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New drilling technologies

Applications of nanotechnology in drilling operations

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Abstract

During the last decade much attention has been drawn to the innovation and applications of nanotechnology in different drilling aspects, which is reflected through the huge amount of funds invested on the research and development and the increasing number of publications each year with respect to the nanotechnology applications. the aim of this work is to perform a comprehensive review for the applications of nanotechnology as key solution to overcome drilling challenges and makes drilling operations more efficient, less problematic and cost effective. It is summarizing different successful nanotechnology applications including drilling fluid applications, well cementing applications, drill bits and MWD and LWD applications. and the main challenges associated with the use of nanoparticles, that could be helpful for further researches.

1. Introduction

Oil and gas have been the primary source of energy over hundreds of years historically and for the time being, although more attention is being paid to alternative, sustainable sources of energy, the Oil and Gas Industry is still playing a vital rule to meet the world's energy requirements in different life sectors. with the continuous increase of oil and gas demand and continuous decrease of production of the readily exploitable resources due to oilfields maturity. oil and gas industry will face greater technical challenges in the coming decades. the need to explore more hydrocarbon reserves would require drilling more wells in unconventional and deep formations, harsh or remote locations and the developing of challenging reservoirs that previously were not economic to produce. that means more exploration expenses associated with more difficult and problematic drilling and production operations.

As the hydrocarbon exploration and extraction activities moves further deep in the earth crust the drilling challenges and associated risks prevails with complex drilling hazards that are not usually encountered in onshore and shallow drilling operations

So the industry needs technological innovations to enhance and optimize the drilling operations to successfully meet the energy challenge. only a small amount of success has been achieved in solving these problems by use of conventional macro and micro materials.[1]

Nanotechnology is a General-Purpose Technology (GPT) that can fulfill the needs of humanity in every industry sector, it has had a revolutionary impact in many industries, from healthcare to aeronautics, With the increased attention toward nanotechnology and their innovative use for different industries, the application of nanotechnology in the oil and gas industry is a subject undergoing intense study by major oil companies, which is reflected through the huge amount of funds invested on the research and development, with respect to the nanotechnology. Nanotechnology has been recently investigated extensively for different applications in the oil and gas industry such as drilling fluids and enhanced oil recovery in addition to other applications including cementing and well stimulation.[2], [3]

With this great attention for the application of nanotechnology in oil and gas industry, which is obvious from the increasing number of publications concerning this subject each year during the last decade. (Fig. 1), it is necessary to review and summarize the available application and the work that has been done up to date.

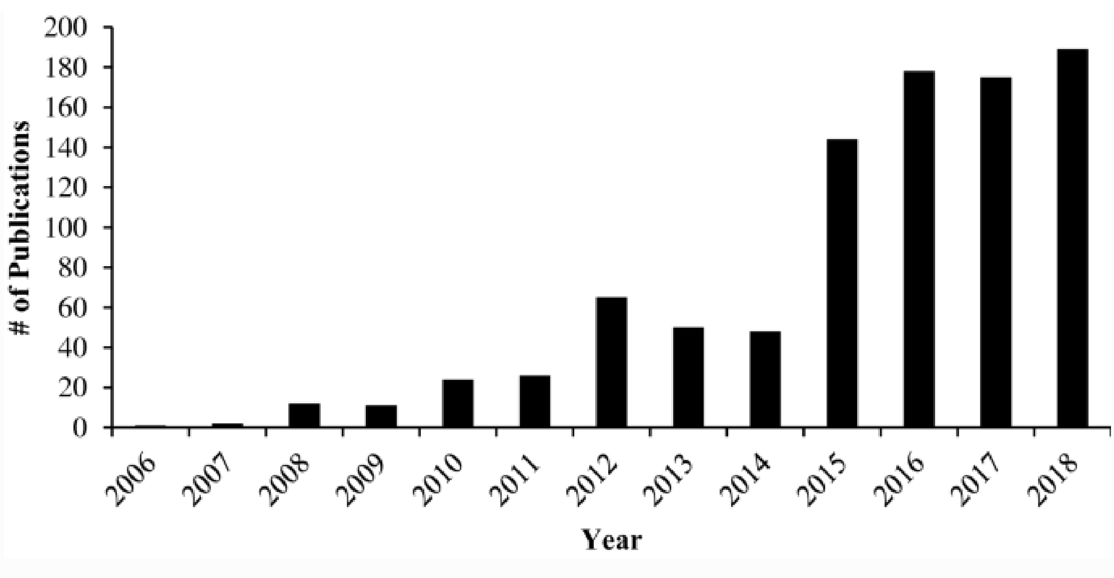

Fig. 1: Nanotechnology oil and gas applications Number of publications per year

This work concentrates on the nanotechnology applications in oil and gas drilling operations, a comprehensive literature review was conducted for the applications of nanotechnology in different drilling operations including drilling fluid applications, well cementing applications, drilling bits, MWD and LWD applications. And summarizing all nanoparticles that have been used and their rule in overcoming drilling problems through improving targeted parameters along with the associated challenges for nanotechnology applications.

But,

Before we go through the applications of nanotechnology. it's important to know what the nanotechnology is? and what makes nanoparticles more efficient than macro or even microparticles?

Nanoparticles are substances with dimensions in the order of 1–100 nm (nm). Over years, many researches proved that the transition from micro scale particles to nano scale particles will bring about a revolution in many industries. the wide applications of nanoparticles resulted in a new field of technology that deals with the design, characterization, production and application of materials and devices based on nanometer scale. Which is the nanotechnology [5].

Nanoparticles possess unique magnetic, electrical, thermal and optical properties due to their small size and greater surface area per unit volume (Fig. 2), they show a higher magnitude of reactivity or interaction with other molecules, higher adsorption potential and higher heat conductivity.

Fig. 3 shows a comparison of the surface area to volume ratio of spherical particles of the same material with radius of 1 mm (mm), 1 µm, and 1 nm, It is clearly indicating that more than a millionfold increase in surface area per unit volume will be obtained by converting a particle from a millimeter scale to nano-sized particles[6].

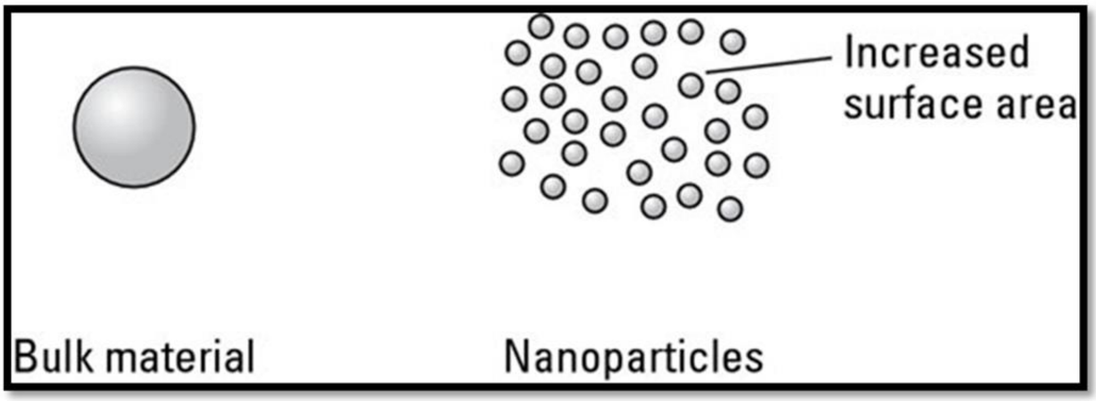

Fig.2: Increasing the surface area with nanoparticles.

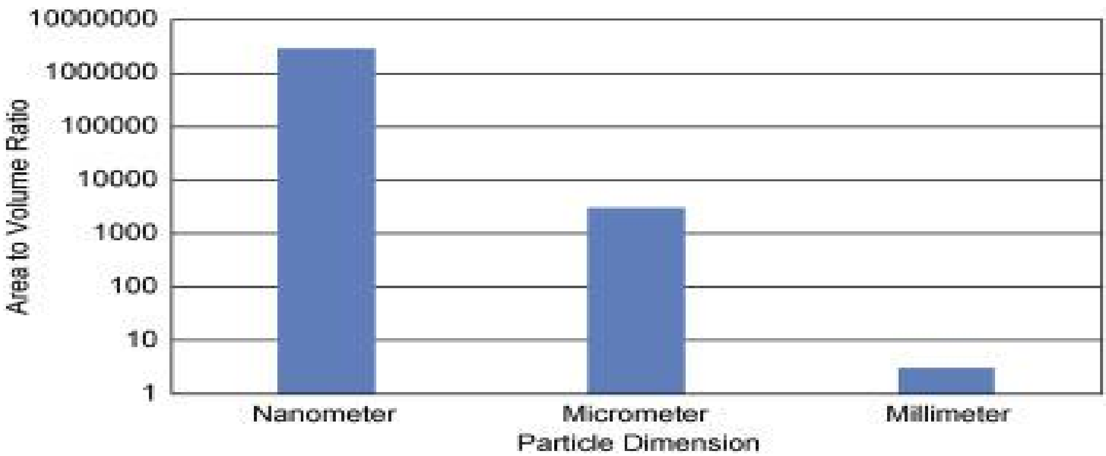

Fig. 3: Surface area to volume ratio of the same volume of materials.

Materials that have nanoparticles embedded in their structures are termed nanomaterials. Most of the qualities of the nanoparticles are inherited by these materials, and that explains the enhancement in their properties. The nanoparticles are knitted into the structure of materials and bring about reinforcement. In conventional materials, the atoms are located in the interior of the particles; but, for a typical nanomaterial, most of the atoms are located on the surface of the particles. Reactions that produce superb chemical, optical, mechanical, electrical, thermal, magnetic properties etc., occur in nanomaterials [7]. These properties attract great attention for the applications of nanotechnology to overcome challenges encountered during different drilling operations in deep and unconventional environment where macro and micro materials fail to fulfil the required functions.

Fig.4 shows the percentage of the conducted investigations of nanoparticles across the oil and gas industry, as we can see from the chart more than 50% of nanotechnology applications in the oil and gas industry related to drilling operations "drilling fluid and well cementing applications".[8] Now will go through deep investigation for nanotechnology application in different drilling operations.

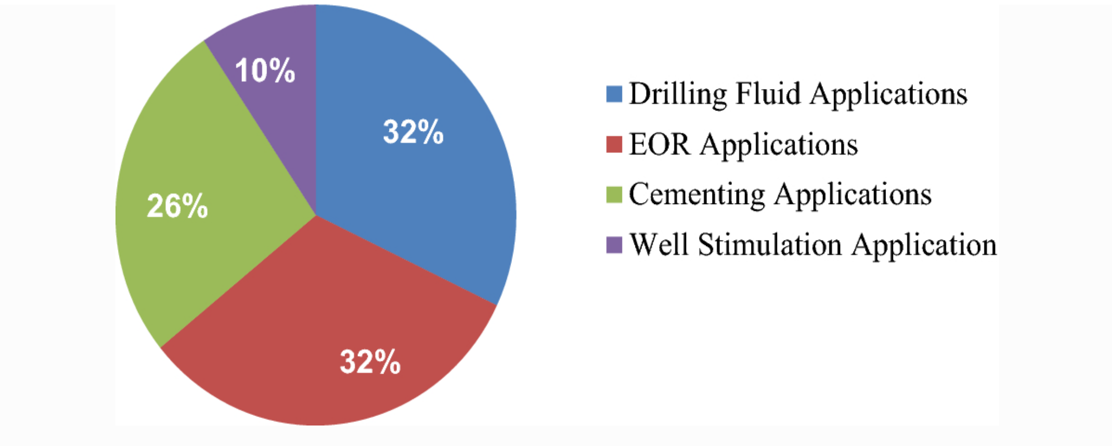

Fig. 4: Percentage of the conducted investigations of nanoparticles in the oil and gas industry

2: Nanotechnology applications in drilling fluids.

A drilling fluid is defined as a pre- designed fluid which is circulated through a well in order to perform certain functions which can be achieved through the suitable choice of mud type and continuous maintenance of the mud properties using the right additives [10].

The drilling fluids are critical in the oil and gas drilling operations. To reach the target formations in the well, the drilling fluid program should be designed carefully to safely drill the well with economical wise. Drilling fluids cost is considered to share a portion of around 25–40% of the total drilling operations cost [11]. Some problems that occur during the drilling operations such as mud losses will add more cost to the total drilling cost. Several factors affect the ratio of the drilling fluid cost to the total drilling cost, such as well location, drilled formation type, and other technical problems that might be encountered during the drilling operations [12]. Un properly designed drilling fluid often contributes to the failure of the drilling operations Thus, it is essential to condition drilling fluid properties in accordance with the wellbore environment.[13]

2.1 Main functions for drilling fluids:

The drilling fluids should be properly synthesized to perform efficiently during the drilling operation and modifiable according to the formation to be drilled. The drilling fluid performs a number of functions, these functions are: [14]

1-Hole cleaning:

The most basic function of drilling fluid is to transfer cuttings to surface. To achieve this function, the fluid should have adequate suspension properties to help ensure that cuttings and commercially added solids, such as barite weighing material, do not settle during static intervals.

2- Prevent well-control issues

Under normal drilling conditions the hydrostatic pressure exerted by column of drilling fluid on the wellbore must exceed the natural formation pressure by maintaining safe margin to help prevent the influx of formation fluids into wellbore "kicks" or "blowouts." But if the density of the fluid becomes too heavy, the formation can break down causing drilling loss into the resultant fractures, a reduction of hydrostatic pressure occurs that leads to pressure reduction and influx of formation fluids into the well. Therefore, maintaining appropriate fluid density for the wellbore pressure regime is critical to safety and wellbore stability.

3- Preserve wellbore stability

Maintaining the optimal drilling-fluid density not only helps contain formation pressures, but also helps prevent hole collapse and shale destabilization. The wellbore should be free of obstructions and tight spots, so that the drill string can be moved freely in and out of the hole (tripping).

4- Cool and lubricate the bit and drill string

Drilling action requires mechanical energy in form of weight on bit, rotation and hydraulic energy. A large part of energy dissipated as heat that must be removed to allow drilling. The circulation of drilling fluid through the drill string and up the wellbore annular space helps reduce friction and cool the drill string.

5- Minimize formation damage

The invasion of drilling fluid filtrate with fine solids and chemicals contained in the drilling fluid into the producing formations can cause formation damage, this damage can be minimized with careful fluid design based on tests performed on cored samples from the formation of interest.

6- Provide information about the wellbore

Because drilling fluid is in contact with the wellbore, it reveals substantial information about the formations being drilled, and serves as a conduit for much data collected downhole by tools located on the drill string and through wireline-logging operations performed when the drill string is out of the hole. An optimized drilling-fluid can enhance the quality of the data transmitted by downhole measurement and logging tools as well as by wireline tools.

7-Minimize risk to personnel, the environment, and drilling equipment

Drilling fluids require daily testing, and continuous monitoring by specially trained personnel. The safety hazards associated with handling of any type of fluid are clearly indicated in the fluid's documentation. Drilling fluids also are closely scrutinized by worldwide regulatory agencies to help ensure that the formulations in use comply with regulations established to protect both natural and human communities where drilling takes place.

2.2 Drilling fluid types and selection criteria

Drilling fluids can be classified into four types base fluids. all types are used in variable situations and with different additives. Galal, M. [15] stated that the correctly selected and engineered drilling fluid plays a significant role in delivering a high quality wellbore. This only can be achieved by an appropriately designed drilling fluid that must be tailored to satisfy many diverse parameters. The four drilling fluid types are [16]:

1- Water based mud.
2- Oil base fluids.
3- Synthetic base fluids.
4- Pneumatic or Compressible Fluids.

Previous research on drilling mud concludes that oil-based mud is the best drilling fluid but is not recommended because it is unsustainable and environmentally unfriendly. Water-based drilling fluids account for 80% of the total drilling operation carried out due to their environment friendly nature and they are highly cost effective as compared to the synthetic or oil-based drilling fluids. Therefore, research has been conducted on additives that can be used for water-based mud, making it equal or even superior in quality to oil-based mud. Since the drilling operations are carried out at higher costs so the selection of the drilling fluid should be made carefully considering all the following factors:

1. The location and the type of formation which is to be drilled.
2. The variation in the pressure and temperature of the wellbore.
3. The nature of the formation fluids i.e. strength, porosity and permeability.
4. Production factors, environmental factors and safety are the other important factors which are also considered while making the selection of the drilling fluids.[17]

2.3 Drilling fluid characteristics

Once the type of drilling fluid is selected using the above considerations, the drilling fluid characteristics should be designed. These characteristics could be listed as follows [18]:

1. **Drilling Fluid Density or Mud weight:**

   Mud weight or mass per unit volume depend on solids in the liquid either in solution or suspended. It increases by adding solid materials and decreased by adding water or oil or aerating the liquid. Mud weight is measured by mud balance and expressed in ppg, pcf or kg/m3.

2. **Rheological properties:**

   Mud Rheological properties include plastic viscosity, yield point and gel strength.

   2.1. Plastic Viscosity (PV):

   Plastic viscosity of the drilling fluid controls the magnitude of shear stress develops as one layer of fluid slides over another. It measures the friction between layers and provides a scale of the fluid thickness. Plastic viscosity decreases with increasing temperature. Plastic viscosity and yield point are measured by Viscometer.

   2.2. Yield point:

   Yield point is a measure of the attractive forces between particles due to positive and negative charges. It measures the forces causes mud to gel in case of motionless. It shows a minimum level of stress must be provided before mud flow and is expressed in lb/100ft2.

   2.3. Gel strength:

   Gel strength is the ability of mud to develop gel structure. It defines the ability of mud to held solids and measure thixotropy it is measured by using viscometer and is expressed in lb/100 ft2.

3. **Fluid Filtration Properties:**

   Drilling fluid loss against porous and permeable rock is called filter loss occurs when mud pressure is higher than formation pressure causing the formation of a layer of solids deposited on the rock is described as filter cake. The quantity of mud loss depends on volume of filtrate and thickness and strength of filter cake. Ideal mud gives small filter loss and thin and tough mud cake and differential pressure. It is measured by using filter press.

4. **Chemical Properties:**

   PH of mud describes the acidity or alkalinity of the mud. It is measured by pH meter or strips. pH value Plays a major role in controlling calcium stability. A minimum value of 7 should be maintained to control corrosion.

2.4 Conventional drilling fluid additives

The drilling fluid characteristics should be properly synthesized to perform efficiently during the drilling operation and modifiable according to the formation to be drilled through adding different additives to the base fluid. That are used to develop the key properties of the drilling fluids. These additives can be classified as [19]:

1) Reactive Solids are added to provide viscosity and yield strength.
2) Inert Solids include low gravity and high gravity are added to adjust mud weight.
3) Chemical Additives divided into thinners and thickeners are used to control mud properties.

The most common types of additives used in water base and oil base muds are [20]:

1. Weighting Materials, such as (Barite, Illmenite, Calcium Carbonate, and Siderite).
2. Viscosifiers, such as (CMC, HEC, Xanthan gum).
3. Filtration Control Materials (PAC and CMC).
4. Rheology Control Materials (Thinners).
5. Alkalinity and pH Control Materials (NaOH, KOH, Ca (OH)2, NaHCO3 and Mg(OH)2).
6. Lost Circulation Control Materials (Flakes (mica and cellophane), Granular (nutshells, calcium carbonate and salt), and Fibrous (glass fiber, wood fiber and animal fiber).

7. Lubricating Materials (oil (diesel, mineral, animal, or vegetable oils), surfactants, graphite, asphalt, gilsonite, polymer and glass beads.
8. Shale Stabilizing Materials (high molecular weight polymers, hydrocarbons, potassium and calcium salts (e.g. KCl) and glycols).[21]

2.5. Conventional drilling fluid limitations

As the hydrocarbons exploration and extraction activities moves further deep down the Earth's crust, the challenges and risks involved prevails associated with complex drilling hazards usually not encountered in onshore and shallow drilling. That makes great challenges for conventional drilling fluids and resulted in may drilling problems can be summarized as follows:[22]

1. High Pressure - High Temperature (HPHT) Environment.

As the depth of drilling increased, more severe drilling conditions are expected where deep wells are mostly associated with HPHT environment which may exceed temperature of 600°F (315°C) and pressure as high as 40,000 psi [23]. In a HPHT environment the ability of drilling equipment, tools and materials to perform optimally is jeopardized that will affect the efficiency of the drilling. More critically, the efficiency of the drilling fluid properties will be severely impacted due to the extreme temperature and pressure where the rheological properties of the drilling fluid especially the polymer-based additives which will degrade under high temperature. When drilling fluids destabilize, it will cause various drilling, logging and completion issues which may eventually lead to kicks or even blowout. With conventional invert emulsion fluids, the major challenges encountered under HPHT environment are related to the thermal degradation of emulsifiers and fluid-loss reducer that can lead to gelation and loss of rheological properties that can cause weighting material sagging, and other associated well control problems. Fig-2 shows the effect of HTHP on the rheology of a conventional invert emulsion fluids. The highlighted area shows the impact on rheology after 60 minutes at temperatures above 400°F (204°C) [24]

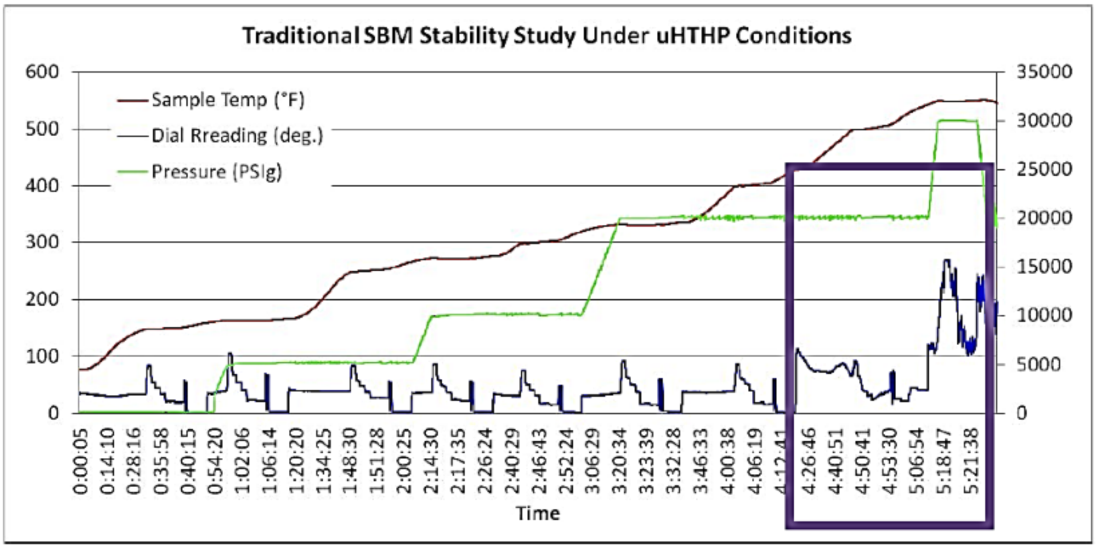

Fig.5. Effect of temperature and pressure on the rheology of a conventional invert fluid.

2. Well Formation Instability

The instability of the well formation is another major challenge need to be faced in deep well drilling operations. Formation instability such as caving, sloughing and collapsing are some of the examples frequently faced especially while drilling through shale formations. They happen mostly due to the hydration of the shale formations or by formation geo-mechanical failure due to the in-situ formation pressure anomalies. In many deep well cases, both factors co-exist and effective simultaneously, hence, may cause the shale formation to swell and cause geo-mechanical failures. These may result in the slough of the shale formation which may lead to other drilling problems (stuck pipe and etc). The hydration of the formation caused by fluid invasion, can generally be minimized by the formulation of a proper fluid chemistry – adding appropriate additives (shale hydration inhibitors) such as bentonite into the drilling fluid. Hence, it is important to have a robust drilling fluid with the ability to prevent excessive fluid invasion into the formation while strengthening the mechanical strength of the formation.

3. Narrow Drilling Tolerance Window (DTW)

The hydrostatic pressure exerted by the drilling fluid in normal drilling conditions must be higher than the pressure of the formation to avoid kicks and / or blowouts but also must be lower than the fracture pressure of the formation. DTW is the range or difference between pore pressure and fracture gradient where the drilling operations can safely operate in without the risk of kicks or blowout. drilling in conditions of wide DTW provides a certain extent of safety and flexibility for formulating drilling fluid suitable for different pressure zones. But when DTW becomes narrower, especially in deep well environment, the formulation of drilling fluid to cater for the different pressure zones becomes trickier. Narrow DTW environment increases the complexity of the drilling activities.

4. Fluid Circulation Loss:

Typical overbalance drilling conditions cause invasion for drilling fluid filtrates and associated drilling fluids into the formation to a particular extent especially in the highly porous and permeable zones and naturally fractured zones. Fluid circulation loss may lead to well control issues and may even results in potential kicks and blowouts which will bring adverse impacts to the environment and personnel. To minimize the fluid loss with conventional drilling fluids plugging materials such as bentonite to perform mud cakes to avoid fluid loss. But too thick mud cake, it impedes the movement of the drill strings; making it stuck. This is often called differential sticking.

5. Differential Sticking

Differential sticking occurs when the drill string is “sucked” up against the formation due to the pressure difference between the wellbore and the formation. This normally occurs at permeable zones where the mud cake is formed (Fig.6). Thick mud-cake may increase the possibility of differential sticking during drilling operations. Hence, it is vital that the mud cake formed by the drilling fluid is kept at a minimum thickness while maintaining its effectiveness in preventing or minimizing fluid loss.

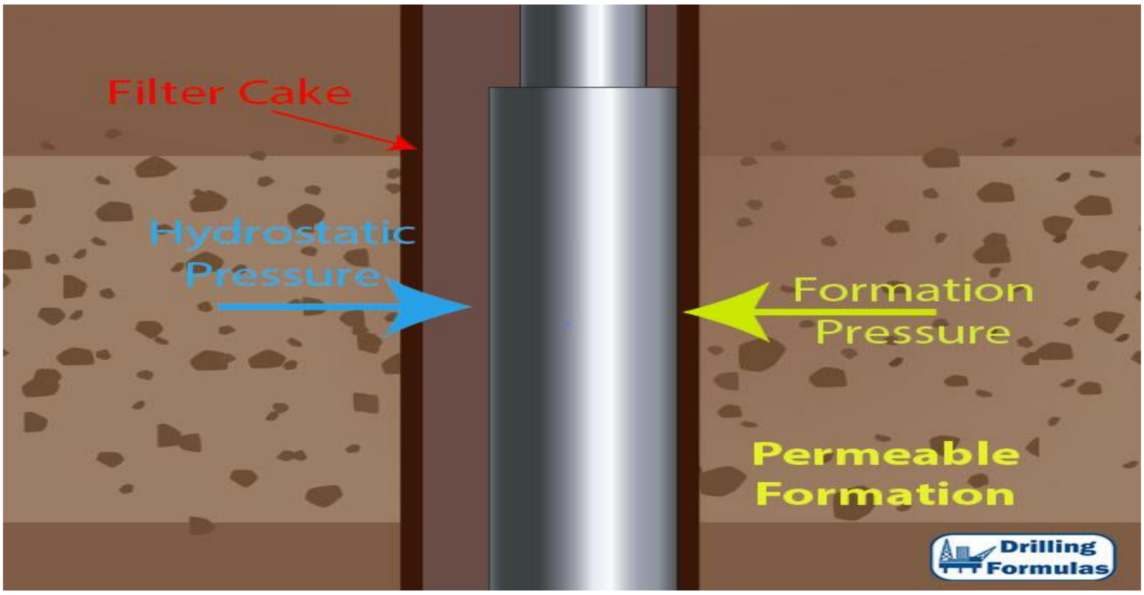

Fig.6: *Differential Sticking against permeable formation*

2.6 Nano based drilling fluids applications:

There are different limitations that are faced when designing drilling fluids using conventional additives such as the temperature and the additives particle size limitations. Therefore, nanoparticles were investigated extensively to study their applicability in overcoming these limitations.

Nanotechnology-based drilling products have demonstrated their unique characteristics such as huge surface area, high thermal conductivity, and pollution resistance. Nanomaterials are expected to show excellent fluid properties with very low concentration in fluid systems. They are regarded as the most promising materials to develop highly efficient and economic new generation of smart drilling fluids.

This generation of drilling fluids must possess enhanced rheological properties to form high-quality mud cake, improve the wellbore stability, provide advantages like wettability alteration, advanced drag reduction and sand consolidation along with superior thermal and filtration control properties and high anti-pollution power that meet complicated requirements during drilling. Hence, Nano-base drilling fluid is recommended in the application of current and future high-temperature high-pressure (HTHP) drilling operations, unconventional drilling conditions, and deep-water drilling operations. The use of Nano-base drilling fluid in such drilling conditions results in:

1. Increasing drilling fluid stability in HPHT Environment

The stability of additives in HPHT conditions is often the determinant for the drilling fluids to be able to fulfill the expected functional tasks as temperature above 200°C and downhole pressure of 20,000 psi and above are very common in deep water wells. In fact, when temperature exceeds 400°F (204°C), the stable additive options are almost nonexistent for both water based and non-aqueous based fluids [25]. The extremely high surface area to volume ratio of nanoparticles leads to a more effective interaction between the nanoparticles surfaces with external and internal rock surfaces and enhance the thermal conductivity of nano-fluids, which in turn enhances the efficiency of the cooling system. Hence, the nanoparticles, with their excellent thermal conductivity are deemed to be the most suitable materials of choice for application in such environment [26].

Experimental study on OBM with nanomaterials added as replacement of the conventional polymer-based additives and the fluid formulation was subjected to high temperature (175°C) aging for up to 96 hours. The rheological properties measured showed that the nano-fluid formulation maintained the desirable properties after aging and exposure to high temperature [27].

2. Controlling Fluid Circulation Loss & Minimizing Formation Damage

The prevention of circulation and filtrate loss by current drilling fluid with conventional lost circulation materials showed limited success. However, due to the extremely small size of the nanoparticles, they can provide effective sealing effect in the porous and permeable zones, fractured and cavernous formations. Nanoparticles can access the smallest pores and pore throats in the matrix and act as sealing agents in all lithology types including even shales.[28]

3. Increasing wellbore stability & overcoming NDW challenges

Previous experience and drilling data reveal that various drilling problems arise while drilling unconsolidated formations using the conventional macro or even micro-material-based drilling fluid. These fluid formulations are often not able to prevent sanding, hole collapse, washout, fracturing problems due to their inability to generate effective inter-particle cohesion and cementation to strengthen near wellbore formation. Due to the ultra-fine size, nanomaterials are able to access the pores and the inter-granular contact surfaces of the unconsolidated sand particles. Hence, nanomaterials with gluing and cementing properties are expected to form bonded networks of particles within the formation matrix creating an integrated ring of rock mass around the wellbore wall [26].

4. Minimizing differential Sticking possibilities

Since the presence of thick mud cake may increase the likelihood of differential sticking during drilling operations, it is important to produce a thin and low sticking mud cake on the wellbore wall in preventing pipe sticking problems [26]. Nanofluids has proven to possess the ability to produce thin, non-erodible, impermeable mud cake that are effective in preventing fluid loss. In addition, nano-fluids would be able to reduce the adhesive tendency of mud cake by forming another thin non-adhesive nano-film on the drill pipe surface. This would help to decrease the likelihood of stuck pipe to occur. Due to the extremely small particle size, the nanoparticles added into the formulation of nano-fluids can easily enter the pipe-mud cake interface to form an effective lubricating film, isolate the mud cakes or even destroy the mud cake for an effective de-bonding of the pipe from the mud cake surface. This demonstrates the potential of nanomaterials application in the formulation of both drilling and spotting fluids to address the pipe sticking problems. Therefore, in curbing the stuck pipe problems, [29].

5. Reducing torque and drag problems and increases rate of penetration

The application of nanoparticles in the drilling fluid would be able to form a continuous layer of a very thin film on the surface of wellbore surfaces, mud cake and even on the surface of the drill pipes. This characteristic of nano-fluids would be able to provide enough lubricating features, minimize the frictional resistance between the drill pipes and the wellbore surfaces, minimize the torque and drag problems and hence improve the overall ROP.

On the other side solid contents of in the drilling fluid is one of the factors that reduces the ROP. Hence, it is important to keep the amount of solid contents in the fluid at a minimum required level [30]. Due to high surface area to volume ratio of nanoparticles less solid content is required to achieve certain derailing fluid characteristics in case of using nano based drilling compared to conventional drilling fluid as indicated by excremental results in Fig.8 [64]. The unweighted nano-based drilling fluid could be the ideal candidate to drill hard rock formations to enhance the rate of penetration.

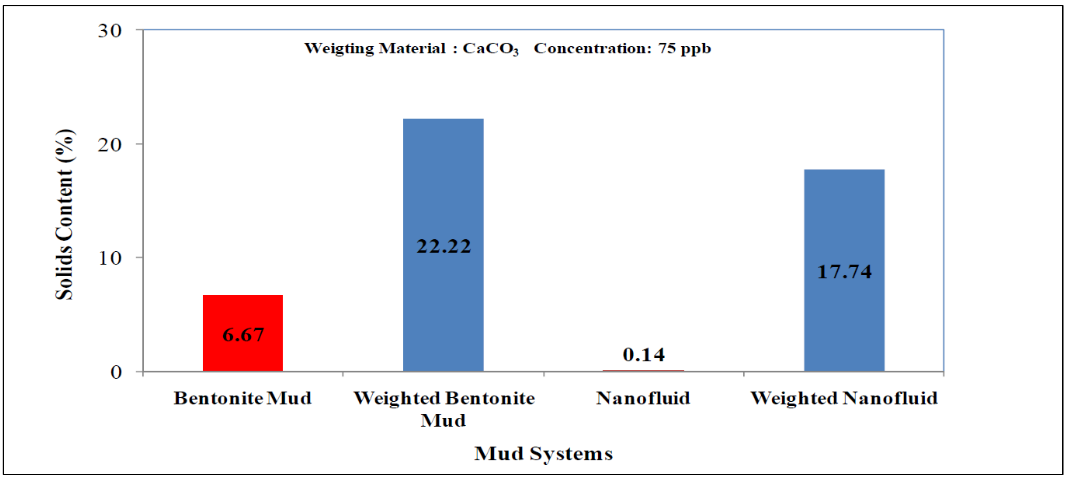

Fig.7 Solid content Comparison of bentonite based and nano based drilling fluids

6. Minimizing bit balling problems:

The progressive sticking and accumulation of shale on the bit tooth gaps and the tooth surfaces can turn the drill bit into a ball-like structure which would drastically reduce the ROP and the drilling efficiencies [31]. This could lead to a significant increase in the total drilling cost should the operations need to be stopped to clean or change the drill bit. Hence, nano-fluid formulation containing a combination of inhibitive and hydrophobic film forming nanomaterials can eliminate and minimize the bit balling problems and could potentially lead to cost saving measures.

7. Decreasing the environmental impact of drilling fluids:

The use of nanoparticles decreases the environmental impact of drilling fluids due to decease of the required amount of additives to achieve certain drilling fluid properties compare to conventional additives (typically less than 1% concentration) in the fluid formulation. Hence, nano-fluids could be the fluid of choice in conducting drilling operations in sensitive environments [22].

8. Removal of Toxic Gases:

Hydrogen sulfide is a very dangerous, toxic and corrosive gas. It can diffuse into drilling fluid from formations during drilling of gas and oil wells. Hydrogen sulfide should be removed from the mud to reduce the environmental pollution, protect the health of drilling workers and prevent corrosion of pipelines and equipment. Sayyadnejad et al., 2008 [32], used 14-25 nm zinc oxide particles size and 44-56 m2/g specific surface area to remove hydrogen sulfide from water-based drilling fluid according to the following chemical reaction.

$$(ZnO + H2S \rightarrow ZnS + H2O)$$

The efficiency of these nanoparticles in the removal of hydrogen sulfide from drilling mud was evaluated and compared with that of bulk zinc oxide. Their results demonstrated that synthesized zinc oxide nanoparticles are completely able to remove hydrogen sulfide from water-based drilling mud in about 15 min., whereas bulk zinc oxide is able to remove 2.5% of hydrogen sulfide in as long as 90 min. under the same operating conditions.[33]

9. Increase down hole tools life:

The down hole tools and equipment are always exposed to abrasive forces due to high kinetic energy associated with the particles present naturally in the subsurface formations and the drill solids added to the drilling fluid system for specific functions. These forces cause the wear and the tear for most of the down hole equipment, especially in deviated and horizontal wells where the tools are more exposed to these abrasive forces.

Because of their extremely small size, nanoparticles are preferred to be used in drilling fluid design as their abrasive forces are negligible with less kinetic energy impact. In addition to all advantages of using nanoparticle in mud design, it is safer than conventional mud from the point of environmental view. The nanoparticles are added to mud in small amount, with low concentration about 1%. So, Nano-based drilling fluids could be the fluid of choice in conducting drilling operations in sensitive environments to protect other natural resources [30].

10. Preventing of flushing drill

Drilling mud containing nanoparticles because of their ability to form a hydrophobic film on the head of drill and sustainable levels are able to fully prevent of flushing drill and sustainable levels [33].

2.7. Nano drilling fluid additives

Due to the small size of nanoparticles, is preferred to be used them in drilling mud. Because of the friction forces of these nanoparticles is negligible and have lower motor power efficiency. Moreover, from an environmental standpoint, the use of nanoparticles in drilling mud is better than conventional additives. Because nanoparticles at low amounts and low concentrations are added as a percent [33]. In this section a few examples of nano-additives to be expressed along with their effects for improving drilling fluid properties:[28]

1. Nano metal oxide

Nanoparticles of metal oxides are one type of nanoparticles that widely used as drilling mud additives Nanoparticles to improving the mechanical and rheological properties of drilling mud, preventing of mixing mud and shale, reducing the permeability of the filter cake , reducing fluid loss, maintaining mud properties at High temperature-High pressure, improving the electrical properties of mud, increasing the wellbore stability and also is used as a lubricant.

2. Nano zinc oxide

Adding zinc oxide nanoparticles in drilling mud causes that during a chemical reaction, all of the hydrogen sulfide gas, which is highly toxic and corrosive gas and have a negative and harmful effects on drilling process, removed of mud. The use of these nanoparticles improved the mechanical and rheological properties of drilling mud, reducing the permeability of the filter cake, increasing well bore stability and reducing fluid loss in condition of High Pressure-High temperature.

3. Nano-iron oxide (III)

The use of nano-iron oxide (III) as add to mud torque and drag forces is reduced. The high-pressure high temperature conditions also nano additives used to reduce fluid loss. Add this nanoparticle to enhance sustainability goals wells, mechanical and rheological properties of drilling mud and filter cake permeability is also reduced.

4. Nano Silica

Nano silica of the most widely used in the drilling mud. Silica nanoparticles can have different effects on drilling mud such as reducing fluid loss, improving the stability of the well (to reduce formation damage), as well as maintaining high-temperature properties of drilling mud under high pressure.

5. Carbon nanostructure

Another nano additive that most widely used in drilling mud is carbon nanostructures. These nanostructures applied to improve the heat transfer coefficient, rheological properties and muds sustainability, improve the electrical properties of mud, increase fluid weight, reduce fluid loss, reduce corrosion of drilling equipment and protection of rheological properties of drilling mud at high temperature [34]. In following are two common types of carbon nanostructures is introduced:

5.1. Graphene

Graphene is a type of nanostructures that is used in drilling mud for reducing fluid loss, increasing the stability of wells, reducing torque and drag, improving electrical properties and improving dielectric constant of drilling mud, improving the rheological properties of the fluid and increasing the stability of drilling mud [33,34].

5.2. Carbon nanotubes

By adding carbon nanotubes to drilling mud meanwhile, reduce fluid loss, can control the weight of the mud. Moreover, can be used of these nanostructures in drilling mud in high-pressure high temperature condition. Other benefit of these nanotubes is including increase the stability of wells, reduce of flushing drill and decrease the torque and drag forces can be mentioned [33,34].

6. Nano-Iron hydroxide

Iron hydroxide nanoparticles can be used to drilling mud for reducing fluid loss and increasing the stability of the well.

7. Nano Emulsions

Nano emulsions are used in drilling mud to reducing fluid loss, decreasing formation torque and drag forces [35].

8. Nano Polymers

Different kinds of nano polymers for improving the rheological properties of drilling mud is used in drilling mud. In other words, nano-polymers are one of the most widely nano structures that used in drilling mud. Some of these nano polymers are including poly methyl methacrylate, hydroxyethyl methacrylate and nano-cellulose fibers [33,35].

9. Boehmite nanoparticles

Boehmite a stable quasi phases of aluminum oxide by simultaneously links of Hydroxide and oxide. Boehmite with hydroxyl functional groups of active and functional nanostructures in the surface. The use of Boehmite nanoparticles reduces fluid loss. Quality of mud cake that created by the combination of Boehmite nanoparticles and biopolymer is better and thinner than the quality of mud cake that produced by polymer [36].

A summary of Promising nanoparticle applications in drilling fluids is shown in Fig.8 [77] and table.1 summarizes the recent researches and investigations for the applications of different nanoparticles to improve the drilling fluid parameters [4].

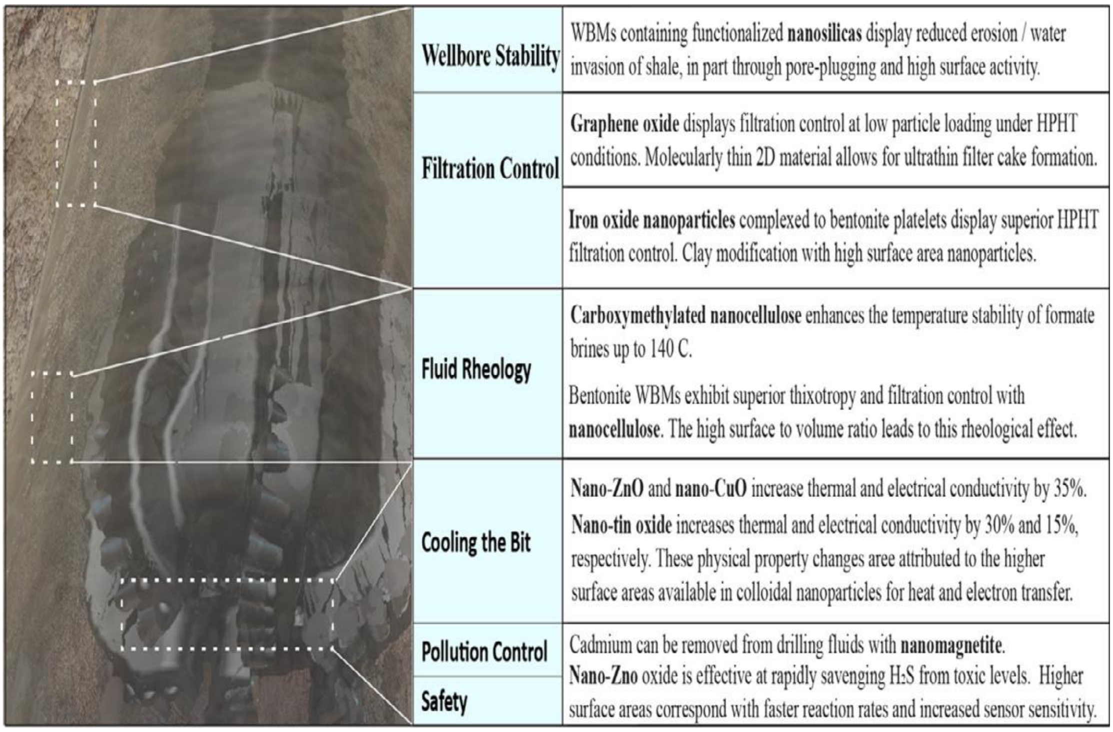

Fig.8 Promising nanoparticle applications in drilling fluids

Table.1 Summary of application of nanoparticles for drilling fluids.

Investigated NP	Improved parameters	References
Aluminum oxide Copper oxide Magnesium oxide	Improving rheological properties Improving filtration characteristics	Alsaba et al. (2018)
Copper oxide	Plug nanopores in shale Improving hole stability	Kumar et al. (2018)
CNT–polymer nanocomposite	Improving rheological properties Improving wellbore stability Improving filtration characteristics for HPHT drilling application	Hafiz et al. (2018)
Iron oxide	Improving filtration characteristics	Mahmoud et al. (2018)
Iron oxide	Improving lubricity of drilling fluids Improving filtration characteristics	Alvi et al. (2018)
Iron oxide	Improving filtration characteristics at high temperature	Barry et al. (2015)
Multiwall carbon nanotube (MWCNT) Zinc oxide Silicon dioxide	Improving heat transfer Improving rheological properties	Hassani et al. (2016)
Multiwall carbon nanotube (MWCNT) Silicon dioxide	Improving lubricity of drilling fluids Improving rheological properties Improving filtration characteristics	Ismail et al. (2016)
Nanoclay	Improving filtration characteristics Reducing electrical resistivity	Vipulanandan et al. (2018b)
Nanoclay	Improving rheological properties for synthetic-based drilling fluids Reducing electrical resistivity	Pan et al. (2018)
Nanopolymer	Improving filtration characteristics Wellbore strengthening application	Xu et al. (2013)
Non-modified silica nanoparticles Sulfonated nanoparticles	Improving sealing of pores Improving wellbore stability for shale formation	Wang et al. (2018)
Silicon dioxide	Improving rheological properties Improving hole cleaning	Gbadamosi et al. (2018)
Silicon dioxide	Improving shale inhibition Mitigating pore pressure transmission Improving wellbore stability	Yang et al. (2017)
Titanium oxide	Improving rheological properties Improving thermal and electrical conductivity Improving filtration characteristics	Parizad et al. (2018)
Titanium oxide Silicon dioxide Aluminum oxide	Improving rheological properties Improve hole cleaning	Minakov et al. (2018)
Zinc titanate	Improving rheological properties Improving thermal stability Improving filtration characteristics	Perween et al. (2018)

3: Nanotechnology applications in well cementing.

3.1 Well cementing definition and main functions

Oil well cementing is the process of placing cement slurry to fill the annulus space between the casing and the formation (Nelson and Guillot, 2006). The economic longevity of a producing oil and gas well is directly linked to the quality of the cementing job, and without complete isolation in the wellbore, the well may never reach its full production potential (Nelson and Guillot, 2006). [37] The main Functions of cement can be summarized as follows [38,39]:

1. Provision of mechanical support of the casing string.
2. Provide zonal isolation of the formations which have been penetrated by the wellbore.
3. Prevent corrosion of the casing by formation fluids.
4. Support of the well-bore walls to prevent collapse of formations
5. Cement job is also used to close an abandoned portion of the well.
6. Confines abnormal pore pressure and increases the possibility to hit the target.

3.2. Cement API classes:

According to drilled formation depth, bottom hole pressure and temperature and drilling conditions such as the presence of gases and corrosive fluids there are nine API classes of cement:[40]

Class A

• Depth surface – 6000 ft (1830 m).

• No special properties.

• Similar to ASTM C 150,Type I.

Class B

• Depth surface – 6000 ft (1830 m).

• Moderate to high sulphate resistance.

• Similar to ASTM C 150 Types II.

Class C

• Depth surface – 6000 ft (1830 m).

• High early strength.

• Moderate to high sulphate resistance.

• Similar to ASTM C 150 Types III.

Class D

• Depth from 6000 ft – 10,000 ft (1830 m – 3050 m).

• Moderate and high sulphate resistance.

• Moderately high pressure and temperature.

Class E

• Depth from 10,000 ft – 14,000 ft (3050 m – 4270 m).

• Moderate and high sulphate resistance.

• High pressure and temperature.

Class F

• Depth from 10,000 ft – 16,000 ft (3050 m – 4270 m).

• Moderate to high sulphate resistance.

• Extremely high pressure and temperature.

Class G

• Depth surface – 8000 ft (2440 m), as basic cement, fine.

• Can be used with accelerators and retarders for other specifications.

• Moderate to high sulphate resistance.

• No addition other than calcium sulphate or water.

Class H

• Depth surface – 8000 ft (2440 m), as basic cement, course.

• Can be used with accelerators and retarders for other specifications.

• Moderate to high sulphate resistance.

• No addition other than calcium sulphate or water

Class J

• Depth 12,000 – 16,000 ft (3660 m – 4880 m).

• Extremely high pressure and temperature.

• Can be used with accelerators and retarders for other specifications.

• Moderate to high sulphate resistance.

• No addition other than calcium sulphate or water.

3.3. Cement properties

The cement must possess certain properties in order to fulfil the prementioned functions, these cement properties can be summarized as follows: [41]

1. **Slurry density:**

   Slurry density should be the same as mud to minimize the risk or blowouts or lost circulation. It's measured using mud balance. Low density are prepared with bentonite, pozzolan, gilsonite, perlite, Diatomacous earth. Density increases by adding barite, iron ores or galena.

2. **Thickening Time:**

   Thickening Time determine the length of time the slurry can be pumped. It is the time necessary for the slurry consistency to reach 100 poises under stimulated bottom hole pressure and temperature, Measured using cement consistometer, In practice the thickening time should be at least 25% higher than the time necessary to accomplish the cement job.

3. **Cement Strength:**

   Cement in oil wells is subjected to static and dynamic stresses. Static stress due to dead weight of pipe; compressive stresses due to the action of fluid and formations. Dynamic stresses resulting from drilling operation, especially the vibration of drill string. To withstand these stresses a compressive strength of 500 psi after 24 hours period is needed.

4. **Filtration:**

   Water loss of neat cement is very high, Laboratory tests show that up to 50% of mixing water is lost by filtration through rock or filter papers. Presence of small thickness mud cake reduces filtration. High density slurry results in higher filtration loss.

5. **Permeability:**

   Naturally permeability of set cement should be the lowest possible. Bentonite cements are known to be very permeable (values up to 10 md are reported, while special cements (latex cement) have permeabilities as low as one micodarcy. The following factors influence the permeability of the set cement:

- Water/cement ratios: High W/C ratio increases the permeability
- Downhole conditions: high pressure and confinement due to their compacting effects decrease the permeability of set cement.

6. **Perforating Qualities:**

   Ordinary cements, when they are completely hardened, fracture excessively when perforated. Low strength cements are usually less brittle and have less tendency to shatter upon perforating. Shattering of cement is not a desired quality when near an O.W.C. or O.G.C.

7. **Corrosion Resistance:**

   Set cement could be penetrated by corrosive liquids especially those containing CO3 or SO4 irons. Cement corrosion decreases the final compressive strength render the cement more permeable. Reduction of the hardening time improves the cement resistance to corrosion by corrosive fluids.

8. **Bond Requirements:**

   For clean surfaces (rock or metal) the bond increases with time and moderate temperatures. Mud cake and dirty casing surfaces reduce markedly the bond between casing or rock and cement. Additives such as salt and fine sand increases the bond between casing and the set cement.

3.4. Conventional cement Additives.

The rate at which hydration occurs when water is mixed with cement can be altered using chemical additives. Additives are chemicals and materials blended into base cement slurries to change the performance of the cement. Due to the inherent nature of base cements and because of the demands placed on the cement sheath throughout the life of the well, the performance properties of the cementing slurry are modified to address the specific and unique conditions of each well. Many of the additives currently used are organic, polymeric materials which have been specifically formulated for use in well cementing operations. Typical chemical additives for oil and as well cementing operations can be divided into eight categories [42]:

1. **Accelerators**

   Accelerator is a chemical additive used to speed up the normal rate of reaction between cement and water which shortens the thickening time of the cement, increase the early strength of cement, and saves expensive rig time. Cement slurries used in shallow wells where temperatures are low requires accelerators to shorten the time for "Waiting-on-Cement (WOC)" before drilling operation can be resumed [43]. In deeper wells the higher temperatures promote the setting process, and accelerators may not be necessary. Accelerators do not increase the ultimate compressive strength of cement but promote rapid strength development [44]. Calcium Chloride and Sodium Chloride are the most commonly used cement accelerators. However, Calcium Chloride (CaCl2) is undoubtedly the most efficient and economical accelerator [45]. Other types of accelerators include, Sodium Metasilicate, Potassium Chloride and gypsum].

2. **Retarders**

   Retarders are chemical additives used to decrease the speed of cement hydration [46]. The cements commonly used in well applications do not have a sufficient Long fluid life (thickening time) for use at Bottom Hole Circulating Temperatures (BHCTs) above 100 °F (38°C) [47]. For extending the thickening time, additives known as retarders are required. Retarders inhibit hydration and delay setting, allowing sufficient time for slurry placement in deep and hot well. That is, it increases the thickening times for pumping the cement into place [20,21].

   Retarders do not decrease the ultimate compressive strength of cement butg do slow the rate of strength development [47]. Besides extending the pumping time of cements, most retarders affect the viscosity to some degree. The most common retarders are natural lignosulfonates, cellulose and sugars derivatives [47,43].

3. **Extenders:**

Many formations will not support long cement columns of high density slurries, these slurries weights need to be reduced to protect formations that have low fracture gradient or for economics purposes. To reduce the weight of cement slurries, extenders are used [50]. Extenders are also known as water adsorbing or lightweight inert materials [51]. They are broad class of materials that are used for reducing slurry density and increasing the yield of cement slurry. A reduction of slurry density reduces the hydrostatic pressure during cementing of weak and fragile formations or depleted reservoirs [51]. This helps prevent the breakdown of weak formation and loss circulation [52]. Extenders also reduce the amount of cement needed for cementing operation and because they are less expensive than cement, they bring considerable savings. These additives change the thickening times, compressive strengths and water loss. In reducing slurry density, the ultimate compressive strength is reduced and the thickening time is increased [53]. Bentonite and Sodium Silicate are the most commonly used chemical extenders for cement slurries.

4. **Heavy Weight Agents:**

The main purpose of heavy weight additives is to restrain high formation pressures. They have specific gravity greater than the cement, consistent particle size distribution and low water requirement. Chemically weighting agents are inert in the cement slurry and do not interfere with logging tools [54]. When high pore pressures, unstable wellbores, and deformable/plastic formations are encountered, high weight muds of over 18 ppg may be used and correspondingly cement slurries of equal weight must be used. The most obvious way of increasing cement density is to reduce the amount of water in the cement slurry. However, slurries with densities greater than 17.5 lb/gal would be too thick to mix and pump without weighting agents. This would therefore require dispersants to maintain pumpability. When weights higher than 17.5 lb/gal are required, materials with high specific gravities are added. To Lake and Mitchell [55], heavy weight agents are normally required at densities greater than 17 lb/gal where dispersants or silica is no longer effective. The most common weighting agents are Hematite, Ilmenite and Barite.

5. **Fluid Loss Additives (FLA):**

   Fluid loss additive is also known as permeability plugging additive. Fluid loss additives are commonly employed in field cementing operations reduce the rate at which water from cement is forced into permeable formations when a positive differential pressure exits into the permeable formation. That is, it prevents dehydration of cement slurry. In the presence of differential pressure, filtrate loss to permeable strata can dramatically alter the physical properties of oilwell cements. Thickening time, rheology, and mud displacement efficiency are all impacted by the changes in the water-cement (w/c) ratio brought on by the loss of cement filtrate. According to Adams and Charrier [44] cellulose derivatives are the most common fluid loss additives.

6. **Lost Circulation Additives:**

   Lost circulation additive is also known as macro plugging materials. Lost-circulation additives are used to plug zones that have a tendency to draw in fluid because they are unconsolidated or weak. Large particulates can be placed in the cement slurry to prevent fracturing or to bridge existing fractures. These particles should have a broad particle size distribution, should not accelerate or retard excessively, should have sufficient strength to keep a fracture bridged, and should be inexpensive and non-toxic. Common lost circulation additives are Gilsonite, Fibrous and flake materials.

7. **Expansion Additives:**

   Expansion additives cause the exterior dimensions of set cement to grow slowly when the cement is in the presence of down-hole fluids. This minor growth of the exterior dimensions of the slurry causes the cement to bond better to pipe and formation. The most common additives for this use are based on calcium sulphoaluminate and calcium oxide [56].

8. **Dispersants:**

   Dispersants also known as friction reducing additives are added to improve upon the flow properties of cement slurry [53]. In particular, they are used to offset overly-high viscosity and some slurries tendency. The most common dispersant is the sodium salt of Polynapthalene Sulfonate (PNS)

9. **Antifoam Agents:**

   Many additives cause foaming problems, but if slurry foams excessively, during mixing, centrifugal pump will air lock, and mixing must be stopped [52]. Therefore antifoams are introduced in cement slurries to decrease foaming and minimise air entrainment during mixing. Excessive foaming can also result in an underestimation of the density downhole and cavitation of the mixing system. The cheapest and the most commonly used antifoam agents are Polypropylene glycols, [55] but Polyethylene glycols are also used.

3.5. Nanotechnology well cement applications

With the expansion of oil and gas exploration and development towards deep strata and new fields, drilling and completion engineering is confronted with cementing problems under complex geologic conditions and operating conditions involving HTHP, salt gypsum formations/brine formations, sour gas reservoirs, long cemented sections, where conventional cement additives failed to provide the required properties to achieve zonal isolation. Several studies addressed the use of nanoparticles in oil well cementing to enhance cement properties and to be used as cement spacer.

1. Enhancing Cement Properties:

Due to the very high surface area of nanomaterials, they can be used in oil well cementing to accelerate the cement hydration process, increase compressive strength, help control fluid loss, reduce probability of casing collapse and prevent the gas migration which is one of the cementing problems in gas wells. Moreover, they are often required in small quantities. Experimental results showed that nanotechnology succeeded to enhance cement properties in challenging conditions such as [33,57]:

- **Extensive low temperature:**

  In the oil and gas cement system, it is crucial for a cement sheath to maintain the long-term integrity of the wells. The temperature condition is an important factor of the oil cement system. Excessive low temperatures can result in the extension of delay time and increase the cost of the project. Pang investigated nano silicas as additives for low temperature conditions. It was observed that the use of nano silicas increased cement hydration without a decrease for a long time. To reduce the particle size and increase the aspect ratios, both contribute to the nano silica performance. Nano silica also shows superior compatibility with calcium chloride [58].

- **HPHT conditions:**

  The HPHT condition is another problem. An experiment conducted by Murtaza et al. concluded that nanoclay enhanced oil cement slurry. The enhanced cement had compressive strength and rheological properties under conditions of the API standard [59].

- **Bulk shrinkage:**

  Bulk shrinkage is a big problem of oil cement applications in wells, which leads to the loss of long-term zonal isolation. Because of the nanostructure and hydration reactivity, MgO NPs show expansive properties for the cement system. An investigation by Jafariesfad et al. showed that MgO NPs significantly improved the expansion of cement and prevented bulk shrinkage. They also found that the addition of MgO NPs significantly reduced the setting time compared with the original system [60].

- **Fluid loss problems:**

  The use of nanoparticles decreases the fluid loss of the cement slurry. In Fig - 7 [63] the liquid loss from the oil-well cement with varying contents of nanoparticles was tested, and the temperature range was between 70 and 90 C. As the Figure indicates, the loss of fluid from the slurries decreased gradually with the accruing dosage of the nanoparticles. The highest rate of the cement to trap its water was obtained at 3% nano silica concentration compared to 4 % concentration in case of using nano titanium and nano Aluminum oxides was employed. In general, at all observed temperatures, the nanoparticles showed useful results, and the filtration loss of the slurry was below 100 mL which is generally considered to be adequate for most primary cementing operations. Compared to the control samples, the slurry containing NS particles reduced the loss of fluid by 70–72%, while the specimens containing NT and NA powders reduced the loss by 61–63% and 57–60% respectively.

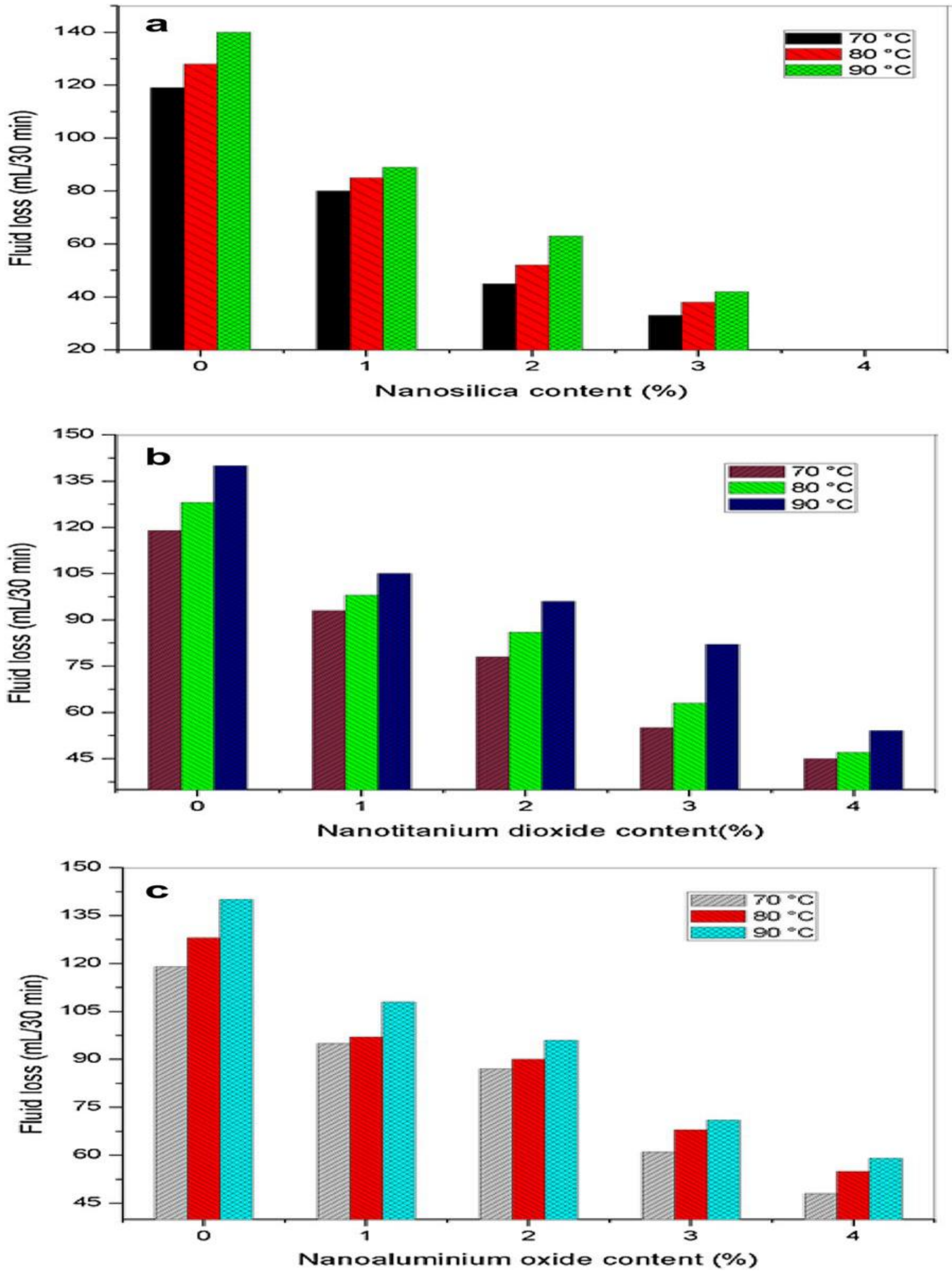

Fig-9 Effect of nanoparticles in decreasing fluid loss of cement slurry [63]

2. Nano-emulsions for cement spacers

Depending on the task, it is necessary to displace one fluid system with another during drilling activities; hence, spacers are usually placed in between fluid systems during the displacement operation. Oil based mud (OBM) needs to be removed by spacers when displacing cement or completion fluid to avoid contamination [61].

Nano-emulsions are emulsions where the droplet size of the internal phase is in the nanoscale (<500 nm). Due to their small dimensions they have a high surface area and show very different properties. Maserati et al., 2010 [62] proposed that solvent in water nano-emulsions used as cement spacer formulation could allow optimizing the cleaning of the casing during the cement job with a high improvement of the performances of the spacers currently in use. Maserati et al., 2010, studied the formulation of direct nano-emulsions (O/W), with a selected solvent as internal phase, in order to improve the casing – open hole cleaning and reverse the surfaces wettability to allow better adhesion of slurry between casing and hole. Using this methodology, based on high efficiency system with reduced chemical dosage, can also result in a considerable optimization of product cost of effective cement operation [33].

A summary of the wide range of investigated nanoparticles and their effects on cement properties is presented in Table 2 [4].

Table.2 Summary of application of nanoparticles for well cementing.

Investigated NP	Improved parameters	References
Aluminum oxide	Increasing the electrical resistivity Enhancing the compressive strength	Vipulanandan et al. (2018a)
Aluminum oxide	Accelerating the setting time Improving mechanical properties	Deshpande and Patil (2017)
Aluminum oxide	Improving mechanical properties	Nazari and Riahi (2011)
Graphene nanoplatelets (GNP)	Improving mechanical properties Reducing chemical shrinkage	Alkhamis and Imqam (2018)
Graphene nanoplatelets (GNP)	Improving mechanical properties	Peyvandi et al. (2017)
Iron oxide	Improve sensing properties Enhancing the compressive strength	Vipulanandan et al. (2015)
Magnesium oxide	Accelerating the setting time Reducing chemical shrinkage	Jafariesfad et al. (2016)
MWNTs Aluminum oxide Silicon dioxide	Accelerating the setting time	Santra et al. (2012)
Nanosynthetic graphite	Improving the early compressive strength development	Ahmed et al. (2018)
Silicon dioxide	Accelerating the setting time Enhancing the compressive strength Improving the filtration characteristic	Patil and Deshpande (2012)
Silicon dioxide	Accelerating the setting time Enhancing the compressive strength	Pang et al. (2014)
Silicon dioxide Iron oxide	Improving mechanical properties Improve sensing properties	Li et al. (2004)
Silicon dioxide	Improving mechanical properties	Jalal et al. (2012)
Silicon dioxide	Improving mechanical properties	Shih et al. (2006)

4: Nanotechnology other drilling applications and challenges.

Although the applications of nano technology in drilling fluids and well cementing are the main applications in drilling operations which counts for 58% from the nano technology applications in oil and gas industry as seen in Fig.4 there are many other applications for nano technology related to drilling operations such as nano technology applications in drilling bits and measurements and logging while drilling.

4.1 Nano technology drilling bits applications:

A drill bit has been used to drill through the rock of the earth’s surface to where the oil and gas deposits lie. Drill bits are broadly classified into two main types according to their primary cutting mechanism [65]:

1. Rolling cutter bits drill largely by fracturing or crushing the formation with "tooth"-shaped cutting elements on two or more cone-shaped elements that roll across the face of the borehole as the bit is rotated.
2. Fixed cutter bits employ a set of blades with very hard cutting elements, to remove material by scraping or grinding action as the bit. The most common type in use today is the polycrystalline diamond cutter (PDC) bits.

Now adays over 80% of the footage drilled for oil and gas production is done using PDC Bits. This has been made possible by advances in PDC. They are now capable of drilling the hardest and toughest formations, more economically and effectively than any other technology. Only ~20% of the footage drilled uses the older roller-cone and impregnated bit technologies.

Despite such widespread use, conventional PDC has several major drawbacks, including low thermal stability (failure at temperatures above 350°C) and low impact strength. The resulting blunting and shattering of drill bits greatly slows the drilling process. One attempt to improve upon conventional PDC has been the development of thermally stable polycrystalline (TSP) diamond composites using silicon carbide (SiC) binders. These composites are stable up to 1,200°C, but have reduced fracture toughness (6–8 MPa·m1/2) due to the brittleness of the SiC and diamond.

Nano diamond PDC Technology:

Carbon nanomaterials are extremely interesting because of their unique combination of mechanical, structural, electrical and thermal properties. In case of challenging drilling operations, harsher conditions are met and the need for effective drilling bits increases. Nano diamond particles have been functionalized for polycrystalline diamond applications such as polycrystalline diamond compact (PDC) cutters for drill bits. They give PDC cutters unique surface characteristics that allow them to integrate homogeneously into PDC synthesis. Chakraborty[66], studied the functionalization of nano diamond, integration into the PDC matrix and subsequent property enhancement in comparison to the base PDC matrix. The performance of PDC cutters produced, the behaviors and proposed mechanisms are still an area of interest [33].

4.2 Logging-while-drilling (LWD) applications:

It is a normal practice to collect information about the lithology, reservoir fluid and rock properties, etc. during the drilling stage or at other stages during the life of a well. The process of this information gathering is called logging. The idea of nanotechnology if applied in any of the technological fields will put LWD and MWD as outdated technology and can prove to be a boon for the next technical revolution.

4.2.1 Nanorobots MWD and LWD applications:

Nanorobotics involves the design of robots that have dimensions in the micrometer range, but equipped with components of nanometer sizes. However, the conceived nanorobots will have sizes in the order of centimeters. They gave strong arguments to support the possibility of nanorobots rendering measurements-while-drilling (MWD) and logging-while-drilling (LWD) technologies outdated. Since nanorobots are very small, compared to conventional logging tools, they can get very close and deep into the formation; thereby, promoting the acquisition of more accurate real time drilling and formation parameters. The nanorobots could be used for logging purpose by circulating these nanorobots, which have nanomotors being driven by the ions in the mud or by mud circulation system. Expensive wireline tools are conventionally used in all types of wells to find important formation properties. Nanorobots can eliminate use of these tools, entirely and small particles of order of nano meter can be put in the drilling mud to obtain useful information. These robots equipped with nano sensors could be used to measure various properties of formation, borehole environment, mud properties and many more. Nanorobots can be constructed in a manner so that they possess sensors, on-board driving mechanism and microcomputer as well as interface mechanism from where it can send instructions to microcomputers from surface computers. Transmission to surface is by means of electromagnetic waves and detected by means of probes on surface. They facilitate wire-less communication and real time surveillance. Thus, in comparison to the conventional logging they can save rig hours and can be more accurate and precise as compared to presently used techniques like logging while drilling and measurement while drilling. They can move with circulating mud or they can be made to propel or stop by the on-board computer instructions depending upon the measurement to be taken. They will also be able to invade the formation and get important petrophysical parameters [67].

4.2.2 Li-6 scintillation nanostructured glass-ceramics LWD applications:

Almost all available neutron porosity logging-while-drilling (LWD) tools use He-3 detectors to detect neutrons down hole due to their mechanical robustness and the absence of the limitations to operate at high temperatures. Unfortunately, the lack of sufficient quantities of the He-3 isotope caused by the depletion of its stockpile accumulated during the Cold War makes this material unavailable to well logging industry for the next 3 to 5 years. Among all other available neutron detection technologies, only Li-6 scintillation detectors do not have limitations on neutron detection efficiency that would prevent them from consideration for LWD applications. The key component of Li-6 scintillation detector is the scintillation material containing Li-6 isotope. To be used as detectors for neutron porosity LWD tools based on pulsed neutron generators (PNG), such material should be able to operate at high temperature and enable large neutron detector constructions. Nikitin and Korjik [68], presented new Li-6 scintillation nanostructured glass-ceramics that perform substantially better than all available Li-6 scintillation materials. It is this performance improvement provided by nanostructured nature of obtained material which enables its use in the neutron detectors of PNG-based neutron porosity LWD tools.

4.3 Nanotechnology field applications and challenges:

The different applications of nano technology in drilling operations have been proposed based on laboratory experimental work. And most of results reported in literature showed that the drilling industry can reap huge benefits from the nanotechnology applications in different drilling operations. Despite the growing number of investigations with respect to the high potential of using nanoparticles a very limited field trials have been reported.

More field trials are recommended for further advancement of nanotechnology in this industry. The reason behind the lack of field applications of nano technologies despite the fact that a good number of major oil services companies investing a lot in terms of research with respect to nanotechnology is due to the presence of several challenges associated with these applications such as [69]:

1. **High cost of nano particles:**

   Almost all studies have been performed in laboratories with small quantities of nano particles. Different application requires different type of nano particles with specific surface, electrical, mechanical, magnetic, optical, chemical and thermal properties. These highly customized NPs are not only expensive but also challenging to produce in bulk for field application. There are many studies on different ways of synthesizing nano particles, but simple and low-cost method has yet to exist due to the higher embodied energy required to produce nanomaterials per unit mass compared to bulk materials [70]. Moreover, the efficiency of nano particles is highly dependent on their size, shape or surface properties a precise control in manufacturing them is also imperative. Unless and until a cost-effective manufacturing of NPs is realized, nanotechnology application in the industry will remain restricted.

2. **Stability of nano particles in liquid carrier fluid:**

   Due to their surface charge NPs are tending to aggregate. This agglomeration becomes aggressive in extreme conditions such as high salinity and high temperature [71]. The addition of Viscosifiers can increase NPs stability [3] Also surface modification or coating can help minimize these problems. However, this would reduce or even eliminate special properties of NPs such as catalytic property, magnetism, sensing ability, affinity to rock or fluid etc. [72].

3. **Transportation of nano particles into the formation:**

   The lack of general understanding of migration behavior of NPs in porous medium is another difficulty requiring extensive theoretical modelling and core samples work to investigate the transport and retention properties of nanoparticles in subsurface formation [73].

4. **Nano particles environmental impact:**

   Although the use of nanoparticles reduces the environmental impact as they are used in much less concentrations compared to conventional particles the impact of nanoparticles on health, environment, and safety, they can be very hazardous and might lead to severe health issues [74- 75] since they have higher potential of being inhaled or absorbed through skin due to their unique properties of nanoparticles in terms of size and surface area to volume ratio. As a result, standards, regulations, recommended practices, and working guidance are being developed by regulatory agencies such as local and international Environmental Protection Agencies (EPA), International Standardization Organization (ISO), American Society for Testing and Materials (ASTM) to minimize or prevent any unwanted health and environmental associated risks when handling nanoparticles[75].

5. Conclusions

1. The extensive review over the recent investigations of nanoparticles within the oil and gas industry has shown that nanotechnology has recently emerged as an attractive topic of research related to drilling operations in different aspects including drilling fluids, well cementing, drilling bits and Logging while drilling and many studies have shown very promising results in terms of their performance and effectiveness.
2. The promising results are due to the distinctive properties of nanoparticles. As they have significantly different mechanical, chemical, thermal, and magnetic properties compared to their macroscopic counterparts. Due to the large surface-to-volume ratio and huge particle number in one-unit mass This enables their ability to solve problems that the conventional methods cannot address.
3. The nano based drilling fluids show higher stability and better rheological and filtration characteristics that enable them to overcome drilling challenges in HPHT and narrow drilling window environments, Increase wellbore stability, minimize differential Sticking possibilities, reduce torque and drag problems, minimize formation damage, increase rate of penetration and decrease the environmental impact of drilling fluids.

4. Most of the investigated nanoparticles resulted in enhancing the mechanical properties of cement as well as providing a better control for the set time.

5. The most widely investigated nanoparticles that showed significant improvement for the different applications across drilling operations was found to be the nano silica. Which suggests it’s high potential in being applied in the field.

6. Despite a large number of laboratory-scale investigations published in the literature, a very few filed trials were performed with promising results due to some challenges such as their economic feasibility and their impact on HSE.

7. Based on the challenges discussed, more research should be conducted in order to reduce the cost of producing nanoparticles. And mitigate health and environmental risks related to nano particles handling and More field trails are highly recommended for better evaluation of the technology.

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