



Evolution of nanomaterials in petroleum industries: application and the challenges

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Received: 30 August 2019 / Accepted: 15 May 2020 / Published online: 25 May 2020
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Abstract

Due to soaring demand for universal energy, industry forced to look forward in either expand the limit of conventional energy resources or to look at other possibilities such as renewable energy resources and unconventional hydrocarbon resources. The challenges might be figured out by revolutionary technological developments in the energy sector by science and technology. The industry needs splendid technological breakthroughs in the energy sector to push the final frontier of conventional energy resources. Owing to its superior particle size and properties, nanotechnology can likely of moving far that current energy supply by introducing new technologies. The exact exploitation and manipulation of matter at measurements of (1–100) nanometres have revolutionized many sectors, including the petroleum sector. The upgrade in nanoscale organized materials represents one of the fascinating, inventive viewpoints bringing innovative advances in numerous industries. The charge of oil extraction is under heavyweight, and it becomes increasingly difficult to legitimize it when the gross price of oil is powerless and depressing. There is a universal belief that nanotechnologies can be to produce new, more valuable nanomaterials to oppose these technological limitations. Many research endeavours are being coordinated towards the opening of immense and diverse advantages of nanotechnology in the oil and gas industry. The research experts have experienced the utilization of different nanoparticle types and sizes. Nanoparticles show exceptional properties because of their large surface area and highly activated particle surface. The nanotechnology can be performed at a different scale in petroleum engineering from exploration, drilling, cementing, reservoir, completion, production, and processing and refinery in each stage. This paper intends to give a concise thought of the significant uses of nanoparticles, their potential advantages, associated economic and technical challenges, and solutions.

Keywords Nanomaterial · Nanofluids · Oil recovery · Drilling fluids

Introduction

The control, coordination and integration of atoms and molecules at the nanoscale lead to emerging technological materials, structures, tools, devices, circuits, sensors and systems employing nanotechnology (Darjani et al. 2017; Mozaffari et al. 2016; 2018a; Li et al. 2019). Physically nano-sized particles have dimensions of one-billionth of a metre. Even dimensions of water molecules are roughly

one-tenth of nanometres (Mozaffari et al. 2018b, 2019). The nanotechnology can construct and manipulate material at the molecular level that makes it likely to form something which has superior properties such as both being lightweight and high strength, and some capabilities like optical, mechanical, electrical and heat conductivity. The thermo-physical properties change with changes in shape, size, base fluid and volume proportion of fluid. Some of the researchers carried out theoretical and experimental studies on a nano-fluid containing different shapes of nanoparticle (Hamilton and Crosser 1962; Timofeeva et al. 2009; Aaiza et al. 2015; Ellahi et al. 2016; Khan 2017). The rise of nanotechnology as a new power to rule in a multidisciplinary research study has prompted the advancement of nanomaterials and nanofluids, where the oil and gas industry can accept the modern advanced nanotechnology to tackle down to issue experienced in oilfield, particularly in enhanced oil recovery

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efficiency (Liu et al. 2017; Patel et al. 2020a, b; Pandya et al. 2019; Shah and Shah 2020; Shah et al. 2020). Owing to its superior nanometre scale ranging from 0.1 to 100 nm and unique properties, nanotechnology poised the significant influence on all sectors (Mokhatab et al. 2006; Muraza and Galadima 2015; Khalil et al. 2015, Wei et al. 2007, Chen et al. 2009). Nanoparticles, for their unique physicochemical characteristics, have brought attention in many industries, including the petroleum industry. Already, nanoscience is used or explored in critical areas related to remote sites including arctic and harsh deep sea condition and also unconventional reservoirs in every significant field of these industries, including exploration, drilling, monitoring, generation and processing and distribution. Notable of these are in the production sector. Here, the main objective of using nanometric particles is to change the reserve conditions needed to improve production economically. Nanomaterials can also solve problems with oil drilling by changing the quality of cake and reducing the sticking problems of tubes. Damage problems near the reservoir depend on the quality of the slime cake, which can be effectively modified using nanomaterials (Khan 2017; Thakkar et al. 2019).

Exploration and reservoir characterization

Hydrocarbon exploration is significant but very costly and risky assessments in the petroleum area (Patel et al. 2020a, b). Hydrocarbons are being investigated to determine the accumulation of hydrocarbons below the earth's surface. However, it often encounters many challenges, such as geometric uncertainty and unexpected hazards that can affect the overall cost. Current probing technologies are not yet capable of exaggerating the high-resolution backup display and are unable to delve into the water to obtain adequate information about plumbers. Backup helps to estimate the reserve, characterize the tanks and monitor its performance. Moreover, many sensitive techniques, such as conventional electro-profiling, often cannot exaggerate reliable information under specific backup conditions. Despite advanced research techniques such as 3D and 4D seismic graph studies, the oil and gas sector still need an advance electrical method, sensitive electromagnetic imaging methods, sophisticated modelling and simulation techniques to improve deep-water understanding (Kong and Ohadi 2010).

Implementation of nanotechnology can enable predicting the accumulation of hydrocarbon and characterization of the reservoir. The size-dependent optical, chemical, electrical and magnetic characteristics of the nanoparticle can be used as nanosensor as it would be easily percolating through geological structure and give the information of the reservoir. A new sensing technique can also enable obtaining data of

deeper reservoir region and complex interaction of geological formation with the immiscible fluid.

Magnetic nanomaterial can be potentially useful as a contrasting agent to control and evaluate the formation behaviour. The fundamental concept is that magnetic nanomaterial generates a magnetic field, which in turn decreases the speed of the electromagnetic wave, and 3D motion graph is obtained by determining the temporal fluctuations. The motion of magnetic nanoparticles/nanomaterial could be known precisely using electromagnetic waves which are transmitted by it and recorded on the receiver. From this method, the plot of the flow of reservoir fluid can be drawn assuming the laminar movement along with nanomaterials. In a recent study, Rahmani and co-workers carried out and experimented on ferrofluid to monitor the EM conductivity and magnetic tracing of its slug by the use of superparamagnetic iron oxide nanoparticle (SPION). It observed that ferrofluid alter the magnetic permeability of rock in a specific region at a shallow frequency which provides a high-resolution image of the flood (Rahmani et al. 2015).

In another study, Chi et al. (2016) used SPION as a contrasting agent and injected into rock and characterize their effect on Nuclear Magnetic Resonance (NMR). The combination of SPION with NMR relaxometry enables enhancing the characterization process to find the pore size distribution, its connectivity and fractures in rocks.

The previously fabricated all the experiments show that the nanosensor and nanorobot would be able to sense the reservoir condition (high salinity, pH, Ca^{2+} , high temperature, fluid behaviour and all the information about useful reservoir mapping).

To detect hydrocarbons in oilfield rocks, Berlin et al. (2011) and Hwang et al. (2012) used sulphated and unsulphated polyvinyl alcohol-functionalized oxidized carbon black (PVA-OCB) nanoparticles. In this approach, nanoreporter (sulphated PVA-OCB) helps to transport noncovalently attached probe molecules through the heterogeneous formation and selectively anticipating when the rock contains oil. It gives quantitative information on oil content based on probe molecule remaining in the nanoreporter. Additionally, the same concept is applied by Hwang et al. (2014) for the detection of H_2S . In this approach, polyvinyl alcohol-activated carbon black with H_2S sensor is injected in oil and water containing porous medium and based on the enhancement of fluorescent level in production, well H_2S content can be determined.

Another new implemented application of nanomaterial-based sensing device for monitoring substance such as toxic, hazardous and flammable gas is essential for crew member's health and safety in petroleum extraction and storage operation. In a recent study, Piantanida and co-workers have demonstrated a small, economically feasible, low magnitude

power, highly sensitive and correctly sensing for the hydrogen sulphide (H_2S) based on WO_3 nanoparticles. In another study, Turkenburg et al. (2012) have demonstrated water-dispersed nanosensor for the waterflooding process which is based on a cocktail containing InP/ZnS quantum dots (QDs) and atomic silver (Ag) cluster with a bright luminescence to improve sensor functionalities (Fig. 1).

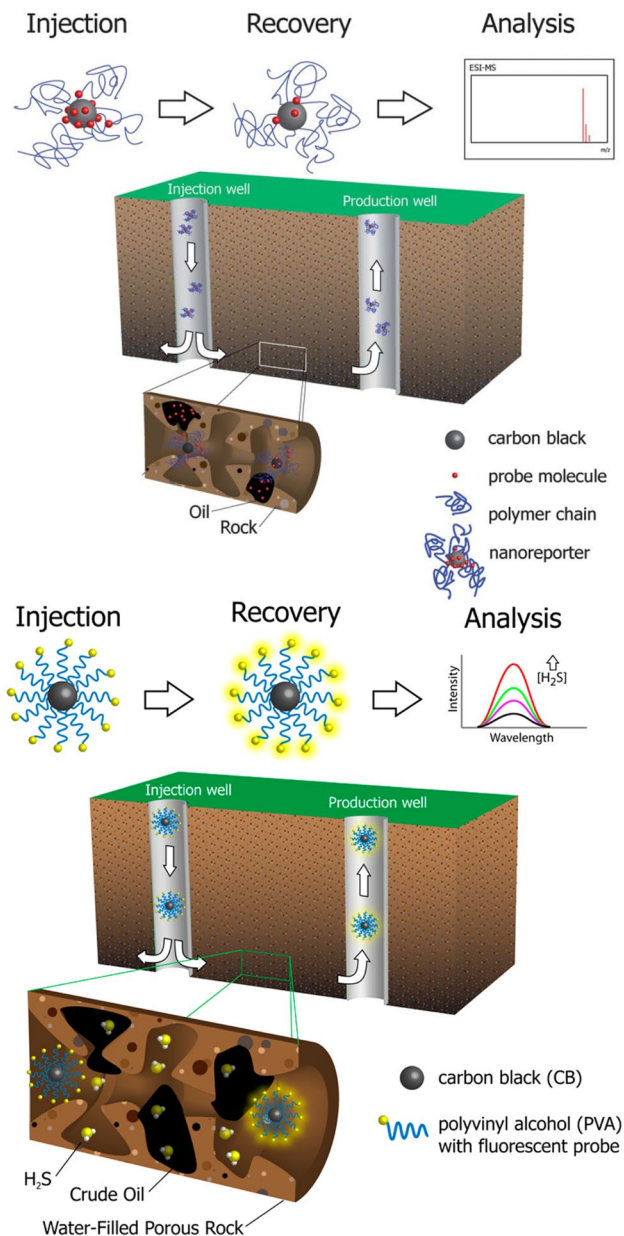


Fig. 1 Schematic diagram for subsurface oil detection and H_2S detection by nanoreporters

Drilling

Drilling fluids

The drilling operation is the most critical, high-risk operations to access the reservoir in the oil and gas sector. The perfect formulation and expertly designed drilling fluids are a road map to exceed the target depth of the hydrocarbon reservoir. There are water-based fluid, oil or synthetic-based fluids and pneumatic-based fluids generally used in the oil and gas industry in different conditions (Sadeghalvaad et al. 2015). The different types of nanoparticles (NPs) of size (1–100 nm) are in colloidal suspension considered to be nano-based fluids. In the account of physico-chemical properties of NPs, higher surface area and higher thermal conductivity, NPs in addition of additive could be able to improve the characteristics and performance of drilling fluid in terms of thermal stability, wellbore stability, salinity control, the formation of filter cake, rheological stability and mud filtration properties.

The rheology of drilling fluid is an important term which affects the drilling performance. The prime objective of a drilling fluid should be less resistant at higher shear rate, and that can be obtained by shear thinning characteristics of a drilling fluid. NPs can improve the rheological properties of drilling fluid by various mechanisms, and that depends on type and characteristics of NPs. Table 1 gives the summaries of various NPs on modification of rheological properties of drilling fluid.

For the better development of drilling fluid, William and co-workers identified that the nanofluid CuO and ZnO with xanthan gum aqueous solution which are termed as nanofluid-enhanced water-based drilling muds (NWBM) improve the rheological, thermal and electrical properties. They also reported that NWBM based on CuO nanofluid shows enhanced thermal properties and offers more resistant to HPHT condition in contrast to ZnO-based NWBM (William et al. 2014). Again, Ponmani and co-worker investigated the alteration of thermal, electrical and fluid loss properties of NWBM. They studied an effect of nanofluid CuO and ZnO with the base fluids such as polyvinylpyrrolidone (PVP), polyethylene glycol (PEG) and xanthan gum for the application of drilling fluid. They viewed that fluid loss decreases with the addition of nanofluids in WBM and also increases the thermal and electrical properties of nano-based drilling mud (Ponmani et al. 2016). Additionally, Liu et al. (2017) investigated new synthesized cellulose nanofibres (CNFs) which are renewable, non-toxic and relatively less expensive to synthetic polymers and its impact on water-based drilling fluid for rheology and filtration control. They observe that CNFs

Table 1 Summary of recent literature investigating various NPs to improve the rheological properties

Types of NPs	NPs size (nm)	Base fluid	Modified properties	Experimental conditions	References
Clay and silica	Not specified	Oil	Plastic viscosity and gel strength	HPHT at 437 °F and 500 psi	Agarwal et al. (2011)
SiO ₂	20	Oil	Plastic viscosity	HPHT at 77–284 °F and pressure up to 6000 psi	Anoop et al. (2014)
Palygorskite	10–20	Water	API fluid loss, filter cake thickness and improve heat transfer	HPHT at 100–392 °F and 100–16,000 psi	Abdo and Haneef (2013)
Nanocomposite of ZnO, montmorillonite and palygorskite	5–50	Water	Plastic viscosity and yield point	HPHT at 109–370 °F and 150–18,500 psi	Abdo et al. (2014)
Fe ₂ O ₃ and SiO ₂	Not specified	Water	Plastic viscosity, yield point and improve heat transfer	HPHT	Mahmoud et al. (2016)
SiO ₂	Not specified	Water	Viscosity	LPLT	Srivatsa et al. (2012)
Cellulose nanoparticles	8.2	Water	Viscosity, API fluid loss and filter cake thickness	LPLT	Song et al. (2016)
SiO ₂	Not specified	Water	Plastic viscosity, gel strength and yield point	High temperature at 250 °F	Taraghikhah et al. (2015)
Fe ₂ O ₃	Not specified	Water	API fluid loss, HPHT fluid loss and Improve Heat Transfer	LPLT and HPHT	Barry et al. (2015)
Carbon nanotubes	–	Water	API fluid loss, HPHT fluid loss, shale inhibition and improve heat transfer	LPLT and HPHT (248, 302, 347, 392 °F)	Halali et al. (2016)
Graphene and carbon nanotubes	–	Oil	HPHT fluid loss	HPHT (59–199 °F)	Madkour et al. (2016)
Nanographite	40	Oil	API fluid loss	LPLT	Nasser et al. (2013)
TiO ₂	Not specified	Water	API fluid loss and filter cake thickness	LPLT	Sadeghalvaad et al. (2015)
Boron	Not specified	Water	Improve heat transfer	HPHT	Krishnan et al. (2016)
Latex particles and aluminium complexes	80–345	Water	Improve heat transfer	LPLT and HPHT	Liu et al. (2015)
Fe ₃ O ₄ /PAA	10–20	Water	API fluid loss and filter cake thickness	HPHT	Tian et al. (2019)

provide ideal performance for rheology and mud filtration control which transcend thermal stability of xanthan gum.

For filtration loss of drilling fluid into the formation, Shakib et al. (2016) studied the effect of different nanomaterials like nano-titanium, nano-copper oxide, nano-alumina and nano-clay on water-based drilling fluid. The experimental studies show that all these materials have superior properties in comparison with conventional additive and mud cake formed by the nano-clay has significantly lower permeability which reduces the filtrations.

Recently, Ahmad and co-workers studied the effect of novel water-soluble polymers and NPs on bentonite drilling fluid. They observed that NPs improve the filtration properties by decreasing the fluid loss in the formation and highly permeable zone by making thin filter cake for the smooth drilling operation. In contrast, the polymers enhance the rheological characteristics and dispersion of bentonite (Ahmad et al. 2017).

For high-pressure, high-temperature (HPHT) drilling, Fe₂O₃ and Fe₃O₄ are found to be an excellent and effective additive in drilling fluid. An optimum concentration of NPs bring significant benefits to obtain better cake quality. The Fe₂O₃ and Fe₃O₄ nanoparticles are enabled to improve the filter cake and filtration characteristic of bentonite-based drilling fluids at downhole condition up to 500 psi and 350 °F. Additionally, NPs can also allow developing the filtration characteristics in the static and dynamic state (Vryzas et al. 2016; Mahmoud et al. 2017).

Drilling bits

A drilling bit is a tool for cutting and grinding of formation which is placed at the distal end of the drill string. Polycrystalline diamond compact (PDC) bits are commonly used in drilling technology. Nanotechnology has the potential to

design drill bits more appropriate and affordable for drilling jobs. Due to having a unique property of nanomaterials such as mechanical, electrical and thermal properties, they can be able to improve the performance of drilling bits. Chakraborty and co-workers investigated the working rule of nanodiamond, return on PDC cutters and property alteration in contrast to base PDC matrix. They witnessed that nanodiamond PDC technology can enable one to drill in harsher condition and demanding reservoir condition (Chakraborty et al. 2012).

Furthermore, Sengupta and Kumar (2013) studied the effect of Al_2O_3 – TiO_2 coating on drilling bit via a plasma coating method to improve the bit life and mitigate bit string trips. They observed that bond strength and toughness are doubling compared to conventional coating.

Cementation

The principal challenges in ensuring the well integrity in oil and gas exploration are the stability and integrity of the cement sheath around the carbon steel casing. Typically, there are several cementing problems during the drilling and production operation, such as casing centralization, inadequate cement formation, excessive wellbore damage during drilling, shrinkage of cement, incomplete cement placement, filtration of cement slurry to nearby formation and well integrity, micro-annuli in cement, cement failure due to mechanical or thermal stress, corrosion of casing and many more. To overcome this issue, selecting cementing material and its operation play a significant role in oil and gas exploration and production. Recently, developed smart cement materials in nanoscale act as additives with superior characteristics to solve or improve numerous practical issues by enhancing mechanical strength, heat and electrical conductivity and reducing permeability and porosity.

There are many types of metal oxide NPs with different additives, such as nano-silica (Lin et al. 2008; Jo et al. 2007; Qing et al. 2007; Jalal et al. 2015; Nili and Ehsani 2015), TiO_2 (Nazari and Riahi 2010a, b, 2011a, b, c, d; Zhang et al. 2015), Al_2O_3 (Nazari and Riahi 2011a, b, c, d, 2012), ZrO_2 (Nazari and Riahi 2010a, b, 2011a, b, c, d), Fe_2O_3 (Li et al. 2004; Khoshakhlagh et al. 2012), Fe_3O_4 (Sikora et al. 2016; Horszczaruk et al. 2017), CuO (Riahi and Nazari 2011; Khotbehsara et al. 2015), ZnO_2 (Nazari and Azimzadegan 2012) and other types of magnetic nanoparticle (Blyszko et al. 2008), which improve the properties of concrete and cements, such as strength, resistance to water or air penetration, and provide self-compacting and many more.

Recently, it is noted that multi-walled carbon nanotubes (MWCNTs) can improve the properties of cement, such as impact toughness and durability, dry shrinkage capacity and permeability resistance (Yu and He 2015; Wang 2015).

Additionally, the ultra-low proportion of carbon nanotubes (CNTs) and carbon nanofibres (CNFs) can able to modify the electrochemical properties of cement paste (Wong et al. 2015). Furthermore, Konsta-Gdoutos and co-workers investigated the impact of the carbon nanotubes (CNTs) and nanofibres (CNFs), and their dispersion on the corrosion performance, strength, electrical resistivity and mechanical properties of nano-modified Portland cement mortars (Konsta-Gdoutos et al. 2017). They conclude that CNTs and CNFs reduced corrosion rate by postponing onset corrosion activity, and so, ultimately, the increase in corrosion resistance is noticed.

Reservoir characterization and management

Nanotechnology enhances production by improving the effectiveness of various parameters at the nanoscale. Reservoir characterization has more importance in the petroleum industry. The optimization of the lifetime of a reservoir gives better performance for a long time. Many factors affected the reservoir characterization and management. In this unit, it involves the different NPs that are suitable to get more production.

Enhanced oil recovery

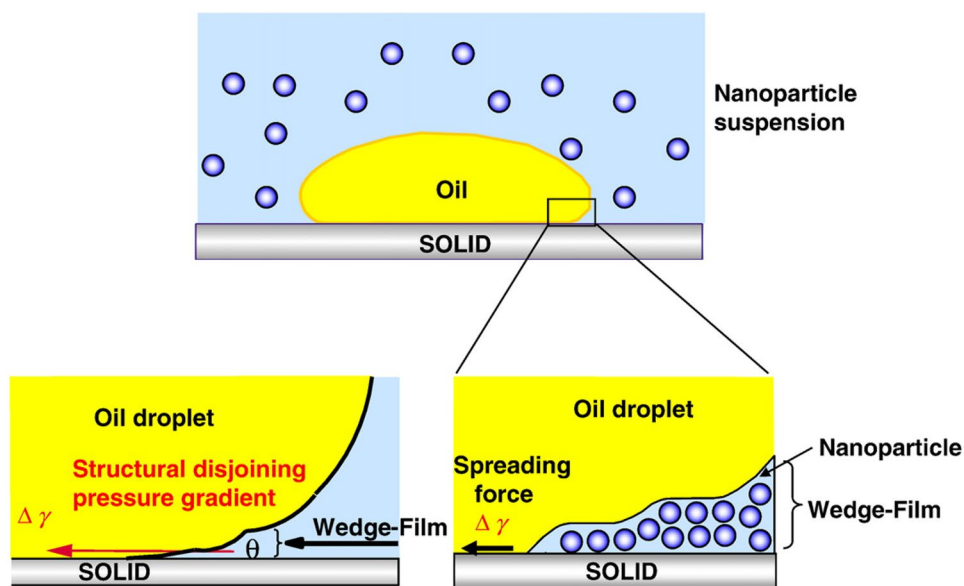
The nanotechnology enhanced oil recovery based on the incorporation of NPs and nanofluids to improve the conventional EOR processes. It covers the application of NPs in both chemical enhanced oil recovery (CEOR) and thermal enhanced oil recovery (TEOR).

Chemical enhanced oil recovery (CEOR)

Chemical methods for EOR can modify some important parameters which have high importance for the production of hydrocarbons (HCs), such as mobility ratio (M), interfacial tension (IFT), wettability and the effect of chemical solutions on a reservoir rock surface. CEOR can alter this parameter in favour of improving oil recovery by changing the mechanism of HCs such as IFT reduction, viscosity and wettability alteration and trapped out the HCs from pore spaces (Ali et al. 2018). NPs can change the oil recovery mechanisms to trap out the oil from pore spaces of the reservoir.

Interfacial tension (IFT) reduction NPs can alter the rheological properties of the reservoir fluid by improving the efficiency of the surfactant solution for oil recovery. NPs focus on reducing the interfacial tension between the oil and rock interface or between the surfactant and oil interface. The NPs reduce the adsorption on a rock surface by enhanc-

Fig. 2 Nanoparticle structuring in the wedge-film resulting in structural disjoining pressure gradient at the wedge vertex



ing disjoining pressure by forming wedge film on structure at the interface of oil and rock surface (Wasan and Nikolov 2003; Wasan et al. 2011) (Fig. 2).

Surfactant flooding reduces the interfacial tension by injecting surfactants such as indium oxide (IO) NPs coated with Si substrates (Munshi et al. 2008). Munshi et al. (2008) studied the variation in the value of the static contact angle, which was measured on indium oxide (IO) NPs that have different nano-sizes. The study showed that the NPs size has a direct impact on contact angle measurements.

Suleimanov et al. (2011) studied the nanofluids, which are a mixture of NPs and fluids for improvement in properties of liquid with low volume proportion. The study showed that a solution of anionic surface active with light non-ferrous metal NPs was able to reduce surface tension up to 70–90% with a comparison of any surface-active agent aqueous solution. It is observed that in the presence of NPs the sulphane adsorption process is more stable and the value of surfactant adsorption exceeds by 14.5–18.5 times.

Ahmadi et al. (2017) studied the integration effect of hydrophilic nano-silica in addition to surfactant separated from leaves of *Ziziphus spina-christi*. The result showed that with a rising proportion of hydrophilic nano-silica, ultimately recovery rises from 81.08 to 83.45% originally oil-in-place (OOIP). The oil recovery increased due to a reduction in the mobility ratio between oil and injection fluid with increasing viscosity of the injecting fluid.

Pouriya Esmaeilzadeh et al. (2014) demonstrate the mixture containing both surfactants and ZrO₂ to understand the air–water and oil–water tension of the system. The study also involved the ionic and nonionic surfactant in decreasing air–water surface tension. Some anionic surfactants are sodium dodecyl sulphate (SDS), cationic surfactant dodecyl

trimethyl ammonium bromide (C12TAB) and nonionic surfactant lauryl alcohol 7-mole ethoxylate (LA7).

Joonaki and Ghanaatian (2014) introduce the NPs such as aluminium oxide, silicon oxide and iron oxide treated by saline. The study showed that with the addition of silicon, it changes the rock wettability rather than a decline of interfacial tension between oil and water. The survey of Moghadam and Azizian (2014) involved the measurement of interfacial tension between sodium dodecyl sulphate as an anionic surfactant and ZnO NPs. They witnessed that the ZnO NPs make the SDS molecules more capable of reducing the interfacial tension.

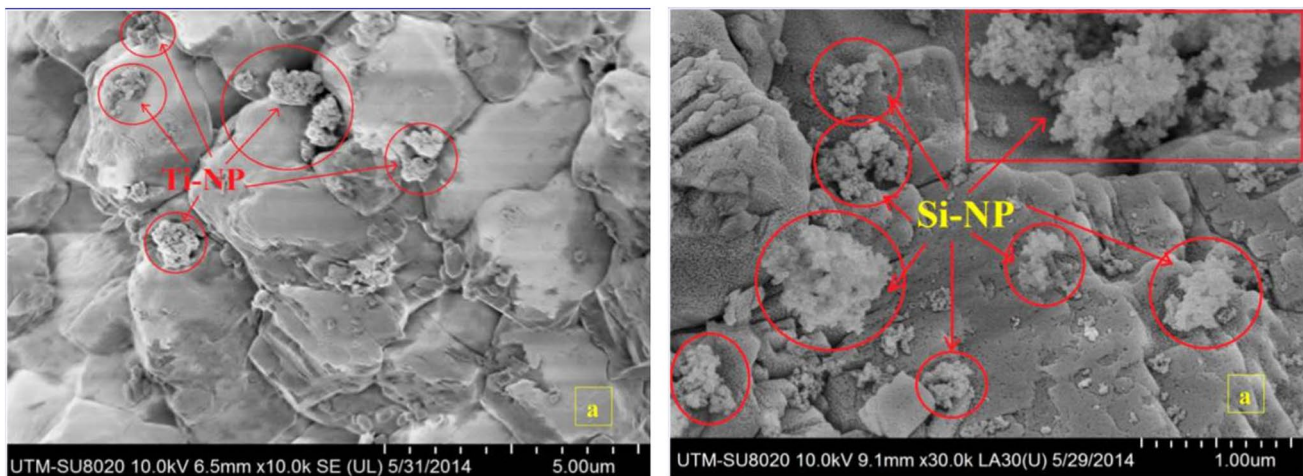
Javad Saïen et al. (2013) studied the impact of hydrophobic NPs and hydrophilic solutions on interfacial tension of oil and water. The alumina as a hydrophilic and hexadecanoic acid act as a hydrophilic solution, and these NPs are dissolved in aqueous or organic phases to design a stable nanofluid. Still, with a change in temperature, the reduction in interfacial tension occurs (Table 2).

Wettability alteration Ali Esfandyari Bayat et al. (2014) studied the aluminium oxide (Al₂O₃), titanium dioxide (TiO₂) and silicon dioxide (SiO₂) to enhance the oil recovery from an intermediate-wet limestone sample for various temperatures. The adsorption of Al₂O₃ was the highest, and for SiO₂ and TiO₂ adsorption was the highest on the limestone surface. By adsorption of NPs, the wettability of the limestone was changed from oil-wet to water-wet. The experiments showed that Al₂O₃ and TiO₂ have a higher effect on the wettability alteration than the SiO₂.

Moghaddam et al. investigate in 2015 the impact of nanomaterials on the susceptibility of moisture to carbonate rocks. Nanocomposites are consisting of titanium dioxide

Table 2 Effect of NPs on IFT with various parameters

NPs	NPs' size (in nm)	NPs' concentration	Dispersion medium	Porous medium	IFT (mN/m)		References
					With NPs	Without NPs	
FNP	7–16	0.05 wt. %	DIW	Sandstone cores	16.41	12.61	Aurand et al. (2014)
CNP	8–75	0.05 wt. %	DIW	Sandstone cores	16.41	12.15	Aurand et al. (2014)
SiO ₂	7–12	1.0 wt. %	SDS	Sandstone cores	20	1.87	Zargartalebi et al. (2014)
SiO ₂	20–30	5 wt. %	Surfactant	Sandstone cores	35	10.9	Emadi et al. (2017)
TiO ₂	10–30	50 mg/L	DIW (60 oc)	Limestone rocks	21.1	12.4	Esfandyari Bayat et al. (2014)
Fe ₂ O ₃	40–60	0.5–3 g/L	Propanol	Sandstone cores	38.5	2.75	Joonaki and Ghanaatian (2014)
SiO ₂	12	1–4 g/L	Brine (5 wt. % NaCl)	Sandstone cores	26.5	1.95	Roustaei et al. (2012)
ZrO ₂	5–15	10–500 mg/L	Surfactant	Bidentate carbonates	48	10	Roustaei et al. (2012)
HLP	10–40	4 g/L	Ethanol	Sandstone rocks	26.3	1.75	Roustaei et al. (2013)
NWP	10–20	4 g/L	Ethanol	Sandstone rocks	26.3	2.55	Esmailzadeh et al. (2014)

**Fig. 3** FESM image from limestone grains after the flooding of TiO₂ and SiO₂ (Moghaddam et al. 2015)

(TiO₂), silicon dioxide (SiO₂), magnesium oxide (MgO), aluminium oxide (Al₂O₃), cerium oxide (CeO₂), zirconium dioxide (ZrO₂) and carbon nanotubes (CNT). The study indicated that the disjoining pressure gradient is the primary factor for changing wettability. From theoretical experiments and calculations, it proved that the separation pressure of the NP layer nearby contact point was able to remove oil from the surfaces (Fig. 3).

Hendraningrat and Torsæter (2014) studied the hydrophilic metal oxide NPs for EOR in various reservoir rock samples. This study shows the better result for oil recovery than the conventionally used silica-based nanofluids. Also, the quartz plates changed from oil-wet to water-wet system by metal oxide nanoparticles, and by adding

PVP of 1 wt.%, the durability of metal oxide nanoparticle improves significantly.

Ju and Fan (2009) investigated about the polysilicon nanoparticles (PN) for EOR process. The result shows alteration of wettability of sandstone by lipophobic and hydrophilic polysilicon nanoparticles (LHPNs), which proves that injecting polysilicon nanoparticles is beneficial for the water injection process (Table 3).

Thermal enhanced oil recovery (TEOR)

Thermal enhanced oil recovery is an approach to improve the residual oil from the reservoir by heating the reservoir. Applied heat reduces the viscosity of oil or vaporizes the

Table 3 Effect of NPs on wettability alteration in term of contact angle

NPs	NPs' size (in nm)	NPs' concentration	Dispersion medium	Porous medium	Contact angle (in degree)		References
					With NPs	Without NPs	
γ -Al ₂ O ₃	10–20	0.5–1.5 wt.%	Brine (180,000 ppm NaCl)	Carbonate rock	40	119	Mohammadi et al. (2014)
ZrO ₂	24	0–0.1 g/cc	Surfactant	Carbonate core	40	180	Karimi et al. (2012)
ZrO ₂	> 35	0.05 g/100 ml	Tween80/Span85	Carbonate core	60	140	Moghaddam et al. (2015)
MgO	> 40	0.05 g/10 ml	LA3 + Tween80/ Span83	Carbonate core	98	140	Moghaddam et al. (2015)
SiO ₂	30–40	0.3 g/105 ml	Ethylene/glycol + LA3EO	Carbonate core	68	140	Moghaddam et al. (2015)
TiO ₂	> 35	0.05 g/10 ml	LA-7EO	Carbonate cores	51	140	Moghaddam et al. (2015)
Al ₂ O ₃	> 40	0.03 g/100 ml	SDS	Carbonate cores	103	140	Moghaddam et al. (2015)
SiO ₂	12	1–4 g/L	Brine (5 wt.% NaCl)	Sandstone cores	66	165	Moghaddam et al. (2015)
LHPN	10–500	0.056 g/cc	Brine (5 wt.% NaCl)	Sandstone core	45	125	Ju and Fan (2009)
Al ₂ O ₃	–	0.005 wt.%	Deionized water	Limestone	71	90	Esfandyari Bayat et al. (2014)
TiO ₂	–	0.005 wt.%	Deionized water	Limestone	57	90	Esfandyari Bayat et al. (2014)
SiO ₂	–	0.005 wt.%	Deionized water	Limestone	26	90	Esfandyari Bayat et al. (2014)
ZrO ₂	20	0.008 mol/L	Formation of water	Carbonate rock	63.21	166.33	Rezvani et al. (2018)

part of the oil, and so mobility ratio is decreased. Also, by heating, the permeability of the reservoir is increased, and the surface tension is reduced. TEOR includes various methods such as cyclic steam injection, combustion and steam flooding.

Hamedi Shokrlu and Babadagli (2010) studied the mechanisms to reduce the viscosity of heavy oil or bitumen by nano-sized metal particles for steam injection processes. The main advantage of the nano-size metal particle is that it can able to reduce the oil viscosity even at room temperature without steam stimulation. The study observed that catalysing the hydrogenation reactions of aqua-thermolysis process was the primary mechanism behind the function of nano-size metal particles. These NPs can improve the oil recovery with different methods such as steam stimulation, electrical or electromagnetic technique. NPs affect the properties of reservoir like dielectric properties, electrical conductivity and magnetic permittivity in favour of improving the displacement efficiency and sweep efficiency.

Hamedi Shokrlu and Babadagli (2014) reported the various types of metal suitable for conventional and unconventional heavy oil or bitumen recovery. The study involved the micron to nano-size particle of metal iron, nickel and copper. The study observed that the heat transfer magnitude altered by changing the size of NPs and reduction in

viscosity affected by the oil composition. The selection of metal is critical, and the thermal conductivity of the metal should be high.

Davidson (2012) studied the superparamagnetic NPs for magnetic induction heating using the concept of Neel relaxation. The study involved the single-domain Fe₃O₄ NPs of approximately 10 nm size and noted that the rate of heat transfer is three times greater than the static fluid.

Nano-sensors for hydrocarbon detection in oilfield rocks

With increasing concern of hydrocarbon contamination and increasing need for low cost and in situ instrumentation, the hydrocarbon detectors provide a better detection. The function of the indicators depends on the characteristic of the compounds which are to be detected. Nowadays, optical fibres are generally used to identify hydrocarbon such as PetroSense hydrocarbon sensors.

NPs can detect the fluid and rock properties because NPs have a minimum retention time. Yu et al. (2010) studied the paramagnetic NPs to detect fluid saturation. The NPs identify the fluids by the application of a magnetic field and measuring the response of the NPs towards the magnetic field.

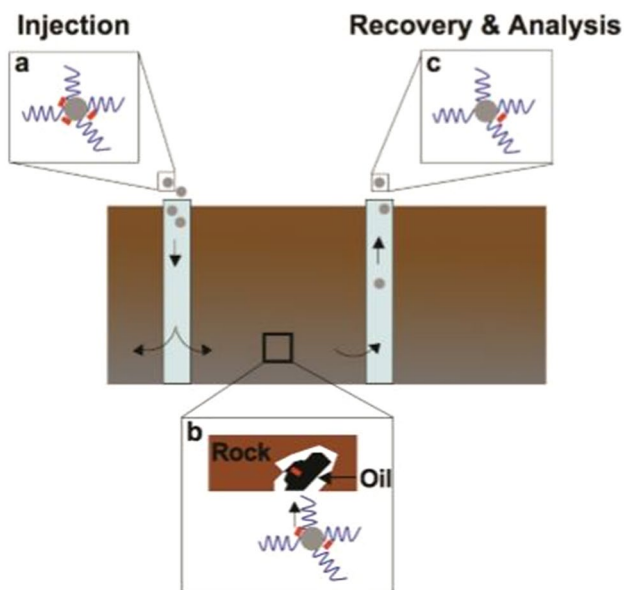


Fig. 4 Schematic of oil detection by nanoreporters. **a** Polyvinyl alcohol (PVA)—organic carbon black (OCB) NPs are injected into the subsurface. **b** The nanoreporters sense the oil and release their hydrophobic cargo into the oil. **c** The nanoreporters are recovered and analyzed for the presence of the cargo's absence in the PVA-OCB, which indicates the extent of subsurface oil

Berlin et al. (2011) demonstrate the basic design for a sequestering hydrophobic compound in an oxidized carbon core composed of NPs. By using the oxidized carbon black (OCB) as the core and polyvinyl alcohol (PVA) as the shell, effective release of 2,2',5,5'-tetrachlorobiphenyl (PCB) occurs. By injecting the NPs bearing cargo into the subsurface, and then recovering and analysing for the presence of cargo, a release of cargo predicts the presence of oil. When NPs are used in such approaches, NPs can be called as nanoreporters (Fig. 4).

Oil microbe detection tool using nanoparticles

NPs have a stronger magnetic, electrical and specific optical properties compared to the bulk one. Thus, nanotechnology has a more significant application in oil microbe detection.

Ramanan Krishnamoorti, University of Houston 2006, observed the formation of imaging contrast agents by altering the magnetic, electrical and optical properties of NPs at lower volume fraction and showed that nanomaterials are suitable for the development of detection tool. Taking the advantage, the relation of the anisotropic nature of NPs and the relationship of percolation with orientation, nanomaterials have an ability for oil microbe detection. Such nanomaterials, with a combination of smart fluids, can be applied

in sensitive sensors for prediction of temperature, downhole stress and pressure.

Jahagirdar studied the detection of downhole by resonance Raman spectra based on the identification of chemotaxonomic markers presence. The study also involved the nanoscale optical fibre and microbes for microbially enhanced oil recovery. The study concludes that the tool will help in the detection of hidden droplets of oil and the zones which cannot recognise easily.

Refining and processing

The commercial utilization of miniaturization of materials serves a lot in petrochemical industries for almost 100 years (El-Diasty and Ragab 2013). In the refining process, nanocatalyst is utilizable for upgrading low API crude to improve refining potential and efficiency (Fan et al. 2010; Almao 2012; Peng et al. 2017).

Crude with API gravity less than 20° can be upgraded to lighter crude using high temperature and long reaction duration along with severe environmental pollution. However, carbon NPs can enhance and improve this cracking process by completing the same reaction at relatively less temperature (about 150 °C) and shorter time (< 1 h) in a cheaper and more environmentally friendly way (Li et al. 2014).

The alternative way for thermal cracking of hydrocarbon is implemented by powder catalyst, which lowers the activation energy of the reaction, along with an increase in reaction sites by increasing the surface energy. Use of zeolite catalyst in face-centred cubic (FCC) structure has been a revolution in the petrochemical industry whose contributions are continuously felt hitherto; over seven million of chemicals and petroleum products are annually produced using this catalyst (Zhou 2007).

Nano-filters and nanomaterials can remove toxic materials from petroleum products such as sulphide by unsupported metal sulphide catalyst. Furthermore, to improve the efficiency of desulfurization, the particles size needs to be reduced, and this simplifies the application process (Li and Zhu 2012). Also, catalysts based on cobalt, nickel and molybdenum on various supports are beneficial for desulfurization (Sudhakar 1998; Mohajeri et al. 2010; Li and Zhu 2012; Etim et al. 2018). This catalyst can also be reusable because after three rounds of oxidative desulfurization it also exhibits an excellent catalytic activity which is quite valuable for industrial utilization (Rafiee and Rezaei 2016; Etim et al. 2018).

Future challenges

Nanotechnology can improve the outcomes of the various ongoing conventional methods in an efficiently and environmentally friendly manner. The following are the potential possibilities that nanotechnology can enhance the undergoing process (Jackson 2005; Mokhatab et al. 2006; Esmacili 2009):

1. It improves the accuracy of exploration data, which is useful to avoid the problem of drying wells and identify shallow risks.
2. It enhances the mechanical durability of drilling tools, which in turn improves drilling performance and reliability in harsh HPHT conditions.
3. It promotes greater accuracy in production data, which ensures proper diagnosis useful for management strategies.
4. It is useful for building corrosion-resistant production and drilling tools.
5. The manufacture of materials with many nanomaterials reduces machine weight and is necessary for offshore operations.
6. It modifies the properties of the reservoir, which can convert a large amount of probable and possible reservoirs into the proved reservoir.
7. Modified waste management strategy is a new advanced option and can also allow selective water filtration.
8. It is useful in refining and petrochemical techniques.

Conclusion

Nowadays, the pioneering nanotechnology has been extensively implemented in various aspects of the oil and gas sector, and it may become one of the critical factors to rupture through the bottleneck of oil and gas development technologies. The unique sized nanomaterial has done revolutionary changes in each sector of hydrocarbon exploration, drilling production and development. In oil and gas exploration sector, the nanotechnology will be practically applied and developed mainly in the reservoir mapping, as it is helpful in reserve estimation, reservoir characterization and its performance monitoring. Nanoparticles improve the efficiency of downhole imaging tools by advancing the downhole electrical methods and increase the sensitivity of the electromagnetic imaging methods; this in turns useful for sophisticated modelling and better understanding of the reservoir. In the drilling section, the use of NWBM has been mentioned, and its different functions in enhancing the rheological properties compared to the conventional one. Nanoparticles can make the drilling operation runs smoother, effective and in

cost constraint. The modification of the drilling equipment and various fluids are potential for making drilling operation run without the problems of high fluid loss in the formation, wellbore instability, friction, dragging in wellbore and pipe sticking. Cement properties are improved by utilization of nanoparticles, improving properties like toughness, durability and dry shrinkage. This solution is useful for overcoming the significant challenges that occur in the unconventional and deep-water reservoir. Nanoparticles with the surfactant effectiveness at the interfacial layers reduce IFT.

Additionally, in the form of catalysts and absorbents nanoparticles can able to improve or enhance heavy oil recovery. Various techniques developed by researchers could perform the synthesis of nanoparticles. The nanoparticle-based drilling fluid can alter the wettability to improve the hydrocarbon recovery. Furthermore, nanofluid injection into porous and permeable media can cause the change in viscosity by inhibiting the precipitation, agglomeration and deposition of asphaltene molecules onto the rock surface, which leads to improving oil recovery factor. The newly invented synthesis method of nanomaterials, widespread application of conventional nanomaterials and unique properties of nano-sized particles will continuously emphasize the nanomaterials in the oil and gas industry.

Acknowledgements The authors are grateful to the School of Petroleum Technology and School of Technology, Pandit Deendayal Petroleum University, for the permission to publish this research.

Authors contribution All the authors make substantial contribution in this manuscript. JS, VS, KD and MS participated in drafting the manuscript. JS, VS and KD wrote the main manuscript; all the authors discussed the results and implication on the manuscript at all stages.

Availability of data and material All relevant data and material are presented in the main paper.

Compliance with ethical standards

Competing interests The authors declare that they have no competing interests.

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