MEDWIN PUBLISHERS
Committed to create value for Researchers

Petroleum & Petrochemical Engineering Journal

# The Potential of Nanotechnology in Petroleum Industry with Focus on Drilling Fluids

**Irfran Y, Sui D, Agista MN and Zhixin Yu***

Department of Petroleum Engineering, University of Stavanger, Norway

**Research Article**

Volume 1 Issue 1

**Received Date**: March 10, 2017

**Published Date:** March 23, 2017

DOI: 10.23880/ppej-16000106

***Corresponding author** Zhixin Yu, Department of Petroleum Engineering, University of Stavanger, 4036 Stavanger, Norway, Tel: +47 51 83 22 38; Email: zhixin.yu@uis.no

## Abstract

This paper aims at highlighting potential benefits that can be achieved by using nanotechnology and nanoparticles in petroleum industry particularly in the field of drilling fluids. Firstly, it throws light on the application of nanotechnology in different disciplines of oil and gas industry such as exploration, drilling, reservoir protection, hydrocarbon recovery and processing, which is extensively covered in this paper. Several revolutionary changes can be made in drilling industry with the help of nanotechnology. It can bring benefits to the industry in various manners such as improving the quality of mud cake, decreasing the frictional resistance in the well, minimizing the risk of pipe sticking, establishing borehole stability, preventing reservoir from formation damage, and augmenting the recovery of oil and gas. Researchers have tested the application of nanoparticles in drilling fluids and have concluded with very promising results in terms of reduction in torque and drag, stabilizing the well bore, controlling fluid loss and improving hole cleaning efficiency. A comparison between conventional and nanodrilling fluids is presented to illustrate the impact of nanoparticles in drilling fluids.

**Keywords:** Nanotechnology; Nanoparticle; Petroleum; Drilling fluids

## Introduction

Nanotechnology is a field of science that is applied to study the matter on nanometer scale. Over the past decades, significant progress has been achieved in nanotechnology which has emerged as a tool and technology that has been implemented successfully in different fields including medicines, electronics equipment and composite materials. Now it is possible to design and synthesize materials at atomic level with extraordinary mechanical, optical and magnetic properties for different applications.

Nanotechnology defines a particle as a small object that can act as a complete unit with regards to its properties and transport. Nanoparticle is a basic component in nano structural frame which is smaller than daily objects of world (Newton's law of motion) but larger in size than an atom or molecule (quantum mechanics).As the dimension of Nanoparticle lies in the neighboring area between the clusters and the macroscopic materials, they will not directly demonstrate atomic and macroscopic properties, but bring with their own unique effects, for instance small size effect, surface effect and quanta size effect [1]. As the

size of particle is very small, both physical and chemical properties of these particles may differ from the bulk material. Surface areas, melting point, optical properties, magnetic properties and mechanical strength are among few of them [2,3]. Table 1 presents a brief summary of major physical and chemical properties that a Nanoparticle exhibit [4]. These properties also give an overview of why nanoparticles are used in industrial applications.

| Physical Properties | Chemical Properties |
|---|---|
| Shape, size, aspect ratio, surface area | Molecular structure and structural formula |
| Aggregation/agglomeration rate | Composition |
| Particle size distribution and particle structure | Phase identity |
| Topography/morphology of surface | Chemistry of surface (charge, reactive sites, zeta potential, photo catalytic properties) |
| Particle solubility | Lipophilicity/hydrophilicity |

Table 1: Physical and Chemical Properties of Nanoparticles.

Energy industries have been taking advantages from the recent developments of nanotechnology. Companies have invested both money and time in order to get the benefits of nanotechnology in the various disciplines of petroleum industry. They have now realized several advantages of nanotechnology nanoparticles in the areas of exploration, drilling, reservoir protection, hydrocarbon recovery and processing. Nanotechnology can provide solution to certain problems faced by drilling industry and improve the overall performance of oil and gas sector [5,6].

In the field of drilling fluid, nanotechnology can aid in maintaining bore hole stability and minimizing fluid loss which will lead to better and efficient drilling operation [7,8]. The technology allows generating special characteristics in the drilling fluid which can work in complex environment to protect the reservoir from formation damage [9,10]. Therefore, nanomaterials are nowadays considered as promising material to design and develop nano based drilling fluid which may offer optimized solutions to the problem that the conventional drilling fluids cannot solve.

## Nanotechnology and Petroleum Industry

Various disciplines in petroleum industry are taking benefits from the development of nanotechnology. These phases include exploration, drilling, production, processing and refining. Subsurface imaging resolution has been made possible by incorporating nano sensors in exploration stage. Enhanced oil recovery is also making the most of nanotechnology to get more hydrocarbons out of the reservoir by modifying the molecules and by manipulating the interfacial properties. This section highlights the potential application of nanotechnology in various discipline of oil and gas industry.

### Exploration

Use of nano sensors in exploration phase caught significant attention from petroleum geoscientists [11]. Imaging contrast agents and sensors can be developed with nanoparticles as they behave differently from their bulk counterparts with respect to magnetic, optical and electrical properties [3]. Deep wells exhibit hostile environments as the temperature and pressure are relatively high. A special type of sensor, called nano dust, is placed in the pore space to serve for several purposes such as recognition of fluid type, monitoring of fluid flow and characterization of reservoir [12]. Micro computerized tomography cannot detect effectively pore structure of tight formations. Thus, nano computerized tomography (NCT) can be used to image these formations [13].

### Drilling and Completion

Various fields of drilling phase are getting benefits from nanotechnology such as drilling fluid, drilling bit, down hole tools, cement and well logging. Use of nanoparticles in drilling fluid enables the engineers to maintain wellbore stability and control fluid loss specially in shale formation where the permeability is in nanodarcy (nD) [14]. Bit and stabilizer balling can be eliminated by using nano based drilling fluid as it creates a hydrophobic film on the surface [9]. Nano based drilling fluid can also aid in reducing torque and drag in extended reach and multilateral wells as they form an ultrafine thin film between pipe and hole wall [9]. This film provides ease when pipe is being rotated or tripped in/out of the well. Some nanoparticles in drilling fluid such as ZnO can be used to remove $H_2S$ from water based mud before it reaches to surface [15]. It ensures reduction in pollution



Copyright© Zhixin Yu, et al.

to environment, prevention of corrosion and protection of personnel.

In high pressure high temperature (HPHT) drilling operations, nano based drilling fluid system can perform efficiently as it contains particles of high surface area, large thermal conductivity, and better interaction with rock and large heat tolerances [16]. These fluids can also reduce the wear and tear of down hole tools as they provide less abrasive force. From environmental perspective, nano based drilling fluid are also important as it utilizes very less concentration of nanoparticles which can be beneficial in sensitive environments [16]. Use of nano diamond in drill bit application and its integration into matrix of polycrystalline diamond compact (PDC) bit have been studied by Chakraborty et al., which can give unique characteristics to the bit [17]. As the engineered nanostructures have high mechanical strength, these structures can be used in making of down hole tools so that the tools can be run in hostile environments. Spacers with nano emulsions in cementing operations can also be optimized by using nanoparticles so that hole cleaning can be carried out effectively during cementing [18]. Several nanoparticles such as nanosilica, nanoalumina and carbon nanotube (CNT) have been studied to improve the performance of cement with respect to its hydration process, fluid loss, gas migration and compressive strength [19].

### Production

In production phase of an oil well, various application areas of nanotechnology are investigated by researchers such as hydrate recovery, scale inhibition and stimulation fluid. The recovery of hydrate can be improved if the water cage decomposes and release hydrocarbon (methane). This can be achieved by injecting Ni-Fe nanoparticles into hydrate formations if the particles are suspended in air having a self-heating property [20]. In the field of stimulation, it is very common to use polymer based fluid containing high molecular weight cross linked polymer. As they produce large amount of residue, researchers are also studying the effect of low molecular weight surfactants as fracturing fluid with nanoparticle [21]. The nanoparticle gives desired properties to the fracturing fluid which helps in conducting efficient stimulation operation. Scale deposition in production tubing can be reduced by nano structures as they develop hydrophobic surface inside the tubing [22].

### Enhanced Oil Recovery

Enhanced oil recovery (EOR) has been focused from quite a while as the resources are moving towards the depletion phases. Nanotechnology has also brought its benefits to the field of EOR. As the size of nanoparticle is very small as compared to pore throat, they cannot be retained by the formation (at least after post flush). Aqueous dispersion containing nanoparticles displaces the discontinuous phase (oil, gas) due to the confinement of force of extremely large amount of nanoparticles at the vertex [23]. Oxides of zinc, aluminum, iron, magnesium, nickel, zirconium, silicon and tin are studied by Ogoloet al.with regard to their application in EOR in which the particle sizes are kept to nano scale [24].

Fluid saturations can be evaluated by delivering paramagnetic nanoparticles to the reservoir by using measurement of response and magnetic field [25]. It means that nanoparticles carrying hydrophobic compounds can be injected into the reservoir and leave its hydrophobic component on its way to the recovery well if there is oil present in the reservoir [26]. It can enable us to determine the saturation of oil in the reservoir.

### Refinery and Processing

Nanotechnology has been applied in the refinery for a long time especially with catalyst of nanometer size. Nanoparticles have a tendency to extract harmful substances like sulfur dioxides, nitrogen oxides and acids from the vapor. Nano membranes can be used to separate gas streams and to take impurities out from the oil [27]. Upgrading of heavy oil and bitumen can be done on site by using nanocatalyst so that the need to transport and handle them can be avoided [28].

## Nano Drilling Fluid

Drilling fluid plays the similar role in the drilling operation as blood does in our body. Any issue in drilling fluid can severely affect the performance of whole operation. Therefore, it is always urged to understand the behavior and function of drilling fluid in the well. Drilling fluids are always a focal point of many researchers so that improvement can be made in mud design and properties. Researchers are looking into the use of nano particles in drilling fluid because it can bring several benefits to mud. This section highlights the important work and milestone achieved in the field of nanobased drilling fluid so that the merits of nanotechnology can also be seen in this area.

### Overview of Nano Drilling Fluid research

Based on an extensive literature review, Table 2 represents an overview of the research on the effects of nanoparticle addition in drilling fluid which are



Copyright© Zhixin Yu, et al.

experienced by different researchers in their experimental studies [29-36].

| Nano Particles | Concentration | Type of Drilling Fluid | Effect of Nanoparticle Addition |
|---|---|---|---|
| GrapheneOxide | 0.57-1.71% | WBM | Improve rheology, reduce fluid loss after heat aging, act as transport vehicle for placing stabilizers in shale, stability problem |
| CNT | 0.14% | OBM | HPHT applications, Improve rheology, fluid loss problem, works very good with low concentrations |
| NanoSilica | 3% w/v | WBM | Excellent rheology and stable wellbore by plugging pores of shale |
| NanoSilica | 1-3% | WBM | Improve rheology, reduce filtrate loss, thin filter cake, works very good with high concentration |
| Iron hydroxide | 0.5-2.5% | OBM | Do not affect rheology significantly, considerable filtrate reduction under LPLT, better result with high graphite level, acceptable filter cake, lower concentration are efficient at HPHT |
| Calcium carbonate | 0.5-2.5% | OBM | Do not affect rheology significantly, considerable filtrate reduction under LPLT, better result with low graphite level, acceptable filter cake, higher concentration are efficient at HPHT but low at LPLT |
| Iron Oxide | 0.1-0.4% | WBM | Shear thinning behavior was observed. Higher yield point and more viscous behavior. High thermal stability |
| MutilwalledCNTs | Upto 2% | WBM | Better plastic viscosity, yield point, gel strength |
| Nano CMC | 10% | WBM | Water loss and mud cake thickness gets reduced |
| Carbon Black | 2% | WBM | Continuous and integrated mud cake formation |

Table 2: Effect of Nanoparticle Addition in Drilling Fluid.

Contreras discussed the use of iron based (iron hydroxide) and calcium based (calcium carbonate) nanoparticles in oil based mud (OBM) along with graphite as loss circulation material (LCM) [32]. They measured the rheological properties of drilling fluid both with and without nanoparticles and LCM at different concentrations. In the study, they found that calcium based nanoparticles gave high gel strength and plastic viscosity (PV) as compared to sample without nanoparticle. Iron based nanoparticles led to reduction in yield point (YP) at high graphite concentration but they did not affect plastic viscosity and gel strength significantly. Both nanoparticles resulted in filtrate loss significantly and formed relatively thick mud cake.

Price studied the use of graphene oxide (GO) and carbon nanotubes as nanoparticles in drilling fluid [29]. Graphene oxide was used in water based mud at different concentrations. Addition of GO after heat aging WBM at 150°C for 16 hours resulted in reduction in fluid loss at high concentrations but long term stability was an issue with GO. CNT was used in synthetic base fluid at HPHT



Copyright© Zhixin Yu, et al.

conditions (600°F). Significant low shear viscosity was observed along with better yield point & gel strength but fluid loss was still high.

Oscar studied the effect on wellbore strengthening by using nanoparticle with graphite in oil based mud (OBM) [37]. They observed an increase in fracture pressure by quantifying it on sandstone core using hydraulic fracturing tests. On using calcium based nanoparticles, fracture resistance was improved by 65% whereas iron based nanoparticles increase it by 39%. Mud filtration was also studied in ceramic plate under HPHT conditions. They found out that the tip isolation mechanism associated with the production of immobile mass was responsible for higher fracture resistance.

Zakaria and his colleagues worked on the use of nanoparticles as loss circulation material (LCM) [38]. According to them, limited success is usually shown by micro and macro sized materials used in LCM particularly when the pore throat size is in micro scale. In house nanoparticles were prepared either in OBM or in water. Low temperature and low pressure filtration tests were conducted with both fluid containing conventional LCMs as well as nano sized LCMs. It was found out that fluid loss got reduced by 70% through nano sized LCMs. Filter cake thickness was also measured through API standard procedure and better results were obtained by using nanobased drilling fluid. Nanoparticles were also added to drilling fluid by Price et. al. to study the effect on shale permeability of two different shale formations [39]. The idea was to understand the phenomenon of how pores got physically plugged by nanoparticles. Silica nanoparticles of different sizes were selected based on the pore throat size of shale. The study also revealed that if the surface of nanosilica was treated then its performance in plugging the shale pores can be improved.

Fakoya et al. carried out experimental work to investugate the effect of nanoparticles on rheological properties of polymeric and surfactant based fluids [40]. At different temperature, viscosity and frequency sweep test were conducted in rheometer by using 20 nm silica particles with its different concentrations. Maximum limit for concentration of nanoparticle which can improve the rheology was determined for both surfactant and polymer based fluids.

## Comparison between Conventional and Nano Drilling Fluid

By using nanoparticle in drilling fluid, several drilling challenges could be combated. The advantages achievable by utilizing nano drilling fluids can be summarized as below.

**Reduction in formation damage:** Formation damage refers to alteration of formation characteristic typically due to drilling mud invasion. Due to this, pore volume and effective permeability tend to decrease near wellbore region. Formation damage is mostly due to spurt losses. Use of nano based fluid minimizes the spurt losses. It also protect the porosity/permeability characteristics of the near- wellbore reservoir section and increases productivity.

**Increase in shale stability:** Shale formations are very complicated when it comes to solving the wellbore problems associated with them. Several chemical and mechanical actions are responsible for instability of reactive shale. Interaction between shale and mud can be minimized by using nanofluid because of its ultra fine particle size. It can also enhance the shale's resistance to fracture and collapse. Chemical reaction associated with shale-mud interaction can also be controlled using nanoparticles as it has several numbers of functional groups.

**Strengthening of unconsolidated formation:** Unconsolidated formations are often encountered such as formations below deep sea bed due to low pressure from overlying rocks. Borehole problems are directly connected to the degree of unconsolidation. Conventional particles present in drilling mud are unable to generate effective inter particle cohesion and cementation as it comprises of macro or micro sized solid components. Nano particles can access to the pores and then to inter granular contact surfaces of unconsolidated sands. Use of nanoparticle increases fracture pressure thus strengthens the well bore.

**Formation of ultrafine mud cake:** Mud cake is usually formed on the face of permeable formation when a fluid is forced against the formation. It is very vital to know filtration properties and filter cake characteristics so that the downhole problems such as stuck pipe can be avoided. Conventional drilling mud comprises of micro and macro size particle which has a tendency to form thick filter cake. Nanobased drilling fluids form well dispersed, thin and tight mud cake, reduce the differential sticking problem, minimize torque & drag and decrease the scope of embedded cuttings bed formation in deviated, horizontal, and extended reach wells.



Copyright© Zhixin Yu, et al.

**Efficient in HPHT environments:** HPHT environments have temperatures and pressures above 150°C and 690 bar respectively. Conventional macro and micro based fluids (chemicals and polymers) have limited thermal stability. They can get thermal degradation above 125-130°C. Due to degradation, these chemicals cannot perform their desired function effectively in the mud system. Therefore, in order to get desired viscous and gelling properties at high pressure and high temperature, drilling mud must comprises of the components that have stability under extreme conditions such as nanoparticles. Excellent thermal conductivity of nano based fluids with temperature and pressure tolerances can be a better choice.

**Shallow water flow:** Shallow water flow is potentially a problem in different wells especially deep water. It requires an additional casing to isolate them from other formation. It can also trigger several other borehole problems like instability of subsurface tools, fracturing of formation, well collapse, mud loss, erosion of seabed, mud properties alteration during well site operations [41]. Thus the cost of the well can be increased several folds due to well control issues, instability of rig, additional casing string and lost wellhead. As the size of nanoparticle is very small, it can penetrate the shallow water sands and result in improving bond strength between grains as it exhibits better cementing properties.

**Loss circulation:** Oil and gas wells frequently experience loss circulation problem due to several reasons. These reasons include unconsolidated nature of formation, presence of fracture network, and selection of improper mud weight especially when the window between pore pressure and fracture pressure is narrow. There are several loss circulation materials available in macro and micro sizes but there performance is not up to the mark. Customized nanoparticles can be made to act as structural barrier along the loss path so that effective sealing can prevent fluid loss. This will result in saving huge amount of revenue especially in case of oil based mud systems.

**Torque and drag:** In order to extract more hydrocarbons, the industry nowadays has inclined towards drilling horizontal and extended reach wells. But these well display enormous torque and drag due to high frictional resistance between down hole tool and borehole wall. Therefore, drilling fluid which can give better lubrication between tools and wall can provide solution to the problem.

Oil based mud lowers the frictional resistance but it is an expensive solution with environmental concerns as well. Other water based mud containing macro and micro sized particles can reduce the friction to very limited extent. The friction at pipe and wall interface can be significantly reduced by using nano based drilling mud as it forms a thin and fine lubricating layer. A ball bearing effect, created by spherical nanoparticles also aid in sliding pipe in and out of the hole during tripping operation.

**Stuck pipe:** Both mechanical and differential pipe sticking can lead to an enormous increase in well cost. The risk of differential sticking can be easily reduced if drilling mud leaves a thin low sticking mud cake on the wall of borehole. Nano drilling fluid not only forms an ultrafine mud cake on the face of formation but also develop a non-sticking film on the down hole tools which helps to avoid triggering of differential sticking. In situation of stuck pipe, nanoparticles can be added to spotting fluid which will go inside the mud cake-pipe interface and release the stuck pipe. Conventional spotting fluid, comprising of bigger size than nanoparticle, find itself difficult to enter the interface.

**Bit balling:** Bit balling is quite frequent drilling problem especially in reactive formations such as gumbo shale. It not only creates problems for the bit but also for the stabilizers and tool joints. Due to bit balling, rate of penetration (ROP) gets drastically reduced as the clay accumulates in the tooth gaps of bit. Therefore, cost of drilling operation becomes high due to slower progress in drilling. Use of nano based drilling fluid can form a hydrophobic film which acts as barrier to bit balling.

**$CO_2$ and $H_2S$ environments:** Acid gases such as $CO_2$ and $H_2S$ can cause severe problems related to environment, process, tools, health and safety. $H_2S$ gas in particular is deadly gas even at low concentration, therefore it is very important to control and treat it as quickly as possible during any operation. In drilling, formation may contain these gases and the solution is to neutralize them by using certain scavengers. Nanobased drilling fluid can be custom made to contain functional groups that can neutralize $H_2S$ into less hazardous compound.

**Economics:** Low cost is one of the most promising features of nano drilling fluid along with the other technical benefits. Small concentration of nanoparticle can yield extraordinary results in terms of performance. This is due to their high surface area which makes them highly reactive.



Copyright© Zhixin Yu, et al.

## Conclusion

Nanotechnology has emerged as a game changer in different areas of petroleum industry particularly in the field of drilling engineering. The paper has comprehensively covered the recent progress in the field of drilling fluid with nanoparticles addition to enhance its performance and improve drilling efficiency.

Nanoparticles have been tested quite along as an additive to drilling fluid due to their unique properties. They have a potential to become a permanent constituent of all drilling mud as they can contribute in the solution of many down hole problem such as formation damage, loss circulation, pipe sticking, formation integrity issues, high torque and drag. In this way, nanoparticles not only replace traditional strategies but also allow current drilling industry to go beyond its limits in order to reach those hydrocarbons which are inaccessible these days.

## Acknowledgement

The authors would like to thank the financial support from Department of Petroleum Engineering, University of Stavanger for this project.

## References

1. Nabhani N, Emami M, Moghadam ABT (2011) Application of Nanotechnology and Nanomaterials in Oil and Gas Industry. AIP Conference Proceedings 1415(1).

2. Morales D, Gutiérrez JM, García-Celma MJ, Solans YC (2003) A Study of the Relation between Bicontinuous Microemulsions and Oil/Water Nano-emulsions formation. Langmuir 19(18): 7196-7200.

3. Krishnamoorti R (2006) Extracting the Benefits of Nanotechnology for the Oil Industry. Journal of Petroleum Technology 58(11): 24-26.

4. May 2016 http://ec.europa.eu/health/scientific_committees/opinions_layman/nanomaterials/en/l-3/2.htm.

5. Mokhatab S, Fresky MA, Islam MR (2006) Applications of Nanotechnology in Oil and Gas E&P. Journal of Petroleum Technology 58(4): 48-51.

6. Kong XL, Ohadi M (2010) Applications of Micro and Nano Technologies in the Oil and Gas Industry-Overview of the Recent Progress. Society of Petroleum Engineers, Abu Dhabi International Petroleum Exhibition and Conference, Abu Dhabi, UAE.

7. Abdo J, Haneef MD (2011) Nano-Enhanced Drilling Fluids: Pioneering Approach to Overcome Uncompromising Drilling Problems. J Energy Resour Technol 134(1): 1-6.

8. Chaaudhury MK (2003) Complex Fluids: Spread the Word about Nanofluids. Nature 423(6936): 131-132.

9. Amanullah M, Al-Tahini AM (2009) Nano-Technology-Its Significance in Smart Fluid Development for Oil and Gas Application. Society of Petroleum Engineers, SPE Saudi Arabia Section Technical Symposium, AlKhobar, Saudi Arabia.

10. Singh SK, Ahmed RM, Growcock F (2010) Vital Role of Nanopolymers in Drilling and Stimulations Fluid Applications. Society of Petroleum Engineers, SPE Annual Technical Conference and Exhibition, Florence, Italy.

11. Pitkethly MJ (2004) Nanomaterials-The Driving Force. Materialstoday 7(12): 20-29.

12. Song Y, Marcus C (2007) Hyperpolarized Silicon Nanoparticles: Reinventing Oil Exploration?.

13. El-Diasty AI (2013) Applications of Nanotechnology in the Oil & Gas Industry: Latest Trends Worldwide & Future Challenges in Egypt. Society of Petroleum Engineers, North Africa Technical Conference and Exhibition, Cairo, Egypt.

14. Hoelscher KP, Stefano GD, Riley M, Young S (2012) Application of Nanotechnology in Drilling Fluids. SPE International Oilfield Nanotechnology Conference and Exhibition, Noordwijk, Netherlands.

15. Sayyadnejad MA, Ghaffarian HR, Saeidi M (2008) Removal of hydrogen sulfide by zinc oxide nanoparticles in drilling fluid. Int J Environ Sci Technol 4(5): 565-569.

16. Amanullah M, Al-Arfaj MK, Al-Abdullatif Z (2011) Preliminary Test Results of Nano-based Drilling Fluids for Oil and Gas Field Application. SPE/IADC Drilling Conference and Exhibition, Amsterdam, Netherlands.

17. Chakraborty S, Gaurav Agrawal, Di Giovanni A, Scott D (2012) The Trick Is The Surface – Functionalized Nanodiamond PDC Technology. SPE International



Copyright© Zhixin Yu, et al.

Oilfield Nanotechnology Conference, Noordwijk, Netherlands.

18. Maserati G, Daturi E, Belloni A, Gaudio LD, Bolzoni SW, et al. (2010) Nano-emulsions as Cement Spacer Improve the Cleaning of Casing Bore during Cementing Operations. SPE Annual Technical Conference and Exhibition, Florence, Italy.

19. Santra AK, Boul P, Pang X (2012) Influence of Nanomaterials in Oil well Cement Hydration and Mechanical Properties. SPE International Oilfield Nanotechnology Conference, Noordwijk, Netherlands.

20. Bhatia KH, Chacko LP (2011) Ni-Fe Nanoparticles: An Innovative Approach for Recovery of Hydrates. Society of Petroleum Engineers, Brasil Offshore, Macaé, Brazil.

21. Huang T, Crews JB (2007) Nanotechnology Applications in Viscoelastic Surfactant Stimulation Fluids. European Formation Damage Conference, Scheveningen, Netherlands.

22. Kumar D, Chishti SS, Rai A, Patwardhan SD (2012) Scale Inhibition using Nano-silica Particles. SPE Middle East Health, Safety, Security, and Environment Conference and Exhibition, Abu Dhabi, UAE.

23. Kondiparty K, Nikolov AD, Wasan D, Liu KL (2012) Dynamic Spreading of Nanofluids on Solids. Part I: Experimental. Langmuir 28(41): 14618-14623.

24. Ogolo NA, Olafuyi OA, Onyekonwu MO (2012) Enhanced Oil Recovery Using Nanoparticles. SPE Saudi Arabia Section Technical Symposium and Exhibition, Al-Khobar, Saudi Arabia.

25. Zhang T, Espinosa D, Yoon KY, Rahmani AR, Yu H, et al. (2011) Engineered Nanoparticles as Harsh-Condition Emulsion and Foam Stabilizers and as Novel Sensors. Offshore Technology Conference, Houston, Texas, USA.

26. Berlin JM, Yu J, Lu W, Walsh EE, Zhang L, et al. (2011) Engineered Nanoparticles for Hydrocarbon Detection in Oil-Field Rocks. Society of Petroleum Engineers, SPE International Symposium on Oilfield Chemistry, Woodlands, Texas.

27. Kong X, Ohadi MM (2010) Applications of Micro and Nano Technologies in the Oil and Gas Industry-Overview of the Recent Progress. Abu Dhabi International Petroleum Exhibition & Conference, Abu Dhabi, UAE.

28. Ying JY, Sun T (1997) Research Needs Assessment on Nano-structured Catalysts. Journal of Electroceramics 1(3): 219-238.

29. Hoelscher KP, Young S, Friedheim J, Stefano GD (2013) Nanotechnology Application in Drilling Fluids. Offshore Mediterranean Conference and Exhibition, Ravenna, Italy.

30. Riley M, Stamatakis E, Young S, Friedheim J, Stefano GD, et al. (2012) Wellbore Stability In Unconventional Shale - The Design of A Nano-Particle Fluid. SPE Oil and Gas India Conference and Exhibition, Mumbai, India.

31. Ji L, Guo Q, Friedheim JE, Zhang R, Chenevert ME (2012) Laboratory Evaluation and Analysis of Physical Shale Inhibition of an Innovative Water-Based Drilling Fluid with Nanoparticles for Drilling Unconventional Shales. SPE Asia Pacific Oil and Gas Conference and Exhibition, Perth, Australia.

32. Contreras O, Hareland G, Husein M, Nygaard R, Al-saba M (2014) Application of In-House Prepared Nanoparticles as Filtration Control Additive to Reduce Formation Damage. SPE International Symposium and Exhibition on Formation Damage Control, Lafayette, Louisiana, USA.

33. Amarfio E, Abdulkadir M (2015) Effect of Fe4O3 Nanoparticles on the Rheological Properties of Water Based Mud. Journal of Physical Science and Application 5(6): 415-422.

34. Ismail AR, Seong TC, Buang NA, Sulaiman WRW (2014) Improve Performance of Water-based Drilling Fluids Using Nanoparticles. The 5th Sriwijaya International Seminar on Energy and Environmental Science & Technology, Palembang, Indonesia.

35. Saboori R, Sabbaghi S, Mowla D, Soltani A (2012) Decreasing of water loss and mud cake thickness by CMC nanoparticles in mud drilling. International Journal of Nano Dimension 3(2): 101-104.

36. Paiaman AM, Al-Anazi BD (2008) Using Nanoparticles To Decrease Differential Pipe Sticking And Its Feasibility In Iranian Oil Fields. Oil and Gas Business.

37. Contreras O, Hareland G, Husein M, Nygaard R, Alsaba M (2014) Wellbore Strengthening In Sandstones by Means of Nanoparticle-Based Drilling Fluids. SPE Deepwater Drilling and Completions Conference, Galveston, Texas, USA.



Copyright© Zhixin Yu, et al.

38. Zakaria M, Husein MM, Harland G (2012) Novel Nanoparticle-Based Drilling Fluid with Improved Characteristics. SPE International Oilfield Nanotechnology Conference and Exhibition, Noordwijk, Netherlands.

39. Hoelscher KP, Stefano GD, Riley M, Young S (2012) Application of Nanotechnology in Drilling Fluids. SPE International Oilfield Nanotechnology Conference and Exhibition, Noordwijk, Netherlands.

40. Fakoya MF, Shah SN (2013) Rheological Properties of Surfactant-Based and Polymeric Nano-Fluids. SPE/ICoTA Coiled Tubing & Well Intervention Conference & Exhibition, Woodlands, Texas, USA.

41. Amanullah M, Boyle R (2006) Experimental Evaluation of the Formation Strengthening Potential of a Novel Gel System. IADC/SPE Asia Pacific Drilling Technology Conference, Bangkok, Thailand.

42. Mitchell RF (2007) Drilling Engineering. In: Lake LW (Ed) Petroleum Engineering Handbook, Society of Petroleum Engineers 2.

43. Ju B, Dai S, Luan Z, Zhu T, Su X (2002) A Study of Wettability and Permeability Change Caused by Adsorption of Nanometer Structured Polysilicon on the Surface of Porous Media. SPE Asia Pacific Oil and Gas Conference and Exhibition, Melbourne, Australia.

44. Wang D, Liu WM, Xiao-Bo D (2012) Nanoparticle-based lubricant additives. Springer-Verlag, Berlin Heidelberg.

45. Horikoshi S, Serpone N (2013) Microwaves in Nanoparticle Synthesis: Fundamentals and Applications. Wiley, pp: 352.



Copyright© Zhixin Yu, et al.