Effect of Nanoparticles in Drilling Fluids on the Transportation of Different Cutting Sizes in a Rotating Horizontal Pipe

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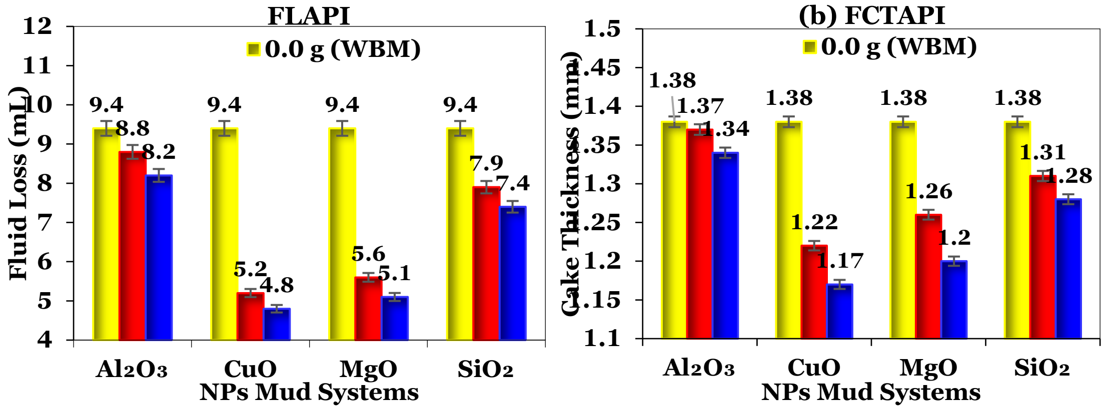

ABSTRACT: Cutting transport is difficult in horizontal borehole regions due to the limited axial velocity distribution. This causes transported cuttings to gravitate to the bottom, generating cutting beds and leading to drilling mishaps. Water-based mud (WBM) that includes nanoparticles (NPs) to determine the cutting transport ratio (CTR) performance using copper II oxide (CuO), aluminium oxide (Al_2O_3), magnesium oxide (MgO), and silicon dioxide (SiO_2) in a horizontal borehole needs further investigation. These NPs ability to transport 0.80–3.60 mm cutting sizes was tested using concentrations of 1.0 and 2.0 g circulated through a horizontal annulus at 3.5 m/s and 120 rpm. With 2.0 g, MgO lowered the viscosity by 60%, whereas SiO_2, CuO, and Al_2O_3 increased it by 49%, 10%, and 87%, respectively. CuO NP decreased the fluid loss (FLAPI) the best, followed by MgO, SiO_2, and Al_2O_3. The FLAPI of the WBM, which was 9.4 mL, dropped to 4.8, 5.1, 7.4, and 8.2 mL with CuO, MgO, SiO_2, and Al_2O_3 NPs, respectively. The CTR performance of the NPs increased with concentration and decreased with increasing cutting size. CuO, having less viscosity than Al_2O_3 and SiO_2, carried the most cutting at all concentrations and sizes. It increased the CTR by 28.8–31.1%, whereas Al_2O_3 and SiO_2 increased it by 22.7–26.7% and 16.7–22.2%, respectively. The lowest increase was 13.6–17.8% for MgO NP. This study demonstrates the favourable impact of NP concentrations on the performance of drilling fluids while presenting many choices for the selection of NPs.

Keywords: CTR; Cuttings diameter; Drill pipe rotation; Horizontal annulus; Nanoparticles; Water-based muds.

تأثير الجسيمات النانوية في سوائل الحفر على نقل أحجام الفتات المختلفة في أنبوب أفقي دوار

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الملخص: يُعد نقل الفتات في مناطق الآبار الأفقية تحديًا بسبب التوزيع المحدود للسرعة المحورية، مما يؤدي إلى تراكمها في القاع وتشكيل طبقات من الفتات، مما يسبب مشاكل في الحفر. يحتاج استخدام الطين المائي (WBM) مع الجسيمات النانوية (NPs) لتحسين نسبة نقل الفتات (CTR) في الآبار الأفقية إلى مزيد من البحث. تتناول هذه الدراسة استخدام جسيمات أكسيد النحاس (CuO) II، أكسيد الألومنيوم (Al_2O_3)، أكسيد المغنيسيوم (MgO)، وثاني أكسيد السيليكون (SiO_2) لنقل الفتات بحجم يتراوح بين 0.80–3.60 مم، وتم اختبارها بتراكيز 1.0 و 2.0 جم تم تداولها عبر حلقة أفقية بسرعة 3.5 م/ثانية و 120 دورة في الدقيقة. مع تركيز 2.0 جم، قلل MgO اللزوجة بنسبة 60٪، بينما زاد كل من SiO_2 و CuO و Al_2O_3 اللزوجة بنسبة 49٪ و 10٪ و 87٪ على التوالي. كان CuO الأكثر فعالية في تقليل فقدان السوائل (FLAPI)، يليه MgO و SiO_2 و Al_2O_3. تحديداً، انخفض FLAPI للطين المائي من 9.4 مل إلى 4.8 مل (CuO)، 5.1 مل (MgO)، 7.4 مل (SiO_2)، و 8.2 مل (Al_2O_3). تحسن أداء CTR مع زيادة تركيزات الجسيمات النانوية وانخفض مع زيادة حجم الفتات. كان CuO، الذي يمتلك لزوجة أقل من Al_2O_3 و SiO_2، الأكثر فعالية في نقل الفتات، حيث زاد CTR بنسبة 28.8–31.1٪، مقارنة بـ 22.7–26.7٪ لـ Al_2O_3، 16.7–22.2٪ لـ SiO_2، و 13.6–17.8٪ لـ MgO. تُبرز هذه الدراسة التأثيرات المفيدة لتركيزات الجسيمات النانوية على أداء سوائل الحفر وتوفر خيارات متعددة لاختيار الجسيمات النانوية المناسبة.

الكلمات المفتاحية: الشبكات الذكية؛ الطاقة المستدامة؛ الأمان؛ العصر الرقمي؛ البيانات الضخمة.

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NOMENCLATURE

Al_2O_3 NP	Aluminum oxide nanoparticle
API	American Petroleum Institute
CNCs	Cellulose nanocrystals
CNPs	Cellulose nanoparticles
CTR	Cuttings transport ratio
CuO NP	Copper II oxide nanoparticle
ECD	Equivalent circulating density
ERD	Extended-reach well drilling
FCT	Filter cake thickness
FL	Filtrate loss volume
FLAPI	API Fluid loss
HCl	Hydrochloric acid
MgO NP	Magnesium oxide nanoparticle
Na_2CO_3	Soda ash
NaOH	Caustic soda
NPs	Nanoparticles
OBM	Oil-based mud
PAC-R	Polyanionic cellulose reagent
ROP	Rate of penetration
SiO_2 NP	Silica nanoparticle
WBM	Water-based drilling mud
ZP	Zeta potential

1. Introduction

Progress in drilling horizontal wells has proven advantageous for the development of both conventional and unconventional oil and gas reserves (Mahmoud et al., 2020; Pang et al., 2019; Shu and Ma, 2016; Baris et al., 2007). Nonetheless, cutting transport-related wellbore instability and hole-cleaning issues persist in the well's horizontal portion. When drilling long, intricate horizontal wellbores, drilled cuttings have a tendency to separate from the circulating drilling fluid, move towards the bottom side of the wellbore, and build up. The excess buildup of drilled cuttings leads to the formation of cutting beds, which hinder cutting transfer (Wang and Sterling, 2007). When the cutting bed is made, it can cause major problems such as pipes getting stuck, formation damage, more bit wear, lost circulation, low rate of penetration (ROP), high equivalent circulating density (ECD), and high torque and drag (Oseh et al., 2020; Mahmoud et al., 2020; Ozbayoglu et al., 2008).

In addition, progressive wellbore obstruction may lead to challenges in well cementing, wireline logging, running casing, and pipe tripping (Abbas, 2021; Ismail et al., 2012). Inadequate cost of transport may lead to time-consuming and costly issues, even resulting in the abandonment of the well. The extreme horizontal well conditions pose risks and technological complexities for exploring and developing unconventional resources (Pang et al., 2019; Velden and Jawari, 2013).

Drilling operators and oil service firms have been using several methods to improve the efficiency of cutting transport. These methods involve reverse circulation, downhole equipment, gel sweeps, and water jetting (Ernesto et al., 2016; Pervez et al., 2012). However, the effectiveness of these techniques declines significantly as the hole angle widens and becomes more difficult. To improve drilling operations at high hole angles and horizontal angles, there is a need to explore more efficient strategies. This involves converting or substituting contaminated fluid with an alternative fluid system that is clay-free, salt-tolerant, or thermally stable (Hassiba and Amani, 2013).

During the cutting transport process, the main forces acting on a particle suspended in a moving fluid are the downward gravitational force, buoyancy force, lift force, and hydrodynamic drag force (Hyun et al., 2000). The annular space will be filled with stationary cutting beds when the resultant upward force is equal to or lower than the downward gravitational force, which causes drill cuttings to build up on the bottom of horizontal wells (Abbas et al., 2021; Hyun et al., 2020). Since the drilling fluid absorbs the cuttings, there is enough buoyancy to reduce the gravitational pull during cutting transport in vertical wells (Gbadamosi et al., 2018). In an inclined or horizontal well, cuttings travel in the circulating fluid against the flow of the fluid in turbulent conditions. The cuttings may be more easily brought up to the surface due to hydrodynamic drag and lift forces. The movement of mud around the cutting particles generates a hydrodynamic drag force parallel to the mud flow in inclined wells and a lift force perpendicular to the mud flow in horizontal wells (Hyun et al., 2000).

Previous research (Erge and van Oort, 2020; Boyou et al., 2019; Minakov et al., 2018; Ismail et al., 2012) has shown that the type of drilling fluid, its flow regime, the speed of annular mud, and its rheological properties can all have a big effect on the forces acting on drill cuttings. The mud's rheological attributes are crucial for the proper transport of drilled cuttings, according to field tests (Abbas et al., 2021; Oseh et al., 2020; Minakov et al., 2018; Gbadamosi et al., 2018). Drilling fluid must have the correct rheological properties to prevent cuttings from settling and falling back down at low shear rates. This is especially important when the fluid is moving in a wide annulus or when mud flow stops. At high shear rates, the rheological components of the fluid must exhibit shear-thinning behaviour to reduce pressure on surface equipment (Minakov et al., 2018).

According to Abbas (2021), drilling fluid velocity on the low side of the hole decreases with increasing horizontal planes, especially for high-viscosity fluid, lowering the efficiency of cutting transport (Abbas, 2021). Ozbayoglu et al. (2008) found that low-viscosity fluids are more effective at removing cuttings in horizontal wells, which supported this finding. The low-viscosity fluid allows turbulent flow conditions to be achieved at low flow rates. Turbulence increases the fluid velocity near the cutting bed particles, leading to enhanced cutting transport and removal. But Mahmoud et al. (2020) seem to have a different view. They reported that controlled viscous mud is needed to keep the wellbore from collapsing in horizontal wells, as long as there is turbulence flow and little pressure loss (Alsaba et al., 2020; Erge and van Oort, 2020).

According to these analyses, fluid rheology is critical for cutting transfer in both horizontal and inclined wells. Furthermore, a fluid's rheological characteristics might have a large beneficial influence on one aspect while having a detrimental effect on another. Therefore, it is necessary to strike a balance to increase cutting transfer, reduce pump pressure, prevent fluid or formation influxes, and prevent the formation being drilled from losing circulation (Al Kindi et al., 2017).

Cutting size, another cutting transport parameter influences cutting lifting. Larger cutting sizes tend to concentrate at the bottom of the annulus, increasing the risk of pipe jams. Smaller-diameter cuttings can easily be transported with a suitable flow rate (Katende et al., 2019). For years, the fluid performance of conveying various cutting sizes has been disputed, and no clear, generally recognized report exists. While Boyou et al. (2019) concluded that smaller cuttings were easily removed compared to larger cuttings at all hole angles, a recent study by Blkoor et al. (2023) found that larger cuttings are easier to remove with adequate flowrate at horizontal wells. Furthermore, Oseh et al. (2020) discovered that larger-sized cuttings in a horizontal annulus are easier to clean at high annular velocities than smaller-sized cuttings. However, at all hole angles, smaller cuttings were removed using low annular velocities (Oseh et al., 2020).

Pipe rotation is another positive wellbore-influencing parameter for cutting transport. The cutting transport efficiency is greatly enhanced when the drill pipe is rotated, according to many studies (Abbas, 2021; Oseh et al., 2020; Boyou et al., 2019; Katende et al., 2019). This is because the drill pipe's orbital motion disturbs an already established cutting bed. According to Erge and van Oort (2020), drill pipe rotation improves cutting transport by minimizing pressure loss and increasing the effective flow area. This, in turn, reduces the existing cutting bed (Abdo et al., 2017).

Today, most drilling projects employ water-based muds (WBMs) because they are cheaper, greener, and easier to prepare than oil-based muds (OBMs). For shallow-formation drilling, WBMs are recommended. Other factors that limit OBM include cost, environmental restrictions, and regulations (Adil et al., 2024). However, WBMs often formulated with bentonite clays and polymers degrade at temperatures exceeding 200°C (Minakov et al., 2022). Bentonite particles also make thicker filter cakes because more bentonite is added to change the rheology and control fluid loss. This has led to stuck-pipe incidents and increased drilling costs (Salam et al., 2022). As a result, the arrival of nanoparticles (NPs) was seen as a possible way to improve the WBM and get around its problems.

These recent studies show that NPs can fix some wellbore issues and make the WBMs better (Blkoor et al., 2023; Adil et al., 2024; Minakov et al., 2022; Medhi et al., 2020; Ghasemi et al., 2018). A lot of research has been performed on the benefits of NPs-based additives, like how they can make materials more stable at high temperatures, hinder clay from swelling, prevent fluid loss, keep wellbore stable, and make materials flow better (Yahya et al., 2023; Blkoor et al., 2023; Alsaba et al., 2020; Ernesto et al., 2016).

Various NPs assessed so far have the rheological qualities needed for cutting transport and hole-cleaning activities in WBMs. These studies have shown that the rheological features of NPs positively affect cutting transport (Alsaba et al., 2020; Minakov et al., 2018; Elochukwu et al., 2017). Recent studies using NP-based drilling muds containing nano-silica (SiO_2), aluminium oxide (Al_2O_3), magnesium oxide (MgO), and copper II oxide (CuO) found that the carrying capacity of the mud in concentric annuli using low and medium annular fluid velocity increased with increasing rheological properties (Minakov et al., 2022; Boyou et al., 2019).

In addition, Abbas (2021) used cellulose nanofluids ranging from 0.1 to 1.5 wt% for horizontal wellbore operations. The research showed that using cellulose nanocrystals (CNCs) and cellulose nanoparticles (CNPs) made it easier to remove drilled cuttings from WBM by 13–22% and 16–24%, respectively. The selection of a high-functional material with enhanced rheological properties, like NP-based additives, will improve cutting transport efficiency and drilling performance in WBM operations.

One of the most crucial functions provided by drilling fluid, according to the research mentioned, is to carry cuttings from the drill bit to the surface via the annulus. Predicting how well drilling fluid will lift cuttings out of the annulus to the surface is a challenging issue since there are so many variables to consider. It is quite astounding how NPs recently introduced into drilling fluid to tailor its characteristics have improved the drilling fluid's performance. There has not been much study on the cutting transport performance of drilling fluid with NPs. To further progress the use of NPs for drilling fluids, it is important to understand the effects and processes responsible for their improvement in the cutting transport process.

So, this study examined the rheological properties and fluid loss control parameters of different WBMs with four different NPs: SiO_2, Al_2O_3, MgO, and CuO NPs. It then compared how well they transported drilled cuttings through a 90° annular pipe in a specially made field-oriented cutting rig simulator. An understanding of these NPs under the horizontal annulus is essential for directional and extended-reach well (ERW) drilling for enhanced drilling operations.

2. METHODOLOGY

2.1. Acquired study materials

Table 1 provides the properties of the commonly used NP powders according to the suppliers' specifications. Other chemicals used to formulate conventional WBM are as follows: A retail chemical outlet, R&M Malaysia, supplied caustic soda (NaOH) pellets, barite, and bentonite. Sigma-Aldrich, Selangor, Malaysia supplied xanthan gum (XG), polyanionic cellulose (PAC-R), sodium carbonate (Na_2CO_3), and all the NP additives.

Table 1. Properties of NP additives.

Materials	Diameter (nm)	Density (g/cm³)	Surface area (m²/g)
SiO_2 NP	12	4.21	175–225
MgO NP	<50	3.56	250–300
Al_2O_3 NP	13	3.96	85–115
CuO NP	<50	6.29	29–45

2.2. Dispersion of NPs and zeta potential test

The selected NPs were fully dispersed using an ultrasonic pulse of 20.1 ± 1.8 kHz and 800 W power to improve the surface chemistry and fluid system dispersion stability. Following the ultrasonication procedure, zeta potential (ZP) measurements were utilized to confirm the NPs' electrical stability at room temperature. Malvern ZetaSizer (version 7.11, Malvern Instruments, UK) was used to assess the ZP of the NPs in water at different pH levels using HCl and NaOH titrations at room temperature.

2.3. Preparation of NP-based drilling muds

Table 2 shows the formulation procedures for the different drilling solutions based on a 350-mL recommended standard, according to previous research by Boyou et al. (2019).
Previous studies have shown that the concentration of NPs in drilling fluid systems can alter their rheological properties, either improving or worsening the drilling solution's rheological performance (Blkoor et al., 2023; Adil et al., 2024; Minakov et al., 2022; Medhi et al., 2020; Boyou et al., 2019). In this study, the base drilling mud (WBM = 0.0 g) was prepared and measured before NPs at 1.0 and 2.0 g mass concentrations were added to it. Using the Herschel-Bulkley rheological model, the drilling fluids were characterized. The drilling muds were stirred for 90 minutes using a high-rotational speed mud homogenizer at 1100 rpm. All the tests were conducted in the drilling technology laboratory in the Department of Petroleum Engineering at Universiti Teknologi Malaysia.

Table 2. Composition of drilling muds.

Additives	0.0 g	1.0 g	2.0 g
Tap water (mL)	210.05	209.49	209.2
Bentonite (g)	20.0	20.0	20.0
NaOH (g)	0.15	0.15	0.15
Na_2CO_3 (g)	0.15	0.15	0.15
XG (g)	0.65	0.65	0.65
PAC-R (g)	0.45	0.45	0.45
Barite (g)	118.55	117.93	117.4
*NPs (g)	0.00	1.0	2.0

*NPs refers to Al_2O_3, SiO_2, MgO, and CuO

2.4. Rheological properties measurements

To determine the rheological properties of the WBM with the concentrations of NPs (1.0 and 2.0 g), a Fann viscometer model 35A was used. At 25° C, the pH and mud density were measured using a pH meter and a mud balance, respectively. In this experiment, the drilling fluids were subjected to six different shear rates, ranging from 3 to 600 rpm. Equations (1) – (5) show how the shear stress was used to find the viscosities (AV and PV), yield point (YP), and gel strength (10-s GS and 10-min GS).

$$AV\ (cP) = \frac{\theta_{600}}{2} \quad (1)$$

$$PV\ (cP) = \theta_{600} - \theta_{300} \quad (2)$$

$$YP\ \left(\frac{lb}{100ft^2}\right) = \theta_{300} - PV \quad (3)$$

$$GS\ at\ 10\ s\ \left(\frac{lb}{100ft^2}\right) = \theta_3\ after\ 10\ s \quad (4)$$

$$GS\ at\ 10\ m\ \left(\frac{lb}{100ft^2}\right) = \theta_3\ after\ 10\ min \quad (5)$$

Thereafter, the Herschel-Bulkley rheological model was adopted to predict the effective viscosity and shear stress of the NPs at different shear rates. These rheological properties were measured using a Rheo3000 RST Brookfield Ametek rheometer. Each of the drilling fluids was measured for 5 minutes at 25° causing 11 different shear rates ranging from 5 to 1000 s^{-1}. The mud samples were measured three times to ensure reproducibility, and the mean data were calculated. This model can be represented by Equation (6) (Magnon and Cayeux, 2021).

$$\tau = \tau_{oHB} + K_{HB}(\gamma)^{n_{HB}} \quad (6)$$

$\tau_o \geq 0$, $0 < n < 1$, and $k > 0$

where τ_{oHB} (Pa) = Herschel-Bulkley yield stress, τ (Pa) = shear stress (Pa), and γ (s^{-1}) =

shear 2rate. In addition, K_{HB} (Pa.sn) = Herschel-Bulkley consistency coefficient, n_{HB} (dimensionless) = Herschel-Bulkley flow behaviour exponent.

2.5. Determination of API filtration properties

The American Petroleum Institute (API) standards recommend the API filter press 300 series as an efficient instrument to determine the filtration properties at API conditions. This equipment was used to measure the fluid loss volume (FLAPI) of the NPs at 100 psi differential pressure at room-temperature measurement. The FLAPI was recorded after 30 minutes of filtration. Once the test was complete, the fresh filter cakes formed during filtration were carefully removed from the apparatus. The filter cake is a crucial component of drilling fluid and it is used to stabilize porous and permeable formations (Aird, 2019). The drilling fluid-formed filter cake is a thin layer that is placed on the resulting formation wall, which is porous and permeable. To avoid damaging the formation or impaired permeability, the filter cake typically covers the wall of the borehole and inhibits the flow of drilling fluid into the formation (Aird, 2019). The thickness of the filter cake (FCTAPI) was measured immediately using a vernier calliper. There were three measurements for FLAPI and FCTAPI conducted on the drilling slurries, and the average values of the measurements were given. This was performed to ensure that accurate results were obtained.

2.6. Preparation of sandstone cuttings

The cutting transport performance of the NP-based drilling muds under different wellbore conditions was determined using a specifically constructed simplified field-oriented rig simulator, as illustrated in Figure 1. The test cuttings were sandstone particles of varying sizes. The samples were prepared in accordance with the American Society for Testing and Materials (ASTM) standard (2006). After cleaning and drying in an oven at 80 °C for 18 hours, the cuttings were put into a sieve shaker and separated into three groups of acceptable sizes, as indicated in Table 3. These cutting diameter ranges are chosen to simulate genuine field-drilled cuttings produced by the drill bit (Blkoor et al., 2023). For the purpose of establishing a clear distinction between the various sizes of the cuttings, a constant difference in cutting diameter of 1.0 mm was maintained throughout using the three sorted cutting sizes.

Table 3. Prepared sandstone cutting diameters.

Size	Density (g/cm^3)	Diameter (mm)
Small	2.61	0.80 – 1.60
Medium	2.61	1.62 – 2.78
Large	2.61	2.80 – 3.60

2.7. Cuttings lifting experiments using NPs

To simulate a horizontal drilling wellbore, a variety of prepared muds were used in the cutting transport using a field-customized rig simulator (Figure 1).

From the beginning, a conventional WBM was developed. The concentrations of 1.0 and 2.0 g of Al_2O_3, SiO_2, MgO, and CuO NPs were then compared. To measure the annulus velocity, a flow velocity sensor was attached to the annular area and the velocity was adjusted to 3.5 m/s, which corresponds to a field pump output of 689 ft/min (Boyou et al., 2019). A 10-hp hydraulic pump was used to circulate the different drilling muds throughout the annular flow zone, as shown in Figure 1.

The test annular area was concentric, with 0% eccentricity relative to the wellbore. The annular area acrylic tubing was 16 feet long (4.9 m). At 120 rpm, the annular gap mimics a cased hole with 2.4 in. (0.061 m) of ID acrylic pipe and 1.2 in. (0.031 m) of OD revolving inner drill pipe. WBM without NPs was first assessed, and subsequently, NP-based drilling fluids with concentrations of 1.0 and 2.0 g were tested. Each of the prepared drilling muds was stored in a mud mixer linked to the rig simulator, which contains 42 gallons (160 litres). Each drilling mud was multiplied by 476 to achieve an equal density of 11 ppg (1.32 g/cm^3). Before using the drilling fluids, the muds were thoroughly mixed in a mud tank for 5 hours. The cuttings inlet valve was shut before the experiment after selecting the needed hole angle and cutting diameter.

For each experiment, 180 g of varied-size sandstones were injected into the annulus to convey sandstone cuttings to the surface. The prepared drilling mud was pumped from the mud tank using a hydraulic pump, and it was circulated for 5 minutes without cuttings to allow the flow to stabilize. Thereafter, the cuttings were injected into the flow loop through the cutting's injection unit, and the cutting control valve was opened. For eight minutes, the drilling mud was allowed to circulate with the cuttings. Thereafter, the circulation was stopped by shutting off the mud pump. The trapped cuttings were retrieved from the mud using a 0.50 mm wire mesh cutting sieve after eight minutes of conveying the drilled cuttings and four minutes of removing the remaining cuttings.

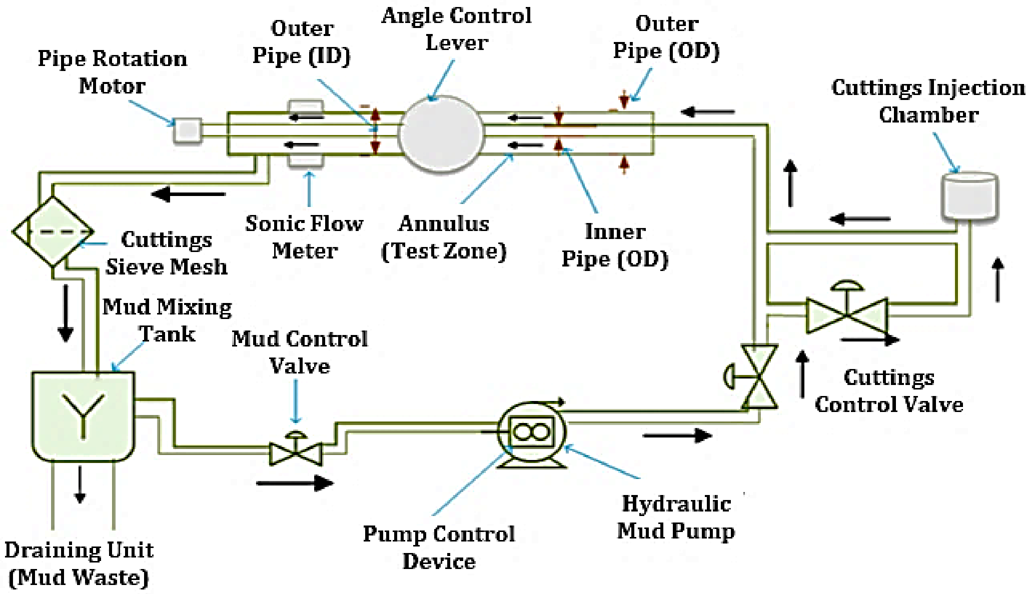

Figure 1. A simplified customized cuttings rig simulator showing the test annulus at a horizontal hole angle.

$$CTR\ (\%) = \frac{M_x}{M_i} \times 100 \quad (7)$$

where Mx (g) is the weight of lifted cuttings to the surface and Mi (g) is the weight of initially injected cuttings into the wellbore. If CTR = 1.0, then the cuttings are being carried at the same rate as the circulating mud, and the well's cleaning-out performance is optimal. If CTR = 0, then the cuttings will not be removed at all. If CTR is >0, but<1.0, it signifies that the cuttings are not moving at the same velocity as the circulating mud. This implies that the drilled borehole is not operating at peak efficiency in transporting cuttings to the surface (Minakov et al., 2018).

3. RESULTS AND DISCUSSIONS

3.1. ZP Magnitudes of NPs

The ZP is an important indicator of the stability of colloidal dispersion. The magnitudes of the ZP of the NPs are shown in Table 4.

Table 4. Average maximum ZP of NPs at 25° C.

	CuO	SiO_2	MgO	Al_2O_3
Test pH	4.8	11	3.5	4.3
ZP (mV)	+48.9	−53.1	+41.8	+43.7

Particles may agglomerate rapidly when the ZP value falls between the range of -10 and +10 mV unless they have steric protection (Mahmoud et al., 2017). According to Elochukwu et al. (2017), stable colloidal suspension systems have ZP magnitudes that are either more than +30 mV or less than -30 mV. According to Table 4, the ZP magnitudes indicate that the NPs are very stable colloids. The NPs created a stable suspension on water, which is beneficial for the long-term stability of the drilling fluid system (Blkoor et al., 2023). Except for SiO_2 NP, all of the NPs had positive charges greater than +30 mV, while SiO_2 NP has a high ZP magnitude of -53.1 mV, which is less negative than -30 mV. These results point to a useful property for limiting water loss from drilling slurry, improving fluid flow, and removing cutting (Elochukwu et al., 2017).

3.2. Rheological properties of NPs

The apparent viscosity and shear-stress curves of NP-based drilling muds predicted by the Herschel-Bulkley regression model are shown in Figure 2. Figure 2 reveals that when shear rates increased, the apparent viscosity of all the drilling mud formulations exhibited a shear-thinning tendency. The high apparent viscosity will aid in suspending drilled cuttings and keep the weighting material, such as barite, from settling in the event that the shear rate drops to zero during a drilling stoppage (Boyou et al., 2019). With higher shear rates, the effective viscosity decreases, resulting in reduced resistance for the injected drilling fluid downhole (Figures 2a and b). Drilling fluids with this exceptional quality are thus frequently needed in drilling operations to address different operational problems associated with horizontal drilling operations.

Due to the strong water absorption and swelling capacity of bentonite platelets, the WBM exhibits an effective viscosity of 0.166 Pa. s at a 1000 s^{-1} shear rate (Alsaba et al., 2020; Akhtar et al., 2013). The viscosity of the NPs at 1.0 and 2.0 g concentrations increases with increasing concentrations above the base mud. However, the viscosity of the MgO NP-based sample was lower than that of the base mud (Figure 2). At 1.0 and 2.0 g concentrations, Al_2O_3 NP has a viscosity that is 77% and 87% greater than WBM, respectively. When Al_2O_3 NP was compared with other NPs, it had the greatest viscosity impact on the base mud system (Figure 2).

At 2.0 g, SiO_2 NPs and CuO NPs increased the viscosity of the WBM by 49% and 10%, respectively (Figure 2b). Both 1.0 and 2.0 g of MgO NP lowered the apparent viscosity of the WBM by 53.4% and 60%, respectively, at a shear rate of 1000 s^{-1} (Figure 2). Figures 2c and d show the shear stress curves of WBM and WBM with the selected NPs. At 1.0 and 2.0 g concentrations, all the fluid systems exhibited increasing shear stress that increased with increasing shear rate. The rheological curve of the WBM shows a shear-thinning, non-Newtonian fluid tendency. The addition of the NPs resulted in an upward shift in the shear stress of the drilling fluids at all shear rates.

Overall, the 2.0 g concentration of NPs (Figure 2b) increased more than the 1.0 g concentration (Figure 2a). MgO NPs in the base mud reduced the shear stress, but other WBMs containing NPs enhanced it. The shear stress of the WBM increased by 22%, 16%, and 11% when 2.0 g of Al_2O_3, SiO_2, and CuO NPs were added at a shear rate of 1000 s^{-1}. On the other hand, MgO NPs lowered the shear stress by 5%.

Table 5 displays the results of the mud properties measured at 25° C with 1.0 and 2.0 g of the NPs. With the exception of the MgO NP, the base mud system's mud properties were seen to be enhanced with an increasing mass concentration of the NPs. At both concentrations, Al_2O_3 has a higher enhancement capacity than other NPs. As a result, with 1.0 g of Al_2O_3, the AV increased by 50%, PV by 33.3%, and YP by 25%. A further 32.1% rise in AV, 43.8% in PV, and 16.7% in YP was observed with SiO_2 NP. CuO improved the rheology by 21.4% for AV, 25% for PV, and 16.7% for YP. MgO, on the other hand, decreased these properties by 7.14% for AV, 6.25% for PV, and 8.33% for YP at a 1.0 g concentration. With a higher concentration of 2.0 g, the rheological characteristics of the base mud increased, except for the MgO, which decreased the drilling solution by 18.9% for AV, 14.3% for PV, and 8.33% for YP. This is due to a repulsive force between MgO and water molecules that causes the rheological properties to decrease as concentration increases (Falih et al., 2018). However, with 2.0 g CuO, the base mud's AV, PV, and YP increased by 35.7%, 43.8%, and 25%, respectively. In a similar pattern but with higher enhancement, the SiO_2 recorded a 53.6%, 68.8%, and 33.3% enhancement in AV, PV, and YP, respectively. These values improved significantly over the base mud with Al_2O_3. The AV, PV, and YP all increased by 71.4%, 87.5%, and 50%, respectively.

Al_2O_3 NP and bentonite particles enhanced the water's frictional force, leading to a thicker solution, according to recent research (Medhi et al., 2020). In the same way, SiO_2 and CuO NPs that contain more solids induce increased colloidal interactions between the particles, which causes the drilling fluid to become more viscous (Minakov et al., 2018). It was also found by Medhi et al. (2020) that increasing the hydrodynamic interaction between XG molecules and CuO NP makes water solutions thicker. The NPs' rheological behaviour in the WBM system showed good rheological data for improved drilling efficiency (Alsaba et al., 2020). This will help improve cutting transport, increase drilling efficiency, and avoid major drilling problems related to cutting transport and hole cleaning.

Table 5 further demonstrates that, compared with the base mud, the GS values of the NPs are higher. MgO exhibited higher GS values at both concentrations than the base mud. An increase in GS may be seen in NP mud systems due to their increased electrostatic potential and higher solid content (Boyou et al., 2019). As the concentration of solids increases, the distance between drilling mud particles becomes smaller. This resulted in gelling and increased internal friction, which reduced particle mobility (Alsaba et al., 2020). To be effective, drilling mud must develop gel properties over time. At 10 and 10 minutes, the drilling fluid starts to gel and shows minor changes.

According to Elochukwu et al. (2017), the mud system gels are ideal for drilling since they are flat, non-progressive, and weak. These authors highlighted that breaking this gel and starting the flow of drilling fluid after a lengthy period would not require much pressure, namely shear force. Bayou et al. (2019) found that NP flat gels developed between 10-s and 10-min are appropriate for drilling operations. Additionally, the gels indicated that the drilling fluids can slowly recover with shearing time and not immediately return to a gel state once the applied shear force is withdrawn. This action, due to the proper suspension of barite and rock particles, will prevent sagging problems (Elochukwu et al., 2017).

The base mud's pH and density at 25° C with both 1.0 and 2.0 g concentrations of NPs are shown in Table 5. After adding NPs to the drilling fluid systems, neither the density nor the pH changed much. Among all the mud systems, CuO had the greatest density and pH. For drilling purposes, these density and pH measurements can be used. In general, the enhancement capacity of the base mud occurs in the following order: Al_2O_3, SiO_2, CuO, and MgO.

There is a direct correlation between the concentration of NPs in the mud and the rheological characteristics of the base drilling fluid. The rheological properties of the chosen NPs are affected by how they interact with the base mud system, especially with the XG polymer and bentonite. The NPs interact with other base mud additives more strongly because of their vast surface area and small diameter. The NPs' internal friction and colloidal activities were both enhanced by this interaction, leading to an improvement in the overall mud characteristics (Medhi et al., 2020).

Table 5. Mud characteristics of WBM with NPs measured at 25° C.

	WBM	1.0 g concentration of NPs				2.0 g concentration of NPs			
		Al_2O_3	MgO	SiO_2	CuO	Al_2O_3	MgO	SiO_2	CuO
AV (cP)	28	39	26	37	34	48	24	43	38
PV (cP)	16	24	15	23	20	30	13	27	23
YP (lb/100ft^2)	24	30	22	28	28	36	22	32	30
10-s GS (lb/100ft^2)	7	13	9	11	10	16	11	14	13
10-min GS (lb/100ft^2)	11	17	14	6	15	20	15	19	18
Density	9.89	9.89	9.90	9.91	9.92	9.90	9.91	9.91	9.92
pH	9.64	9.68	9.74	9.66	9.84	9.70	9.75	9.68	9.87

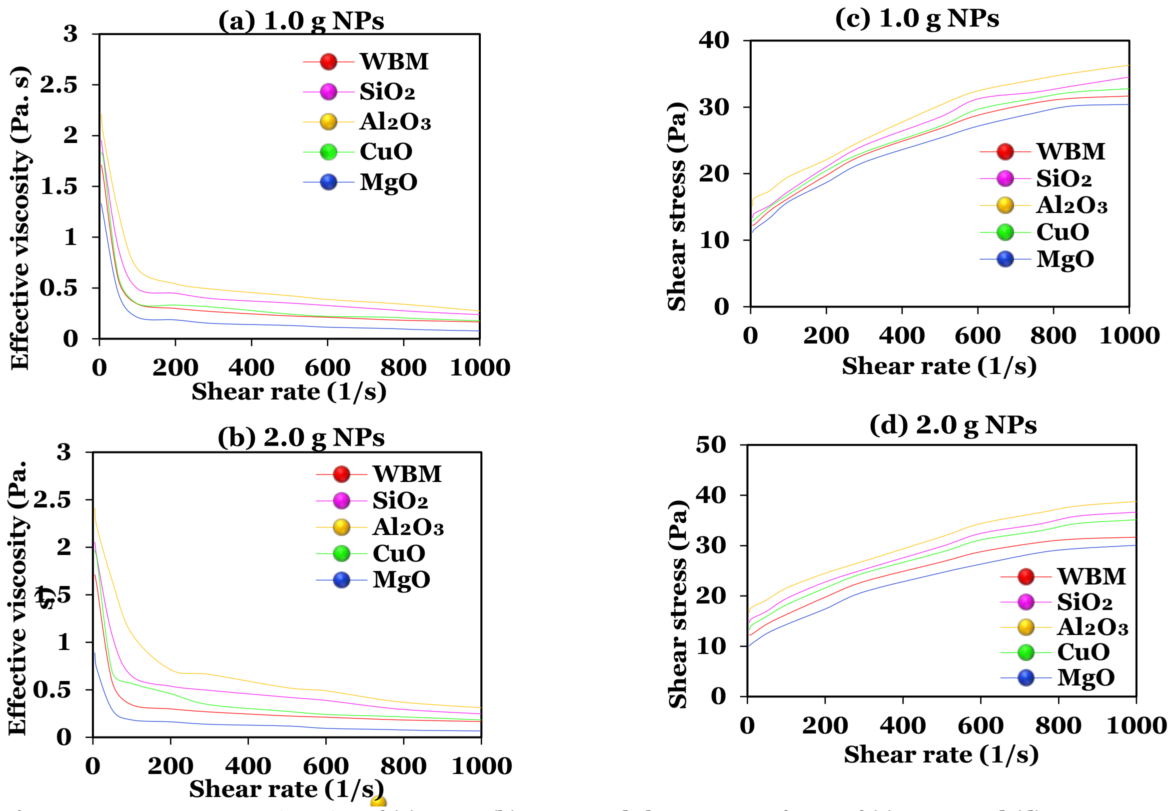

Figure 2. NPs apparent viscosity of (a) 1.0 g, (b) 2.0 g, and shear stress of NPs of (c) 1.0 g, and (d) 2.0 g.

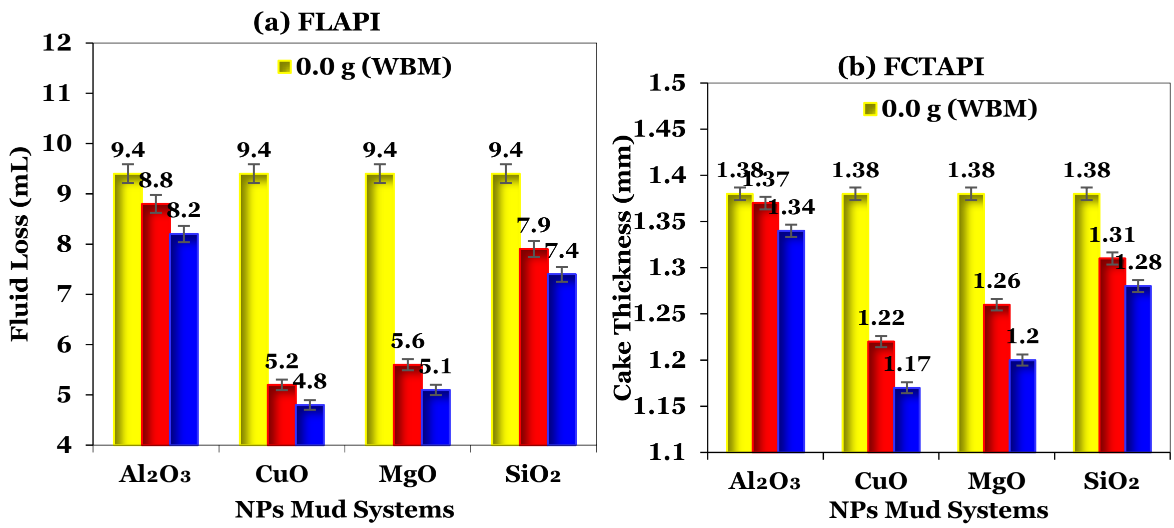

Figure 3. Filtration data of WBM with different concentrations of NPs: (a) FLAPI and (b) FCTAPI.

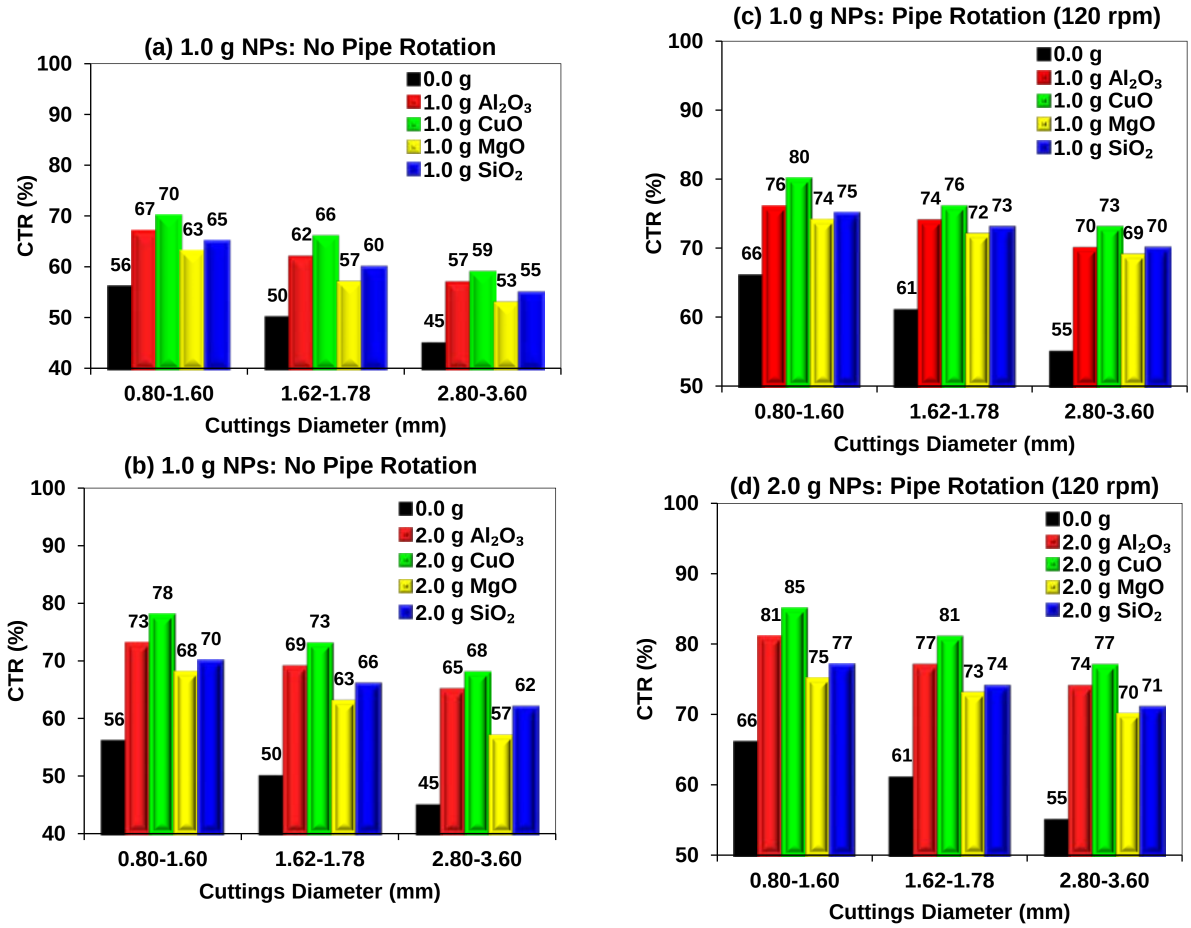

Figure 4. Effect of NPs on the CTR of WBM with (a) non-rotating drill pipe and (b) rotating drill pipe.

3.3. NPs effect on filtration properties

Figure 3b shows that as the concentration of NPs rises, the FCTAPI levels drop. All the mud systems show thin cakes (less than 1.5 mm) and only minor differences in the deposited filter cakes. Filter cake provides a physical barrier to prevent further fluid penetration and loss of drilling fluid, including the loss of produced fluids, into a permeable formation. The investigation showed that a filter cake with the characteristics of being thin, robust, flexible, and low-permeable, suitable for drilling operations, was created. The filter cake that was created may separate the wellbore fluids from the pore fluids at the wellbore wall. This is crucial for maintaining wellbore stability and avoiding differential sticking (Mahmoud et al., 2020).

3.4. CTR performance of WBM with NPs

Figure 4 shows the CTR performance of different NP concentrations without and with pipe rotation at a horizontal annulus (90°) using different cutting diameters. As the cutting size increased, the NPs' CTR decreased.

In terms of the effect of NP concentration, it increases with increasing concentration, and it was found that the higher concentration of 2.0 g exhibited superior improvement over the 1.0 g concentration. The CTRs of WBM, Al_2O_3, CuO, MgO, and SiO_2 NPs are 56%, 67%, 70%, 63%, and 65%, in that order, at 1.0 g when the pipe is not rotated and the cutting size is between 0.80 mm and 1.60 mm. As the concentration doubled (i.e., with 2.0 g), the CTR increased to 73% (Al_2O_3), 78% (CuO), 68% (MgO), and 70% (SiO_2) (Figure 4b). According to the CTR data shown in Figures 4a and 4b, the WBM had the lowest CTR. Even though CuO NP had the smallest surface area, it had the biggest increase in CTR of all the NPs that were tested. This suggests that it had the most fluid hydrodynamic drag force and buoyancy force to overcome the resistive force (gravity) that was pushing the cuttings downward. Al_2O_3 came next before SiO_2, while MgO NP had the lowest CTR among the NPs. Further observation in Figure 4 revealed that CuO NP increased the CTR by 28.8 to 31.1%, while Al_2O_3 and SiO_2 increased it by 22.7 to 26.7% and 16.7 to 22.2%, respectively. MgO NP had the least increasing effect on the CTR, at 13.6–17.8%.

Furthermore, as shown in Figures 4c and d, the cleaning of cuttings was simplest with a pipe rotation speed of 120 rpm compared to all cases with no pipe rotation. For instance, when the NPs transported cuttings of 2.80 to 3.60 mm diameters to the surface, the recovered cuttings with a pipe rotation speed of 120 rpm were more than the cuttings obtained without pipe rotation. With 2.80–3.60 mm diameters, WBM exhibited a CTR of 55% and 45% with and without pipe rotation, respectively. Similarly, without pipe rotation, the CTR of the NPs ranges between 53 and 68% (Figures 4a and b), and with pipe rotation, it increases to a range between 69 and 77% between 1.0 and 2.0 g concentrations (Figures 4c and d).

In addition, CuO NPs have a relatively high surface area of 29–45 m^2/g, whereas the surface areas of SiO_2, Al_2O_3, and MgO NPs vary from 85 to 300 m^2/g. The NPs interact favourably with sandstone particles and increase the colloidal interaction of the drilling fluid, which facilitates the movement of cuttings to the surface. The contact between the NPs and the drilling fluid particles is greater due to their large specific surface area per volume ratio and small particle diameter (Oseh et al., 2020; Alsaba et al., 2020). This, in turn, increases the hydrodynamic and buoyancy forces required to remove cuttings from the annulus.

Additionally, according to Abbas (2021), the drill pipe's rotating and whirling movement creates a flow that flows in the same direction as the cuttings for the horizontal annulus. In this case, the fluid's axial velocity path and the drill pipe's whirling motion both cause the cutting particles' axial velocity distribution to travel in the same direction. This allows the cuttings to flow from the bottom of the hole to the top of the annulus, where the flow velocity is highest, where they are effectively suspended and then easily carried to the surface (Abbas, 2021). This procedure improved the cutting and lifting process under a horizontal rotating drill pipe.

Cutting diameters have a considerable amount of impact on hole cleaning. The tests using a non-rotating drill pipe with different amounts of base mud and NP revealed the following CTR results: 66.7% for a cutting diameter of 0.80–1.60 mm, 61.6% for a cutting diameter of 1.62-2.78 mm, and 56.6% for a cutting diameter of 2.80–3.60 mm. When the pipe was rotated at 120 rpm, the drilling muds were more effective at lifting drilled cuttings to the surface. By running the different drilling fluids through a drill pipe that was rotating horizontally at 120 rpm, 75.5%, 72.2%, and 68.4% of the cuttings with diameters of 0.80-1.60 mm, 1.62-2.78 mm, and 2.80-3.60 mm were transported. These findings showed that the cuttings with the smallest diameters are the simplest to transport to the surface; those with intermediate sizes are next; and the ones with the largest diameters are the most difficult to lift to the surface. This data suggests that the drilling fluid's effectiveness in cleaning the annulus of drilled cuttings is directly proportional to the cutting size.

The study's findings also demonstrate that the nanosized particles in the WBM have good rheological and filtration properties, as well as stronger cutting transfer capability compared to the base mud. These characteristics could aid drilling fluids to prevent some wellbore drilling issues, such as differential pipe sticking, high torque and drag, bit balling, high ROP, and hole collapse (Mahmoud et al., 2020; Ernesto et al., 2016). This finding is also in line with the overall cleaning results of Minakov et al. (2018). These authors pointed out that adding CuO NPs, SiO_2 NPs, TiO2 NPs, and Al_2O_3 NPs to the base mud system equalizes the pulling and sticking forces of gravity by raising the fluid's hydrodynamic drag and lift forces on cuttings, which leads to better CTR. Another study by Boyou et al. (2019), which used enriched SiO_2 of 12 nm diameter, revealed that the size of NPs has a beneficial effect on drilling mud, and this effect will increase with decreasing NP size. This is due to the increased frictional and colloidal forces between the NPs and water molecules.

In general, the drilling fluids based on NPs, except for MgO, have the capability to overcome several challenges encountered during drilling operations. Nevertheless, the progress of NPs in WBMs has not yet achieved the highly expected degree of enhancement, necessitating more work in this area. When materials with a much smaller diameter are added to WBM, it may improve the rheological properties, fluid loss control, and filter cake quality compared to the conventional drilling mud system. These attributes are critical for preserving the wellbore's stability and improving the efficiency of drilling operations, thereby guaranteeing the safe and effective extraction of oil and gas (Al-Yasiri et al., 2015). Drilling is a crucial process in the oil and gas industry, providing the foundation for exploration and extraction activities. By using effective drilling fluids containing NPs, the energy sector may access untapped oil and natural gas reserves to meet increasing global oil demand (Al-Yasiri et al., 2015).

Optimal drilling fluids are essential for optimizing efficiency, minimizing expenses, and guaranteeing secure and environmentally responsible operations. Additionally, they provide faster drilling rates, leading to enhanced efficiency, less time needed to reach desired formations, and improved total production (Borah and Das, 2022). Using an effective drilling fluid will lead to reduced expenses. It will also limit drilling time and optimize output, helping operators reduce operating costs related to manpower, equipment leasing, and fuel usage (Borah and Das, 2022). Furthermore, effective drilling fluids will prevent costly issues such as wellbore instability or equipment breakdowns. Continuous improvement efforts could lead to the development of efficient drilling fluids. The industry's dedication to research and development, dissemination of information, and cooperation will drive continuous progress in the drilling process, which will improve the oil and gas industry's energy transitions (Schneider et al., 2013).

Learning from previous encounters and accepting new ideas and technologies increases productivity and lays the groundwork for future achievements. Efficient drilling fluids and sound industrial processes are important for the success of the oil and gas sector. They provide advantages such as enhanced production, reduced costs, improved safety, optimized resource utilization, and ongoing improvement (Schneider et al., 2013). By placing a high value on effectiveness and adopting new ideas, the oil and gas energy sector can successfully overcome obstacles, optimize profits, and have a positive impact on creating a sustainable energy future.

4. CONCLUSIONS

The effect of 1.0 and 2.0 g mass concentrations of NPs (MgO, SiO_2, Al_2O_3, and CuO) on the CTR of WBM was investigated in a cutting-rig simulator that was positioned horizontally. The cutting sizes ranged from 0.80 to 3.60 mm, and the annular fluid speed was set at 3.5 m/s. A summary of the key findings is itemized as follows:

1. The results showed that the selected NPs enhanced the viscosity of the WBM by 10–87%, and they also kept the FLAPI between 8.8 and 4.8 mL from the reference value of 9.4 mL.
2. While Al_2O_3 NP had the greatest increase in rheological characteristics, it had the lowest impact on fluid loss control.
3. Although CuO NPs and MgO NPs had the best fluid loss control, their rheological properties were weak compared to those of Al_2O_3 and SiO_2.
4. The CTR of the NPs increases with increasing NP concentration for all cutting diameters, and 80–3.60 mm cuttings are the most difficult in the cleaning process.
5. CuO transported the most cuttings at all concentrations and sizes, despite having a lower viscosity than Al_2O_3 and SiO_2.
6. Regardless of other drilling parameters, pipe rotation produced the greatest CTR as compared to the non-rotated drill pipe.
7. This study's findings propose CuO NP and Al_2O_3 NP as the most desirable additives with suitable rheological properties for improved cutting transport.

5. LIMITATION AND FUTURE SCOPE

Following up on this study's findings about the impact of pipe rotation speed on CTR with various NPs, it would be prudent for researchers to examine how the eccentricity of the pipe affects cutting transport. In directional wells, the annulus is often not centered and may vary in eccentricity due to changes in the drilling process and load-bearing capacity. The eccentric drill pipe generates a small annular zone where cutting beds stay, owing to the little flow in that area. Fluid flows more easily through the bigger annulus in an eccentric annulus; hence, changing the eccentricity will lead to various rates of hole cleaning. Therefore, the deviations in pipe alignment may have a significant impact on the average axial velocity distribution of the drilling fluid in the annulus. Enhancing the fluid velocity in the annulus is an effective method to improve cutting transport. Therefore, understanding the effect of pipe eccentricity on cutting transport under varied annular fluid velocity is crucial when clearing a hole for cuttings.

CONFLICT OF INTEREST

All the authors have examined and approved this work and disclosed no conflicting interests.

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