Effect of Nanoparticles on the Performance of Drilling Fluids

Gomathi Rajalakshmi Seetharaman and Jitendra S. Sangwai

Abstract Owing to the extinction of conventional reservoirs, it is imperative for engineers to find the unconventional oil and gas resources. Drilling an unconventional field requires engineered drilling fluids because an efficient drilling operation purely depends upon the performance of drilling fluid. Drilling fluid which is a combination of solids and fluids performs many functions, such as cooling the drill bit, cleaning the wellbore, maintaining the wellbore pressure and development of a filter cake to prevent the invasion of fluid into the formation. The drilling fluid can be classified into oil-based mud (OBM), water-based mud (WBM) and pneumatic fluid (or) air-based fluid. Conventional drilling fluids which are in use lose their efficacy during drilling a complex reservoir, like high temperature high pressure (HTHP) and highly saline reservoir. Nanomaterials which are unique due to their distinctive properties, like high surface to volume ratio, thermal stability and conductivity, found their application in almost all fields of engineering. Many studies have been conducted to analyse the enhancement of drilling fluids through the application of nanoparticles. The studies resulted in enhancement in rheological, filtration, thermal properties of the drilling mud and also improved the wellbore stability. This chapter elaborately discusses about how the application of various types of nanoparticles/nanocomposites helps to enhance the rheological and filtration properties of the drilling mud.

Keywords Drilling fluids · Rheological properties · Nanoparticles · High temperature high pressure

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1 Introduction

1.1 Drilling Fluids

A well-organized reservoir operation consists of many important stages, starting from finding the presence of crude oil to extracting the oil from the reservoir. An important parameter in-between these two stages that decides the fate of drilling is the drilling fluids. A successful drilling operation depends upon the effectiveness of the drilling fluid. Drilling a long hole from surface till deep inside the earth produces a huge amount of heat, which reduce the performance of drilling bit. A drilling fluid (or) mud, which is a combination of various chemicals, solids and liquids, is generally used to cool down the drilling bit. The drilling fluid also needs to perform other functions such as to carry the cuttings from the subsurface, minimize formation damage by producing a filter cake and to maintain the wellbore stability. The drilling fluids are classified into water-based drilling mud or fluids (WDM), oil-based drilling mud or fluids (OBM) and pneumatic drilling fluid. Since drilling fluids encounter high temperature high pressure (HPHT) environment, maintaining the viscosity of drilling fluid is the crucial part for effective functioning. Any deviation in the rheological, physical and chemical properties of the drilling fluids severely affects the performance. The flowchart in Fig. 1 briefs about the role of the properties and their functions in drilling fluids.

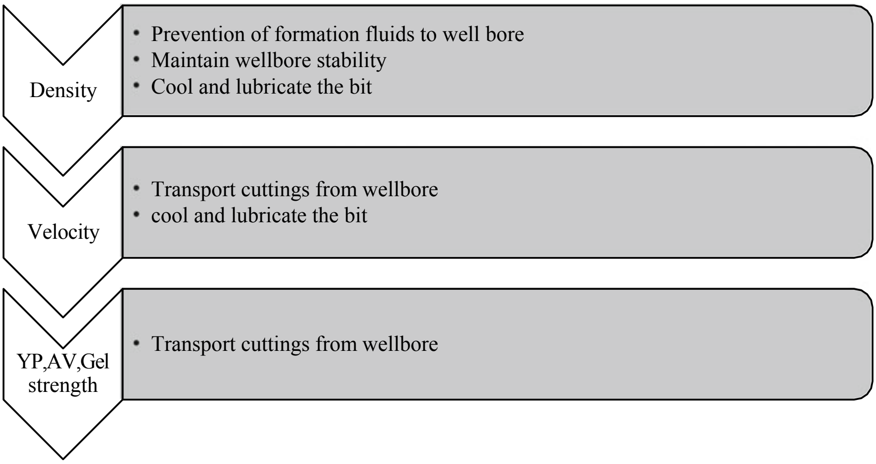

Fig. 1 Properties and functions of drilling fluid

1.2 *Classification of drilling fluids*

1.2.1 Water based drilling fluids

Water, brine or formate salt is used as the continuous phase in water-based mud. Since this mud is inexpensive and environmental-friendly, this is most commonly used in the industry. These are also referred to as water-based mud (WBM). Table 1 shows the various additives added to improve the properties of water-based drilling fluids.

1.2.2 Oil-Based Drilling Fluids (ODF)

The oil-based drilling fluid is also referred to as oil-based mud (OBM). The base fluid is mostly mineral oil, diesel, olefins or paraffin. Barite is used to increase the system density and bentonite clay is used as the viscosifier. Oil-based mud significantly retards the clay swelling and showed better performance in deviated well and provides a high degree of lubricity. Even though the performance of oil-based mud is superior to water-based mud (WBM) due to the toxic nature of the mud, it is strictly restricted at environmentally sensitive areas. OBM is also classified into invert emulsion method in which the water is emulsified in oil.

1.2.3 Pneumatic (or) Air-Based Drilling Fluids

Air or nitrogen is commonly used in pneumatic drilling fluid technique. The main advantage of air-based drilling fluid is it offers higher penetration rates, better hole cleaning efficiency and less formation damage, whereas air-based drilling fluid does not provide enough pressure for the prevention of inflow of the reservoir fluids.

Table 1 Additives for drilling fluids

S. No.	Additive	Property
1.	Clay	Viscosity control
2.	Barite, starch, organic colloid (sodium carboxy methyl cellulose), polyacrylates, lignosulphonates, polyanionic cellulose	To improve the rheological properties and control the density
3.	Polymers like xanthum gum, polyacrylamide and carboxymethyl cellulose	Viscosity control (HTHP affects the performance)

2 Nanotechnology and Nanomaterials

It was in 1959 when Richard Feynman coined the term “There is a plenty of room at the bottom” that leads to the invention of a new technology called nanotechnology. The materials involved in the revolution of nanotechnology are called nanomaterials which are of 10^{-9} m size. Owing to its exceptional property, like high surface to volume ratio, nanoparticle found its application in almost all fields of engineering and technology. The surface of nanoparticle offers greater area of chemical reactivity and alters the quantum effects that lead to changes in optical, magnetic, electrical and other substantial properties. Nanomaterials are extremely small in size, having dimension from 1 to 100 nm or even less. For example, the one-dimensional nanomaterial is surface film, two dimension is strands or fibres, three dimension is particles and the most common types of nanomaterials which found application in engineering and technology are nanotubes, dendrimers, quantum dots and fullerenes. There are several approaches to produce nanomaterial of various sizes; they are top-down and bottom-up approach. The nanomaterial should be dispersed in the base fluid and used as a nanofluid in drilling operation.

2.1 Importance of Nanoparticles in Drilling Muds

Owing to deterioration of conventional drilling mud at HTHP, the drilling muds failed to maintain the rheological properties. This results in loss of mud filtrate volume, which subsequently leads to failure in drilling operation. Nanoparticles, such as metal oxide, can support heat transfer from the drilling fluids by increasing the thermal conductivity. In addition, due to their extremely small size, nanoparticles plug the pores of formation and reduce the mud filtrate volume. Nanoparticles, because of their large free energy of adsorption, attach themselves to the interface between oil and water in an emulsion (Agarwal et al. 2011). The rheological properties of the drilling fluids are further enhanced due to the physiochemical, electrical and thermal properties of the nanoparticles. Hassani et al. (2016) showed that quantum effects of nanoparticles in drilling fluids make many physical changes without altering the bulk chemistry. Comparing the performance of bulk phase material, nanoparticle enhances the rheological properties, fluid loss control, wellbore and shale stabilization, wellbore strengthening, cuttings suspension and thermal properties.

3 Enhancement in Drilling Fluid Properties Due to Nanoparticles

Nanoparticles enhance the rheological properties of the drilling fluids using various mechanisms which mostly depends on the concentration, physical and chemical properties of nanoparticle and continuous phase of drilling fluids.

3.1 Effect of Nanoparticles on Rheology

Since drilling fluid is a combination of solids and fluids, controlling the rheological properties deep under the earth under high pressure and temperature is always a crucial part. Rheological properties are the basics for all analysis of wellbore hydraulics and to assess the functionality of the mud system. The rheological characteristics of drilling mud include apparent and plastic viscosity, yield point and gel strength. Researchers found that addition of various types of nanoparticles to the drilling mud modified or enhanced the rheological properties. Addition of nanoparticles to the drilling mud enhanced the plastic and apparent viscosity and maintained the yield point and gel strength.

The increment in rheological property of the bentonite-based mud by iron oxide nanoparticles was studied by Jung et al. (2011). Iron oxide nanoparticle of concentration 0.5–5 wt% increased the yield stress and viscosity of the mud. The observed enhancement in rheological properties is due to the fact that the nanoparticles got embedded in randomly distributed pore structure on the surface of clay particle in mud and confers a link between bentonite suspensions and promotes gelation of the mud. The increment in rheological properties is stable even at high temperature. At high temperature of 99 °C, the ferric oxide nanoparticle displaces the dissociated cations from clay and yields a different clay platelet microstructure and gives higher yield stress value (Mahmoud et al. 2016). Barry et al. (2015) showed that iron oxide clay hybrid and drilling fluid containing various concentration of iron oxide nanoparticle showed higher stresses at all shear rate compared to the bentonite-based drilling mud. The nanoparticles can improve the rheological properties of the drilling mud without the need of any rheological additives and this is also confirmed by Contreras et al. (2014). They used an oil-based drilling fluid prepared with iron oxide nanoparticle and graphite as a lost circulation material (LCM) rheological additive. The combination of both the nanoparticle and LCM reduced the yield point at high graphite concentration. Figure 2a shows the rheogram of bentonite and iron oxide-based drilling mud. Addition of iron oxide nanoparticle to the bentonite-based mud increased the shear stress with increase in temperature.

It is to be noted that higher temperature yielded higher yield stress of value 7.15 Pa at 60 °C because higher temperature create continuous gel strength in the bentonite suspension. The yield stress is calculated from the rheograms after extrapolating the graphs to zero shear rate and fitted in Herschel–Buckley (HB) model; τ =

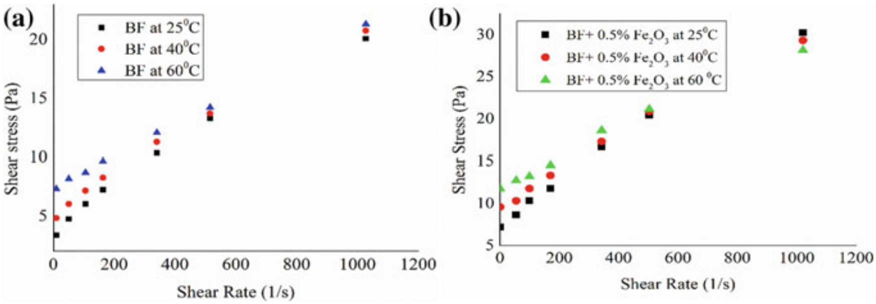

Fig. 2 **a** Rheogram of base fluid, BF, with 7 wt% bentonite at different temperature; **b** base fluid bentonite containing iron oxide nanoparticles at different temperature (Vryzas et al. 2018) (Reprinted and modified with permission from Elsevier copyright at 2018)

$\tau_{HB} + K(\gamma)^n$, where τ and γ are shear stress and shear rate, τ_{HB} is the yield stress and K is the flow consistency index which indicates suspension viscosity and n indicates flow behaviour index. $n < 1$ shows shear thinning and $n > 1$ shows shear thickening behaviour (Vryzas et al. 2018).

The dimension and concentration of the nanoparticle is also one of the decisive factors in altering the rheological properties of the drilling fluids. The silica nanoparticles dispersed in oil-based mud enhanced the viscosity of the drilling mud and remained stable at HTHP when the diameter is 20 nm (Anoop et al. 2014). But for low temperature and low pressure (LTLP) condition the dimension of the silica nanoparticle can be further reduced to 10 nm with concentration of 0.5 wt%, and it has enhanced the plastic viscosity and yield point at LTLP condition (Ghanbari et al. 2016; Hassani et al. 2016). The rheological properties of the drilling mud can be further enhanced by enhancing hydrogen bond in the drilling mud by making nanocomposite from nanoparticle mixed with polyacrylamide grafted/polyethylene glycol (Jain et al. 2015).

The enhancement in rheological properties by the addition of silica nanoparticle was also confirmed by various researchers (Mao et al. 2015a, b; Srivatsa and Ziaja 2012; Taraghikhah et al. 2015). Figure 3 shows the enhancement in apparent viscosity of the drilling mud. It is to be noted that the enhancement in viscosity is high for carbon nanotubes (CNT) and SiO_2 than ZnO nanoparticles.

Abdo and Haneef (2013) showed that when nano-palygorskite (PAL) added to the montmorillonite (Mt), which is an important constituent of bentonite-based mud, increased the gel strength by about 200% from 0.3 to 4.5. This behaviour confirms the superior performance on holding the drill cuttings under static condition. The Mt-based drilling fluid is subjected to flocculation at HPHT, while when the nano-PAL added as an additive in small quantity improves the quality of drilling mud at HPHT. Further, the rheological properties of Mt-based mud can be increased by preparing a nanocomposite of ZnO, Mt and PAL (Abdo et al. 2014). Because ZnO–clay nanocomposites impart stable colloidal mechanisms to clays as it highly discourages flocculation of clays in water, this renders significant stability to the

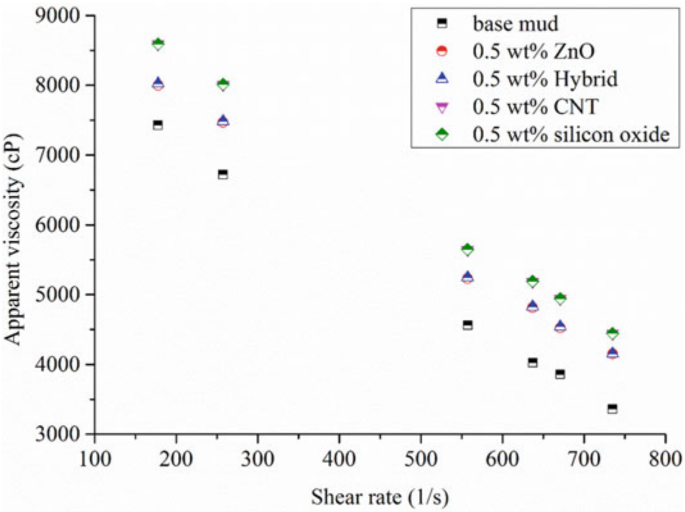

Fig. 3 The apparent viscosity versus shear rate for the water-based drilling mud in the presence of various nanoparticles (Hassani et al. 2016) (Reprinted and modified with permission from Elsevier Copyright 2016)

drilling fluids sepiolite which is an important class of clay when used in nanoform and improved rheological properties of water-based mud like plastic viscosity and yield point at both LTLP and HTHP conditions (Abdo et al. 2016; Needaa et al. 2016). Figure 4 shows the viscosity of graphene-oil nanofluid and hydrogenated oil at 30 °C by Ho et al. (2016). It is found that increase in graphene nanoparticle concentration increased the viscosity. At concentration 25 ppm and shear rate of 125 (1/s), a sharp increase in viscosity is observed due to jamming of nanoparticles at the bottom of apparatus. The shear thinning behaviour of graphene-oil-based nanofluid OBM was confirmed by decrease in viscosity with increase in shear rate. Further enhancement on rheological properties by various other nanoparticles is presented in Table 2.

3.2 Wellbore Stability and Strengthening

Wellbore instability is one of the serious issues in drilling operation. The main reasons for wellbore instability are sloughing (or) swelling and abnormal pressured formations. Owing to shale inhibition property of OBM, maintaining the wellbore for effective drilling operation is quite easy, but owing to high cost, environmental restriction and mud disposal difficulties, the application of OBM in field is restricted. For formation with low permeability (nanodarcy), the conventional drilling fluids cease to produce a filter cake. A reasonable way to overcome this problem is to prevent pressure increase at near wellbore. The nanoparticles employed in the drilling

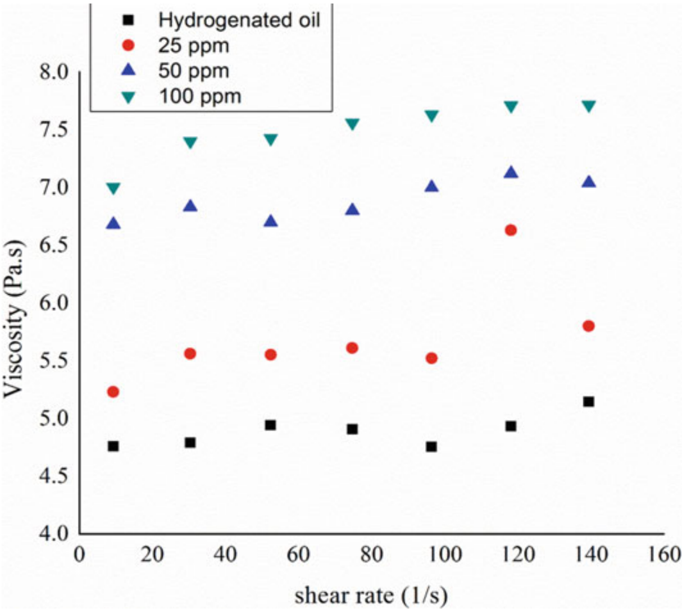

Fig. 4 Comparison of viscosity for 25, 50, 100 ppm of graphene-oil nanofluid and hydrogenated oil OBM at 30 °C (Ho et al. 2016) (Reprinted and modified with permission from Elsevier (Ho et al. 2016))

fluids penetrate through the pores of the shale and act as a bridging material and a wellbore strengthening material.

Akhtarmanesh et al. (2013) showed that silica nanoparticles reduced the fluid penetration into Grupi shale up to 68% in comparison with WBM, and the minimum concentration required to reduce the permeability and minimize the fluid invasion is 10 wt%. Nanoparticles with diameter of 35 nm showed better plugging efficiency than 50 nm sized nanoparticle due to the pore size in the formation. 1 wt% of nanosilica in WBM improved the shale stability by plugging the pores through physical pore plugging mechanism (Taraghikhah et al. 2015). Silica nanoparticles of 10–30 nm produced a lowest amount of fluid loss of 4 ml in an American Petroleum Institute (API) fluid loss test using a hydrophilic filter membrane with 100 nm pores (Hoelscher et al. 2012). Since biopolymers are stable at high temperature, xanthum gum combined with silica nanoparticles in a particle plugging apparatus at pressure of 1000 psi and a temperature of 93 °C (200 F) produced a minimum fluid loss of 7.9 ml and also very effective in plugging the pores (Srivatsa and Ziaja 2012). But the same silica nanoparticle with dimension of 10–20 nm in OBM produced higher filtration than the base mud and further increasing the concentration of nanoparticles, the cracks in the mud cake propagates, because of poor dispersion of silica nanoparticles in OBM (Kang et al. 2016).

Nwaoji et al. (2013) combined the lost circulation material (LCM) with nanoparticles to control the well instability problem. Iron (III) hydroxide nanoparticle when

Table 2 Application of nanoparticles on modification of rheological of properties drilling fluids

S. No.	Author	Types of NPs	Base fluid	Enhancement in rheological properties[a]
1	Agrawal et al. (2011)	Clay and silica	Oil	• Improved the viscosity and gel strength of invert emulsion at HTHP • A combination of 2 wt% of nanoclay and 1 wt% nanosilica showed enhanced rheological properties
2	Li et al. (2010)	Cellulose particle	Water	Improved PV, YP and gel strength at 0.5 wt% at HTHP
3	Song et al. (2016a, b)			Improved PV, YP and gel strength at 3.5 wt% at LTLP
4	Sadeghalvaad and Sabbaghi (2015)	TiO_2/PAM nanocomposite	Water	Increased PV and YP compared to nanoparticle
5	William et al. (2014)	CuO and ZnO	Water	Better rheological stability for nano-based WBM compared to base fluids at HTHP

[a]*PV* Plastic viscosity; *YP* Yield point

mixed with graphite (LCM) increased the fracture breakdown pressure by 70% over unblended water-based mud, and the increment in fracture breakdown pressure is 47% higher than OBM because WBM is primarily made of organophillic clay and water. It interacts strongly with nanoparticles, thereby stabilizing them. There are no electrostatic attractions or van der Waals forces between nanoparticles and the fluid constituents unlike OBM.

3.3 Enhancement in Thermal Property

Enormous amount of heat is produced due to drilling deep down the earth and the friction between drilling bit and the surface of rock added on the heat to the drilling bit which deteriorates the performance of the drilling fluid. The metal oxide nanoparticle in nature generally has high thermal conductivity, so the applicability of nanoparticles in drilling fluids improves the rate of heat transfer. The particle is in micrometre range and does not possess Brownian motion, leading to lower thermal conductivity. For example, a carbon nanoparticle with 0.2 wt% in WBM showed higher thermal conductivity than 0.4 wt% due to increase in distance between particles (Ho et al. 2014). Increase in temperature increased the thermal conductivity of the nano-enhanced drilling fluid. Silver nanoparticles with diameter 5 nm dispersed in kerosene-based mud showed higher conductivity at 50 °C than at 25 °C because of the enhanced Brownian motion (Li et al. 2010). The increment in thermal conductivity of the drilling mud by the addition of nanoparticles made the mud to cool faster as it moves up the surface. The increase in nanoparticle concentration increased the thermal property of the drilling fluid. The enhancement in thermal conductivity was higher in the case of CuO than ZnO for a particle concentration of 0.1, 0.3 and 0.5 wt% (William et al. 2014). The enhancement in thermal conductivity for nano-sized particle was significant than with micro-sized particle. Nanoparticle concentration (0.5 wt%) promoted better thermal conductivity and the value of thermal conductivity will be lowered if the nanofluid was prepared in base fluid which are highly viscous in nature (PEG 600) because the nanoparticles may get entrapped in the microstructure of network forming aggregates (Ponmani et al. 2016). Figure 5 shows the comparison of thermal conductivity for various concentrations of ZnO nanoparticle. It is clear that increase in nanoparticle concentration increased the thermal conductivity.

Since multiwalled carbon nanotubes (MWCNTs) are hydrophobic in nature, dispersion in WBM remains a greater challenge. Modifying the surface with hydrophilic (nitric acid) group produced a stable dispersion in WBM, leading to enhancement in thermal conductivity by 23.2% for 1 vol% of functionalized MWCNTs (Sedaghatzadeh and Khodadadi 2012). CNTs which are functionalized by hydrophilic group through acid treatment increased the thermal conductivity by 31.8% at 50 °C and the increment in thermal conductivity is even higher for oil-based mud (Fazelabdolabadi et al. 2015).

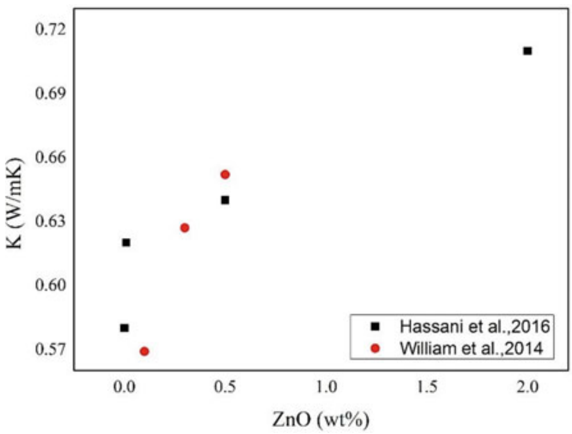

Fig. 5 Comparison of thermal conductivity for ZnO nanoparticle from Hassani et al. (2016) and William et al. (2014). Reprinted and modified with permission from Elsevier, copyright (Elsevier 2014, 2016)

Table 3 Application of nanoparticles on modification of rheological properties of drilling fluids

S. No.	Author	Drilling mud	NPs	Enhancement in lifting capacity
1	Boyou et al. (2019)	Water	Silica (0.5, 1, 1.5 ppb)	The SiO_2 nanoparticles increased the cutting transport efficiency for all inclination and increase in nanoparticle increased the efficiency
2	Gbadamosi et al. (2019)	Water	Silica (0.001–1.5 wt%)	Smaller the cutting particles, higher the efficiency Larger particles are least affected by buoyancy and viscous force
3	Samsuri and Hamzah (2011)	Water	MWCNTs (0.001–0.003 wt%)	Low concentration of MWCNTs has minimum impact on cuttings recovery

3.4 Enhancement in Lifting Capacity

The most important function of the drilling fluid is transporting the cuttings to the surface. There are many factors which affect the cutting capacity of the drilling mud, like flow rate of the mud, particle settling velocity, geometry, orientation and concentration of the particle. The cutting transport remains a major problem in vertical and inclined well due to gravitational force.

The nanoparticles added to the drilling mud increase the annular viscosity of the drilling mud which helps to increase the lifting capacity of the mud. Another phenomenon which is commonly encountered is by balancing the gravity force or overcoming the gravity force. The nanoparticles added to the drilling mud increased the drag force on the drilled cuttings which helps to overcome the gravity force by increasing the surface force. The enhancement in lift capacity for various nanoparticles is presented in Table 3.

3.5 Fluid Loss Control by Nanoparticles

One of the very important properties of drilling mud is filtration control. Drilling through the depleted, deep water and deviated reservoir result in regular huge loss of mud and results in fluid invasion. The reason behind the fluid loss is the differential pressure that occurs between the formations and the wellbore. In the process of filtration, a solid cake (or) filtration cake is produced by the solids and chemicals present in the mud, to inhibit (or) stop the fluid invasion into the formation. Since the particles associated with the conventional drilling fluids are usually large in size than the pores of formation, it fails to inhibit the fluid loss. In this case, the filtration cake produced by the drilling mud is usually thick resulting in pipe sticking and inability to plug the pores. Loss circulation is another important issue in drilling fluid in which the drilling fluid is lost at any depth. The nanoparticles added to the drilling mud produces a filter cake of minimum thickness because volume of filtrate entering the formation is very less due to low permeability and low porosity. Moreover, due to the relatively small size of the nanoparticle it can enter the pores of the formation and inhibit the fluid invasion (Fig. 6).

Silica nanoparticles with concentration of 3% by volume and size ranges from 40 to 130 nm in WBM reduced the mud cake thickness up to 34% than the normal WBM (Javeri et al. 2011). While the same silica nanoparticle in bio-polymer and surfactant-based mud reduced the filtration loss up to 40% (Srivatsa and Ziaja 2012) and once the filter cake is produced by the polymer, the nanoparticles create a thin layer of deposit on the surface of the formation, which helps to prevent the polymer invasion into the formation. Mao et al. (2015) used silica-based drilling fluid with dimension of 12 nm and performed API fluid loss. The results revealed that the nano-based drilling mud reduced the fluid loss up to 80%. Mahmoud et al. (2016)

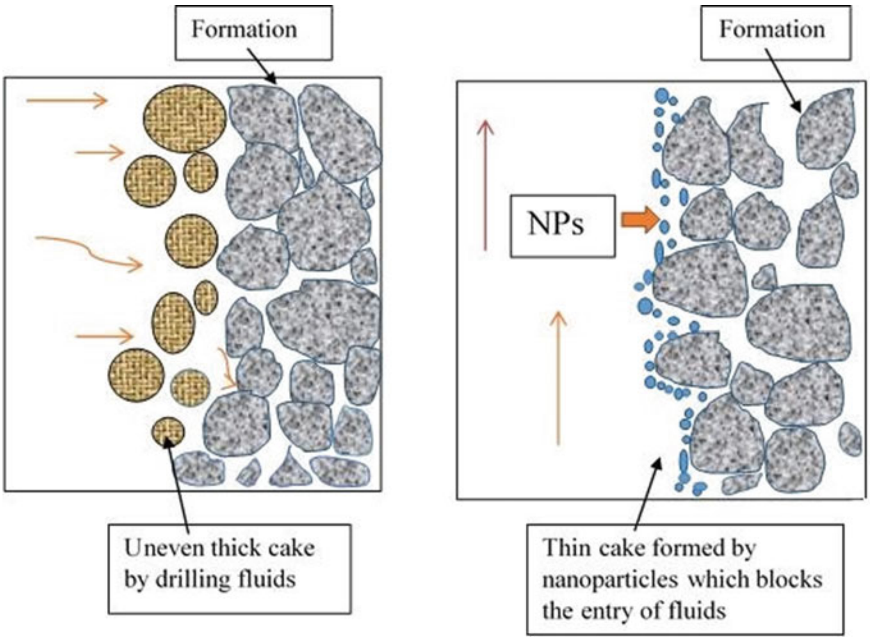

Fig. 6 Nanoparticles act as a barrier to prevent the inflow of mud into the formation

produced a minimum mud cake thickness of 1 mm for a silica nanoparticle of 0.7 wt%. Even though increase in nanoparticle concentration reduced the filtration due to agglomeration of particles, an increase in porosity and permeability was found in the mud cake. The particle size distribution of nanoparticles in the drilling mud is one of the decisive factors that decide the fate of filtration, because bentonite nanoparticles of 4–9 nm in WBM increased the filtration loss due to poor distribution or the fact that the nanoparticles are so small and they just pass through the filter cake (Abdo and Haneef 2013). So in order to attain the larger particle size distribution, the nanoparticles were mechanically prepared and the filter cake produced was also more compact in nature such that sealing pressure is tolerable (Akhtarmanesh et al. 2013). Nasser et al. (2013) observed the effect of pressure on fluid loss for nanographite-based mud and normal drilling mud. It is found that normal drilling fluid will lose its fluidity with increase in pressure, whereas for nano-based mud the observed loss is very minimum.

Figure 7 shows the filtration loss properties of ZnO in PEG and PVP-based drilling fluids (Ponmani et al. 2016). Though the trend of increase in fluid loss with time is the same for all the mud, the loss in quantity of fluid is decreased by the introduction of 0.1 wt% nano ZnO. Further increase in concentration of nanoparticles from 0.1 to 0.5 wt% showed considerable improvement in reducing the fluid loss. The obtained results in fluid loss for nano-based mud are also compared with micro-based mud and the results confirm that nano-based mud shows superior performance in reducing the fluid loss than micro- and polymer-based mud. Jung et al. (2011) compared the fluid filtration behaviour of bentonite mud and mud with bentonite and iron oxide nanoparticles. Compared to the raw bentonite-based mud, the mud with iron oxide nanoparticles reduced the filtrate volume. Perween et al. (2018) produced a thin filter cake with zinc titanate nanoparticles dispersed in bentonite-based mud consisting of various additives of viscosity, fluid loss and clay stabilizer. The API filtrate test

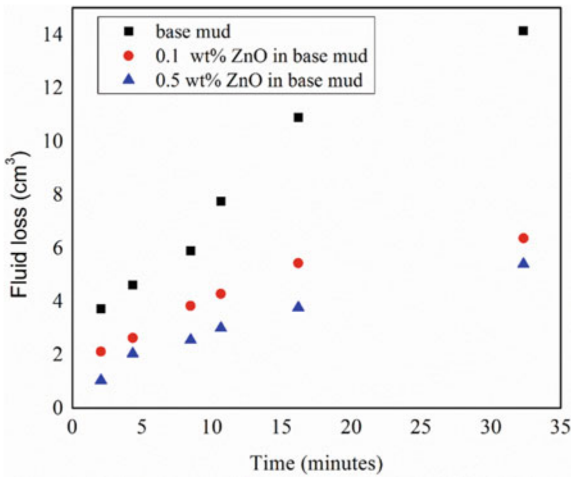

Fig. 7 Fluid loss during a period of 30 min for WBM and NWBM (ZnO) (Reprinted and adopted from SPE, (Ponmani et al. 2016))

Table 4 Thickness of mud cake produced by nano clay–silica (CS) composite with increase in temperature

Sample*	Thickness of mud cake (in.)	
	25 °C	90 °C
Base mud (WBM)	0.137	0.149
WBM + 0.1 wt% nano CS	0.066	0.068
WBM + 0.5 wt% nano CS	0.059	0.058
WBM + 1 wt% nano CS	0.052	0.053
WBM + 1.5 wt% nano CS	0.054	0.051
WBM + 0.1 wt% nano SiO_2	0.071	0.077
WBM + 0.5 wt% nano SiO_2	0.067	0.079
WBM + 1.0 wt% nano SiO_2	0.066	0.076
WBM + 1.5 wt% nano SiO_2	0.066	0.074

*WBM+nano CS or WBM+SiO_2

result shows that the action of $ZnTiO_3$ in drilling fluid produced mud cake of ~1 mm thickness.

Table 4 shows the thickness of the mud cake produced by Cheraghian et al. (2018) for nanocomposite of clay and silica and silica nanoparticles alone. It is found that increase in nanoparticle produced mud cake of minimum thickness. The mud cake produced by silica nanoparticles alone is off high in thickness whereas for nanocomposite consisting of silica and clay, the mud cake thickness is low. This is due to the fact that the synthesized nanocomposite is smaller in size than the silica nanoparticle and the effective plugging can also be easily achieved. There is a considerable reduction in fluid loss by nanocomposite of silica and clay than WBM and silica-based mud. A low concentration of nanocomposite is sufficient to reduce the fluid loss. Table 5 presents the work done by various researchers on fluid loss with various nanoparticles.

4 Field Application

Field test was conducted in horizontal wells in Canada. The calcium-based nanoparticle emulsion is produced via water–oil micro emulsion approach. The calcium nanoparticle was selected because of its good compatibility with invert emulsion, low toxicity and is inexpensive. The field application of calcium-based 0.5 wt% nanoparticle in invert emulsion-based mud was presented by Borisov et al. (2015). Table 6 shows the comparison of various properties of calcium-based drilling fluid at field and lab scale.

Addition of 10 vol% of carrier emulsion fluid did not affect the basic properties of OBM drilling fluids but the average filtrate volume is reduced to 20–30% of control wells. The filtrate volume remains unchanged once an optimum concentration

Table 5 Reduction of filtration loss of drilling fluids by nanoparticles

S. No.	Base fluid	NPs	Modification in filtration property	Author
1	Water	ZnO/polymer nanocomposite	Under HPHT condition 1.0 g of ZnO nanoparticle reduced the filtrate loss	Aftab et al. (2016)
2	Oil	1. Iron 2. Calcium	LCM (graphite) was used in minimum concentration with minimum Fe and Ca nanoparticles. Iron nanoparticle showed better performance than Ca	Contreras et al. (2014)
3	Water	Carbon nanotubes	0.8 wt% of CNT reduced the filtration loss under HPHT	Halali et al. (2016)
4	Water	Cellulose nanoparticle	Reduced fluid loss at an optimized concentration of 0.5 wt%	Li et al. (2015)
5	Water	Graphene	Reduced filtrate loss up to 30% in 10 ppg WBF	Taha and Lee (2015)
6	Water	1. CuO 2. ZnO	Fluid loss and filtrate cake thickness reduced significantly under LPLT and HPHT condition, ZnO nanoparticle showed a better result than CuO	William et al. (2014)
7	Synthetic	SiO_2	A quantity of 40 wt% of silica nanoparticles was needed to reduce the filtrate loss at HTHP condition	Yusof and Hanafi (2015)

of calcium nanoparticles in the circulating mud is attained. Taha and Lee (2015) presented a field data using nanographene blended in a surfactant for extremely hard formation in Myanmar with temperature up to 176 °C (349 °F). It was found that drilling fluid performance is directly proportional to nanoparticle concentration, and once the nanoparticle concentration reduced 2% by volume, the rate of penetration also reduced. In the field trail when the graphene nanoparticle concentration was

Table 6 Comparison between carrier emulsion samples having 5 wt% calcium nanoparticles prepared on an industrial scale

Properties	Field scale	Lab scale
MW (kg/m^3)	1045 ± 5	1049 ± 3
ES (mV)	582 ± 57	780 ± 20
PV (cP)	12 ± 2	12 ± 2
YP (lb/100ft^2)	5 ± 2	5 ± 2
GS 10 s (lb/ft^2)	4 ± 0.5	4 ± 0.5
GS 10 min (lb/ft^2)	5.0 ± 0.5	6.0 ± 0.5
OWR	83/17	83/17
Solids (vol%)	8.0 ± 0.5	8.0 ± 0.5

kept between 2 and 3%, it improved the rate of penetration up to 125% and improved bits lifespan by 75%. The improvement in drilling performance and bits' lifespan had reduced operator's operational time and cost.

5 Recommendations and Challenges of Nanofluids

Though a lot of studies and positive results were available on the applicability of nanoparticles in drilling muds, application of nanoparticles in a field study has a serious of challenges and issues. Stability of nanoparticle dispersion in drilling fluid is a major problem. Even after performing high shearing with ultrasonic baths, magnetic stirrers or homogenizers nanoparticle try to re-agglomerate due to strong van der Waals forces. Though introduction of surfactant in a drilling fluid effectively disperse the nanoparticles, surfactants are very expensive and can alter the rheological properties of the mud. Another major issue associated with the nanoparticle is sedimentation and flocculation. If flocculation and sedimentation is not controlled in drilling muds, it leads to plugging in drilling lines, mud pumps which yield poor rheological performance and shale inhibition. As suggested in the literature, instead of single sphere molecule, metal oxide and polymer composite reduced the problem of flocculation and sedimentation in drilling mud, but much results are not available in the area.

6 Conclusion

The overall studies on the application of nanoparticles in the drilling fluids showed a greater improvement in rheological properties, thermal stability, and reduction in fluid loss and wellbore stability. Addition of nanoparticles to the drilling mud increased the viscosity, and the shear thinning behaviour of the drilling fluids was also maintained at HTHP condition. Though the positive effect of increasing the concentration of nanoparticles increased the viscosity, sometimes it leads to agglomeration which reduces the performance of drilling mud. Thus tuning the appropriate concentration of nanoparticles in a drilling fluid is an important step to remember. Further with the addition of nanoparticles, the nano-enhanced drilling mud exhibited continuous gel strength while maintaining the yield stress value. The enhancement in the drilling fluid properties by the addition of nanoparticles completely depends on the particle shape, size and concentration. The shale permeability of the formation can also be reduced by physical plugging of pores by nanoparticles. The filtrate cake which has been produced by the nanoparticles is of very minimum in thickness compared to conventional drilling mud. The API tests proved that nano-enhanced mud can reduce the filtrate volume up to 60%. Since nanoparticles are oxide in nature, addition of nanoparticles to the drilling mud increased the thermal conductivity, which allowed the mud to cool in a faster. Thus addition of nanoparticles to the drilling mud could be a better solution for drilling complex, depleted and deviated reservoir and HTHP environment.

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