F leads to the reduction in its overall performance [10].

The reduction in the performance of the synthetic based mud has elicited severe effects and this has necessitated the oil and gas industries to research further on how to develop a better type of synthetic based mud. The addition of other components such as surfactants has improved the quality of SBM and consequently its performance in HPHT conditions. However, the components that have been proposed by various companies have greatly increased the cost of drilling due to the increased complex nature of HPHT reservoirs. The stability of synthetic based mud has also been put to question and thus better additives need to be used to further improve the quality and promote stability of the drilling fluid [11].

Nanoparticles are the new way to go since they possess qualities such as a high surface area to volume ratio meaning that it provides more surface for reactions making the fluids more sensitive to physical and chemical reactive agents. Apart from that, they have proven to greatly reduce the drag and torque within drilling fluids as they reduce the friction between the clay particles within the drilling fluid and also friction between the clay particles and the wellbore assembly. This mitigates problems such as pipe sticking and in addition it greatly reduces the equivalent circulating density of the drilling fluid which is ideal for HPHT tight gas formations [12].

The specific type of nanoparticle additive that is used is nano-silica which has been used to enhance the performance of synthetic based mud. It possesses properties that can withstand HPHT conditions such as high melting and boiling points. [13]. Identification of nano-silica as the best kind of nanoparticle additive is not enough to improve the performance of synthetic based mud, the amount added needs to be controlled keeping economics in mind. An optimum concentration is required to give the best performance when added into drilling fluids and in this case synthetic based mud to be used in HPHT tight gas reservoirs. There is no specific study on this.

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2. Methodology

The study focuses on evaluating the performance of synthetic based mud when it is used in HPHT conditions in tight gas reservoirs. Various experiments were conducted to understand the behaviour of synthetic based mud and to optimize its performance using nano-silica in order to mitigate the problems encountered via HPHT tight gas reservoirs, therefore; to realise high productivity and to improve formation tests which determine reservoir potentials.

Synthetic based mud was formulated using different amounts of nano-silica and operating temperatures, 12ppg (200°F) and 13.5ppg (350°F). The synthetic based mud formulated was submerged in the water bath for 12 hours. Nano-silica was added into the synthetic mud under different concentrations 35, 40, and 45 ppb. The chemicals that were used are weighed accordance to the mud weight of synthetic based mud. The samples are mixed for a total of 60 minutes with each addition of chemicals having their own mixing time. Table 1 shows nano-silica specifications. The amount of nano-silica that was added is based on the amount of fluid loss agent that is added. The same procedure was carried out and the values were compared with the base values to examine the influence of nano-silica addition.

Table 1. Nano-silica specification [14]

Product Name	Silicon dioxide – Nano powder
Purity	99.5% trace metals basis
Size	10-20 nm particle size
Appearance	White powder
Boiling Point	2230°C
Melting Point	>1600°C
Density	2.2-2.6 g/mL at 25°C

3. Result and Discussion

3.1. Comparisons of Mud Rheology Performance

As can be noticed Figure 1, there is a significant difference in the rheological profile between SBM without Nano-silica and SBM enhanced with nano-silica at the concentrations of 35, 40 and 45% for both mud systems. The behaviour of the flow of drilling fluids is often described using the Bingham plastic model for the higher shear rates of values more than 500 sec^{-1} and the Modified Law model is used to define the behaviour of those fluids with lower shear rates of less than 500 sec^{-1} [15]. In Figure 1, it can be seen that the mud formulated for the 200°F and 350°F system exhibit a non-Newtonian behaviour even with the addition of nano-silica at different concentrations. Drilling fluids are conventionally supposed to have non-Newtonian behaviour and the SBM formulated conforms to this desired property. This serves to prove that the drilling mud formulated is representative of actual drilling fluids to be used in both normal and HPHT conditions.

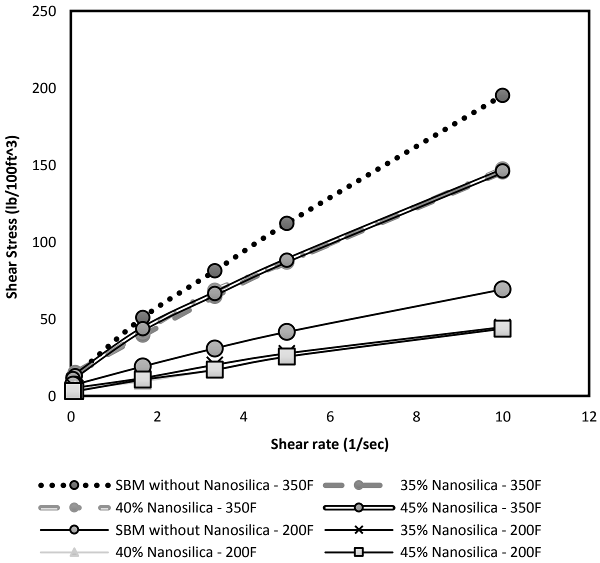

Figure 1. Shows relationship between shear stress and shear rate

Introducing nano-silica in the synthetic based mud plays a vital role in changing the rheology of the mud because of the properties it possesses such as high surface area to volume ratio, particle size and the interaction of the nano-silica particles with the drilling solids in the synthetic based mud. The interaction between particles serves to reduce flocculation that occurs within the drilling fluid and this enhances the performance in terms of having a superior rheology [16]. Looking at the mud formulated for the 200^{o}F and the 350^{o}F mud systems, the rheological properties are increased and this is due to the effect of the increased temperature on the material in the mud that flocculates. Once the material is exposed to increased temperatures, it flocculates and thus the rheological properties are increased and this makes the mud thicker and more viscous. This is positive as it increases the carrying capacity of the mud due to the increased viscosity [17].

The shear stress for both mud systems reduces with the addition of Nano-silica, which makes the drilling fluids easier to pump into wells because it reduces the energy that is required to circulate the mud in the well. As much as the viscosity increases due to increased temperatures, nano-silica contributes to reduce the shear stress exerted. Looking at the 350oF system, SBM with 35-45% Nano-silica is sufficient to reduce the shear stress by a considerable amount. Therefore, addition of nano-silica reduces the shear rates.

The mud rheology is stable under 200^{o}F and 350^{o}F temperatures due to the addition of nano-silica which results in reduced shear stress for a given shear rate. Nano-silica has high boiling and melting points which makes it favourable for such elevated temperatures. It also does not flocculate under high temperatures which contributes to a stable mud rheology for tight gas HPHT conditions. A stable mud rheology is important because it reduces problems such as downhole pressure surges and it reduces the circulating density of the mud. The 350^{o}F system has also increased carrying capacity which reduces the problems associated with cuttings remaining in the wellbore such as stuck pipe problems and reduced or ineffective rates of penetration [18].

3.2. Plastic viscosity (PV)

Figure 2 shows the plastic viscosities of the two mud systems and how the vary with the concentration of Nano-silica added into the mud sample. From the graph, it can be seen that there is a decrease in the plastic viscosity with an increase in nano-silica concentration. Comparing the plastic viscosities of the mud samples that have nano-silica, the plastic viscosity has a very small deviation meaning it has stabilized. The plastic viscosity reflects the resistance of the drilling fluid to flow. Compared to the standard performance of a 13.5ppg mud system for 350ºF, the plastic viscosity should be less than 45cP, although this is not the case and this can be attributed to the chemical degradation of the samples after the samples have been exposed to elevated temperatures. However, this increase can be a good indicator that the drilling fluid has an increased ability to carry cuttings to the surface from bottom hole as long as the pump pressure required to pump out the mud is not excessive [19].

The emulsion in the SBM that is stabilized by the emulsifier that is added in the components usually degrades at high temperatures and the oil and water phases separate [20]. Looking at the stabilization of plastic viscosities, it is can be concluded that the emulsion has been stabilized and does not degrade due to the addition of nano-silica. This is because the size of nano-particles is much smaller than the wavelength of conduction electrons which has a size of roughly 100nm and due to this phenomenon, the boundary conditions become damaged and thus optical pressure, the chemical reactions and thermal resistance change drastically unlike what happens with normal particles [21].

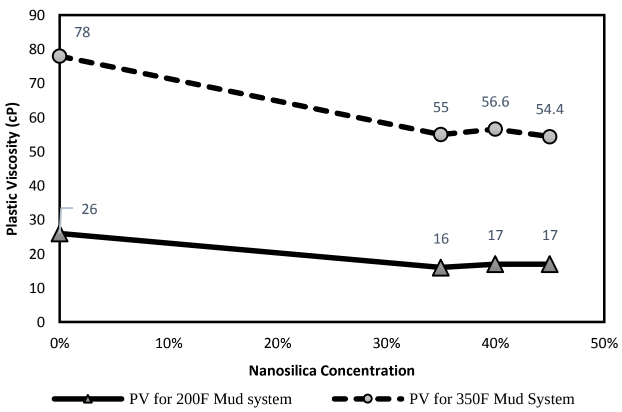

Figure 2. Shows the effect of nano-silica on PV

This allows the nanoparticles to become coalescent with the other drilling solids promoting a better and stabilized emulsion that does not degrade under high temperatures. This in turn does not affect the plastic viscosity of the fluids making it more stable. The decrease in plastic viscosity with increase in concentration of nano-silica is a good effect because it reduces the amount of pump pressure that is needed to pump the SBM into the wellbore and also reduces the equivalent circulating density. This decrease in the plastic viscosity can be attributed to the dispersion of nano-silica particles within the drilling fluid as this makes the mud less viscous compared to SBM without nano-silica for both 200ºF and 350ºF mud systems. Another school of thought is that the reduction of bentonite in the mud due to increased concentration of nano-silica results in lesser solid particles which reduces the interaction of clay minerals that would have resulted in increased plastic viscosity [22].

Comparing the two mud systems, the mud system used for 350ºF drilling conditions has a higher plastic viscosity than the mud for 200ºF drilling conditions and this translates to an increased carrying capacity for the SBM. Figure 3 shows an effective viscosity against the shear rate which shows a decreasing trend of the effective viscosity with change in the shear rate and this property is one that is exhibited by non-Newtonian fluids and is referred to shear thinning which shows that the effective viscosity of the fluids will decrease with increasing shear rates [23].

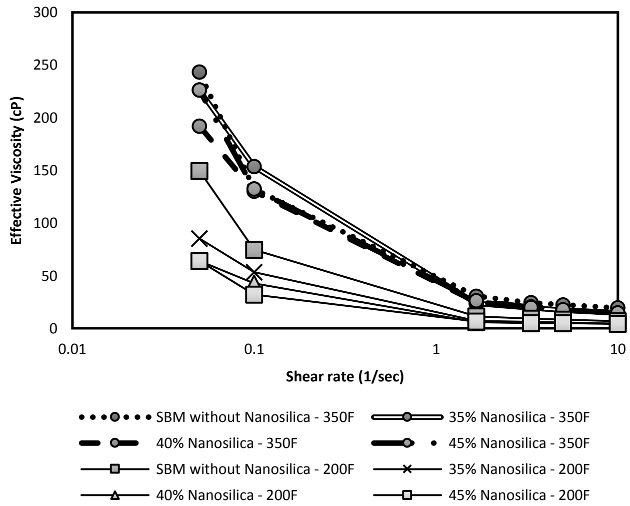

Figure 3. The effective viscosity against shear rate

Moreover, the graph shows that synthetic based mud that has nano-silica experiences more shear thinning behaviour and this reduces problems such as circulation pressure loss between the drilling fluids that is used in hole-cleaning which has a higher velocity compared to that in the annulus which has a lower velocity. It can be seen that the 350ºF mud system has a higher shear thinning rate as compared to the 200ºF system which translates to reduce shear thickening which causes problems such as high shear rates and lowers the pump quality of the SBM. Therefore, the mud system formulated for HPHT conditions thus has both the benefits of shear thinning and reduced shear thickening.

3.3. Yield Point

Figure 4 shows the plot of yield points of the various samples for both mud systems. From the plot, it can be seen that the yield point decreases with increasing concentration of Nano-silica. Although for the 350ºF mud system, the yield point increased when a nano-silica concentration of over 40% was added into the formulation. The yield points are within an acceptable range comparing it to a benchmark of 10 lb/100 ft^3 of commercially synthesized SBM for a 12ppg mud system and about 25 lb/100 ft^3 13.5ppg mud system [17]. The yield point is used to show the ability of the synthetic based mud to be able to carry and lift the cuttings and other suspensions to the surface. It can be seen that there is a high initial yield point which can be explained because of the long exposure of the mud to high temperatures and this is due to the degradation of some of the components that have been used in forming the synthetic based mud in a process known as flocculation [24]. Adding nano-silica into the formulation of synthetic based mud is seen to lower the yield point of the drilling fluid to a more stabilized value because of the addition of nano-particles to the emulsion phase of the synthetic based mud.

As can be also seen in Figure 4 that the effect of adding nano-silica to the yield point of the synthetic based mud. There is a decrease in the yield point which can be attributed to the repulsive nature of the nano-silica with the water phase and other solid clay particles within the synthetic based mud. This repulsive nature serves to prevent the flocculation that occurs due to high temperatures which causes problems such as pump pressure loss which translates to the drilling fluid needing an increased amount of pressure in order to pump it through the wellbore [25]. It is seen that the yield points stabilize which gives the synthetic based mud a much stable rheological profile compared to when there is not any nano-silica within the SBM formulation and thus it can be used to effectively allow suspension and transportation of cuttings to the surface. The carrying capacity of the synthetic based mud improves.

Comparing the 200ºF and 350ºF mud system, there is an increased yield point value meaning that the carrying capacity of the mud formulated for HPHT conditions is better and serves the goal of this experiment. From the results of the plastic viscosity and yield point, it can be seen that there is a balance in the intermolecular forces when the SBM is enhanced with nano-silica reducing the chances of flocculation.

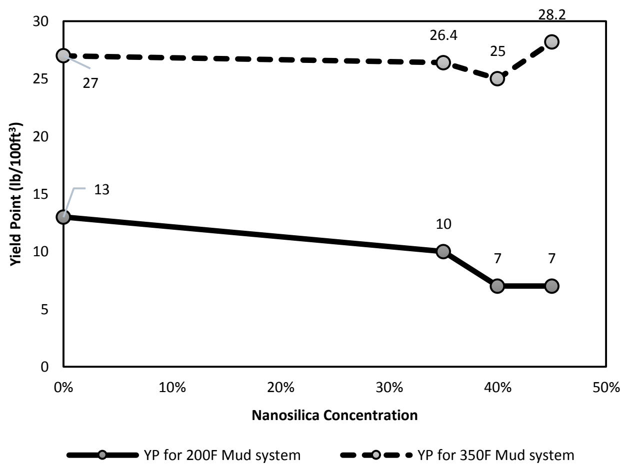

Figure 4. The effect of nano-silica on the Yield Point

4. Conclusion

From the experimental tests that were conducted, it is clear that the overall performance of SBM has increased with increase in concentration of nano-silica up to 40% concentration after which further increase results to a decrease in SBM performance. Nano-silica has also improved the rheological properties of SBM by reducing the plastic viscosity and yield points. The mud concentration of 13.5ppg has lower plastic viscosities and yield points as compared to 12ppg mud, translating to better SBM for HPHT conditions. In addition, there is increased stability to SBM rheology due to reduced shear rates required to maintain a specific shear rate. It also contributes to a shear thinning ability of SBM which reduces problems such as circulation pressure loss between the SBM in the annulus and that in the pore-hole. The 13.5ppg at 350^{o}F has better shear thinning rates and reduced shear thickening which reduces problems such as low quality SBM.

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