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Overview of Developments in Oil And Gas Nanoparticles-Based Drilling Fluids

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Abstract

Nanoparticles (NPs) posseses great potential for drilling fluids (DFs) improvement. NPs is a unit of Nanotechnology (NT), with NT as a new innovation isrelatively gaining momentum in the petroleum and gas industry. The application of NT for performance improvement of wellbore fluids, drilling equipment, enhanced recovery of oil and gas techniques attest to the fact that NPs posses distinctive properties with unprecedented potentials for the energy sector. In recent times, nanomaterials are utilized for the fabrication of wellbore tubulars and drilling bits. In this work, comprehensive review of NPs applications to DFs system - water based and oil-based DFs, classification of NPs and their methods of manufacture is carried out. The roles NPs play in filtration, rheology and thermal stability features are discussed. To date, utilization of NPs have greatly improved diverse drilling proceses. Several NPs in DFs significantly enhance thermal stability, filtration properties and lower fluid loss, particularly under high pressure-high temperature (HPHT) conditions. These characteristics potentially proffers substantial savings for the drilling industry. Issues related to environmental impacts as well as fluid/material cost are also addressed in this review. With the comprehensive overview of successful NPs applications in DFs, this work gives a guide to the identified research issues/challemges to be addressed and future applications of NPs.

Keywords: *Subsurface formation; Borehole; Cuttings; Additives; Nanomaterials.*

1. Introduction

The success of any drilling operation is strongly dependent on the effectiveness of the utilized drilling fluid (DF). Oil and gas drilling entails drilling telescopic hole from the surface to the subsurface formation (reservoir) usually some kilometers far away from the surface [1-2]. Drilling is executed with the aid of drilling bit which is connected to drill pipe. With the application of weight and subsequently bit rotation, the rocks are crushed into small fragments termed cuttings. The utilized DF is then circulated from the surface; through the long string drill pipe (DP) to bit face [1]. DF is a complex system of liquids that involves aeration, suspended particles and emulsions which are customized for application in various sub-surface formations [3-4]. DFs are pumped around wellbores mainly with the utilization of closed-loop circulating system. This facilitates the flow of DF from the surface equipment to the drill bit, bringing to the surface rock cuttings. These drill cuttings are removed from the DFs at the surface, and the cleaned DFs are recycled [5]. DFs must have acceptable features, to conduct economical and cost-efficient drilling operation [6]. The properties of DFs needs to be carefully monitored and maintained to carry out major tasks such as drilling bit lubrication and cooling [7-9], hole cleanup by the transportation of rock cuttings from hole [10-11], hole stability, formation damage reduction through creation of suitable filter cake on the walls of the wellbore [12], subsurface pressure control to prevent formation fluid encroachment into the borehole and reducing potentials of blow-out [13]. To achieve these functions effectively, DFs require the right features. Features such as shear stress, density, viscosity and fluid loss are very crucial. The density is determined with a hydrometer, with value range of 1000-2500 kg/m^3. The conditional type viscosity is measured by the time a defined volume of solution flows from an API standardized funnel. In the case of effective viscosity, a viscometer which shows the relationship between velocity gradient and total flow stress is used for measurement. Viscometer determines shear stress, with values ranging from 0 to 20 Pa. The filtrate volume released through the treatment facility at pressure decline of 100 or more kPa within 30 minutes determines the fluid loss [14-15]. The major properties of DF can be enhanced using additives. The variation of fluid additives shows the complex nature of DF systems currently in use for drilling of increasingly hostile rock formations [9,16]. For oil and water-based DFs, common additives introduced provides filtration control [5], viscosification, pH control, rheology control, shale stabilization, lubrication and lost circulation control [17]. Polyanionic cellulose (PAC), nanoparticles (NPs), carboxymethyl cellulose (CMC) and starch are majorly included in DFs as filtration control materials [18]. Rheology-enhancer additives regularly used includes CMC, xanthan gum (XG), guar gum powder and lately salt-responsive zwitterionic polymer which was first utilized as viscosifier in water-based DF (WBDF) [19-20]. Sodium hydroxide (NaOH), potassium hydroxide (KOH) and citric acid monohydrate ($C_6H_8O_7.H_2O$) are predominantly utilized as pH control chemicals [21]. Additives such as surfactants (polyglycols), mineral salts (KCL, NaCl), organic inhibitors, mixtures of polymer modifiers, silicates and asphaltenes are frequently used for stabilization of shale [22]. Additives such asphaltenes, oils of various grades, glass beads, oil-surfactants and polymer are used for lubrication [23]. Additives such as paper pulp, shredded vehicle tires, fibrous minerals, cotton and wood are used for lost-circulation. For control of fluid-loss at the wellbore, granulated inert chemicals such as nut shells, nano-polymers, fragments of plastic laminate, shredded cellophane and plate-like chemicals like mica flakes are utilized [24-25]. In recent times, NPs are widely evaluated as DF additives to improve carefully selected properties [26]. The term Nanotechnology (NT) comprises the engineering/production/characterization chain of NPs and its systematic application to provide targeted features to fluids and materials that are measured by nanometer-scale NPs shape and size [27]. NT refers to the approach utilized for the creation of nano-sized materials and/or to manipulate them into utilizable formats. The potentials of the technique were first recognized by Feynman who made a proposition in 1959. He explored the potentials of devices and materials to be favorably produced to exploit its atomic features. Feynman's idea of "manipulating atoms with atoms" was widely accepted as early as 1980s [28].

Further advances in NT transformed several industrial quarters and yielded substantial investments in production, development and nanomaterial (NM) research. Since its inception, the National Nanotechnology Initiative (NNTI) of the United States have been a recipient of over $31 billion dollars, including 2021 proposed annual budget. Such study has contributed to the demand of NMs, by the oil and gas sector [29-30]. Some of the contribution includes, improvement in the design of material with high resistivity to corrosion and/or erosion, oil or/and gas recovery improvement [31], introduction of nano-sensors and prevention of unwanted deposit by adhesion using nano-coatings [32]. These applications of NT are above and over several uses relating to drilling and wellbore completion chemicals. Modern DFs have various properties, which can be influenced to certain degree by the introduction of NPs [33-34]. NPs can enhance shale stability, filtration and rheological properties. The ability of NPs to withstand HPHT condition and high surface-to-volume ratios makes them highly effective as chemicals in DFs [35]. In addition, particles size should be three times smaller than the pore throat for effective plug off of the pores in sub-surface rocks and wellbore filter cakes. For these requirements, NPs are the ideal chemicals [36]. The reduction of particle size from bulk to nano makes the size of the particular lesser than the flow pathway of electron in certain structures, and these lead to energy levels that are quantized in terms of band structure. These as well lead to the emergence of new properties such as its ability to resist HPHT conditions [37]. Thermal conductivity is another crucial feature of NPs and greater heat transfer efficiency can be provided to DFs by NPs than conventional DFs. NPs could potentially lower environmental effects on DFs [38] and as such, adverse impacts of harmful heavy metals and compounds (Pb, As, Cd, Hg, Cr and Cu) can be limited by some specific NPs [39]. The recent application of NPs to DFs can be considered on the basis of NTs evolution, NPs classification and production methods. In view of these, various review studies have been conducted on NP application in DFs [6]. These review studies were unable to give detailed categorization, description, application and production of NPs with regards to DFs. This overview therefore focuses on categorization, description, application and production of NPs in the oil and gas industry, with special emphasis on DFs. Specifically, these are: (i) Categorization, Production and characterization of NMs (ii) Brief definition of NMs application in oil and gas industry. (iii) Detailed description of DFs properties and the impact of NPs on such fluids (iv) Discussion on the role of NMs incorporation in potentially improving DF performance to wit: rheological features: Plastic Viscosity, Yield point, Gel strength, Lubricity and Borehole cleaning.

2. Characterization, production, categorization and application of NPs

2.1. NPs characterization

It is very difficult to differentiate natural NP concentration from engineered NP in materials having naturally occurring NPs with random distribution. As such characterization of NPs becomes eminent. X-ray diffraction (XRD), UV-visible spectroscopy, transmission electron microscopy (TEM), scanning electron microscopy (SEM) and Fourier transform-infrared spectroscopy (FTIR) are the commonly exploited NP characterization approaches [40]. Table 1 highlights some NPs characterization approaches.

Table 1. Some NPs characterization methods [40].

S/N	Technique	Medium	Principle and Size range	Limitations	
1	Laser diffraction	Powder	Ensemble method utilizes Mielight and Fraunhofer scattering.NP sizes: 1µm to 1000µm	Morphological details restricted to aspect ratio	Inclusion of range of NP sizes < 1µm not available
2	Light microscopy	Aerosol/Powder	Light scattering utilizes single particle approach NP sizes: > 1µm	Limited resolution due to light wavelength	Inclusion of range of NP sizes < 1µm not available
3	SEM	Aerosol/Powder	Particle/Imaging counting utilizes single-particle method NP sizes: 50nm - 1cm	Limited resolution due to light wavelength	Inclusion of range of NP sizes < 1µm not available
4	TEM	Aerosol/Powder	Particle/Imaging counting NP sizes: 5nm - 500µm	Sample preparation complicated	Requires vacuum environment and expensive equipment

The microscopic methods are important because they show single NP details for characterization such as shape, size, surface condition and location within the parent material. The scanning-probe microscopes and electron microscopes are important due to the NP size which is small. These microscopes are sometimes run with spectroscopic methods to determine the elemental analysis of the NP [41]. Microscopic methods can be destructive and entails complex sample preparation methods, which can affect the dispersion of NP, particularly as it involves vacuum and/or drying. In addition, a change in the condition of the samples can happen when they are contacted by the tip of probe from scanning-probe microscopes. Measurement carried out with microscopes can be time-consuming due to the need to test and observe several individual particles before valid properties/dimension can be validated and established. Recent method involving darkfield microscopy can be configured to generate hyperspectral image. This method can image NP accurately in complicated matrices, giving more rapid and improving contrast processing of samples [42]. Spectroscopic measurement focuses on how electromagnetic radiation and NP interact using wavelength as discriminating agent. This yields better NP characterization based on their concentrations, sizes and shapes within their host media. Certain metallic NPs and semi-conductors could function as quantum dots yielding surface –plasmon absorption and fluorescence, making them susceptible in ultraviolet spectrum. Spectroscopic study carried out in nuclear-magnetic resonance (NMR), X-ray and Infrared are importance for NP evaluations yielding optimum for NP sizes [43]. Moreover, atomic force microscopy (AFM) gives unique chances for obtaining quantitative and qualitative information on the physical feature of NMs such as surface roughness, texture, morphology and size. In this scenario, AFM is widely preferred for solving technical control and nanometrology problems. AFM have lots of merits over SEM. The building of 3D surface profile images with atomic adjustment in diverse environment can be achieved using AFM. AFM in particular, makes it easy to design 3D images of the surface profile with the least resolution in various environments. SEM however, has a scanning field measuring several square millimeters and greater field depth also measuring about one millimeter [44].

2.2. NPs production methods

NPs can be artificially produced and also exists in natural materials. There are two major generic groups of NPs production techniques: (1) bottom-up (2) top-down. NPs are manufactured by lowering the bulk size of materials with their production, thermal process, electrical, physicochemical or physical utilized. Such techniques include sonochemistry, mechanical grinding and constituents' removal that are components of base heterogeneous materials [45]. The coconut shell (CS) NP for example is produced using this method. The NP of CS can be manufactured using grinding technique, in which the crude CS powder is finely crushed at different period using balls of ceramic in a planetary mill. To measure the NP size at the stages of crushing, characterization study is deployed using TEM, SEM, etc. Schere equation is used to measure the rate at which crystals size of NPs drop with corresponding rise in grinding time [46]. Also, the form and shape of NPs change with the time of grinding. For CS, the brown coloration of the crushed powder gradually vanishes with increase in grinding time, and this is due to the reduction in the sizes of the NPs. XRD and SEM analysis methods are utilized for the confirmation of NP size with increasing crushed period of time. NPs are produced at the molecular or smallest level and then processed by the application of chemical techniques [47]. This is known as "construction" techniques. Examples of construction methods are recovery and precipitation. Specifically, biochemical synthesis, spinning, green synthesis and sol-gel are also construction techniques [45]. There have been successes in the synthesis of colloidal metal NPs from variations of precursor chemicals using several chemical techniques. These techniques involve chemical reductants that are associated with nonaqueous and aqueous solvents. This entails chemical reducing agents tied with non-aqueous and aqueous solvents. These chemical techniques comprise reverse micelles (nanoreactors), sol-gel interactions, reverse micelles that act as nanoreactors, decomposition of compounds containing metals and thermal decomposition [48-49].

Four different techniques are required to obtain NPs directly from chemical compounds:

- Extraction of NPs from chemical compounds: Thermolysis (thermal decomposition) utilizes heat to collapse chemical bonds in precursor compounds, particularly in endothermic reactions leading to synthesis of NP. When carrying out the reaction in liquid environment in the presence of surfactants or polymers, it stabilizes the resulting amorphous NPs diameter up to 10 nm. The 2-stage thermolysis of $FeCO_5$ presents a good example. At the first stage, at 100°C, the oleate of iron is extracted from oleic acid and $FeCO_5$, and decomposes at 300′C with the production of mainly loose NPs (from 4 to 11 nm). At 500°C heating temperature, the particles transformed into b-Fe NPs of crystalline shape. For the same causes, laser photolysis of eruptive heat dissipation can be used for metal containing compounds (carbonyls metal mostly) [50].
- Putrefaction of compounds that contain metal under the influence of ultrasound: In this method, carbonyls metals or their derivatives are usually deployed as metal-containing compounds, though some studies with other organometallic compounds have proved to be successful. In the synthesis of CO NPs, the putrefaction of $CO_2(CO)_8$ solution in toluene under the influence of ultrasound was utilized. To avoid resultant particles aggregation and manage monodispersity, sodium salt is introduced to the solution. The action of ultrasound on $CO(CO)_3(NO)$ decane solution in the presence of oleic acid, leads to the formation of shapeless CO-containing NPs [51].
- Sol-gel technique can be applied to obtain metal oxides NPs. It can also be deployed for the synthesis of ultra-small metals, and blended hetero-element and bimetallic particles [49].

- Reverse micelles can act as nanoreactors. NPs syntheses in reverse micellar surfactant solutions have yielded positives results in the aspect of modern nanochemistry. The ternary system of water-saturated hydrocarbon-surfactant composition makes up the reverse micelles, with the surfactant molecule dissolving inside the water. In the reverse micelle, there is orientation of surfactant molecules with polar "heads" directing towards the aggregate center, non-polar (tail) are directed outwards while dissolved water in the center of the micelle produces the water pool [48].

2.3. NPs categorization

The categorization of NPs can be according to their sizes which can be in 1-dimensional (1-D), 2-D and 3-D types. In the case of NP with complex structure and/or shape, the structural size of the element, instead of the linear size is considered as feature [44]. NPs can also be grouped into hybrid, organic and inorganics. Organic nanomaterial (NM) comprises of fullerenes, which are made up of carbon-based nanotubes. These include carbon nanotubes (CNT), carbon nanofibers (CNF), multi-walled carbon nanotubes (MWCNT), graphene nanoplatelets (GNP) and graphite. In contrast, metal oxide and metal NPs, quantum dots such as ZnO, ZnS and CdSe are metalloid NM which are generally described as inorganic NM [52].

3. NPs application in petroleum and gas industry

There have been a continuous expansion of the upstream oil and gas sector into more hostile and remote terrains, such as deep subsurface and deep-water locations, to explore and exploit large untapped resources [33]. The increase in complex wellbore trajectories and operational depths, penetration into wider array of likely downhole geo-hazards, coupled with strict environment regulation, requires the development and deployment of light-weight, durable, stable, strong and environmentally friendly materials [26]. These requirements in many cases can be satisfied using NT. In reality, nano and microtechnology have the likelihood to beneficially improve materials utilized by most petroleum and gas sector such as drilling, exploration, completion, refineries, production facilities, EOR as well as gas recovery and distribution networks for petroleum products [30,52].

3.1. Application of NPs for enhanced recovery of oil and gas

NPs has been successfully utilized and tested in diverse projects pertaining to EOR. NPs of various types have been specifically synthesized for improving production efficiency of oil and gas, or/and increasing recovery [53]. Table 2 highlights selected NPs applications for EOR.

3.2. Application of NPs in petroleum and gas exploration

Nanosensors are becoming extensively utilized in exploration operations. Some microbes possess practical environmental features which enable them to be utilized in the indirect measurement of tank conditions such as temperature, salinity and pressure. Surface sensors and carbon nanostructures (CNS) have been utilized for the provision of real-time, 2-D study of oil sands [54]. Also, the detection of reservoir fluid interface and fluid contacts in water-flood operations can be carried out using magnetic NPs. Nano robots are being deployed for oil and gas exploration. The applications show the potential of NP to be extensively utilized in characterizing vital reservoir features of the oil and gas [55].

3.3. Application of NPs in refinery operations

The reduction in the level of sulfur in refined products and lowering of CO_2 and other toxic emissions are major challenges, the refining industry faces today. The desire for cleaner energy to improve quality of air increases year by year. As cost continues to go up, refineries strive to increase efficiency, lower energy consumption and use cheaper and/or fewer feedstock and raw materials. However, low API crude oil, despite not being expensive requires more refining, and they yield higher carbon emission due to their higher carbon contents. These have prompted refineries to seek for newer or alternative technologies that can aid overcoming the tough environmental regulations without significantly affecting the thin profit margins. NPs can aid refiners in many ways. Nano filters developed with NPs have been successfully deployed in the refining process [60]. MCM-41 (Mobil composition of matter - 41), a 1-D mesoporous catalyst can be altered by NPs to work as nano filter to remove unwanted impurities from water, crude oils and refinery sludge. Impurities typically focused on, are oxides of sulfur and nitrogen, mercury, acid anhydrides and other heavy metals. In addition to enhancing refinery effectiveness, nanosensors and nanocatalysts can also provide ongoing surveillance of refining products and processes to ensure that impurity levels are adequately tackled [33,53].

Table 2. Selected NPs utilizations for EOR.

No	Investigated NP	Improved parameters	Results	Reference
1	Al_2O_3, TiO_2, CuO and SiO_2	Oil viscosity reduction, enhancement of stability of injected water	Al_2O_3 (8.2%) yielded the least water adsorption by the limestone formation compared to SiO_2 (43.4%) and TiO_2 (27.8%). Due to NP adsorption, limestone becomes water-wet. Contact angle was determined in nanofluids presence with SiO_2, TiO_2 and Al_2O_3 yielding $26^o \pm 2^o, 57^o \pm 2^o$ and $71^o \pm 2^o$ respectively	[56]
2	Cellulose nanocrystals (CNCs)	Oil-in-water emulsion stability management	Evaluation of Berea sand conducted. Carbon (IV) oxide and Polydimethylsiloxane (PDMS) were utilized in EOR process. It yielded higher viscosity nanofluid but lowers viscosity of oil. Moreover, viscosity of CNC-stable emulsion improved over time and acts like a gel as a result of the strong droplets' network.	[57]
3	Al_2O_3, TiO_2, CuO and SiO_2	Oil viscosity reduction, enhanced injected water stability	Evaluation of Berea sand also onducted with the utilization of alumina NPs. The utilization of polyvinylpyrrolidone (PVP, which exhibits instability in salt water yields elevated production of a stable nanofluid which serves as an excellent recovery agent.	[58]
4	Zirconia NPs based Sodium Alginate Polymer	Oil viscosity reduction. enhanced injected water stability	The viscosity reduction with shear rate increase from 0.1 to $100s^{-1}$and from 25 to 47^oC temperature. The results indicate lowest viscosity at 0.1wt% conc. of NaCl in comparison to 0.05-0.015wt%. Apparent viscosity increase occurred as NaCl conc. improved from 0.015 to 0.1wt, with the impact stronger at temp. range of 25 to 35^oC. Apparent viscosity reduction with increase in salinity is due to reaction/introduction of salt antisense (NaCl) to the polar heads of the polymer (NaAlg), which lowers their overall charges and stabilizes the system. 0.2 and 0.5 wt% conc. of ZrO_2 *and NaAlg* respectively showed viscosity reduction compared to the suspension of polymer without NP. Due to stronger emulsion and foams stability, better stability and solubility, and ease of transfer across porous media, polymer-coated nanocomposites are suitable for EOR.	[59]
5	Fumed silica NPs (FNP)	NP stability control at subsurface conditions	The composition of formation (shale, chalk and limestone) had significant effect on NP stability. Polymer and HCl surface modifications acted to improve the stability of NP at 70^oC at synthetic saline seawater. The pH of fluid was indicated to be a key factor affecting NP stability	[57]

4. NPs applications in DFs

There have been increased difficulties in the management of DFs with the advent of increased drilling depths, complex geology and length of horizontally drilled locations. In typical fashion, the drilling sectors aims at biodegradable natural materials, non-toxic, thermally stable, easier to deploy cheaper and eco-friendly chemicals, particularly those that can substitute the conventional solvents and polymers. NPs with certain features such as large surface area and/or elevated thermal conductivities can solve some of the DFs problems [61]). NPs that can be added to DFs can be grouped into four: (a) Polymeric NPs: These can be made up of either natural or synthetic materials (b) Ceramic NPs: Inorganic materials made up of carbide, carbonate, phosphate and oxide compounds (c) Metal NPs: Thess can be produced by electrochemistry, photochemistry and other chemical methods (d) Carbon-based NPs: These can be further grouped into CNTs and fullerenes [40].

4.1. Utilization of metal NPs

Metal NPs are made-up of at least metallic core, composed of either metal oxide(s) or inorganic metal (s). This core is typically plated with either metal-oxide shells or non-metallic materials. The metal particles such as zinc, silver, iron, copper, calcium and zirconium are gotten from their respective hydroxides, metal oxides and sulfides [62]. Transition metal NPs can positively modify the thermal conductivities of water-based DFs. For example, HPHT study by zinc and copper-based NPs yielded improved thermal conductivities in the DFs by 23% and 53% respectively. The enhancement in the thermal conductivity of DFs measures the fluid's ability to cool quickly as it flows to the surface due to the zeta potential and charge of NPs [63].

4.1.1. Iron-based NPs (IBNPs)

Iron oxides NPs remains the most generally utilized of the metal oxides with applications in the medical sector, as a result of its intrinsic magnetic features and ease of bulk synthesis, at very low cost. The rheological properties of DFs under HPHT conditions can be modified beneficially with iron oxide NP (of about 0.5wt% concentration). The filtration and filter cake test carried out on WBDFs at HPHT conditions (@ 200°C and 7 mPa) indicated the performance of IBNPs as it lowered the filtration to a larger extent than at LPLT condition [64]. In recent study, the effects of hydrophilic iron NPs were studied in bentonite WBDF. Elemental studies of DFs filter have also been carried out. From the bentonite WBDF, coefficient of friction was reduced to 47% by 0.019 wt% (0.1g), while fluid loss lowered by 20% when 0.0095 wt% (0.05g) was used. NPs are forced through smaller pores using hydrostatic pressure for purposes of plugging the pores. By lowering pore spaces and permeability of the filter cake, the volume of filtrate is also lowered. In addition, the result of the filtration study reported showed the ineffectiveness of the plugging processes. This is believed to be due to the inadequate dispersion of NPs inside the bentonite WBDF. For iron-xanthan gum NPs and iron NPs, there is agglomeration of NPs, which might inhibit fluid loss reduction as a result of small particles' cumulation [65].

4.1.2. Calcium NPs (CaNPs)

Calcium NPs exhibits useful features for DFs like compatibility with OBDFs as well as invert emulsions, and also being low in toxicity and very cheap [66]. A study carried out by Nwaoji *et al.* [67] showed the compatibility of Ca-carbonate NPs with OBDF improved fracture pressure by 36% when optimally blended. Contreras *et al.* [68] carried out comparative filtration performance study between calcium and iron NPs. Using NP concentration of 0.5 to 2.0 wt% graphite and 0.0 to 2.5 wt% plus lost circulation material (LCM), they conducted OBDFs study at LPLT and HPHT (121.2°C and 3.4 mPa) conditions. At LPLT condition CaNPs yielded better performance than IBNPs, while the reverse occurred at HPHT conditions, the increase in filter cake thickness is as a result of the interaction between graphite and CaNPs at HPHT.

4.1.3. Silver NPs (SNPs)

SNPs gain from overall stability and very good electrical/thermal conductivity. These features make them practical for a wider range of uses, such as oil-based nano-fluids [69]. Thermal-conductivity experiment carried out on fluids mixed with 5-nm SNP and kerosene at the temperature range of 25°C to 50°C indicated an increment in thermal conductivity with increasing NP concentration. The addition of graphene nanosheet and silver NPs to WBDFs at ambient temperature, improved DFs plastic viscosity by 89.2% and 64.2% respectively. NPs presence in the design of DF improves both the waterborne particles stability and solid contents. Consequently, there is increased PV measurement without harming the DF additionally [70].

4.1.4. Zirconium NPs (ZrNPs)

Zirconium dioxide possess polar surface, with zirconium atoms functioning as strong Lewis acid locations. Due to its empty orbital, there is attraction between electron-rich Lewis bases (such as anions of phosphate) and Zr. Consequently, the high cation transfer feature of zirconium oxide surface results in mixed retention mechanism [74]. ZrO_2 (zirconia nanofluid) have recorded huge successes when applied as EOR agent with the chemical altering oil-wet limestone reservoir to water-wet conditions [71]. The addition of Zirconium citrate to DFs improves the gelation of bentonite under elevated temperature (>204.5°C). There is improvement in the thermal stability of DF diluents such as chromium lignosulfonate and potassium dichromate when the additive is introduced. The rheological study was carried out using dynamic vibration and rotation tests. Zirconium citrate also acts as organic stabilizer. Improved DF stability was achieved when a mixture of zirconium citrate and gallic acid was introduced into the mixture. ZrO_2 NPs can potentially improve DF rheology when mixed with biopolymer. As an additive, ZrO_2 enhances the thermal stability of DF(s) by positively influencing elasticity and viscosity, while reducing filtration [72]. At 176.67°C and 6.89475 MPa, 0.5 wt% ZrO_2 NPs added to WBDF was discovered to significantly enhance its rheological and filtration properties [35].

4.2. Utilization of carbon-based NPs

4.2.1. Graphene NPs (GNPs)

The formation of 2-D hexagonal graphene lattice is solely from the atoms of carbon. The lattice essentially is two triangular lattices that alternate [73]. Graphene oxide (GO) is generally used in producing graphene via chemical redox. GO has to deal with the edges and base of oxygen-bearing functional groups. They are very efficient in the stable diffusion and chemical alteration of the GO sheets in water. For a GO sheet, the apparent thickness is equivalent to 1 nm while the lateral size ranges from nanometers to micrometers. In addition, the elastic and soft properties of GO sheet, makes its very useful as DF additive [74]. The lubrication, rheology, filtration and stability of DFs is improved by the introduction of GO and Graphene. Though bentonite is conventional DF additive, its density is not enough to successful inhibit loss of fluid due to particle size. The GO/GNPs is much denser and smaller than bentonite particles. However, the lateral dimension of GO/graphene can lead to poor dispersion and flocculation of wellbore fluids [75]. The applications of GNPs as DF additive are highlighted in Table 3.

Table 3. GNPs application as DF additives.

S/N	NPs Type	Base fluid	Condition of experiment	Result	Ref.
1	Graphene nano-platelets (GNP)	WBDF	Conducted at room condition in the lab	High diffusion level in the DFs was achieved by the chemicals. This showed minor improvement in fluid viscosities at low shear stresses, combined with enhanced thinning at elevated shear stresses. Also, shear-thickness mechanism was economically redesigned at low diffusion	[76]
2	Graphite-Alumina hybrid	WBDF 20g sodium bentonite	Conducted at room condition in the lab	This chemical enhanced the gel structure of DF. It favorably enhanced the extent and rate of zeta potential, electrical/thermal conductivities, structural recovery and filtration losses	[77]
3	Graphite/improved n-alkanes	WBDF	Conducted at room condition in the lab	The introduction of 5wt% of the blended phase-changed chemicals, significantly improved the viscosity (YP/PV= 0.58, ΔAV<20%). There was a 20% drop in API fluid loss, and this aids to harmonize the gas hydrate formations.	[78]

4.2.2. Carbon NPs (CNPs)

CNPs called fullerenes are spherical concentric collapsed graphite sediments which are typically designed. They are made of unusual thermodynamic (chemical/physical) features. The NPs directional and relative shell rotation using directed energy supply, makes it subject of interest for nanomechanics. CNPs are utilized to positively influence rheological features, filtration and shale stabilization for various DFs [79]. Cylindrical structures such as CNTs possess diameter specifications which range from one to tens of nanometer, and tubular lengths of several micrometers. This entails one or many hexagonal graphite planes which is inserted into a tube and ends at a hemispherical head. Their surface comprises of conventional six-membered carbon rings (hexagon). At elevated HPHT conditions, CNTs have recorded successes in improving emulsified DFs stability for several formulations [80]. Multilayer or single-layer tubulenes can be designed based on the defined preparation conditions. Single-walled nanotubes (SWNTs) comprises of carbon atoms designed into a shell, while multi-walled nanotubes (MWNTs) comprises of more than one carbon tubes [81]. Chai *et al.* [82] designed multi-walled carbon nanotubes (MWCNTs) based nanofluid on OBDF. Hydrodynamic deformation of the dispersion was utilized for enhancement of the suspended dispersion stability using 3hr bath sonication process. From the result of the study, the thermal conductivity improved by 9.8%, 7.2% and 4.5% respectively when nanotubes mass concentration of 0.01%, 0.005% and 0.0025% were used at 50°C temperature. The effective thermal conductivity of CNTs diminished intensively when comparative study was made with inherent thermal conductivity of suspended CNTs. Chai *et al.* [82] model considers contact resistance of matrix-additive interface, which leads to lower CNT effective thermal conductivity when diffused in hydrogenated oil. In addition, various physical flaws in CNTs have likelihood to influence low effective thermal conductivity. These agglomerates need to be split into smaller size particle by the action of high-power hydrodynamic cavitation and low pressure. In addition to the destruction of CNT's microscopic structure, shear pressure can continuously disfigure the shape by bending it, resulting in serious surface defection. The applications of CNPs as DFs additives are highlighted in Table 4.

Table 4. CNPs applications as DFs additives.

S/N	NPs Type	Base fluid	Condition of experiment	Result	Ref.
1	MWCNTs	WBDF	70°C temp. and 101.4KPa at lab. conditions	Two MWCNTs designed enhanced fluid stability, thermal conductivity, viscosity and filtration	[83]
2	MWCNTs in isolation, MWCNTs plus COOH plus OH MWCNTs	WBDF	conducted at room condition in the lab	The DF friction of 34%, 37% and 33% and filtration of 8.6%, 7.1% and 71.9% were achieved when MWCNTs were modified.	[84]
3	CNPs plus polymer	WBDF	148.89°C temp. and 38.61MPa pressure at lab. conditions	The fracture sealing capabilities of the DFs were improved with introduction of carbon NPs and polymer. At 38.61MPa and 148.89'C pore pressure transmission reduced	[85]
4	MWCNTs	WBDF	180°C temp. and 170MPa at lab. conditions	With two MWCNTs formulated, there was improved thermal conductivity, filtration, fluid stability and viscosity of the DF.	[86]

4.3. Utilization of ceramic NPs

Ceramic NPs otherwise called nano-ceramics can be described as inorganic, heatproof non-metallic solids, comprising of metallic and non-metallic compounds. They were first produced by the continuous process of heating and cooling in the 1980s. Sol-gel method is used in their formation. Solution based particles mixes with gels to produce NPs. Sintering (heating and pressure) is another method used in their production. They have consistent and small size of <50 nm and these make them very useful for pharmaceutical as well as medical applications and also for DFs. Nano-ceramics are execellent for improving rheological, thermal stability and filtration properties of DFs. There was fluid loss and filter cake thickness reduction in both LPLT and HPHT conditions when the additives were studied [87].

4.3.1. Silica NPs

Silica NPs are applied in several industries as inorganic due to their cost effectiveness, low toxicity, high stability and ability to effectively work with several other molecular materials, most especially polymers [77]. Silica NPs can enhance the rheology of DFs. The preparation and study of hybrid materials by Da Luz *et al.* [88] using nano-silica chitosan showed the strong dependence of hybrid materials on the method used in their production. There was an observable interaction between chitosan's amino group and silica'silanol groups. There was 23% increase in the apparent viscosity keeping the suspended rock fragments. In turn, the volume of filtrate reduced by approximately 60%. The results show a relationship with the fluid's higher viscosity, presence of chitosan, colloidal silica and hybrid materials majorly combination of chitosan and silica NPs. Hybrid NP materials can be essential in the design of complex structures having very high permeability. Some of silica NPs applications in DFs are highlighted in Table 5.

Table 5. Silica NPs applications as DFs additives.

S/N	NPs Type	Base fluid	Condition of experimental	Result	Ref.
1	SiO_2	WBDF	0.7MPa pressure and 95ºC temp.	At 0.7%wt conc. SiO_2 NP (20-30nm diameter), polyethylene glycol grafted with polyacrylamide (and silica NPs) composite material at 95ºC showed stable rheological curve. It also showed strong inhibitory impact on shale/clay mineral swelling during drilling operations.	[89]
2	SiO_2	WBDF	5.MPa pressure and 5ºC temp.	The loss of DF into the formation during drilling operation reduced with hydrophobic silica NPs utilization, thus improving stability. The risk of hydrate nucleation reduced, leading to viability increase for drilling gas hydrate formation unlike conventional WBDFs.	[90]
3	SiO_2	WBDF	HPHT: 7MPa and 93.34ºC LPLT: 0.7MPa and 21.12ºC	At 0.3wt% concentration (and 5.7nm), SiO_2 enhanced rheological features at HPHT and LPLT conditions.	[91]
4	SiO_2	WBDF	2.7MPa to 3.2MPa pressure and 200ºC to 230ºC	At 1wt% concentration, SiO_2 improves the YP and PV at condition of LPLT. The design was stable within the 2.7MPa to 3.2MPa pressure range and 200ºC to 230ºC temperature range.	[92]

4.3.2. Zinc oxide NPs (ZnO NPs)

ZnO NPs are introduced with <100 nm diameter size. Their catalytic capabilities are improved by high surface areas. The physical and/or chemical features of ZnO NPs are dependent on the process used for its synthesis [93]. In often cases, they are produced in conjunction with silica and titanium dioxide NPs. ZnO NP can enhance the rheology of DF. Experimental study shows the potential of ZnO in improving PV by about 150%, with PV and AV improved by almost 100% compared to DF that have not been treated [94]. In addition, the treated fluids' shear-thinning feature was observed to follow Herschel-Buckley model. ZnO NPs have been studied in WBDF with three concentrations of 0.5wt%, 0.3wt% and 0.1wt% and also with ZnO NP of < 50nm size used. The additives lowered filter cake thickness and fluid losses in HPHT/LPLT state (187.8ºC to 42.8ºC /127.5 MPa to 1.034 MPa). ZnO NP performed better when compared to CuO-based NP [63]. Salehnezhad *et al.* [95] studied how the quantity of ZnO NP in the DF influences the rheological parameters of the DF. The optimized values of ultrasonic time variables, NPs and starch evaluated were 65.0 min, 0.2 wt% and 0.82 wt%, respectively. In the system, the interaction between variable showed statistical significance. Hydrogen bonds generated between polymers and molecules tend to be destroyed by ultrasonic vibrations, and increased surface loading due to NPs. SEM was utilized to conduct morphological investigation of bentonite and synthesized ZnO NPs.

4.3.3. Titanium dioxide NPs (TiO_2 NPs)

TiO_2 NPs have distinct antibacterial and magnetic, as well as electric conductivity and importantly ionic properties, making them perfect for application in many industries. TiO_2 NPs is useful in DFs as a result of economical thermal-transition features [96]. Some of TiO_2 NPs applications as DF additive are highlighted in Table 6.

Table 6. TiO_2 NPs application as DFs additive.

S/N	NPs Type	Base fluid	Condition of experimental	Result	Ref.
1	TiO_2	Polymeric-WBDF	0.7MPa and LPLT room temperature 3.5MPa and HPHT 150°C	0.195wt% TiO_2 NP concentration yielded friction coefficient of 0.34% shale recovery of about 97.2% while volume of filtration increased by 27%. These results show the ability of TiO_2 NPs in increasing DF's capacity to protect shale cuttings from being damaged. It further shows that the DF's resistant nature to shale inhibition is improved, and this is as a result of their high-volume ratio and NPs size.	[97]
2	TiO_2	WBDF	0.7MPa at 11000 rpm and 25°C	. TiO_2 NPs lowered filter cake thickness and filtration loss by about 64% as a result of NPs sizes being slightly larger, especially when base fluid is stable for four weeks compared to the initial base fluid.	[98]
3	TiO_2	WBDF	6.9MPa to 110.32MPa 65.56°C to 315.56°C	TiO_2 NPs lowered capillary suction time, YP, PV and fluid loss, while improving the strength of gel. The research work indicated the potential of DFs containing TiO_2 NPs in reducing formation damage	[62]
4	TiO_2	WBDF	80'C, 60°C and 40°C during 16h at static conditions	TiO_2 NPs lowered YP by 24%, PV by 13% and ratio of YP/PV by 13%. At 0.6% (w/w) TiO_2 NPs can effectively improve DF lubricity and rheological properties through stable formulation.	[99]

4.3.4. Cupric oxide NPs (CuO NPs)

CuO exhibits very narrow band-gap of 1.2 eV energy. This makes it beneficial as DF additive due to the thermal-conductivity features, and also its deployment in industries that utilizes heat transfer fluids [100]. The comparison of ZnO NPs and CuO NPs in WBDFs showed an increase in the thermal conductivity of about 23% and 53% respectively [63]. Table 9 highlights some of the applications of CuO NPs in DFs.

Table 7. CuO NPs application as DFs additive.

S/N	NPs Type	Base fluid	Condition of Experimental	Result	Ref.
1	CuO	WBDF	Room condition	Thermal and electrical conductivity improved by 50% and 25% respectively when CuO and ZnO were introduced to the DF	[101]
2	CuO	WBDF	0.7MPa and 48.9'C [LPLT] 3.5MPa and 121.2'C [HPHT]	There was YP increase and PV decrease by 84% and 50% respectively for 0.5% by volume concentration of CuO NPs under HPHT. The 10-sec gel strength yielded 95% increase. At LPLT conditions, there was 30% reduction in fluid losses. As a result, thicker filter cake was achieved at high concentration due to the presence of more NPs in the fluids.	[102]
3	CuO	WBDF	1.4MPa and 80'C	The PV of the DF decreased at 0.5wt%, 0.8wt% and 1wt% concentration of CuO NP. At 0.8wt% NP, the optimum PV drop was recorded. This could be due to clay plates deflocculation, just like that of Silica NP-based DFs.	[103]

4.3.5. Clay NPs

Clay are typically phyllosilicate chemicals (i.e, they have sheet-like crystalline forms) that usually strengthen and solidify when dry. These properties are essential for DFs. For instance, 1% concentration of clay NPs introduced to synthetic DFs increases PV by 290% at 85°C and

100% at 25°C, while reducing electrical resistivity by 30% [104]. Table 8 highlights some of the applications of clay NPs in DFs.

Table 8. Clay NPs application as DF chemicals.

S/N	NPs Type	Base fluid	Experimental Requirement	Result	Ref.
1	Nanoclay	Bentonite-bearing WBDF (BBWBDF)	0.7MPa and 25′C-85′C	Fluid losses reduced to zero at 1%-8% concentrationsof clay NPs with electrical resistivity also dropping from 15%-36%. This is as a result of water retention by the nano-clay materials and the combination of nano-clay and bentonite materials.	[105]
2	Modified Nanoclay	OBDF	3447KPa and 148.9′C	Modified clay NPs improved fluid rheological properties (YP, PV, AV and gel strength) better than graphene NPs. However, the minimum fluid loss for DFs used was achieved by graphene NPs. The modified nanoclay was able to stabilize water-in-oil emulsion due to its amphiphilic attributes at all concentrations and temperatures. However, high conductivity graphene tends to lower emulsion stability.	[106]
3	Clay/Silica (CS) Nanocomposite	WBDF	0.7MPa	At 25°C, PV and YP were improved by 70% and 40% respectively by CSNPs. By comparative study, SiO_2 NPs yielded 41% and 22% improvement respectively. At 90°C PV and YP improved by 82% and 65% respectively by CSNP compared to 53% and 38% enhancement achieved by SiO_2 NPs. When compared with SiO_2 NPs, CSNPs enhanced DF filtration by averages of 45% and 60% at low temperature while 10% and 65% at elevated temperature. Due to the smaller size of CS particles, they plug more efficiently.	[107]

4.4. Polymer-based NPs (PBNPs)

PBNPs are produced by polymerizing monomers such as biocompatible and biodegradable alkyl cyanoacrylate. An example of its application as an additive to DFs is the polyacrylamide grafted polyethylene glycol silica. The acrylic resin/SiO_2 NPs can enhance fluid rheology, such as plugging efficiency and lowers loss of fluid to the formation [105]. Davoodi *et al.*, [108] posited that addition of synthetic acrylamide-styrene copolymer (SASC) NPs to WBDF at the sizes < 100nm enhances filtration and rheological performance of the base clay before and after experimental studies on aging. The largest reduction in filtrate volume at HPHT and API conditions was achieved with 3g of SASC NPs and lowered it respectively by 47.5% and 38.8%. This was attributed to polymer-chain retention on the diffused solid particle surfaces. Table 9 highlights some applications of PBNPs as DFs additive.

Table 9. PBNPs applications as DFs additive.

S/N	NPs Type	Base fluid	Experimental Requirement	Result	Ref.
1	(Polystyrene-methyl methacrylateacrylic acid)/clay	WBDF	21.MPa and 121.12°C	At less than or equal to 121.12°C, the nano-clay hybrid NPs attains stable fluid rheology. When compared to a conventional DF, the hybrid NPs reduced the fluid filtration of the API nano-clay and polymer-based API by 22% and 65% respectively. The increase in this parameter is attributed to the design of terpolymer connections between layered clay NPs. Due to the reaction between clay NPs and charged polymer chains in the polar medium, the addition of clay NPs to the polymer structure reduces the movement of polymer chains in the composite materials, thus yielding higher flow resistance.	[109]
2	Nanocomposites (NC) combining synthetic polymers with CuO/ZnO NPs	WBDF	3.5MPa and 204.45°C	At 204.45°C, rheology stabilization and minimum loss of filtrate happens. The thin filter cake produced under LPLT conditions, exhibits minimal filtrate losses and low permeability. At HTHP conditions, there is 14% increase in rheology	[47]

S/N	NPs Type	Base fluid	Experimental Requirement	Result	Ref.
				while fluid losses drop by 25% due to the existence of large NPs number (of small diameter size) with high fluidity, high-temperature stability, thermal conductivity and high surface area.	
3	Lignosulfonate / Acrylamide graft copolymers (LS-gPAM)	WBDF	690 KPa and 25.56°C, 121.12°C	There is improved DF rheology, pH control and filtrate control when 2.45g to 3.5g of grafted copolymer is introduced to 350ml water between the temperature range of 25.56°C and 121.12°C. Thermal stability and high salt resistance were also exhibited by the grafted copolymer.	[110]
4	Nano and bulk carboxyl methyl cellulose/polystyrene (nanoCMC) plus core-shell NC	WBDF	690KPa and 70°C	The AV and PV of DFs were improved by nanoCMC and core-shell NC. The yield stress greatly affects bulk CMC than both nanoCMC and core-shell NC. Filtration reduced by 22% and 31% for core-shell and nanoCMC respectively, when compared to bulk CMC. As a result of the high surface area to volume ratio of NPs, chemical and physical properties are altered at low concentrations in DFs	[36]
5	Modified polymer (hydrophobic)/ SiO_2 NC (NFC)	WBDF	2MPa, 5MPa at 8000rpm and 70°C, 120°C, 350°C	Stable filtrate volume and fluid rheology can be achieved when 2.0wt% NC (164nm-38nm particle sizes) is maintained at 120°C for 16-hour period. In these conditions, the WBDF is expanded by the NC under set conditions. The yield stress and PV improved by 25% and 7.1% respectively, while 21.2% API filtration dropp was observed. The shale's recovery rate was observed to be 90.7%. As a result of NFC retention, the shale surface becomes more hydrophobic, which is very vital for shale stability. Overall, NFC possess excellent chance to behave as shale stabilizer in WBDFs and can be used in drilling operations, particularly problematic shale rocks.	[111]

4.5. Influence of NPs on DF rheology

The ability of dispersed phase fluids to flow makes them to be typically deployed as DFs in commercial operations. As fluids flow, the liquid particles' original arrangement deforms and also changes. The deformation properties of fluid while flowing is considered by Rheology. These characteristics are defined by certain parameters which are readily measured with values that are independent of design of the measuring apparatus and measurement conditions [114]. The rheological properties of DFs, mainly related with aspects of their strength and viscosity, influences their quality directly [15]. Strength and viscosity must be adequately high to mitigate losses of fluid to the reservoir and ensure the removal of cuttings from the wellbore [113]. Moreover, the rheological characteristics of DFs affect several drilling performance aspects. These include: performance of drill-string trips in and out of the borehole, pressure fluctuations as the fluid pump start and stop, hydrodynamic pressure values at the bottomhole positions and wellbore wall during drilling operations, establishment of adequate hydraulic opposition throughout the circulation of fluid in the system, cooling of the drill bits, lifting up of drill cuttings to clean the borehole, and workover operations on wells having staggered drill strings. As drill cuttings are transported by DFs, solid material improves both the erosion rate at the wellbore wall and circulation fluid strength [5]. The beneficial effects of various NPs on filtration losses and fluid rheology have been studied and confirmed. In particular, NPs reduces the friction coefficient of drill-string/wellbore, and as a result averts differential sticking of drill equipment. Most research works carried out showed the substantial influence of NPs on DFs properties, compared to when larger non-nano chemicals are introduced into DFs. Moreover, this influence is exhibited at ultra-low NP concentrations, depending on chemical properties and NP size. Indeed, studies have shown that the optimum performance of DF is not achieved with NPs of higher concentrations [24]. The properties of DF can be degraded or improved with the addition of several NP types. For instance, filtration can be increased up to 80% when Al_2O_3 NPs are introduced to BBWBDFs; however, the quality of the mud cake generated by the fluid loses it quality by action of NPs [114]. When TiO_2, SiO_2 and CuO NPs are introduced to defined fluids, there is a drop in filtration losses, especially for NPs concentrations lower than 0.5 wt%. However, other rheological features such as gel strength, can be improved by the introduction of Al_2O_3, TiO_2 and CuO NPs [6,115-116]. Table 10 highlights the impact of NPs on DFs rheology.

Table 10. Impact of NPs on DFs rheology.

S/N	NPs Type	Base fluid	Improved Parameters	Condition of experiment	Result	Ref.
1	ZnO NPs	Non-damaging DF (NDDF)	Filtration, rheological properties and thermal stability	1.4MPa and 80°C	The thermal stability improved by more than 300% with the introduction of ZnO NP compared to NDDF at temperature of 80°C. Fluid loss recorded 49% reduction with the introduction of 1%wt ZnO NPs.	[115]
2	Amorphous SiO_2 NP (AS NP)	Glycol-based DF	Shale, Filtration and Rheological properties	2.1MPa and 121.2′C	Minimal shale instability was achieved with 10wt% concentration NP (22nm size). Fluid losses dropped with increasing NP size	[22]
3	TiO_2 NP	Two distinct DFs: polyanionic cellulose (PAC) Hydroxyethyl cellulose (HEC)	Filtration, rheological properties and thermal stability	Simulated HPHT (110°C at 30rpm for 16h)	TiO_2 NPs enhanced DFs rheological properties and thermal stability, while reducing fluid losses.	[116]
4	ZnO / CuO NP	WBDF	Filtration and rheological properties	3.4MPa / 100°C	Lower shear stress in DFs was achieved by ZnO NPs than CuO NPs. Shear stress improved when 0.1 to 1.0wt% concentrations of both CuO and ZnO are introduced. ZnO NPs bearing fluids exhibited poorer rheological features than DF containing CuO NPs at the same concentration. The 10-minute gel strength of 0.8wt% CuO and 0.8wt% ZnO yielded significant performance than their 1wt% concentration. The electrical and thermal conductivities of CuO and ZnO nano-fluids improved by approximately 50% and 25% respectively.	[117]
5	Zn TiO_3 NP produced by two distinct techniques: (a) polymerization of bulk sol-gel (SNP) (b) sol-electro spinning (ENP)	WBDF	Thermal stability, Fluid loss and rheological properties	0.69MPa and 20′C-70′C	Laboratory tests were conducted on 0.05-0.3wt% SNP-Zn TiO_3NP and ENP concentrations at 20′C and 70′C. At 0.69MPa and standard temperature, the API filtrate improved by about 6% and 12% for SNP and ENP respectively. With 0.3w/v% NP at 20°C, AV of hot-rolled WBDF improved by about 20.9% (21.5-26) for ENP and 9.3% (21.5-23.5) for SNP. At the end of hot rolling process, the WBDF API filtrate dropped by 35.86% and 33% for 0.3% concentration of ENP and SNP respectively. ENP therefore, will influence the DF more positively than SNP.	[118]
6	Zn TiO_3 NP produced by sol-gel technique	WBDF	Viscosity and shear thinning behavior	0.69MPa and 25′C-90′C	Fluid rheology was significantly improved with small concentration of Zn TiO_3 NP. Even with the presence of salt in the fluid, 1wt% NP improved viscosity by 30.76% (2% salt) and 32.16% (1% salt) at 90′C	[119]

S/N	NPs Type	Base fluid	Improved Parameters	Condition of experiment	Result	Ref.
7	Graphene	OBDF	Fluid loss and rheological properties	LPLT: 25°C, 0.69MPa HPHT: 120°C, 3.5MPa For 30 min.	At 0.08% concentration, the graphene NP (of 2.71nm particle size) yielded reduced filtration (up to 38.96%) and improved thermal conductivity (up to 57.9%) in both HPHT and LPLT states	[120]
8	Graphene oxide (GO) NP in nano-sheet form (GO-NS)	NDDF	Fluid loss and thermal stability	0.69MPa-1.4MPa, 30’C, 60’C and 80’C	GO-NS of 0.5wt% concentration yielded lesser deposition at various bends than other materials. The notched ring adsorption of 0.5wt% GO-NS got lowered by 31% incomparison to NDDF. Less deflection and higher lift rate were also achieved by GO-NS.	[115]
9	TiO_2 NPs-bentonite (TNBT)	WBDF	Filtration, Shale swelling and lubricity at HPHT conditions	0.7MPa, 25°C-85°C	Filtration loss was mitigated by 0.7g of TiO_2/bentonite NP in HTHP and LTHP conditions by 30% and 17%, respectively.	[121]
10	Poly-propylene-nano-silica composite (PP- SiO_2 NC) blended with partially hydrolyzed polyacrylamide (PHPA)	Complex Water-based DFs	Transportation of cuttings	LPLT: ambient temp. 0.69MPa HPHT: 105°C, 3.5MPa	At 0.457, 0.63, 0.823 and 0.96 m/s DF velocities, the least-sized cuttings were the easiest to separate. However, the transport of cuttings of large sizes was improved when fluid velocity was increased to 1.8m/s. The result also showed the better cuttings carrying capacity the PP- SiO_2 NC DF has than PHPA DF. This is as a result of improved colloidal interaction force, irrespective of pipe rotation speed.	[122]
11	SiO_2 NP (NS) and Poly-propylene beads (PP) closed with sodium carbonate (Na_2CO_3)	WBDF	Transportation of cuttings	LPLT: 25.6°C, .69MPa HPHT: 1489°C and 3.5MPa	Introduction of PP beads with NS lowered gel strength, yield strength, fluid viscosity and filtration of the tested DFs.	[123]
12	NP with hydrophilic properties: SiO_2 , TiO_2 , Al_2O_3, CuO	BBWBDF	Rheological properties and Filtration properties	0.69MPa and 27°C	Al_2O_3 NPs at 1wt% concentration achieved maximum yield strength with BBWBDF at 21.45Pa. In contrast, yield strength attained by CuO NPs dropped from 10.54Pa (at 0.01wt% NP) to 8.62Pa (at 1wt% NP). With concentration increase of 0.01wt% to 1wt% for Al_2O_3 NPs, about 250% improvement in gel strength (10min. and 10sec.) was achieved. There was slight fluid loss reduction at 0.1wt% with CuO NPs.	[114]
13	Laponite (an artificial clay with disk-shaped NPs with charged surface)	WBDF	Plugging, Shale inhibition and lubricity	1.034MPa and room temperature	2.0wt% laponite materials (20nm size) potentially hinders shale than conventionally used polyamine and KCL chemicals. It also significantly lowers pore volume and shale porosity by establishing seamless nanofilm. Fluid losses and friction reduces when laponite containing DF are tested.	[124]
14	Carbon dots	WBDF	Lubricity properties	1.3.10 (-4) Pa and 25°C	1wt% carbon dots (1 and 4nm size) significantly reduces the friction coefficient by 0.03 and 0.055, and fluid friction by 33% and 80% respectively.	[125]

S/N	NPs Type	Base fluid	Improved Parameters	Condition of experiment	Result	Ref.
15	Al_2O_3 and SiO_2 NP	Salt-water and Fresh-water-based DFs	Rheological and filtration properties	700KPa, 0’C-80ºC	0.1wt% was discovered to be best concentration at 80ºC for both NPs in salt and fresh water fluids for rheological features. For fresh water, fluid filtrations improved up to 8.2% and 6.9% for 0.05 and 0.01wt% SiO_2. For salt water, fluid filtration improved up to 11.2% and 12.5% for 0.05 and 0.01wt%. In the case of fresh water, the rate of fluid filtration improved up to 53.4 at 0.2wt% Al_2O_3 concentration.	[126]
16	Magnesium Aluminum Silicate (MAS)	WBDF	Rheological and filtration properties	LPLT: 25ºC, 0.69MPa HPHT: 150ºC, 3.5MPa	Improvement in rheological characteristics of DFs and smoothing of the filter cake was achieved using MAS NP. Optimum concentration was achieved at 2.0% MAS NP following hot rolling of outperforming DF with 8.0% bentonite.	[127]
17	Fibre form (CNFs) and crystalline forms (CNCs) cellulose NP	WBDF	Hole cleaning	0.69MPa and 27ºC	Laboratory tests were conducted for CNF and CNC within the range of 0.15wt% and 0.6wt%. Unlike CNF which recorded between 8.25% and 12.83% base fluid shear stress, the CNC increased between 9.91% and 13.05%. The effective base fluid viscosity for CNC improved between 7.43% and 12.21% while CNF recorded between 9.64% and 12.83% with increasing NP concentrations.	[6]

4.5.1. Plastic viscosity of DFs

Plastic viscosity (PV) is a general value that describes the viscous opposition of fluid to flow. PV as a parameter that is not dependent on shear stresses, using mathematical correlation of the Bingham model [5]. PV is primarily used for the assessment of the DFs ability to suspend its cuttings. A high solids content, involving clays having low density, improves the strength and plastic viscosity of the DF. Slower drill speeds and thicker filter cake seems to be associated by high-solids DFs. High percentage of sand in DF makes it coarse, leading to likely damage to tubulars, pumps and downhole equipment. To lower PV, the solids contents is expected to be lowered by dilution of DFs with water or fluid cleaning modification [35]. The improvement of DF rheological characteristics during drilling activities can be achieved with materials such as bentonite, though various NPs can be used for this improvement as ddepicted in Table 11. Bentonite is widely accepted for improvement and regulation of DF rheological characteristics, and is relatively cheap. NPs have shown their ability in improving rheological characteristics, particularly PV. The addition of various NPs (TiO_2, CuO, $Al_2O_3$and SiO_2) at 1 wt% concentration into BBWBDFs significantly improves PV and yields other changes in their rheological characteristics [114]. Addition of MgO NP to improved starch 0.5% concentration yielded a 45% increase in PV of WBDF. At HPHT conditions, the addition of ZrO_2 NP and MWNT-TiO_2 hybrids enhanced PV but could not influence filtrate volume [35]. At concentration range of 0.01 wt% to 0.5 wt% FMWCNTs were discovered to enhance DF PV due to higher solid content, higher surface area and higher surface area per volume of the nanotubes. With the addition of HGNs to base DFs, there was 9.5% increase in PV. There was a favorable improvement in DFs rheology and thermal stability before and after hot rolling when 0.05 w/v% content TiO_2 NP were introduced to HEC, PAC and XG at various temperatures [116] (see Table 11).

Table 11. Impact of various NPs on DFs properties.

No	NPs Types	Fluid Type	Den-sity	Viscosity	Plastic viscosity	Gel strengths	Yield Point	Filtration	Ref.
1	Al_2O_3				114.2% (1wt %)	150s / 54.6 mn% (1wt %)	45% (1wt %)	95.2% (1wt %)	[114]
2	MgO	-	-	-	50% (0.5wt %)	67% (0.5wt %)	231% (0.5wt %)	14.2ml (0.5wt %)	[102]
3	Nano-$CaCO_3$,	(OBDF)	-	-	27/25% (0.5 poly-styrene-butadiene rubber copoly-mer + 0.5 NP wt.%), (48.9°C, 3.45 MPa/ 148.9°C, 3.45 MPa)	-	23/21% (0.5 polystyrene-butadiene rubber copol-ymer + 0.5 NP wt.%), (48.9°C, 3.45 MPa / 148.9°C, 3.45 MPa	-	[128]
4	Hematite NP Fe_2O_3,	KCL-Gly-col-PHPA polymer-based DF	-	-	15% (3.0wt %)	3.0% (3.0wt %)	12.5% (3.0wt %)	13.6 and 40% (0.5w %)	[129}
5	ZnO nan-owires (3wt%) at 25°C	BBWBDF	10.4%	20%	-		-	-	[130]

4.5.2. Yield points of DFs

Yield point (YP) is the aspect of fluid flow resistance that is manipulated by the underlying conditions of the chemical. As the forces of attraction declines, as a result of the influence of some chemical treatment, the yield stress also declines. A drop in the yield stress results in a drop in AV. YP is one of the variables of the Bingham plastic rheological correlation; the yield stress is determined by extrapolation at zero shear rate. YP is correlated using viscometer measurement at 600 and/or 300 revolutions/minute (rpm), through the subtraction of PV from the 300rpm dial reading. High YP reading shows a better suspension capacity of the drill cuttings than a low YP solution (of the same density) [131]. There is increase in the YP of a DF: (a) with the surface area and concentration of clay particles; (b) when there is contamination of DF with cement, gypsum, hydrogen sulfide, carbon dioxide, anhydrite or halite and (c) when bicarbonate and barite sodium carbonate chemicals are deployed. YP drops when: solid phases are removed; chemicals such thinners de-flocculants (phosphates, lignites, and lignosulfonates) are used for treatment; pollutants being neutralized by chemicals; and water is used to dilute the fluid [132]. The YP of DFs can be significantly enhanced. For example, the PV and YP of WBDF at LPLT conditions was greatly improved when 0.5 wt% concentration of 10nm-sized SiO_2 NP was introduced. Various types of NPs can significantly enhance YP when introduced. For instance, YP improved by close to 45% when 1wt% concentration of Al_2O_3 NP was introduced while YP improved by about 14.3% when TiO_2 and SiO_2 NP of 1 wt% concentration was introduced [114].

4.5.3. Gel strengths of DFs

Gel strength (GS) is important to the Bingham's plastic rheological correlation. It defines the gel's formation rate, and the gel strength formed under static conditions. The stronger the strength of the gels formed, the bigger the particle size that can hang in a fluid and will not readily drop to the bottom due to forces of gravity. Solid phases cannot be suspended if there is insufficient gel strength, and this is as result of static shear stresses. When the fluids stay still within a specific period of time due to low-shear rates, shear stress are established. The standard API procedure suggests 10sec and 10min specified time, though measurement can often be taken after 30min or 16hrs. The gel strength of a drilling fluid can be positively improved by introduction of NPs. The introduction of 0.5wt MgO NP chemicals to DFs, improved its gel strength by about 67% [102]. Comparatively, the introduction of 3.0wt% Fe_2O_3 NP chemicals to DFs, improved its gel strength by just 3% [129] [see Table 11]

4.6. Lubricity of the DF

Drilling the wellbore of oil and gas reservoir typically deals with high frictional forces and large torques of the drilling tool against the walls of the borehole. To lower them, special lubricating chemical are introduced into DFs to generate enhanced surface active and anti-seizure features [133]. Several existing chemical lubricants have by field experience demonstrated to lose its efficiency both in drilling of salt reservoirs using saline-saturated DFs and when drilling formations having high divalent metal salt such calcium salt. The introduction of NP chemicals can improve the lubricity of DFs [134]. At HPHT conditions (at 149ºC and 3.5MPa), hydrophilic natural Gilsonite (HGN) NP lowered the torque by 15% and 13.63%, enhanced lubricity by positively affecting YP and PV, reduced filtration losses and decrease differential sticking risks by 61.5%. This can be tied to the value of YP/PV for the DF sample which upon completion of hot rolling process, improved by 9.5% while that of the base fluid decreased by 67% after going through the same process. Upon addition of HGHs to the hot rolling process, the base mud lubricity was improved. As a result of HGHs introduction, the likelihood of differential sticking is lowered [135]. Table 14 highlights some NP additives that can essentially improve DFs lubricity.

Table 14. NPs that can enhance DFs lubricity.

No	NPs	Based fluids	Summary	Ref.
1	SiO_2	WBDF	Introduction of SiO_2 NP (10 nm size) at concentration ranging from 0.013wt. % and 0.53wt.% was studied. 25% friction factor reduction occurred at 0.013wt% concentration.	[136]
2	Modified Boron-based nanomaterial (PQCB)	WBDF	At concentration of 5wt% and 1wt%, PQCB reduced torque by 80% and 30% respectively	[137]
3	Titanium Nitride (TiN)	KCL/CMC water-based DF	At 0.0095wt% TiN (20 nm), the friction coefficient was reduced by 46%.	[138]
4	MWCNT	KCL/XG water-based DF	At 0.38wt% and 0.02wt% MWCNT (40 nm and 20 nm size) concentration, friction coefficient reduced by 50% and 30% respectively.	[134]

4.7. Hole cleaning capabilities

The transportation of cuttings from the subsurface through the annulus to the surface fluid facilities and efficiently cleaning of the borehole poses major obstacles for DFs [114]. Inadequate well cleaning result to cuttings accumulation in the borehole, which potentially cause serious drilling challenges (e.g., stuck drill string). Solving some of these drilling challenges typically involves considerable incremental cost, more times as high as the cost of the measures available to enhance the DF's hole cleaning attributes. Some NPs have shown capacity to enhance cuttings transportation [123] and hole cleaning attributes of DFs. CNPs have improved DFs attributes in the circulation and transportation of drill cuttings from the borehole. This is achieved by enhancing the flow consistency coefficient and yield stress of the DF. SiO_2 NPs have shown to be used for improving cutting transport capacity of WBDF from 1078.44 to 1318.1 kg/m^3 compared to untreated WBDF at 150 RPM [6]. Abbas *et al.* [6] studied CNF and CNC concentration range of 0.15 wt% to 0.6 wt%. The shear stress of base fluid for CNC improved by 9.91% to 13.05% range, while the CNF recorded improvement range from

8.25% and 12.28%. For CNC, an observable 7.43% and 12.21% improvement in the effective viscosity was recorded by the base fluid while 9.64% and 12.83% improvement were achieved by CNF. Att 0.6 wt% CNC, the rate at which the cuttings were transported improved when compared to the base fluid by 14.69%/13.88%/18.75% for large/medium/small cuttings sizes respectively. The high surface area to volume ratio which enables better colloidal forces and efficient contact with cuttings, influences the better performance of conventional WBDFs containing CNCs. In many experimental studies on fluid samples, the DFs containing CNFs showed a better attribute, specifically at elevated annular fluid velocities. Several efficiencies of transported cuttings have been observed in CNFs and CNCs enhanced DFs due to the long dimension nature of the CNFs and its tendency to form much entangled chains [139].

5. Conclusions

From the review conducted the following conclusions are drawn: NPs more efficiently tackled various difficulties arising from drilling activities, and aids control of fluid properties to fit operational conditions. Alterations in NP size, shape, composition and concentration in DFs significantly affected the properties imparted on by these fluids. Aluminum oxide (Al_2O_3) and Silica (SiO_2) NPs have been mostly studied for applications in the oil and gas industry; The best plastic viscosity for BBWBDFs was achieved when 1wt% concentration Al_2O_3 NP was utilized compared to TiO_2, CuO and SiO_2 NPs. A broad range of NPs substantially improved the rheological features, specifically WBDFs. To some extent, many NPs affect crucial DFs properties when introduced at low concentration for both OBDFs and WBDFs. This enables them to enhance the suspension of drill-cuttings, thereby improving the fluids' hole-cleaning and lifting capabilities. Several NP chemicals in DFs significantly enhance the filtration properties of DFs and lower fluid loss, particularly under HPHT conditions. These characteristics potentially proffers substantial savings for the drilling industry. However, certain NP materials at higher concentration hinder the temperature responsiveness of the DFs rheology; and this necessitates the search for very inexpensive NP chemicals for use as DFs additive. The high unit costs of producing certain NPs impact their economic competitiveness negatively. Thus, as the cost of producing NPs continues to go down, the utilization of NPs as DFs additives will continue to increase.

Nomenclature

DF	*Drilling fluid*	*NT*	*Nanotechnology*
PAC	*Polyanionic cellulose*	*DP*	*Drill pipe*
NP	*Nanoparticle*	*AFM*	*Atomic force microscopy*
NPs	*Nanoparticles*	*CS*	*Coconut shell*
CMC	*Carboxymethyl cellulose*	*XRD*	*X-ray diffraction*
WBDF	*Water based drilling fluid*	*TEM*	*Transmission electron microscopy*
NM	*Nanomaterial*	*SEM*	*Scanning electron microscopy*

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