Review Article

Smart Fluids and Their Applications in Drilling Fluids to Meet Drilling Technical Challenges

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This article presents extensive analysis and review on recent developments in smart fluids as well as future opportunities of smart drilling fluids utilization in oil and gas well drilling while focusing on the following smart fluids: smart nanoparticles, electrorheological, magnetorheological, and viscoelastic surfactant (VES) fluids. The distinctive properties of nanoparticles such as tiny particle sizes, high specific surface area, mechanical strength, and thermal stability make them suitable for utilization in drilling fluids. In bentonite water-based drilling fluid systems, this review suggests that charged nanoparticles are capable of displacing exchangeable ions in between bentonite clay platelets, thereby forming intercalates which can interact with clay surfaces through electrostatic attraction or repulsion. In improving wellbore stability, it is presented in this review that nanoparticles are able to invade and plug ultratiny pore spaces in shale formations, thereby further enhancing shale formations’ mechanical strength and wellbore stability. According to this review, the magnitude of changes in properties of smart electrorheological and magnetorheological fluids largely depends on the intensity of applied electric and magnetic fields. The intensity of smart fluids properties alteration due to applied field would equally depend on wt.% concentration and chemical compositions of particles susceptible to electric and magnetic fields. Based on review carried out on VES smart fluids, attractive and repulsive forces in the smart VES fluids solution result in the formation of micelles which can cause changes in viscoelastic property of the formulated smart viscoelastic fluids. The more the concentration of charged ions in the base fluid which VES fluids come in contact with, the higher the viscoelasticity of the smart VES fluids. According to this review, utilization of smart materials in drilling fluids can result in meeting oil and gas well drilling technical challenges including enhancing wellbore stability, improving hole cleaning performance, lost circulation control, fluid loss control, enhancing rate of penetration, pressure drop control, and easing cutting carrying efficiency of drilling fluids. This review equally suggests that the utilization of smart fluids such as smart magnetorheological and electrorheological fluids would facilitate drilling automation and real-time data acquisition processes, which is the future technology in oil and gas drilling.

1. Introduction

Smart fluids are referred to as fluids whose properties can be influenced by changes in external conditions (such as pressure, temperature, and electric and magnetic field) [1]. Types of smart fluids studied in the past include smart nanoparticle fluids, smart electrorheological (ER) fluids, smart magnetorheological (MR) fluids, and smart viscoelastic surfactant (VES) fluids. The ability of these fluids to be fine-tuned due to external stimuli makes them suitable for a variety of applications with the aim of meeting technical challenges especially in the oil and gas industry. In recent years, the development and utilization of additives which provide the necessary smart properties in smart fluids have cut across different industries including medicine, sports, electricity, sensor, oil, and gas industry [2].
Recently, smart fluids in the oil and gas industry have been applied for various purposes, and the majority of smart fluids’ applications have been in enhanced oil recovery for improving sweep efficiency in response to changing reservoir conditions [3]. Smart nanoparticles fluids have been utilized in enhanced oil recovery due to their ability to induce wettability alteration, interfacial tension alteration, and invasion/plugging of nanopore spaces which conventional bulk particles are incapable of accessing [4, 5]. On the other hand, nanoparticles smart fluids have been utilized for corrosion inhibition due to their ability to adhere to and form ultrathin films with high spatial distribution arising from their high specific surface area [6]. Smart nanoparticles have equally been applied in the development of sensing devices for improving data acquisition by facilitating the collection of physical quantities in reservoirs, thereby transmitting these quantities into understandable and readable data for real-time quick decision-making.

Numerous studies have been carried out on the influence of external conditions including temperature, pressure, electric field, magnetic field, wt.% concentration of particles, and chemical composition on the behavioral changes in smart fluids [7]. During oil and gas well drilling, high-temperature higher-pressure (HTHP) conditions are usually encountered as deeper wells are drilled, and so the application of smart fluids to fit these changing conditions is of importance. In practice, high depth oil and gas wells can experience HTHP conditions up to 250°C and 10000 psi, respectively. Hence, controlling drilling fluid performances under these wellbore conditions is of utmost importance. Xiangru et al. [8] presented a study on the stability and fluid loss control of silica grafted nanoparticle in water-based drilling fluid systems. Other studies on the influence of electric and magnetic fields have also been presented in the past [9, 10]. In particular, studies have shown that these changes have greatly influenced rheological properties of base fluids.

In oil and gas well drilling, applications of smart fluids have been widely focused on the dispersion of nanoparticles in base drilling fluids with the aim of enhancing drilling fluid properties [11–13]. In smart nanoparticle drilling fluids, nanoparticles have been known to influence drilling fluid performances due to changes in wt.% concentrations, higher specific surface area, and high quantum activity [14–16]. When considering the effects of nanoparticles on wellbore stability, it is suggested that, due to their tiny particle sizes, they are able to invade and plug shale nanoporous media, thereby enhancing the mechanical strength of unconsolidated shale formations and thus improving wellbore stability [17, 18]. On the influence of nanoparticles on water-based drilling fluids, since bentonite clay surfaces are considered to be net negatively charged with clouds of cations due to electron deficiency owing to isomorphic substitution in their unit layer, functionalized and charged nanoparticles (cationic and anionic) can cause either an increase or decrease in drilling fluid rheological properties through electrostatic attractive and repulsive forces [13]. It is suggested that this electrostatic interaction can equally result in an increase or decrease in fluid loss volumes by drilling fluid systems, hence making research on smart drilling fluids an area of importance when considering meeting technical challenges during oil and gas well drilling operations.

In view of this, several reviews on the utilization of nanoparticles have been published in the past and in recent times. Hussain et al. [19] in their review highlighted the importance of nanoparticles in meeting technical challenges in oil and gas well drilling. The review suggested that technical challenges such as wellbore instability, poor hole-cleaning, rate of penetration decline, and formation damage can be met through the utilization of nanoparticles in drilling fluids. Cheraghian et al. [20] presented a review on current nanoparticles utilized in oil and gas drilling fluids. Their study mainly focused on analysis of state-of-the-art nanoparticles and their effects on drilling fluid performance. Their review highlighted that high surface-to-area volume ratio, stable dispersion behavior, and improvements in heat and mass transfer were all important factors required by nanoparticles to improve drilling fluid performance.

While these reviews have been mainly focused on smart nanoparticle drilling fluids, there is yet to be a comprehensive review on smart drilling fluids covering a wide range of smart materials. This literature review aims to bridge this gap by presenting studies on different smart fluid systems, their performance mechanisms, and how they could be applied in drilling fluids to meet technical challenges. For relevance to the subject matter and review objective, emphasis will be placed on the application of smart fluids in oil and gas well drilling (smart drilling fluids). Smart fluids presented in this review include nanoparticles, electrorheological, magnetorheological, and viscoelastic surfactant smart fluids. In our literature review on ER and MR fluids, the influences of electric and magnetic fields on the rheological properties of drilling fluids are analyzed. The application possibility and influence of smart VES drilling fluids are equally reviewed. According to [21], smart VES fluids possess different elasticity behaviors under variety of conditions causing an alteration to drilling fluid rheological properties due to development of micelle colloid agglomerates. It is suggested that incorporation of smart VES fluids with long chain polymers can induce thermal stability as well as increase in drilling fluid rheological properties. Since one of the technical challenges of drilling fluid utilization in oil and gas well involves meeting changes in temperature and pressure conditions, this review analyzes how changes in temperature and pressure conditions affect the performance of smart drilling fluids. Current challenges and future opportunities for smart fluids in oil and gas drilling are equally provided in this literature review.

In carrying out this review, extensive online searches were carried out from online databases including Elsevier, Scopus, OnePetoro, Web of Science, and Google Scholar between the years 2000 and 2022. More than 100 articles from high impact journals were selected from these available online resources. From results in the online search, emphases were placed on smart fluids including smart nanoparticles, electrorheological, magnetorheological, and viscoelastic surfactant fluids going in-line with review objectives.
2. Smart Nanoparticles Drilling Fluids

Nanotechnology can be defined as the manipulation of atoms and molecules on the nanoscale (1–100 nm) to fabricate devices and materials which provide solutions to real-world problems [6]. On the other hand, nanoparticles are ultrafine colloid particles with sizes in the nanoscale range [22]. The distinctive properties of nanoparticles such as particle size, high specific surface area, thermal stability, and mechanical, optical, and electrical conductivity have made studies on nanoparticles an area of interest for researchers in recent years. According to [23], a good nanoparticle must be stable in an aqueous solution forming proper dispersion. This dispersion phenomenon usually results from several mechanisms including electrostatic repulsion and steric repulsion. A colloid system contains nanoparticles with same charges which tend to repel each other, thereby forming particle dispersion. Controlling nanoparticle dispersion behavior in turn greatly influences the viscosity of base fluids. As particles become micronized, they tend to behave differently due to their quantum effects resulting from changes in bonding state of atoms and molecules making nanoparticles behave in smart ways [24]. One distinctive property of nanoparticles is the relatively high specific surface area. Smaller particles tend to display an increase in specific surface area when compared with the bulk materials (Figure 1) [6]. Particles with higher specific surface area would react and form better bonds with other colloid particles in the drilling fluid system. In addition, due to higher activity of particles on the nanoscale, nanoparticles exhibit a reduction in melting point as opposed to the bulk materials, which further highlights their unique property [2]. Another advantage of the high specific surface area of nanoparticles is that very little concentration can be applied in the base fluid to achieve desired purposes [25], suggesting an ability to reduce operational cost, improve particle transportation, and solve other logistics issues in relation to nanoparticle oil and gas industry utilization.

2.1. Current Applications of Nanoparticles in Drilling Fluids. The ability to design and apply engineered and functionalized nanoparticles in drilling fluids can greatly influence operational cost and overcome technical challenges which may arise during drilling operations [19]. This makes the functionalization of nanoparticles an important factor when considering the ever-changing wellbore temperature conditions, hence the necessity to implement novel colloid systems that would improve the performance of drilling fluids during oil and gas drilling operations at dynamic conditions. Studies have suggested that the addition of nanoparticles in drilling fluids has resulted in the improvement of drilling fluid properties. Research on smart nanoparticle drilling fluids has been widely conducted on water-based drilling fluids, generally due to environmental safety and cost effectiveness when compared with oil-based drilling fluids [15]. Therefore, this review is mainly focused on water-based drilling fluids.

One of the influences of nanoparticles on drilling fluids has been the influence on the rheological properties of drilling fluids. Rheology can simply be put as the study of the deformation and flow of matter. The effects of nanoparticles on drilling fluid rheological properties such as plastic viscosity (PV), apparent viscosity (AV), yield point (YP), and gel strength (GS) have been extensively studied in the past [26]. An understanding of drilling fluid rheological properties would facilitate the enhancement of rate of penetration, improvement in cutting carrying, cutting suspension, and overall hole cleaning efficiency [27, 28]. In addition, utilization of nanoparticles in drilling fluids has been reported to influence filtration rate, lubricity performance, and corrosion inhibition of drilling fluids.

Li et al. [10] presented a study on smart drilling fluids through the incorporation of silica nanoparticles alongside other base fluid additives aimed at optimizing drilling fluid performance. According to their study, addition of silica nanoparticles in base fluid was able to increase the drilling fluid rheological properties as wt.% concentration of the nanoparticles increased. Carpenter (2017) [29] highlighted that the addition of Fe3O4 nanoparticles in water-based drilling fluid causes an increase in the drilling fluid rheological properties. Based on that study, the Fe3O4 nanoparticles drilling fluid system displays a shear-thinning behavior where viscosity decreases with increasing shear rate. At low shear rate, the colloid particles tend to form stronger interparticle bonds. These bonds are a result of electrostatic attractive forces between colloid particles in the drilling fluid system causing an increase in rheological properties such as apparent viscosity, gel strength, yield point, and plastic viscosity. However, as shear rate increases, the particles tend to dissociate, making the interparticle bonds become weaker. A reflection in the drilling fluid properties would be decline in yield point, gel strength, and viscosity, hence the decrease in apparent viscosity at higher shear rate conditions. Dutta and Das (2021) [30] further highlighted the effects of iron oxide nanoparticles on neat...
bentonite water-based drilling fluid. Based on their study, addition of iron oxide excluding other additives in the base fluid provided the necessary changes in the drilling fluid rheological properties (increasing viscosity, yield point, and gel strength). This ability to improve the drilling fluid properties at low wt.% concentration without further addition of other additives elucidates more on the smart capabilities of nanoparticles in water-based drilling fluids. It is suggested that this effect is attributed to the distinctively high surface area of the nanoparticles.

When compared with bulk particles, nanoparticles become more active and reactive with other particles in the base drilling fluid forming necessary bridges, interparticle bonds, intercalation, and exfoliation resulting in changes in drilling fluid properties. Vipulanandan et al. (2018) presented a study on smart spacer fluids containing iron oxide nanoparticles aimed at providing effective separation between the cement slurry and drilling fluid. Formulated nanofluids have equally been reported to improve the lubricity performance of drilling fluids. The reported action mechanism of the nanoparticles on lubricity performance has been the formation of thin films through the adhesion of nanoparticles on metal surfaces. Due to their relatively high surface area, these nanoparticles are able to form spatially distributed thin films on metal surfaces resulting in improved smart lubricity performance. Due to their ultratiny particle sizes, nanoparticles have been reported to enhance wellbore stability by invading and effectively plugging shale nanoporous media, helping to provide necessary stability for the wellbore [18]. Though capable of enhancing wellbore stability, bulk materials in the microscale are incapable of invading and plugging porous media on the nanoscale, hence the distinctive smart effect of nanoparticles in drilling fluids.

Studies suggest that when drilling deeper wells, higher-temperature higher-pressure conditions are encountered; hence it is generally a good practice to take into consideration the performances of formulated drilling fluid systems in HTHP conditions. Several studies on the effects of HTHP conditions on the performance of nanoparticle smart drilling fluids have been presented in the past. Huang et al. [32] presented a study on the thermal stability of drilling fluid system with the incorporation of laponite nanoparticles. According to their study, addition of laponite nanoparticles resulted in an increase in plastic viscosity and apparent viscosity at temperatures between 150°C and 180°C. Based on their study, the increasing performance effect of the laponite nanoparticles on the drilling fluid system at HTHP conditions is attributed to the high electrostatic attractive force between the laponite nanoparticles and the bentonite clay platelets due to the high specific surface area of the nanoparticles leading to higher quantum activity. A study presented in [33] highlighted that silica nanoparticles were able to prevent thermal degradation of drilling fluid systems as rapid decrease in rheological properties was prevented. Beg et al. [34] presented a study on the performance of TiO₂ nanoparticles drilling fluid system at high-temperature condition. Their study suggested prevention in rheological properties degradation at temperature up to 250°C and a control of fluid loss performance. According to results from the following review, nanoparticles possess the capability of meeting drilling fluid technical challenges during oil and gas well drilling operations such as HTHP conditions, rheological properties stability, fluid loss control, lubricity performance, and wellbore stability (improving shale inhibition and reducing clay swelling and shale dispersion). Table 1 highlights the recent studies on nanoparticles utilization in drilling fluids and their effects on property alteration.

2.2. Carbon-Based Nanoparticles. Among recently studied nanoparticles, carbon-based nanoparticles have become an important area of interest. Studies have suggested that carbon-based nanoparticles possess distinctive properties including high tensile strength, thermal stability, and high chemical reactivity. Examples of these nanoparticles include graphene oxide nanoparticles, carbon nanotubes (single-walled (SWCNT), double-walled (DWCNT), and multi-walled (MWCNT) carbon nanotubes), and fullerene nanoparticles (Figure 2 and Table 2) [44]. 2D graphene nanoparticles generally are comprised of carbon atoms bonded together in a honeycomb configuration, while 1D carbon nanotubes are rolled graphene sheets as highlighted in Figure 2. Graphene oxide and carbon nanotubes have been known to possess high thermal stability, electric conductivity, and mechanical strength. The tensile strength of carbon nanotubes has been reported to be over 100 GPa [45]. MWCNT however possess higher tensile strength due to an increase in the thickness of the concentric carbon sheets. It is suggested that this effect causes improved thermal stability displayed by CNT. Surface modified and functionalized CNT have been reported to improve the rheological performance of base fluids [48]. This is attributed to the hydrophilic and hydrophobic effect induced by the functional groups linked with the carbon nanotubes. The 3D graphite, which is an allotrope of carbon and is also characterized by high mechanical strength, thermal stability, and electric conductivity, is composed of carbon atoms held together by strong covalent bonds. A graphical illustration of all carbon-based nanomaterials and their different dimensions is given in Figure 2.

According to [9], the carbon nanotube forms bridge in-between dispersed clay platelets, thereby reducing the interlayer spacing between the bentonite colloidal particles. This causes an increase in the drilling fluid rheological properties. Afra et al. [48] further highlighted a study on functionalized multiwalled carbon nanotube incorporated with viscoelastic surfactant aimed at increasing viscosity at different temperature conditions. In their study, it was suggested that the action mechanism of carbon nanotubes on viscosity increase was the interaction between the functional groups present in the CNT and amide/nitrogen oxide in the viscoelastic solution resulting in an increasing repulsive force between the particles, further causing a formation of micelle-like structure, which leads to viscosity increase of the fluid. It is suggested that the presence of multiple walls in the CNT which causes an increase in its tensile strength further induces its thermal stability. A study
on the synergistic effect of silica and graphene oxide nanoparticles on drilling fluid properties was presented in [35]. That study suggested that the rheology modification and filtration control capabilities of the nanoparticles were due to high surface activity of the nanoparticles due to their particle size. OD fullerene nanoparticle, an allotrope of carbon which has a structure of a spherical molecule, is equally one of the carbon-based nanomaterials which pose potentials in drilling fluid application. These are characterized by their high electric conductivity, high tensile strength, and thermal stability alongside their ultratiny particle sizes (approximately 1 nm) [45]. While their application has become handy in areas such as drug delivery, sensor devices development, and solar devices fabrication, very few studies have been presented on oil and gas engineering, most especially on drilling fluid technology. These distinctive properties make fullerenes excellent candidates in drilling fluid applications when formulating smart drilling fluids.

### Table 1: Recent studies on nanoparticles in drilling fluids.

| Drilling fluids          | Nanoparticles                        | Functions                                                                 | References |
|--------------------------|--------------------------------------|---------------------------------------------------------------------------|------------|
| Water-based drilling fluids | Asphalt, Fe₃O₄, Fe₂O₃, Silica and graphene oxide | Rheology modification, reducing shale dispersion | [18]       |
|                          | Silica, laponite                      | Rheology modification and filtration control | [29, 30]   |
|                          | Zinc oxide                           | Thermal and wellbore stability                                           | [35]       |
|                          | Graphene oxide                       | Rheology optimization, thermal stability, shale stabilization, fluid loss control | [8, 10, 16, 32, 36] |
|                          | Polymer nanocomposites                | HPHT, shale stabilization                                               | [15]       |
|                          | Polymer latex styrene/n-butyl acrylate/ acrylic acid (SDNL) | Fluid loss control, shale inhibition                                      | [35, 37]   |
|                          | Acrylic resin/nano-SiO₂               | Fluid loss control, rheology modification                                 | [8]        |
|                          | Styrene butadiene resin/nano-SiO₂     | Shale inhibition, fluid loss control                                      | [36]       |
|                          | SiO₂, ZnO, and TiO₂                   | Pore plugging and shale stabilization                                    | [38]       |
|                          | Calcium carbonate nanoparticles       | Pore plugging and shale stabilization                                    | [39]       |
|                          | Zinc oxide                           | Shale inhibition                                                          | [40]       |
| Salt-water-based drilling fluids | SiO₂                                | Density increase, rheology and fluid loss control                        | [36]       |
| Glycol-based drilling fluids       | SiO₂                                | Circulation friction resistance, shale stabilization                     | [41, 42]   |
|                          | SiO₂                                 | Shale stabilization                                                       | [43]       |

#### 2.3. Performance Mechanisms of Nanoparticles in Water-Based Drilling Fluids.

Due to distinctive effects on the performance of drilling fluids, several studies have been presented on the action mechanisms and phenomena related to the addition of nanoparticles in drilling fluids. Some action mechanisms include electrostatic adsorption, adsorption bridging, intercalation, and exfoliation [41]. The following points highlight some of these action mechanisms:

- (i) Electrostatic adsorption. In water-based drilling fluids, when bentonite clay particles absorb water into their interlayer spaces, the exchangeable cations (Na⁺) in between unit layers tend to hydrate and the water molecules form hydrogen bonding with oxygen atoms in the clay layer surfaces. This results in increasing surface area of the bentonite water-based drilling fluid causing dispersion phenomenon [49]. Usually, these cations can be displaced and exchanged with divalent and multivalent cations which can lead to increasing attractive forces between the cations and net negatively charged clay surface. When wt.% concentrations of cationic nanoparticles are added to the clay water-based drilling fluid, ion fixation and exchange usually occur, which causes an increase in electrostatic attractive forces between negatively charged clay platelets and the incorporated nanoparticles (Figure 3) [49, 50]. Functionalized nanoparticles which possess charges (anionic and cationic) can readily interact with the clay surfaces forming electrostatic interparticle bonds which can lead to an increase or decrease in drilling fluid rheological properties and alteration of other properties [38]. Incorporation of anionic nanoparticles would rather result in increasing repulsive force between the clay platelets and the nanoparticles. The resultant effect of this interaction on drilling fluids would be decrease in rheological properties. As earlier highlighted, nanoparticles are
known to be more active when compared with the bulk materials due to quantum effects. This high surface activity of nanoparticles would further facilitate an increase in particle-particle attraction and repulsion interactions in the water-based drilling fluid.

(ii) Adsorption bridging. In shale formations water-based drilling fluids colloid particles and filtrates invade porous media with sizes ranging from the nanoscale to the microscale. This invasion can cause changes in mechanical and tensile strength of the rocks leading to wellbore instability problems. Unlike bulk materials, nanoparticles possess the capability to invade ultratiny pore spaces on the nanoscale, thereby forming physical adsorption bridges and effectively plugging pore spaces. This in turn enhances wellbore stability and improves drilling operations. On the interactions with other colloidal particles in the drilling fluid, non-functionalized nanoparticles are capable of forming adsorption bridging layers in between bentonite clay colloidal particles, thereby causing an alteration in drilling fluid properties. This alteration would be attributed to their tiny particle size and high surface area.

3. Smart Electrorheological (ER) Drilling Fluids

Smart electrorheological fluids are fluids with fine particles dispersed in electrically insulated liquids. According to their nomenclature, their properties can be altered by the application of electric field and they are mostly characterized by changes in their rheological properties [7]. Colloid particles usually dispersed in the base fluid include metal oxides, phosphorus, silica, alumina, and polymers [51]. Meanwhile, the base fluid could be comprised of non-Newtonian fluids with low viscosity. When an electric field is absent, the fluid behaves and remains in its natural formulated state [1]. The alteration magnitude of the smart ER drilling fluid properties would generally depend on the applied electric potential. The greater the electrical energy applied, the higher the smart drilling fluid rheological properties alteration. In a smart ER fluid containing positively and negatively charged colloids, it is suggested that the increase in electric potential on the fluid results in an increasing attractive force between fine particles present in the drilling fluid system leading to several possible phenomena including particle dispersion, agglomeration, flocculation, and aggregation (Figure 4). This increasing interparticle electrochemical attractive force causes an increase in viscosity, yield point, and gel strength. Once the applied field is reverted, the fluid returns to its initial shear stress. This phenomenon becomes practical when considering the rate of penetration, cutting carrying, suspension, and hole-cleaning performance of drilling fluids.

In practice, drilling fluid gel strength and viscosity are usually a function of colloid particle wt.% concentration, electrostatic attractive/repulsive forces between particles, and temperature and pressure conditions. A highly viscous liquid would typically reduce the drill bit rate of penetration, while moderately viscous fluids would improve and facilitate rate of penetration. It is suggested that as attractive forces
between particles in the smart fluids become stronger as a result of applied electric field, viscosity and fluid loss properties of the drilling fluid can be controlled. Hence, in situ control of drilling fluid rheological properties induced by electric field can improve the rate of penetration. This leads to traditional factor (electric field) which can influence the drilling fluid rheological properties in addition to the conventional factors (solid concentration, particle size, electrostatic interactions, temperature, and pressure).

Growcock et al. [52] presented a study on the electric stability of invert-emulsion drilling fluids by inducing electric current. Based on their study, it was shown that colloidal suspensions in the invert-emulsion drilling fluid formed conductive bridges linking the two electrodes under the influence of electric field. The electric field was reported to cause no alteration to the drilling fluid chemical properties. Huang et al. [27] presented a study on the influence of applied high-voltage and high-frequency electric field on drilling fluid rheological properties. Based on their study, the application of electric current induced an interparticle dipole-dipole interaction which caused an increase in drilling fluid viscosity. This further suggests the capabilities of ER fluids to enhance cutting suspension, cutting carrying, and overall hole-cleaning efficiency. In considering the performance of smart electro rheological fluids at high-temperature conditions, Li et al. [53] presented a study on the thermogravimetric analysis of ionic liquid crystal aniline smart electrorheological fluid. The result from their study suggests high thermal stability of formulated ER fluids at temperature conditions up to 210°C, indicating that smart ER fluids possess the capability to withstand HTHP wellbore conditions. In view of this, the implementation of smart ER fluids in oil and gas well drilling becomes advantageous when overcoming field technical challenges as presented in this review.

Incorporation of density control colloids in smart ER drilling fluids could induce increased downhole counter-pressure, thereby making it advantageous when drilling abnormally pressured zones to avoid kicks and potential blowouts. Electric current induced devices could be installed in strategic drill string locations (above the drill bit for instance) to facilitate field implementation. In general, the exact amount of the electric potential will depend on the desired effect on the fluid and the formation characteristics such as in situ stress, formation pressure, and temperature. For field application, technological configuration for implementing ER fluids would be fitting multiple electrical sources or other means of imparting an electrical current to the smart drilling fluid in the drilling column. Figure 5 highlights the change in the fluids morphological behavior due to electric field application.

4. Smart Magnetorheological (MR) Drilling Fluids

Like the smart ER fluids, properties of smart MR fluids can be altered due to induced magnetic field. These kinds of fluids are comprised of base fluids with dispersed magnetic particles such as ferromagnetic nanoparticles or microparticles [29, 54–56]. Base fluid can be selected based on desired rheological properties [57]. Due to the susceptibility of dispersed magnetic particles to magnetic field, these particles form chainlike agglomerated structures in the presence of magnetic field, thereby causing increasing resistance to flow [55] (Figures 6(a), 6(b), and 6(c)). When considering the effects of magnetic field on rheological properties, the resultant yield stress exerted by the fluid is a function of the applied magnetic field [29]. According to [54], magnetic...
particles form structures/chains in fluids giving rise to an increase in viscosity due to the impact of magnetic fields (Figure 6). The strength of these chains, which is determined by the intensity of the applied field, provides an increased resistance to flow. This increased resistance exists in the form of a controllable yield stress, which has much widely been described as fluids highlighting Bingham plastic fluid behavior. In the “Field-Off” condition, the response is often approximated to that of a Newtonian fluid where the shear stress is linearly proportional to the shear rate.

In practice, drilling fluid properties are tuned at the surface and thereafter circulated into and through the wellbore. Installation of wellbore magnetic devices would facilitate the activation of smart MR drilling fluids. Estrada-Giraldo et al. [54] presented a study on the utilization of MR fluids for creating pressure drop for potential applications in zonal isolation and fluid loss control in oil and gas wells. A study which was facilitated by a fabricated concentric tube with magnets installed at strategic positions provided pressure drop control for formulated fluid which involved magnetic field susceptible carbonyl iron powders. According to their study, pressure drop was increased as a result of the duration of exposure to the magnetic field. It was suggested however that the in situ rheology change at the magnet induced location of the pipe had little effect on the pressure drop. This study suggested that exposing the drilling fluid to magnetic field for certain period of time could facilitate the reduction of fluid loss and lost circulation. Vryzas et al. [25] presented a study on the effect of custom-made Fe₃O₄ on the rheological properties of smart magnetic drilling fluid. According to their study, the fluid viscosity increased with increasing magnetic flux and shear rate displaying a shear-thinning behavior. This study suggested that the dispersed magnetic particles developed colloidal clusters which resulted in higher shear stress values on account of magnetic influx. In view of this review, the utilization of smart MR drilling fluids becomes possible in field application through the installation of magnetic and electromagnetic devices in the drill string at desired wellbore locations with possibility of influencing rheological properties and filtration control and preventing lost circulation, thereby solving wellbore technical problems. Another study in [25] on the thermal stability drilling fluid system with the incorporation of magnetic nanoparticles suggested the control of drilling fluid properties such as rheology and fluid loss at temperatures of about 121°C. Hence, based on this study, it is suggested that application of MR fluids in drilling operations can be considered for HPHT conditions.

5. Smart Viscoelastic Surfactant (VES) Fluids

Smart VES fluids are basically fluids comprised of additives with viscous and elastic behavior [58]. These are generally regarded as amphiphilic compounds with hydrophilic (containing cations and anions) and hydrophobic heads (containing hydrocarbon chains). Smart viscoelastic surfactant drilling fluids possess numerous advantages including inducing viscosity increase and reversal, emulsification, thermal stability, and shear-thinning behavior. Attractive and repulsive forces in the VES solution result in the formation of colloidal structure known as micelles [21]. This causes a change in the viscoelastic property of the formulated solution. When considering viscosity and fluid loss properties changes due to interactions between VES and other colloid particles in the base fluid, the intensity of viscosity changes is usually a result of

![Figure 6: Influence of magnetic field on smart MR fluids [54].](image-url)
increasing or decreasing ionic concentration in the base fluid. When considering the utilization of drilling fluids with hydrophobic colloidal suspension like oil-based or invert-emulsion drilling fluids, surfactants present in the VES fluids are equally capable of reducing oil-water interfacial tension to a point above the critical micelle concentration creating liquid colloidal agglomerates known as micelles. It is suggested that the reduction in interfacial tension in this case is due to the interaction between the hydrophilic head with water and hydrophobic head with the nonaqueous part, which causes stable dispersion and emulsification of the nonaqueous smart fluid system, thereby improving the drilling fluid system. Utilizing nanosmart VES fluids further enhances the effectiveness of the VES fluid due to quantum effects by the nanoparticles. Studies have suggested that incorporating viscoelastic surfactant to be thermally stable. Wu et al. [21] presented a study on smart VES fluid induced by triggering CO2, which resulted in reversible changes in the viscoelasticity of the fluid. Based on their study, triggering CO2 caused reversible changes in the viscoelastic behavior of the smart VES fluid causing changes in its rheological behavior. The changes in rheological behavior in this fluid would largely depend on the additive concentration, ionic charges, and chemical composition. Thus, when considering solving oil and gas well drilling technical challenges, smart VES fluids offer a wide range of possibilities in improving the drill bit rate of penetration, cutting suspension and carrying, and overall hole-cleaning performance. Ettehad et al. [59], in their study on the nonlinear viscoelastic behavior of bentonite/sepiolite drilling fluid, highlighted that, due to the incorporation of long chain polymers in the bentonite/sepiolite formulated drilling fluid, an increase in structural stability and thermal degradation prevention is observed making smart viscoelastic drilling fluids great candidates when considering high-temperature conditions. Besides, studies show that incorporation of long chain polymers such as HEC, PAC, and CMC can induce drilling fluid thermal stability up to 260°C [8]; therefore development of smart VES fluids provides huge potentials when considering HTHP wellbore conditions.

6. Discussion (Challenges and Future Opportunities)

According to this review, formulation of smart fluids in oil and gas well drilling has been widely based on the dispersion of nanoparticles in base fluids, thereby inducing alteration of drilling fluid properties by several mechanisms including electrostatic adsorption, adsorption bridging, intercalation, and exfoliation. The review suggests that the main reason for nanoparticle utilization is its ultratiny particle size which induces a large specific surface area when dispersed in drilling fluids. This causes higher interparticle molecular activity leading to improved properties of the drilling fluid. Based on this review, application of nanoparticles comprised of different compounds can optimize the drilling fluid rheological behavior, pore plugging performance, filtration control, and lubricity performance. When compared with the silica, iron oxide nanoparticle, and zinc oxide nanoparticles, very few studies have been carried out on the effects of novel nanoparticles such as carbon-based nanomaterials (CNT, graphene oxide nanoparticles, fullerenes) on drilling fluid performance. A reason for this could be the cost effectiveness of their utilization as opposed to other conventional additives. However, the possibility of application of carbon-based nanomaterials in drilling fluids becomes ever promising due to their distinctive properties such as thermal stability, high tensile strength, and ability to optimize rheological performance of drilling fluids. According to this review, the overall studies carried out on nanoparticles have been based on laboratory studies with very few reporting field applications. This is another challenge in nanoparticle utilization in drilling fluids in addition to cost reduction challenge.

Electrorheological and magnetorheological fluids equally highlight future potentials in oil and gas well drilling applications. This review highlights that few studies have been carried out on the influence of electric field on drilling fluid in situ performance. Studies carried out have illustrated that rheological properties such as plastic viscosity, apparent viscosity, gel strength, and yield point can sharply increase under the influence of electric current and return to their initial state when current is removed, an effect which will be mostly beneficial when considering rate of penetration, hole-cleaning, cutting suspension during tripping operations, and cutting carrying. According to this review, the application of magnetic oxide nanoparticles has been dispersed in drilling fluids to alter the fluid properties under the influence of magnetic field. However, oil and gas field application of magnetic field induced smart MR drilling fluids remains relatively unclear. A review carried out on smart magnetic fluids also suggests the ability of these kinds of fluids to alter drilling fluid rheological behavior. Like the ER fluids, utilization of smart MR fluids could equally facilitate improvements in rate of penetration, cutting carrying and suspension, and hole-cleaning performance during oil and gas well drilling operations.

A review on smart VES fluids equally highlighted the potentials of VES fluids to induce viscoelasticity in drilling fluids through the formation of micelle structures during colloidal particle interactions. The review suggests that the magnitude of viscosity changes would generally be a result of increase of decrease in ionic concentrations in base fluids. A major challenge however in the utilization of smart VES fluid is the control of viscosity behavior at high-temperature conditions during in situ drilling fluid circulation as little work on field application has been published. This has made the utilization of smart VES fluids limited in its application to hydraulic fracturing and fracture packing treatments. This review suggests that the incorporation of long chain polymers in smart VES fluids can potentially induce thermal stability of formulated drilling fluids as presented in this review. This study which focuses on four different smart fluids, smart nanoparticles, ER, MR, and VES drilling fluids, highlights the possibilities of their utilization in oil and gas well drilling. Meanwhile, there is huge potential for future applications of a wide range of smart materials with the aim of improving drilling performance.
Finally, with the current global shift towards automation and incorporation of real-time systems in drilling operations, utilization of smart drilling fluids can become highly effective in such situations. A future opportunity lies in the installation of electric and magnetic devices in drill pipes across the drilling automation systems. This not only would induce changes in drilling fluid properties through the application of electric and magnetic fields on the MR and ER fluids but also would equally facilitate real-time data acquisition and monitoring processes, which eventually translates into quick decision-making during oil and gas drilling operations.

7. Conclusions

This review article has provided analysis of four types of smart fluids (nanoparticles, electrorheological, magnetorheological, and viscoelastic surfactant smart fluids) and their impact in drilling fluids to meet oil and gas well drilling technical challenges. Based on this literature review, the following conclusions can be drawn:

(i) Utilization of nanoparticles in drilling fluids offers a wide range of possibilities due to their ability to influence drilling fluid properties. The effects of nanoparticles on drilling fluid properties are usually functions of their particle sizes, high specific surface area, and interparticle interactions. In addition, the chemical composition of the nanoparticles plays an important role in improving the properties of the drilling fluid system due to improvements in particle-particle interaction in the atomic level. According to this review, nanoparticles are capable of influencing the performance of water-based drilling fluids by performing different mechanisms which include electrostatic adsorption, intercalation, exfoliation, and adsorption bridging mechanisms. Carbon-based nanomaterials equally pose huge potentials in meeting technical challenges due to their relatively high mechanical strength, surface area, thermal stability, and tiny particle size.

(ii) Smart ER and MR fluids offer a wide range of possibilities in oil and gas well drilling operations due to their ability to influence drilling fluid rheological properties. This influence is generally a function of the intensity of applied magnetics, electric fields, and the presence of particles susceptible to electrical and magnetic fields. Utilization of smart MR and ER drilling fluids possesses the potentials of meeting technical challenges including drilling in HTHP conditions, improving rate of penetration, enhancing hole-cleaning performance, pressure drop control, and lost circulation control, and facilitating drilling automation processes.

(iii) Smart VES fluids have been reported to highly influence the rheological behavior of drilling fluids. This is greatly due to the presence of ionic charges which could result in increase or decrease in rheological properties. Their utilization would greatly improve drilling in HTHP conditions, enhance hole-cleaning performance, improve rate of penetration, and enhance cutting suspension and carrying capacity.

(iv) Utilization of smart materials in drilling fluid systems would eventually facilitate drilling automation and real-time data acquisition as the oil and gas industry experiences a global shift towards drilling automation.

Abbreviations

AV: Apparent viscosity
CMC: Carboxyl methyl cellulose
CNT: Carbon nanotube
DWCNT: Double-walled carbon nanotube
ER: Electrorheological
GS: Gel strength
HEC: Hydroxyethylcellulose
HTHP: High-temperature high-pressure
MR: Magnetorheological
MWCNT: Multiwalled carbon nanotubes
PAC: Polyanionic cellulose
PV: Plastic viscosity
SWCNT: Single-walled carbon nanotube
VES: Viscoelastic surfactant.

Conflicts of Interest

The authors declare no conflicts of interest.

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