

Role of Nanotechnology in Enhanced Oil Recovery: A Review

Abstract

Nowadays, nanotechnology has emerged as one of the revolutionary approaches in Enhanced Oil Recovery (EOR), having a high capability for solving many of the challenges related to conventional methods. This technology applies nanoparticles to achieve higher recovery through various mechanisms, which include the alteration of wettability, reduction of interfacial tension, and stabilization of emulsion. These different nanomaterials include silica, metal oxides, and carbon-based nanomaterials, which showed great improvement in oil displacement and recovery rates both in laboratory experiments and in field trials. However, some problems of nanofluids' stability, economic feasibility, and environmental safety have to be overcome. This reminds one that the current trend in research is focused on hybrid, biodegradable nanoparticles, integrated nanotechnology with low-salinity water flooding, and smart nanomaterials responsive to reservoir conditions. In essence, since this is a field in continuous evolution, the accomplishment of full potential regarding nanotechnology application for efficient and sustainable oil recovery practices calls for unending research and collaboration.

Keywords

Nanotechnology; Enhanced Oil Recovery (EOR); Nanoparticles; Wettability Alteration; Interfacial Tension Reduction; Emulsion Stabilization

Introduction

Enhanced oil recovery is an important process in petroleum industries for extracting the maximum amount of crude oil from a reservoir (Cheraghian et al., 2014a). The conventional methods of extracting crude oil, namely primary recovery by natural pressure and secondary recovery by water or gas injection, recover merely 20-40% of the original oil in place (Cheraghian and Wistuba, 2020). Of these, EOR techniques include thermal, gas injection, and chemical methods that can increase recovery rates as high as 30-60% or more, making the

process one of the optimization means in oil production amid diminishing resources and increase in energy demand (Mansour & Elshafei, 2024; Gbadamosi et al., 2019; Alsaba et al., 2020; Al Yousef et al., 2020). Different EOR methods are categorized into four major groups (Fig. 1) [Torsater et al., 2012; Cheraghian and Nezhad, 2016; Huang et al., 2020;]. Nanotechnology refers to a number of techniques for producing and processing ultrafine powder materials with sizes from 1 to 100 nanometers (Rezk & Allam, 2019; Medina et al., 2019; Sircar et al., 2022). Agglomeration, either hard or soft, may give these nanomaterials special physical and chemical properties, different from their bulk states (Cheraghian et al., 2014a). Over the last decade, “nanoparticles have developed greatly and uncloaked their potential applications in EOR” [Engeset, 2012; Hendraningrat and Torsæter, 2013; Cheraghian et al., 2014, 2018; Cheraghian, 2017]. Recently, the application of nanotechnology in EOR has gained considerable attention, as it is expected to bring significant improvements in recovery efficiency and possibly decrease adverse environmental impacts (Cheraghian et al., 2014b). It has been established that nanoparticles change wettability, reduce IFT, and increase mobility in flow within the reservoir, thus making NPs effective in the EOR process (Cheraghian and Wistuba, 2020). “The use of NPs as additives in polymer and surfactant solutions can change the rock wettability, reduce the Interfacial tension and improve the rheological properties” (Cheraghian et al., 2020).

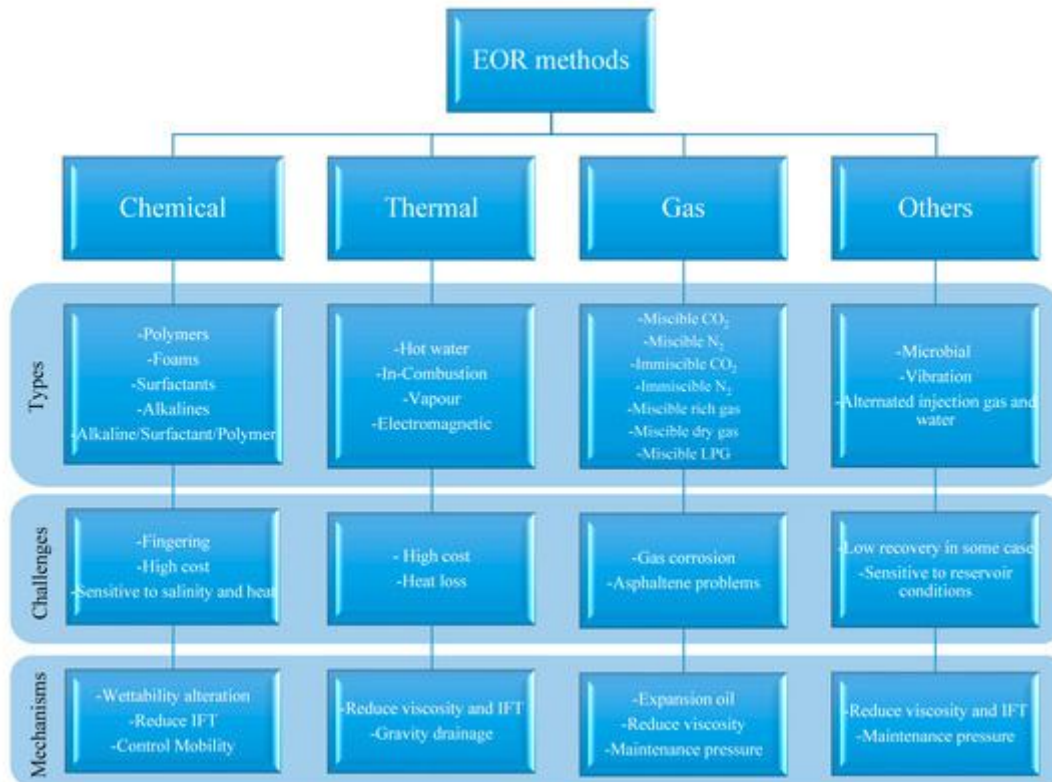


Figure 1. Flow sheet of enhanced oil recovery methods, mechanisms and challenges (Cheraghian et al., 2020).

The Role of Nanotechnology in EOR

Nanotechnology can introduce new ways of solving part of the problems that have prevailed in oil recovery (Al-Shargabi et al., 2022; Zhou et al., 2019; Bahru & Ajebe, 2019). The use of nanoparticle can drastically benefit EOR by “changing the wettability of the rock, improving the mobility of the oil drop and decreasing the interfacial tension (IFT) between oil/water” (Cheraghian et al., 2020). Wettability alteration has been considered among the first modes of action in nanoparticles' enhancing oil recovery (Aliabadian et al., 2020). Many reservoir rocks are naturally oil-wet-a factor limiting water from efficiently displacing oil in the rock. Adding hydrophilic nanoparticles to the reservoir can create such an effect to change the wettability from oil-wet to water-wet and hence increase efficiency in water flooding (Cheraghian et al., 2014b). This change in wettability is critical for achieving maximum oil recovery, because it allows the trapped oil to be displaced more effectively.

Another important benefit of nanoparticles in EOR is the decrease in IFT between oil and water. Lower values of IFT can mobilize oil droplets more easily through the porous media in the reservoir. This reduction of IFT is highly desirable for heavy oil recovery, where high viscosity is a key barrier against extraction. Nanoparticles can also stabilize emulsions, which may enhance the oil recovery further due to improved flow characteristics of the injected fluids (Miranda et al., 2012). Researchers also found that nanoparticles have great potential to enable two main mechanisms i.e., wettability alteration and IFT reduction between fluids and rocks on micro- and nanoscales (**Figure 2**) [Le et al., 2011; Cheraghian et al., 2020].

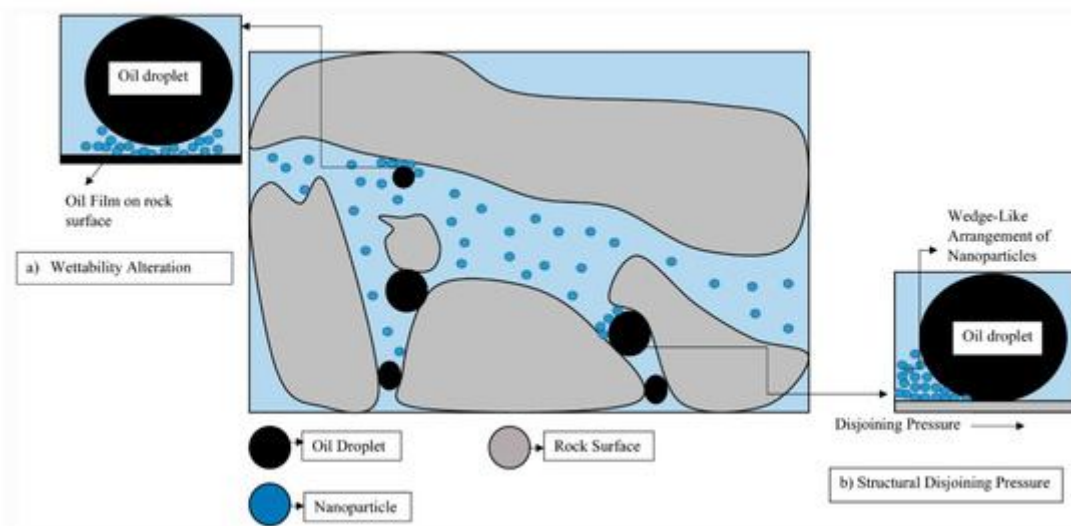


Figure 2. Mechanism of nanoparticles EOR. (a) Changing wettability and (b) structural pressure by nanoparticles [Afolabi, 2019; Cheraghian et al., 2020].

Current Research and Developments

Recent research has illustrated how different types of nanoparticles can help in enhancing oil recovery. For instance, it was found that silica nanoparticles can alter the wettability characteristics of carbonate rocks very profoundly and hence enhance recoveries of oil (Roustaei et al., 2013). There are hybrid applications involving nanoparticles together with surfactants and polymers, too, in which synergistic effects have been found to further enhance the performances of these EOR methods (Ju et al., 2006). These advances prove that nanotechnology faces the various challenges of oil recovery. With these promising results, the application of

nanotechnology in EOR is not devoid of challenges (Nezhad et al., 2017). Amongst the vital concerns arising in this connection is the stability of nanofluids under harsh reservoir conditions because nanoparticles may agglomerate or precipitate, hence reducing their efficiency (Huang et al., 2020).

As observed by Ehtesabi et al. [2015] the use of TiO₂ nanoparticles resulted in an 80% increase in oil recovery in oil-wet sandstone. The performance of oil recovery with CuO nanoparticles was investigated by Shah [2009] and it was found that CuO nanoparticles lead to a 71% increase in oil recovery. Kanj et al. [2011] found that “carbon-based fluorescent nanoparticles increased the oil recovery factor in carbonate reservoirs by more than 96%”.

Furthermore, economic viability concerning large-scale production and deployment of nanoparticles remains one of the key barriers to its widespread adoption (Cheraghian and Nezhad, 2016). These challenges need further research and interaction between academia and industry.

Environmental Considerations

In addition, the environmental impacts of the EOR methods are a great concern for the oil industry. The conventional EOR techniques may have very high greenhouse gas emissions and potential groundwater resource contamination (Torsater et al., 2012). On the other hand, nanotechnology could develop more environmentally friendly EOR techniques. It is possible to design biodegradable nanoparticles with a minimum ecological footprint that enhances oil recovery (Hendraningrat et al., 2013). In fact, this trend of sustainability has become an actual need for the future in the oil industry, as regulatory pressure and publicity about environmental impacts are on the rise.

In brief, nanotechnology application in the enhanced oil recovery process stands as one of the most prospective approaches toward improvement regarding environmental issues in oil extraction efficiency (Cheraghian et al., 2018). Due to the specific properties of nanoparticles, salient improvements can be noticed in such areas as wettability alteration, reduction of interfacial tension, and enhancement of fluid mobility (Cheraghian et al., 2014). However, instability, economic feasibility, and environmental impacts are challenges that have to be met

for fully capturing the potential of nanotechnology in EOR (Shokrlu and Babadagli, 2010). As these approaches are continually developed through research, so will their benefits to the oil industry. In that case, more sustainable and efficient ways of recovering oil can be realized (Skauge et al., 2010).

Fundamental of Nanotechnology

Nanotechnology is an interdisciplinary study that involves the need for manipulation and engineering of materials on a nanoscale, normally in size from 1 to 100 nanometers (Cheraghian, 2015). At this scale, the material assumes unique physical, chemical, and biological properties remarkably different from their bulk material. This technology has been used to transform many areas of medicine, electronics, materials science, and energy (Cheraghian, 2019). It explains the basics of nanotechnology in order to understand its potential applications better, especially in some particular sectors like EOR.

Nanotechnology is the design, characterization, production, and application in changing shape and size at the nanoscale. The word "nano" is derived from a Greek word "nanos," which means dwarf, indicating the small size of the material involved. At the nanoscale, because of quantum effects and high surface area-to-volume ratios, materials exhibit novel properties, hence displaying higher reactivity and strength (Cheraghian, 2016).

Types of Nanomaterials

Nanomaterials can be categorized based on their dimensionality, composition and functionality:

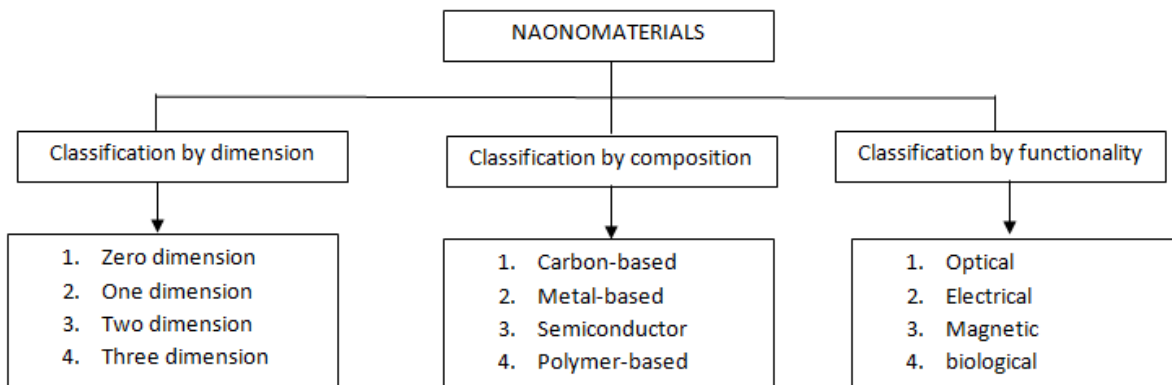


Figure 3: Categorization of Nanomaterials.

A. Zero-Dimensional (0D) Nanomaterials

These materials are confined in all three-dimensional space. Examples include some NPs, for instance, those of metals like gold or silver or oxide, for example, silica and titanium dioxide. As the sizes are so small it is possible to be possessed with unique optical electronic and catalytic behavior (Nezhad and Cheraghian, 2015).

B. One-dimensional nanomaterials

One-dimensional nanomaterials have only one dimension in the nanoscale, such as nanowires and nanotubes. The important example is carbon nanotubes (CNTs). Such nanomaterials possess superior mechanical properties, electrical conductivity, and find applications in sensors to energy storage (Nezhad and Cheraghian, 2015).

C. Two-Dimensional Nanomaterials

2D materials such as graphene and transition metal dichalcogenides, while they extend in two dimensions, have nanoscale thickness. Graphene is one-atom-thin sheet of sp²-hybridized carbon atoms arranged in a hexagonal lattice; it has emerged as one of the hot topics in nanotechnology research due to its exceptional electrical, thermal, and mechanical properties (Nezhad and Cheraghian, 2015).

D. Three-Dimensional Nanostructures

In these materials, even though structured at nanoscale, the dimensions extend beyond this. Examples include nanocomposites, which combine nanoparticles with bulk material to improve mechanical, thermal, or electrical properties (Nezhad and Cheraghian, 2015).

Synthesis of Nanomaterials

In general, the synthesis of nanomaterials can be conceived to fall into two major approaches: the top-down and the bottom-up methods.

A. Top-Down Approaches

In top-down processes, larger bulk materials are subsequently reduced into nanoscale particles. Techniques include mechanical milling, lithography, and etching. While these methods can often produce high-purity nanoscale materials, they often give a wide size distribution and may not take full advantage of the unique properties of nanoscale materials (Cheraghian et al., 2013).

B. Bottom-Up Approaches

Bottom-up methods will build the nanoscale structures from molecular or atomic building blocks. Common techniques are CVD, sol-gel synthesis, and self-assembly. These methods may result in materials of higher uniformity and specificity of properties, and thus of potentially novel applications.

Characterization Techniques

Characterization of nanomaterials is an important aspect for understanding their properties and behaviors. Some of the various techniques include the following:

Transmission Electron Microscopy, TEM: generally offers high-resolution images of nanostructures, whose size, shape, and morphology are directly observable.

Scanning Electron Microscopy: provides detailed topography of the surface and detailed information on the composition.

Atomic Force Microscopy: measures forces and surface topography at the nanoscale, hence used to obtain insight into mechanical properties.

DLS (Dynamic Light Scattering): This technique is used for the determination of the size distribution of nanoparticles in suspension. XRD (X-ray Diffraction): This analysis characterizes the crystalline structure of nanomaterials.

Unique Properties of Nanomaterials

Their reduced size and increased surface area-to-volume ratio give nanomaterials unique properties.

A. Optical Properties Some nanomaterials exhibit size-dependent optical properties, including quantum confinement effects. Quantum dots are semiconductor nanoparticles whose size determines the wavelength of the emitted light and are being used in displays and biomedical imaging (Cheraghian et al., 2013).

B. Mechanical Properties

Mechanical strength in the case of nanomaterials is usually higher than that of bulk materials. For example, carbon nanotubes have very high tensile strength and elasticity, which enable their application as reinforcing materials in composites (Cheraghian et al., 2013).

C. Chemical Reactivity

High surface area increases the rate of reactivity in nanomaterials, thereby increasing the catalytic activity. This attribute finds a useful application in various fields like catalysis and environmental remediation.

Applications of Nanotechnology

Nanotechnology spans a wide fan of fields due to its versatility:

A. Medicine: The use of nanoparticles in medicine is done in drug delivery systems, imaging agents, and diagnostic tools. It can target specific cells. It may do less collateral damage, thereby allowing a minimization of side effects (Le et al., 2011).

B. Electronics: Nanotechnology has completely revolutionized the field of electronics. It has become possible to miniaturize components which have led to faster and more efficient devices. Some nanoscale electronic devices include nanoscale transistors and memory devices (Afolabi, 2019).

C. Energy: Nanomaterials have important applications in energy industries relating to solar cells, fuel cells, and batteries, among others. In fact, the improved conductivity and reactivity of such materials may lead to the improvement of energy conversion and storage efficiencies (Le et al., 2011).

D. Environmental Remediation: Nanotechnology provides novel opportunities for solving environmental problems, especially those concerning water treatment and soil remediation. Thus, nanoparticles efficiently can perform degradation of organic pollutants or contaminant adsorption (Afolabi, 2019).

Challenges in the Application of Nanomaterials

Despite all the brilliant prospects, nanotechnology also has its challenges, which should be pursued:

Safety and Environmental Issues: Toxicity and environmental impact will be fully studied for safe use in nanomaterials.

Economic Feasibility: Production cost and scaling up of nanomaterials remain so high that the development of more economical methods of synthesis is urgently needed.

Regulatory Framework: The establishment of transparent regulations and standards regarding the use of nanotechnology will help gain public confidence about safety concerns. Nanotechnology represents the frontier of the latest developments in science and engineering, offering transformational solutions within a wide array of fields. Having gained an understanding of the basics regarding nanomaterials, especially types, synthesis, characterization, and unique properties, it should be easier to work with such materials with the ultimate aim of coming up with interesting applications. As advancements continue, addressing the associated challenges will be crucial for realizing the full benefits of nanotechnology in fields such as enhanced oil recovery and beyond (Afolabi, 2019).

Application of Nanotechnology in Enhanced Oil Recovery (EOR)

The role of EOR techniques becomes indispensable in present times when the efficiency of conventional methods is sharply falling. Nanotechnology has cropped up as a promising approach towards EOR processes' improvement using nanoparticles and nanomaterials to increase the efficiency of oil recovery. This application of nanotechnology addresses several challenges related to high interfacial tension, wettability issues, and the need for more effective surfactants in traditional EOR methods (Le et al., 2011).

Mechanisms of Nanotechnology in EOR

Nanotechnology can enhance oil recovery through several modes of action, including the following:

A. Wettability Alteration

Wettability is a term that can be used to explain the spreading of a liquid on or adhesion to a solid surface. Most reservoir rocks are oil-wet, which negatively impacts the effectiveness of water in displacing oil. Nanoparticles can cause changes in the wettability of reservoir rocks from oil-wet to water-wet, a process that cannot help but improve the efficiency of water flooding. For instance, hydrophilic nanoparticles might be injected into the reservoir and modify the surface properties of the rock to allow for an improved displacement of oil by water (Le et al., 2011). In a research study, “the performance of nano hydrophilic metal oxide was investigated as a polymeric nanofluid for oil recovery by adding polyvinylpyrrolidone. Between NPs, TiO_2 has better performance in polymer flooding and wettability alteration in comparison to silica-based nanofluid” [Hendraningrat and Zhang, 2015].

B. Reduction of Interfacial Tension IFT

Nanoparticles can significantly reduce the interfacial tension between oil and water, which is an important phenomenon for mobilizing the trapped oil droplets. A lower IFT value will help the oil to move more easily within the porous media in a reservoir. Some research has illustrated those different types of nanoparticles, such as silica and titanium dioxide, can lower IFT with very positive effects on oil recovery rates (Mohajeri et al., 2015). Hendraningrat and Zhang (2015) investigated the stability of hydrophilic TiO_2 nanoparticles in polyvinylpyrrolidone for the EOR process. In this work, “ TiO_2 -based nanofluid had excellent performance in wettability alteration and effectively reduced the IFT between the aqueous and oleic phases. Validation of this performance was confirmed with flooding experiments”.

C. Emulsion Stabilization

Emulsions are mixtures of oil and water that have an improved flow characteristic injected. The emulsions are stable with nanoparticles, allowing the oil dispersion in water to persist as a function of creating dispersed oil droplets in water, which enhances the recovery during flooding with the so-dispersed droplets (Mohajeri et al., 2015).

D. Improved Mobility Control

Nanotechnology can improve the mobility of fluids within the reservoir. The addition of nanoparticles can modify the viscosity of the injected fluids, allowing better displacement of oil. This is particularly helpful in heavy oil recovery because high viscosity is usually one of the major obstacles to extraction (Le et al., 2011).

Types of Nanomaterials used in EOR

Various nanomaterials were explored in EOR applications, including:

A. Silica Nanoparticles

Of all the different nanomaterials used in EOR, silica nanoparticles have been studied the most. They are capable of changing wettability and reducing IFT, hence enhancing oil recovery. Research indicates that heavy oil recovery can be improved by silica nanoparticles through changes in the injected fluids' flow characteristics (Mohajeri et al., 2015).

B. Metal Oxide Nanoparticles

Other metal oxides nanoparticles like titanium dioxide (TiO₂) and zinc oxide (ZnO) have also been checked for EOR applications. These nanoparticles can reduce IFT and stabilize emulsions thus turning out to be suitable for enhanced oil recovery applications (Mohajeri et al., 2015).

C. Carbon-Based Nanomaterials

Carbon-based nanomaterials like carbon nanotubes and graphene exhibit some unique properties that are useful in the EOR process. High surface area with mechanical strength

makes them effective for modifying the properties of reservoir fluids, hence improving oil recovery efficiency (Cheraghian and Hendraningrat, 2016).

D. Polymer Nanocomposites

There is growing interest in the application of polymer nanocomposites, comprising nanoparticles combined with polymers, for EOR applications. This is due to their potential to enhance the viscosity and stability of injected fluids, which could result in improved oil displacement and recovery rates (Cheraghian and Hendraningrat, 2016).

Recent advances in Nanotechnology for EOR

Recent studies indicated the effectiveness of nanotechnology for enhanced oil recovery through various experimental works and field trials.

A. Laboratory Studies

Many laboratory experiments are showing the prospect of nanoparticles in enhanced oil recovery. For instance, the work presented by Nezhad et al. (2017) considered the application of hydrophilic silica nanoparticles during the course of polymer flooding processes. Results showed there was a significant increase in oil recovery rates due to changes in wettability and IFT reduction provided by the nanoparticles.

Another study by Aliabadian et al., 2020 focused on the application of graphene oxide nanosheets to heavy oil recovery. The results presented that the addition of graphene oxide enhanced the flow behavior of the injected fluids, which improved oil recovery accordingly (Mohajeri et al., 2015).

B. Field Trials

Field tests have also been conducted to assess the effectiveness of nanotechnology in EOR. For instance, one of the pilot projects undertaken in the Middle East utilized silica nanoparticles in the process of water flooding. The results indicated clearly that the oil recovery ratio was greater compared to conventional methods, proving that the use of nanotechnology is practically viable in the field (Mohajeri et al., 2015).

Effect of Nanoparticles on Oil Recovery

A combination of surfactants and NPs facilitates releasing the oil droplets trapped in narrow throats and micro-channels of reservoir rock for improved oil recovery. These processes are associated with various factors that enhance oil recovery, such as changes in wettability of reservoir rocks, formation of spontaneous emulsion, variations in the interfacial tension between reservoir fluids, and flow property changes of porous media. Over the years, various types of NPs have been tested and studied regarding enhanced oil recovery. Among others, the addition of TiO₂ NPs increased oil recovery by 80%, as Ehtesabi et al. claimed, in oil-wet sandstone. Shah carried out experiments with CuO NPs. He also reported an increase in oil recovery-as high as 71%. Kanj et al. carried out the flooding performance of surface-modified carbon nanoparticles and reported an increase in the oil recovery factor for carbonate reservoirs of more than 96% by carbon-based fluorescent NPs. To study emulsion stability as well as polymer solutions at reservoir conditions, several researchers have prepared different NP-modified polymers. Wang et al. studied the effects of Na-Mt particles and hydrolyzed polyacrylamide on the stability of emulsions by examining the interfacial properties of water-oil, dilatational viscoelasticity, IFT, and zeta potentials. It was reported that at increasing concentrations of NPs, IFT, the zeta potential of oil droplets decreased while it increased in dilatational viscoelasticity. More precisely, while the dilatational viscoelasticity and the IFT increased with the concentration of NP, the zeta potential reached its saturation value above 250 mg/L. During EOR in heavy oil reservoirs, pH conditions could be influenced by nanoparticles coated with polymers.

Hendraningrat et al. performed an extended laboratory experiment on hydrophilic silica dioxide nanoparticles for EOR under different wettability conditions and different temperatures of the reservoir (oil-wet, intermediate-wet, and water-wet). They examined how temperature, initial wettability, extra oil recovery, and the process of nanofluid flooding-or nano-EOR-interact. Experimental results demonstrated that these NPs were stable at high temperature, which, in turn, hindered particle aggregation in porous media. In all, their findings provided a critical review of nanofluid properties for EOR within a wide range of reservoir conditions.

Recently, several systematic studies have been done on the effects of NPs on surfactant flooding.

Recently, Zargartalebi et al. conducted a study on surfactant flooding with nanoparticles. It was demonstrated that NPs can enhance oil recovery, especially at an equal concentration of NPs and surfactants. Besides, hydrophobic NP-modified surfactants exhibited higher efficiency compared to their hydrophilic counterparts.

In one recent study, a new type of polymer nanocomposite was prepared with nano-silica and free-radical polymerization in order to enhance properties for the polymer flooding system. Properties such as oil displacement efficiency, mobility control, salt and temperature tolerance, and rheological characteristics were studied in different states. The results showed that the studied polymer nanocomposite exhibited excellent performances as a chemical agent for strong mobility control, high temperature tolerance, and good rheological properties for polymer flooding.

Other important work by Hendraningrat also illustrated that polymeric nanospheres have enormous potential in the recovery of residual trapped oil within porous media. His findings demonstrated that NPs reduce water permeability and mobility ratio, which enables the polymer solutions to reach the unswept zone of oils and thereby recover them. Moreover, NPs have an important role in changing the oil displacement mechanism and wettability.

Current research trends in the application of nanotechnology in Enhanced Oil Recovery (EOR):

1. Hybrid Nanomaterials

The interest in using hybrid nanomaterials comprising more than one type of nanoparticle to enhance properties and performances is presently in the learning curve. For example, nanoparticles of silica combined with a polymer result in better stability and improved viscosity of injection fluids and hence may yield better results in oil recovery. The trend aims at combining strengths of different materials for efficient EOR methods (Cheraghian and Nezhad, 2015).

2. Biodegradable Nanoparticles

Much emphasis is being placed on the development of biodegradable nanoparticles with less environmental impact. With this in mind, fundamental research using naturally derived materials, for example, chitosan or starch-based nanoparticles, is done, and these materials turn out to be

effective in altering wettability through a reduction of interfacial tension with minimal environmental impact, showcasing an increasing awareness of sustainability within the EOR practice (Cheraghian, 2017).

3. Nanotechnology in Low Salinity Water Flooding

Recent research has focused on the combined synergistic effects of nanotechnology with low-salinity water flooding techniques. By adding nanoparticles to low-salinity water, there is an attempt to enhance oil recovery through better wettability alteration and reduction of IFT. This may provide an economical and environmentally friendly approach toward enhanced oil extraction (Cheraghian, 2017).

4. Smart Nanomaterials

Therefore, smart nanomaterials will come into the light that can sense the environmental stimuli such as temperature, pH, or salinity and would release certain agents or alter the properties at pre-specified conditions along the reservoir. This will dynamically help in enhancing the process of EOR. The current trend in research is focused on modifying nanomaterials according to specific features of the reservoir (Cheraghian and Nezhad, 2015).

5. Advanced Characterization Techniques

The improved understanding of the nanoparticle interactions with the reservoir rocks at the nanoscale is now possible thanks to advances in various characterization techniques, including high-resolution microscopy and spectroscopy. Enhanced characterization will help in designing nanomaterials for intended applications and achieving better EOR performance.

6. Field-Scale Applications and Pilot Studies

There is more emphasis on scale-up from lab studies to field-scale applications and pilot projects. The researchers are focusing on the effectiveness of nanotechnology under realistic conditions, performance evaluation of nanoparticles under different reservoir conditions, and data on their economic viability (Cheraghian, 2017).

7. Collaboration between Industries and Academia

Currently, the bridging between fundamental research and applied research is increasingly being done through collaboration of research efforts among academia, industry, and governmental organizations. Such collaborations will result in knowledge exchange that will promote innovative nanotechnology solutions for EOR (Cheraghian and Nezhad, 2015).

8. Computational Modeling and Simulation

Computational modeling and simulation have also become important methods to predict nanoparticle behavior under reservoir conditions. Researchers applied advanced modeling techniques to investigate nanoparticles interacting with crude oil and reservoir rocks, allowing them to design and optimize EOR processes (Cheraghian, 2017).

9. Emphasis on Safety and Environmental Impact

Safety and environmental concerns in the application of nanomaterials in EOR are also increasingly being put under research. Testing toxicity and ecological effects of different nanoparticles are being conducted so that their applications do not harm human health or create environmental hazards (Cheraghian and Nezhad, 2015).

These trends are a reflection of the dynamism of the research landscape into the application of nanotechnology in enhanced oil recovery. In fact, as the field continues to evolve, further innovation and collaboration will be integral in harnessing the full potential of nanotechnology toward even more efficient and sustainable oil recovery practices.

Challenges and Limitations

Despite such promising results, the following challenges have to be resolved for the effective deployment of nanotechnology in EOR:

A. Stability of Nanofluids

The most important factor is the stability of nanofluids under hostile reservoir conditions. This can lead to aggregation or sedimentation of nanoparticles, reducing their effectiveness. Further research is required to formulate a stable formulation that can survive the harshest conditions of oil reservoirs (Cheraghian, 2017).

B. Economic Feasibility

The final major barrier to nanoparticle application is a basic economic one: manufacture and deployment at appropriate scales is expensive. Expensive synthesis methodologies and studies of economic viability in regard to nanotechnology-based EOR processes are essential to develop if commercialization is ever to be pursued (Cheraghian and Nezhad, 2015).

C. Environmental Impact

The application of nanomaterials in EOR practices needs a comprehensive environmental impact analysis. The knowledge on the toxicity and ecological impacts of nanoparticles will help design safe and sustainable oil practices (Cheraghian and Nezhad, 2015).

Future Directions

The future of nanotechnology in EOR has tremendous scope and areas that could be pursued:

A. Advanced Nanomaterials

Further investigation of new nanomaterials, including hybrid nanoparticles and biodegradable nanoparticles, may lead to much more effective and environmentally acceptable EOR applications. Synergetic effects of various combinations of nanoparticles may also lead to significant improvements in the recovery rates (Zargartalebi et al., 2015).

B. Integration with Other Technologies

The combination of nanotechnology with other EOR methods, such as MEOR or low-salinity water flooding, could even further improve the overall efficiency of recovery. It is these types of multidisciplinary approaches that may yield the innovative solutions being searched for to solve some of the multidimensional problems in oil recovery (Kanj et al., 2011).

C. Regulatory Framework

Obviously, clear legislation and directives on the application of nanotechnology in EOR will be required for safety and public confidence. Responsible utilization of nanotechnology in the petroleum industry will involve researcher-industry-regulator cooperation in formulating a proper code that addresses all the potential risks posed by nanotechnology (Ehtesabi et al., 2015).

Conclusion

Nanotechnology-enhanced EOR techniques presently engage nanoparticles to alter wettability and reduce interfacial tension. Nanoparticles can also be used as emulsions stabilizers. All this helps in improving oil displacement and an increase in oil recovery ratios. The main materials involved in EOR are silica and metal oxide nanoparticles, which so far are effective in both laboratory and field studies. In spite of such advancement in this field, issues related to stability of nanofluids, economic viability, and environmental safety are yet to be sorted out. Current research trends include hybrid and biodegradable nanoparticles, nanotechnology combined with low-salinity flooding, and intelligent nanomaterials which are sensitive to reservoir conditions. All in all, still promising, the successful implementation of nanotechnology in EOR calls for continued research and agreement among the parties involved to ensure efficiency and sustainability.

Nanotechnology can indeed play a great role in enhanced oil recovery processes by providing solutions to many problems that traditional EOR methods have been facing. Nanoparticles might improve oil recovery efficiency by altering wettability, reducing interfacial tension, and emulsion stabilization. Quite a few laboratory and field trials in recent times have reported encouraging oil recovery rates with different nanomaterials, including silica nanoparticles, metal oxides, and carbon-based materials. However, their viable applications need to be complemented by stability issues, economic feasibility, and environmental concern. Eventually, when research will be continually upgraded, the incorporation of nanotechnology with EOR could help in introducing different sustainable and economical methods for the extraction of oil.

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