An Overview of the Application of Magnetic Nanoparticles in the petroleum sector

Abstract

The development of magnetic nanoparticles (MNPs) has attracted a lot of attention recently, owing in part to their benefits, including their size, physico-chemical characteristics, and low production costs. Under the influence of an external magnetic field, MNPs can be used to selectively attach, manipulate, or transfer targeted species to a desired location. The super-paramagnetic nature of magnetic nanoparticles comes from their small size. They can be used either uncoated or coated with a functional group and surface coating specifically designed for a given use. In the oil and gas industry, MNPs are used in a wide range of upstream processes, including enhanced oil recovery, drilling fluids, corrosion control, hydraulic fracturing, and sand control. The unique properties of MNPs include their small size, their large surface-to-area ratio, which results in a large contact area, and the nanoscale properties of materials, such as optical, chemical, magnetic, and interfacial, which are dependent on size and can be manipulated to contain these specific properties. The objective of this review, is to outline and discuss the latest applications of MNPs in the petroleum industry. In addition, to understanding the modern uses of the traditional methods employed in the petroleum sector.

Keywords: magnetic nanoparticles, applications, petroleum sector, properties.

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Introduction

MNPs are a class of nanoparticles typically comprising two constituents: a functional chemical component, usually possessing biorecognition or bio-catalytic properties, and a magnetic component, typically composed of iron, nickel, and cobalt**[1]**. The properties of magnetic nanoparticles differ significantly from those of their bulk materials because of their small size, which allows for an increased surface-to-volume ratio, and their close approach to the domain size**[2,3]**. Magnetic nanoparticles (MNPs) are widely applied in different sectors including petroleum sector. Applications of magnetic nanoparticles in the petroleum sector have been reported. These include enhanced oil recovery (EOR)**[4]**, heavy oil recovery**[5]**, magnetic separation, enhanced production and drilling operations, imaging and sensing of reservoirs, flow assurance, and configuration control. This paper presents a review of the current state of research on magnetic nanoparticles (MNPs), which are used in the petroleum industries. It identifies the current state of the field and assesses its future possibilities.

Classification of MNPs

On the basis of their intrinsic magnetic dipoles and net magnetization in the presence and absence of an external magnetic field, MNPs are usually classified as ferromagnetic, ferrimagnetic, antiferromagnetic, diamagnetic, paramagnetic, and superparamagnetic. The maximum magnetization in the presence of an external magnetic field occurs when the MNPs' magnetic moment is oriented in the direction of the magnetic field. When an external magnetic field is removed, MNPs' magnetic moment keeps its previous direction and magnetization. Since their high sensitivity results in increased sensing efficiency, MNPs with high saturation magnetization values are generally chosen for biosensing applications; additionally, saturation magnetization values tend to rise with MNP size (**Figure 1**).

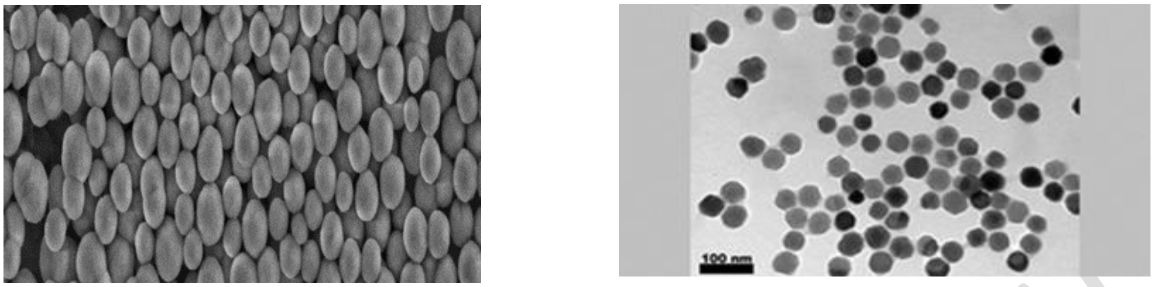

Figure 1: Examples of magnetic nanoparticles (MNPs).

Ferromagnetism

A material can become a permanent magnet due to a property known as ferromagnetism, which is present in some materials (like iron) and produces a notable magnetic permeability as well as, frequently, a notable magnetic coercivity**[6]**. Material magnetism has been classified into several categories. The most common type of magnetism found in magnets used in daily life is called ferromagnetism, which also has the similar effect of ferrimagnetism. Ferromagnetic materials fall into two categories: magnetically hard materials, which tend to remain magnetized, and magnetically soft materials, such as annealed iron, which can become magnetized but do not usually do so**[7]**.

Ferrimagnetism

A ferrimagnetic material is one in which the populations of atoms have opposite magnetic moments, as in anti-ferromagnetism, but the moments are not equal in magnitude, allowing for the persistence of spontaneous magnetization**[8]**. Similar to ferromagnetic materials, ferrimagnetic materials can be magnetized to create permanent magnets and are attracted to magnets. Among transition metal compounds, particularly oxides, antiferromagnetic materials are frequently found. Hematite, metals like chromium, iron manganese (FeMn) alloys, oxides like nickel oxide (NiO), and alloys like these are a few examples**[9]**.

Antiferromagnetism

Antiferromagnetic materials are commonly found in transition metal compounds, especially in their oxide forms. Examples include hematite, metals such as chromium, alloys of iron manganese (FeMn), oxides such as nickel oxide (NiO), and alloys similar to these**[10]**. The first demonstration of antiferromagnetic structures was achieved by neutron diffraction of transition metal oxides, including oxides of nickel, iron, and manganese**[11]**.

Diamagnetism

Materials with diamagnetic properties are those that are repelled by magnetic fields; an applied magnetic field induces a magnetic field in them that is directed in the opposite direction, producing a repulsive force**[12]**. A magnetic field, on the other hand, attracts paramagnetic and ferromagnetic materials. A material is referred to as diamagnetic when diamagnetism is the sole source of magnetism, a quantum mechanical effect present in all materials**[13]**.

Paramagnetism

A kind of magnetism known as paramagnetism occurs when certain materials create internal, induced magnetic fields in the direction of an applied magnetic field despite being only weakly attracted to an

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externally applied magnetics field**[14]**. This behavior is in contrast to that of diamagnetic materials, which form induced magnetic fields in the opposite direction of the applied magnetic field and are repelled by magnetic fields. The majority of atoms with partially filled atomic orbitals are paramagnetic because paramagnetic materials have unpaired electrons**[15]**.

Superparamagnetism

MNPs in the superparamagnetic state respond quickly to changes in the magnetic field without coercivity, or the necessary magnetic field to bring the magnetisation back to zero, and without residual magnetization**[16]**. A type of magnetism known as super-paramagnetism can be found in tiny ferromagnetic or ferrimagnetic nanoparticles. Under the influence of temperature, magnetisation in sufficiently small nanoparticles can randomly reverse direction**[17].**

Applications of magnetic Nanoparticles in petroleum sector (Table 1)

Enhanced oil recovery

Enhanced oil recovery (EOR) is one of the most significant areas of application for magnetic nanoparticles since it ensures a quicker return on investment by producing more oil during the extraction process**[18-20]**. The main advantage of enhanced oil recovery process is to improve traditional surfactant flooding as its acts as a piston and increase the sweep efficiency of oil. Using nanotechnology in the enhanced oil recovery (EOR) process facilitates the extraction of trapped oil that is found below the surface. Certain ultra-fine nanoparticles are both economical and environmentally benign. An environment that is favorable for oil recovery is produced by the injected fluid's interactions with the rock/oil system**[21]**.

Heavy oil recovery

This process helps to upgrade heavy oil by reducing its viscosity through the use of magnetic induction heating and prevents the viscoelastic network from forming by adhering asphaltenes**[22]**. There are various forms of naturally occurring crude oil. The most well-known to most people is light crude oil, which flows easily at room temperature and is less dense than water. The most promising and easily accessible oil resource to meet energy demands in the upcoming decades is heavy oil, which is estimated to make up roughly 70% of the remaining oil reserves**[23]**. The high mobility of injected fluids, polymer degradation, surfactant adsorption, significant chemical consumption, significant energy and water consumption, significant greenhouse gas emissions, high operation costs, and the requirement for sturdy facilities pose significant challenges to conventional enhanced oil recovery (EOR) methods for heavy oil [**24]**. The technology of nanoparticles has emerged as a viable substitute for improving heavy oil recovery in recent years. This is because of their exceptional features, which include ultra-small size, high surface area to volume ratio, cost-effectiveness, and environmental tolerance**[25]**. Two main categories of nanoparticle applications for improving heavy oil recovery are hybrids of conventional EOR techniques and nanofluid flooding. The different uses of nanofluid flooding are summarised up in terms of EOR mechanisms and incremental oil recovery performance**[18]**. The second category highlights new developments in the study of hybrids between nanoparticles and conventional EOR techniques, such as gas injection, chemical, and thermal injection**[24]**.

Drilling and completion improvement

This application uses filter cakes to stop the formations from being invaded by excess filtrate, increase the spacer fluids' cleaning effectiveness, preserve the drilling fluids' stability and rheological integrity in challenging reservoir conditions, and improve the rheological characteristics of the drilling fluids**[26,27]**. Recently, artificial Intelligence (AI) is becoming a necessary tool for the petroleum industry. AI is

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regarded as an innovative technology in drilling and completion engineering that can save costs and greatly increase drilling efficiency (DE). The number of artificial intelligence (AI) tools used in the petroleum industry has rapidly increased in recent years, indicating their enormous potential**[28]**. Artificial Intelligence (AI) has been applied to many problems in the oil and gas industry, such as the identification of seismic patterns, characterization of reservoirs, prediction of permeability and porosity, prediction of PVT properties, diagnosis of drill bits, estimation of pressure drop in pipelines and wells, optimization of oil well production, performance of oil wells, portfolio management, and general decision-making operations**[29]**.

Flow assurance and conformance control

This application reduces the incremental water production from the mature reservoirs by controlling the formation of gel or magnetic solid-like structures, and it also prevents the deposition of wax and the formation of methane hydrates by heating the production tubing. Oil companies are facing a critical operational challenge of one or more fluid-flow assurance issues during pipeline production and transportation in cold environments as a result of increasing hydrocarbon production from conventional and unconventional reservoirs in harsher environments. Therefore, a detailed explanation of the fluid flow assurance problems is necessary to overcome these operational difficulties**[30,31]**. The application of flow assurance is needed to ensure the smooth and cost-effective transportation of hydrocarbons from the reservoir to the point of sale. Applications from several fields are needed in order to solve these flow assurance problems, especially production chemistry, multi-phase hydrodynamics, thermodynamics, and materials science. All phases of the petroleum flow path's production, including system selection, thorough design, monitoring, troubleshooting operational issues, and enhanced recovery, are subject to flow assurance**[32]**. The production of multiphase flow through pipelines and risers in offshore or onshore oil and gas field developments requires careful consideration of several flow assurance issues, including hydrates, waxing, asphaltenes, slugging, naphthenates, scales, corrosion, erosion, and emulsions**[33]**.

Magnetic separation

The magnetic separation process has the advantage to separate oil or injected polymer from the produced water, remove emulsified water from the crude oil and bitumen, in addition to the removal of divalent cations. The discharge of oily wastewater from industrial activities and the frequency of oil spill accidents have drawn a lot of attention to oil-water separation recently**[34]**. Before releasing oily wastewaters, it is essential to remove any oil-containing materials because they can pose a major threat to human health by entering the food chain and causing serious environmental problems**[35,36]**. Under some circumstances, flocculation has been suggested in recent years to be a helpful technique for removing emulsified oil droplets; however, the flocculation process is costly and the resulting flocs have a tendency to float, which reduces the effectiveness of oil-water separation. Therefore, it is imperative to create new materials or technologies for treating emulsified oil wastewaters at a reasonable cost. Magnetic nanoparticles (MNPs) have garnered particular attention in the last ten years because of their surface characteristics and possible for recycling**[37]**. The hydrophobicity or amphiphilicity of MNPs can be modified via a variety of surface modification techniques to enhance their sorption at oil-water interfaces and/or within dispersed droplets, giving the dispersed oil droplets magnetic properties. Consequently, an external magnetic field can be used to easily separate the magnetically tagged oil droplets from the continuous phase**[38]**.

Reservoir sensing and imaging

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This application deals with the establishment of the fluid front's magnetic-permeability-contrast zones, monitors the source of crude oil, produces distinct and highly contrasted signal regions within the fractures, enhances the interpretation of NMR data for the evaluation of porosity distribution, and establishes the fluid front's magnetic-permeability-contrast zones [**39]**. Soil erosion in the reservoir's watershed areas, which is nearly infinitesimal at the source, has become a serious issue for dams. This erosion is responsible for sedimentation in the reservoirs**[40]**.

Table 1: Applications of the MNPs in petroleum sector.

Specific area	Application & Properties	Reference
Enhanced oil recovery	• Increases the oil's sweep efficiency by acting as a piston. • Enhance conventional surfactant flooding.	Anirbid et al., 2022; Ehsan et al., 2018a; Ehsan et al., 2018b
Heavy oil recovery	• Reduce heavy oil viscosity via magnetic induction heating. • Adsorb asphaltenes to their surface and therefore inhibit the formation of the viscoelastic network. • Help to the upgrading of heavy oil.	Goma et al., 2023; Wei et al., 2023.
Drilling and completion improvement	• Enhance the drilling fluids' rheological characteristics. • Increase the spacer fluids' cleaning effectiveness. • Create filter cakes to stop the formations from being invaded by excess filtrate. • Keep the drilling fluids stable and rheologically sound under challenging reservoir circumstances.	Li et al., 2022; Tran et al., 2020; Yin et al., 2017; Mohaghegh, 2005.
Flow assurance and conformance control	• Stop the development of gel or magnetic solid-like structures to minimize the additional water production from the mature reservoirs. • Use heat to stop the production tubing from accumulating wax and forming methane hydrates.	Asheesh, 2023; McMullen, 2006; Joshi et al., 2003.
Imaging and sensing reservoirs	• Monitor the source of crude oil. • Produce distinct and highly contrasted signal regions within the fractures. • Enhance the interpretation of NMR data for the evaluation of porosity distribution • Establish the fluid front's magnetic-permeability-contrast zones.	Tesfaye et al., 2023; Nasser et al., 2020.
Magnetic separation	• Separate the produced water from the injected polymer or oil. • Take the emulsified water out of the bitumen and crude oil. • Divalent cation removal.	Bowman, 2023; Yi et al., 2022; Kaibo et al., 2020.

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Conclusion

Applications for MNPs in the petroleum industry have shown them to be extremely promising, and during the last ten years, some progress has been made. The behavior of MNPs can be remotely controlled by an external magnetic field due to their special magnetic properties. This has several potential applications in the fields of magnetic separation, enhanced oil recovery, heavy oil recovery, flow assurance, conformance control, reservoir sensing, and imaging. Moreover, because of their size effects, MNPs have been developed as injected fluid additives to enhance rheological behavior in the absence of a magnetic field. The use of MNPs offers exciting opportunities for the development and improvement of the petroleum industry. Nevertheless, these applications continue to face a number of significant obstacles. The development of novel MNP modification materials, the enhancement of MNP synthetic routes, and additional investigation into the distinct properties and mechanisms of MNPs are among the fundamental research attempts that hold the answers to overcoming the pivotal challenges.

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