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ESEARCH ARTICLE

Impact of Ferric Oxide Nanoparticles on Water-Based Drilling Fluid Properties Under Low-Pressure, Low-Temperature and High-Pressure, High-Temperature Conditions

AKRAM R. TOUBAR [1*], ADEL M. SALEM[2], HESHAM H. ABUSEDA [3], MOHSEN G. ELNOBY [4]

[1] MSc Student, Department Of Petroleum Engineering, Future University in Egypt, Egypt
[2]Professor in Petroleum Engineering, Faculty Of Petroleum And Mining Engineering, Suez University , Egypt
[3]Professor and Head Of Drilling Fluid Lab, Egyptian Petroleum Research Institute (EPRI) , Egypt
[4] Lecturer in Petroleum Engineering, Department Of Petroleum Engineering, Future University in Egypt, Egypt

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***Corresponding Author:**
Akram.tobar@fue.edu.eg

ABSTRACT

The application of nanotechnology has the potential to revolutionize additive properties and behavior by modifying particle characteristics to meet specific technological, environmental, and operational needs. Consequently, creating customized nanoparticles through nanotechnological research holds significant promise for developing smart fluids for various industrial applications. Due to their size, which is smaller than typical microparticles but larger than atom clusters, these ultrafine particles possess a high specific surface area and extensive contact area. Nano-scale fluid additives are designed to enhance fluid properties at much lower additive concentrations because their small particle size provides both external and internal inhibitory potential at very low concentrations. This paper explores the impact of adding Fe2O3 nanoparticles to a water-based mud. In this study, ferric oxide nanoparticles were prepared through milling and evaluated in KCl-polymer mud for their rheological properties and filtration performance under both Low-pressure, low-temperature (LPLT) and high-pressure, high-temperature (HPHT) conditions. The study demonstrates that even a minimal concentration of nanoparticles can significantly improve the performance of drilling fluids. Additionally, the results suggest that nanoparticles can effectively fine-tune the properties of drilling fluids.

INTRODUCTION

The success of drilling oil and gas wells heavily relies on the drilling fluid used during both drilling and completion. The selection of drilling fluid and its additives becomes increasingly complex as new products with diverse functions are introduced over time. The need for new solutions or formulations becomes more pressing, particularly as hydrocarbon exploration extends into geologically complex formations. Today, the number of deep well explorations is rapidly increasing to meet the growing global demand for oil and gas. Drilling operations face significant technical challenges, especially in deep-water operations, where high pressure and high temperature (HPHT) conditions can adversely affect the rheological properties of drilling fluids.

Maintaining the desired rheological properties of drilling fluid is one of the primary challenges in deep well drilling. Numerous factors in deep drilling can significantly influence and alter these properties. Research has explored the effects of HPHT on the viscosity of both oil-based and water-based drilling fluids [1,2]. Findings indicated that HPHT conditions cause changes and negative impacts on the fluid's rheological properties. Oil-based drilling fluids are preferred for HPHT conditions due to their superior stability and ability to maintain rheological properties under extreme conditions. However, under HPHT conditions, drilling fluids may also experience gelation, degradation of weighting materials, and breakdown of polymeric additives that serve as viscosifiers, surfactants, and fluid-loss additives [3,4].

Furthermore, many muds contain solid particles that can cause formation damage due to poor quality filter cake. Cuttings generated during drilling can produce micro-sized and colloidal particles that lead to severe formation damage if poor quality filter cake is deposited on the wellbore wall. The oil and gas industry acknowledges the damage caused by solid particle invasion and the difficulty of cleaning it, thus prioritizing the prevention of formation damage [5].

Another issue is filtrate loss, which occurs in high permeability formations where drilling fluid filters through the wellbore wall and invades the formation. The solid residue of the drilling fluid deposits a layer of mud cake on the borehole wall. In high permeability formations, the high-pressure difference caused by drilling fluid invasion can cause the drill pipe to get stuck in the thick mud cake, a phenomenon known as differential sticking. In practice, various fluid loss agents are used in drilling fluids to reduce fluid loss. However, it is often impossible to reduce fluid loss with micro and macro type fluid loss additives due to their physio-chemical and mechanical characteristics. Normal fluid loss additives with diameters ranging from 0.1 to 100 μm are ineffective in reducing fluid loss in formations with pore sizes less than 0.1 μm [6].

Iron oxides are naturally occurring substances that can also be manufactured in the lab. Iron oxide (IO) nanoparticles possess magnetic characteristics, making them highly effective for use in magnetic and electrical applications, such as sensors, imaging, and data storage, drug-delivery, and so forth due to their biocompatibility and non-toxicity [7]. Fe2O3 nanoparticles provided formation strengthening, and reduced filtrate and filter cake thickness [8,9]. The addition of Fe2O3 nanoparticles at concentrations between 0.3-0.5 wt.% improved the rheological behavior and filter cake properties of bentonite-based drilling fluids. Moreover, incorporating Fe2O3 nanoparticles resulted in the formation of a high-quality filter cake [10].

Both technical and environmental challenges greatly increase the cost of drilling a well. However, the oil industry views this as an opportunity to develop cost-effective and environmentally sustainable drilling fluids that meet technical requirements. Consequently, nanotechnology has garnered interest in the oil and gas industry as a potential solution to these challenges due to its unique properties. The objective of this research is to use nano ferric oxide in drilling fluids to improve rheological and filtration performance under LPLT and HPHT drilling conditions.

MATERIALS AND METHODS

In this research, KCl-polymer mud was used as a reference to examine the effect of adding ferric oxide nanoparticles. Each nano-based drilling fluid was prepared and subjected to testing. Key rheological properties, such as mud weight, plastic viscosity, yield point, gel strength, in addition to filter cake thickness, and filtrate loss at LPLT, and HPHT conditions.

2.1 Ferric oxide NP preparing

Ferric oxide material in microscale was processed through milling at the Egyptian Petroleum Research Institute (EPRI), depicted in Figure 1. To investigate the impact of adding nanoparticles (NPs) on drilling fluid properties, various nanofluids were created by blending the base fluid with different concentrations of NPs under high shear conditions. Our study capped NP concentrations at 1.1 wt.%, leveraging their high surface-area-to-volume ratio to potentially enhance water-based mud properties even at low levels. This approach aims to mitigate costs and prevent NP aggregation by maintaining optimal dispersion in the drilling fluid. Different NP concentrations were introduced into the base fluid, detailed in Table 1. Experimental evaluations focused on identifying optimal performance through rheological tests and filtration assessments under room temperature conditions (75°F) to choose the optimum nano particles concentration and test it in HPHT conditions.

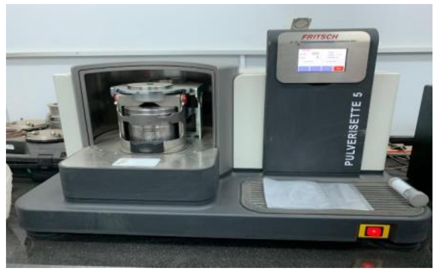

Figure 1: Milling Instrument at EPRI

Table 1: Fe2O3 Nanoparticles Concentrations

Percent (%)	Lab Units (gm)
0.3	1.05
0.5	1.75
0.7	2.45
0.9	3.15
1.1	3.85

2.2. Formulation of drilling fluid

A fully formulated KCl-polymer mud was utilized to study the effect of nanoparticles (NPs) on the properties of drilling fluid [11]. The mud included caustic soda for alkalinity control, high-yield bentonite to provide primary viscosity, and XC-polymer to fine-tune the rheological properties of the base fluid. KCl was incorporated as a shale inhibitor. Polyanionic cellulose low-viscosity (PAC-LV) and pre-gelled starch were added as standard filtrate loss additives, while barite was used as a weighting agent. All additives were sourced from various service companies and used as received. The formulation outlined in Table 2 was used to prepare the base drilling fluid. This study assumes that adding 1 gram of material to 350 ml of fluid in the lab equates to adding 1 pound mass (lb-m) of material to 1 barrel (bbl) of fluid in the field. Preparation began with adding caustic soda to adjust the pH to 9.5, followed by incorporating bentonite into 350 ml of deionized water while agitating with a Hamilton Beach mixer at speed-1 for 15 minutes. Subsequently, the other chemicals were added gradually to prevent the formation of 'fisheyes' in the drilling fluid, keeping the mixer at the initial speed. Adequate stirring time was allowed between additives as specified in Table 2.

Table 2: KCL-Polymer mud formula

Product	**Lab Units (gm)**	**Mixing Time (min)**
Fresh water	350 (ml)	-
Caustic Soda	0.5	-
Bentonite (High Yielding)	5	10
KCL	28	10
XC Polymer	0.75	10
Starch	4	10
PAC LV	0.5	10
Barite	35	15

2.3. Rheological Measurements

The OFITE rotational viscometer (Model 800) was utilized to evaluate the rheological characteristics of the drilling fluids at atmospheric pressure and room temperature in additional to 194 °F for the optimum concentration nanoparticle according to the LPLT rheological and API filter press measurements, and API filtrate loss results. Shear stress readings were recorded at seven predetermined speeds: 600, 300, 200, 100, 60, 6, and 3 revolutions per minute (rev/min). The device was operated until the dial indicator displayed a stable reading for each speed. Key drilling fluid parameters, including Plastic Viscosity (PV) and Yield Point (YP), were calculated in accordance with standard procedures [35]. PV, expressed in centipoise (cp), was determined by subtracting the 300 rpm reading from the 600 rpm reading. YP, measured in pounds per 100 square feet (lb/100 ft^2), was calculated by subtracting the PV from the 300 rpm dial reading. The initial gel strength (GS) or Gel 0 (in lb/100 ft^2) was obtained by shearing the fluid at high speed and then letting it rest for 10 seconds, with the maximum dial reading at 3 rpm recorded as Gel 0. To determine the final gel strength or Gel 10 (in lb/100 ft^2), the same process was repeated, allowing the fluid to rest for 10 minutes instead.

2.4. API Filtrate Loss Measurements

Filtrate loss tests were performed using an OFITE API filter press, which includes a metal cylinder with pressure seal rings. The setup also featured a regulated air pressure system and standard filter papers. The API filter press was utilized to assess filtration properties under low-temperature/low-pressure (LT/LP) conditions of 75 °F and 100 psi. Each test lasted for 30 minutes, with the filtrate collected in a graduated cylinder, and the total volume measured to the nearest 0.1 ml. After each test, the thickness of the filter cake was measured using a digital Vernier calliper.

2.5. HPHT Filtrate Loss Measurements

An HPHT (High-Pressure/ High-Temperature) filter press is a device used to simulate the downhole Conditions of drilling wells, helping evaluate drilling fluid properties like filtration and mud-cake formation under extreme conditions. The mechanism involves applying a controlled amount of pressure and heat to the drilling fluid in a cell containing filter paper. As pressure is applied, the liquid phase (filtrate) is forced through the filter, while solids form a mud-cake on the surface. Measurements of filtrate volume and mud-cake thickness help assess fluid performance at high temperatures and pressures. The pressure used in an HPHT (High-Pressure/ High-Temperature) filter press is typically 500 psi. This high pressure is applied to simulate downhole conditions in drilling operations, allowing for accurate measurements of filtration properties and mud-cake formation under extreme conditions. The exact pressure setting depends on the specific test being conducted and the desired replication of well conditions. Three tests will be conducted using the HPHT filter press at three different temperatures—194°F, 302°F, and 392°F— based on the optimum nanoparticle concentration on LPLT rheological and API filter press measurements. Each test lasted for 30 minutes, with the filtrate collected in a graduated cylinder, and the total volume measured to the nearest 0.1 ml. After each test, the thickness of the filter cake was measured using a digital Vernier calliper.

3. RESULTS AND DISCUSSION

A summary of all the rheological tests conducted at 75°F, and 194°F, along with their results under various conditions. Also Filtration and filter cake properties were measured using an API filter press at 100 PSI and 75°F, in addition to using a high-pressure, high-temperature filter press at three different temperatures and a 500 PSI differential pressure.

3.1. Plastic Viscosity (PV) for LPLT

Figure 2 illustrates the effect of nanoparticles (NPs) on the plastic viscosity (PV) of drilling fluid. The PV is primarily influenced by the friction between inert solids (their shape, size, and distribution). As the concentration of NPs increases, the PV also rises till 0.5 wt% and decrease after that. The addition of 0.7 wt.%, and 1.1 wt.% of ferric oxide NPs, (86 nm) led to a decrease in the PV by 10%, and 23%, respectively. However, the addition of 0.3 wt.%, and 0.5 wt.% causes a rise in the PV where 0.9 wt % show no changes. Maintaining a minimum PV is crucial in drilling operations to enhance the rate of penetration, reduce energy consumption for mud circulation, cool and lubricate downhole equipment, and minimize mud circulation losses caused by excessive equivalent circulating density, which can result in formation fractures.

Table 3: Summary of the rheological measurements at 75 °F

								Gel (lb/100ft2)			
Blends #	Ɵ 600	Ɵ 300	Ɵ 200	Ɵ 100	Ɵ 60	Ɵ 6	Ɵ 3	10 Sec	10 Min	PV (cp)	YP ((lb/100 ft2)
0%	47	36	28	20	15.5	8	6.5	7	8	11	25
0.3% Fe2O3 nm	45	32	26	19	16	7.5	8	8.5	9	13	19
0.5% Fe2O3 nm	52	37	30	21	16.5	7.5	8	9	9.5	15	22
0.7% Fe2O3 nm	43	33	27	20	16	8	7	8	9	10	23
0.9% Fe2O3 nm	42	31	27	19	16	8	5	6	7	11	20
1.1% Fe2O3 nm	41.5	33	26.5	19	15	7	7	8	9	8.5	24.5

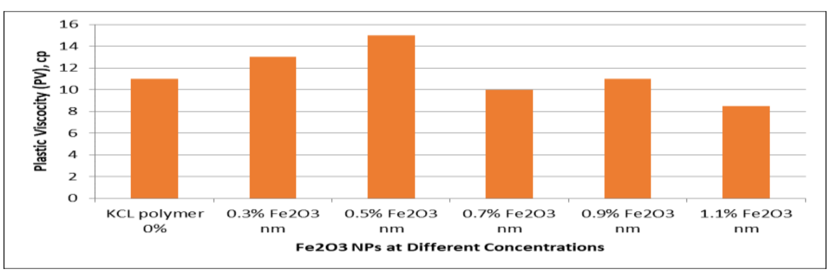

Figure 2: Impact of Fe2O3 nanoparticles on plastic viscosity

3.2. Yield Point (YP) for LPLT

Yield Point (YP) influences the ability of drilling fluid to carry cuttings. Generally, a higher YP increases frictional losses, leading to a higher equivalent circulation density (ECD). A higher YP is particularly useful in large-diameter wells for effective hole cleaning. Conversely, a low YP can result in the settling of barite and drilled cuttings. Figure 3 demonstrates the effect of adding ferric oxide NPs in YP. With the addition of 0.3 wt.% , 0.5 wt.%, 0.7 wt.%, 0.9 wt.%, and 1.1 wt.% of ferric oxide NPs, a reduction of 24%, 12%, 8%, 20%, and 2% respectively. A balance must be maintained between excessively high and low yield points (YP) in drilling fluids. A high YP can result in excessive pressure losses, which in turn necessitates increased pump pressure to circulate the mud effectively. On the other hand, a low YP can lead to inadequate cuttings transport and problems with hole cleaning. Thus, managing the yield point is essential for ensuring efficient cuttings transport, particularly in high-angle or horizontal drilling operations. Proper control of YP helps in managing pressure losses and preventing the settling of solids, thereby optimizing overall drilling performance.

3.3. Gel Strength for LPLT

It refers to the measurement of shear stress at very low shear rates after the mud has been left stationary for a period of time. This property enables the mud to suspend cuttings and weighting materials during pauses in circulation. Initial gel strength represents the amount of shear force needed to break the gel after the fluid has been static for 10 seconds, indicating its ability to keep cuttings suspended in the drilling fluid under stationary conditions. Final gel strength, like initial gel strength, measures the torque needed to break the gel but after the drilling fluid has been at rest for 10 minutes. Figure 4 illustrates how different concentrations of ferric oxide nanoparticles (NPs) affect the gel strength of the drilling fluid. This property ensures proper suspension of rock cuttings and barite, helping to prevent sagging issues. An increase in gel strength was observed with most concentrations of ferric oxide NPs, with the highest increase seen at 0.5 wt. %, resulting in a 22% and 16% rise in gel strength at 10 seconds and 10 minutes, respectively. However, both 0.3 wt.% and 0.7 wt.% produced nearly identical results. On the other hand, the NPs at 0.9 wt.% showed a reduction in gel strength by 14% at 10 seconds and 12.5% at 10 minutes.

3.4. Impact of nanoparticles on Filtration Characteristics for LPLT

Figure 5 illustrates the effect of ferric oxide nanoparticles (NPs) on the filtration volume of KCL-Polymer mud. The results show that all concentrations of NPs improve the filtration properties of the mud (as shown in Table 4). The optimal concentration was found to be 0.5 wt.%, which led to a 44% reduction in filtrate volume. This suggests that the particle size and charge density of the NPs influence the filtrate loss in NP-based drilling fluids by altering the interactions between the KCL-Polymer mud particles and filling the spaces between them. The extent of this internal filling depends on the size of the NPs, with greater filling leading to more significant reductions in filtration. Reducing or preventing filtrate loss is essential for minimizing wellbore instability and related issues.

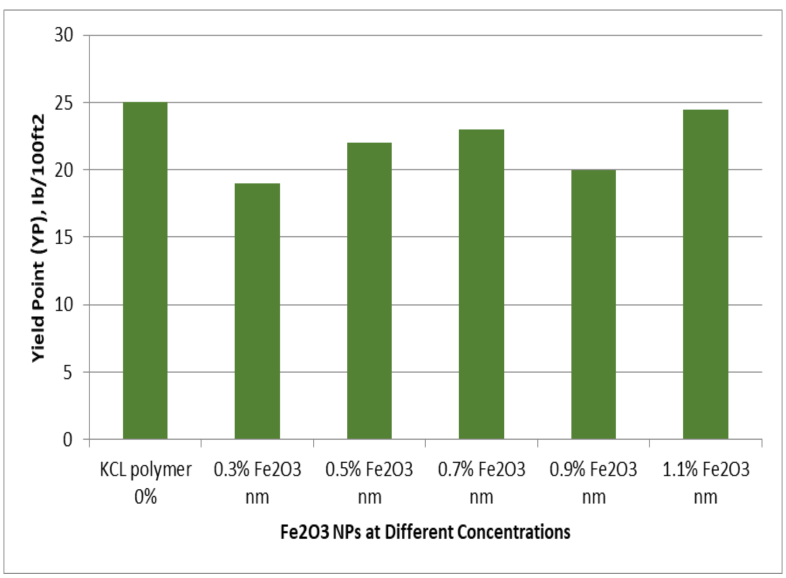

Figure 3: Impact of Fe2O3 nanoparticles on yield point

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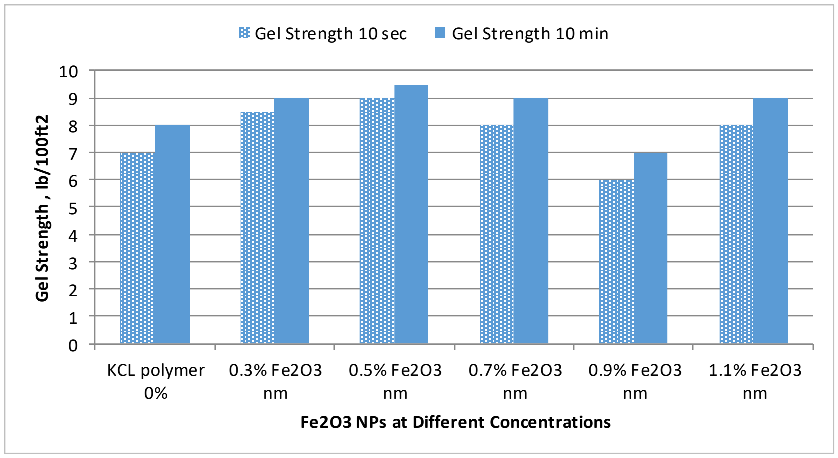

Figure 4: Impact of Fe2O3 Nanoparticles on gel strength.

Table4: Influence of Adding Fe2O3 Nanoparticle with API Filtration

Time, min	**Fluid Type**					
	Base Fluid	Fe2O3 nm				
	Concentration of Nanoparticles					
	0%	0.3 wt.%	0.5 wt.%	0.7 wt.%	0.9 wt.%	1.1 wt.%
	Fluid Loss Volume (ml)					
5	3	1.5	1	2	2	2
10	4.1	2.7	2.5	3	3	3
15	5.8	3.5	3.2	3.7	3.8	3.7
20	7.1	4.1	3.7	4.5	4.5	4.5
25	8.2	4.7	4.5	5	5.1	5.1
30	9	5.3	5	5.6	5.7	5.6

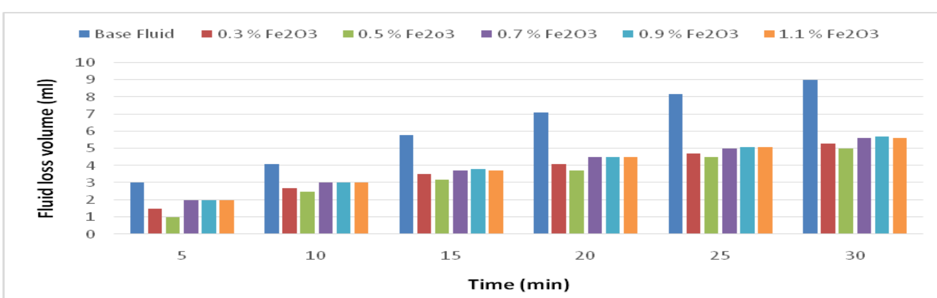

Figure 5: Influence of Adding Fe2O3 Nanoparticle with API Filtration.

3.5. Impact of nanoparticles on Filter Cake Thickness for LPLT

In drilling operations, mud cake refers to the layer of solid particles that forms on the walls of a borehole due to the use of drilling fluids. The thickness of this mud cake, typically measured in millimetres, is crucial to wellbore stability and fluid circulation, ideally ranging between 1 to 2 mm. Excessively thick mud cake can reduce permeability, hinder oil or gas flow, cause the drilling pipe to become stuck, and create pressure imbalances, leading to well control issues. To manage mud cake thickness, the properties of the drilling fluid—such as density, viscosity, and solid content—are adjusted to ensure a thin, uniform layer. Table 5 shows that the effect of different concentrations of Fe_2O_3 nanoparticles on mud cake thickness in KCL-Polymer mud was analyzed by varying the nanoparticle concentrations from 0% to 1.1%. At 0% concentration, the mud cake thickness was 0.6 mm, serving as the baseline. With the addition of 0.3% nanoparticles, the thickness decreased to 0.5 mm, indicating that a small concentration of nanoparticles can reduce mud cake formation. However, as the concentration increased to 0.5%, the thickness rose to 0.7 mm, suggesting that higher concentrations may cause a slight increase in thickness. At 0.7%, the thickness further increased to 0.75 mm, followed by a reduction to 0.65 mm at 0.9%, indicating some fluctuations. Finally, at 1.1%, the thickness returned to 0.7 mm. These variations suggest that nanoparticle concentration influences mud cake formation, with optimal reductions at lower concentrations, while higher levels may lead to slight increases.

Table 5: Influence of Adding Fe_2O_3 Nanoparticles on Mud-Cake.

Mud	KCL-Polymer Mud					
Concentration Of Nanoparticles	0%	0.3%	0.5%	0.7%	0.9%	1.1%
Mudcake Thickness (ml)	0.6	0.5	0.7	0.75	0.65	0.7
Filter Paper with Mudcake						

3.6. Impact of nanoparticles on Rheology for HPHT

A concentration of 0.5% wt ferric oxide nanoparticles was selected to establish HPHT tests based on comprehensive analysis of rheology and filtration results. Rheological studies indicated that this concentration provided optimal viscosity, ensuring proper flow behaviour and stability of the fluid system. Additionally, filtration tests demonstrated that 0.5% wt ferric oxide nanoparticles significantly improved the fluid's ability to control particle invasion and reduce filtrate loss. This balance between enhanced rheological properties and efficient filtration performance makes 0.5% wt the ideal concentration for achieving both mechanical stability and filtration control. Table 6 show that at 194°F, the rheological measurements of the KCL-Polymer mud containing 0.5% Fe_2O_3 nanoparticles showed a reduction in viscosity compared to lower temperatures, indicating a temperature-dependent thinning behaviour. At this elevated temperature, the readings were 33 at 600 rpm, 24 at 300 rpm , 20 at 200 rpm , 17 at 100 rpm , and 13 at 60 rpm . At lower shear rates, 6 and 3 rpm, the values were 7 and 4, respectively. The gel strength at 10 seconds and 10 minutes was 4.5 lb/100ft^2 and 4.6 lb/100ft^2, indicating minimal gel development over time. The plastic viscosity (PV) was measured at 9 cp, while the yield point (YP) was 15 lb/100ft^2. This overall reduction in rheological properties with increasing temperature reflects the fluid's lower resistance to flow and decreased structural build-up under static conditions.

Table 6: Summary of the rheological measurements at 194°F.

								Gel (lb/100ft2)			
Blends #	Ɵ 600	Ɵ 300	Ɵ 200	Ɵ 100	Ɵ 60	Ɵ 6	Ɵ 3	10 Sec	10 Min	PV (cp)	YP (lb/100ft2)
0.5% Fe2O3 nm	33	24	20	17	13	7	4	4.5	4.6	9	15

3.7 Impact of nanoparticles on Filtration Characteristics for HPHT

Table 7 highlights the influence of adding 0.5% Fe_2O_3 nanoparticles on fluid loss behaviour using a High-Pressure High-Temperature (HPHT) filter press at different temperatures. At 194°F, the fluid loss volume after 30 minutes was 2.9 ml, demonstrating minimal filtration. As the temperature increased to 302°F, the fluid loss volume rose to 4.9 ml, indicating a significant reduction in fluid retention capacity. At the highest temperature of 392°F, the fluid loss volume further increased to 7.3 ml, showing a pronounced decline in the fluid's ability to prevent filtration at elevated temperatures. This trend at figure7 suggests that higher temperatures negatively affect the performance of the 0.5% Fe_2O_3 nanoparticle with KCL-Polymer mud in controlling fluid loss.

Table 7: Influence of Adding 0.5 % Fe2O3 Nanoparticle with HPHT Filter press.

Time, min	Fluid Type		
	0.5 % Fe2O3 nm		
	Temperature (°F)		
	194 °F	302 °F	392 °F
	Fluid Loss Volume (ml)		
30	2.9	4.9	7.3

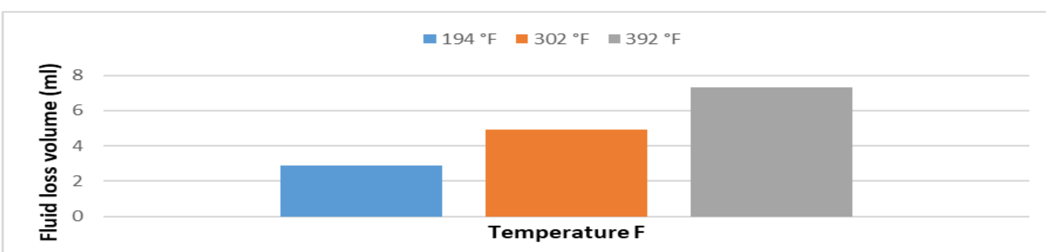

Figure 7. Summary of the filtration measurements at HPHT.

3.8 Impact of nanoparticles on Filter cake thickness for HPHT

Table 8 shows the influence of adding 0.5% Fe_2O_3 nanoparticles to KCl-polymer mud on the mud-cake thickness using a HPHT filter press at different temperatures. At 194°F, the mud-cake thickness was measured at 1.4 ml, increasing to 1.9 ml at 302°F, and further to 2.1 ml at 392°F. This indicates a progressive increase in mud-cake thickness with rising temperature, suggesting that higher temperatures result in a thicker, possibly less permeable filter cake, which could affect wellbore stability and fluid loss during drilling operations.

Filter Paper with Mudcake			

Table 8: Influence of Adding 0.5 % Fe_2O_3 Nanoparticles on MudCake at HPHT Filter Press.

4. CONCLUSIONS

The addition of ferric oxide nanoparticles (Fe_2O_3 NPs) to water-based drilling fluids has demonstrated significant improvements in both rheological properties and filtration performance under various conditions. The study highlights the potential of nanotechnology in addressing common drilling fluid challenges, particularly in low-pressure, low-temperature (LPLT) and high-pressure, high-temperature (HPHT) environments.

Ferric oxide nanoparticles, when added at an optimal concentration of 0.5 wt%, exhibited notable benefits, including enhanced plastic viscosity (PV), yield point (YP), gel strength, and reduced fluid loss. These improvements were particularly pronounced in high-angle and horizontal drilling operations, where efficient cuttings transport is essential. The nanoparticles also contributed to better formation of filter cakes, improving wellbore stability and reducing filtrate invasion, which is crucial for preventing formation damage.

However, the study also found that higher nanoparticle concentrations did not always yield further improvements. In some cases, such as with PV and filter cake thickness, increased concentrations led to diminishing or negative returns. For instance, mud cake thickness increased with nanoparticle concentrations beyond 0.5 wt%, which could negatively impact permeability and drilling efficiency.

HPHT tests showed that as temperature increased, the rheological properties of the mud declined, and filtration losses increased. This suggests that while ferric oxide nanoparticles enhance fluid performance, their effectiveness may diminish in extreme HPHT conditions. Nonetheless, even under these conditions, the nanoparticles helped maintain a reasonable level of fluid stability and filtration control.

Summary of LPLT Results:

Plastic Viscosity (PV): The PV increased with lower concentrations of NPs but decreased significantly at higher concentrations, indicating that optimal NP concentration can enhance the fluid's flow behavior.

Yield Point (YP): A reduction in YP was observed with increasing NP concentration, with a notable decrease at 0.7 wt% and 1.1 wt% of ferric oxide NPs. This suggests that while a high YP can improve cuttings transport, excessive values may lead to increased frictional losses.

Gel Strength: Initial and final gel strength increased with most NP concentrations, particularly at 0.5 wt%, but decreased at higher concentrations. This shows that NPs can enhance the mud's ability to suspend cuttings, though excessive NP concentrations might reduce gel strength.

Filtration Characteristics: All NP concentrations improved filtration properties, with a significant reduction in filtrate volume observed at 0.5 wt%. This indicates that NPs effectively reduce filtrate loss and enhance wellbore stability.

Filter Cake Thickness: The effect of NPs on filter cake thickness varied, with a decrease observed at lower concentrations but an increase at higher concentrations. This suggests that optimal NP concentrations can minimize mud cake thickness, while higher concentrations may lead to thicker cakes.

Summary of HPHT Results

Rheological Properties:

A reduction in viscosity and gel strength occurred compare to lower temperatures. Specifically, viscosity measurements decreased with increasing temperature.

At 194°F, the drilling fluid exhibited a viscosity of 33 at 600 rpm, with gel strength values of 4.5 lb/100ft^2 at 10 seconds and 4.6 lb/100ft^2 at 10 minutes. These values suggest minimal gel development over time, reflecting a decrease in structural build-up.

Filtration Characteristics:

The filtration volume increased with temperature. At 194°F, the fluid loss was 2.9 ml after 30 minutes. As temperatures rose to 302°F and 392°F, the fluid loss increased to 4.9 ml and 7.3 ml, respectively. This trend indicates a reduced ability of the fluid to control filtrate loss at elevated temperatures.

Filter Cake Thickness:

The thickness of the filter cake increased with temperature. At 194°F, the mud-cake thickness was 1.4 mm, rising to 1.9 mm at 302°F and 2.1 mm at 392°F. This progressive increase suggests that higher temperatures lead to a thicker and potentially less permeable filter cake, which could affect wellbore stability and fluid loss during drilling operations.

Comparison Between LPLT and HPHT Results:

Rheological Properties: At HPHT conditions, the drilling fluid exhibited reduced viscosity and gel strength compared to LPLT conditions. This temperature-dependent thinning behavior indicates that the fluid's resistance to flow decreases with increasing temperature, which may improve the ease of circulation but could affect overall performance under extreme conditions.

Filtration Characteristics: The filtration volume increased with temperature at HPHT conditions, highlighting a reduced ability to control fluid loss as temperatures rise. While NP addition improved filtration at LPLT, the performance diminished at higher temperatures.

Filter Cake Thickness: In HPHT conditions, the filter cake thickness progressively increased with temperature, contrary to the variable effects observed at LPLT. This suggests that higher temperatures lead to thicker, potentially less permeable filter cakes, which could impact wellbore stability and fluid loss.

In conclusion, Fe_2O_3 nanoparticles represent a promising additive for improving the performance of water-based drilling fluids, particularly in challenging environments. Their ability to enhance fluid properties at lower concentrations can reduce costs and minimize environmental impact. Future research could explore optimizing nanoparticle dispersion and further improving performance under extreme HPHT conditions, as well as evaluating the long-term effects of nanoparticle usage on well integrity and operational efficiency.

5. Acknowledgments

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6. REFERENCES

[1] M. Amani, and M. J. Al-jubouri, "An Experimental Investigation of the Effects of Ultra High Pressures and Temperatures on the Rheological Properties of Water-Based Drilling Fluids", SPE/APPEA International Conference on Health, Safety and Environment in Oil and Gas Exploration and Production, Perth, Australia, 11-13 Sept. 2012

[2] Y. Jung, M. Barry, J. K. Lee, P. Tran, Y. Soong, D. Martello, and M. Chyu, "Effect of Nanoparticle-Additives on the Rheological Properties of Clay-Based Fluids at High Temperature and High Pressure", AADE National Technical Conference and Exhibition, Huston, Texas, 12 - 14 Apr. 2011

[3] D. J. Oakley, K. Morton, A. Eunson, A. Gilmour, D. Pritchard, and A. Valentine, "Innovative Drilling Fluid Design and Rigorous Pre-Well Planning Enable Success in an Extreme HTHPWell", IADC/SPE Asia Pacific Drilling Technology Conference, Kuala Lumpur, Malaysia. 11 - 13 Sept. 2000.

[4] S. Shah, and M. Fakoya, "Rheological Properties of Surfactant-Based and Polymeric Nano-Fluids", SPE/ICoTA Coiled Tubing & Well Intervention Conference & Exhibition, Woodlands, TX, USA. 26 - 27 Mar. 2013

[5] M. Amanullah, M. AlArfaj, and Z. Al-Abdullatif, "Preliminary Test Results of Nano-Based Drilling Fluids for Oil and Gas Field Application", SPE/IADC Drilling Conference and Exhibition, Amsterdam, Netherland, 1 - 3 Mar. 2011

[6] M. Amanullah, and A. M. Al-Tahini, "NanoTechnology - Its Significance in Smart Fluid Development for Oil and Gas Field Application", SPE Saudi Arabia Section Technical Symposium, AlKhobar, Saudi Arabia, 9 – 11 May 2009

[7] Laurent,S.,Forge,D.,Port,M.,Roch,A.,Robic,C.,Elst,L.V.,andMuller,R.N.2008.MagneticIronOxide Nanoparticles: Synthesis, Stabilization, Vectorization, Physicochemical Characterizations, and Biological Applications. *Chem. Rev.* vol. 108, no. 6, pp 2064–2110

[8] Nwaoji,C.O,Hareland,G.,Husein,M.,Nygaard,R.,andZakaria,M.F.2013.WellboreStrengthening-Nano-Particle Drilling Fluid Experimental Design Using Hydraulic Fracture Apparatus. Paper SPE-163434 presented at the SPE/ IADC Drilling Conference and Exhibition, 5-7 March, Amsterdam, The Netherlands

[9] Zakaria,M.F.,Husein,M.,Hareland,G.2012.Novel Nanoparticle Based Drilling Fluid with Improved Characteristics. Paper SPE-156992-MS, presented at the SPE International Oilfield Nanotechnology Conference, 12-14 June, Noordwijk, The Netherlands

[10] Mahmoud, O., Nasr-El-Din, H. A., Vryzas, Z. et al. 2018b. Effect of Ferric Oxide Nanoparticles on the Properties of Filter Cake Formed by Calcium Bentonite-Based Drilling Muds. *SPE Drill & Compl* 33 (4): 12–26. SPE-178949-PA. https://doi.org/10.2118/184572-PA.

[11] Ahmed Mady., Omar Mahmoud, Abdel Sattar Dahab. Nanoparticles as Promising Additives yo Improve The Drilling of Egyptian Oil and Gas Fields. *Proceedings of the ASME 2020 39th International Conference on Ocean, Offshore and Arctic Engineering OMAE2020. OMAE2020-18858*

[12] Renecynth B. Jaurigue, Noemi G. Laspinas, Hyacin S. Inojales, Reygei B. Hermano. 2023. Rank-and-File Employees' Work Attitude, Motivation and Performance in an Academe. Pakistan Journal of Life and Social Sciences. E-ISSN: 2221-7630; P-ISSN: 1727-4915, Pak. j. life soc. Sci. (2023), 21(1): 236-254. https://www.pjlss.edu.pk/pdf_files/2023_1/236-254.pdf

[13] Tangkin Hong, Panutporn Ruangchoengchum. 2024. Analyzing the Impact of Performance Metrics on Profitability: A Case Study of SMEs in Cambodian Food, Beverage, and Tobacco Industries. Pakistan Journal of Life and Social Sciences. E-ISSN: 2221-7630; P-ISSN: 1727-4915, Pak. j. life soc. Sci. (2024), 22(1): 394-408. https://www.pjlss.edu.pk/pdf_files/2024_1/394-408.pdf

[14] Phuoc Tai Nguyen. (2024). Contemporary Interpretation of Marx's Philosophy of Life: New Era "Good Life" Inspiration. Pakistan Journal of Life and Social Sciences. E-ISSN: 2221-7630; P-ISSN: 1727-4915, Pak. j. life soc. Sci. (2024), 22(1): 1178-1186. https://www.pjlss.edu.pk/pdf_files/2024_1/1178-1186.pdf