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Experimental Study on Improving the Rheological Properties of Drilling Fluids Using Silca Nanoparticles

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بسم الله الرحمن الرحيم

(قُلْ هَلْ يَسْتَوِي الَّذِينَ يَعْلَمُونَ والَّذِينَ لا يَعْلَمُونَ إنَّما يَتَذَكَّرُ أُولُو الألْبابِ)

صدق الله العلي العظيم

سورة الزمر ايه (٩)

الإهداء

"من قال أنا لها "نالها

و نحن لها إنْ أبت ، رغماً عنها أتينا بها.

نلناها، وعانقنا اليومَ مجداً عظيماً ، فقد كانت الدروبُ قاسيةً ، وكانت طرقاً خسرنا بها الكثير ، **ولكننا وصلنا.**

الحمد لله حبّاً وشكراً و امتناناً، والحمد لله الذي أدركَنا بفضله أسمى الغايات.

و صرنا حين ننظر إلى أنفسنا و إلى نجاحنا نكون كمن ينظر إلى حلمه الذي طال انتظاره قد تحققَ بفضل الله تعالى وحسن توفيقه وكرم عطائه، فأصبح واقعاً نفتخر به.

<u>إلى عوائلنا الحبيبة</u>

مصدر القوة والإلهام في حياتنا، من زرعوا في قلوبنا حبّ العلم والتعلم، أمهاتنا، آبائنا، إخواننا و أخواتنا... فلكم منا كل الحب والاحترام .

<u>إلى أساتذتنا وزملائنا</u>

شكراً لكم على كل لحظةٍ كنتم بجوارنا، وعلى كل كلمة ومعلومة لم تبخلوا بها علينا.

ختاماً: الفضل والشكر لله علينا للصبر والعزيمة والإصرار، فها نحن اليوم نختتم كل ما مررنا به بفخر ونجاح ، والحمد لله من قبل ومن بعد، راجين الله تعالى أن ينفعنا بما علمنا، و أن يعلمنا ما نجهل؛ ليجعله حجة لنا لا علينا.

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Abstract

Silica nanoparticles are a promising addition to the oil and gas industry, contributing to improved drilling fluid performance and reduced environmental costs. However, more research is needed to determine the best ways to use these particles and overcome the challenges associated with them. Use of Silica Nanoparticles in Drilling Fluids Improving Rheological Properties: Silica nanoparticles contribute to increased drilling pressure, which leads to continued carrying of cutting to the surface and Reduce fluid loss. The particles plug the pores in the rock, reducing the loss of drilling fluid during the drilling process and Increased thermal stability, Silica nanoparticles increase the resistance of drilling fluid to high temperatures and high pressures and Improve cake properties. The particles reduce the formation of cake layer on the well walls, which contributes to improving the drilling process.

These include enhanced lubrication, improved drilling fluid properties, increased efficiency, and reduced environmental impact. The continued growth in publications suggests that research in this area is gaining momentum and that the integration of nanotechnology into drilling practices is becoming an increasingly important area of exploration.

Silica nanoparticles improve the properties of drilling fluids through several mechanisms, The particles interact with water and clay molecules in the drilling fluid and Preferably small in size, nanoparticles can reach the tiny pores in rocks, helping to seal them and reduce fluid loss and Uniform distribution of particles in the drilling fluid allows for a homogeneous improvement in properties.

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List of Abbreviations

Abbreviations	Key
nm	Nanometer
lbm	mass, pounds
Bbl	unit of volume, barrel
ppb	concentration, pounds per barrel
rev/min	revolution per minute
ζ	zeta-potential, Mv
YP	yield point, lbf/100ft2
PV	plastic viscosity, Cp
Gel	timed gel strength, lbf/100ft2
psi	pressure, pound per square inch
°F	temperature scale, Fahrenheit
γ	Shear rate, sec-1
τ	Shear Stress, lbf/100ft2
P	gram per cubic centimeter, pounds per gallon
nm	Nanometer
lbm	mass, pounds
Bbl	unit of volume, barrel
ppb	concentration, pounds per barrel
rev/min	revolution per minute
ζ	zeta-potential, Mv

Chapter one

INTRODUCION

1. Introduction

The oil and gas industry has witnessed significant developments in drilling technology, enabling it to access difficult oil reservoirs in harsh conditions. However, drilling operations face constant challenges, such as high temperature and pressure, which affect the performance of the drilling fluids used. The rheological properties of drilling fluids, such as viscosity and shear strength, are critical factors that determine the efficiency of drilling operations. In this context, the importance of using nanotechnology to improve the performance of drilling fluids is highlighted. Silica nanoparticles are promising materials that can be used to enhance the rheological properties of drilling fluids. These particles have unique properties, such as their large surface area and high chemical activity, which make them able to interact with components of the drilling fluid and improve its properties. previous studies have shown that adding silica nanoparticles to drilling fluids can increase their viscosity, improve their thermal stability, increase shear strength, and reduce fluid loss. These improvements contribute to enhancing the ability of the drilling fluid to carry drilling output, clean the well, prevent well wall collapse, and reduce pressure loss, ultimately improving the efficiency of drilling operations and reducing costs. this study contributes to developing adeeper understanding of the effect of silica nanoparticles on the rheological properties of drilling fluids, and provides innovative solutions to improve the performance of these fluids in extreme conditions. the results can help in the design and development of improved drilling fluids with better performance, benefiting the oil and gas industry by improving the efficiency of drilling operations and reducing costs.

1.1 Background

Drilling fluids are a vital part of oil and gas exploration operations, playing a critical role in the success and efficiency of these operations. they cool and lubricate the drilling tool, transport the drilling output to the ground surface, control strata pressure, and prevent collapse of the well walls. these require multiple functions Specific rheological properties of drilling fluid, such as viscosity and shear strength, which must be matched to different operating conditions. However, drilling fluids face various challenges, such as high temperature and pressure, which can negatively affect their rheological properties and performance. advances in nanotechnology have led to the emergence of new materials, such as silica nanoparticles, that can be added to drilling fluids to improve their rheological properties. and enhance its performance. preliminary studies have shown that silica nanoparticles can be used to improve the viscosity of drilling fluid, reduce fluid loss, and improve its ability to hold drilling output.

1.2 Problem Statement

The oil and gas industry faces significant challenges in maintaining high-efficiency performance of drilling fluids under the increasingly complex conditions of drilling operations. The rheological properties of drilling fluids are considered one of the most important factors affecting their performance, as they play a decisive role in achieving various drilling objectives.

Problems of rheological properties in drilling fluids.

- Loss of viscosity at high temperatures: Drilling fluids are exposed to very high temperatures at deep depths, which results in a loss of their viscosity and a deterioration in their ability to hold drilling output and clean the well.
- Change of rheological properties with pressure: High pressure at depth affects the viscosity of drilling fluids, which can lead to problems in controlling flow and pressure inside the well.
- Instability: The rheological properties of drilling fluids may change over time due to various factors such as contamination and chemical reactions, affecting their long-term performance.

1.3 Study Objectives

- Studying the effect of adding silica nanoparticles at different concentrations on the rheological properties of a water-based drilling fluid.
- Determine the optimal nano-silica concentration and particle size to achieve desired viscosity, plastic viscosity, and yield point for different drilling conditions.
- Analysis of the mechanisms of influence of silica nanoparticles on the rheological properties of drilling fluid.

By achieving these specific goals, this research will contribute significantly to a better understanding of the mechanisms of action of nano-silica in drilling fluids and its potential to improve drilling efficiency, wellbore stability, and environmental sustainability.

1.4 Significance of the Study

This study contributes to developing a deeper understanding of the effect of silica nanoparticles on the rheological properties of drilling fluids. The findings can help in the design and development of improved drilling fluids with better performance, improving the efficiency of drilling operations and reducing costs. This study can also contribute to enhancing the use of nanotechnology in the oil and gas industry. And the development of new materials with unique properties. In addition, the results of this study can benefit researchers and engineers working in the field of petroleum engineering in selecting and developing the best types of drilling fluids and Providing a deeper understanding of the mechanisms by which silica nanoparticles interact with drilling fluids and influence their properties.use of SiO_2 NPs in drilling fluids can reduce drilling time and costs, leading to faster well completion and increased profitability.

Chapter two

Literature view

2.Nano Fluids

Nanofluids are a subset of engineered fluids that contain nanoparticles (NPs) suspended within a base fluid. They typically measure from 1 to 100 nanometers and are composed of metallic, non-metallic, or composite materials [1]. These fluids employ water, oil, ethylene glycol, or other common fluids as a base in which nanoparticles, including metal oxides (alumina, silica, titania), carbon-based materials (graphene, carbon nanotubes), and metallic nanoparticles (gold, silver), are mixed to form a nanofluid [2]. The characteristics of nanofluids are enhanced thermal conductivity, improved rheological properties, good stability, increased heat capacity, and enhanced surface properties. In drilling fluids, they work through the mechanisms of forming a nano-filter cake that is thin and impermeable, bridging microfractures, and improving the fluid properties such as viscosity and gel strength that assure the reliable suspension and cutting transportation abilities of the fluid [1].The preparation of drilling fluids with nanoparticles requires following sequential process steps:

- Selection of nanoparticles: Identify the exact properties, such as improved viscosity, increased thermal conductivity, and enhanced stability, to be addressed in a drilling fluid. Choose the appropriate nanoparticle, for example silica for viscosity, copper for thermal management, zinc oxide for antimicrobial characteristics, and titanium dioxide for stability.

- Synthesis of nanoparticles: Based on the chosen nanoparticles, employ respectivesynthesis methods such as the sol–gel process (suitable for generating metal oxides at controlled sizes), hydrothermal synthesis (includes elevated operational nEng 2024, 5 2466 conditions of temperature and pressure for nanoparticle generation), and chemical vapor deposition (appropriate for generating pure/high-quality nanoparticles. Characterize the generated nanoparticles through their size, morphology, and surface properties using transmission electron microscopy (TEM) or scanning electronmicroscopy (SEM) [3].

- Preparation of base fluid: Select water or oil for the base of the drilling fluid, depending on the drilling environment. Choose the necessary additives, such as weighing agents or polymers, based on the drilling environment and based on which could complement the functions of selected nanoparticles.

- Dispersion of nanoparticles: Add dispersing agents such as surfactants or stabilizers to prevent the agglomeration of nanoparticles in the base fluid. Use high-shear mixers or ultrasonic dispersers to confirm the even distribution of nanoparticles throughout the drilling fluid.

- Mixing process: Add the nanoparticles slowly while maintaining continuous stir-ring to ensure good dispersion. Mechanical mixing or ultrasonication can guarantee a homogeneous mixture [4].

- Testing and optimization: Assess the rheological properties such as viscosity, yield point, and flow performance of the drilling fluid with the help of rheometers. Perform thermal stability tests on the fluid at different temperatures to warrant good performance in high-temperature environments. Analyze the test results and fine-tune the nanoparticle concentrations in the drilling fluid for the desired performance [5].

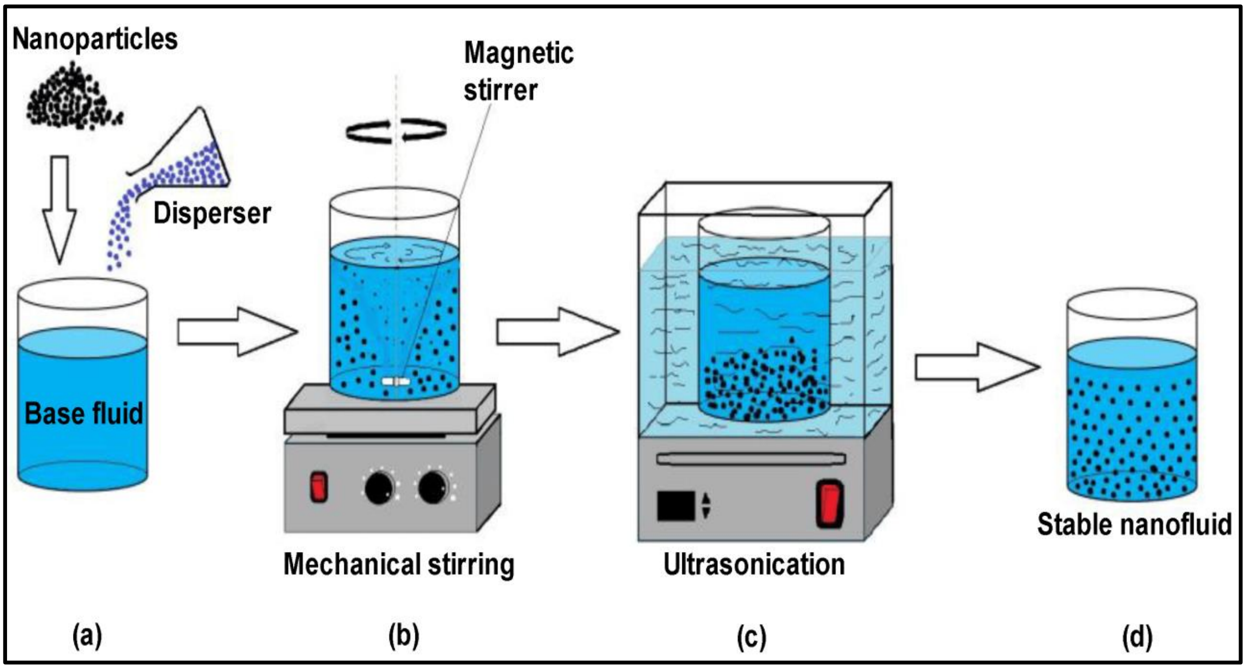

Fig.(2-1) : Nano fluid preparation process: (a) initial mixing of nanoparticles, dispersant, and base fluid; (b) mechanical stirring for preliminary dispersion; (c) ultrasonication for particle size reduction and stability enhancement; (d) final stable nanofluid with well-dispersed nanoparticles

Nanofluids of various types are presented in this section, including metal-based, oxidebased, carbide-based, nitride-based, carbon-based, and composite nitride nanofluids. The composition, characteristics, and uses of each type are described, highlighting their benefits, such as enhanced thermal conductivity, improved lubrication, and increased stability under high-pressure and high-temperature conditions. **Fig.(2-1)** lists the various and most popular nanoparticles used in drilling operations, which are further elaborated on in the following section. While nanomaterials present significant technical advantages in drilling fluids, their challenges cannot be overlooked. High costs related to synthesis and production are significant, mainly because of the required large volumes [6]. Compatibility with the exclusive conditions of individual oil fields, such as temperature and salinity, can also impact performance. Moreover, nanomaterial-related safety hazards and health risks remain vague [7].

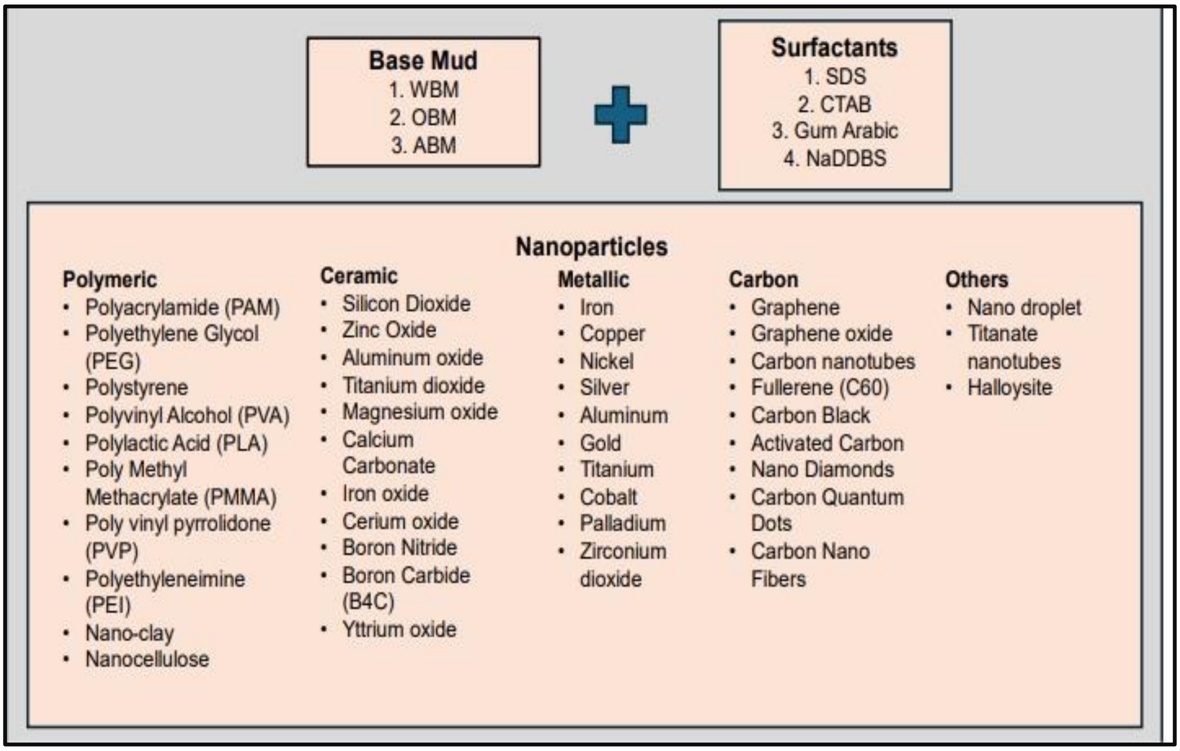

Fig.(2-2): Classification of nanoparticles employed in the formulation of drilling nanofluids.

2.1. Types of Nanofluids

2.1.1. Metal-Based Nanofluids

Metal nanoparticles, such as gold, silver, and copper, are mixed with base fluids (water, ethylene glycol, or oil) to form metal-based nanofluids. Due to its superior corrosion resistance, copper is highly preferred in nanofluids, offering higher suspension stability. Surface-modified copper nanoparticles used with oil-based mud (OBM) have demonstrated enhanced thermal conductivity [1]. Silver nanoparticles, with a diameter of 5 nm, mixed in kerosene-based mud exhibited improved thermal conductivity at 50 ◦C compared to 25 ◦C, attributed to enhanced Brownian motion. The increase in the thermal conductivity of the drilling mud by the addition of nanoparticles made the mud cool faster as it moved up the surface [8]. Gold nanoparticles, recognized for their enhanced optical characteristics, are extensively used as coatings for SEM sampling to improve image quality [9].

2.1.2. Oxide-Based Nanofluids

The metal oxide-based nanoparticles, such as copper oxide (CuO), titanium dioxide (TiO2), and aluminum oxide (Al2O3), are mixed with the base fluid to form oxide-based nanofluids. Copper oxide nanoparticles in OBM improved the yield point, gel strength, and apparent viscosity of the drilling fluid. Additionally, at elevated concentrations, copper oxide nanoparticles enhance filtration results under high-temperature, high-pressure (HTHP) conditions [10]. As titanium oxide nanoparticles are highly thermally conductive, they are mostly suited for heat exchange applications. This increased thermal control is crucial in deep and ultra-deep drilling, where high temperatures can compromise wellbore stability and the efficacy of drilling tools [11]. Moreover, TiO2 nanofluids offer enhanced lubrication, reducing the friction and wear of drilling equipment, thus extending tool lifespan and lowering operational costs [12]. In comparison (see Table 2), aluminum oxide nanoparticle dispersions, even at lower concentrations, improve the thermal stability of water-based drilling fluids more effectively than silica nanoparticles [13].

2.1.3. Carbide-Based Nanofluids

Incorporating carbide nanoparticles, such as boron carbide (B4C) and silicon carbide (SiC), in the base fluid creates carbide-based nanofluid. Despite dealing with price and dispersion stability issues, carbide nanofluids have significant benefits such as enhanced thermal control, improved lubrication, abrasion resistance, enhanced hardness, and improved stability of the wellbore. Boron carbide nanofluids have the capability of Eng 2024, 5 2468 improving rheological and filtration properties and also improving the inhibition of shales for unconventional drilling [14].

2.1.4. Nitride-Based Nanofluids

Nitride nanoparticles, such as boron nitride (BN), aluminum nitride (AlN), and silicon nitride (Si3N4), are dispersed in the base fluid to make nitride-based nanofluids. These nanofluids are known for their high thermal conductivity. Specifically, as the concentration of hexagonal boron nitride (h-BN) in the fluid increases, the thermal conductivity correspondingly improves. Rheological studies suggest that with an increase in h-BN concentration, the viscosity of the fluid also increases [15]. Additionally, Si3N4 NPs can increase the optical absorption capacity of ethylene glycol-based nanofluids. Thermal conductivity also has a linear dependency on the NP concentration [16].

2.1.5. Carbon-Based Nanofluids

These nanofluids are a result of blending carbon nanoparticles, such as Carbon nanotubes, Graphene, and Fullerenes, with base fluid. They offer exceptional thermal and electrical properties. Carbon nanotubes are cylindrically rolled-up sheets of graphene (carbon atoms) and are of two types: single-walled (SWCNT) and multi-walled (MWCNT) carbon nanotubes. They possess superior strength compared to steel and possess high thermal conductivity. Fullerenes, globular and hollow carbon allotropes, are noted for their remarkable strength and high electrical conductivity [17,18]. Additionally, fullerenes are economical materials that can be used to prevent the growth of microorganisms and natural fouling [19].

2.1.6. Composite Nanofluids

When two or more different nanoparticle types are mixed with the base fluid, a composite nanofluid is formed. These composite nanofluids combine the properties of individual nanoparticles to create a fluid with enhanced thermal, chemical, and mechanical characteristics. The benefits of composite nanofluids include improved heat transfer, enhanced lubrication and resistance to wear, superior wellbore stability, and applicability to high-pressure and high-temperature conditions.

Table (2-1) Comparison of various types of nanofluids based on cost, base fluid, reusability, and applicable conditions

Type of Nanofluid	Cost	Base Fluid to be Used with	Reusability	Applicable under Conditions
Metal	High	Water, Oil	Moderate	High temperatures and pressures
Metal Oxide	Moderate	Water, Oil, Glycol	High	Moderate to high temperatures
Carbon-Based	High	Water, Organic Solvents	Moderate	High temperatures and pressures
Composite/Hybrid	Variable	Water, Oil	Moderate	Depends on components and usually high performance
Polymeric	Low	Water, Oil	High	Low to moderate temperatures, variable usage

2.2. Nanofluids in the Drilling Industry

This section explores various nanofluids popularly used in drilling operations and their impact on improved drilling efficiency

2.2.1. Silica Nanofluids

Silica nanofluids are formed by dispersing silica nanoparticles into a base fluid. These are most useful for improving fluid stability and thermal conductivity. The effects of SiO2 nanoparticles on the rheology of WBM show that at lower concentrations of NPs, there is no significant change. However, as the concentration of NPs increases, the rheology of WBM is better observed, and the best rheology was obtained at an NP concentration of 1.5 wt% [21]. A combination of SiO2–xanthan gum (biopolymer/rheology controller) WBM was tested and proved to reduce the volume of filtrate loss. It also improved the swelling inhibition and rheology of the fluid [22]. Silica NPs paired with Gemini surfactants helped to improve thermal stability and reduce filtrate losses, while viscosity was mainly increased by the surfactant [23]. The dispersion of SiO2 nanoparticles in the WBM allowed for improved viscosity that made the lifting and transporting of cuttings easy, ensuring a thorough cleaning of the wellbore [24].

2.2.2. Alumina Nanofluids

Aluminum oxide nanoparticles are mixed with the base fluid to form the alumina nanofluids. These nanofluids offer chemical stability (as alumina nanoparticles are inert), mechanical strength, lubrication, improved cuttings carrying capacity, better viscosity control, and enhanced thermal transfer abilities. Alumina nanoparticles helped increase the gel strength and shale integrity while reducing the fluid loss by 60% [25]. The dispersion of aluminum oxide NPs helps improve the thermal stability even at lower NP concentrations. Under high-pressure, high-temperature (HPHT) conditions, the degradation effect decreases with an increase in nanoparticle concentration. Filtration tests indicated an increase in filtrate loss with alumina nanoparticles, but this was reduced when silica NPs were added [13].

2.2.3. Copper Oxide Nanofluids

The blend of base fluid with copper oxide nanoparticles is known as copper oxide nanofluid. Due to the presence of copper oxide nanoparticles, they exhibit excellent heat transfer and antibacterial properties. When used in polyamine-based non-damaging drilling fluid, copper oxide nanoparticles showed thinning behavior, and this effect was amplified when combined with bentonite, leading to depleted fluid loss control and reduced viscosity [26]. CuO is paired with polyacrylamide PAM to form a nanocomposite, resulting in a significant reduction in fluid loss and the thickness of the filter cake of water-based bentonite drilling fluid. It also helped form a smooth and low-permeable filter cake. The CuO nanocomposite improved thermal conductivity significantly [27]. When used along with ZnO CuO in WBM with xanthan gum, the CuO NPs are stronger even at the demonstrated improved rheology, even under HPHT conditions [28].

2.2.4. Carbon Nanotube (CNT) Nanofluids

CNT nanofluids are a mixture of carbon nanotubes and base fluid. They possess great mechanical strength, high thermal conductivity, and high electrical conductivity, putting them in high demand for critical applications. CNT's thermal conductivity enhancement is higher at elevated temperatures and also showed significant filtrate reduction [29]. MWCNTs enhanced the rheological properties by increasing the gel strength (10 s) and reduced the volume of filtrate losses even at high temperatures of 250 ◦F and 350 ◦F [30]. When tested against TiO2 CNTs showed a better ratio of convective-to-conductive heat Eng 2024, 5 2470 transfer, about 30% greater than that of the drilling fluid, which consisted of TiO2 nanoparticles [31]

2.2.5. Graphene Nanofluids

Graphene nanoparticles are introduced into the base fluid and form a mixture known as graphene nanofluids. These are in demand due to their excellent thermal properties and are employed to design nanofluids that significantly boost heat transfer rates. Graphene is a single sheet of carbon atoms that are orderly set in a hexagonal lattice [17]. Graphene is helpful as a pore-plugging filter in oil-based drilling muds. Due to its dispersion issue in water-based muds, it is not employed. Meanwhile, graphene oxide can be used in WBM as it has the proper stability [7]. Graphene oxide nanocomposites are very promising additives that can improve WBDF rheology. They yielded significant changes in plastic viscosity, gel strength, loss of filtrate, and yield point at both LPLT and HPHT conditions [32].

2.2.6. Titanium Dioxide Nanofluids

These nanofluids are formed when TiO2 nanoparticles are combined with the base fluid. These nanofluids are known for their photocatalytic properties and also their capability to increase the thermal properties of the base fluid. They offer high thermal conductivity, chemical stability (as TiO2 is chemically inert), tremendous mechanical strength, and excellent resistance to UV rays. TiO2 nanoparticles are preferred in some applications because they provide a consistent heat transfer performance, even though they have lower thermal conductivity than CNT nanofluids. Also, the conductive heat transfer coefficient increases by 22%, which is on par with the decrease in NP size [31]. TiO2 nanofluids can be employed in water flooding scenarios as the recovery flow is maximum with TiO2 nanoparticles [11]. TiO2 has proved its potential in producing low permeability filter cakes, eventually leading to a reduction in fluid loss [33].

2.2.7. Iron Oxide Nanofluids

These nanofluids are formed by blending iron oxide nanoparticles with a base fluid and are mostly preferred for their biocompatibility and magnetic properties that can be useful in selected drilling scenarios such as magnetic partition and better drilling path detection. Pure crystallites of magnetite (Fe_3O_4) are used in water bentonite drilling fluid. Under LPLT conditions, fluid loss is reduced compared to the base fluid, but the resulting filter cake is thicker. Increasing the nanoparticle concentration improves fluid loss control by thinning the filter cake and decreasing permeability, performing even better under highpressure, high-temperature (HPHT) conditions compared to LPLT [34]. Smart magnetically controllable custom-made Fe_3O_4 nanoparticles were employed for in situ control of the fluid rheology. The fluid exhibited immense performance in withstanding rapid changes in viscosity and yield stress [35]. Hydrophobic iron oxide NPs are dispersed in hexane (OBM), and after examination, it was discovered that at an NP concentration of 0.5 wt%, the NPs were able to reduce the filtrate losses by 70%, friction coefficient by 39%, and thickness of the filter cake by 55% [37]. Adding Fe_3O_4 NPs improved the plastic viscosity, yield point, and gel strength of KCL-WBM and also reduced the friction coefficient [36].

2.3 Property-Based Applications

The use of nanoparticles in targeted drilling enhances several key properties, which improves efficiency and effectiveness in drilling operations. This section discusses in detail the key physical and chemical properties that are improved by using nanoparticles, with a focus on the underlying mechanisms.

2.3.1 Lubrication

Drilling fluids need lubrication in order to reduce friction, avoid stuck pipe situations, enhance drilling efficiency, dissipate heat, shield the drill bit, sustain wellbore stability, and promote safer and greener operations. Drilling operations can be made more efficient and Eng 2024, 5 2471 economical by using efficient lubricants in drilling fluids. This has been proven by test results carried out in the TPAO research center using an OFITE lubricity tester on the waterbased lignosulfonate mud to which a mixture of light oil and three different lubricants were added and tests were performed under laboratory conditions (room temperature and atmospheric pressure) [38]. The fundamental mechanism of lubrication involves decreasing the friction and wear between the moving components of the drilling setup such as drill bit and drill string to that of the wellbore. This was achieved by developing a lubricating film that can function in boundary, hydrodynamic, and mixed lubrication systems. Nano-titanium borate is an example of one such lubricant that has peak performance under extreme pressure conditions with a lubricity tester (Fann-212) [39,40]. Nanoparticles have an excellent tendency to develop such stable lubrication films on the surfaces and also fill in microscopic asymmetries that can significantly reduce friction between the drilling apparatus and the wellbore. This not only reduces wear and tear on drilling equipment but also enhances the rate of penetration by reducing resistance. Examples include metal oxide-based, diamond-based,and boron-based nanoparticles (withstanding high temperature and high pressure) [42,7,41].

2.3.2. Fluid Stability

A drilling fluid's stability refers to its ability to maintain its anticipated physical and chemical properties even at various operating settings such as temperature, pressure, and shear rate [43]. As the rheological behavior of the fluid mostly influences its physical properties, viscosity control is very crucial for maintaining fluid stability. Preserving proper viscosity is essential as it plays a crucial role in functions like cuttings transportation, particle suspension, wellbore stability, pressure control, lubrication, cooling, fluid loss control, the erosion and wear of the wellbore, and maintaining efficient circulation throughout the drilling operation [44]. Chemical stability in a drilling fluid is vital to ensure a proper balance of various chemical interactions between the components of a drilling fluid. It helps prevent fluid degradation and avoids undesirable reactions that could compromise the performance of drilling fluid [45]. Chemical compatibility, pH, ionic concentration, corrosion inhibition tendency, hydration, and swelling tendencies (towards reactive clay) of fluid additives are the responsible mechanisms of chemical stability [46–47]. The addition of proper thickeners/thinners, pH adjusters, emulsifiers and surfactants, chemical inhibitors, and rheology modifiers and maintaining proper solids and clay dispersion, hydration, shear rates, and temperatures, as well as real-time monitoring and feedback loop adjustments, collectively make up effective viscosity control and chemical stability, ensuring proper overall fluid stability [44,48]. Nanoparticles help control the viscosity of drilling fluids by preventing phase separation under high-pressure and high-temperature conditions typical of drilling environments, therefore increasing the stability of the fluid. Nanoparticles act as effective rheological modifiers, fluid loss reduction agents, thermal stabilizers, and particle suspension and lubrication enhancers. The experimental analysis of nanoparticles of carbon nanotubes (CNTs), SiO_2, and ferric oxide (Fe_2O_3) proved to be effective under both low and high temperature and pressure conditions when dealing with filtration losses. On the other hand, the NPs of graphene, graphene oxide, multi-walled carbon nanotubes (MWCNTs), and gold are successful under low-pressure and low-temperature conditions [49].

2.3.3 Heat Transfer

The crucial roles of heat transfer in drilling fluid are to maintain the rheological properties, prevent thermal degradation, provide wellbore stability, prevent gas hydrate formation, and enhance lubrication [43]. Heat transfer occurs through conduction (the movement of heat through the material without the material in motion) and convection (the circulation of the fluid down through the drill string and back up through the annulus), which helps remove heat from the wellbore surface and the drill bit [50,51]. Thus, some factors such as the rate of mud circulation, properties of the fluid (thermal conductivity Eng 2024, 5 2472 and specific heat capacity), and well design parameters (borehole diameter and annular space) influence the effectiveness of heat transfer in drilling fluids [52]. Due to their high surface area, nanoparticles improve the thermal conductivity of fluids, aiding in more efficient heat transfer during drilling. This is particularly useful in high-temperature drilling environments. One such example is a novel improved drill-in fluid that is high in density, thermally stable, and consists of synthetic polymer, which is stable and effective at high temperatures of 355 ◦F. Multi-walled carbon nanotubes have been proven to improve the thermal conductivity of the drilling fluid by exhibiting linear trends with temperature and becoming stable at high temperatures [2,53–54].

2.3.4 Sealing Microfractures

Microfractures in the formation have to be sealed for various reasons, such as preventing fluid losses, maintaining control over pressure inside the wellbore, protecting the integrity of the formation, protecting the nearby environment (groundwater channels), and collectively assuring the stability of the wellbore [55]. To seal a microfracture, drilling fluids should contain lost circulation materials (LCMs), which aid in sealing. Due to their type (fibrous, granular, and flaked) and size, LCMs can bridge and plug the micro-cracks during mud circulation. As various shaped and sized particles pile up at the entrance of the fracture and form a seal, the additional particles aid in filling the remaining voids eventually strengthening the seal and making it impermeable [56]. The use of chemical additives (polymers and resins) helps in the formation of a gel-like substance that reinforces the seals [57,58]. Nanoparticles can plug microfractures in the rock formation, preventing the loss of drilling fluids and maintaining pressure within the well. Due to their size characteristics (nano-sized), NPs can infiltrate into the tiniest of spaces and cracks. They can form a nano-filter cake that ensures a stable wellbore and targets rheological properties like viscosity [59]. Laboratory experiment results suggest that silica nanoparticles made from rice husks (RH-SNPs) are capable of acting as a lost circulation material by optimizing the filtrate loss at an elevated temperature range (80 ◦F to 250 ◦F) [60]. When cellulose nanofibers (CNFs) and polyanionic cellulose (PAC) hybrids are mixed with bentonite waterbased drilling fluids under laboratory conditions, they can achieve superior rheological and filtration properties [61].

2.4 Drilling Applications

In the previous section, the various physical properties and underlying mechanisms of nanofluids were elaborated on. This section focuses on the application of nanoparticles to enhance drilling operations. Specifically, we examine three key areas: fluid loss control, wellbore stability, and thermal stability. For each application, the importance is discussed, followed by an explanation of the mechanisms through which nanoparticles achieve these improvements and a detailed presentation of the specific nanoparticles used in the industry.

2.4.1 Fluid Loss Control

Drilling fluid loss should be controlled to limit the seepage of drilling fluids into surrounding formations. A suitable fluid loss control is needed to prevent formation damage from blocking natural hydrocarbon pathways and reducing well productivity. It is also essential to maintain wellbore stability because wellbore collapse or other structural problems could result from excessive fluid loss [62,63]. Also, fluid loss management reduces operational expenses by avoiding the need for additional drilling fluids and delays. This also addresses environmental concerns as it prevents the contamination of adjacent formations with drilling fluids. Drilling fluid into these formations may introduce environmental pollution that may persist in ecosystems [64]. The result is that the industry is always looking for better ways of controlling fluid loss and ensuring efficient drilling procedures. Eng 2024, 5 2473 Nanoparticle Solutions for Fluid Loss in Drilling Nanoparticles are unique in limiting fluid loss during drilling operations. **Fig.(1-3)** is a pictorial interpretation of how the nanoparticles aid in fluid loss control mechanisms. Their small size allows them to enter and seal tiny fractures and nanopores in the rock formation to reduce permeability and fluid loss. For example, silica nanoparticles are known to be stability and sealing agents that reduce fluid loss through the quality of filter cake formed on the wellbore wall [65]. Also, graphene oxide nanoparticles are very strong mechanically and create a superior barrier, thus reducing fluid loss [66]. Clay nanoparticles further enhance the rheology of drilling fluids by maintaining cutting suspension and regulating fluid movement, increasing drilling efficiency, and reducing fluid loss [67]. Carbon nanotubes and other carbon nanoparticles improve the thermal stability and general efficacy of drilling fluids [68]. Adding these nanoparticles to drilling fluids may improve fluid loss control and thus increase the efficiency, cost-effectiveness, and environmental sustainability of drilling operations. Numerous research studies have emphasized the efficacy of different nanoparticles in managing fluid loss. In a study by Jung, Y. [69], the utilization of iron oxide nanoparticles in bentonite fluids was examined, revealing that elevating the concentration of these nanoparticles enhanced yield stress, viscosity, and particle interaction strength, particularly in high-temperature and high-pressure environments. The developed fluid suspensions exhibited viscosity variations at different temperatures due to the presence of larger particles linked to increased salinity in the colloidal system and heightened iron oxide content. Barry, M. [70], demonstrated that iron–oxide clay hybrids (ICHs) formed filter cakes with reduced permeability, leading to a substantial decrease in fluid filtrate volumes under both low-temperature, low-pressure (LTLP) and high-temperature, high-pressure (HTHP) conditions. In 2016, Mahmoud, O. [71], investigated the simultaneous use of ferric oxide and silica nanoparticles. They found that while ferric oxide nanoparticles improved the flow properties and controlled fluid loss, silica nanoparticles had a negative impact on flow behavior by increasing repulsion forces between clay platelets. A novel polymerbased micro-nanocomposite (nano-silica and hydrophobics-associated polymers) with a core–shell structure was created. As per **Figure(2-3)** , the particle had a spreading limit from 280 nm to 320 nm with micro-crosslinked properties in aqueous solutions. WBM made of this novel micro-nanocomposite demonstrates its outstanding thermal stability and rheology at lower concentrations of composite. The brilliant sealing ability of this composite can hinder pressure transmission, enhance the pressure-bearing capability of formation, and isolate the fluid interaction (drilling and formation), helping to stabilize the borehole [72].

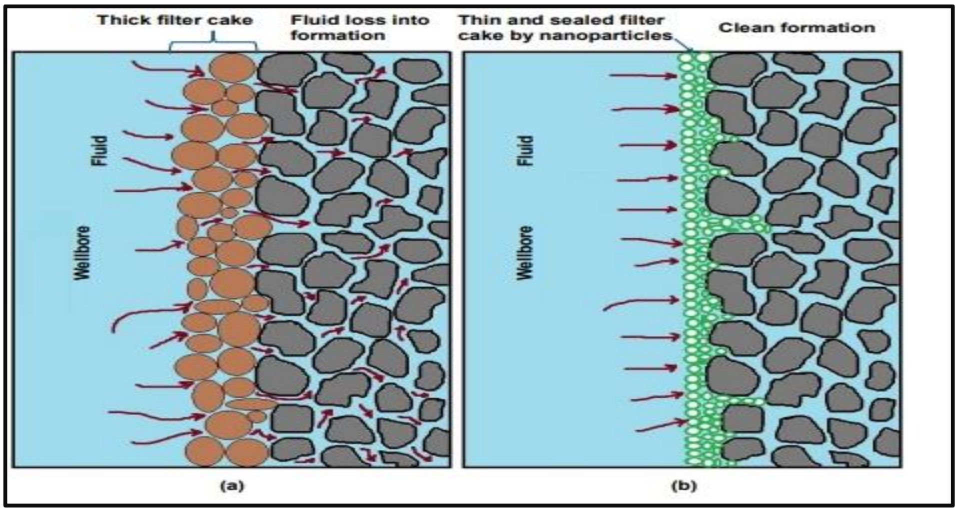

Fig.(2-3) Fluid loss mechanisms: (a) conventional drilling fluid—thick, porous filter cake allows filtrate to escape into the formation; (b) nanoparticle-laden drilling fluid—nanoparticles bridge pore spaces in the filter cake, forming a thin, impermeable barrier that minimizes fluid loss.

Additionally, Vryzas, Z. [2] showed that specially made magnetite nanoparticles notably decreased fluid loss and enhanced filter cake properties, particularly at a 0.5 wt% concentration. Ismail, A.R. [73], and Sadeghalvaad, M. [74], discovered that carbon nanotubes and TiO2 nanocomposites improved the flow properties and fluid loss characteristics of drilling fluids. Cao, Y. [75], demonstrated that cellulose nanocrystals boosted the flexural strength of cementpastes, suggesting potential advantages for drilling fluid formulations. The combined results emphasize the important function of nanoparticles in accomplishing effective, economical, and environmentally conscious drilling activities. Table (2-2) provides a summary of research studies that explored the use of nanoparticles to address fluid loss. The table includes details on the specific types of nanoparticles used in each study and the main findings.

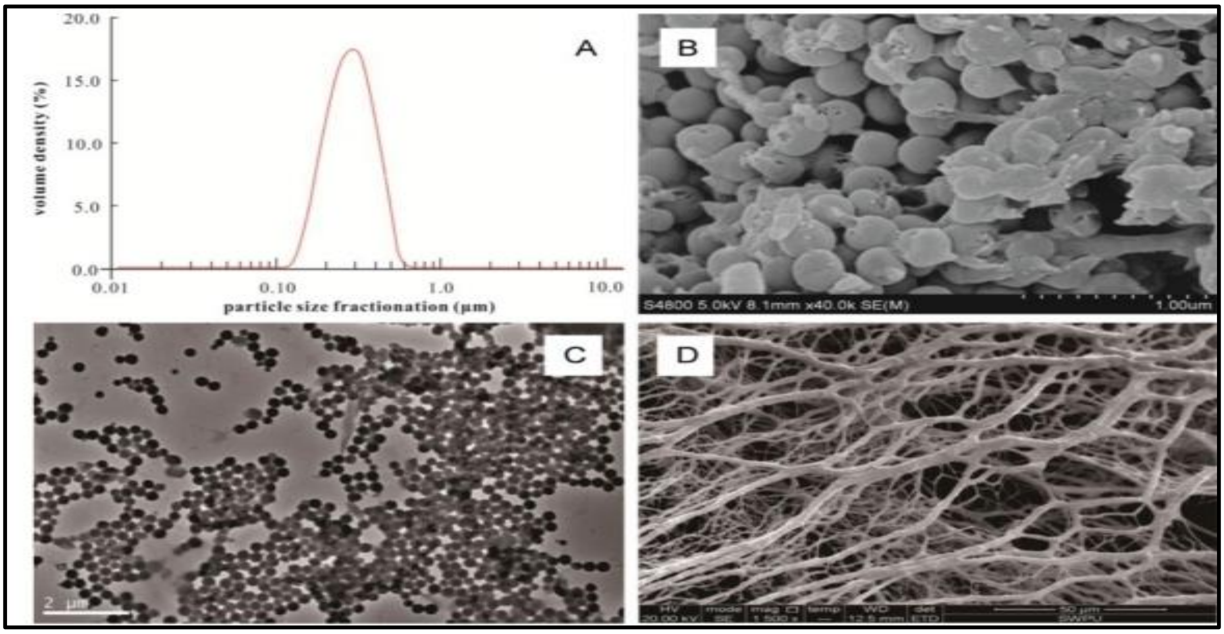

Fig.(2-4): (A) Particle size distribution curve demonstrates the high surface area of the material. (B) SEM image of SDFL (a polymer-based nano-silica composite with a core–shell structure) reveals the morphology of the composite particles. The polymer matrix appears to form connections between the particles. (C) TEM image of SDFL confirms good dispersion in aqueous media, likely due to the hydrophobic polymer coating on the nano-silica particles, which supports the formation of a core–shell structured composite. (D) ESEM image of SDFL shows the strong crosslinking within the composite when nano-silica is mixed with the polymer, resulting in a tightly knit grid-like structure. (figure sourced from [72]).

Table (2-2): Summary of research papers investigating the application of nanoparticles to target fluid loss, including the specific nanoparticles used and key outcomes.

Nanoparticle	Outcomes
Carbon nanotubes and nano-silica	Adding multi-walled carbon nanotubes and nano-silica enhanced mud rheological properties, such as plastic viscosity and yield point, compared to the base fluid.
Nano-silica	Reduced fluid losses by 56% compared to the normal drilling fluid.
Mesoporous nano-silica	Remarkable fluid loss reduction up to 41.81%, even under HTHP conditions.
Fe_3O_4	Reduced fluid losses by 40%, even under HTHP conditions of 250°F and 300 psi.
Poly(sodium p-styrene sulfonate)-modified Fe_3O_4	Enhanced thermal, rheological, and filtration properties.

Table 3. *Cont.*

Nanoparticle	Outcomes
Fe_2O_3	Better rheology and controlled fluid losses.
Fe_2O_3—clay hybrid nanoparticles	Improved rheological properties of the drilling fluid.
Iron-based nanoparticles	Better fluid loss control.
TiO_2 nanocomposites	Less thickness of mud cake and a 64% decrease in fluid losses compared to conventional drilling fluids.
Calcium nanoparticles	Considerable fluid loss reduction and production of thinner filter cake which reduces permeability.
CuO and ZnO	Reduced thickness of mud cake while upholding filtration properties.
Graphene nanoparticles	Improved rheology and fluid loss control.
Polymer graphene oxide	Stable filtration properties using polymer graphene oxide composites.
Graphite–alumina	Reduction in fluid losses.
Sepiolite nanoparticles	Enhanced rheological and filtration properties of the drilling mud.
MgO	Decrease in fluid loss by 52% under HTHP conditions.
Al_2O_3	Enhanced filtration and rheological properties of water-based mud even under HTHP conditions.
$CaCO_3$	Effective plugging of pores and reducing filter losses.
$BiFeO_3$	Enhanced the force of attraction among clay particles due to NPs being highly ferroelectric and carrying permanent polarization, resulting in improved rheological properties, such as apparent viscosity and yield point.
Carbon black	Significant reduction in fluid loss.
Cellulose nanoparticles	Reduction in fluid loss at lower NP concentrations and improved rheology of the fluid.

2.4.2 Wellbore Stability

The ability of the wellbore to maintain its structural integrity and stability throughout the drilling process is called wellbore stability. Warranting wellbore stability is vital to avoid wellbore collapse, blocked and stuck pipe situations, the loss of drilling fluids, and other operational problems (in the completion and production phases), which can increase costs and cause delays [54]. The key factors that affect the wellbore stability include the mechanical properties of the rock, in situ stresses, drilling fluid properties, and drilling practices [70,93]. The mechanical properties of the formation, such as rock strength, porosity, and permeability, are linked to the reaction of the formation while drilling [43]. In situ stresses are prevailing stresses in the subsurface that can lead to wellbore collapse or fracture if not maintained appropriately. The properties of drilling fluid, such as chemical composition, density, and viscosity, play a critical part in maintaining wellbore stability by supporting the wellbore walls. Drilling procedures, such as the rate of penetration, the direction of drilling, and the design of the bottom hole assembly, also affect wellbore stability [87,94]. Mechanisms like improving the filter cake strength, clogging the pores and microfractures, enhancing the rheology of fluid, improving thermal stability, decreasing drag and friction, and ensuring thorough borehole cleaning are contributions of nanoparticles in maintaining wellbore stability [33].

2.4.3 Reinforcement of the Filter Cake

Nanoparticles improve the quality and integrity of the filter cake formed on the wellbore walls. This is achieved when nanosized particles deposit themselves between the larger particles and physically form a bridge across the pores, resulting in a thin, Eng 2024, 5 2476 impermeable filter cake that reduces fluid incursion into the formation and offers a physical barrier that strengthens the wellbore walls. Their ability to form a densely packed matrix results in low permeability. Therefore, the overall stability is improved and the risk of collapse due to fluid loss is reduced [87]. Hydrophobic nano-silica is used in water-based drilling fluid to enhance wellbore strength. **Fig. (2-5)** shows scanning electron microscopic (SEM) images of shale surfaces before and after treatment with HNS. Inhibiting osmotic hydration, inhibiting surface hydration, decreasing the capillary action, and increasing the effectiveness of pore-plugging shale contributed to wellbore stability [65]. A new nanofluid using various concentrations of nano-ZnO (0.25%, 0.50%, and 0.75%) resulted in increased shale stability due to the positive charge, size, and hydrophilic behavior of NPs [69].

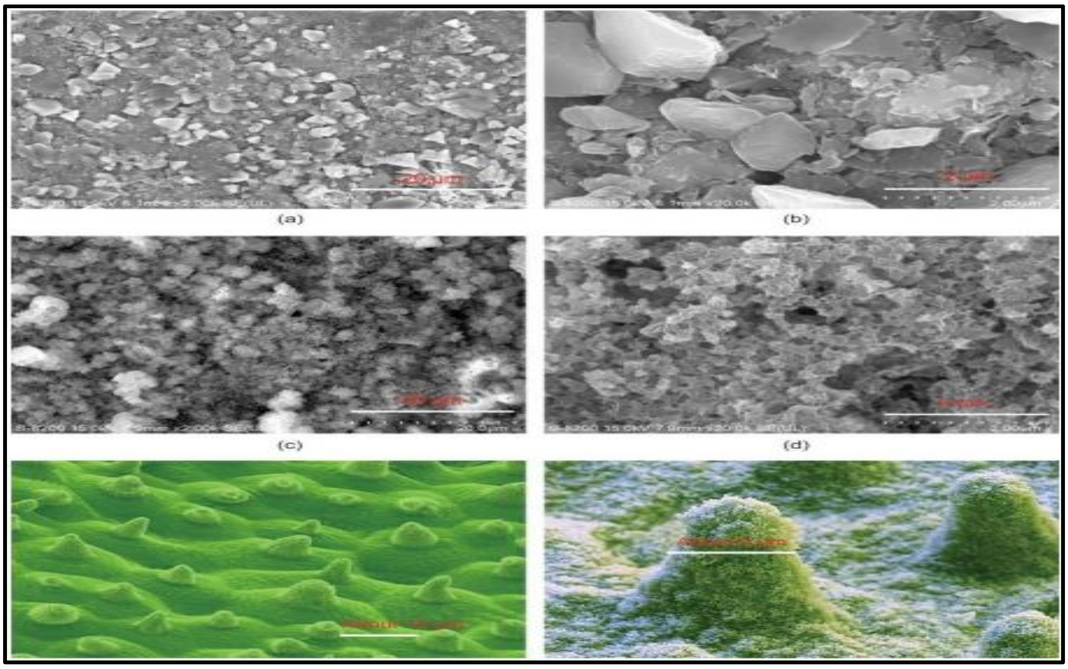

Fig. (2-5): Scanning electron microscopy (SEM) images of (a,b) an untreated shale surface; (c,d) a shale surface treated with 1.0 wt% hydrophobic nano-silica (HNS) at 120 ◦C for 16 h; and (e,f) a lotus leaf surface (for comparison). HNS adsorption modifies the shale's microstructure, significantly increasing the contact angle and thus reducing surface free energy. This change in wettability hinders hydration and enhances wellbore stability by efficiently closing shale pores and forming a smooth, water-resistant film (figure adapted from [98]).

It can be adsorbed by shale (clay) particles that are negatively charged and block the pore throats. ZnO NPs are widely dispersed in cores and are capable of bridging the pore throats [23]. Using ferric oxide NPs enhanced the filter cake and filtration characteristics of Ca–bentonite-based drilling fluids with polymer additives. The NP concentration of 0.3–0.5 wt% helped in generating a very good quality filter cake characteristics [96]. Calcium carbonate (CaCO3) nanoparticles can also be a great additive that offers superior filtration properties and smooth filter cake surfaces. At an optimum NP concentration of 0.07 wt%, there is a 64% reduction in filter cake thickness [49].

2.4.4 Closing Microfractures and Pores

One of its advantageous characteristics of being very small in size (nanometers) enables the nanoparticles to efficiently penetrate and close microfractures and pores inside the Eng 2024, 5 2477 formation. They build a more consistent particle size distribution helping in clogging the pore spaces. This helps to stop the invasion of formation fluids into the wellbore, reducing the chances of weakening the wellbore; this results in wellbore integrity.

Fig.(2-6) is a schematic representation of how nanoparticles close the microfractures. In unstable formations, an appropriate shale stabilizer for the WBDF is the combination of polyethylene glycol and nano-silica. Additionally, the combination was used as an efficient agent to plug shale cracks and pores. Graphene derivatives are used as a filter or pore-plug in oil-based drilling fluids as they enable stability in the aqueous medium [76]. However, the poor dispersion is the reason for the poor performance of graphene derivatives in water-based drilling fluids [78].

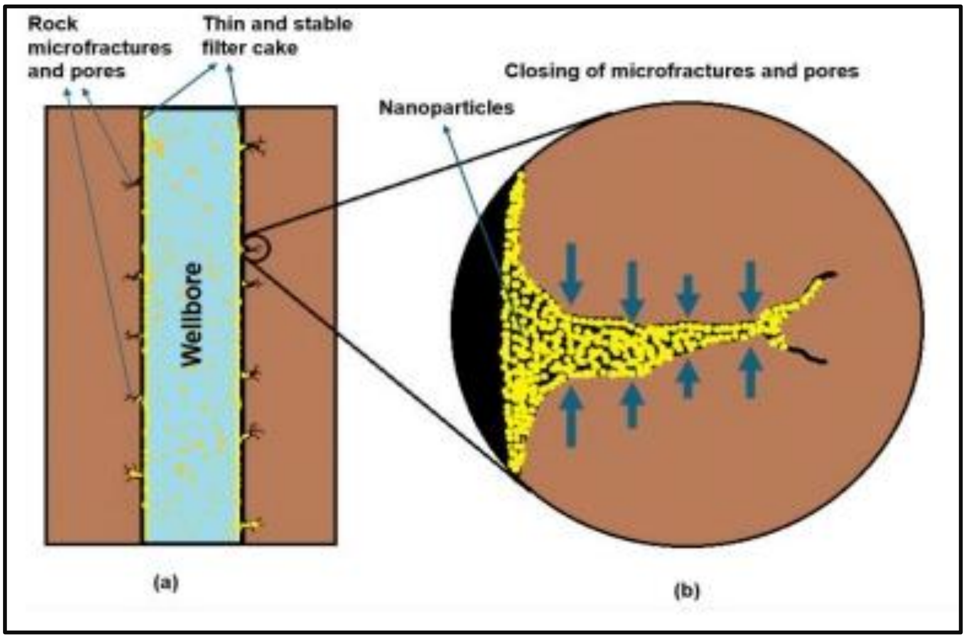

Fig. (2-6):Wellbore stability mechanisms. (a) A stable wellbore is characterized by the presence of tiny microfractures and pores, which are effectively sealed by a thin layer of filter cake. (b) An enlarged view of a microfracture illustrates how nanoparticles can penetrate and fill the void spaces within the fracture, further enhancing wellbore stability and preventing fluid loss.

Nanofluids made with a combination of hydrophobic CaCO3 nanoparticles and cetyl trimethyl ammonium chloride (CTAC) as a dispersion agent help to reduce filtrate losses with increasing nanoparticle concentrations, demonstrating that nanoparticles can efficiently plug the pores and thus decreasing the size of fluid loss channels [79]. Silica nanoparticles in a Pickering emulsion with low mass concentrations will settle on the fracture surfaces, evenly stabilizing the shale and preventing the hydration of clay [76,78].

2.4.5 Improving Fluid Rheology

Rheology is the representation of a fluid's viscosity behavior under the variable conditions of temperature and pressure. Viscosity is the ratio of shear stress to shear rate and describes the behavior of the fluid flow. It is a constant number for Newtonian fluids like water and oil [80]. Conversely, once polymers are mixed into a Newtonian fluid, the polymer chains develop resistance to flow which is not directly proportional to the shear rate. Increasing shear rates cause expansion and alignment in polymer chains. Due to this, the viscosity becomes low at high shear rates and vice versa. This behavior is known as shear thinning, non-Newtonian or power law behavior. In simpler terminology, the effective viscosity becomes less compared to water while the shear rate increases. Shear stress is associated with the pressure required to initiate the flow. So, even a small pressure can start the flow in both Newtonian and non-Newtonian fluids [12]. Therefore, the rheological properties of drilling fluid are of utmost importance and are explained as follows.

- Drilling fluid Density/Mud Weight: Density is the mass per unit volume of drilling fluid and is mostly measured in PPG (parts per gallon) or g/cm3 (gram per cubic centimeter). Mud weight is mainly responsible for maintaining hydrostatic pressure inside the wellbore to counteract formation pressures and prevent blowouts. Lower densities of the drilling fluid would lead to borehole breakout (shear failure of rocks) and wellbore collapse, while higher densities would result in problems such as decreased rate of penetration, probable loss of circulation, and formation damage. Nanoparticles can help in maintaining the fluid density through weight Eng 2024, 5 2478 addition by using heavier nanoparticles like barite, which would improve its overall density [78,81].
- Plastic Viscosity (PV): The resistance of the fluid to flow due to the friction between the solid particles and the fluid layers of the drilling fluid. As PV depends on the viscosity of the base fluid (water, oil, and solids concentrations), higher mud weights and solids concentrations in drilling fluid would lead to higher PV values, resulting in reduced drilling speeds that are unfavorable [49]. Nanoparticles can improve plastic viscosity by increasing the contact area among the particles in the fluid, enhancing interparticle interactions, and leading to a thicker fluid structure. Silica

nanoparticles are well known for improving viscosity by developing a network that stabilizes the fluid [82].

- Yield Point (YP): The point (stress level) at which the fluid yields its ability to resist the initial flow (shear thinning behavior) in non-Newtonian drilling fluids. The YP facilitates the capability of carrying drill cuttings through suspension during mud circulation (dynamic condition) in the wellbore, thereby avoiding differential sticking. Smaller particle sizes (of solids/additives) could lead to higher YP values due to the enhancement of the attractive forces between the solid particles and result in the better carrying of drill cuttings and in better hole cleaning [12]. Nanoparticles can yield thixotropic properties, resulting in fluid thickening when at rest and thinning under shear stresses, resulting in a better yield point when the fluid is still. Bentonite nanoparticles are one of the examples that exhibit thixotropic behavior. They increase the yield point by preserving a gel structure that refuses to flow until enough stress is employed [83].
- Gel Strength (GS): This is the force required to break the gel structure (attraction force between particles) of a fluid after resting for some time. GS is the measurement of drill cuttings suspension capability while the fluid is at rest (static condition), in contrast to YP. GS is time-dependent; if the fluid is static for longer, then the GS increases and more pressure is required to break the gel to restart circulation [49]. Nanoparticles such as palygorskite (Pal), a natural hydrous clay mineral with a fibrous rod-like needle microstructure, provide exclusive colloidal properties that help to improve gelation and the better suspension of drill cuttings in drilling fluids [67].
- . Filtrate Loss and Mud Cake Thickness: Filtrate loss is the volume of liquid that escapes through a solid mud cake formation and infiltrates the surrounding formations due to the hydrostatic pressure being higher than the pore pressure. Suspended solids in the drilling fluid will fill the pores and

form a mud cake. Higher solids concentrations in fluids tend to decrease the filtrate loss. Higher filtrate loss and mud cake thickness lead to differential pipe sticking. A good mud cake should be thin, strong, compressible, and have very low permeability [12,49]. The careful monitoring of factors such as drilling fluids composition, the amount of fluid loss control additives, the characteristics of suspended solids, and the thermal stability of the system helps us to achieve control over filtrate loss and mud cake thickness. Nanoparticles such as multi-walled carbon nanotubes (MWCNT) help us to achieve low filtrate volumes and thin impermeable filter cakes through high surface areas and nanotube structures [85,84].

Nanoparticles can alter the rheological properties of drilling fluids under variable temperature and pressure conditions to help make them more stable during the drilling process. Keeping the viscosity of the drilling fluid in check helps to improve cuttings suspension and transportation efficiency and the wall support of the wellbore. Metal oxide nanoparticles, such as copper oxide, aluminum oxide, and magnesium oxide, can reduce plastic viscosity by 50% and improve yield point and gel strength under low-temperature and low-pressure conditions [86]. Using nano-clay along with bentonite in commercial calcium carbonate drilling fluid will result in increased and stable gel strength and yield point and an overall enhanced fluid rheology [87]. Drilling fluids need to have low stress Eng 2024, 5 2479 for easy pumping during the bit penetration, yet they must be strong enough to suspend the cuttings during operation pauses. Both ZnO and CuO nanoparticles improve the rheological properties of drilling fluid, even at elevated temperatures. At various higher concentrations of NPs, up to 1 wt%, ZnO surpassed CuO in performance [65]. Usually, salts damage the rheological and filtration properties of the WBDF, as it is salt-free. Fe3O4 NPs support and enhance the rheological properties of both salty and salt-free drilling fluids to a remarkable extent. Nano-sized Fe3O4 nanoparticles might reduce the filtration properties of the salt-free WBDF, yet it is an appropriate filtration control agent for drilling fluids contaminated with salt [88]. Table (2-4) outlines research on using nanoparticles to improve the stability of wellbores in drilling operations. It lists the types of nanoparticles studied and the main results observed in each study.

2.4.6 Improving Thermal Stability by Reducing Friction and Drag

Nanoparticles can enhance the thermal stability of drilling fluids by averting the degradation of fluid properties when exposed to high temperatures, which commonly occurs and is explicitly essential in deep and high-temperature wells. This helps preserve drilling fluid integrity and guarantees constant support for the walls of the wellbore. Nanosilica was able to stop the thermal degradation of polymer additives in the drilling fluid due to its increased apparent viscosity and yield point compared to the base mud [89]. Graphene oxide nanoparticles in drilling fluid showed good thermal conductivity. The friction between the drill string and the wellbore walls is reduced with the help of specific nanoparticles like graphene and (CNT) carbon nanotubes. This decreases mechanical stresses and benefits from sustaining the wellbore stability by reducing the risk of pipes becoming stuck and collapsing because of mechanical forces.

2.4.7 Improving Borehole Cleaning

Nanoparticles help improve the suspension and transportation capabilities of cuttings in the drilling fluid, ensuring that the cuttings stay suspended even under static or low flow conditions. Such suspension capabilities help to avoid the settlement and packing of cuttings that can result in stuck pipe scenarios and thus destabilized the wellbore. **Fig. (2-7)** illustrates a stuck pipe situation and how the filter cake thickness contributes to the scenario. Ensuring a stable and clean wellbore also helps to reduce operational difficulties.

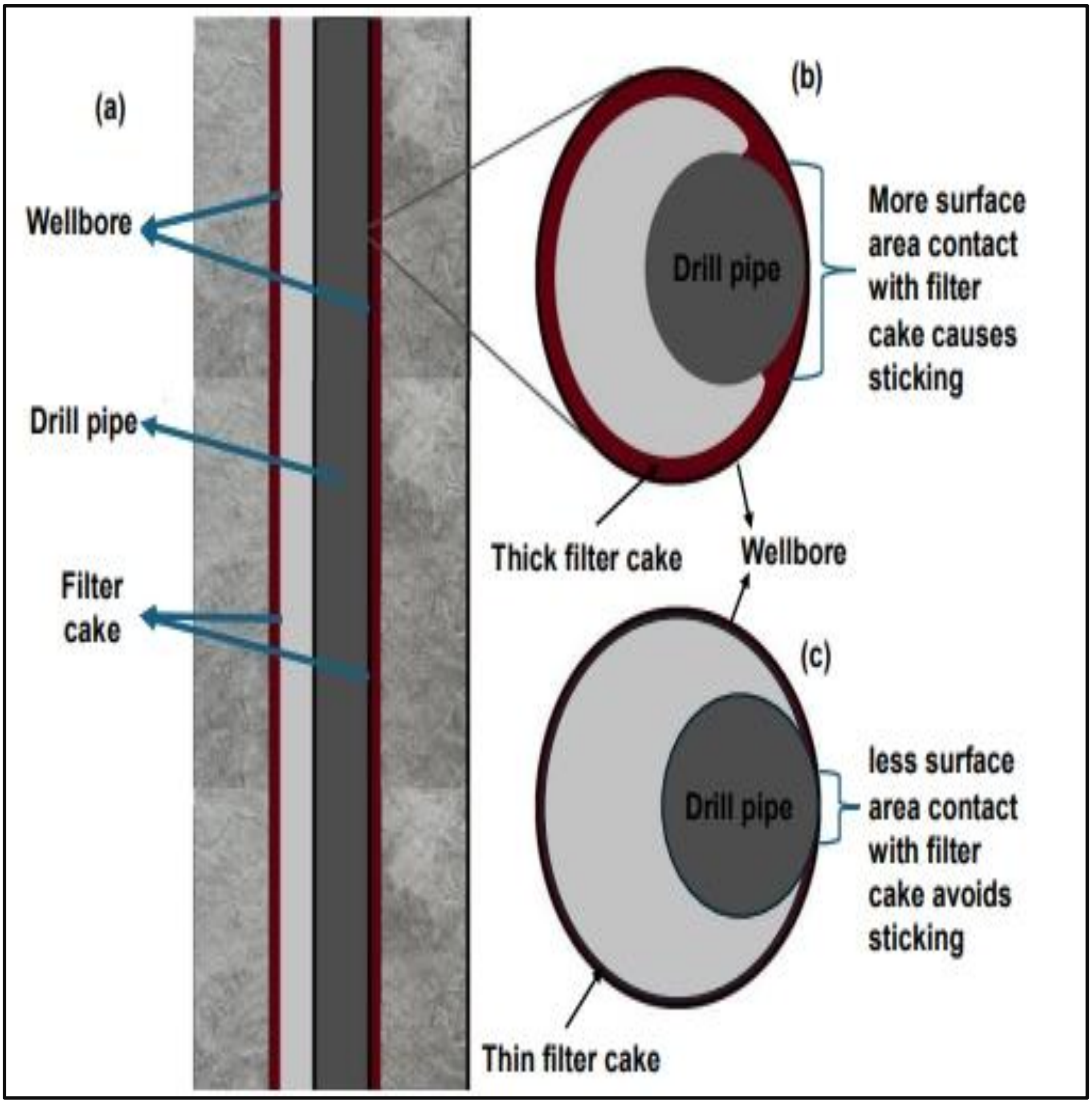

Fig. (2-7): **Schematic illustrating the stuck pipe mitigation with nanofluids. (a) A wellbore scenario where a drill pipe becomes stuck due to thick filter cake buildup on the wellbore wall. (b) Enlarged cross-section illustrating how the increased contact surface area of thick filter cake contributes to the pipe sticking. (c) Nanofluids offer a solution by forming a thin filter cake, reducing contact area, maintaining good particle suspension, and enhancing cuttings transport to prevent stuck pipe incidents.**

Table (2-3): Summary of research papers investigating the application of nanoparticles to address wellbore stability issues, including the specific nanoparticles used and the key outcomes.

Nanoparticle	Outcomes
Silica (SiO_2)	Due to high surface area and chemical stability, it enhanced mud rheology and reduced fluid loss.
Amino nano-silica	Improved plugging performance compared to nano-silica.
Alumina (Al_2O_3)	High hardness and thermal stability of the nanoparticles aided in improving lubrication and increasing cutting transportation.
Titanium dioxide (TiO_2)-bentonite nanocomposite	Improved lubricity and mud cake development, layering on shale and bentonite plugs, easing of clay and shale swelling, and a decrease in friction coefficient.
Iron oxide (Fe_2O_3)	Improved coefficient of friction and fluid loss (filtrate loss).
Graphene oxide (GO)	The linear swelling, filtration, uniaxial compressive strength, and imbibition of shale help prevent wellbore instability.
Carbon nanotubes (CNTs)	Carbon nanotubes improve the performance of water-based drilling fluids in high-salinity and high-temperature conditions.
Zinc oxide (ZnO)	Zinc oxide nanoparticles enhance the rheological properties of water-based drilling fluids even at high temperatures.
Copper oxide (CuO)	Copper oxide nanoparticles are efficient in decreasing fluid loss and increasing wellbore stability in drilling fluids.
Magnesium oxide (MgO)	Magnesium oxide nanoparticles in water-based drilling fluids can improve rheological, filtration, and viscoelastic properties and enhance wellbore stability.
Bentonite nanoparticles	Decreases filtration loss by a mean of 34%, leading to better filtration; the nano-bentonite particles are layered onto the wellbore wall and close off the pores in the mud cake, thus helping with the "tight spot problem" in wellbores.

2.4.8 Practical Precautions

While choosing the nanoparticles, the selection should be made depending on the well conditions, alongside temperature, pressure, and formation characteristics. The compatibility of nanoparticles with drilling fluids should be checked by confirming that respective nanoparticles are cooperative and fit with the base drilling fluid and its other additives as it is important to avert hostile reactions and sustain fluid performance. The nanoparticle usage should be in compliance with environmental regulations and have safety standards so as to avoid any possible health risks and adverse environmental impacts (see Table 4).

Table (2-4): Environmental impacts and best application details of respective nanofluids.

Type of Nanofluid	Best Application for	Environmental Impact
Copper	Improved thermal conductivity and lubrication properties.	Moderate, yet toxic in higher concentrations.
Alumina (Al_2O_3)	Enhanced stability and viscosity.	Low, deemed safe in general but needs supervision.
Zinc oxide (ZnO)	Better lubrication and antimicrobial properties.	Moderate, toxic to aquatic life if released.
Titanium dioxide (TiO_2)	Enhancement of fluid stability at high temperatures.	Low, safe yet concerning for inhalation risks.
Iron oxide (Fe_2O_3)	Effective removal of cuttings.	Low and non-toxic, yet accountable disposal is required.
Silver	Fluid quality maintenance and antimicrobial nature.	High, toxic for aquatic life in higher concentrations
Silica	Improved fluid stability and transportation of cuttings.	Low and relatively non-toxic but carries risk of dust exposure.
Graphene oxide	Enhanced mechanical properties and sealing of micropores.	Moderate, caution required due to environmental persistence and potential toxicity.

2.5 Thermal Stability

Drilling projects require thermal stability, which refers to how well drilling fluids can withstand the heat underground [90]. This heat comes from several places: the friction from the actual drilling itself, the temperature increase with depth (geothermal gradient), and the proximity to the hot drill bit [91]. Such high temperatures destroy the properties of drilling fluid. For instance, high temperatures make the fluid thinner (less viscous). This may result in the poor removal of rock cuttings, unstable wellbores, and fluid loss into the rock. High temperatures also impede the fluid's ability to lubricate and reduce friction, and equipment failure is more likely [92]. Other problems include heat accelerating undesirable chemical reactions in the drilling fluid [14]. Such reactions give off noxious byproducts, change the chemistry of the fluid (pH and salinity), and damage equipment or stop drilling operations altogether. In conclusion, drilling fluid stability at high temperatures is very important. It impacts the viscosity, lubrication, and overall performance of the drilling fluid—which in turn affects the safety and success of the drilling operation. Nanoparticles have proven their ability to maintain the thermal stability of the drilling fluid by preventing the degradation of fluid by proficiently managing thermal conductivity (effective heat distribution due to smaller size and more surface area to accept heat), viscosity control (maintenance of viscosity at elevated temperatures), shear thinning behavior (being less viscous at high shear and more viscous at rest), and fluid loss reduction (stable filter cake) [67,93,94,95]. The following subsections will elaborate on how nanoparticles aid in achieving thermal stability in a drilling fluid.

2.5.1. Nanoscale Heat Management Mechanisms

Heat transfer at the nanoscale is controlled by nanoparticles for thermal stability improvement. Nanoparticles are generally good thermal conductors that can effectively radiate heat away from critical areas [2,54]. Two key mechanisms (static and dynamic) are responsible for heat movement in nanofluids. **Fig.(2-8)** illustrates static (structural) mechanisms forming a liquid layer at the solid–liquid interface which acts as the heattransporting bridge and a chainlike transportation path for heat due to particle aggregation. **Fig. (2-9)** shows the dynamic mechanism comprising the particle's Brownian motion and its induced convection in the base fluid [96]. Nanoparticles form a physical barrier to protect the components of the drilling fluid from heat and damage [97]. Some nanoparticles also possess optical properties that reflect or absorb infrared radiation, reducing heat buildup [53].

Nanoparticles may stabilize emulsions and colloidal suspensions within the drilling fluid by foiling phase separation and maintaining homogeneity even under thermal stress. Higher concentrations of multi-walled carbon nanotubes in ester-based drilling fluids achieve better emulsion stability and other rheological properties [98]. This multifaceted thermal management makes nanoparticles an effective tool to maintain the stability and performance of materials at high temperatures [69]. The following paragraphs describe the influence of nanoparticles on the thermal stability, viscosity control, chemical stability, and lubrication control of drilling fluids at high temperatures.

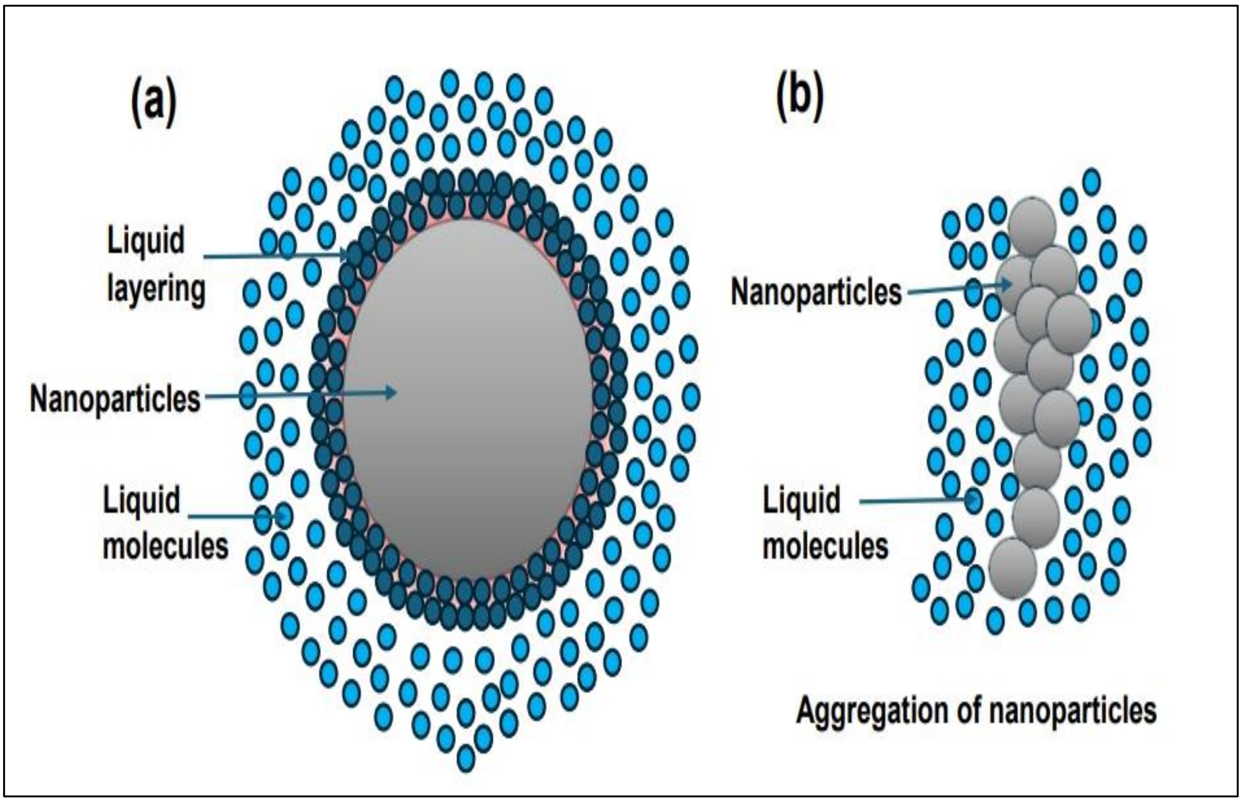

Fig. (2-8) The static mechanism of heat transfer in nanofluids: (a) representation of how the liquid layering occurs at the solid–liquid interface of the nanoparticles; (b) aggregation of nanoparticles that act as a pathway for heat transfer.

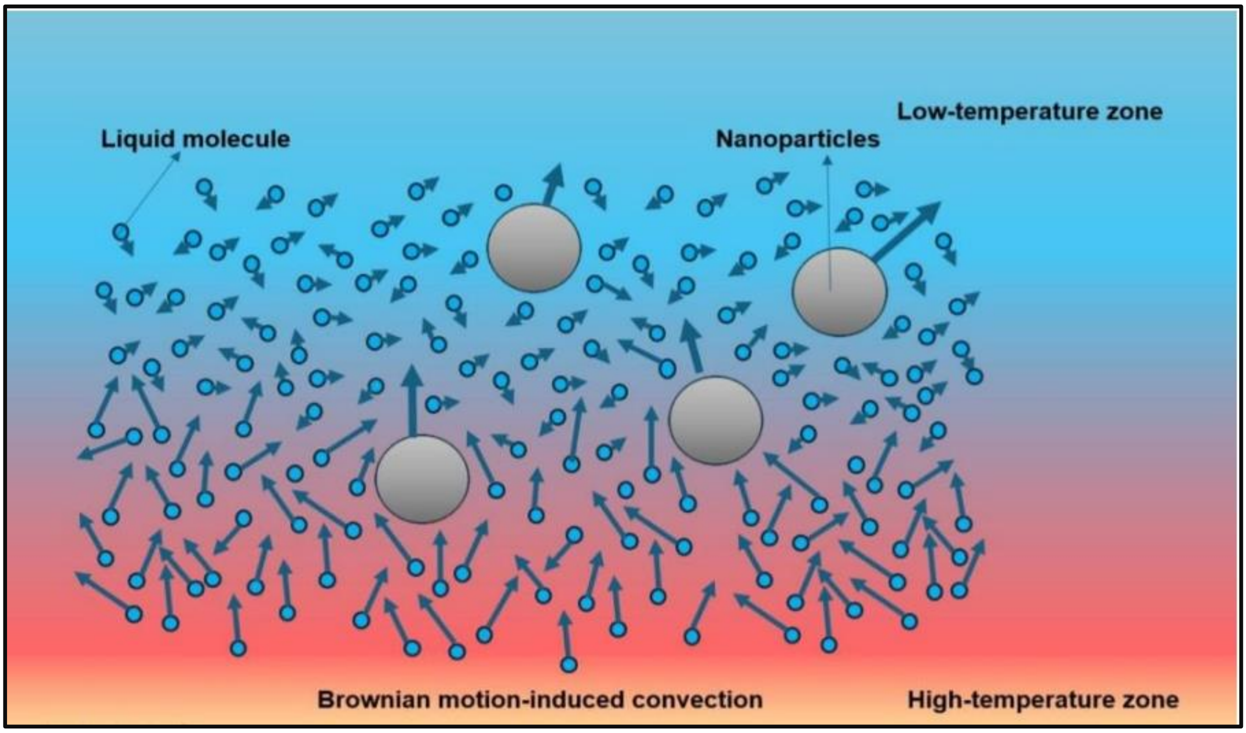

Fig. (2-9). Dynamic mechanism of heat transfer: as the particles move in a Brownian motion (irregular movement), they collide with each other and also induce convection for the nearby liquid molecules of the base fluid, thus increasing the thermal conductivity.

2.5.2. Temperature Resistance

The nanoparticles of metals (iron oxide, silica, titanium dioxide) and carbon-based materials (graphene oxide, carbon nanotubes) themselves are very thermally stable. If they are dispersed in the drilling fluid, these nanoparticles can act as heat sinks that absorb and dissipate heat efficiently. For example, iron oxide (Fe_3O_4) nanoparticles possess high thermal conductivity that helps maintain the thermal stability of drilling fluids. These nanoparticles can maintain shear stresses at predefined shear rates at elevated temperatures [99]. Modified Fe_3O_4 nanoparticles combined with poly-sodium p-styrene sulfonate enhanced the shear thinning of drilling fluids at different temperatures, particularly at 0.1% [91]. Nanoparticles help prevent the degradation of the base fluid by stopping the breakdown of polymers employed in the fluid through temperature resistance, extending its effective lifetime at higher temperatures. Improving the concentration of TiO_2 nanoparticles led to a decrease in the flow behavior index and an increase in yield stress. This leads to increased viscosity and the enhanced shear thinning behavior of drilling fluids. Also, adding the TiO_2 nanoparticles noticeably increased the low shear rate viscosity of the drilling fluid, confirming the enhancement of the fluid's rheology and affirming the better performance with higher viscosities at elevated temperatures [22]. Al_2O_3 nanoparticles also exhibit Eng 2024, 5 2483 thermal stability by sustaining shear stresses at different temperatures and rates. Also, Al_2O_3 nanoparticles added to bentonite-based water-based mud (WBM) improved the gel strength, yield point, and plastic viscosity of the drilling mud [100]. Copper oxide (CuO) and zinc oxide (ZnO) nanoparticles also demonstrated their ability to improve the thermal and electrical properties of water-based drilling muds. With just 1% volume addition, these nanoparticles can improve these properties by 35% [29]. Yttrium oxide nanoparticles have shown good thermal stability at 300 degrees Fahrenheit and 10,000 psi. The optimum concentration for this purpose is 2.5 g of yttrium oxide nanoparticles [73]. Triton-X100 and coconut shell-based graphene (GN-CS) were added together, obtaining better dispersed modified graphene (GN-TX) particles. When used in WBM, results confirmed that GN-TX had excellent thermal resistance up to 300 ◦C. The graphene sheets become aggregated and form a crumpled topology due to microscopic buckling and crumpling that ensures enhanced thermal stability.

Fig. (2-10) gives a well-explained pictorial representation of this process [96]. A review of studies exploring the use of nanoparticles to address fluid loss, detailing the types of nanoparticles employed and any notable findings, is presented in Table 5.

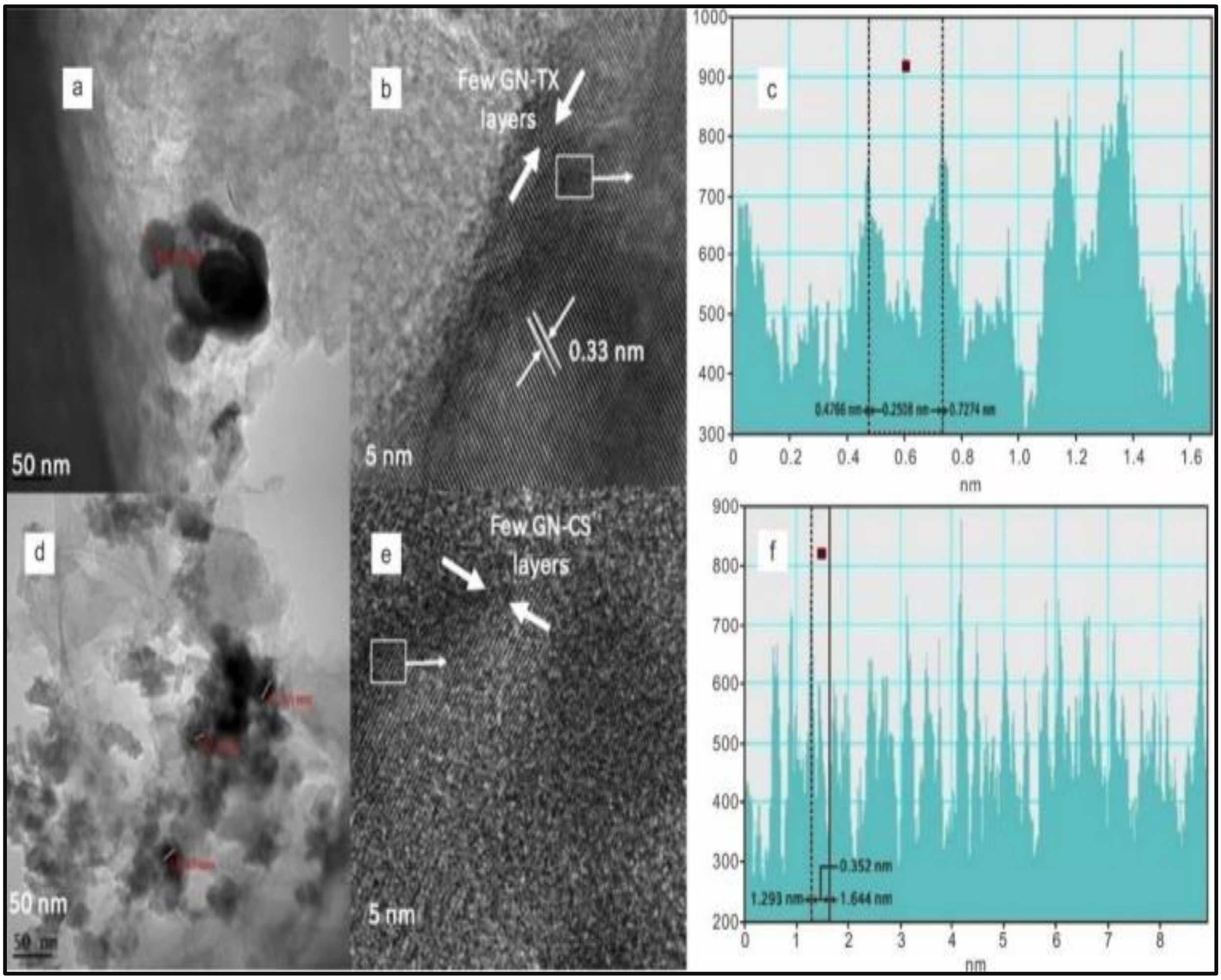

Fig. (2-10). High-resolution transmission electron microscopy (HR-TEM) analysis of graphene nanoplatelet composites (GN). (a) HR-TEM image of modified GN-CS (GN-TX) surface postmodification, revealing significant alterations in surface morphology. (b) Magnified image of GN-TX highlighting the firm attachment and dispersion of the modified materials after ultrasonic treatment. Visible wrinkles (represented by arrows) indicate the presence of multiple (squares with dotted lines) graphene layers. (c) Intensity pattern of GN-TX, confirming the strong attachment of Triton to the GN-CS surface. (d) HR-TEM image of GN-CS, emphasizing the wrinkly regions with entangled graphene sheets. (e) Magnified image of GN-CS showing the multiple (squares with dotted lines), wrinkly (indicated by arrows) graphene layers that contribute to the composite's thermal stability. (f) Intensity patterns of GN-CS further reveal the structural details (figure adapted from [99]).

2.5.3. Viscosity Control

High temperatures weaken drilling fluids and reduce their ability to carry rock cuttings out of the wellbore [76]. Nanoparticle additives can ameliorate this by controlling the rheological properties—viscosity and flow behavior—of the drilling fluid, even at high temperatures. By combining nano-clay with nano-silica, for example, the stability and flow properties of oil-based inverted emulsion drilling fluids under extreme temperature and pressure were improved [95]. Also, nanoparticles of palygorskite (Pal), a naturally occurring hydrous clay mineral, can help drilling fluids keep their basic properties, even at elevated temperatures and pressures [67]. These include density, viscosity, gel strength, fluid loss, and filtration control. The maintenance of such properties is essential for drilling operations in diverse geological formations and under various conditions.

2.5.4. Chemical Stability

Elevated temperatures alter the chemical properties of drilling fluids or cause undesirable byproducts. Nanoparticles can make the drilling fluid chemically stable and less susceptible to thermal degradation or chemical reactions that change its properties. Particularly, titanium, iron, aluminum, zinc, copper, silver, and graphene metal oxide nanoparticles (NPs) improve the mechanical and thermal resistance of the drilling fluid [7]. Furthermore, silver, copper, and zinc oxide NPs have antimicrobial activity and may prevent the microbial degradation of fluid [22]. Other nanoparticles include carbon nanotubes/nano-clays and silicon dioxide, which provide better rheological and filtration properties and the better suspension of drilled cuttings which prevents their settling in the wellbore [88]. The diverse functionalities of different nanoparticles contribute to the chemical stabilization of the drilling fluid. Addressing individual property parameters can help reduce the risk of nanoparticle degradation and ensure compatibility with other chemical additives in the drilling fluid [13,93].

2.5.5. Lubrication Control

Elevated temperatures encountered during deep drilling operations pose a significant challenge to the lubrication properties of drilling fluids. This is primarily due to several interconnected mechanisms. Firstly, high temperatures can induce the thermal degradation of polymeric viscosifiers and lubricant additives, reducing the fluid’s viscosity and its ability to form a lubricating film [83]. Secondly, elevated temperatures accelerate fluid loss into permeable formations, hindering the formation of an effective filter cake and increasing frictional forces [92]. Additionally, the precipitation of solids at high temperatures can further impede fluid flow and exacerbate wear [83]. Consequently, the degradation of lubrication under elevated temperatures can lead to increased friction, the premature wear of drilling equipment, and potential wellbore instability. Nanoparticles have emerged as encouraging additives to enhance drilling fluid lubrication, particularly in high-temperature environments where traditional lubricants falter. Silica nanoparticles, for instance, contribute to the formation of robust lubrication films [30], while carbon nanotubes act as nano-bearings, reducing friction and wear [31]. Graphene and graphene oxide, renowned for their low friction coefficients, offer additional lubrication benefits. Molybdenum disulfide [32], nanodiamonds, and various metal oxide nanoparticles also exhibit lubricating properties, collectively minimizing friction and wear between the drill string and wellbore surfaces. These nanomaterials thus offer a viable solution for maintaining drilling efficiency and mitigating equipment damage in challenging drilling conditions.

Table (2-5): Summary of research papers investigating the application of nanoparticles in maintaining thermal stability, including the specific nanoparticles used and key outcomes.

Nanoparticle	Outcomes
CuO and ZnO	Proved to have better thermal and filtration properties.
Fe_3O_4	Increase in rheological and filtration properties along with improved thermal properties.
TiO_2	Improved thermal properties.
Y_2O_3	Improved rheology and thermal properties.
CuO and ZnO	Enhanced thermal characteristics.
Carbon nanoparticles	Enhanced thermal conductivity.
Al_2O_3	Intensified thermal properties.
Al_2O_3	Improved thermal and rheological properties.
Silver nanoparticles	Enhanced thermal properties.
CuO	Enhanced the thermal and rheological properties.
Multi-walled carbon nanotubes	Non-linear enhancement of thermal conductivity.
Graphene nanosheets	Enhanced thermal conductivity of the nanofluid.
Multi-walled carbon nanotubes	Modified MCNT enables the drilling fluid to have increased thermal conductivity and viscosity.
Graphite–alumina	Improved zeta potential, electrical conductivity, thermal conductivity, and degree of structural recovery.
Nano-silica	Improved thermal conductivity at high temperatures.
Molybdenum disulphide	Improved lubricity and thermal stability.
Palygorskite (Pal)	Good rheology modifier and improved thermal stability.

2.6. Challenges and Future Scope

2.6.1 Challenges in Nanoparticle Stability

Maintaining the stability of nanoparticle (NP) dispersions in the harsh drilling environment is challenging. However, high temperatures, pressures, and the chemical composition of drilling fluids may lead to NP agglomeration and sedimentation, mainly due to van der Waals forces and high surface energy. All these phenomena can severely compromise the desired properties of drilling fluids like viscosity, rheology, and thermal conductivity. To alleviate these problems, researchers have coated NPs with silanes, phosphonates, and polymeric surfactants. Such coatings provide steric or electrostatic stabilization to prevent NPs from aggregating and settling [65]. The stability and rheological properties of WBDFs were demonstrated by surface-modified silica NPs [59]. Also, polyvinylpyrrolidone (PVP) and polyethylene glycol (PEG) dispersants have shown promise for improving NP dispersion stability [67].

2.6.2 Interactions with Drilling Fluid Components

The polymers, surfactants, salt, and other additive complexes present in drilling fluids may affect the behavior of NPs. For instance, copper NPs increased the viscosity and yield point of water-based drilling fluids [50]. Additionally, NP interactions with drilling fluid components may affect fluid loss properties, filter cake formation, and wellbore stability [39]. As such, a complete understanding of these interactions is necessary for the formulation of tailored drilling fluid formulations, which can extract maximum benefit from NP addition and minimize undesirable side effects.

2.6.3 Environmental Concerns

Drilling operations release NPs into the environment, which has raised concerns about their consequence, transport, and possibly toxic effects. Recent studies of NPs' behavior in aquatic environments suggest that thorough assessments of their environmental impacts are required [98,75]. Such studies highlight the need for biodegradable or environmentally benign NPs and the development of robust mitigation strategies to limit ecological risks [87].

2.6.4 Heat Transfer Efficiency

NPs have promising potential applications in drilling fluids to improve heat transfer efficiency. Yet optimal thermal performance requires the precise control of particle properties such as material, shape, and size distribution [87]. These parameters have shown that they affect the heat transfer properties of nanofluid-based drilling fluids [85]. NPs have to be adapted to the drilling conditions to maximize heat transfer properties.

2.6.5. Economic Viability

The economic feasibility of nanotechnology incorporation in drilling fluids is a critical consideration. Producing specialized NPs requires expensive techniques such as chemical vapor deposition and laser ablation. The scalability and cost-effectiveness of these methods prevent their widespread adoption [19]. Therefore, alternative synthetic routes such as wet chemistry methods [45] and long-term cost–benefit analyses are necessary for economically viable NP-enhanced drilling fluids.

2.6.6. Safety Considerations

The potential toxicity and environmental impact of nanomaterials require detailed risk assessments and strict regulatory frameworks. The health and environmental hazards of NPs have been questioned [95,92]. Such studies show that strict safety evaluations, including toxicity testing and exposure assessment, are necessary before deploying nanotechnology in field application.

2.6.7. Other Technical Challenges

Other technical hurdles, besides those mentioned above, that must be overcome include the following: High Cost of NP Synthesis and Functionalization—High-quality NPs with tailored surface properties are expensive to produce and are thus limited in their large-scale implementation in drilling fluids [2]. Scalability Issues—It is still challenging to scale up NP production to meet oil and gas industry demands through developing economically viable manufacturing processes [63]. Standardization of Characterization Techniques—A lack of standard methods for characterizing NP properties such as size, shape, and surface chemistry can lead to discrepancies in research results and prevent the development of reliable performance metrics [72].

2.7. Future Scope and Technical Innovations

2.7.1 Strategies for Nanoparticle Stability and Compatibility Improvement

Robust surface modification strategies for nanoparticle stability under extreme drilling conditions should be targeted in future research. This could involve the investigation of new charge-neutral coating materials, such as zwitterionic polymers, which are resistant to pollution in harsh environments [39]. The mechanical and chemical inert oxide coatings of silica or alumina also impart enhanced stability [87]. Optimizing coating thicknesses and investigating multi-layered coatings combining electrostatic and steric stabilization mechanisms may further enhance nanoparticle dispersion and prevent agglomeration, as shown in studies with silica nanoparticles coated with polymer coatings [65]. Understanding the interactions of nanoparticles with drilling fluid components is needed. Systematic studies with advanced characterization techniques like dynamic light scattering (DLS) and zeta potential measurements can elucidate the influences of different polymer types (xanthan gum, polyacrylamide), surfactants, and salts on nanoparticle behavior. In one study, salts were shown to be able affect the stability of nanoparticles in drilling fluids and divalent cations were able to increase aggregation [188]. This knowledge might help to modify drilling fluid formulations to maximize nanoparticle benefits and minimize adverse effects.

2.7.2 Environmental Stewardship and Sustainability

Sustainable nanotechnology applications in drilling require environmentally friendly nanoparticles and strict mitigation strategies. Research should focus on biodegradable nanoparticles synthesized following green chemistry principles, such as using plant-based surfactants from cellulose or starch and avoiding hazardous chemical usage [27]. Nanoparticles' destination and transport can be monitored during drilling operations using realtime monitoring systems like nanoparticle tracking analysis (NTA) or inductively coupled plasma mass spectrometry (ICP-MS) with minimum environmental compliance and eco- Eng 2024, 5 2487 logical risks. Studies show that such techniques can detect and quantify nanoparticles in environmental matrices [90,11].

2.7.3 Nanomaterial Tuning for Heat Transfer Optimization

An adequate understanding of the relationship between nanoparticle properties and thermal performance is required for the optimal heat transfer efficiency of nanofluidbased drilling fluids. Studies should investigate the effects of nano-particle material (e.g.: graphene, carbon nanotubes), shape (spherical, rod-like), size, and concentration on thermal conductivity and viscosity. Some studies report enhanced thermal conductivity when nanoparticles like graphene and carbon nanotubes are added to base fluids. Simulations of heat transfer in drilling scenarios can be used to predict optimal nanoparticle configurations for given well conditions [49,98].

2.7.4 Economic Feasibility and Scalability

To become a standard part of drilling operations, nanotechnology has to be cost effective. Developed scalable and economic nanoparticle synthesis methods deserve further research and attention. This may include investigating innovative synthesis methods like continuous flow reactors or microwave-assisted synthesis that offer improved yield with reduced expenses instead of batch processes. These techniques have shown that they can produce nanoparticles with precisely regulated dimensions at a larger scale [90,94]. LCAs can evaluate the financial and ecological effects of nanoparticle-enhanced drilling fluids and provide insight into feasibility and long-term sustainability [98].

2.7.5 Safety First: Rigorous Risk Assessment and Regulation

Nanomaterial safety is of prime concern in drilling applications. Future studies should focus on the detailed risk assessments of nanoparticle toxicity and the long-term environmental impact in drilling fluids. This involves performing detailed toxicity studies with relevant model organisms like zebrafish or Daphnia, which are commonly used in ecotoxicological research [62,79]. Exposure limits must be established considering realistic scenarios such as nanoparticle release rates and environmental persistence [88]. Normative protocols for the handling, storage, and disposal of nanomaterials in accordance with international guidelines and regulations are needed for safe and responsible nanotechnology use in the oil and gas [54].

2.8. Summary

Nanofluids, enriched fluids containing nanoparticles, are an emerging technology in the drilling industry that may improve efficiency, cost, and environmental impact. Nanoparticles less than 100 nanometers in size possess unique properties that enhance drilling fluid performance. Their large area-to-volume ratio facilitates interactions with the drilling fluid and forms, improving rheological properties, reducing friction, and increasing heat transfer. This provides certain benefits, including the better lubrication, improved fluid stability, enhanced heat transfer, and improved sealing of microfractures in the rock formation for better wellbore stability.

Nanoparticles have been used in various drilling applications, including fluid loss control, wellbore stability, and thermal stability. Still, there are challenges to be overcome before wide adoption. These include maintaining nanoparticle stability in harsh drilling conditions, avoiding interactions with other drilling fluid components, addressing environmental issues, improving heat transfer efficiency, and ensuring economic viability. High production costs, safety issues, scalability, and nonstandard characterization techniques also create difficulties.

Developing robust surface modification strategies to improve nanoparticle stability, understanding the interactions of nanoparticles with drilling fluid constituents, designing environmentally benign nanoparticles, and implementing mitigation strategies are future research directions. The safe and responsible use of nanotechnology in the oil and gas Eng 2024, 5 2488 sector is crucial, and future studies should concentrate on standardizing protocols for the handling, storage, and disposal of nanomaterials in accordance with international guidelines and regulations.

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Chapter Three

EXPERIMENTAL

3. Experimental

3.1. Experimental Materials

- **Conventional Drilling Fluid Additives.** The micro size additives used in this work included API bentonite to provide primary viscosity and xanthan gum (XG) to adjust the final rheological properties of the basefluid. Polyanionic cellulose low-viscosity (PAC-LV) and pre-gelled starch were included as conventional filtrate loss additives. Graphite was used as conventional LCM additive. Potassium hydroxide (KOH, 85%) was included as an alkalinity control agent. All the mentioned products were provided by different service companies and used as received.
- **Nanomaterials.** Silica oxide nanoparticles (SiO2-NPs) were supplied by US Research Nanomaterial, Inc. in a white powder form. The SiO2-NPs are near spherical with an approximate diameter ranging between 15 nm – 20 nm. The NPs were unmodified (bare surface) and non-porous with a density of 0.1 g/cm3, a specific surface area of 170–200 m2/g, and purity greater than 99.5 wt. % as detailed by the provider. Graphene oxide nanoplatelets (GNPs) used in this study were provided by Nanographene Inc. in a dark-gray powder form with a density of 0.13 g/cm3. The GNPs have a two-dimensional (2D) structure with an average particle size from 1.3 μm to 2.3 μm and thickness < 3 nm. The GNPs' flake shape result in a specific surface area of 536 m2/g and 1 to 10 layers with a purity greater than 99.8wt.% as specified by the provider. Figure 1 shows a scanning electron microscope (SEM) of (a) the SiO2-NPs and (b) the GNPs.

- ***Shale Rock Properties.*** Woodford shale was used in this work to test the impact of using NPs to enhance the inhibition capabilities of WBM. This rock is described as a late Devonian-Early Mississippian marine shale (Gupta et al., 2013). The shale sample was supplied by a provider in Catoosa, Oklahoma. In this study shale samples of 1 in. in diameter and a length range of 0.5 to 2 in. were cored and stored in high-purity mineral oil to avoid properties alterations. XRD of the shale powder was analyzed with the x-ray tube set at a voltage of 40 kV and a current of 45 mA, employing copper Kα radiation (1.54Å). The mineralogical composition is listed in **Table (3-1).**

Table (3-1): The Woodford shale mineral composition

component	CONTENT (wt.%)
Quartz	67
Total clay	31.5
Pyrite	1.5

It contains 31.5% clay minerals (22.8% illite, 5.4% chlorite, and 3.3% kaolinite), 67% quartz and 1.5% of pyrite. The above indicated a high degree of brittleness as well as low water sensitivity due to the lack of swellable clays (i.e. smectite, mixed-layers) and a cation exchange capacity (CEC) of 1.5 meq/100g, which is a common feature of unconventional shales. SEM images of the Woodford shale gave an insight into the rock pore structure properties. Figure 2 shows a sequence of the SEM images, where, the image (A) is equivalent to 7k, and (B) 30k magnification respect to the original sample size.

3.2 Base Drilling Fluid Formulation.

The formulation listed in **Table (3-2)** was used to prepare the base drilling fluid (Basic A) for the NP-WBM. For instance, this study considered that adding 1 g of material to 350 ml of fluid is equivalent to adding 1 lbm of material to 1 bbl of fluid at field scale. The concentration for each additive was design based on a final volume of 925 ml. Preparation of the base fluid started by adding the bentonite concentration to the deionized water (625 ml) while mixing the fluid at 11000 rev/min in a laboratory blender for 30 minutes. The bentonite slurry was allowed to hydrate undisturbed for 12 hrs at 77°F (room conditions). Then, the other chemicals were added carefully to avoid ‘fish eyes’ in the drilling fluid with the mixer set at the initial speed. Enough stirring time was allowed between additives. Finally, KOH was added to adjust the alkalinity of the drilling fluid as needed. The remaining volume (300ml) to complete the final sample (925 ml) was used in the preparation of the NPs dispersions.

Table (3-2): Formulation of water-based drilling fluid A (base fluid)

ADDITIVE	Water	Bentonite	Xhantan	Starch	PAC-LV	KOH
CONCENTRATION (PPB)	1.0	10	0.25	1.85	1.85	*

3.3 Nanoparticle Colloidal Solution Mixing Procedure

Prior to the addition of NPs to the base fluid, a separate mixing procedure was required to disperse the NPs in deionized water in order to reduce their aggregation tendency. A high-resolution balance (±0.0001g) was used to weight the required concentration of NPs. Then, 300 ml of deionized water were poured into an Erlenmeyer flask and the NPs were slowly added. A magnetic stirrer was used to mix the dispersion. A final ultrasonication step was carried out at 40 kHz and 185 W for 1 hour to promote a better dispersion of the NPs, improving their colloidal stability. The water in the sonic bath was changed 3 times during the process and aluminum foil was used to cover the opening of the Erlenmeyer flask to prevent evaporation of the NPs colloidal solution. Previous researchers have indicated advantages of including this step for NP-WBM (Ponmani et al., 2016). In the case of adding both, SiO_2-NPs and GNPs to a single drilling fluid formulation, the remaining volume (300 ml) was divided into equal parts for each nanomaterial and the dispersions were prepared individually to avoid cross-contamination.

3.4 NP-WBM Preparation and Screening Criteria

Different nanofluids were prepared by mixing the drilling fluid A with the desired NP dispersion at a high shear rate (22000 rev/min) for 20 minutes while adjusting the pH to 9.5. This study established a concentration of 1% by weight of NPs as an upper limit. Their extremely high surface area to volume ratio suggested that small concentrations might enhance the overall WBM properties (Amanullah, 2011). Also, low concentration aims to reduce the costs associated with the technique as well as aggregation tendencies due to larger distances between individual NPs inside the drilling fluid. The initial step of the screening criteria included the addition of different concentrations of SiO_2-NPs or GNPs to the basic A fluid as listed in Table (2-3). The above, serve to initially examined the impact of each nanomaterial separately as well as narrow the NPs' concentration to the ones that exhibited the best performance based on rheological and filtration tests at room conditions (77°F).

Table (3-3):Nanomaterials initial concentrations

Silica Oxide NP (wt.%)				Graphene Oxide Nanoplatelets (wt.%)			
0.1	0.25	0.5	1.00	0.1	0.25	0.4	0.75
S1	S2	S3	S4	G1	G2	G3	G4

The second step in the design of the NP-WBM includes the mix of the best two concentrations of each nanomaterial in a single NP dispersion as shown in **Table(3-4).**

Table(3-4):Silica oxide and graphene oxide NP combinations

Nanofluid	Silica Oxide Np (wt.%)	Graphene Oxide Nanoplatelets (wt.%)
B	0.25	0.25
C	0.5	0.25
D	0.25	0.4
E	0.5	0.4

This stage included the analysis of four different combinations of both nanomaterials. The drilling fluid that showed remarkable properties by means of API filtrate, HTHP filtrate, and rheology at fresh conditions compared to the others was designated as the optimal NPs concentration. Finally, graphite was included as conventional shale stabilizer. Its benefits have been mentioned in previous studies (Contreras et al., 2014). Cooperation between the NPs and the LCM additive is believed to take place, impacting positively the performance of the optimized NP-WBM, more specific, its inhibition capabilities. **Table(3-5)** shows the optimized formulation of the NP-WBM.

Table(3-5): Formulation of the np-wbm

ADDITIVE	Water	Bentonite	Xhantan	Starch	PAC-LV	Graphite	NPs	KOH
CONCENTRATION (PPB)	1.0	10	0.25	1.85	1.85	7	[Table 4]	*

* KOH was added until a pH value of 9.5 was reached.

3.5 Experimental Methodology

The methodology used in the design of a NP-WBM for unconventional shales started with the evaluation of the colloidal stability of the selected nanomaterials. The second step includes the laboratory analysis of the base fluid as well as the different formulations with NPs to evaluate their rheological and filtration properties based on API standard procedures. Finally, the optimized NP-WBM formulation was tested against the Woodford shale to evaluate the impact of using NPs to reduce the exposure of micro-fractures and cutting dispersion. This section describes the laboratory tests proposed for each step and their procedure.

Zeta-potential Measurements. Unstable NPs tend to experience higher attraction forces. The above can lead to the coalescence of individual NPs forming larger aggregates that can negatively impact the colloidal stability (Korada, 2017), leading to uncontrollable viscosities or increments in filtrate losses of WBM (Amanullah et al., 2011). To evaluate the behavior of the selected NPs, the zeta-potential (ζ) technique was used. This method provides a quantitative approach to evaluate the stability of NPs in a colloidal solution. In other words, ζ-values provide an insight of the repulsion and attractive tendency experience by NPs. ζ-values above 30 mV or below −30 mV indicate that the repulsion forces between the NPs are strong enough to keep them dispersed within the liquid medium. The zeta-potential of the NPs under this study were determined using a Malvern Zetasizer NANO ZS instrument. Ultra-pure deionized water (18.2 MΩ.cm @ 77°F) was used to prepare the NPs dispersion. Low concentration (0.1 mg/ml) of NPs and ultra-sonication was carried out following Malvern guidelines. Three different measurements were obtained for each nanomaterial.

- **Rheological Measurements**. The Ofite rotational viscometer (Model 800) was used to measure the impact of adding the SiO2-NPs and GNPs on the rheological properties of the WBM formulations at atmospheric pressure and 120°F. The rheograms were obtained by measuring eight different readings (shear stress) at eight different fixed speeds of 600, 300, 200, 100, 60, 30, 6, and 3 rev/min. The equipment was operated until a steady value was reached in the indicator dial for each speed. Drilling fluid properties (i.e., Plastic viscosity-PV, Yield point-YP) were calculated based on the API procedure (API RP 13B-1 2003). Furthermore, three gel strength measurements were carried out by keeping the drilling fluid undisturbed for the required amount of time (i.e., Gel10sec, Gel10min, Gel30min). Then, the viscometer was set at the fixed speed of 3 rev/min and the maximum value reached in the indicator dial was recorded as the gel measurement.

- **API Filtrate Loss Measurements.** Filtration tests were performed to observe the filtration capability of the formulated drilling fluids and the filter cakes' quality. The standard API filter press with a regulated air pressurized system and a standard filter paper (Whatman 50, 3 ½ in diameter, 2.7 µm estimated pore size) was used to evaluate the filtration properties at low-temperature/low-pressure (LTLP) conditions of 77°F and 100 psi. The test was run for 30 minutes and the filtrate volume was collected in a graduated cylinder, (10 ml), reporting the cumulative volume to the nearest 0.1 ml. High-temperature/high-pressure (HTHP) conditions were tested at 250°F and 500 psi for a period of 30 minutes using an Ofite HTHP filter press. Cartridges of CO_2 were used to provide pressure and the filter medium was a standard filter paper. The filtrate was collected in a graduated cylinder. The cumulative volume was doubled to report as API fluid loss. The same consideration was followed for the spurt volume calculations as per API guidelines. The filter cake thicknesses were measured after running each filtration test using a digital Vernier caliper.

- **Immersion Test.** When the shale formation interacts with WBM a water absorption phenomenon can take place. The severity of this phenomenon can overcome the internal stresses of the clay structure creating microfractures or exposing the natural ones if present. The immersion or swelling test used is a simple observation method designed to evaluate the impact of fresh water and the NPs dispersions on the surface structure of the Woodford shale. For this test, the thin-sections of shale were cut from a plug parallel to the bedding planes. Then, the sample was immersed in a beaker containing the fluid to be tested and placed inside an oven at 150°F for 14 days. Photographs of the initial and final conditions were captured using a Hirox optical digital microscope.

3.6 Selection and Characterization of Nanomaterials

The design of a NP-WBM began by analyzing the characteristics of the formation intended to drill. In the case of the Woodford shale, which is an unconventional reservoir, a key step was to analyze its mineralogical composition to have an insight about how it might behave in the presence of a WBM and based on this data selected the appropriate additives that can enhance the performance of the drilling fluid. The mineralogical composition of the Woodford shale listed previously in Table 1 showed that no swellable clays such as smectite are present. The lack of this type of clays and a high percentage of the non swellable ones, more specific the illite, suggested that the Woodford shale is a brittle rock more susceptible to experienced cuttings dispersion instead of clay swelling. Moreover , conventional additives in the micro and macro size region used to stabilize clays can't either build a filter cake (Sensoy et al., 2009) or reduce the effects of water influx in the pore pressure, since no water absorption takes place and a hydraulic flow into the shale matrix is more likely to happen, increasing the sloughing tendency of the wellbore walls while drilling. The selection of SiO2-NPs was based primarily on their size that can theoretically fit the unconventional pore size of the Woodford shale as well as the performance showed in previous studies with other shales (Cai et al., 2012; Ji et al., 2012). Also, their low cost due to well-known preparation methods makes them economically attractive (Riley et al., 2012). on the other hand, GNPs were included based on the belief that at downhole temperatures its malleable nature might seal the shale counters, especially in high illitic shales that are known to experience dispersion as well as openings of natural micro-fractures along the bedding planes, increasing the chances of fluid invasion and wellbore instability (Deville et al., 2011; Gomez & He, 2012). Authors of this study believe that both nanomaterials together might help to reduce the fluid invasion and its consequence. However, NPs are very sensitives to environmental influences, thus, their colloidal stability was evaluated before mixing them with the base fluid. The ζ-potential measurements evaluated the stability of the NPs at 77°F and a pH of 9.5, which was selected for all the WBM formulations. The benefit of this technique relies on the ability to test the NPs at in-situ conditions.

The average ζ-potential for the SiO2-NPs was −34.66 mV and for the GNPs was −41.00 mV. The negative sign reveals the surface charge of the NPs. The results below −30 mV for both nanomaterials suggest good stability of the individual NPs, supporting the belief that once added to the basic A fluid no aggregation tendencies between individual NPs should rise.

Chapter Four

RESULTS AND DISCUSSION

4. Results and Discussion

4.1 Effect of SiO2-NPs and GNPs in Drilling Fluids

Initial Step of the Screening Process.

summarizes the rheological and filtration properties of the basic A fluid and the nanofluids containing different concentrations of SiO2-NPs and GNPs in the initial step of the screening process In general, the addition of NPs did not cause an excessive impact in the PV and YP of the control fluid indicating these additives might be added to WBM as long as stable NPs are used. However, under stati conditions, the GNPs generate higher gel strength values (i.e., Gel10min, Gel30min) compared to the fluids containing SiO2-NPs. Probably, due to the GNPs' negative charges and flake-shape that promote a horizontal interaction with the positive edges of the bentonite structure, causing a tighter network. Still, No progressive gels were observed. The latter is an advantage since progressive gels required elevated pump rates to re initiate the circulation of the well, which increases the risk of inducing fractures.

Filtrate results at LTLP conditions showed that SiO2-NPs had a negative impact at concentrations above 0.5 wt.%. The reduction of interparticle spaces at higher concentration might promote the aggregation of NPs, resulting in a high-permeable filter cake that allows more fluid to pass. In the case of GNPs, it was observed that concentration above 0.4 wt.% did not give further reductions in the filtrate test, a similar result was obtained elsewhere (Kosynkin et al., 2012), suggesting that this concentration might be the upper limit for this additive. For both nanomaterials the best concentration was 0.25 wt.%, resulting in a filtrate reduction of 11.63% and 13.95% for the SiO2-NPs and the GNPs, respectively, compared to the control fluid (A). The same NP concentration (0.25 wt.%) showed the best performance for both additives at HTHP conditions (250°F and 500 psi). Higher concentrations lead to more filtrate volume. Overall, the NPs' performance at HTHP conditions was better compared to the behavior at LTLP conditions. Probably due to better hydration of the conventional additives at higher temperatures that allow the NPs to be more dispersed in the system, producing less permeable filter cakes. Based on the initial outcomes, the best two concentration of SiO2-NPs (0.25wt.% and 0.5wt.%) and GNPs (0.25wt.% and 0.4wt.%) were selected to continue with the second step in the screening process.

Final Step of the Screening Process. Fig. (4-1) and Fig. (4-2) shows the rheological properties (i.e., PV, YP) of the NP formulations previously listed in Table 4. The measurements were performed at atmospheric pressure and 120°F. The combination of both nanomaterials resulted in a reduction of the PV for all the formulations in comparison to the basic fluid (A). These conditions could be caused by the interaction between the negative charged NPs and the negative charges located on the clays' surface, which increased the repulsive forces between the particles in the drilling fluid. Also, it was observed that as NPs' concentration increased above 0.75 wt.% the effect on PV started to decreases. Nevertheless, it is important to emphasize that lower PV are beneficial to the drilling operations, promoting a higher rate of penetrations as well as reducing total pressure losses and equivalent circulation densities (ECD) (Salih et al., 2016). A more uniform distribution of the additives in the drilling fluid could have taken place due to the presence of the well-dispersed NPs,allowing polymers to experience better hydration, which resulted in a slight increase of 4 to 5 units in the cuttings transport capacity (YP) of the basic fluid A fluid.

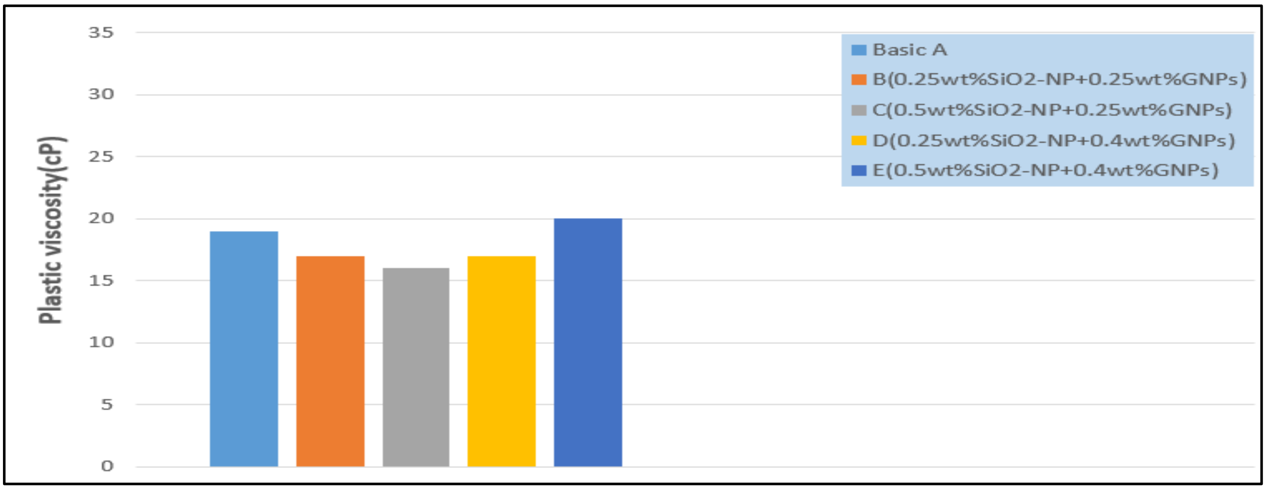

Fig. (4-1): Plastic viscosity values of different NPs formulations compared to the basic A fluid at 120°F

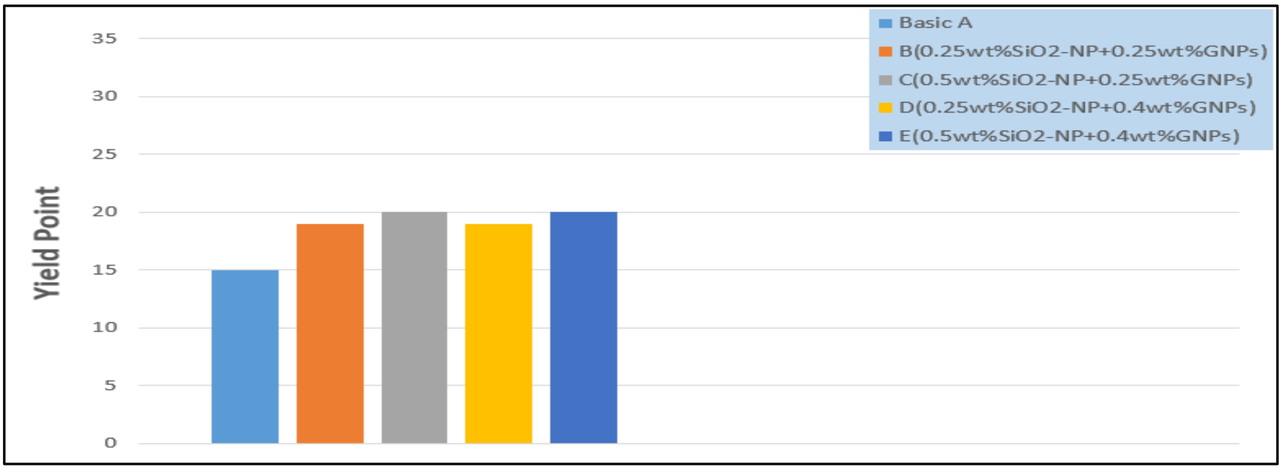

Fig. (4-2): Yield point values of different NPs formulations compared to the basic A fluid at 120°F

Fig. (4-3) shows the timed gel strength of the different NPs' combinations compared to the control fluid (A). The results indicated a clear increase in both 10 min and 30 min gel strength, representing an improvement in the cutting suspension capability of the basic WBM without generating progressive gels. The latter suggested a good electrochemical balance at static conditions between all the additives in the different formulations. Since the rheological result were very similar, the impact of the NPs on the filtration properties was the key to decide the optimal concentration.

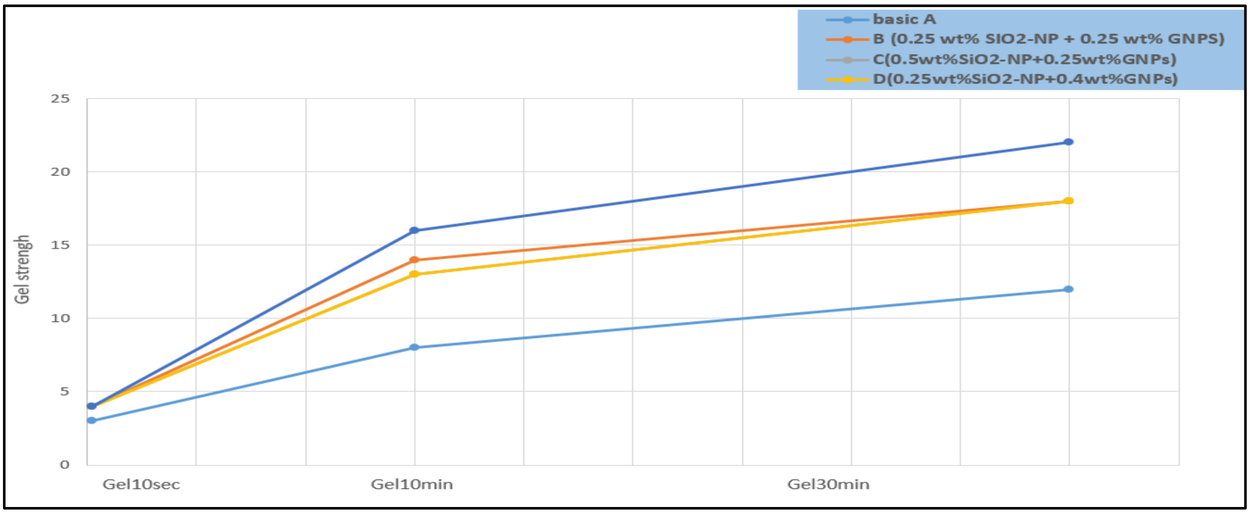

Fig. (4-3): **Gel strength behavior of different nanofluids compared to the basic A.**

Fig. (4-4) and Fig. (4-5) represents the percentage of filtrate reduction at (a) LTLP conditions and (b) HTHP conditions for the different combinations of SiO2-NPs and GNPs respect to the basic A filtration properties (Table 6). Overall, the nanofluid C showed the best performance among the different combinations and was selected as the optimal concentration to be included in the final NP-WBM design (Table 5). Once again it was evident that the NPs has a better effect at HTHP test conditions. Also, comparing these results to the ones obtained in the NPs' individual tests, the combined formulation exhibited just a slight improvement in respect to the nanofluids containing just GNPs. However, the positive effect of reducing the PV was only achieved after mixing both nanomaterials in a single formulation. Still, it is important to keep in mind that each additive has its own objective. For instance, SiO2-NPs should help to plug the nanopores present in the unconventional shale while the GNPs might have a greater effect in controlling the micro-fractures. Still, techniques such as permeability reduction tests should be run in shale cores with and without fractures in future projects to extend the characterization of this nanofluids. Interestingly, the addition of NPs did not cause changes either in the pH of the basic fluid or its density. In fact, a drilling fluid density of 8.5 ppg was found to be constant for all the fluid samples.

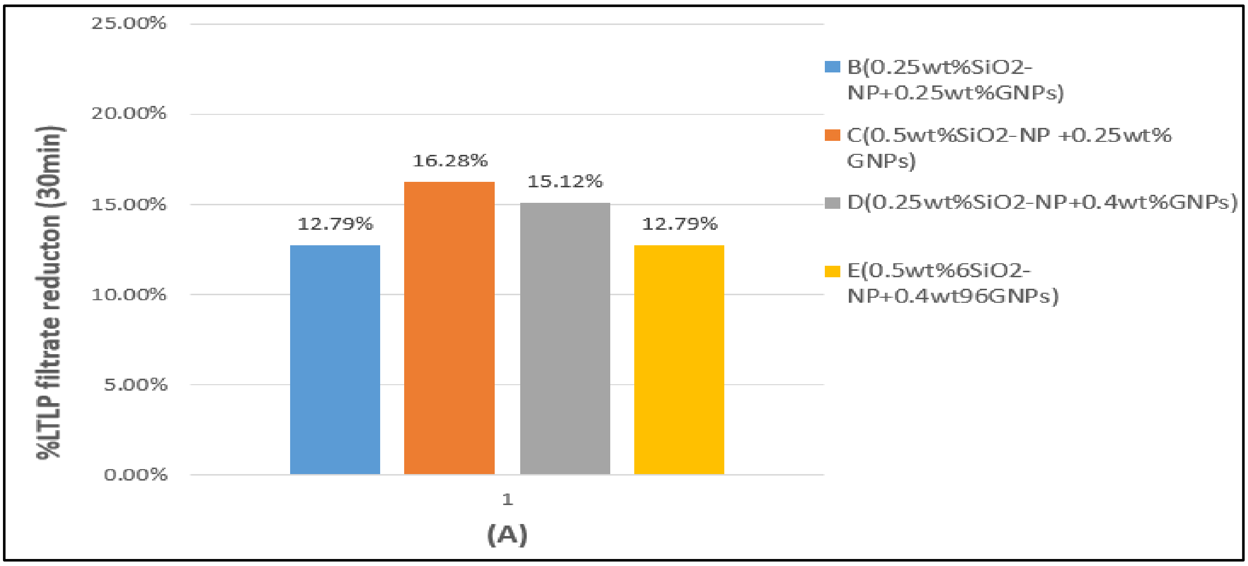

Fig. (4-4): Percentage of filtrate reduction of the (A) LTLP filtrate tests of different NPs formulations.

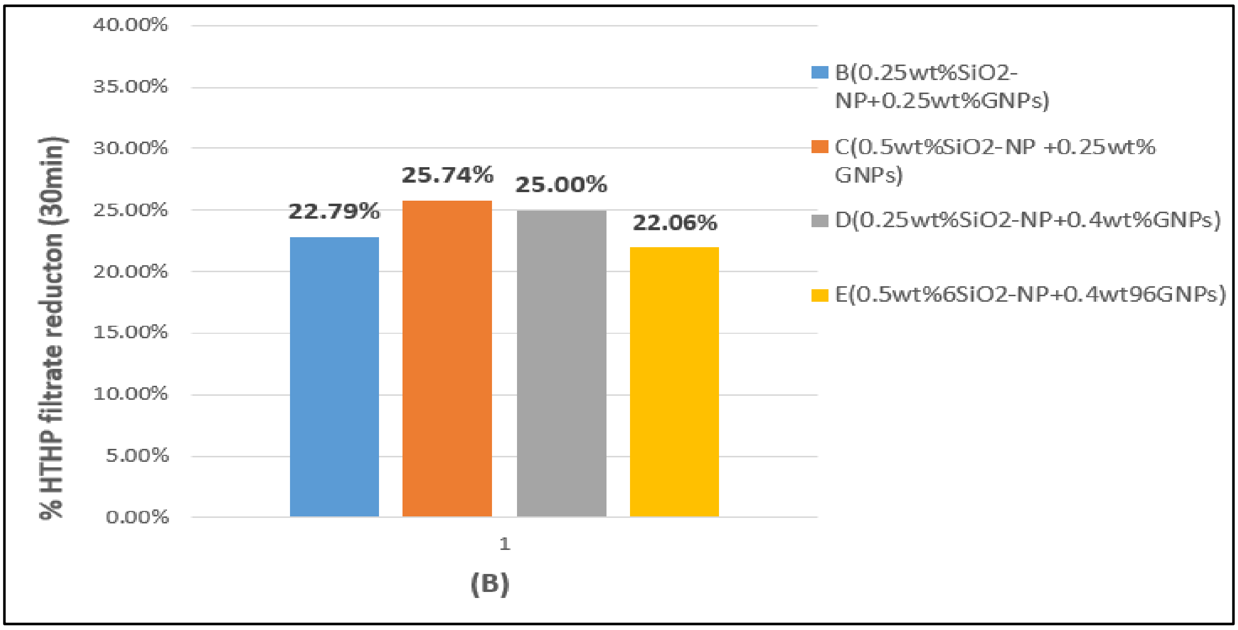

Fig. (4-5): Percentage of filtrate reduction of the (B) HTHP filtrate tests of different NPs formulation.

4.2. Characterization of the Final NP-WBM Formulation

Rheological Performance of the Optimized NP-WBM. To further optimized the nanofluid C and evaluate a possible cooperation effect between NPs and conventional LCM additives, graphite was added to the final formulation at a concentration of 2 wt.%. Rheology and filtrate tests were performed on the optimized NP-WBM for a final characterization. The results were compared against the base fluid (A) and a fluid containing only graphite plus the basic formulation. **Fig. (4-6) and Fig. (4-7)** shows (a) the rheograms of the optimized NP WBM and the other two fluids at 120°F and 14.7 psi. and (b) the gel strength measurements for the same drilling fluids.

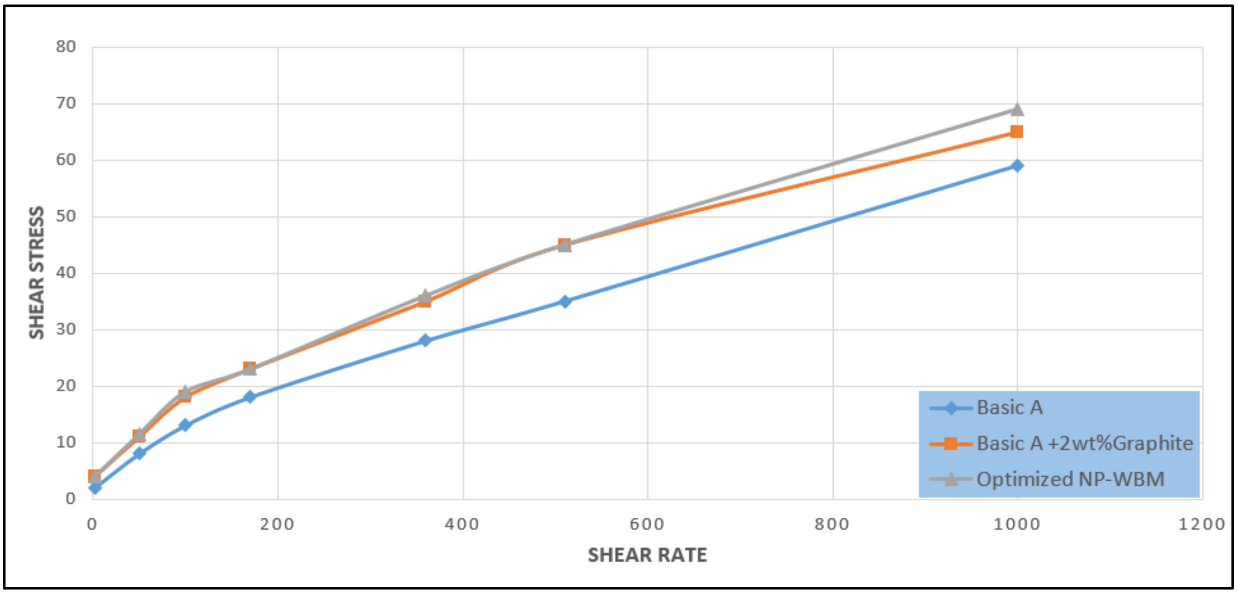

Fig. (4-6): Rheograms measurements of the optimized NP-WBM and the conventional WBM formulations.

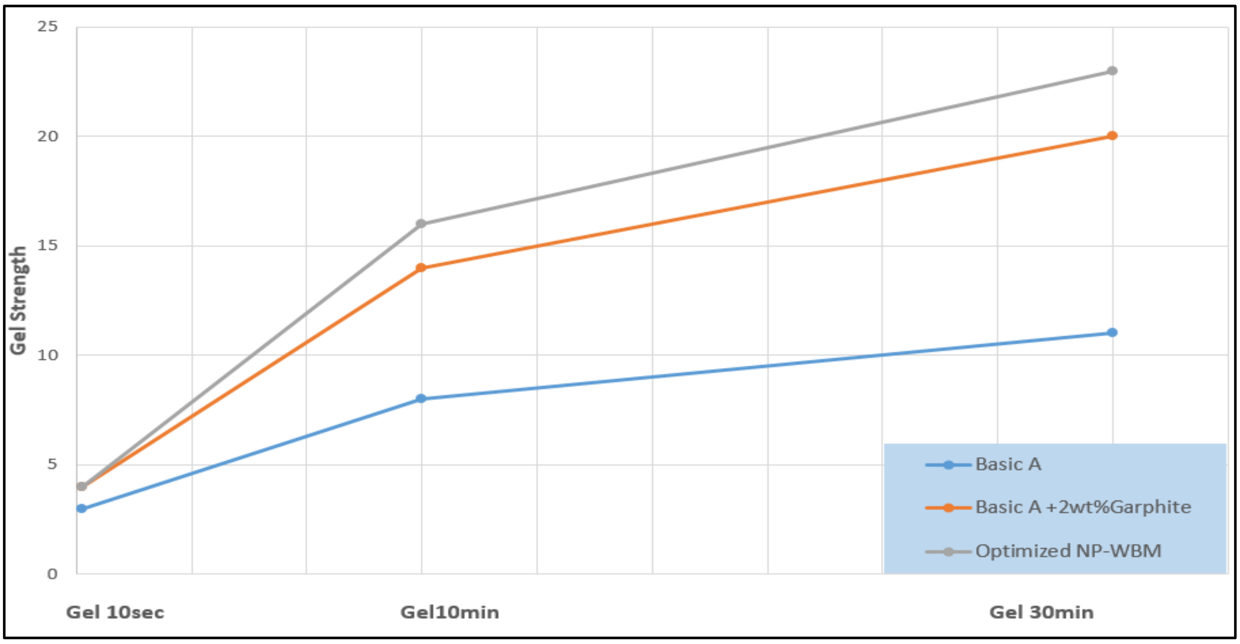

Fig. (4-7): gel strength measurements of the optimized NP-WBM and the conventional WBM formulations.

The results showed there was a minimal effect of graphite on the optimized NP-WBM and no extreme changes were observed in its gel strength behavior, which indicated that NPs maintained their dispersibility within the drilling fluid despite the increase of additives. Therefore, it can be concluded that all the products selected for the optimization of the NP-WBM could perform at field conditions with no need for rheological modifiers.

4.3.Filtration Performance of the Optimized NP-WBM.

Fig. (4-8) shows the filtrate performance of the optimized NP-WBM at (a) LTLP and (b) HTHP conditions compared to conventional WBM formulations. HTHP results showed the cumulative volume after 30 min. To report as API fluid loss the value should be doubled since the filter paper used in the HTHP is half the area of the standard API test. This principle also applies for the final spurt volume estimated from the HTHP test.

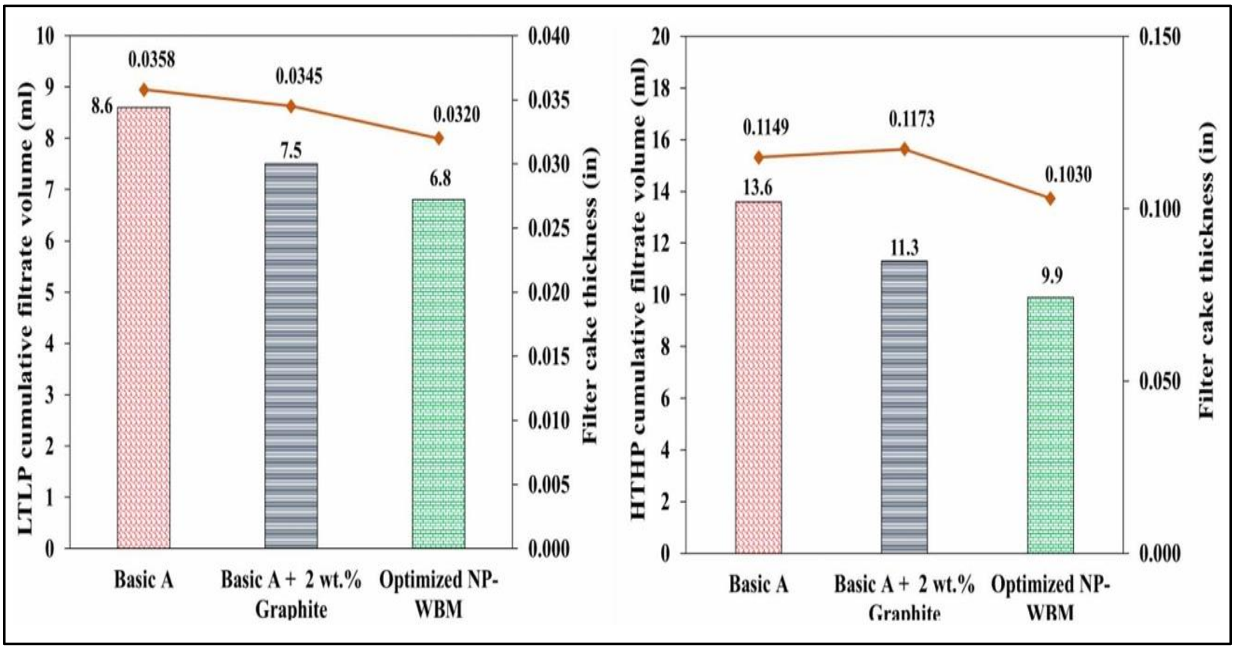

Fig. (4-8): Cumulative filtrate and filter cake thickness at (a) LTLP and (b) HTHP conditions for the optimized NP-WBM and the conventional WBM formulations.

The results showed a decrease in the filtrate volume by 12.79 % for the Basic A plus graphite at LTLP conditions when compared to the base fluid. The optimized

NP-WBM exhibited a better performance after mixing the conventional LCM additive with the NPs, leading to a final reduction of 20.93 % respect to the fluid A. The same benefit was observed for the NP-WBM at HTHP conditions. The cooperation effect between the NPs and the graphite yield to a 27.21% reduction while the addition of just graphite decreases the cumulative filtrate volume by 16.91%. Despite, that both NPs and graphite helped in the filtration process, the performance of the conventional additive was below the effect of NPs alone. Nevertheless, it was possible to observe a synergistic effect when combining the products in a single WBM formulation. The latter is very important from the design point of view of WBM for unconventional shales since previous studies have shown the same benefits of the graphite when mixed with NPs, especially as a bridging agent against micro-fractures (Contreras et al., 2014). Also, the optimized NP-WBM exhibited a reduction > 10% in the thickness of the filter cakes generated after both LTLP and HTHP tests. The latter is directly connected to the filter cake's permeability. It seems that stable and well-dispersed NPs can generate more compact and less permeable filter cakes and thus reduce the filtrate that can pass through this medium. Results for spurt loss volume after the HTHP test confirmed the mentioned idea and are shown in **Fig. (4-9)** The NP-WBM has no spurt loss volume, while the other two conventional WBM reported spurt loss volumes > 2.5 ml. This is extremely beneficial for the application of NPs in WBM for unconventional shales since NPs with the appropriate size might be able to create external filter cakes while drilling, reducing the fluid invasion into the shale matrix that can increase the stability problems. Previous studies have shown similar benefits of including GNPs or SiO2 NPs. (Fakoya & Shah, 2014; Kosynkin et al., 2012; Salih & Bilgesu, 2017).

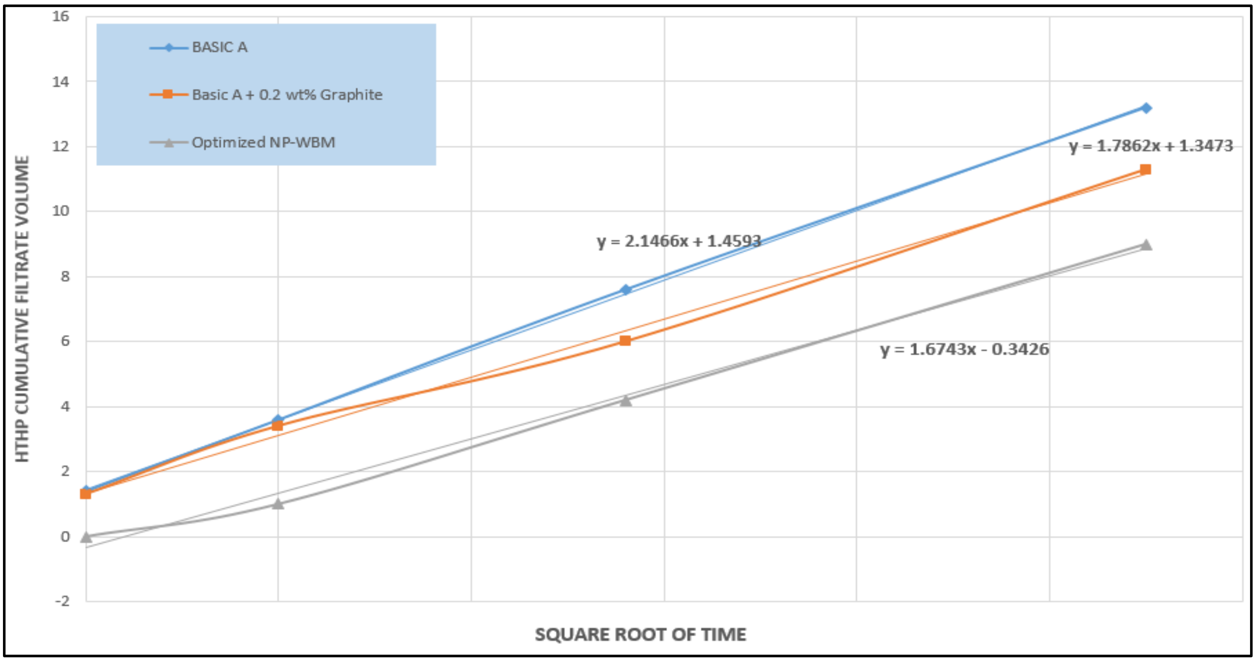

Fig. (4-9): HTHP spurt loss volume of the NP-WBM and the conventional WBM formulations.

Fig. (4-10) shows the filter cake's conditions of the optimized NP-WBM and the conventional fluids after the HTHP filtrate test.

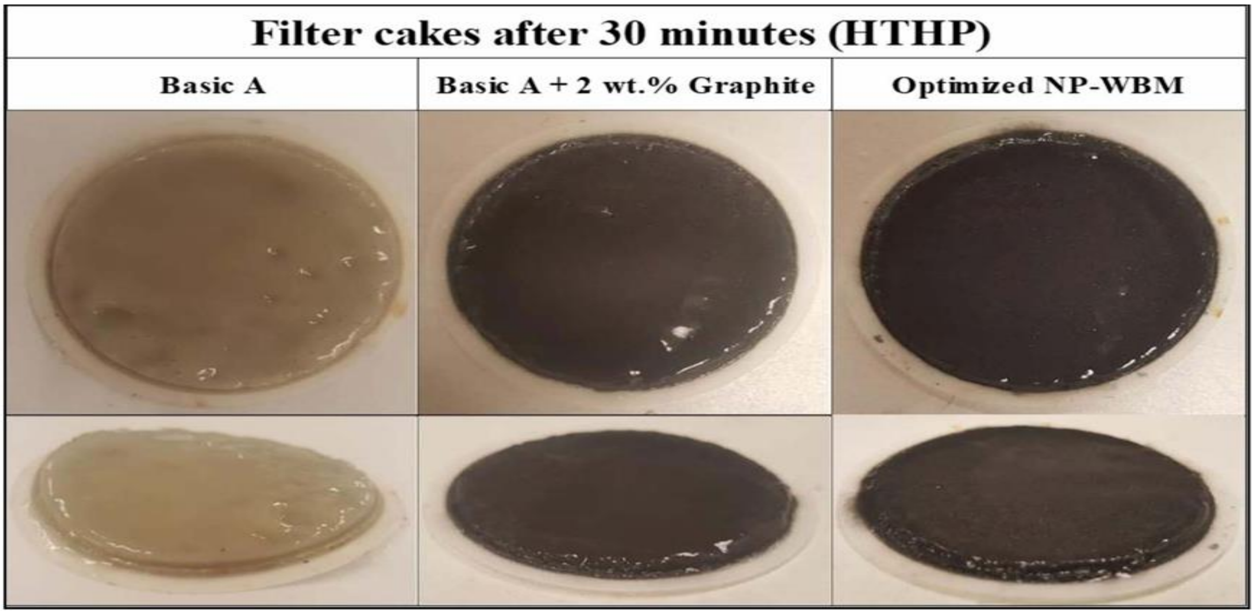

Fig. (4-10): HTHP spurt loss volume of the NP-WBM and conventional WBM.

4.4 Immersion Analysis Results.

To have an insight about the hydration effect that could take place when the Woodford shale is exposed to water, thin shale sections with no cracks were immersed in the fluid to be tested for a soaking period of 14 days at 150°F.

4.5 Dispersion Test Results.

The initial characterization of the Woodford shale suggested that the rock has a high tendency to experience cutting disintegration when exposed to WBM. This belief has its roots in the mineralogical composition of the rock. Results of the rock's XRD analysis indicated that the illite clay was the main clay mineral and no smectite or mixed-layers were present. In the absence of swellable clays, Illitic shales will be more prone to experience a high percentage of shale dispersion and very poor swelling**. Fig. (3-11)** shows the dispersion results of the Woodford shale after being hot-rolled with different fluids.

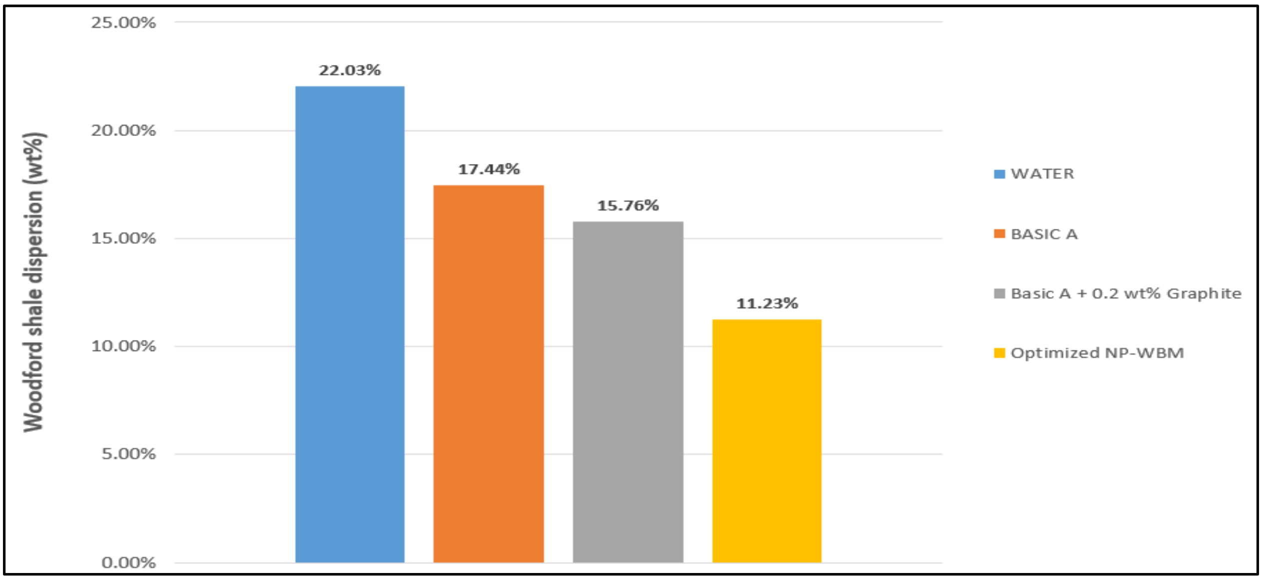

Fig. (4-11): The dispersion test results of the Woodford shale under different fluids.

The results indicated a high erosion for the Woodford shale when exposed to the alkaline water (pH10) without any other additive, resulting in a shale dispersion of 22.03%. Basic A fluid still exhibited a high dispersion (17.44%). The addition of only graphite to the base fluid improved just by 9.63% its performance. However, when mixed the optimal concentration of NPs with the appropriate concentration of the conventional LCM additive, the tests exhibited the lowest value of cutting dispersion (11.23%). In other words, the optimized NP-WBM reduced the shale erosion by 35.61% compared to the base fluid. This result suggests that the addition of SiO2-NPs and GNPs might enhance the inhibition capabilities of WBM for unconventional shales. Mostly, due to their unique sizes and plugging effects that can reduce the dissolution of grain boundaries and micro-fractures, which can lead to lower cutting dispersions.

Conclusions

Conclusions

The effect of adding a low concentration of silica and graphene oxide NPs on the rheological and filtration properties of a single WBM formulation has been evaluated to find the optimal combination. Also, chemical interaction tests were conducted to have an insight into the inhibition capability of the NP-WBM against the Woodford shale. Based on the results, the following conclusions are presented.

- The high illite content in the Woodford shale indicated that the rock is prone to dispersion. Also, the pores at the nanoscale and the appearance of micro-fractures when exposed to water suggested stability problems related to fluid invasion. Thus, NPs due to their size and shape might work as bridging agents to reduce the hydraulic flow to the shale matrix.

- Zeta-potential measurements indicated good stability for both nanomaterials with ζ-values of −34.66 mV and −41 mV for silica oxide and graphene oxide, respectively. The excellent response of the NPs to the pH 9.5 facilitated the mixing procedures of the WBM.

- The screening process indicated that SiO2-NPs might experience aggregation at concentration above 0.5 wt.%, suggesting this point as the upper-limit concentration. The GNPs show no evidence of aggregation, however, concentration above 0.4 wt.% did not give further benefits.

- The fluid C (0.5 wt.% SiO2-NP + 0.25 wt.% GNPs) showed the best results in the final screening step and was selected as the optimal concentration to formulate the optimized NP-WBM.

- NPs caused minimum effects on the rheological properties of the base fluid at 120°F, allowing NPs to be used without additional rheological agents. The NP-WBM reduced the LTLP and HTHP filtrate in 20.93 % and 27.21%, respectively in comparison to the base fluid. The impact of graphite was less than the effect of the NPs. Nevertheless, a cooperation effect was evident.

- The optimized NP-WBM experience no spurt-loss volume and thinner filter cakes compared to the formulation without NPs, suggesting that stable NPs might reduce the permeability of the filter cakes, reducing fluid invasion to the formation.

- Immersion tests of the shale sample soaked in water resulted in the exposure of micro-fractures along the bedding planes. Contrary, the addition of the NPs provided a better bridging network, decreasing their appearance.

- The Woodford shale experienced an 11.23% cutting dispersion when exposed to the optimized NP WBM, representing a reduction of 35.61% compared to the base fluid. These results indicated that the NPs used can reduce the effects of WBM in illitic shales, improving their inhibition capabilities.

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