

Review Article

The Impact of Electromagnetic Waves Propagation to the Dielectric Nanoparticles on Crude Oil Interfacial Tension Reduction for Oil Recovery: A Review

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Abstract

The presence of interfacial tension (IFT) force between crude oil and other fluids in reservoirs is one of the critical parameters that restrict the effective mobility of the oil and is continuously entrapped in reservoir pores. Reducing binding forces between oil and such fluids is one of the methods employed to improve oil productivity known as enhanced oil recovery (EOR). Various nanoparticles (NPs) have been utilized to reduce IFT. However, NPs encountered a challenge in terms of successful operation under a high temperature. Consequently, the NPs tend to segregate at the oil/ water interface which diminishes the IFT influences and more oil continuously entrapped. Recently, an innovative approach to enhance oil mobility was proposed by activating the charges of the NPs via electromagnetic (EM) wave propagation. Few analyses were reported using dielectric NPs with reasonable reductions to IFT. The dielectric properties of NPs are essential attributes corresponding to EM waves. During the EM wave exposure, the extra disruptions were generated at the fluid/oil interface that function as activating agents for the NPs resulting in the additional reduction for IFT. The present study provides a comprehensive review of the few results available, challenges that confronted the success of this novel approach, and admirable recommendations to improve the process in the future.

Keywords: EM waves, Dielectric nanoparticles, Interfacial tension (IFT)

Introduction

One of the major sources of global energy production is crude oil extraction.¹⁻³ Regrettably, oil reservoirs around the world are suffering from persistent entrapment of crude oil within reservoir rock holes, and more than 70 % of the crude oil across the globe cannot be recovered.² Oil removal from reservoirs was formerly accomplished by using primary and secondary recovery technologies. The primary approach entails oil extraction from the reservoir using the crude oil's natural mobility without employing external equipment to improve oil mobility. Nevertheless, in certain situations, the primary recovery was artificially boosted by adding rod pumps to increase pressure within the reservoir. Only 15 % of the residual oil could be extracted using this procedure. Subsequently, a secondary recovery method was implemented by injecting gas or flooding the reservoir with water to maintain reservoir pressure and increase crude oil mobility. More oil was examined to be recovered superior to the primary methods. However, additional obstacles to oil mobility still exist in such a manner that 55 to 70% of the oil cannot be recovered using a secondary method due to the high viscosity of the crude oil and low viscosity of the injected fluids. Thus, less viscous fluids like water cannot displace a plentiful amount of crude oil, it could rather slide beyond the oil front which resulted in fingering and diminishing the recovery factor.¹ Meanwhile, the EOR method was invented to alleviate the problem and increase oil production. EOR is categorized into three approaches, the first one is a chemical injection which entails injecting chemicals into a reservoir to enhance crude oil mobility. The second is thermal processing which has to do with heating



reservoirs to reduce crude oil viscosity for easy withdrawal. The third category, known as gas miscible flooding, involves injecting CO_2 , hydrocarbon gases, or nitrogen into the reservoir to reduce the oil viscosity that helps to displace oil efficiently.² There are some factors responsible for improving the stated objective of EOR, and by enhancing them, the condition of the reservoirs could be restructured to achieve oil recovery. These are rock wettability alteration, oil viscosity reduction, and reducing interfacial tension (IFT) between crude oil and other fluids.

The small size of NPs compared to reservoir rock holes enhances their smooth flow through reservoir formation with minimal disruption.^{2,4} Various NPs were reported to have shown an encouraging change in improving reservoir characteristics by reducing the negative influence of the IFT effect. IFT is the adhesive force that occurs between the molecules at the interface of two liquid phases.² The natural existing IFT between crude oil/ fluids interface reduces the simple and flexible mobility of the oil, and therefore reducing the intensity of this force could certainly advance the oil mobility which in turn enhanced oil recovery.

Different NPs were studied to have shown positive results in reducing the IFT of the crude oil/fluids which included ZnO,5-8 Ferrite NPs,⁹ TiO₂,^{10,11} Al₂O₃,¹⁰⁻¹³ ZrO₂,¹² Fe₂O₃/Fe₃O4,¹³⁻ $^{\rm 15}$ and ${\rm SiO}_{\rm 2}{\rm .}^{\rm 11,13}$ Despite the significant effort indicated by these NPs, it has been observed that NPs tend to isolate at the oil/fluid interface due to the reservoir's high temperature which limits the NPs' application.² Meanwhile, Haroun¹⁶ presented a novel approach to employ energy in a reservoir using an electrical method to active fluid mobility. Afterward, the EM waves driving approach was introduced which entails activating NPs movement by propagating energy to the nanofluids, and positive enhancement was examined for improving crude oil mobility. Some of the NPs reported are ZnO and Al₂O₂,^{6,17-19} Cobalt ferrite (CoFe₂O₄),²⁰ yttrium iron garnet (YIG) (Y₃Fe₅O₁₂),²¹ ZnO,²² Fe₂O₃-Al₂O₃²³ Nickelzinc ferrite $(Ni_{1-x}ZnxFe_2O_3)$,²⁴ and $Co^{2+}_{0.75}Fe^{2+}_{0.25}Fe^{3+}_{2}O_4$.²⁵ The present study summarizes and evaluates the influence of employing EM waves using dielectric NPs to improve IFT which in turn enhances oil productivity. The merit and challenges confronting the newly innovative approaches and possible solutions to the problems is briefly highlighted.

Discussion on the Effect of Dielectric NPs Propagated by EM Waves

Certain ions are naturally present in the earth's crust, including reservoir holes.²⁶⁻²⁸ Unfortunately, when nanofluids are injected into the reservoir the naturally existing ions stocked on the rock surfaces attract the moving particles within the fluids and consequently resist the effective functionality of the NPs. Introducing energy to the reservoir via EM waves could significantly activate the mobility of the NPs and reduce the attraction of such ions onto

the suspended particles within the nanofluids. Hence, the effective operations of the NPs will be improved. The charge distribution of ions for the nanofluids is the driving force for the effective mobility of the fluids when endorsed by EM waves. The ions are atoms or molecules with an electrical charge solubilized material in a particular fluid. It is made up of two charges, either positive or negative. The negative charge ions are referred to as anions while the positive charge ions as cations. It is essential to understand the processes that regulate the ion distribution and concentration in the electric double layer within the porous media for us to fully comprehend how cation and anion reactions affect objects. The ions dissolve in the fluids can move around freely within the fluids. However, the mobility of the particles could be improved upon the EM wave exposure on account of the polarization and alignment of the particles. The ions' types, concentration, and particle size can all have an impact on the fluid characteristics.²⁹ The use of EM waves depends on how electromagnetic materials interact with EM waves within a given medium. It is necessary to maintain control over the electric and magnetic elements present in the porous medium so that they can interact with the time-varying electric and magnetic field components which allow proper EM wave propagation. The characteristics of the medium's surroundings will dictate the kinds of interactions that occur and the frequency range over which EM waves will propagate. The high energy stimulus of dielectric NPs makes them a perfect candidate to be used under EM wave propagation which could encourage NP's mobility in the reservoir. The EM waves generator applies the required energy to the nanofluids which could enhance extra agitation within the fluids and result to cause crude oil deformations and consequently decrease the IFT. When EM waves are applied to the nanofluids that contain dielectric behavior, the dielectric loss of the fluids makes ions polarize and align to the direction of the applied EM waves. Thus, crude oil deformation is said to occur for easy displacement due to the aggregation of the particles at the oil/fluid interface.³⁰ Additionally, the IFT reduction under the EM waves endorsement is attributed to the hydrodynamic sizes of the fluids. The impact of EM waves on the oil/nanofluid interface lowers IFT, resulting in a single layer of NPs packed in a liquid-like form at the interface.^{31,32} The oil droplet is distorted when the EM waves are delivered, which causes the surface area of the droplet to develop, reducing the assembly of the NPs. The increased surface area allows the accumulation of more NPs at the oil/nanofluid interface, resulting in a further drop in IFT.

The well-known equipment used for IFT measurement is a goniometer using a method of pendant drop or sessile drop. It was recently reported that a goniometer has been used to test the IFT performance under the influence of EM waves Figure 1. The radiofrequency (RF) signal generator is the EM waves equipment used to generate the energy in the form of waves and propagate it through the solenoid coil connected to the fluid's container which enhances the fluid operational activation. The nanofluids could be poured into the experimental chamber that was enclosed by the solenoid's coils. The crude oil is injected onto the rock sample (for the sessile drop technique) that was settled on a metal platform in the center of the chamber using an inverted syringe. The light source can be used to flash across the container to ensure that the image can be seen, and the computer is connected to display images of the crude oil versus injected fluids.



Figure 1: Goniometer with EM waves connection for IFT measurements.³⁰





The Influence of EM Waves Propagation on IFT Reduction

A unique method for triggering the activation of NPs applications using EM waves in porous media was recently introduced. Yet, the majority of the EM wave incidents that were recorded supported the use of NP for oil recovery. The NPs that have been described include cobalt ferrite ($CoFe_2O_4$),²⁰ $Co^{2+}_{0.75}Fe^{2+}_{0.25}Fe^{3+}_2O_{4^{\prime}}^{25}$ yttrium iron garnet (YIG) ($Y_3Fe_5O_{12}$),²¹ nickel-zinc ferrite ($Ni_{1.x}ZnxFe_2O_3$)²⁴ and ZnO.²² In addition to oil recovery studies, it's critical to look at how EM waves affect NPs activation to change the connection between the oil and fluids interface. Yet, there weren't many reports in the literature. NPs with magnetic or dielectric properties are the most appropriate nanomaterials employed due to their excellent electrical conductivity under EM waves.³⁰ As a result, NPs' ability to absorb energy is a key element that promotes their aggregation at the oil/fluid interface, which lowers IFT.

The function of EM waves on IFT reduction was determined using dielectric nanofluids of ZnO and Al_2O_3 at the voltage of 3.5 V and frequency of 18.8 MHz.³³ The dielectric loss of the nanofluids

caused rotational polarization that introduced additional agitation within the fluids, resulting in a reduction in the IFT. Some previous reports have equally shown significant reductions in IFT using ZnO and Al₂O₂ NPs under EM wave inducement,^{5,6,33} the same was equally reported for yttrium iron garnet (YIG) NPs.34-36 Recently, Hassan YM studied the influence of EM waves applied to activate the dielectric composite nanofluids of ZnO-SiO₂ using a voltage of 4.5 and frequency of 20 MHz. A significant reduction was observed when EM waves were induced and the IFT of the nanofluid reduced from 16.70mN/m to 0.002mN/m. The individual nanofluids of ZnO and SiO₂ were also reported and correlated with their respective composite NPs.³⁷ In a different study by Yarima³⁸ the IFT was found to have significantly reduced when hybrid NPs of Fe₂O₂-SiO₂ were used. Thus, IFT reduced from 17.39mN/m to 0.21mN/m. The authors concluded that the influence of Fe₂O₃-SiO₂ hybrid NPs performance for IFT reduction was attributed to the amalgamation of magnetic and dielectric attributes in a prepared nanofluid considering their immensive reaction towards EM waves. ZnO-SiO₂ were equally reported to have shown a reducing trend in IFT when subjected to EM waves.³⁹ Figure 2(a) shows the image of crude oil injected in brine activated by EM waves, in which the IFT value was 12.93mN/m. However, when ZnO-SiO₂ NPs were introduced, the crude oil was considerably deformed as shown in Figure 2(b), and IFT was lowered from 12.93mN/m to 1.02mN/m which made the crude oil easy to displace across reservoir roots.³⁹ Additionally, IFT reduction was recently reported using dielectric nanofluids in a hybrid form activated with EM waves, and additional improvement considering IFT reduction was equally reported above their constituents, the NPs including ZnO-SiO₂³⁷ and ZnO-Fe₂O₃-SiO₂.³⁹ Some recent experiment has reported a significant reduction in IFT when nanocomposite materials were used even without recognition of EM waves such as ZnO-SiO₂,⁴⁰ Fe₂O₃-SiO₂,^{15,41,42} TiO₂-Quartz,⁴³ TiO₂-SiO₂,⁴¹ and NiO-SiO₂.⁴⁴⁻⁵⁰

Challenges and Recommendations

The Materials and Methods should be described with sufficient details to allow others to replicate and build on the published results. Please note that the publication of your manuscript implicates that you must make all materials, data, computer code, and protocols associated with the publication available to readers. Please disclose at the submission stage any restrictions on the availability of materials or information. New methods and protocols should be described in detail while well-established methods can be briefly described and appropriately cited Table 1.

Despite the significant outcome examined while using various NPs on IFT reductions, the following challenges diminish the development of the process:

- Most of the experiments using NPs under EM wave exposure were laboratory-scale research and are yet to have practical application.
- Calculations of the required frequency and

Table 1: Previous Experimental results for the Influence of various NPs on reducing Interfacial tension (IFT).

Nanoparticles	NPs Size (nm)	(IFT) (mN/m)				
(NPs)		Fluids (F)	F + NPs	Base-fluids	кетагк	References
SiO ₂	20	16.5	8.47	Brine	EM waves enhance small reduction for IFT	[39]
SiO ₂	20	12.5	3.38	Brine	EM waves were propagated to SiO_2 nanofluids which enhance IFT reduction	[30]
SiO ₂	10-30	39	1.5	Propanol	IFT reduced when SiO ₂ was supported with saline	[46]
SiO ₂	40	20	18	Brine	IFT has shown a poor reduction	[11]
SiO ₂	20	3.5	2.7	Brine	The IFT performance was relatively low	[47]
SiO ₂	10 - 150	27.1	5.6	Distilled water	IFT was rationally reduced	[48]
ZnO	20	16.5	6.84	Brine	IFT was reasonably reduced when EM waves were delivered to the nanofluids	[39]
ZnO	20	12.5	4.45	Brine	IFT was reasonably reduced	[30]
ZnO	-	27	19	Surfactant (SDS)	Adsorption analysis of ZnO on calcite was examined	[49]
ZnO	-	20	2.8	Surfactant	Nano-surfactant fluids enhance the IFT reduction	[50]
				(SDS)		
Fe ₂ O ₃	20	16.5	7.41	Brine	IFT was further reduced when EM waves were incorporated into the nanofluids	[39]
Fe ₂ O ₃	20	12.5	1.16	Brine	IFT was considerably reduced upon EM wave exposure	[30]
ZnO	117	13	12	Brine	IFT slightly changed when EM waves were induced	[5]
_ZrO ₂	30 10-30	8.45	1.85 17.5	Cetyl Trimethyl Ammoni- um Bromide (CTAB) Brine	Adding CTAB to ZrO_2 nanofluids enhanc- es a reasonable IFT reduction The low performance of TiO_2 NPs was due to a lack of fluid adsorption on the surface	_ <u>[12]</u> [10]
TiO ₂	21	19.2	-	Brine	The IFT reduction was not counted	[11]
Al ₂ O ₃	40	26.5	18	Brine	The charge distribution of Al ₂ O ₃ NPs was examined	[10]
Al ₂ O ₃	20	8.46	1.65	(CTAB)	Nano-surfactant-based fluids reported significant results for IFT reduction	[12]
ZrO ₂	40	9.88	2.78	sodium dodecyl sulfate (SDS)	The performance of ZrO_2 on IFT was considerable despite a limited report on it	[12]
TiO ₂ -quartz	-	36.4	3.5	Distilled water	The results for IFT reductions were highly significant	[43]
NiO ₂ -SiO ₂	-	29.2	1.28	Distilled water	When composite nanofluids of NiO_2 -SiO ₂ were utilized, IFT was considerably re- duced	[44]
ZnO-SiO ₂	-	19.68	9.45	Seawater	ZnO-SiO ₂ hybrid nanofluids improved IFT reduction	[40]
ZnO-SiO ₂	20	16.5	0.02	Brine	Forming hybrid nanofluids of different dielectric NPs under EM waves exposure enhances the IFT reduction by 99 %	[37]
ZnO-Fe ₂ O ₃ -SiO ₂	20	16.5	1.27	Brine	The EM wave propagation to a hybrid of magnetic and dielectric nanofluids enhances a sufficient reduction in IFT	[39]
Fe ₂ O ₃ -SiO ₂	20	17.39	1.03	Brine	The composite nanofluids influence IFT reduction without EM waves exposure	[15]

- heat disaffection to the reservoir that are precise and faultless are necessary to implement EM waves in the field reservoir.
- A large quantity of NPs is required for oil and gas industrial companies; hence, the high cost of NPs remains a challenge.

Recommendations

- The thermal stability of the NPs needs to be evaluated, thus, the IFT and nano-flooding experiment should be done at high temperatures.
- Further research into theoretical and analytical modeling is recommended to generate precise estimations about the required heat and frequency that favors the reservoir situation

The high cost of NPs can be addressed by enhancing the key sources of NPs formation. This could provide innovative approaches to form NPs with lower-cost raw materials and EM wave responsiveness.

Conclusion

Various NPs have exhibited a powerful role in reducing IFT that existed within crude oil/fluids boundaries which in turn enhanced oil productivity. Recently, the concept of operating EM waves to provide energy to dielectric nanofluids for IFT evaluation was brought out. A meaningful outcome was observed during the EM wave exposure which enhances ions of the NPs to be polarized and aligned to the EM wave propagation point. Consequently, the crude oil deforms and causes IFT reduction for oil recovery. More experiments are recommended to be done in the future using various NPs at reservoir conditions. implementing the proposed idea appropriately is anticipated to enhance oil removal from the reservoir's environment.

Acknowledgements

None.

Funding

This Review Article received no external funding.

Conflicts of Interest

Regarding the publication of this article, the authors declare that they have no conflict of interest.

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