A comprehensive review of nanoparticles applications in the oil and gas industry

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Abstract
With the increased attention toward nanotechnology and their innovative use for different industries including but not limited to food, biomedical, electronics, materials, etc, the application of nanotechnology or nanoparticles 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. In this paper, comprehensive literature was conducted to review the different applications of nanotechnology in the oil and gas industry. A summary of all nanoparticles used along with a detailed analysis of their performance in improving the targeted parameters is comprehensively presented. The main objective of this review was to provide a comprehensive summary of the different successful applications of nanotechnology and its associated challenges, which could be very helpful for future researches and applications.

Keywords Nanoparticles · Nanotechnology · Nanofluids · Review

Introduction
The concept of nanotechnology was inspired after Richard Feynman talk “There’s Plenty of Room at the Bottom” at the California Institute of Technology in 1959 (Gribbin and Gribbin 2018) where he discussed the idea in which scientists would be capable of handling individual atoms and molecules. The term “nanotechnology” was then first introduced and used by Professor Norio in 1974 (Norio 1974), where it was defined as “the production technology to get extra high accuracy and ultra-fine dimensions, i.e., the preciseness and finesse of the order of 1 nm (nanometer) 10–9 in length”. In addition, it was stated that “nanotechnology” mainly involves “the processing of separation, consolidation, and deformation of materials by one atom or one molecule” (Norio 1974). Since then, different researchers started using the term “nanotechnology”. The general definition of “nanotechnology” as per the National Nanotechnology Initiative (NNI) (National Nanotechnology Initiative 2000) is “science, engineering, and technology conducted at the nanoscale, which is about 1 to 100 nm”.

The increased interest in nanotechnology-related research and development is clearly reflected through the huge amount of money invested in nanotechnology R&D. The NNI alone has received almost $27 billion including the proposed budget for 2019 (National Nanotechnology Initiative 2018). Another example is the huge investment of $350 million by Massachusetts Institute of Technology (MIT) for the state-of-the-art nanoscale research center named “MIT nano” (Chandler 2014). NanoMech, which is a leading company in nanomanufacturing, has received $10 million investment from Saudi Aramco Energy Ventures (SAEV).

Nanotechnology has been used in different industries including but not limited to food, biomedical, electronics, materials, etc. One of these industries is the oil and gas industry, where the revolution of nanotechnology applications covered different areas in both upstream and downstream. A quick look at the recent published applications related to nanotechnology reveals a wide range of
nanotechnology such as nanoparticles (Sensoy et al. 2009; Ogolo et al. 2012; Hafiz et al. 2018), nanocomposite (Lecolier et al. 2005; Pourafshary et al. 2009; Chauhan and Ojha 2016; Kumar et al. 2018), nanomembrane (Seland et al. 1992; Kong and Ohadi 2010; Shen and Sheng 2016; Guo et al. 2013; Ventura et al. 2017; Folio et al. 2018), nanosensors (Sudarshan et al. 2001; Piantanida et al. 2013), nanorobot (Singh and Bhat 2006; Joshua 2014), nanofluids (Kanj et al. 2009; Alomair et al. 2014; Gerogiorgis et al. 2017; Yuan and Moghanloo 2018).

A lot of questions are always raised when proposing a new application of nanotechnology in the oil and gas industry, these questions include; why nanoparticles? What makes nanoparticles better than the conventional solution? The answer to these questions can be summarized as follows: Nanoparticles have some distinctive properties such as their size and their relatively large surface-to-area ratio when compared to the same volume that is made from larger particles, which can result in a higher magnitude of reactivity or interaction with adjacent surfaces, hence enhancing the properties of the carrying fluid with a lower amount of the same material. In addition, the small size of nanoparticles empowers them in terms of transportation through the small pores in the formation, which will help the used nanoparticles in flowing easily inside the pore spaces. Therefore, the use of nanoparticles in the oil and gas industry can be justified due to their above-mentioned unique characteristics.

With this growing attention and development of nanotechnology in the oil and gas industry, which can be clearly observed through the number of related publications (Fig. 1), it is crucial to review the available application and summarize what has been done up to date.

The main objective of this paper is to provide the reader with a comprehensive summary of the successful application of nanotechnology and its associated challenges. This paper highlights, in particular, the different applications of nanoparticles (NPs) in enhancing related parameters to enhanced oil recovery (EOR), drilling fluids, cementing, and well stimulation.

Applications of nanoparticles in oil and gas industry

In this section, a comprehensive review of the most recent applications of nanoparticles in the oil and gas industry including EOR, drilling fluids, cementing, and well stimulation, is discussed. The discussion includes a tabulated summary of the used NPs, the investigated parameters, and their effectiveness in terms of improving the targeted parameters.

Enhanced oil recovery applications

Due to the fact that two-thirds of the oil in place is left behind after the primary and secondary recovery (Bai 2008), and based on the significant increase observed in oil recovery using enhanced oil recovery techniques (EOR), which includes chemical injection, thermal recovery, and gas injection, a good number of researches have been conducted to improve the different EOR techniques by the addition of nanoparticles. Table 1 shows a summary of the recent investigations on the application of nanoparticles to enhance EOR techniques along with the targeted parameters and the investigated nanoparticles. The main objective of these investigations is to study the effect of nanoparticles in improving oil recovery by improving one of the parameters related to oil recovery.

Despite the fact that NPs might improve some parameters, it could also negatively affect some other parameters. Hogeweg et al. (2018) found that zinc oxide tends to form larger particles resulting in injection difficulties. Adding NP to brine or ethanol could result in poor recovery compared to brine or ethanol alone. Injection blockage and settling issues have also been reported previously (Ding et al. 2018). NP...
could modify the permeability up to a certain limit when all contact surfaces are covered with NP and at that point, a reduction in porosity and absolute permeability would initiate (Ogolo et al. 2012; Druetta et al. 2018).

**Drilling fluids applications**

Drilling fluids can be simply defined as a heavy viscous fluid mixture that is used during the drilling stage in order to perform different tasks including lifting the drilled cuttings, controlling the formation pressure, maintaining wellbore stability, etc. Different additives are used to enhance the different properties of drilling fluids such as the rheological properties, filtration properties. 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.

| Investigated NP | Improved parameters | References |
|-----------------|---------------------|------------|
| Aluminum oxide | Reducing oil viscosity | Hogeweg et al. (2018) |
| Titanium dioxide | Improving the stability of the injected water for EOR application | |
| Aluminum oxide | Improving oil recovery using low salinity hot water (LSHW) injection with addition of nanoparticles | Ding et al. (2018) |
| Silicon dioxide | Improving the rheological properties of the injected water for EOR application | Abdullahi et al. (2019) |
| Titanium dioxide | Improving oil recovery | |
| Cellulose nanocrystals (CNCs) | Conformance control | Pandey et al. (2018) |
| | Stability of oil in water emulsions | |
| Graphene oxide | Reducing oil viscosity | Elshawaf (2018a) |
| Graphene oxide | Reduction in oil viscosity | Elshawaf (2018b) |
| Graphene oxide | Improving oil recovery | |
| Graphene oxide | Improving the stability of the injected water for EOR application | |
| Graphene oxide | Improving oil recovery | |
| Graphene oxide | Improving rheological properties | |
| Graphene oxide | Improving oil recovery | |
| Magnesium oxide | Altering wettability | Ogolo et al. (2012) |
| Aluminum oxide | Reducing interfacial tension | |
| Zinc oxide | Reducing oil viscosity | |
| Zirconium oxide | Reducing mobility ratio | |
| Tin oxide | Altering permeability | |
| Iron oxide | | |
| Nickel oxide | Enhancing oil recovery at low concentration | Giraldo (2018) |
| Hydrophobic Silicon dioxide | Reducing interfacial tension, hence increasing oil recovery | |
| Nickel oxide/silicon dioxide | Improving mobility control, altering surface wettability | ShamsJazeyi et al. (2014) |
| Janus nanoparticles | Improving mobility reduction factor (MRF) | Khajehpour et al. (2016) |
| Polymer-coated nanoparticle | Improving foam stability | |
| Silicon dioxide | Improving mobility control, altering surface wettability | Ibrahim and Nasr-El-Din (2018) |
| Silicon dioxide | Improving foam stability | |
| Silicon dioxide | Improving foam stability | |
| Silicon dioxide | Reducing surfactant adsorption on the porous media of an oil reservoir | Suresh et al. (2018) |
| Silicon dioxide | Improving emulsion with lower surfactant concentration | Arab et al. (2018) |
| Silicon dioxide | Improving oil recovery | |
| Silicon dioxide | Reducing oil viscosity | Pinzón (2018) |
| Silicon dioxide | Improving surfactant properties | Zargartalebi et al. (2014) |
| Silicon dioxide | Reducing surfactant adsorption on the porous media of an oil reservoir | |
| Surface-functionalized nanocellulose | Improving oil recovery using “green” chemical EOR through water flooding | Wei et al. (2018) |
in overcoming these limitations. A summary of the recent investigations to improve the drilling parameters by means of nanoparticles is given in Table 2.

Based on the review, it was found that high NP concentration is not recommended due to the insignificant performance increase observed between low and high NP concentrations (Alsaba et al. 2018; Mahmoud et al. 2018). High concentration could also result in increasing the particles friction coefficient, which may alter lubricity and hole cleaning efficiency (Alvi et al. 2018). At high temperatures, some NP could result in a negative effect on filtration characteristics. Alsaba et al. (2018) showed that copper oxide has better thermal stability when compared to magnesium oxide and aluminum oxide in terms of rheological properties. In addition, it was found that silicon dioxide NP might increase the pressure losses in bentonite water-based mud (Minakov et al. 2018) due to the increase in the frictional forces.

### Cementing applications

Well cementing, which can be defined as the process of mixing and pumping cement slurry downhole in the annuls and allowing it to cure and bond between the formation and the casing, is a crucial element in well construction. There are at least six common API classes of cement that meet certain requirement such as sulfate resistance or high

| Investigated NP | Improved parameters | References |
|-----------------|---------------------|------------|
| Aluminum oxide  | Improving rheological properties | Alsaba et al. (2018) |
| Copper oxide    | Improving filtration characteristics | Alsaba et al. (2018) |
| Magnesium oxide | Improving rheological properties | 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) |
| Multivall carbon nanotube (MWCNT) | Improving heat transfer | Hassani et al. (2016) |
| Zinc oxide      | Improving rheological properties | Hassani et al. (2016) |
| Silicon dioxide | Improving lubricity of drilling fluids Improving rheological properties Improving filtration characteristics | Ismail et al. (2016) |
| Multivall carbon nanotube (MWCNT) | Improving rheological properties | Ismail et al. (2016) |
| Silicon dioxide | 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 | Improving sealing of pores Improving wellbore stability for shale formation | Wang et al. (2018) |
| Sulfonated nanoparticles | 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) |
| Silicon dioxide | Improving rheological properties | Parizad et al. (2018) |
| Titanium oxide  | Improving thermal and electrical conductivity Improving filtration characteristics | Minakov et al. (2018) |
| Titanium oxide  | Improving rheological properties | Minakov et al. (2018) |
| Silicon dioxide | Improve hole cleaning | Minakov et al. (2018) |
| Aluminum oxide  | Improving rheological properties Improving thermal stability Improving filtration characteristics | Perween et al. (2018) |
early strength (Mangadlao et al. 2015). Cement additives are added to improve specific parameters such as; density, setting time, filtration, and viscosity. Several studies addressed the use of nanoparticles in well cementing to enhance cement properties. A summary of the wide range of investigated nanoparticles and their effects on cement properties is presented in Table 3.

The curing fluid, such as limewater or water, can greatly affect the cement compressive strength. It was found that cement can be preferably replaced with 2% aluminum oxide NP when cured in limewater and 1% aluminum oxide NP when cured in water. However, the addition of the NP can reduce the workability of the cement where different materials need to be added such as plasticizers (Nazari and Riahi 2011). Alkhamis and Imqam (2018) found that graphene nanoplatelets cause a reduction in cement sheath thermal gradient, which may cause thermal cracks when acceding the tensile stress. Experimental evaluation performed by Santra et al. (2012) using multiwalled carbon nanotubes (MWNTs) did not show an improvement in cement mechanical properties.

### Well stimulation applications

Well stimulation can be simply defined as treatments used to enhance the well productivity either by hydraulic fracturing and matrix acidizing to increase the permeability or by increasing the well production. Few investigations showed an improvement in the well stimulation jobs by means of nontechnology. The targeted properties included filtration and rheological properties of the fracturing and acidizing fluid. A short summary of the investigated nanoparticles and their effects is listed in Table 4.

Nasr-El-Din et al. (2013) found that the salt concentration greatly affects the viscoelastic surfactant fracturing fluid including NP and causes some viscosity stability. The addition of magnesium oxide NP causes a decrease in apparent viscosity of the fracturing fluid. Silicon dioxide acid showed different behavior in limestone compared to shale. Fracture conductivity of shale rock showed better improvements when compared to limestone rock (Singh et al. 2018). Fakoya and Shah (2018) found that there is an optimum concentration to improve rheological properties of surfactant-based fluids for hydraulic fracturing applications, where higher concentration was not recommended.

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

Figure 2 shows the distribution of the different nanoparticles investigated in the reviewed literature. It can be clearly seen that silicon dioxide is the most widely used nanoparticles across the oil and gas industry followed by aluminum oxide.

Figure 3 shows the highest targeted property for improvement by means of nanoparticles. It can be clearly seen that nanoparticles have been investigated heavily to study their effect on increasing the oil recovery, which falls down under EOR applications followed by improving the filtration characteristics of drilling fluids and improving cementing, while the least investigated property was found to be the lubricity of drilling fluids.

The percentage of the conducted investigations of nanoparticles across the oil and gas industry for the four applications discussed above is shown in Fig. 4. It can be observed that nanoparticles have attracted researchers in EOR, drilling, and cementing applications. However, the application of nanoparticles for stimulation applications is still not as high as the other applications.

Challenges for nanotechnology in the oil and gas industry

Despite the growing number of investigations with respect to the high potential of using nanoparticles, there are few challenges that are still controversial. These challenges arise from the following questions; is it economically feasible to replace conventional materials with nanoparticles? Can they result in the same performance on a larger scale (field conditions) similar to the small scale (lab condition)? What is their implication on health, safety, and environment (HSE)? Can they be produced easily and economically? In
this section, a brief discussion of these challenges will be presented.

In regard to the economic feasibility of nanoparticles versus conventional materials, the main reason behind this question is basically the relatively higher cost of producing some nanoparticles compared to conventional material. The higher cost of production is basically due to the relatively higher embodied energy required to produce nanomaterials per unit mass compared to bulk materials (Kim and Fthenakis 2012). The other reason is the shortage of commercially available nanoparticles for oil and gas applications, despite the fact that a good number of major oil services companies investing a lot in terms of research with respect to nanotechnology.

The other challenge with respect to their effectiveness when applied to a larger scale in the field rather than the laboratory-scale requires better collaboration between oil companies and researchers to validate their performance through pilot testing. It is well known that new technologies require a lot of time before they are applied in the field; however, there are few field trials, which will be discussed in the next section.

When it comes to the impact of nanoparticles on health, environment, and safety, they can be very hazardous and might lead to severe health issues (Nabhani and Tofighi 2010) since they have higher potential of being inhaled or absorbed through skin (Lau et al. 2017) due to their unique properties of nanoparticles in terms of size and surface-to-area 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 reduce or avoid associated risks when handling nanoparticles. Examples of the available standards provided by the National Nanotechnology Initiative (National Nanotechnology Initiative 2019) are given in Table 5.

### Does nanoparticles work in the field?

For the oil and gas industry, in particular, different nanotechnology applications have been proposed based on laboratory experiments. Most of the reported results in the literature showed the potential of nanoparticles in improving the evaluated parameters. Nevertheless, to the best of our knowledge, few field trials have been reported. A summary of the field trials of nanoparticles and nanofluids that shows the potential of nanotechnology applications is given in Table 6.

### Conclusions

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 and many studies have shown very promising results in terms of their performance and effectiveness. These promising results are due to the distinctive properties of nanoparticles. Despite the high potential of using nanoparticles, there are some challenges such as their economic feasibility and their impact on HSE. Based on the comprehensive literature review, the following conclusions were made:

- The most widely investigated nanoparticles that showed significant improvement for the different applications across the oil and gas industry were found to be the nano-silica ($\text{SiO}_2$) followed by aluminum oxide ($\text{Al}_2\text{O}_3$), which suggests their high potential in being applied in the field.
- The investigated nanoparticles have shown a significant positive impact on both the rheological and filtration characteristics of drilling fluids as well as improving the thermal stability of drilling fluids.

| Document | Title |
|----------|-------|
| ASTM E2909-13 | Standard guide for investigation/study/assay tab-delimited format for nanotechnologies (ISA-TAB-nano): standard file format for the submission and exchange of data on nanomaterials and characterizations |
| ISO/TS 80004-1:2010 | Nanotechnologies—vocabulary—part 1: core terms |
| ASTM E249009(2015) | Standard guide for measurement of particle size distribution of nanomaterials in suspension by photon correlation spectroscopy (PCS) |
| ISO/TR 13014:2012 | Nanotechnologies—guidance on physicochemical characterization of engineered nanoscale materials for toxicologic assessment |
| ASTM E2524-08(2013) | Standard test method for analysis of hemolytic properties of nanoparticles |
| ISO/TS 12901-1:2012 | Nanotechnologies—occupational risk management applied to engineered nanomaterials—part 1: principles and approaches |
| ASTM E2996-15 | Standard guide for workforce education in nanotechnology health and safety |
Most of the investigated nanoparticles resulted in enhancing the mechanical properties of cement as well as providing a better control for the set time.

In addition, a significant increase in oil recovery was observed when nanoparticles were applied for EOR application on a laboratory scale by means of wettability alteration and oil viscosity reduction.

Despite a large number of laboratory-scale investigations published in the literature, only four filed trials with promising results were published to the best of our knowledge suggesting the need for more field trials.

Based on the challenges discussed, more research should be conducted in order to reduce the cost of producing nanoparticles.

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Alomair OA, Matar KM, Alsaed YH (2014) Nanofluids application for heavy oil recovery. In: SPE Asia Pacific oil & gas conference

| Used nanoparticle | Application | Location | Results |
|-------------------|-------------|----------|---------|
| Aluminum oxide nanosilica | Inhibition and remediation of formation damage | Columbia | After 8 months of injecting aluminum oxide, the oil rate has increased by 300 bbl/day. Another trial using nanosilica resulted in an oil and gas rate increase of 134 bbl/day and 1 MMSCF/day, respectively. |
| Carbon-based fluorescent nanoparticle named “A-Dots” | Evaluating the stability of nanoparticles in harsh formation environment as water injection tracers by means of recovery percentage | Saudi Arabia | The results showed a high recovery percentage, up to 86%, suggesting their high stability. Another trial was conducted in the same field and confirmed their high stability. |
| Carbon-based fluorescent nanoparticle named “A-Dots” | Stabilizing shale formation using water-based drilling fluid containing nanoparticles | Brazil | The results showed good performance in terms of shale hydration inhibition and well bore stability. The same fluid was stored and used to drill another section in a different well after almost 3 months, which resulted in a 15% reduction in the well cost. |

Table 6 Summary of nanofluids field trials
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