Research Article

Application of nano water-based drilling fluid in improving hole cleaning

Mortadha T. Alsaba[1] · Mohammed F. Al Dushaishi[2] · Ahmed K. Abbas[3]

Received: 4 February 2020 / Accepted: 7 April 2020 / Published online: 15 April 2020

Abstract

This paper presents a laboratory evaluation to study the effect of adding different nanoparticles on the rheological properties of water-based drilling fluids. Four different nanoparticles including aluminum oxide (Al_2O_3), magnesium oxide (MgO), titanium dioxide (TiO_2), and copper oxide (CuO) were added to a 7% bentonite water-based mud at two different concentrations; 0.5% and 1.5% by Vol. The rheological properties including plastic viscosity (PV), yield point (YP), and gel strength, were evaluated using a standard viscometer to quantify the effect of nanoparticle addition by comparing it to the reference drilling fluid containing 7% bentonite. In addition, a parametric study was conducted to better understand the effect of the different parameters including rheological properties, hole size, flow rate, on hole cleaning efficiency. The results show that nanoparticles, in general, have a high potential in improving rheological properties when compared to the reference point. A favorable reduction in the PV up to 50% along with an increase of 231% and 95% in the YP and gels strength, respectively, were observed. The addition of nanoparticles has improved hole cleaning efficiency, when compared to the base case, for up to a maximum of 30% using 0.5% by Vol. of MgO nanoparticles. Also, an improvement by 67% in the hole cleaning was observed with 0.5% MgO for the largest cutting sizes when compared to 7% bentonite. In general, MgO showed the highest improvement in hole cleaning, while TiO_2 resulted in the lowest improvement. The parametric study revealed that rheological properties along with the cutting size have the highest effect on hole cleaning, while the effect of varying the flow rate was minimal when the rheological properties were high. Moreover, the effect of nanoparticles addition on hole cleaning was more pronounced for larger hole sizes with larger cutting sizes when compared to the base case containing 7% bentonite only, which demonstrate the feasibility of using nanoparticles to enhance the hole cleaning.

Keywords Nanoparticles · Nanofluid · Drilling fluid · Hole cleaning · Laboratory investigation

1 Introduction

One of the main functions of drilling fluids is carrying out drill cuttings from the bottom of the well and disposing them at the surface. Different terminologies such as hole cleaning efficiency and cutting transport efficiency are being used interchangeably to indicate whether the hole is being cleaned efficiently. Different parameters could affect the cutting transport efficiency including but not limited to the drilling fluid rheological properties, drilling fluid density, cutting size, cutting shape, cutting density, hole size, flow rate, pipe rotation, rate of penetration, etc.

Improper hole cleaning could lead to a series of unfavorable events such as mechanical sticking, increased equivalent circulation density (ECD), slow rate of penetration (ROP), increased torque and drag, which could result

---

✉ Mortadha T. Alsaba, m.alsaba@ack.edu.kw; Mohammed F. Al Dushaishi, m.aldushaishi@okstate.edu; Ahmed K. Abbas, akayr4@umsystem.edu | [1]Petroleum Engineering Department, Australian College of Kuwait, 13015 Safat, Kuwait. [2]Oklahoma State University, Stillwater, OK 74078, USA. [3]Iraqi Drilling Company, Al Borjsea, Basra 19312, Iraq.

SN Applied Sciences (2020) 2:905 | https://doi.org/10.1007/s42452-020-2723-2

in non-productive time (NPT). Therefore, special considerations for hole cleaning, are taken into account while drilling and during well planning.

Several researchers have studied the effect of improving the drilling fluid rheology utilizing different drilling fluid additives on enhancing hole cleaning [1–4]. The effect of adding nanoparticles (NPs) to drilling fluids to improve the rheological properties have been recently investigated [5–13]. A summary of the used nanoparticles along with the improved parameters is shown in Table 1.

In this work, a laboratory evaluation was undertaken to investigate the effect of adding different nanoparticles including aluminum oxide (Al_2O_3), magnesium oxide (MgO), titanium dioxide (TiO_2), and copper oxide (CuO), in enhancing rheological properties of water-based drilling fluids, and hence improving hole cleaning efficiency. Besides, a sensitivity analysis was carried out to study the effect of the different parameters affecting hole cleaning including; rheological properties, drilling fluid density, hole size, flow rate, cutting size, and cutting density.

2 Methodology

2.1 Fluid used

Eight different water-based drilling fluids containing different nanoparticles at two different concentrations were prepared as shown in Table 2. The evaluated NPs included copper oxide (CuO), titanium dioxide (TiO_2), magnesium oxide (MgO), and aluminum oxide (Al_2O_3). In addition, a water-based drilling fluid containing only 7% bentonite

Table 1 Summary of previously investigated nanoparticles

Improved parameters	Nanoparticle type	References
Filtration characteristics at high temperature	Iron oxide	[5]
Filtration characteristics Rheological properties	Copper oxide Zinc oxide	[6]
Lubricity of drilling fluids Rheological properties Filtration characteristics	Multiwall carbon nanotube (MWCNT) Silicon oxide	[7]
Rheological properties	Nano Bentonite Magnesium oxide Titanium oxide Graphene	[8]
Rheological properties Hole cleaning	Silicon oxide	[9]
Rheological properties for synthetic based drilling fluids Reducing electrical resistivity	Nano-clay	[10]
Rheological properties Thermal stability Filtration characteristics	Zinc titanate	[11]
Rheological properties Thermal and electrical conductivity Filtration characteristics	Titanium oxide	[12]
Rheological properties Hole cleaning	Titanium oxide Silicon oxide Aluminum oxide	[13]

Table 2 Composition of the used fluids

Fluid type	Bentonite (g)	Water (ml)	CuO (g)	TiO_2 (g)	MgO (g)	Al_2O_3 (g)
7% Bentonite	35	465	–	–	–	–
0.5% CuO	35	465	2.5	–	–	–
1.5% CuO	35	465	7.5	–	–	–
0.5% TiO_2	35	465	–	2.5	–	–
1.5% TiO_2	35	465	–	7.5	–	–
0.5% MgO	35	465	–	–	2.5	–
1.5% MgO	35	465	–	–	7.5	–
0.5% Al_2O_3	35	465	–	–	–	2.5
1.5% Al_2O_3	35	465	–	–	–	7.5

(without any weighting materials) to avoid the interference between the other additives and nanoparticles was prepared and used as a reference fluid, i.e. base case, for comparison purposes.

2.2 Laboratory evaluation

To study the effect of NPs addition on the rheological properties, a standard rotary viscometer was used to measure the viscous drag applied by the fluid at different rotational speeds, which would create a torque on the inner cylinder that will be measured as a deflection. The plastic viscosity (PV), which is defined as the resistance of the drilling fluid to flow, and yield point (YP), which indicates the ability of drilling fluid to lift cuttings, were calculated using Eqs. 1 and 2 below:

$$\mu_P = \theta_{600} - \theta_{300} \tag{1}$$

$$\tau_y = \theta_{300} - \mu_P \tag{2}$$

where μ_P is the plastic viscosity measured in centipoise (cP), θ_{600} and θ_{300}. are the dial reading at 600 and 300 revolutions per minute (RPM), respectively, and τ_y is the shear stress measure in lb/1 The gel strength after 10 s (GS10s), which is defined as the ability of the drilling fluid to suspend cuttings and weighing materials when circulation is stopped, was measured as per the API recommended practice [14].

2.3 Hole cleaning efficiency calculations

To evaluate the hole cleaning efficiency, Moore's correlation [15] was used to calculate the cutting slip velocity and then calculate the cutting transport ratio, since it is the most widely used correlation for vertical wells. To calculate the cutting's slip velocity ($\bar{v}_{sl}$), the apparent viscosity μ_a is calculated first using Eq. 3:

$$\mu_a = \frac{K}{144}\left(\frac{d_2 - d_1}{\bar{v}_{fl}}\right)^{1-n}\left(\frac{\left(2 + \frac{1}{n}\right)}{0.0208}\right)^n \tag{3}$$

where d_2 and d_1 are the open hole diameter and drill string outside diameter in incs, respectively. $\bar{v}_{fl}$ is the fluid annular velocity in ft/s, which can be calculated using Eq. 4:

$$\bar{v}_{fl} = \frac{q}{2.448(d_2^2 - d_1^2)} \tag{4}$$

where q is the flow rate in gal/min, the flow behavior index (n) and the fluid consistency index K are calculated using Eqs. 5 and 6:

$$n = 3.32\log\left(\frac{\theta_{600}}{\theta_{300}}\right) \tag{5}$$

$$K = \frac{(510)\theta_{300}}{511^n} \tag{6}$$

The Reynolds number is then calculated using Eq. 7:

$$N_{\mathrm{Re}} = \frac{928\rho_f v_{sl} d_s}{\mu_a} \tag{7}$$

where ρ_f is the drilling fluid density measured in lb/gal, and d_s is the cutting size in inches.

For fully laminar flow, i.e. $N_{Re} < 3.$, the slip velocity is calculated used Eq. 8:

$$\bar{v}_{sl} = 82.87\frac{d_s^2}{\mu_a}\left(\rho_s - \rho_f\right) \tag{8}$$

where ρ_s is the cutting density in lb/gal.

For an intermediate flow, i.e. $3 < N_{Re} < 300$, the slip velocity is calculated used Eq. 9:

$$\bar{v}_{sl} = \frac{2.9d_s\left(\rho_s - \rho_f\right)^{2/3}}{\left(\rho_f\mu_a\right)^{1/3}} \tag{9}$$

For fully turbulent flow, i.e. $N_{Re} > 300.$, the slip velocity is calculated used Eq. 10:

$$\bar{v}_{sl} = 1.54\sqrt{\frac{d_s\left(\rho_s - \rho_f\right)}{\rho_f}} \tag{10}$$

The hole cleaning efficiency in terms of the cutting transport ratio is then calculated using Eq. 11:

$$\textit{Cutting transport ratio} = \frac{\bar{v}_p}{\bar{v}_{fl}} \tag{11}$$

where $\bar{v}_p$ is the net particle velocity calculated as the difference between the fluid velocity ($\bar{v}_{fl}$) and the slip velocity ($\bar{v}_{sl}$).

3 Laboratory results

Table 3 shows a summary of the laboratory evaluation for the different nano-based drilling fluids as well as the reference point, which is the 7% bentonite sample.

Figure 1 shows the effect of varying the nanoparticles type and concentration on the plastic viscosity. It can be observed that all nanoparticles have resulted in a favorable reduction in the plastic viscosity up to 50% compared to the reference point (7% Bentonite) except for the

Table 3 Summary of the laboratory evaluation for the different nanopartcles

Blends #	θ_{600} RPM	θ_{300} RPM	Gel 10 s (lb/100 ft^2)	PV (cP)	YP (lb/100 ft^2)
7% Bentonite	27	23	21	4	19
0.5% CuO	39	37	33	2	35
1.5% CuO	41	39	37	2	37
0.5% TiO_2	44	37	32	7	30
1.5% TiO_2	40	34	35	6	28
0.5% MgO	69	66	35	3	63
1.5% MgO	66	64	34	2	62
0.5 Al_2O_3	46	44	41	2	42
1.5 Al_2O_3	47	45	39	2	43

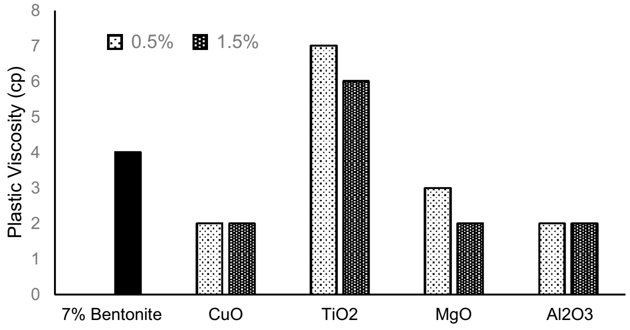


Fig. 1 Effect of nanoparticles type and concentration on the plastic viscosity

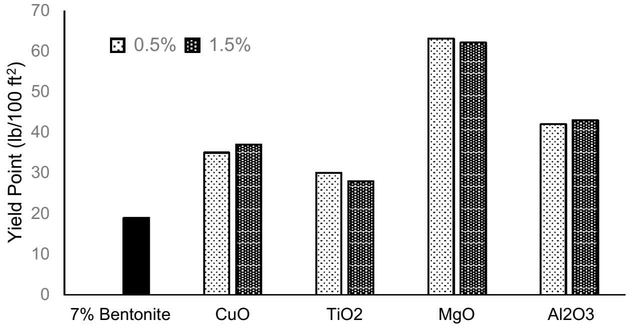


Fig. 2 Effect of nanoparticles type and concentration on the yield point

titanium oxide, where the plastic viscosity has increased by 50% and 75% at 0.5% and 1.5%, respectively.

Figure 2 shows the effect of varying the nanoparticles type and concentration on the yield point. It can be seen that the magnesium oxide nanoparticles outperformed the other nanoparticles, where the yield points have increased by approximately 231% at a low concentration of 0.5% compared to the reference point. When analyzing the effect of varying the concentration of nanoparticles, it is obvious that increasing the concentration has a negligible effect.

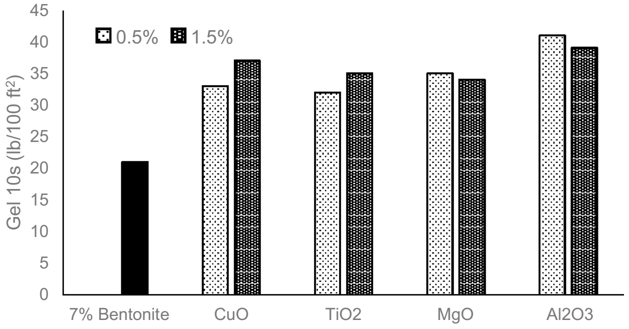


Fig. 3 Effect of nanoparticles type and concentration on the 10 s gel strength

Table 4 Used parameters for the sensitivity analysis

Sensitivity parameter	Base case	Range
θ_{600} and θ_{300}	7% Bentonite	Different nano-based drilling fluids
Flow rate, gal/min	200	50–500
Drilling fluid density, lb/gal	10	10–18
Particle diameter, inches	0.25	0.05–0.5
Particle density, lb/gal	23	19–26
Hole size, inches	34	8–34

The effect of nanoparticles on the 10 s gel strength can is shown in Fig. 3, the results show that all nanoparticles were efficient in improving favorably the gel strength. The increase in the gel strength ranged between 52% and 95% when compared to the reference point (7% Bentonite), where the aluminum oxide showed the best performance in improving the gel strength. Again, the performance of nanoparticles at low and high concentrations was close suggesting the negligible effect of the concentration on the performance.

4 Sensitivity analysis

In this section, a sensitivity analysis was conducted to investigate the effect of different parameters on the hole cleaning efficiency. The drill pipe size (d_1) was kept constant at 5″ for all calculations, while the hole cleaning efficiency was calculated for a wide range of hole sizes ranging between 8 and 34″. Table 4 below shows the parameters used in the sensitivity analysis as well as the range of values used.

4.1 Effect of rheological properties on hole cleaning

Figure 4 shows a graphical representation of the calculated values for hole cleaning efficiency using the measured rheological properties. The *x*-axis shows the calculated hole cleaning efficiency for different hole sizes (*y*-axis) using the different rheological properties for the different investigated fluids. It can be seen that the 7% bentonite resulted in the lowest hole cleaning compared to the other nano-based drilling fluids. Also, it is observed that the TiO_2 resulted in the lowest improvement in hole cleaning compared to the other nano-based fluids.

4.2 Effect of flow rate on hole cleaning

Figure 5 shows the effect of varying the flow rate (using the base case values for all other variables) on the hole cleaning efficiency. It can be seen that as the flow rate increases, the hole cleaning efficiency increases. In addition, it can be observed that for flow rates ranging between 200 and 500 gals/min, the hole cleaning efficiency decreases as the hole size increase until a point where the flow regime changes from fully turbulent (below 14″) to fully laminar flow (above 14″).

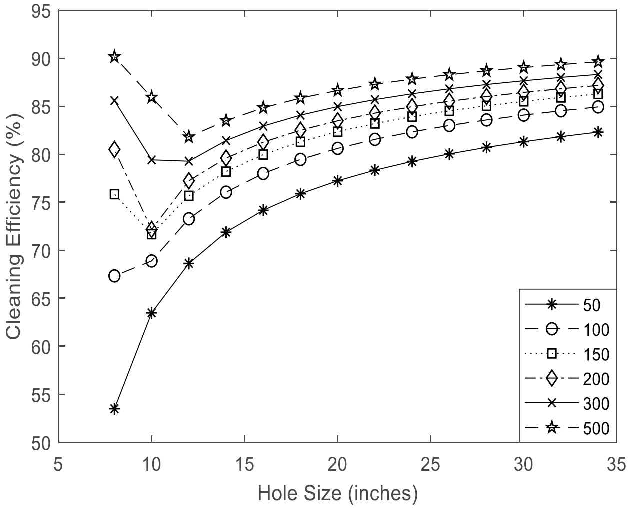


Fig. 5 Effect of flow rate on the hole cleaning efficiency

4.3 Effect of drilling fluid density on hole cleaning

Increasing the drilling fluid density increases the plastic viscosity of the fluid. Plastic viscosity is inversely proportional to the Reynolds number which ultimately affects hole cleaning efficiency. For simplicity, in this study, this effect was not accounted for. Figure 6 shows the hole cleaning efficiency for various fluid density using the base case input parameters. Higher fluid density showed better hole cleaning efficiency, where the highest efficiency was achieved with 18 lb/gal fluid density. The fluid density was increased in an increment of 1 lb/gal, as a result, a corresponding increase in efficiency of approximately 1% is observed for each 1 lb/gal increase.

4.4 Effect of cutting density on hole cleaning

Cutting density is another parameter that alters the drag force. Generally, denser particles reduce hole cleaning efficiency under the same flow rate as a result of

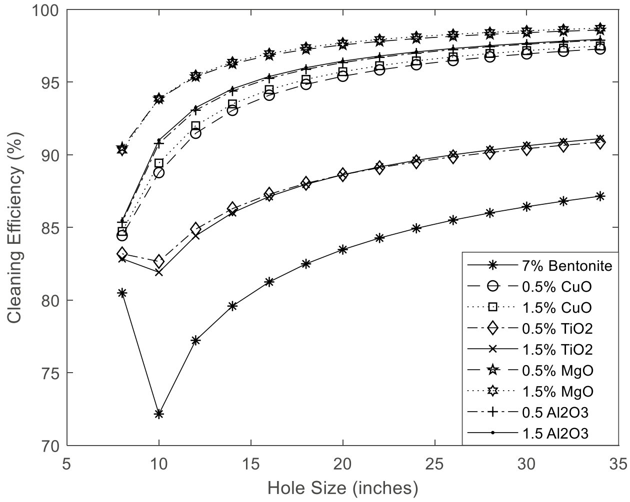


Fig. 4 Effect of nanoparticles type and concentration on the hole cleaning efficiency

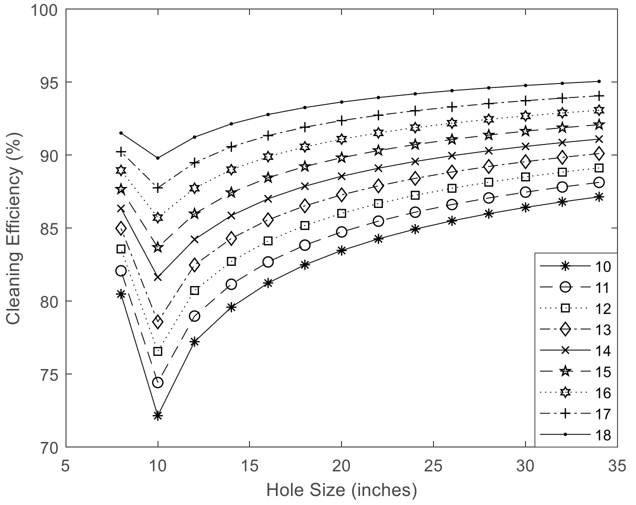


Fig. 6 Effect of fluid density on the hole cleaning efficiency

increasing the drag force. Figure 7 shows the hole cleaning efficiency, using the base case, for different cutting density. Cutting density is inversely proportional to hole cleaning efficiency, the increase in cutting density causes a decrease in cleaning efficiency. It is worthwhile mentioning that the flow regime also plays a significant role in cleaning efficiency. The sharp reduction in hole cleaning efficiency with 10″ hole size is due to the change of the flow regime from turbulent to laminar flow.

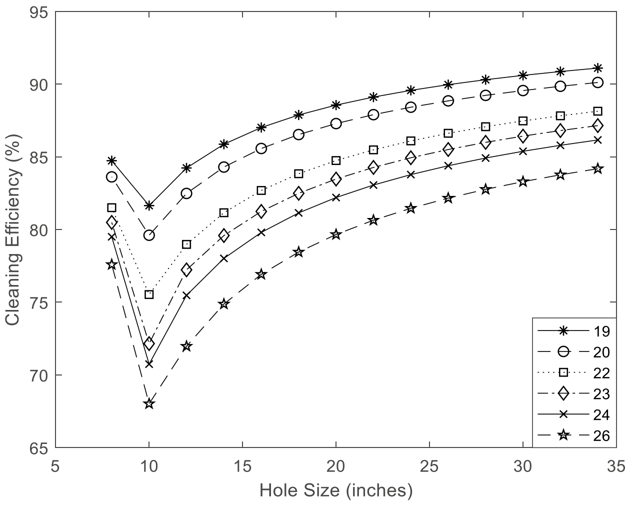


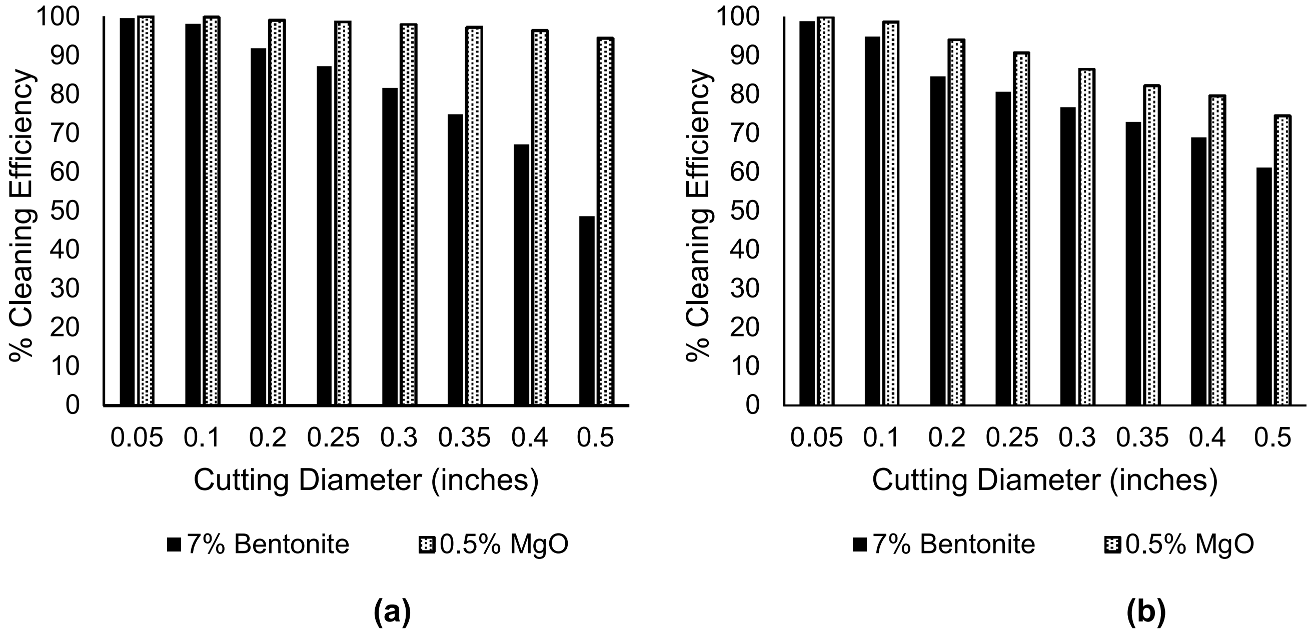
Fig. 7 Hole cleaning efficiency for varying cutting densities

4.5 Effect of cutting size on hole cleaning

Cutting size and shape greatly affect hole cleaning efficiency due to the drag force associated with the different cutting geometry. As the cutting size increases, the drag force increases which requires higher flow rates or better rheological properties to maintain efficient hole cleaning

Figure 8 below shows the hole cleaning efficiency for two different hole sizes, 34″ (Fig. 8a) and 8″ (Fig. 8b) while varying the cutting sizes and keeping all the parameters constant (base case) except for the rheological properties for the two different fluids (7% Bentonite and 0.5% MgO). In general, it can be seen that the highest efficiency is seen with small cutting sizes, and as the cutting size increases the cleaning efficiency decreases. It can also be observed that as long as the cutting size is small, the effect of hole size on the cleaning efficiency is negligible.

Figure 8 also highlight how nanoparticles can improve the hole cleaning efficiency especially for relatively larger cutting size (0.5 inches) when compared to a 7% Bentonite drilling fluid. It can be observed that the effect of adding nanoparticles on hole cleaning is more pronounced as the cutting size increases. Based on the results, it was found that nanoparticles can improve hole cleaning efficiency by 67%. In addition, it can be observed that the effect is significant for larger hole sizes (34″) compared to the smaller hole size (8″).



(a)

(b)

Fig. 8 Effect of nanoparticles on hole cleaning for a range of cutting sizes for **a** 34″ hole size, and **b** 8″ hole size

5 Conclusions

Laboratory evaluation to investigate the effect of different nanoparticles on the rheological properties and hole cleaning efficiency of water-based drilling fluids was conducted and the results were analyzed and presented in this paper. Four different nanoparticles including aluminum oxide, magnesium oxide, titanium dioxide, and copper oxide were added to a 7% bentonite water-based drilling fluid at two different concentrations; 0.5% and 1.5% by Vol. The laboratory results and the sensitivity analysis showed that:

- In general, it was observed that the addition of nanoparticles significantly affects the rheological properties of the drilling fluids depending on the nanoparticle's type and concentration.
- The investigated nanoparticles showed a reduction in plastic viscosity, up to 50%, when compared to the 7% Bentonite. However, Titanium oxide showed an increase in plastic viscosity.
- Magnesium oxide outperformed other nanoparticles in improving the yield point, while aluminum oxide outperformed other nanoparticles in improving the 10 s gel strength. Approximately 231% increase in yield point using magnesium oxide and 95% increase in the 10 s gel strength using aluminum oxide.
- Comparing the different drilling fluids used in this study, it was found that MgO showed the highest improvement in hole cleaning efficiency and the lowest efficiency was observed with TiO_2.
- The addition of nanoparticles improved the hole cleaning efficiency by 67% and this is believed to be due to the fact that the nanoparticles increased colloidal interactions of moving fluids by introducing a wide range of particle size distribution.
- In addition, the results showed that the effect of nanoparticles in hole cleaning efficiency is more pronounced for larger hole sizes (34″) when compared to the smaller hole size (8″).
- The promising results in the cuttings transport performance demonstrate the feasibility of using nanoparticles in drilling operations.

Compliance with ethical standards

Conflict of interest The authors confirm that there are no known conflicts of interest associated with this publication.

References

1. Okrajni S, Azar J (1986) The effects of mud rheology on annular hole cleaning in directional wells. SPE Drill Eng 1:297–308. https://doi.org/10.2118/14178-PA
2. Zamora M, Jefferson D, Powell J (1993) Hole-cleaning study of polymer-based drilling fluids. In: SPE annual technical conference and exhibition. Society of Petroleum Engineers. https://doi.org/10.2118/26329-MS
3. Saasen A (1998) Hole cleaning during deviated drilling—the effects of pump rate and rheology. In: European petroleum conference. Society of Petroleum Engineers. https://doi.org/10.2118/50582-MS
4. Saasen A, Løklingholm G (2002) The effect of drilling fluid rheological properties on hole cleaning. In: IADC/SPE drilling conference. Society of Petroleum Engineers. https://doi.org/10.2118/74558-MS
5. Barry M, Jung Y, Lee J-K, Phuoc T, Minking K (2015) Fluid filtration and rheological properties of nanoparticle additive and intercalated clay hybrid bentonite drilling fluids. J Pet Sci Eng 127:338–346. https://doi.org/10.1016/j.petrol.2015.01.012
6. Ponmani S, Nagarajan R, Sangwai J (2016) Effect of nanofluids of CuO and ZnO in polyethylene glycol and polyvinylpyrrolidone on the thermal, electrical, and filtration-loss properties of water-based drilling fluids. SPE J 21:405–415. https://doi.org/10.2118/178919-PA
7. Ismail A, Aftab A, Ibupoto Z, Zolkifile N (2016) The novel approach for the enhancement of rheological properties of water-based drilling fluids by using multi-walled carbon nanotube, nanosilica and glass beads. J Pet Sci Eng 139:264–275. https://doi.org/10.1016/j.petrol.2016.01.036
8. Al-Zubaidi N, Alwasiti A, Mahmood D (2017) A comparison of nano bentonite and some nano chemical additives to improve drilling fluid using local clay and commercial bentonites. Egypt J Pet 26:811–818. https://doi.org/10.1016/j.ejpe.2016.10.015
9. Gbadamosi A, Junin R, Oseh J, Agi A, Yekeen N, Abdalla Y, Ogiriki S, Yusuff A (2018) Improving hole cleaning efficiency using nanosilica in water-based drilling Mud. In: SPE Nigeria annual international conference and exhibition. Society of Petroleum Engineers. https://doi.org/10.2118/193401-MS
10. Pan D, Vipulanandan C, Amani N, Reddy S, Chockalingam C (2018) Effects of nanoclay on the rheological properties and resistivity of synthetic based drilling fluids under high temperature. In: Offshore technology conference. Society of Petroleum Engineers. https://doi.org/10.4043/28751-MS
11. Perween S, Beg M, Shankar R, Sharma S, Ranjan A (2018) Effect of zinc titanate nanoparticles on rheological and filtration properties of water based drilling fluids. J Pet Sci Eng 170:844–857. https://doi.org/10.1016/j.petrol.2018.07.006
12. Parizad A, Shahbazi K, Tanha A (2018) Enhancement of polymeric water-based drilling fluid properties using nanoparticles. J Pet Sci Eng 170:813–828. https://doi.org/10.1016/j.petrol.2018.06.081
13. Minakov A, Zhigarev V, Mikhienkova E, Neverov A, Buryukin F, Guzei D (2018) The effect of nanoparticles additives in the drilling fluid on pressure loss and cutting transport efficiency in the vertical boreholes. J Pet Sci Eng 171:1149–1158. https://doi.org/10.1016/j.petrol.2018.08.032
14. American Petroleum Institute (2019) Recommended practice for field testing water-based drilling fluids. API RP13B-1
15. Moore P (1974) Drilling practices manual. Petroleum Publishing Co, Tulsa