A comparative study of the filtration rate of water-based mud between silica and zinc oxide nanoparticles of different sizes for the deep well application

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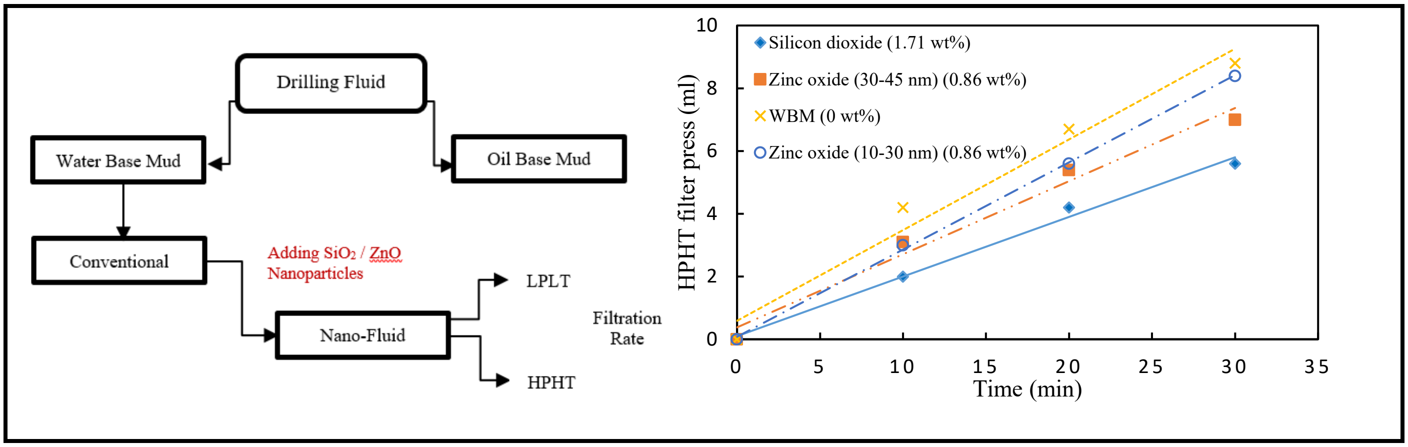

ABSTRACT: In the oil and gas industry, drilling mud plays a vital role in the drilling process. This study aims to analyze the filtration rate of water-based mud with silicon dioxide and zinc oxide nanoparticles. In addition, different concentrations of high-temperature starch with both silica and zinc oxide nanoparticles were also investigated. It further compares the effects of various sized and concentrated silicon dioxide and zinc oxide nanoparticles, emphasizing how well water-based drilling muds filter water and function in well simulation scenarios. The water-based mud used in this study was made by combining various chemicals such as Caustic Soda (NaOH), Sodium Chloride (NaCl), Xanthan Gum, Starch, high temperature (HT) Starch, Calcium Carbonate (CaCO3), and Barite for usage in a deep well. The drilling mud's filtration properties were determined using high pressure and high temperature (HPHT) and American Petroleum Institute (API) filter presses, which were used under very high pressure and high temperature (HPHT) and low pressure and low temperature (LPLT) conditions, respectively. It was observed that nanoparticles provide better filtration rate performance as opposed to conventional mud. Notably, the use of zinc oxide and silicon dioxide nanoparticles reduced the HPHT filtration rate of conventional water-based mud by 26.2% and 52.3%, respectively.

Keywords: Drilling fluid, filtration rate, silicon dioxide, zinc oxide, nanoparticles, comparison.

دراسة مقارنة لمعدل الترشيح في طين الحفر المائي باستخدام جسيمات السيليكا وأكسيد الزنك النانوية بأحجام مختلفة لتطبيقات الآبار العميقة

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الملخص: في صناعة النفط والغاز تلعب سوائل الحفر (الطين) دورًا حيويًا في عملية الحفر. لذلك تهدف هذه الدراسة إلى تحليل معدل الترشيح لسوائل الحفر المائي الذي يحتوي على جسيمات نانوية من ثاني أكسيد السيليكون وأكسيد الزنك. بالإضافة إلى ذلك، تم التحقق من تأثير تركيزات مختلفة من النشا المقاوم للحرارة العالية مع كل من الجسيمات النانوية لثاني أكسيد السيليكون وأكسيد الزنك. كما تتناول الدراسة مقارنة تأثير أحجام وتركيزات مختلفة من الجسيمات النانوية، مع التركيز على كفاءة ترشيح المياه في سوائل الحفر المائية وأدائها في سيناريوهات محاكاة الآبار. تم إعداد سائل الحفر المستخدم في هذه الدراسة من خلال دمج مجموعة متنوعة من المواد الكيميائية، مثل هيدروكسيد الصوديوم (NaOH)، وكلوريد الصوديوم (NaCl)، وصمغ الزانثان، والنشا، والنشا المقاوم للحرارة العالية (HT Starch)، وكربونات الكالسيوم ($CaCO_3$)، والبارايت، لاستخدامه في حفر الآبار العميقة. تم تحديد خصائص الترشيح لسائل الحفر باستخدام أدوات ترشيح ذات ضغط مرتفع ودرجة حرارة عالية (HPHT) وأخرى وفق معايير معهد البترول الأمريكي (API)، والتي تم استخدامها في ظروف الضغط والحرارة المرتفعة (HPHT) وظروف الضغط والحرارة المنخفضة (LPLT) تواليا. وقد أظهرت النتائج أن الجسيمات النانوية توفر أداءً أفضل في معدل الترشيح مقارنة بسوائل الحفر التقليدية. ومن الجدير بالذكر أن استخدام الجسيمات النانوية من أكسيد الزنك وثاني أكسيد السيليكون أدى إلى تقليل معدل الترشيح في ظروف الضغط والحرارة العالية بنسبة 26.2% و52.3% على التوالي، مقارنة بسائل الحفر التقليدي المائي.

الكلمات المفتاحية: سائل الحفر، معدل الترشيح، ثاني أكسيد السيليكون، أكسيد الزنك، الجسيمات النانوية، المقارنة.

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1. INTRODUCTION

Due to the differential pressure, the in-well filtration process invokes a mixture into a permeable reservoir. This permeability is related to the fluid's capability to run across the porous medium. Therefore, drilling mud must create a fine filter mould to insulate the areas of permeability. In order to penetrate and block the rocks, different aggregates of drilling mud are used, ranging from 1 to 100 µm. However, they become ineffective as fillers when using fine particles in rocks with low permeability, mainly due to the pore dimensions that do not surpass 0.1 to 1 micrometre (Mikhienkova et al., 2018).

Mohammadizadeh et al. (2021) investigated the flow transition in porous media. The model simulated an actual porous medium using an orthogonal pipe network that connected spheres with a series of pipes. The pipes represented the ducts in the porous medium, while the nodes (spheres) represented the holes at the duct junctions. They examined the effects of various hydraulic parameters using this model. The combined pressurized-free surface network (CPFNET) method was used to analyze the network. The results of the CPFNET model were generally consistent with the experimental data observed. A sensitivity analysis based on several parameters was also adopted to determine the accuracy of the method. The proposed method was able to accurately capture the flow characteristics in each of the scenarios. In particular, the CPFNET method could accurately simulate the transition from a Darcy-type flow to a non-Darcy flow through the porous medium. It was also found that the CPFNET method was more computationally efficient than other methods that are currently used to simulate fluid flow in porous media.

When mud and nanoparticles are mixed, another type of drilling fluid called nanofluids is produced (Alkalbani et al., 2022). It is a semi-monophasic medium containing a stable colloidal dispersion of ultrafine particles in a given liquid (Manna, 2009). Despite the presence of solid dispersions whose concentration is about (<1 vol%), the nanofluids record a high level of thermal conductivity (Manna, 2009). Due to the characteristics of nanoparticles and their unique and distinct structure, these particles have been added to drilling fluids, leading to the development of a new type of environmentally friendly, low-cost, highly efficient drilling fluid (Ali et al., 2020). This explains a recent hydrocarbon area in difficult subsurface conditions under high temperature and pressure (HT/HP) conditions. One of the most important benefits of adding nanoparticles to drilling mud is the improvement in stability by adjusting the filtration rate and rheological properties (Amanullah et al., 2011). The possibility of manufacturing nanoparticles on demand has an important and dynamic role in the change of nanoparticles since these fluids can be developed according to the needs required for the place of drilling or operation, meaning that these particles can deal with diverse circumstances. The purpose of nanoparticles is to modify drilling fluids features and give the ability to prevail over the problems and overcome the difficulties faced during the drilling operations (Vryzas et al., 2017).

Zakaria et al. (2012) added nanoparticles in the drilling fluid for a filtration properties test under standard filtration conditions. The results showed that the fluid loss rate was reduced by 70% when adding nanoparticles. In addition, they found that a thin filter cake helps to minimise the formation damage and adhesion of the differential pressure. They also concluded that adding nanoparticles does not affect the viscosity and that it maintains the steadiness of the drilling fluid for more than 42 days (Agista et al., 2018). The problem of borehole instability is one of the common problems most drilling companies face during drilling. The most important factor in determining the stability of wells composed of oil shale is the extension and dispersal of micro-cracks in the solid shale. The usual approach to solving the problem of well collapse from oil rocks is to enhance the drilling fluid paste and boost the inhibition of drilling fluid filtration in addition to closing the micro-cracks and pores near the surface of the well bore. Despite these solutions, the collapse of the borehole of rock wells was not yet completely solved due to the difficulty of forming a drilling fluid paste in the sections of oily rocks since the differential pressure is approximately the same in the sand sections because of the sharp drop in the filtration rate (Li et al., 2012). Therefore, nano-drilling fluid was used to solve the problem of wellbore stability.

Sensoy et al. (2009) added various nanoparticles to water-based mud to lower the fluid penetration of oily rocks. It was observed that the tiny pores are blocked by some amount of the nanoparticles, as for the significant gaps, when nanoparticles are added with a concentration of no less than 10% of the weight. As a result, the nanoparticles accumulate, forming a lump that clogs the pores. In one of the experiments, four types of mud were investigated, with and without nanoparticles. It was also noticed that the infiltration of liquids into the rocky Gulf of Mexico increased from 17% to 27% and from 16% to 72% in the Atoka rock when nanoparticles were used (Vryzas and Kelessidis, 2017). Amanullah et al. (2011) added nanoparticles to the drilling fluid to study the rheological properties and filtration rates. It was noticed that nanoparticles helped precipitate a compact and thin mud paste, significantly reducing fluid loss. In addition, this mud paste helps to reduce differential tube sticking in highly permeable formations (Aftab, 2016). When silicon dioxide nanoparticles were added to the water-based mud with an amount of <1 wt%, it was noticed to improve the stability of the shale and has acceptable rock recovery, in addition to enhancing the retarding properties (Taraghikhah et al., 2015; Alkalbani et al., 2024).

Hoelscher et al. (2012) conducted an experiment by adding silica nanoparticles to water-based mud to reduce the permeability of oil rocks by replacing the chemical fixation to block the pores with nanoparticles. This impeded the flow of water between the formation and the well, reducing fractures and swelling in the oil shale. It was concluded that nanoparticles with a diameter of 10 - 30 nm gave the ability to lose the least amount of liquid. In addition, the study confirmed that silicon dioxide nanoparticles with water-based mud can block oil shale and be less cost and environment-friendly (Afolabi, 2018). Sharma et al. (2012) tested another type of water-based mud (WBM) with silicon dioxide nanoparticles of diameter 20 nm. They found that the mixture was relatively stable under HPHT conditions. In addition, they noticed that the invasion of oil shale decreased by 10-100 times. They also conducted another test on the fractured oil shale samples, and it was concluded that the nanoparticles could fill the pores effectively without fine cracks. Alkalbani et al., 2022 used field emission scanning electron microscopy attached with energy dispersive X-ray spectroscopy to investigate surface morphology and elemental composition of ZnO nanoparticles of different diameters. The images revealed the other agglomerations of the zinc oxide nanoparticles, showing the contrast from the colloidal form.

Rheological properties are one of the most important properties to consider when developing any drilling fluid for its effectiveness and stability. These properties also help to reduce fluid loss in drilling operations. For example, the intrusion of external fluids, such as leaching from the drilling process, produces some formation destruction to newly exposed formations. These properties under HPHT conditions help develop a little impermeable filter mud cake on the surface, reducing the appearance of spoilage problems (Mahmoud et al., 2017). Adding 0.00285% silicon dioxide nanoparticles improved the rheological properties and reduced fluid loss (Ismail et al., 2016). The study conducted by Alkalbani et al., 2023 investigated the effect of silica nanoparticles on the rheological properties of water-based mud for deep well usage. It was reported that silica nanoparticles improved the rheological properties of water-based mud by more than 50%. In addition, when zinc oxide is added to the water-based mud, the plastic viscosity is improved, and the fluid loss rate is reduced to 14% (Aftab et al., 2016). The key to preventing water intrusion into the oil shale is to make a mixture of mud and nanoparticles of the proper dimension and concentration.

The effects of different nanoparticle sizes and concentrations on the rheological characteristics and filtration rates of drilling fluids have been the subject of numerous studies; however, a notable gap exists in the comparative analysis between silicon dioxide and zinc oxide nanoparticles. This is especially true when it comes to WBM, or water-based muds, which are designed for deep well applications. Nanoparticles have been demonstrated in earlier studies to considerably improve the performance of drilling fluids; however, little is known about the precise effects of these two types of nanoparticles in high-pressure high-temperature (HPHT) and low-pressure low-temperature (LPLT) scenarios (Hoelscher et al., 2012; Sharma et al., 2012). Therefore, this study aims to investigate the filtration rate of water-based mud with silicon dioxide and zinc oxide nanoparticles. As the conventional water-based mud (WBM) was formed considering the deep reservoir condition, this study highlights the application of different nanoparticles for deep well drilling. Ultimately, this study offers a fundamental viewpoint for the creation of more effective drilling fluids based on nanoparticles that are appropriate for deep well applications, improving wellbore stability and lowering drilling hazards.

2. MATERIALS AND METHODS

Various materials and procedures were used in this experiment. A Hamilton beach mixer (model number: HMD-200) holding roughly 750 ml was used to mix chemicals to make the drilling fluid. At 600 rpm, the rotational viscometer manufactured by OFITE (model number: #130-10-L, Speed Accuracy (RPM): 0.1) was utilized to determine the direct viscosity of drilling fluid. A stainless steel cup was used to place the fluid sample in the rotational viscometer. The cylinder with continuous rotational rates was used to determine viscosity. Filter press was used to test the filtration rates of drilling mud under low-pressure, low-temperature situations (LPLT). The working pressure was 100 psi at room temperature. This equipment is designed to test the filtration qualities of drilling mud under extremely high pressure and high temperature (HPHT) settings of up to 120°C (Khalil, 2020).

The temperature of the drilling fluid was measured with a thermometer in this experiment. The weight of the materials used in the experiment was precisely measured using a weighing balance scale. One method of determining the influence of temperature on drilling fluid as it flows in the wellbore is by using a roller oven (manufactured by OFITE (model number: #173-00)), also known as a four-cylinder furnace (Contreras, 2014). The temperature fluctuates from 38 and 232.2 °C. Drilling fluid and conserving and adding chemicals to fluids are all handled in the beaker. Several sized spoons were employed to remove various material sizes from each packet. In gel strength and filtration rate tests, a stopwatch was utilized to record the mixing time ranging from 2 to 10 minutes.

2.1 Mixing of drilling fluids water-based mud (WBM).

Water base mud for this study was formed according to the William et a., 2014 method. A freshwater of 300 g, caustic soda of 0.25 g, NaCl of 91 g, MB-Xan D of 1.0 g, MB Starch of 3.5 g, $CaCO_3$ (W.M) of 17.5 g, and Barite (4.2 SG) of 17.5 g were prepared and used for the experiment. Initially, the blender was filled with 300 ml of fresh water along with 0.25 g of caustic soda. The produced liquid was then blended for 2 minutes. NaCl of 91 g was poured into the blended liquid and stirred for around 10 minutes. 1 g of xanthan gum was added to the mixture and whisked for around 10 minutes. Once the mixture and whisked were completed, a starch of 3.5 g was added to the mixture and stirred again for around 10 minutes. The nanoparticles are stirred and set aside for 10 minutes to combine. Finally, calcium carbonate of 17.5 g and 17.5 g of barite were added and stirred thoroughly.

2.2 Materials used in the experiment.

As water-based drilling fluid was utilized in the experiment, enormous amounts of 300 ml of fresh water were utilized to combine the chemicals. Sodium hydroxide (NaOH) is a simple chemical compound that dissolves readily in water. It was used to keep the necessary pH in water-based drilling fluids and to create an alkaline environment that aids mud dispersal. Sodium hydroxide (NaOH) is a simple chemical compound that dissolves readily in water. It was used to keep the necessary pH in water-based drilling fluids and to create an alkaline environment that aids mud dispersal. NaCl is an ionic chemical that is formed by combining sodium and chloride. It was one of the most important ingredients in drilling fluid manufacturing because it helps manage filtration rates, thickens drilling fluid, and prevents oil shale swelling and disintegration. It also adds viscosity to aqueous drilling fluids. The consistency of the drilling fluid was maintained with xanthan gum. Silica nanoparticles with sizes ranging from 10 to 30 nanometers were used in this experiment. Calcium carbonate (CaCo3) was added to drilling fluids to thicken and protect well formations. Barite (BaSo2), a mineral made up of barium sulfate, was utilized to keep the borehole stable. Details of the materials used are depicted in Table 1.

2.3 Experimental Techniques.

Thirteen samples of aqueous drilling fluid were prepared, as can be seen in Table 2. The first experiment contained a drilling fluid without adding any of the nanoparticles. In the following three experiments, several different weights of silica nanoparticles, such as 0.86 wt%, 1.71 wt%, and 2.57 wt% were added to a water-based drilling fluid. The next six experiments were conducted by adding different weights (0.86 wt%, 1.71 wt%, and 2.57 wt%) and sizes of zinc oxide nanoparticles (10-30 nm and 30-45 nm). The effects of starch with silicon dioxide nanoparticles were also investigated. In the first experiment, starch (1 wt%) was added with silica nanoparticles with a pH adjustment from around 8-10. The second sample contained silicon dioxide nanoparticles and starch without pH adjustment. The last sample contains silica nanoparticles without the addition of starch, with a pH adjustment from around 8-10. The samples were tested to check the filtration rate at a constant temperature of 50°C and pressures (100 and 600 psi).

When putting the mud sample in the kiln, few measures were taken. The mud cell was first filled with a sample of the mud examined. The rubber ring was then checked if it was unbroken. If otherwise, the mud cell is securely closed with the cover using the screws that are permanently attached to the mud cell cover. Nitrogen gas was poured into the mud cell through the sample cap's valve. The valve is tightly closed, and water drops are placed on the valve to guarantee that the sample does not leak from the mud cell. The samples were placed in the oven for the fifth time. The oven was pre-heated to the desired temperature and set the timer for 16 hours. Finally, the oven was switched off once the stipulated time had passed, and the samples were allowed to cool before being taken to the remaining tests.

Table 1. Chemicals used in this study.

Name	Purity	Molecular Weight
Caustic Soda (NaOH)	NLT 97% & NMT 100.5%	39.997 gram/mol
Sodium Chloride (NaCl)	99.5%	58.44 gram/mol
Xanthan Gum	15%	933.748 gram/mol
Starch	92.57%	100000 gram/mol
HT Starch	95%	100000 gram/mol
Silicon dioxide nanoparticles (SiO_2)	95.9%	60.0843 gram/mol
Zinc oxide nanocomposite (ZnO)	99%	81.408 gram/mol

Table 2. Samples were prepared for the analysis.

Sample	Nanoparticles
1	Silica (with starch)
2	Silica (with starch)
3	Silica (without starch)
4	No Nanoparticles (Control)
5	Silica (0.86 wt%)
6	Silica (1.71 wt%)
7	Silica (2.57 wt%)
8	Zinc Oxide (0.86 wt%, 10-30 nm)
9	Zinc Oxide (1.71 wt%, 10-30 nm)
10	Zinc Oxide (2.57 wt%, 10-30 nm)
11	Zinc Oxide (0.86 wt%, 30-45 nm)
12	Zinc Oxide (1.71 wt%, 30-45 nm)
13	Zinc Oxide (2.57 wt%, 30-45 nm)

2.4 Measuring API and HPHT Filter Press.

The rubber gasket was firmly fixed in the cup chamber, followed by the circular gauze frame placed on the base to place the filter paper on it. The rubber gasket was connected to the base of the cup by twisting and connecting the side screws in the cell body to the holes in the base of the cup, which was locked tightly. The sample cup in the filter press is framed, making sure the rubber gasket is properly installed. The screw (T-screw) was turned to tighten the seal. The graduated measuring cylinder was placed to measure the volume of the liquid loss of the sample. The pressure regulator was set to 100 psi on the cell body and the start time was recorded for the test duration of 30 minutes. After 30 minutes, the gas port was closed, and the graduated measuring cylinder reading was recorded in millilitres (mm). The mud sample was tested before and after being removed from the oven.

To measure the control of fluid loss under high temperature and high pressure, several procedures were carried out. The mud cell was filled with the sample. The rubber ring was installed correctly and HTHP filter papers were placed on top. The mud cell was tightly closed by pores fixed in the cell body. The mud cell was placed in the heater so that the filter drain valve was in a downward direction. The mud cell temperature was measured using a thermometer. The gas capsule was placed in the upper valve of the mud cell and secured with the locking screw. The overhead half valve was made open to stop the mud from boiling when the desired temperature reached 120°C. Extra pressure was added to the lower valve stem and fixed by the locking pin. After reaching the required temperature, the pressure regulator in the lower valve is set to 100 psi, with the valve closed. The pressure regulator was adjusted on the upper valve, and the pressure increased from 100 psi to 600 psi in the mud cell, after which the 30-minute sample test began. The bottom valve overpressure is removed by draining the filter into a graduated glass metering cylinder. After the test period (30 minutes), the upper and lower valve stems were closed, and the pressure held in the mud cell was released by pulling the red bleed off. The filter remaining in the valve is drained into a graduated glass cylinder. The reading was recorded based on the volume of the collected filter in millilitres (mm). The mud sample was tested after it was taken out of the oven.

3. RESULTS AND DISCUSSION

3.1 Effects of silica nanoparticles of different concentrations on the filtration rate.

The filtration rate of a fluid at a constant temperature of 50°C was investigated by adding varying weights of silicon dioxide nanoparticles. Results indicated that the conventional water-based mud (WBM) experienced approximately 4.4 ml of fluid losses as depicted in Figure 1. However, with the gradual addition of silica nanoparticles, the API fluid loss increased proportionally until it reached approximately 8.8 ml. Additionally, the high-pressure high-temperature (HPHT) of the regular water base-mud (WBM) was observed to be about 72.2 ml and steadily decreased to approximately 27 ml at 9 g (2.57 wt.%) of silicon dioxide nanoparticles. The increase in API fluid loss with the addition of silicon dioxide nanoparticles can be attributed to the fact that the nanoparticles acted as pore-forming agents. This led to the formation of more pores in the mud cake, which in turn increased the fluid loss. On the other hand, the decrease in HPHT with the addition of nanoparticles is due to the fact that the nanoparticles form a compact network in the mud cake, reducing the permeability of the mud. As a result, the fluid loss is reduced, making the drilling process more effective. Notably, the reduction in HPHT was observed up to a certain point (9 g or 2.57 wt.% SiO2). Beyond this point, the HPHT began to increase again, which can be attributed to the fact that too much addition of nanoparticles can lead to agglomeration, increasing permeability and fluid loss. Therefore, the optimal amount of silicon dioxide nanoparticles that can be added to the water-based mud can be determined by carefully balancing the reduction in fluid loss and the increase in HPHT. This reduction in HPHT is desirable as it minimizes fluid losses, leading to a more efficient drilling process, as suggested by Ponmani et al. (2016).

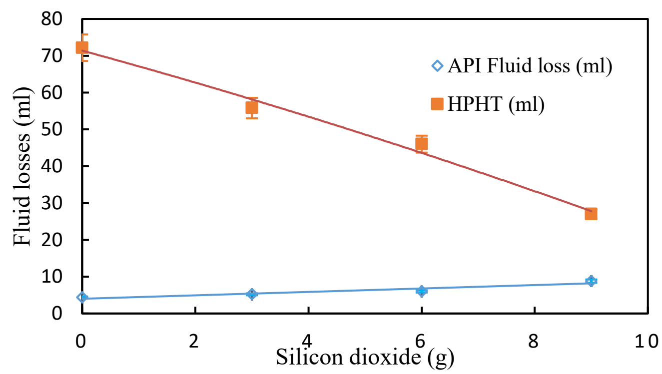

Figure 1. Filtration rate of water-based mud (WBM) with different weights of SiO_2.

3.1.1 Effects of adding HT starch instead of normal starch on the filtration rate.

The study examined the impact of substituting traditional starch with high-temperature (HT) starch on the rates of fluid filtration, as depicted in Figure 2. The outcomes showed that the typical water-based mud (WBM) had an approximate 3.9 ml API fluid loss. On the other hand, the API fluid loss rose proportionately as silicon dioxide (SiO2) nanoparticles were added, eventually reaching around 7.8 ml. In contrast, when the SiO2 content was raised to 2.57 wt%, the high-pressure, high-temperature (HPHT) fluid loss for the typical WBM progressively dropped to about 3.3 ml. Initially, it was roughly 8.8 ml. With the addition of HT starch and SiO2 nanoparticles, there was a decrease in HPHT fluid loss but an increase in API fluid loss. This is probably because the mud cake became more porous, which decreased permeability and increased fluid loss. However, the decrease in HPHT fluid loss suggests a more effective drilling procedure with low fluid losses. According to Salih et al. (2016), this reduction in HPHT fluid loss is therefore regarded as advantageous and helps to make the drilling process more successful.

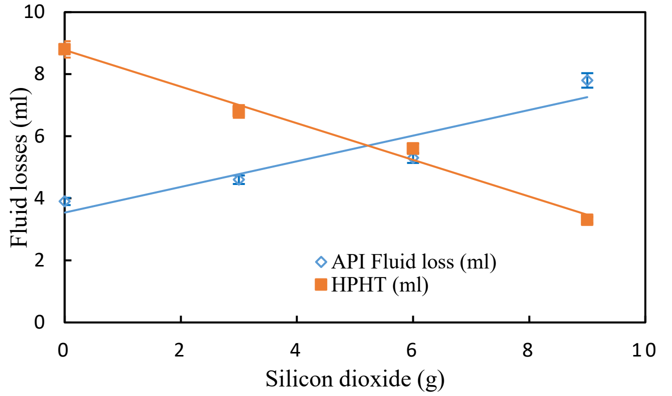

Figure 2. Filtration rate of water-based mud (WBM) with different weights of SiO_2 and adding HT starch instead of normal starch.

3.1.2 Effects of adding starch of different pH in silica nanoparticles on the filtration rate.

The influence of starch and pH on the filtration rate was evaluated by adding different amounts of starch to a constant amount of water-based mud (WBM) containing 6 g (1.71 wt%) of silicon dioxide. The results demonstrate that a decrease in pH causes a gradual rise in API fluid loss of 10%, as seen in Figure 3. Furthermore, removing starch while keeping the pH at 10 dramatically reduces fluid loss. However, the HPHT fluid loss increases significantly when starch with a pH of 10 is introduced to the WBM. On the other hand, eliminating starch reduces HPHT fluid loss much more. WBM with 6 g (1.71 wt. %) of SiO2 at pH 10 and no starch performs better in terms of filtration than the other formulations. Both API and HPHT fluid losses increased when starch was added to the WBM, suggesting a reduction in filtration efficiency. This phenomenon may be explained by the starch molecules' enlargement and formation of gel-like structures in response to water; these structures obstruct the pores in the porous media and decrease fluid flow. Additionally, the lower pH also led to a higher loss of API fluid, possibly as a result of a decrease in the electrostatic repulsion between the mud's particles, enhancing particle aggregation and pore blockage (Kang et al., 2016). However, the elimination of starch from the mud resulted in a decrease in HPHT and API fluid loss, indicating improved filtration efficiency. A larger fluid flow rate through the porous medium may be made possible by the decreased possibility of pore obstruction, which accounts for this improvement. Overall, the results point to the possibility that the best way to achieve ideal filtration rates during drilling operations is to use water-based mud containing silicon dioxide nanoparticles, free of starch, and at a pH of 10.

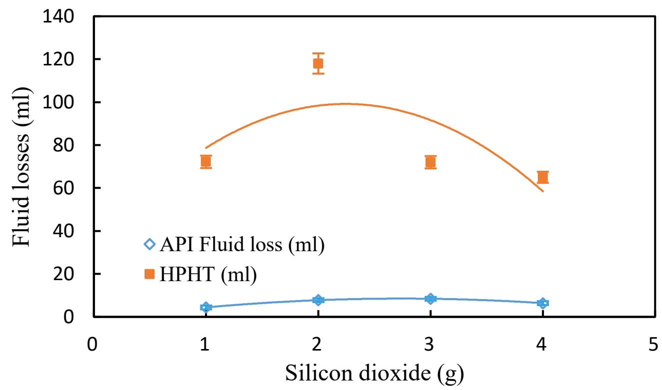

Figure 3. Filtration rate of water-based mud (WBM) with 6g of SiO_2 and adding a starch and pH range.

3.1.3 Effects of adding different amounts of HT starch at different pH in silica nanoparticles on the filtration rate.

Water-based mud (WBM) containing 6 g (1.71 wt.%) of silicon dioxide nanoparticles was mixed with varying amounts of high-temperature (HT) starch. The API fluid loss of standard water-based mud (WBM) with 6 g (1.71 wt.%) of silica and a pH of 10 was roughly 7.8 ml, as shown in Figure 4. On the other hand, 10% more API fluid was lost, or around 8.4 ml, when the pH was lowered. Notably, eliminating HT starch greatly decreased fluid loss while keeping the pH at roughly 10. It appears that the API fluid loss for WBM with a pH of 10, 6 g (1.71 wt%) of silicon dioxide, and no HT starch performs better than the other formulations. In contrast, when HT starch was introduced at a pH of 10, the HPHT fluid loss for typical WBM increased dramatically from 8.8 ml to around 14.4 ml. However, when the pH was lowered to 8, this amount decreased to 8.7 ml. The HPHT fluid loss dropped to 7.9 ml after HT starch was completely removed, and the pH remained at about 10. These results show that WBM with a pH of 10 and 1.71 weight per cent SiO2 performs better at filtration rates than formulations with HT starch. HT starch functions as a viscosity, increasing the viscosity of the mud and increasing resistance to fluid movement, adding it to WBM may result in an increase in HPHT fluid loss. Because there is less crosslinking of HT starch molecules when the pH drops, there is a corresponding decrease in HPHT fluid loss and viscosity. As HT starch usually helps to build a thicker filter cake, which helps to minimise fluid loss and improves resistance to fluid flow, removing it from the WBM can help reduce API fluid loss. Sayyadnejad et al. (2008) suggest that the absence of HT starch could lead to a less dense filter cake, which could result in less fluid resistance and decreased fluid loss.

3.2 Comparison of filtration rate of different nanoparticles.

3.2.1 Overall filtration rate of silica nanoparticles with different concentrations.

The overall API filtering rate of silicon dioxide nanoparticles at different concentrations following integration into traditional water-based mud (WBM) is depicted in Figure 5. The specific filtration rate changed with the concentration of nanoparticles, even though all drilling fluids, nanoparticle-containing or not, showed comparable trends in filtration rate behaviour. The API fluid loss for conventional WBM increased steadily to 3.9 ml at 30 minutes from 2.1 ml at 10 minutes. In contrast, the API fluid loss in WBM containing 3 g (0.86 wt%) of silicon dioxide was 2 ml at 10 minutes and increased to 5.3 ml at 30 minutes. The API fluid loss for WBM with 6 g (1.71 wt%) began at 2.4 ml at 10 minutes and reached 6 ml at 30 minutes. The WBM containing 9 g (2.57 wt%) of silicon dioxide demonstrated a 2.6 ml API fluid loss after 10 minutes, which increased to 8.8 ml at 30 minutes. In general, it is not a good idea to let the API fluid loss get to 10 ml since this could result in a thicker filter cake, which could impede drilling by clogging the borehole. This emphasises how crucial it is to precisely balance the concentration of nanoparticles in order to maximise filtering rates and prevent the development of too many filter cakes.

The total HPHT filtration rate of silicon dioxide nanoparticles in traditional water-based mud (WBM) at different weight concentrations is shown in Figure 6. The specific filtration rate varied based on the concentration of nanoparticles, but all drilling fluids, nanoparticle-containing or not, showed a similar pattern in their filtration rate behaviour, where the rate increased over time. The HPHT fluid loss for traditional WBM was 4.2 ml after 10 minutes and increased to 8.8 ml after 30 minutes. However, WBM containing 3 g (0.86 wt.%) of silicon dioxide showed 2.9 ml of HPHT fluid loss after 10 minutes, increasing to 6.8 ml after 30 minutes. After 10 minutes, the HPHT fluid loss for WBM with 6 g (1.71 wt%) of silicon dioxide was 2.1 ml, and after 30 minutes, it rose to 5.6 ml. With a fluid loss of only 3.3 ml at 30 minutes, the WBM containing 9 g (2.57 wt%) of silicon dioxide exhibited the least amount of HPHT fluid loss, beginning at 1.2 ml after 10 minutes. These findings suggest that raising the silicon dioxide nanoparticle concentration in the water-based mud considerably lowers the HPHT fluid loss, enhancing the mud's overall filtration effectiveness at high temperatures and pressures.

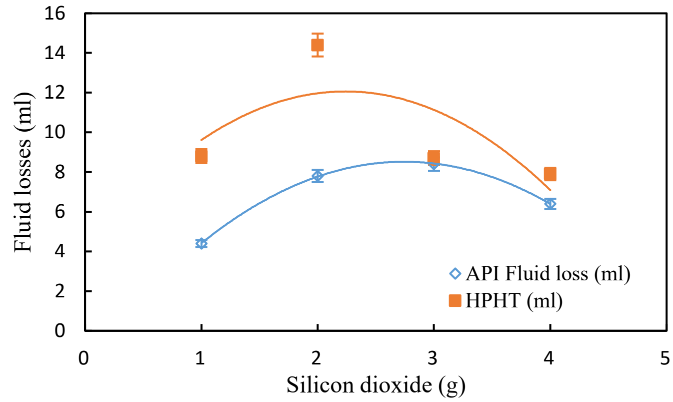

Figure 4. Filtration rate of water-based mud (WBM) with 6 g of SiO_2 and adding an HT starch and pH range.

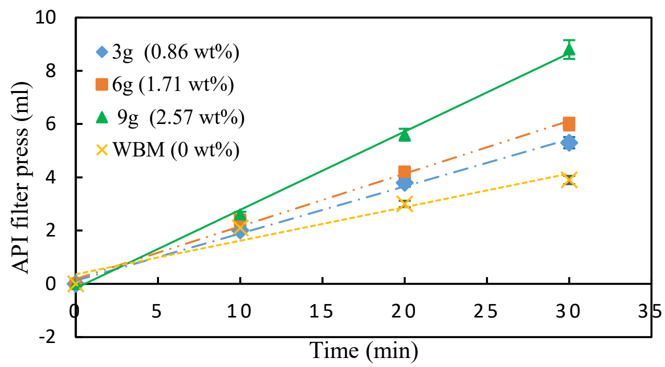

Figure 5. Overall API filtration rate of silicon dioxide nanoparticles with different weights.

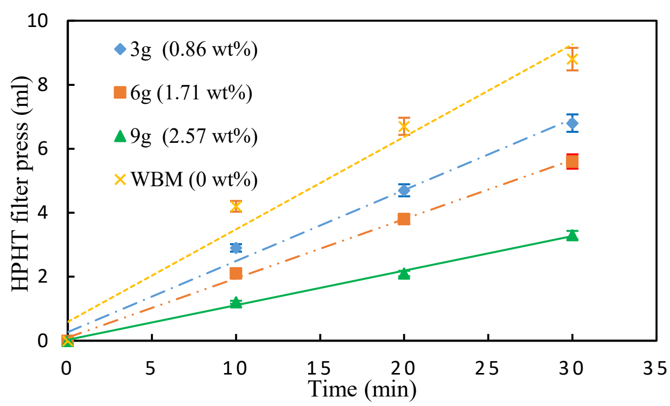

Figure 6. Overall HPHT filtration rate of silicon dioxide nanoparticles with different weights.

3.2.2 Filtration rate of zinc oxide nanoparticle (10 - 30 nm) with different concentrations

The filtering rate of water-based mud (WBM) with different amounts of 10–30 nm-sized zinc oxide (ZnO) nanoparticles is shown in Figure 7. When using standard WBM without any zinc oxide nanoparticles, the API fluid loss is about 3.9 millilitres. However, the API fluid loss increases gradually and proportionately with the addition of 10–30 nm zinc oxide nanoparticles, reaching around 5.2 ml. On the other hand, when zinc oxide nanoparticles of the same size are added, the HPHT fluid loss for conventional WBM starts at around 8.8 ml and subsequently drops to about 8.4 ml at a concentration of 3 g (0.87 wt%). It has been noted that fluid loss tends to increase when zinc oxide nanoparticle weight concentration rises. Ahasan et al. (2021) found that adding zinc oxide nanoparticles especially those with sizes between 30 and 45 nm can improve WBM's rheological characteristics and filtering rate. Their research using zinc oxide nanoparticles at different weight concentrations showed that 3 g (0.87 wt%) is the ideal concentration for HPHT applications. This particular concentration considerably lowers fluid losses, which makes the drilling operation go more smoothly. For HPHT drilling applications, it is therefore advised to utilise 3 g (0.87 wt%) of zinc oxide nanoparticles in order to attain the best results.

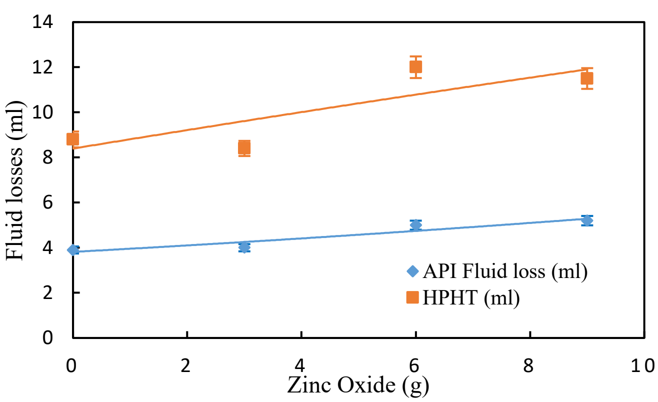

Figure 7. Filtration rate of water-based mud (WBM) with different weights of ZnO (10 – 30 nm).

Figure 8 shows the overall API filtration rate of zinc oxide nanoparticles (10 -30 nm) with different weight concentrations in the conventional water-based mud. It was observed that drilling fluids with or without nanoparticles had an increasing filtration rate with time. When using traditional WBM, the API fluid loss increases steadily over the course of 10 minutes, reaching 4 ml at that point. However, WBM containing 3 g (0.86 wt.%) of zinc oxide nanoparticles has a decreased initial API fluid loss at 10 minutes (1.6 ml), and this increases gradually to 3.9 ml at 30 minutes. The API fluid loss for WBM containing 6 g (1.71 wt%) of zinc oxide starts at 2.1 ml after 10 minutes and rises to 5 ml after 30 minutes. WBM containing 9 g (2.57 wt%) of zinc oxide nanoparticles shows an initial API fluid loss of 2.5 ml after 10 minutes and 5.2 ml after 30 minutes. These findings imply that the API fluid loss is influenced by the concentration of zinc oxide nanoparticles in the WBM, with larger concentrations eventually resulting in higher fluid losses. In contrast to higher concentrations, the 3 g (0.86 wt%) concentration exhibits the most efficient performance, maintaining a lower fluid loss, suggesting a balance between minimal fluid loss and effective filtering.

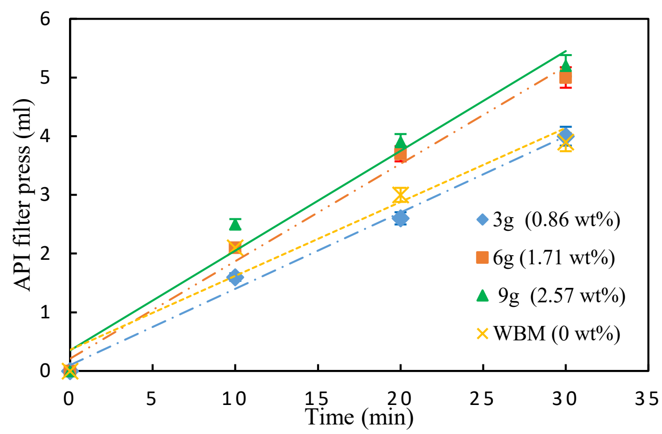

Figure 8. Overall API filtration rate of zinc oxide nanoparticles (10 - 30 nm) with different weights.

Figure 9 shows the total HPHT filtration rate of 10–30 nm-sized zinc oxide (ZnO) nanoparticles at different weight concentrations in conventional water-based mud (WBM). Generally, the filtration rate of every drilling fluid increases with time. The API fluid loss for conventional WBM starts at 4.2 ml at 10 minutes and progressively increases to 8.8 ml at 30 minutes. A similar early API fluid loss of 4.2 ml at 10 minutes is also seen in WBM containing 3 g (0.86 wt%) of zinc oxide nanoparticles; this loss rises to 8.8 ml at 30 minutes. On the other hand, WBM with 6 g (1.71 wt.%) of zinc oxide shows a greater loss of API fluid, with 5.2 ml at 10 minutes and 12 ml at 30 minutes. Additionally, the amount of API fluid lost in WBM containing 9 g (2.57 wt%) of zinc oxide nanoparticles increases from 5.6 ml at 10 minutes to 11.5 ml at 30 minutes. These findings clearly show that increased API fluid loss is a result of higher zinc oxide nanoparticle concentrations. Avoiding losing more than 10 millilitres of API fluid is especially crucial because doing so may cause a larger filter cake to form which could impede drilling by obstructing fluid flow and decreasing drilling efficiency (Li et al., 2016). As a result, during drilling operations, careful consideration of nanoparticle concentration is required to maximise filtration rates while avoiding excessive fluid loss.

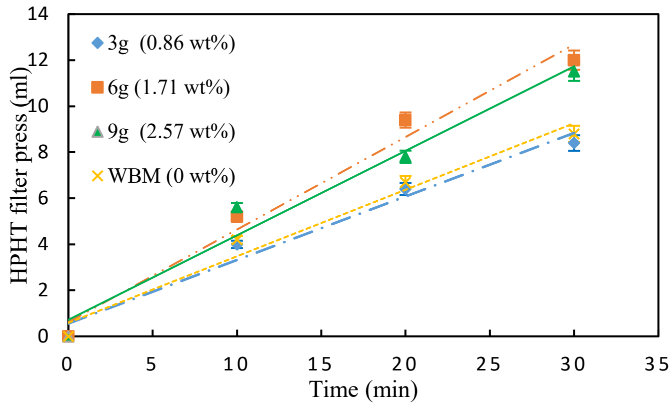

Figure 9. Overall HPHT filtration rate of zinc oxide nanoparticles (10-30 nm) with different weights.

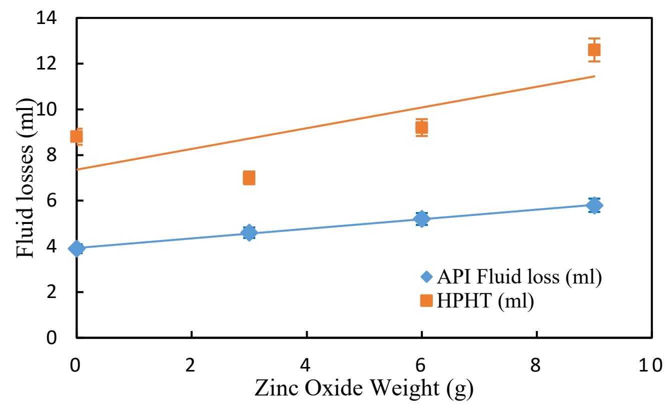

Figure 10. Filtration rate of water-based mud (WBM) with different weights of ZnO (30 – 45 nm).

3.2.3 Filtration rate of zinc oxide nanoparticle (30-45 nm) with different concentrations.

The filtration rate of water-based mud (WBM) with different amounts of 30–45 nm-sized zinc oxide (ZnO) nanoparticles is shown in Figure 10. Without the addition of zinc oxide nanoparticles, the API fluid loss for standard WBM is roughly 3.9 ml. However, with 30-45 nm zinc oxide nanoparticles the amount of API fluid lost increases gradually and proportionately until it reaches 5.8 ml. Regarding HPHT fluid loss, the standard WBM begins at approximately 8.8 ml. When zinc oxide nanoparticles are added, this value steadily drops until it reaches about 7 ml at a concentration of 3 g (0.87 wt%) of 30-45 nm ZnO nanoparticles. According to the experiment, a zinc oxide nanoparticle concentration of 3 g (0.87 wt%) is ideal for HPHT settings since it reduces fluid losses and facilitates more efficient drilling. The capacity of ZnO nanoparticles to enter the mud's pores and raise the effective pore volume, which permits more fluid to escape, maybe the cause of the increase in API fluid loss seen after their addition. However, fluid loss increases with nanoparticle concentration, suggesting that there might be a threshold concentration at which the drawbacks exceed the advantages. In general, the best concentration of zinc oxide nanoparticles to achieve low fluid losses and improve drilling efficiency in HPHT applications appears to be 3 g (0.87 wt%).

The overall API filtration rate of water-based mud (WBM) containing zinc oxide (ZnO) nanoparticles at different weight concentrations, with sizes ranging from 30 to 45 nm, is shown in Figure 11. The findings demonstrate that while the specific filtration rate varied with the concentration of nanoparticles, all drilling fluids saw an increase in filtration rate over time. The API fluid loss for conventional WBM starts at 2.1 ml at 10 minutes and progressively rises to 3.9 ml at 30 minutes. The API fluid loss decreases to 1.6 ml after 10 minutes but rises to 4.6 ml at 30 minutes with the addition of 3 g (0.86 wt%) of ZnO nanoparticles. The API fluid loss in WBM containing 6 g (1.71 wt%) of ZnO nanoparticles is 2.3 ml at 10 minutes and increases to 5.2 ml at 30 minutes. Lastly, the API fluid loss starts at 2.7 ml at 10 minutes and rises to 5.8 ml at 30 minutes with 9 g (2.57 wt.%) of ZnO nanoparticles. The inclusion of 30-45 nm ZnO nanoparticles was found to increase API fluid loss. This increase in fluid loss can be related to the nanoparticles' increased surface area, which may obstruct the mud's pores and hinder the filtration process. At larger nanoparticle concentrations, this blocking action intensifies and increases fluid loss. Consequently, although ZnO nanoparticles can affect WBM's filtration characteristics, larger concentrations may lead to less effective filtering because of increasing pore blockage.

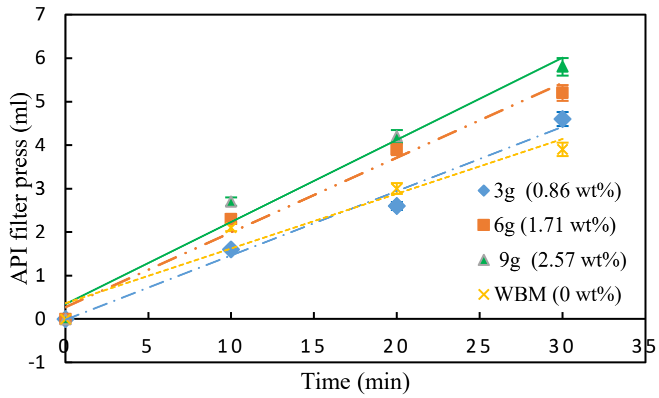

Figure 11. Overall API filtration rate of zinc oxide nanoparticles (30 - 45 nm) with different weights.

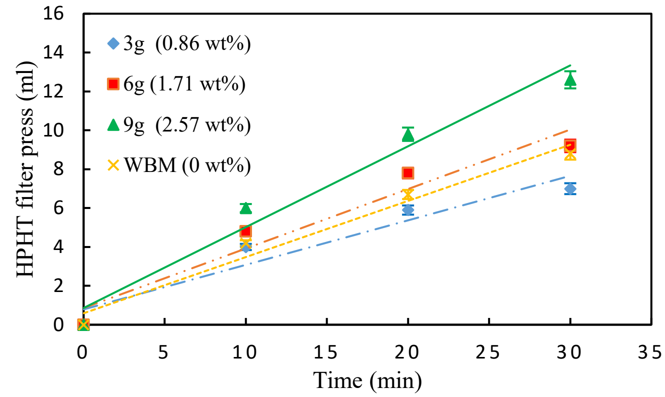

Figure 12. Overall HPHT filtration rate of zinc oxide nanoparticles (30-45 nm) with different weights.

Figure 12 shows the total HPHT filtration rate of water-based mud with zinc oxide nanoparticles (30-45 nm) of different concentrations. The findings show that, for all mud formulations examined, the HPHT fluid loss rises with time; however, the rate of increase differs depending on the ZnO nanoparticle concentration. The HPHT fluid loss for traditional WBM increases to 8.8 ml at 30 minutes from 4.2 ml at 10 minutes. The HPHT fluid loss drops to 4 ml at 10 minutes and rises to 7 ml at 30 minutes with the addition of 3 g (0.86 wt.%) of ZnO nanoparticles, indicating enhanced performance over the typical mud. Nevertheless, the HPHT fluid loss starts at 4.8 ml at 10 minutes and rises to 9.2 ml at 30 minutes when the concentration of ZnO nanoparticles is increased to 6 g (1.71 wt.%). The HPHT fluid loss begins at 6 ml at 10 minutes and increases dramatically to 12.6 ml at 30 minutes at the highest concentration of 9 g (2.57 wt%). According to these findings, adding ZnO nanoparticles can initially enhance WBM's filtration efficiency by lowering HPHT fluid loss, but adding too much of them can be harmful. Higher nanoparticle concentrations may cause a thicker filter cake to form, which would decrease the mud's overall effectiveness by increasing the differential pressure across the cake. This would explain the rise in HPHT fluid loss. Therefore, it seems that there is a ZnO nanoparticle concentration that balances enhanced filtration with little detrimental effect on mud performance. The overabundance of nanoparticles can cause filter cake thickness and pressure differential, which can reduce drilling efficiency and result in less-than-ideal outcomes.

3.2.4 Overall filtration rate of conventional water-based mud (WBM), silicon dioxide and zinc oxide nanoparticles

Figure 13 compares the API filtration rate between conventional water base mud (WBM), WBM with silicon dioxide nanoparticles, and WBM with zinc oxide nanoparticles. According to the findings, all drilling fluid samples with and without nanoparticles have an increasing filtration rate over time. The API fluid loss for conventional WBM begins at 2.1 ml at 10 minutes and progressively rises to 3.9 ml at 30 minutes. On the other hand, WBM with 1.71 wt% silicon dioxide nanoparticles shows a lower initial API fluid loss at 10 minutes (1.2 ml), and this increases to 5.3 ml at 30 minutes. The amount of API fluid lost by WBM containing zinc oxide nanoparticles (30-45 nm, 0.86 wt%) is 2.1 ml at 10 minutes and rises to 4.6 ml at 30 minutes. At 10 minutes, the API fluid loss in WBM containing zinc oxide nanoparticles (10-30 nm, 0.86 wt%) is 1.8 ml, and after 30 minutes, it rises to 4 ml. These results indicate that while the filtration rates of nanofluid-based WBMs are comparable to those of conventional WBM over time, they tend to show lower values at shorter intervals. Silicon dioxide (1.71 wt%) showed the highest filtration rate over time, and zinc oxide (10-30 nm), 0.86 wt%, showed the lowest filtration rate. This suggests that adding nanoparticles, especially zinc oxide (10-30 nm), can effectively lower the filtration rate, especially at shorter intervals. This is advantageous because the reduced filtration rate may help mitigate excessive mud cake formation and reduce drag forces within the wellbore, potentially improving drilling operations (Shah, 2010; Loggins, 2017).

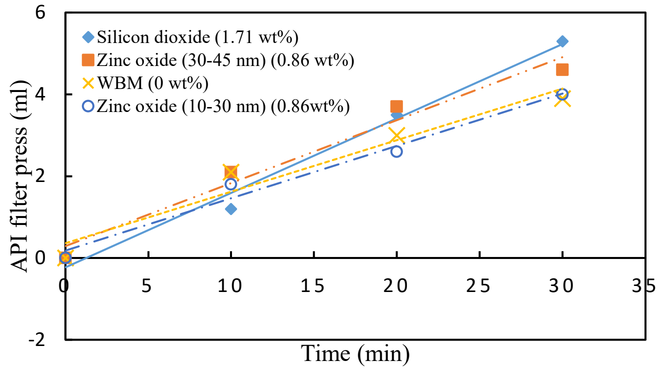

Figure 13. Overall API filtration rate for silica and zinc oxide nanoparticles.

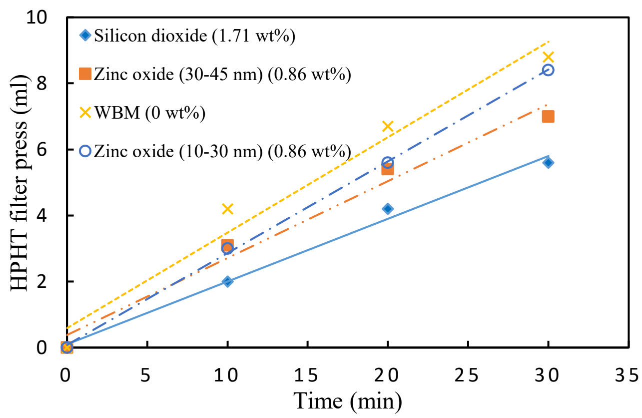

Figure 14. Overall HPHT filtration rate for silicon dioxide and zinc oxide nanoparticles.

The HPHT filtration rates for the conventional water-based mud (WBM), WBM with silicon dioxide nanoparticles, and WBM with zinc oxide nanoparticles are contrasted with time in Figure 14. The findings show that the filtration rate rises with time for all samples of drilling fluid. The fluid loss with conventional WBM begins at 4 ml at 10 minutes and progressively rises to 8.8 ml at 30 minutes. On the other hand, WBM containing 1.71 weight per cent silicon dioxide nanoparticles exhibits a markedly reduced initial fluid loss of 2 millilitres at 10 minutes, which progressively rises to 5.6 millilitres at 30 minutes. The fluid loss in WBM containing zinc oxide nanoparticles (30-45 nm, 0.86 wt%) is 3.1 ml at 10 minutes and increases to 7 ml at 30 minutes. In the meantime, the fluid loss in WBM containing zinc oxide nanoparticles (10–30 nm, 0.86 wt%) increases to 8.4 ml after 30 minutes, from 3 ml after 10 minutes. These results imply that whereas nanofluid-based WBM filtration rates tend to be lower at shorter time intervals, they eventually approach those of traditional WBM. Conventional WBM demonstrated the highest overall filtration rate among the studied samples, whereas WBM with silicon dioxide (1.71 wt%) showed the lowest. This shows that adding silicon dioxide nanoparticles in particular can successfully lower the filtration rate, especially early on. This is advantageous for preventing the production of too much mud cake and lowering drag forces inside the wellbore. The use of nanoparticles reduces the filtration rate, indicating their potential to improve filtration control under HPHT conditions and thereby improve drilling fluid performance.

4. CONCLUSION

This paper presents a study on the filtration rates of water-based drilling mud with silicon dioxide and zinc oxide nanoparticles. The water-based mud (WBM) used in this study was made to constitute different chemicals such as Caustic Soda (NaOH), Sodium Chloride (NaCl), Xanthan Gum, Starch, HT Starch, Calcium Carbonate ($CaCO_3$), and Barite for the usage in a deep well. The experiments were conducted using an HPHT filter press, which simulated very high-pressure and high-temperature conditions, and an API filter press simulating low-pressure and low-temperature conditions. The experiment results with silicon dioxide nanoparticles showed that the water-based mud with a concentration of 1.71 wt% had a better filtration rate than the mud with 0.86 wt% and 2.57 wt% concentrations. Similarly, the experiment with zinc oxide nanoparticles showed that the mud with a concentration of 0.86 wt% and a particle size of 30-45nm had a better filtration rate than the mud with 1.71 wt% and 2.57 wt% concentrations. Overall, the use of nanoparticles improved the filtration rate performance of the water-based mud compared to conventional mud. The HPHT filtration rate of conventional water-based mud was reduced by 26.2% for zinc oxide and 52.3% for silicon dioxide nanoparticles. This finding highlights the potential of using nanoparticles in the drilling process to improve well stability and reduce the risks associated with wellbore instability.

CONFLICT OF INTEREST

The authors declare that there is no conflict of interest in regard to publishing this paper.

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