Review

Application of Magnetic and Dielectric Nanofluids for Electromagnetic-Assistance Enhanced Oil Recovery: A Review

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Abstract: Crude oil has been one of the most important natural resources since 1856, which was the first time a world refinery was constructed. However, the problem associated with trapped oil in the reservoir is a global concern. Consequently, Enhanced Oil Recovery (EOR) is a modern technique used to improve oil productivity that is being intensively studied. Nanoparticles (NPs) exhibited exceptional outcomes when applied in various sectors including oil and gas industries. The harshness of the reservoir situations disturbs the effective transformations of the NPs in which the particles tend to agglomerate and consequently leads to the discrimination of the NPs and their being trapped in the rock pores of the reservoir. Hence, Electromagnetic-Assisted nanofluids are very consequential in supporting the effective performance of the nanoflooding process. Several studies have shown considerable incremental oil recovery factors by employing magnetic and dielectric NPs assisted by electromagnetic radiation. This is attributed to the fact that the injected nanofluids absorb energy disaffected from the EM source, which changes the fluid mobility by creating disruptions within the fluid's interface and allowing trapped oil to be released. This paper attempts to review the experimental work conducted via electromagnetic activation of magnetic and dielectric nanofluids for EOR and to analyze the effect of EM-assisted nanofluids on parameters such as sweeping efficiency, Interfacial tension, and wettability alteration. The current study is very significant in providing a comprehensive analysis and review of the role played by EM-assisted nanofluids to improve laboratory experiments as one of the substantial prerequisites in optimizing the process of the field application for EOR in the future.

Keywords: electromagnetic fields; magnetic nanofluids; dielectric nanofluids; enhanced oil recovery; core flooding

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1. Introduction

It has been projected that the world's energy consumption will increase to 50% above the current level by the year 2050 [1]. This is a great challenge that needs to be given due consideration, because oil resources were regarded as the leading energy source in the world, and such anticipation was made before the outbreak of the coronavirus pandemic, which has contributed immensely to the fantastical deterioration of oil production globally. This shows that the process of oil extraction from the reservoir needs to be improved so that more oils can be produced. Oil reservoirs worldwide are experiencing persistent problems in terms of the extractability of the available natural resources in the oil fields. About two-thirds of the residual oil (75%) cannot be recovered by employing traditional extraction

procedures [2]. Enhanced Oil Recovery (EOR), also known as tertiary recovery, refers to the methods of extracting crude oil from a reservoir that is left behind after primary and secondary recovery. Primary recovery is the oil production process that relies on the natural movement of the oil within the underground pressure. This is attributed to some factors that stabilized the system, such as the expansion of the natural gas at the top surface of the reservoir. Secondary recovery, on the other hand, is the method of supplying external energy to the reservoir by injecting water or gas (CO_2) to increase reservoir pressure, as a result of which more oil can be produced. Therefore, EOR is more needed in the current situation than ever before due to the increasing global energy demand, and also considering the fact that oil production was observed to have been drastically reduced since 1995 [3]. Lack of EOR technology execution in oil extraction can be the downfall of a country in terms of oil production, Indonesia being one of the examples [3].

EOR has fundamentally relied upon three different techniques. The first one is thermal, which deals with heating the crude oil to reduce oil viscosity, as a result of which the mobility ratio will be improved. Heating reservoirs also can stimulate oil permeability and at the same time surface tension will equally reduce. Gas miscible flooding is the second method, in which hydrocarbon gases, CO_2 , nitrogen, or natural gases are injected into the reservoir, which results in reducing the oil viscosity. Chemical injection is the third category, which deals with injecting various chemicals such as polymers and surfactants into the reservoir, which can improve interfacial tension (IFT) reductions, emulsification, and wettability alterations which are worthy of oil stimulations. However, when utilizing these methods, still some persistent problems hinder the success of the process. As an example in the thermal method, there are challenges associated with heat leakage, the poor thermal conductivity of fluids, and a high energy cost [4]. Chemical injections into the reservoir, on the other hand, require a huge amount of chemicals to be employed, which is very expensive, and a lot of damage formations were reported for chemical injections in many instances [5,6]. Additionally, for gas miscible flooding, there is a persistent challenge associated with corruptions caused by CO_2 , high penetration of the injected gas from the injection well toward the production well that consequently renders a huge amount of oil to remain unrecovered [7,8]. Subsequently, nanoparticles (NPs) in the form of nanofluids flooding were proposed and were observed as the most advanced method, less expensive, and more efficient, which have been used over the years. However, still, there is a challenge for the active participation of the nanofluids because the fluids usually were activated by the brine, and brine has limited capacity in reducing interfacial tension. Recently, electrical resistive heating was proposed, in which the energy is carried by the electric field that can be disaffected when two electrodes connected to the AC source are positioned within the reservoir at a certain distance [9,10]. There are some challenges for this approach also, because the electrodes need to be drilled into the reservoir to communicate with hydrocarbons and therefore the installation of the antenna in the reservoir well is very difficult [11,12]. Hence, a different approach that is very effective, significant, less expensive, and environmentally feasible is highly needed, which will be better prepared if nanofluids flooding is going to be improved. Alternatively, the EM-assisted nanoflooding method tends to perform significantly and exclusively in this regard, because the nanofluid's mobility can be activated.

Water flooding was used in recent decades to recover the trapped oil in reservoir rocks; however, a large amount of crude oil remained unrecovered due to the high viscosity of the crude oil and low viscosity of the injected water. Consequently, this has necessitated the introduction of chemical flooding, which has performed soundly for recovering residual crude oil and has been employed extensively [13–15]. The fluid injection of alkaline, polymer, and surfactant are the most common chemicals employed for EOR. Different chemicals have different functions concerning EOR: for example, polymer flooding usually favors improving the mobility of the injected fluids [16], while IFT reduction and wettability alteration were observed during surfactant flooding [14]. Courageously, recent investigation has verified that combining nanoparticles with chemicals during the flooding process has

prevailed a significant outcome over bare chemically flooding injections [13,17,18]. Furthermore, nano-Polymer or nano-surfactant flooding was considered as one of the successful chemical floodings that contain either NPs with polymers or NPs with surfactant which was found to be highly applicable in EOR [17]. However, a combination of all (NPs, polymer, and surfactant), termed nano-polymer-surfactant flooding, was recently proposed by some researchers, and satisfactory outcomes concerning improving oil productivity were reported [16].

Different hydrocarbon compounds exist in crude oil, such as asphaltenes, resins, aromatic, and waxes; the heaviest crude oil component with a complex nature of molecules is asphaltene, which is why the molecular structure of this component is not clearly understood [19–21]. Asphaltenes deposition on the surface of the reservoir rocks is disastrous for the productivity of the hydrocarbons [22]; this is attributed to the fact that the molecules of asphaltene tend to aggregate, and consequently, huge agglomerations will form. Complete removal of deposition of asphaltene from reservoir rock will cost a lot; alternatively, the asphaltene deposition was desired and recommended to be inhibited [19]. Asphaltene tends to accumulate at solid to liquid or liquid to liquid interfaces during the chemical flooding process, as a result of which microemulsions are formed due to IFT reductions and wettability change of the solid surface [23]. More studies are anticipated in the future for better clarifications of this mechanism. While investigation of asphaltene-brine interaction is still ongoing, some studies were made with dissimilar opinions, whereby some researchers advocated that the presence of water microemulsions has no significant effect on the precipitation and deposition of the asphaltene [24,25], whereas the others recommended that asphaltene deposition and aggregation were observed to reluctantly act in the presence of water, and also that the asphaltenes solubility was equally found to have increased when water was present [26,27].

Many researchers have emphasized over the years the idea that the transformation from microparticles to a smaller particle will significantly provide new developments in many industries. Nanoparticles are eminent as a new field of science and technology that has been found to have numerous applications in different fields in modern science and technology [28]. The discipline that deals with the behavior of materials at the nano-scale level is termed nanoscience [29], whereas nanotechnology deals with issues associated with characterization, designing, production, and application of materials at the nanometer scale [29]. Nanoparticles (NPs) are particles with a diameter of less than 100 nanometers (nm) in size, which have contributed to various sectors such as agriculture, biomedical, electronics, engineering, industries, etc. [30,31]. The reactions of the particles (such as mechanical, chemical, electrical, magnetic, etc.) perform well and preferably at the nano-material scale [32]. Nanoparticles have also contributed to almost all sectors in the oil and gas industry such as drilling, reservoir characterization, exploration, refining, production, etc. [33]. Furthermore, adding NPs into various fluids-based materials was found to have recovered more oil [15,34]. This is accredited to the fact that the injected NPs in a reservoir in the forms of nanofluids was observed to have altered some reservoir properties which in turn improved EOR; such factors include mobility ratio improvements, rock wettability alteration, improving quality of the injecting fluid, viscosity change of the injecting fluid, improvement for the interactions between rock surface and oil, conductivity and specific heat improvement, density change with regards to the injecting fluid, and emulsification improvement [17,35–38]. The smaller size and greater surface per unit volume of the NPs provide special and unique properties and granted the NPs the opportunity of flowing in the reservoir rock without being absorbed or withheld by any obstacle; as a result of that, they can deeply penetrate a very long distance through rock pores within the reservoir and execute the required task adequately [39].

Metal nanoparticles are NPs for pure metals (e.g., gold, zinc, etc.) or their compounds (e.g., oxides, sulfide, etc.). The first person who investigated the existence of metallic NPs in solution was Faraday in 1857; subsequently, the varieties of their colors were expressed by Mie for the first time in 1908 [40]. Investigation of metal oxide nanoparticles has been

developed very rapidly and tremendously from the 1990s to date with satisfactory outcomes in various fields [3]. This has aroused and sustains the interest of many researchers performing different experiments and theoretical analyses using metal oxide NPs based on the excellence and exclusiveness observed in their performance in various fields, including the oil sector. Moreover, the application of metal oxide NPs was reported to have improved oil recovery by reducing the viscosity of the heavy oil or acting as a catalyst [18,41]. Besides oil and gas industrial applications, metal oxides NPs contributed to various fields of science and technology, such as physics, chemistry, and material sciences [42–44].

For about 10 years to date, several experimental analyses have been studied by employing some metal oxide nanofluids for EM-assisted EOR, which was found to be significant in recovering trapped oil from the porous media. Therefore, this is a new technology that was proposed for EOR within the last decades. This article will summarize the fundamental concepts and rationale behind this important initiative. Moreover, the published result concerning the activation of nanofluids via electromagnetic waves radiation will be summarized, and the influential role they played in bringing some alteration of the parameters that improve oil recovery will be analyzed. The effectiveness displayed by different dielectric and magnetic NPs on EOR will be summarized, discussed, compared, and evaluated. Some factors that constrain the effective performance of the NPs concerning EOR and possible ways that are preferable and worthy of recommendations to improve in the future time will be addressed.

2. Oil Displacement Mechanisms Using Nanoparticles

2.1. Mobility Ratio Improvement

Mobility ratio is the process of restructuring the flow of crude oil as a result of injecting fluids into the reservoir. Some factors that need to be taken into consideration before the fluid injection are flow rate, permeability, reservoir thickness, and fluids density. Mobility ratio can be achieved by decreasing the viscosity of the crude oil or increasing the viscosity of the injected fluids [45]. A large amount of oil is usually trapped in the reservoir rock pores after water flooding due to some forces (viscous, gravitational, and capillary) exerted upon the oil ganglion, which constrains the effective mobility of the oil. Consequently, the strong attraction of such forces on oil has to be regulated for the attainment or achievement of oil recovery, which could be successively achieved using different NPs, e.g., ZnO [45,46], Al₂O₃ [45], etc. The mobility ratio can be express in Equation (1) [45]:

$$M = \frac{\lambda_i}{\lambda_o} = \frac{K_{ri}/\mu_i}{K_{ro}/\mu_o} = \frac{K_{ri} \mu_o}{K_{ro} \mu_i} \quad (1)$$

where λ_i and λ_o represent mobility of the injected fluids and oil, respectively, K_{ri} the relative permeability of the injected fluid, K_{ro} the relative permeability of the oil, and μ_o and μ_i the viscosity of the oil and injected fluids, respectively.

2.2. Interfacial Tension (IFT) Reduction

Interfacial tension (IFT) is regarded as one of the key parameters that were used to determine the smooth mobility and distribution of the fluids in porous media. This is the method that has to do with the fluid to fluid contact relationship in the reservoir, which is attributed to the existing force that needs to be reduced for the effective movement of the oil. The aim of measuring the IFT between oil, water, and injected fluids is to evaluate their effectiveness on EOR applications. Lowering IFT or increasing the viscosity of the injected fluids can be used to attain the incremental stage of the capillary number, which can lead to oil recovery. See Equation (2) [47]:

$$N_{cap} = \frac{v\mu}{\gamma} \quad (2)$$

where v represents Darcy velocity in m/s, μ viscosity of the injected phase, and γ the interfacial tension (IFT) of the oil phase in N/m.

The required energy to remove a particle from a fluid-fluid boundary E is given by the expression in Equation (3) [48]

$$E = \pi r^2 \gamma_{\alpha\beta} (1 \pm \cos \theta) \quad (3)$$

where r represents the radius of the particles, $\gamma_{\alpha\beta}$ is the interfacial tension between the fluids, θ is the contact angle.

Significantly, NPs are considered as the potential candidate responsible for IFT reduction in porous media. For example, hydrophilic NPs dispersed in brine reduced IFT from 14.7 to 9.3 mN/m [48]. ZnO was dispersed in brine and reduced IFT from 13.38 to 11.60 mN/m [49]. Fe₂O₃ were dispersed in propanol and reduced IFT from 38.50 to 2.75 mN/m [2]. Al₂O₃ were dispersed in propanol and reduced IFT from 38.50 to 2.25 mN/m [2]. Furthermore, NPs concentration was reported to influence IFT improvement [50]; hydrophilic NPs concentration was increased from 0.01 wt. % to 0.05 wt. %, which was found to have decreased the IFT from 9.3 to 5.2 mN/m [51]

Goniometer can be used to measure IFT and wettability, as shown in Figure 1; however, the pendant drop method is the method that is most commonly used in the laboratory experiment for measuring the IFT between the injected fluid and the crude oil [52,53]. The apparatus consists of a light source, experimental cell, microscopic camera, and data acquisition system which were used for reading the IFT value. The IFT can be calculated from the subsequent shape of the oil droplet using the camera and computer, as illustrated in Figure 1 [49].

Figure 1. Goniometer is attached with an Electromagnetic source for the measurement of interfacial tension (IFT) and contact angle; source: Adil et al. [49].

2.3. Wettability Alteration

Wettability is defined as the tendency of one fluid to spread over a solid surface in the presence of another immiscible existing fluid. Moreover, reservoir rock is usually found to be in an oil-wet state, which provides some drawbacks for the successful transportation of the fluids. Consequently, restoring the reservoir rock situation from oil-wet to water-wet will provide a significant improvement in which the trapped oil in the rock pores can be released. Contact angle measurement is the most common method used for evaluating wettability. Different NPs were reported to have contributed immensely in changing the contact angle by making the angle to be either 90 (i.e., neutral wettability) or water wet (less than 90), as illustrated in Figures 2 and 3; some of such NPs are; ZnO [45,46,49,54], Fe₂O₃/Fe₂O₄ [2,55], Al₂O₃ [2,44,51,56], TiO₂ [44,51], SiO₂ [44,51], ZrO₂ [56], etc. For the

three different phases (e.g., crude oil, brine, and injected fluids), the IFT can be determined by Young's law, as illustrated in Equation (4) [57]:

$$\cos \theta = \frac{\sigma_{sw} - \sigma_{so}}{\sigma_{wo}} \quad (4)$$

where θ represents contact angle, σ represents interfacial tensions (IFT), σ_{sw} stands for the IFT of solid–water, σ_{so} the IFT of solid–oil, and σ_{wo} the IFT of water–oil interfaces. Table 1 summarizes some available literature on the influence of NPs on IFT and wettability alteration.

Figure 2. Wettability of rock surface.

Figure 3. (A) Crude oil without nanoparticles (NPs). (B) Crude oil with ferrite NPs. From E. Esmailnezhad et al. [58] reprinted with permission.

For the analysis at ambient temperature and pressure, wettability associated with spontaneous forced and displacement processes can be determined by the Amott test, thereby determining the wettability index I_w ; hence, the wettability index can be obtained using Equation (5) [4]:

$$I_w = \frac{V_{O1}}{V_{O1} - V_{O2}} - \frac{V_{w1}}{V_{w1} + V_{w2}} \quad (5)$$

where I_w represents wettability index, V_o and V_w represent oil volume and water volume respectively, while the subscripts “1” and “2” indicate spontaneous displacement process and forced displacement process, respectively.

Table 1. Summary of the effects of Nanoparticle on Interfacial tension (IFT) and wettability alteration.

Nanoparticles (NPs)	NPs Size	Interfacial Tension (IFT) (mN/m)		Contact Angle (°)		Porous Media	Fluids	Remark	Reference
		Clean	With NP	Clean	With NP				
ZnO	117.1	13.38	11.60	54	50	Sandstone	Brine	Electromagnetic wave has influenced	[49]
Fe ₂ O ₃	20–35	38.50	2.75	132	103	Core plugs	Propanol	IFT is the dominant factor	[2]
Al ₂ O ₃	40	38.50	2.250	131	94	Core plugs	Propanol	performance was satisfactory	[2]
SiO ₂	10–30	38.50	1.450	134	82	Core plugs	Propanol	SiO ₂ was treated with silane	[2]
SiO ₂	40	19.20	17.50	131	38	Quartz plate	Brine	Performance was satisfactory	[51]
Al ₂ O ₃	17	19.20	12.80	131	28	Quartz plate	Brine	IFT doesn't reflect in Enhanced Oil Recovery (EOR)	[51]
TiO ₂	21	19.20	-	131	21	Quartz plate	Brine	The nanofluids were mixed with Polyvinylpyrrolidone (PVP) polymer with significant results.	[51]
TiO ₂	10–30	21.10	17.50	57	46	Limestone	Brine	Lower adsorption on the surface of limestone was observed.	[44]
Al ₂ O ₃	40	26.5	18	71	61	Limestone	Brine	The adsorption capacity was low	[44]
SiO ₂	20	26.5	17	26	18	Limestone	Brine	High adsorption on limestone rock was observed, consequently, EOR was improved better.	[44]
Ferrite NPs	200–500	-	-	50.44	34.14	Sandstone	Brine	Fluids performed effectively	[58]
ZrO ₂	40	8.46	1.85	70	60	Carbonate dolomite	Cetyl Trimethyl Ammonium Bromide (CTAB)	Strong water wet was achieved	[56]
Al ₂ O ₃	20	8.46	1.65	70	52	Carbonate dolomite	CTAB	Strong water wet was achieved	[56]
ZrO ₂	40	9.88	2.78	92	84	Carbonate	sodium dodecyl sulfate (SDS)	The NP performed satisfactory	[56]
Al ₂ O ₃	20	9.88	2.75	92	75	Carbonate	SDS	Al ₂ O ₃ shows better performance than ZrO ₂ in all dispersion	[56]
ZnO/SiO ₂	-	19.68	9.45	137	34	Carbonate rock	Seawater	Wettability was altered from strong oil-wet to strong water-wet	[59]
Fe ₂ O ₄	50	30	17.3	145	90	sandstone	Chitosan	Coating NPs is effective to EOR	[55]

2.4. Disjoining Pressure

The disjoining pressure is the situation in which additional oil can be revealed as a result of wedge-shaped film that was formed by the self-assembly of the nanofluids injected into the reservoir when the fluids are in contact with the oil phase. However, the appearance of the existing pressure was accredited to the fluids' injection pressure; as such, the NPs arrange themselves in a suitable form which leads to the creation of a wedge-shaped film that consequently boosts the mobility of the oil within the reservoir [4]. Figure 4 shows the NPs in a wedge-firm structure.

Figure 4. Nanoparticles in a wedge-film structure. Source: M. Adil, et al. [60] reprinted with permission.

3. Influence of NPs' Surface Modification for Nanofluids Stability

The stability of the dispersed nanoparticles is one of the critical issues that need to be addressed before the injection of the nanofluids in porous media. Ensuring the stability of the nanofluids is considered a prerequisite in optimizing the success of the nanoparticles during fluid injection. The factor that determines the stability of the suspended nanoparticles in fluids is attributed to the balance between gravitational forces, Van der Waals attractive forces, and electrical repulsive forces. If the gravitational and Van der Waals attractive forces between the particles are stronger than the electrical repulsive forces of the particles, it will result in the particles aggregating with each other and sedimentation will occur [61].

Coating surfactant or polymer on the surface of the NPs can bridge the existing gap between nanoparticles and that of the fluids [52]. Consequently, the particles will be prevented and inhibited from attracting each other or the nearby molecules, as a result of which stability can be accomplished [61]. The modifying surface of the particles has a limited application on EOR, although the concept was initiated in the early 1990s [62]. Surface modification of the NPs was reported to influence IFT reduction, and wettability changed [52,59,62]. This observable development is attributed to the incremental stage of the adsorption capacity of the particles at oil to water interface [52]. Moreover, polymer/surfactant coating on the surface of the NPs was found to promote nanofluid properties which include mobility, foams, emulsion, stability, and solubility of the fluids in a porous media [59,61,63,64]. Some experiments have shown that coating silicon dioxide nanoparticles with surfactant/polymer has revealed a productive outcome for EOR [59,61,65–67]. Furthermore, coating silica NP with Al_2O_3 NP has made them appear with a higher surface area, which resulted in better recovery than with bare silica or alumina, as reported by Negin et al. [34]. It will be good if different nanoparticles will be coated by choosing a preferred NP or surfactant/polymer, which could hopefully show better results compared to mere polymer or surfactants or nanoparticles for EOR application. However, extra precautions need to be taken while selecting a polymer or surfactant by considering some environmental features like temperature, pressure, salinity, etc. Otherwise, the wrong selection of an appropriate polymer/surfactant can lead to a low recovery, and indeed it can be disadvantageous and detrimental to the reservoir, as

they can block the reservoir rock pores. Moreover, NPs type, size, and concentrations also play a significant role in this regard.

4. Metal Oxide NPs for EOR Application

Recently, silica-based and metal-based NPs have tested brilliantly and offer promising means in recovering trapped oil from the reservoir, as shown by many researchers [51]. Some metal oxide NPs exhibited special and exclusive advantage with regards to their physical and chemical properties which qualified them as the most widely used NPs for EOR in recent decades. The most commonly used metal oxide nanoparticles that were investigated for EOR are seven, namely: ZnO, TiO₂, Al₂O₃, MgO, ZrO₂, CeO₂, and Fe₂O₃ [68].

Iron Oxide NPs (Fe₂O₃/Fe₃O₄) were observed to perform reasonably towards EOR in a sandstone reservoir when brine and ethanol were used as a dispersion media [18]. Zinc Oxide NPs (ZnO) performed satisfactorily based on the different experimental analyses which testified their numerous contributions to EOR [46,49,69]. Aluminum oxide (Al₂O₃) NPs were observed to reduce the oil viscosity and oil–brine IFT [18]. Nickel Oxide NPs (NiO/Ni₂O₃) were dispersed in diesel and brine as a dispersion medium which improved wettability and viscosity [18]. Magnesium Oxide NPs (MgO) were dispersed in distilled water and brine during core-flooding tests which showed low recovery due to permeability problems [18]. ZrO₂ NPs were observed to bring a change in the wettability of the core samples from oil-wet to water-wet [70]. Moreover, ZrO₂ was reported to improve wettability alteration and IFT when combined with surfactant [71]. Titanium oxide (TiO₂) NPs influenced wettability change from oil-wet to water-wet virtually above other metal oxides NPs [72,73]. Copper oxide NPs (CuO) were found to be good and eligible for oil improvement [72]. Tin Oxide NPs (SnO₂) have shown a reasonable outcome for EOR when dispersed in distilled water at room temperature using sandstone as a porous medium [18].

5. Role of Electromagnetic Waves in EOR

5.1. Background on EM Waves Radiation

EM Radiation refers to the photons of the electromagnetic field, which usually propagate through space, carrying electromagnetic radiant energy. Some examples are microwaves, ultraviolet, visible light, radio waves, X-rays, etc. EM wave radiation usually propagates with oscillations of electric and magnetic fields. The position of an electromagnetic wave in the electromagnetic spectrum is largely attributed to either wavelength or frequency oscillation which eventually influences their interaction with matter. Electromagnetic waves are usually emitted by electrically charged particles which subsequently interact with other charged particles, resulting in exerting force on them. An EM wave carries energy from a respective source and conveys or transmits it to the matter that interacts with it, as illustrated in Figure 5.

Figure 5. Electromagnetic waves propagation process.

5.2. Electromagnetic Heating for EOR

Applying heat to the reservoir from EM sources is one of the most promising means through which the productivity of the oil can be enhanced. As late as the 1980s, an attempt was made in conducting the field application of EM heating to the reservoir which was unsuccessful due to some unavoidable circumstances. The investigation of the role played by the radiofrequency heating reservoir in the field application was conducted for the first time in 1992 at three different places, the first one in California and Utah situated in the USA, the second one at Bashkortostan and Tatarstan situated in Russia, and the last one at Alberta and Saskatchewan situated in Canada, and the outcome was satisfactory for EOR [74,75]. Electromagnetic heating is the thermal mechanism by which the reservoir is heated and the heat is disintegrated into the oil, which ultimately decreases the viscosity of the oil, resulting in increasing oil output. The transmission system from EM sources is usually found to be in the form of electrical energy coupled with some piece of metals or cables that can act as an interconnector that directly transmits heat to the reservoir. Moreover, this has made the situation possible in which electromagnetic heating the reservoir can be produced even at low frequency via radio and microwaves. It can perform at a lower frequency because power dissipates usually if high frequency is supplied from the EM source, as dictated by the expression $p = \sigma E^2$; whereas when electrical energy is applied under a low frequency (e.g., 50 Hz), EM waves can produce resistive heating and eventually power will degenerate, as shown by expression $p = I^2 R$; however, heating can equally take place due to the support movement of the dipole of the molecules with EM waves [76]. The structure of the Electromagnetic heating reservoir for improving EOR is shown in Figure 6.

Figure 6. EM heating for Enhanced Oil Recovery (EOR). Source: Bera A. et al. [75] reprinted with permission.

5.3. Influence of Nanofluids for EM-Assisted EOR

Despite the significant aspect of employing chemical nanofluids in the reservoir being recently regarded as one of the most reliable processes accredited by modern science and technology, the injected nanofluids in the reservoir usually undergo agglomerations due to the harsh situation of the reservoir and consequently cause the segregation of the fluids from the oil/water interface, as a result of which the nanofluids suffer great trapping in rock pores of the reservoir, and hence the nanofluids transportation will be refrained [49]. Furthermore, the injected chemicals are highly disturbed by high temperature and the high pressure of reservoirs, which leads to some failure, fracture, and degradation of their performance [77]. The EM-assisted nanofluids will be a significant substitute to remedy this critical challenge because the energy disaffected from the EM sources can easily penetrate in the nanofluids, which leads to initiating some disturbances at the oil/water interface, and consequently, the movement of the oil can be facilitated. Significantly, utilizing this

method can provide an enabling situation in which the properties of the injected fluids in the reservoir will be administered remotely by an external EM field in such a way that the smoothness mobility control of the fluids will be improved and subsequently the trapped oil can be released [78–80]. The EM-assisted nanoflooding for EOR is economically affordable and environmentally feasible compared to the other categories of EOR such as thermal, gas miscible, and chemical injection.

Experimental analysis using different NPs performed reasonably in this regard, such as $\text{Fe}_2\text{O}_3\text{-Al}_2\text{O}_3$ [77]. CuO, Fe_2O_3 , and NiO [81]. ZnO [49,54,82,83], Fe_2O_3 [84], etc., as will be discussed. This has indicated that this concept offers a significant approach in the laboratory scale analysis; however, it is yet to be effective in the field scale, which is one of the factors that necessities more research of the subject matter to find out the possible means for field scale applicability.

6. Nanoparticles for EM-Assisted EOR

Dielectric or magnetic properties of the metal oxide NPs were reported to have performed differently in EOR when irradiated with EM waves [69]. Magnetic or dielectric properties of the materials are the main properties that qualified material to become eligible to perform well and exclusively under the influence of EM wave radiation. Notably, their ability to absorb energy could lead to initiating some disturbances at the oil/water interface, as a result of which mobility of the oil can be improved [45]. Three basic requirements make particles become a good energy absorber under EM wave irradiation: namely, permittivity, permeability, and resistivity [85]. Some experimental results for EM assisted nanofluids flooding concerning the percentage of oil recovery is shown in Table 2.

Table 2. Summary of the experimental analysis of nanofluids flooding for EM-assisted enhanced oil recovery.

NPs/Fluid Base	Oil Type	Rock Type	Recovery (%)	Reference
ZnO/brine	Heavy Crude oil	Glass parks	14.8–26.2	[83]
$\text{Co}^{2+}_x\text{Fe}^{2+}_{1-x}\text{Fe}_2^{3+}\text{O}_4$ /brine	Heavy oil	Sand parks	11.63–17.44	[80]
$\text{Co}_{0.4}\text{Fe}_{0.6}\text{Fe}_2\text{O}_4$ /brine	Miri Crude oil	Sand parks	15.83	[86]
$\text{Ni}_{1-x}\text{Zn}_x\text{Fe}_2\text{O}_3$ /brine	Crude oil	Glass parks	26.07	[87]
ZnO/brine	Crude oil	Sand park	9.00–10.40	[49]
CoFe_2O_4 /brine	Crude oil	Glass park	8.70–31.58	[78]
Al_2O_3 /brine	Crude oil	Sand park	13.3–24.1	[18]
CuO, NiO/brine	Crude oil	Carbonate	8.19 & 7.59 for CuO & NiO, respectively	[81]
SiO_2 , Al_2O_3 , Fe_2O_3 /brine	Mineral oil	Sandstone	8.99–20.42	[88]
$\text{Fe}_3\text{O}_4/\text{SiO}_2$ & $\text{TiO}_2/\text{SiO}_2$ /brine	Crude oil	Sand park	24 & 23 for $\text{Fe}_3\text{O}_4/\text{SiO}_2$ & $\text{TiO}_2/\text{SiO}_2$, respectively	[89]
Fe_3O_4 /brine	Crude oil	Glass micromodel	22	[90]
$\text{Y}_3\text{Fe}_5\text{O}_{12}$ /brine	Heavy oil	Sand parks	43.64	[91]
$\text{Fe}_3\text{O}_4/\text{SiO}_2$ /brine	Crude oil	Glass micromodel	13.2	[92]
$\text{Fe}_2\text{O}_3\text{-Al}_2\text{O}_3$	Heavy oil	Silica beads	24.25–30.00	[77]
Al_2O_3 , Fe_2O_3 & SiO_2	Crude oil	Core plugs	92.5, 88.6, and 95.3 for Al_2O_3 , Fe_2O_3 & SiO_2	[2]

6.1. Magnetic and Dielectric Nanofluids for EM-Assisted EOR

Magnetic nanofluids deal with the colloidal suspensions of the magnetite NPs in a fluid-based material that consequently creates smart nanofluids that display overwhelmingly both magnetic and fluids properties [93]. The magnetic property of the NPs in the fluid-based material has prodigiously contributed towards the enhancement of the residual oil when activated by EM energy. This phenomenon was found to be consistent upon

changing some parameters, such as IFT improvement, fluid viscosity, rock wettability alteration, fluid property modification, and smoothness mobility of the fluids in a porous medium [94]. Moreover, the influence of the magnetic properties over the alteration behavior of the fluids that could lead to oil stabilization is largely attributed to the size of the magnetic nanoparticles [94]. Magnetic and dielectric nanofluids played an important role in energy exposure, which in turn contributed enormously to EOR [44,49,69,81,83,95].

Dielectric nanofluids, on the other hand, are a fluid-based material with two phases that comprise dielectric liquids as a medium for dispersion, and NPs as solid dispersion phases [96]. The dielectric nanofluids were found to be essential under the influence of EM waves. This is attributed to their dielectric loss, which renders the particles motivated when an external electric field is applied. Hence, the suspended particles in a liquid will eventually undergo polarization, which can result in improving the trapped oil by improving the mobility ratio of the fluids due to the electrorheological effect that leads to the incremental stage of the viscosity of the nanofluids [49]. Various dielectric nanofluids activated by EM wave irradiation have been studied in the last decade and showed promising results for enhanced oil recovery [49,54,60,97,98].

6.1.1. Ferro-Nanofluids

For the first time, Kothari et al. (2010) [99] proposed the idea of employing smart-nanofluid combined with the surfactant and conducted investigations on the EOR applications. The research focuses more on the effect of the rheological properties of the ferrofluids; the report verified that coating surfactant on the surface of the ferromagnetic NPs was significantly reported to have avoided agglomeration. Moreover, IFT was found to be reduced through continual addition of the surfactant, and according to them, this was found to be a worthy application regardless of the type of reservoir situation with regards to wettability, either oil wet or water wet. This idea has roused the interest of researchers to have a special look at hiring magnetic nanofluids for EOR.

Recently, Ali A.M. et al. (2020) [98] investigated the adsorption behavior of the Ferro-nanofluids of Fe_2O_3 and Fe_3O_4 on oil recovery. Studying the role of the adsorption capacity of the nanoparticles is significant because the transport mobility of the nanofluids in a reservoir is largely attributed to the adsorption of the particles on the surface of the rock. The study has shown that the ferrite nanofluids were instilled in reservoir sandstones, and the interfacial energy and adsorption of the ferrite fluids was determined using molecular dynamics simulation. The results showed that Fe_3O_4 ferrite nanofluids performed well and adequately at the liquid/fluids interface, which maximized IFT reduction.

6.1.2. Cobalt Ferrite Nanofluids

Yahya N et al. (2012) [78] studied the role of cobalt ferrite (CoFe_2O_4) nanoparticles in EOR by conducting two experimental analyses. (CoFe_2O_4) NPs with magnetic feeders were used in the first experiment to improve the magnetic field strength, whereas the ferrite nanofluids alone were used in the second experiment. During nanofluids injection, EM waves were introduced, which were observed to have exhibited a substantial outcome with regards to recovering the remaining oil in place (ROIP), in which 31.58% was recovered, whereas the analyzed nanofluids without EM were found to be 8.70%. These ferrite NPs have not been extensively studied for EOR application despite the satisfactory outcome and more experiments are required via different nano flooding methods by using different reservoir rocks, and also to test whether the ability of the particles on IFT, wettability, and viscosity is significant. Similarly, Cobalt ferrite NPs of $\text{Co}^{2+x}\text{Fe}^{2+}_{1-x}\text{Fe}_2^{3+}\text{O}_4$ and $\text{Co}_{0.4}\text{Fe}_{0.6}\text{Fe}_2\text{O}_4$ were reported to be significant in EOR under the EM field as reported by Suleiman et al. (2014) [80] and Suleiman et al. (2019) [86], respectively.

6.1.3. Nickel-Zinc Ferrite Nanofluids ($\text{Ni}_{1-x}\text{Zn}_x\text{Fe}_2\text{O}_3$)

Zaid H.M et al. (2014) [87] investigated the effect of the nickel to zinc ratio of magnetic NPs of Nickel-Zinc Ferrite ($\text{Ni}_{1-x}\text{Zn}_x\text{Fe}_2\text{O}_3$) on oil recovery. The NPs were synthesized at

various ratios by varying the value of x . A core flooding experiment was conducted. The ferrite nanofluids were injected into the compacted sand that was saturated with crude oil; subsequently, EM waves were introduced during the suspension; amongst the preferred magnetic nanofluids sample, the one with highest magnetization was when $x = 0.5$ with the value of 52.6 emu/g, detected using a Vibrating Sample Magnetometer (VSM); moreover, the same sample has also shown the highest recovery of 26.07%.

6.1.4. Lanthanum-Zinc Ferrite ($\text{MnZnLa}_x\text{Fe}_{2-x}\text{O}_4$)

Lee et al. (2019) [100] analyzed Mn-Zn ferrite NPs ($\text{MnZnLa}_x\text{Fe}_{2-x}\text{O}_4$) substituted by Lanthanum (La) at various values of x (0.06, 0.08, 0.10). IFT and wettability of the studied ferrite nanofluids were analyzed. Sol-gel auto-combustion method was used for the synthesis of the materials, and the morphology, crystal structure, and magnetic property of the materials were analyzed via FESEM, XRD, and VSM, respectively. Subsequently, the ferrite nanofluids were prepared at three different weight percents (0.01, 0.03, and 0.05) dispersed in brine as the fluid base, and Sodium Dodecyl-benzene Sulfonate (SDBS) was added as a stabilizer. The outcome of the result has shown that the magnetic properties of the material were observed to be highest at (La) composition when $x = 0.08$. Furthermore, IFT reduction and wettability alteration was analyzed, and the ferrite nanofluids with 0.05 wt% have shown the best result for the analysis. It will be good if the core flooding experiment will be conducted to analyze what percentage of the oil can be recovered using this material.

6.1.5. Yttrium Iron Garnet (YIG) ($\text{Y}_3\text{Fe}_5\text{O}_{12}$)

Suleiman et al. (2016) [91] proposed the feasibility of employing Yttrium Iron Garnet (YIG) nanofluids for the EOR under EM wave exposure. The samples were synthesized and doubly annealed at 1200 °C (YIG 1200) and 1000 °C (YIG 1000) at the particle size of 49.69 and 37.69 nm, respectively. YIG 1200 sample has shown the best property of permeability and magnetization via VSM analysis and therefore was selected for running EOR analysis. The core flooding test was conducted, and two pore volume of YIG nanofluids was injected into the porous media, and EM waves of 13.6 MHz were exposed during magnetic nanofluids suspension. The result has shown that the remaining oil in place (ROIP) was observed to be 43.64%. Significantly, it can be seen that $\text{Y}_3\text{Fe}_5\text{O}_{12}$ is a suitable candidate for EOR. A few experiments were recently conducted by employing Yttrium Iron Garnet (YIG) nanofluids activated by EM waves and displayed a reasonable outcome by improving IFT, wettability, and viscosity [101–103].

6.1.6. Fe_2O_3 - Al_2O_3 Composite Nanofluids

Suleimani et al. (2014) [77] investigated the effect of EM waves on the magnetization property of the composite nanofluids of Fe_2O_3 - Al_2O_3 by EM irradiation at a frequency of 13.6 MHz. The research has reported that Fe_2O_3 - Al_2O_3 nanocomposites material were dispersed in distilled water and subsequently injected via Silica beads as a porous medium at the rate of 1.0 mL/min in 2.4 PV with a size of 0.2 PV for EOR analysis. Three nanofluids samples were labeled as S700, S800, and S900, during the suspension of the magnetic nanofluids, EM waves were introduced concurrently. The S900 nanofluids have shown the highest percentage of oil recovery at 30%. The composite material of hematite and magnetic NPs is essential in terms of energy absorption during EM radiation exposure. Analyzing such composite material to investigate further on the IFT and wettability change under EM exposure will be significant. The different mechanisms of improving oil productivity are illustrated in Figure 7.

Figure 7. Flow chart of EOR experimental procedure.

6.1.7. $\text{Fe}_3\text{O}_4/\text{SiO}_2$ and $\text{TiO}_2/\text{SiO}_2$ Composites Nanofluids

Kazamzadeh et al. (2018) [89] studied the effect of two metal oxide/ SiO_2 nanocomposites materials ($\text{Fe}_3\text{O}_4/\text{SiO}_2$ and $\text{TiO}_2/\text{SiO}_2$) for EOR application at varying pressure. Carbonate sand pack flooding analysis was conducted at three different pressures of 14.7, 1500, and 3500 psi. The outcome of the experiment revealed that the nanocomposite fluid performance was reliant on the pressure increment within the porous media. The result has shown that during TiO_2 and $\text{TiO}_2/\text{SiO}_2$ nanofluids suspension, IFT reduction and wettability were found to be improved at ambient pressure, and the result has shown the recovery factor of 60 and 72% for TiO_2 and $\text{TiO}_2/\text{SiO}_2$ nanofluids, respectively. Moreover, at high pressure (3500 psi), Fe_3O_4 and $\text{Fe}_3\text{O}_4/\text{SiO}_2$ composites nanofluids were observed to have exhibited a higher recovery factor of 56 and 69% for Fe_3O_4 and $\text{Fe}_3\text{O}_4/\text{SiO}_2$ nanofluids, respectively. Conclusively, the studied composite nanofluids at pressures of 3500 and 1500 psi improved the oil recovery by 24 and 23% for $\text{Fe}_3\text{O}_4/\text{SiO}_2$ and $\text{TiO}_2/\text{SiO}_2$, respectively.

Furthermore, Kazamzadeh et al. (2019) [92] investigated the performance of four different fluids for EOR application; the studied nanofluids include $\text{Fe}_3\text{O}_4/\text{SiO}_2$, Fe_3O_4 , SiO_2 , and seawater. These four fluids were analyzed individually in the designed glass micromodel. The result has shown that $\text{Fe}_3\text{O}_4/\text{SiO}_2$ nanofluids were reported to have performed well and been effective with regards to EOR compared to other fluids studied. The dominant mechanism for $\text{Fe}_3\text{O}_4/\text{SiO}_2$ nanofluids was the wettability alteration in a porous medium. Moreover, the emulsion stability was also observed in the first place during $\text{Fe}_3\text{O}_4/\text{SiO}_2$ nanofluids injection till the end of the suspension; consequently, the viscosity of the displacing fluids was increased. However, wettability and IFT were equally improved by nanofluids of SiO_2 and seawater, but the overall leading nanofluids for oil recovery were $\text{Fe}_3\text{O}_4/\text{SiO}_2$, which appeared to be in the order of $\text{Fe}_3\text{O}_4/\text{SiO}_2 > \text{seawater} > \text{Fe}_3\text{O}_4 > \text{SiO}_2$.

6.1.8. Coating Fe_3O_4 NPs

Recently, Izadi et al. (2019) [104] investigated the influence of polymer-citrate-coated Fe_3O_4 NPs using reservoir temperatures and pressure at high salinity for EOR. The salinity

was up to 256,000 ppm at a temperature of 85 °C and pressure of 2700 psi; moreover, the experiment was conducted by using carbonate rocks and sand-pack as a porous medium during nanofluids suspension. The result has shown some level of deficiency while using citrate-coated Fe_3O_4 NPs at room temperatures compared to polymer-citrate-coated Fe_3O_4 with regards to the stability of the particles. Furthermore, the result has shown that polymer-citrate-coated Fe_3O_4 NPs were found to have influenced IFT reduction and wettability alteration. Subsequently, nanofluid flooding was conducted and displayed a reasonable outcome for EOR. Recently, Divandari et al. (2019) [90] studied Fe_3O_4 coated with citric acid and a very good result was reported for EOR improvements.

6.1.9. ZnO and Al_2O_3 Nanofluids

Zinc Oxide (ZnO) is one of the NPs that has contributed immensely to different fields of study, such as food items, semiconductors, rubber material, photocatalysis, and ceramics [43]. Aluminum oxide (Al_2O_3), on the other hand, is also a metal oxide NP that can be invented using different processes, such as modified plasma arc [105], mechanochemical methods [106], or flame spray pyrolysis [107]. Recent experimental analysis testified that zinc oxide and aluminum oxide have contributed immensely to EOR. M. Adil et al. (2017) [97] investigated the electrorheological effect of the nanofluids of ZnO and Al_2O_3 calcined at a various temperature. Nanofluids were prepared at the weight percentage of 0.1, 0.05, and 0.01 using tap water, salt water, and air as dispersion media that were propagated by a solenoid-based electromagnetic (EM) transmitter. The result has shown that the particles of the materials have revealed a very strong attraction at a high electric field, as expected. Moreover, the fluid's viscosity was reported to have increased more preferably in tap water followed by saltwater when the electric field was applied. However, the decrease of the viscosity of the nanofluids was observed for saltwater within the range of 4–10% and 17–24% for ZnO and Al_2O_3 , respectively. This was attributed to the conductive effect of the tap water, and also considering the fact that low salinity of tap water has made them have a low attenuation of energy. Moreover, while using air as propagation medium, the performance concerning viscosity was reasonable only in the presence of an EM wave due to the lower conductivity of the air.

Recently, M. Adil, et al. (2020) [60] studied the characteristics of dielectric nanofluids of ZnO and Al_2O_3 by measuring IFT and wettability under EM waves irradiation. The dielectric nanofluids dispersant for the experiment were brine and SDBS, the size of the particles was within the range of 43.4–47.3 and 25–94.3 nm for ZnO and Al_2O_3 NPs, respectively. The study has shown that the energy applied via EM field enhanced NPs with a high level of absorption has created some disruption by distorting the shape of the oil droplet that consequently make some reduction in IFT from 13.38 to 11.60 and 13.35 to 8.10 mN/m for ZnO and Al_2O_3 NPs respectively as shown in Figures 8 and 9. However, the IFT reduction of the oil/nanofluids was attributed to the dielectric loss of nanoparticles, which was reported to have provided an enabling situation in which the rotational polarization created a high level of agitation of the particles. The contact angle was reduced from 42.70° to 36.01° for Al_2O_3 NPs; this was also attributed to the mobility of the polarized dipoles and free charges that were activated by the EM field.

Adil et al. (2018) [49] investigated the effect of zinc oxide NPs for EOR application at a particle size of 55.7 and 117.1 nm under the irradiation of EM waves at high temperatures (95 °C). Viscosity, IFT, and wettability were measured in the first place. Hence, the nanoflooding system was conducted using sand packs as a reservoir replicator. Zinc oxide nanofluid flooding and surfactant flooding (SDBS) were carried out accordingly; the results have shown that the particle sizes of ZnO NPs were reported to have improved IFT and wettability in such a way that the recovery increases with an increase in the particle size of the material, as similarly reported by Lee et al. (2016) [46]. Moreover, nano flooding of ZnO with high particle sizes of 117.1 nm labelled as ZnO@800 NF was treated as EM-assisted nano flooding, which displayed a higher recovery in comparison to the one with the smaller particle size of 55.7 nm, labeled Zn@500 NF. This was attributed to

the high level of disturbance between the fluids interface because particle sizes undergo polarization which subsequently caused the IFT reduction from 13.38 to 11.60 mN/m for ZnO@800 NF compared to 10.86 to 10.02 mN/m for Zn@500 NF. Hence, the highest oil recovery from the experiment was observed to be $9 \pm 10.4\%$ of Original Oil in Place (OOIP) during EM-assisted nano flooding analysis, whereas $8.5 \pm 10.2\%$ of OOIP was observed during surfactant flooding. The work has recommended promising approaches in which ZnO nanofluids give a rise in recovering more oil by displacing the trapped oil at reservoir temperature. Recently, some experiments were also conducted using ZnO nanofluids under EM exposure at reservoir temperature with a reasonable outcome for EOR, as reported by Lee et al. (2019) [54] and Zaid H.M et al. (2018) [82].

Figure 8. IFT and contact angle of the oil droplet using ZnO nanofluids under the EM field. Source: M. Adil, et al. [60] reprinted with permission.

Figure 9. IFT and contact angle of the oil droplet using Al₂O₃ nanofluids under the EM field. Source: M. Adil, et al. [60] reprinted with permission.

H. Ali et al. (2020) [108] studied the EM wave absorption capacity of NPs using sandstone as a porous medium injected and saturated by three prepared nanofluids of brine, Zinc Oxide (ZnO), and Bismuth ferrite BiFeO_3 (BFO). The facile sol-gel method was used for the synthesis of the NPs, and nanofluids were prepared before the dispersion analysis. Brine, and nanofluids of ZnO and BiFeO_3 were saturated in the prepared sandstone for two days. Vector network analyzer was used for the measurement of the magnetic and dielectric properties of the materials. The result has verified that BiFeO_3 nanofluids were observed to have shown the best magnetic and dielectric properties. Hence, BiFeO_3 displayed high absorption capacity under electromagnetic irradiation which qualified them as the most suitable nanofluids for the EOR test.

7. EM-Assisted Oil Recovery Mechanisms

7.1. Electrorheological Effect

The phenomenon that deals with the properties associated with the flow of matter (i.e., rheology) under the influence of the electric field is termed the electrorheological effect [109]. Therefore, the nanoparticles are to be dispersed in a fluid that consequently undergoes polarization, reorientation, and alteration in the viscosity when an electric field is applied [110]. The polarization of the particles can be observed in which the molecules arrange themselves toward the direction of the electric field which is attributed to the dielectric constant, whereas the particle's reorientation, on the other hand, depends upon the dielectric loss measurement [58]. Significantly, the presence of an electric field in that formation of fluids will cause an alteration of the particles in the fluids within which the mobility ratio will be improved.

7.2. Oil Droplet Deformation

Oil droplet deformation is one of the important mechanisms that show the effectiveness of the EOR by improving the fluid mobility within reservoir rock through surfactant or water flooding [111]. The deformation of the oil shape was observed to be well improved in the presence of the external field [112]. It makes it more productive if the nanoparticles will be employed in the presence of an electric field in such a way that more disturbances will be observed within the fluids' interface and the oil shape will be deformed tremendously as a result of which more oil can be released (see Figure 10) [49]. Previous research on the relevant literature of employing EM-assisted nanofluids for EOR is summarized in Table 3.

Figure 10. Disturbance at oil/water interface when EM waves were applied in the presence of dielectric nanofluids. Source: M. Adil, et al. [60] reprinted with permission.

Table 3. Overview of the experimental analysis for the magnetic and dielectric nanofluids for EM-assisted enhanced oil recovery.

Nanoparticles	Scope of Study	EM Freq. (MHz)	Outcome	Remark	Ref.
ZnO	Determination of fluid viscosity, IFT, contact angle & Nano flooding test.	—	Zinc oxide Nano flooding performed reasonably to EOR under the irradiation of EM waves at a reservoir temperature (95 °C).	Most of the experiments were conducted under ambient temp. It will be essential to have more studies under reservoir temp.	[49]
ZnO	Electrorheological effect of ZnO NPs activated by the electric field.	167 & 18.8	The viscosity increase was highly dependent on the increment of the applied electric field.	Varying the particle size of the material might influence changes in the fluid viscosity.	[82]
ZnO	Nano flooding was irradiated with EM waves	0.001	26.2% of the oil was recovered during EM exposure to the fluids, whereas 14.8% was recovered in the absence of EM waves.	The EM wave facilitates ZnO nanofluids; however, other parameters that influenced the EOR mechanism have not been studied.	[83]
ZnO	Viscosity & IFT test	18.8	Viscosity and interfacial tension (IFT) were found to have increased with an increase in particle sizes	The crystal size of the material has performed effectively by annealing at different temp.	[46]
ZnO	Fluids stability and rheological effect using surfactants	—	Increasing the surfactants led to the increment in the stability of the dispersed nanoparticles.	The presence of EM waves in the fluids has shown an increment to the viscosity.	[113]
ZnO	IFT, viscosity and wettability under EM waves	—	The presence of EM waves has improved the IFT reduction, and increased fluid viscosity and wettability alteration.	The optimum frequency to be applied during EM wave irradiation is a matter of concern.	[54]
ZnO and Al ₂ O ₃	IFT and wettability under EM wave irradiation.	—	IFT was reduced from 13.35 to 8.10 Mn/m for Al ₂ O ₃ NPs, so the contact angle was equally reduced from 42.76° to 36.01°.	The nanofluids of Al ₂ O ₃ performed better than those of ZnO nanofluids.	[60]
ZnO and Al ₂ O ₃	IFT	—	Crystal sizes of the materials have influenced EOR.	It will be essential to investigate the effect of crystal sizes of the materials on viscosity and wettability.	[114]
ZnO and Al ₂ O ₃	Electrorheology	167	The particles of the dielectric NPs have revealed a very strong attraction at the high electric field.	Tap water, salt water, and air performed effectively as a dispersion media for conveying NPs to the reservoir when EM waves were applied.	[96]
ZnO and BiFeO ₃	Adsorption capacity of the material.	8500–12,500	BiFeO ₃ nanofluids were observed to be superior in the adsorption capacity, dielectric, and magnetic properties.	BiFeO ₃ is a very good agent for EOR; hence, more analysis needs to be done by running core flooding analysis, IF, and wettability test.	[108]

Table 3. Cont.

Nanoparticles	Scope of Study	EM Freq. (MHz)	Outcome	Remark	Ref.
ZnO and Al ₂ O ₃	Electrorheology and viscosity	167	The viscosity of the nanofluids for both ZnO and Al ₂ O ₃ has improved when exposed to EM waves	The EM transmitter used in the analysis was observed to have propagated reasonably at an optimum voltage of 1.5 v.	[69]
ZnO and Al ₂ O ₃	Fluids Viscosity, wettability test, and nano flooding	50	When the EM wave was exposed to the dielectric nanofluids, more oil was recovered.	Nanofluids of ZnO have shown lower IFT compared to that of Al ₂ O ₃ nanofluids	[45]
(CoFe ₂ O ₄)	Nanofluids flooding analysis	—	When the EM wave was exposed to the magnetic cobalt ferrite nanofluids, more oil was recovered.	High energy absorbance of the cobalt ferrite NPs leads to reduced oil viscosity, which in turn improves EOR.	[78]
Co ²⁺ _x Fe ²⁺ _{1-x} Fe ₂ ³⁺ O ₄	Core flooding test	78	The total recovery efficiency was observed to be 17.44% with EM and 11.63% without EM.	The mechanisms that influence the efficiency of the EOR have not been studied.	[80]
Co _{0.4} Fe _{0.6} Fe ₂ O ₄	Sand pack flooding	—	15.83% of the residual oil was recovered in the presence of a magnetic field, whereas 7.20% was recovered in the absence of a magnetic field.	The presence of the magnetic field leads to the generation of some resistance to the flowing fluids that consequently increased the viscosity of the ferrofluids.	[86]
Ni _{1-x} Zn _x Fe ₂ O ₃	Core flooding test	—	26% was observed to be the highest recovery for EOR at the value of x = 0.5	More core flooding tests need to be done by varying injection fluids and reservoir rocks.	[87]
MnZnLa _x Fe _{2-x} O ₄	Wettability and IFT	—	IFT reduction and wettability alteration was observed.	This material needs to be studied further on EOR by conducting a flooding test.	[100]
Y ₃ Fe ₅ O ₁₂ Y = Yttrium iron garnet	Core flooding	13.6	Y ₃ Fe ₅ O ₁₂ nanofluids flooding recovered 43.64 % when irradiated with EM waves.	The NPs annealed at a high temp. have shown the best recovery.	[91]
Y _{2.8} R _{0.2} Fe ₅ O ₁₂ (R = La, Nd, Sm) La = Lanthanum Nd = Neodymium Sm = Samarium	IFT, viscosity and wettability under EM waves	100	Wettability was improved in EM exposure to the nanofluids, contrary to IFT and viscosity	Employing material with high-temperature stability will be significant during the prospective analysis.	[101]
Y ₃ Fe ₅ O ₁₂	IFT, and viscosity under EM waves	—	IFT reduction and viscosity were improved more when EM waves were applied.	Y ₃ Fe ₅ O ₁₂ is a suitable NP that has performed reasonably for EOR.	[102]
Y _{3-x} Nd _x Fe ₅ O ₁₂ Nd = Neodymium	IFT, and viscosity under EM waves	18.8	IFT reduction and viscosity were improved more when EM waves were applied.	It will be good to study further by varying the crystal structure of the material.	[103]

Table 3. Cont.

Nanoparticles	Scope of Study	EM Freq. (MHz)	Outcome	Remark	Ref.
ZnO & Fe ₂ O ₃	Core flooding		Good recovery was achieved using a curve antenna with magnetic feeders during nanofluid suspensions.	Electric signal strength using curve antenna with magnetic feeders performed better than the case without magnetic feeders.	[84]
Fe ₂ O ₃ –Al ₂ O ₃	Nano flooding test	13.6	The composite of hematite and magnetic NPs is essential when irradiated with EM waves for EOR.	More investigation is required of the energy activation fluids for the EOR application.	[77]
Fe ₃ O ₄ /SiO ₂ & TiO ₂ /SiO ₂	Sand pack flooding	—	Fe ₃ O ₄ /SiO ₂ & TiO ₂ /SiO ₂ nanofluids increased oil recovery by 24 and 23%, respectively.	Varying pressure can influence and affect the outcome of the oil recovery.	[89]
Fe ₃ O ₄	Glass micromodel flooding	—	Coating the surface of the NPs with citric acid improved the IFT and wettability alteration.	If the coated magnetic NPs are stimulated by EM wave radiation, very good results are expected to be discovered.	[90]

8. Challenges

The emancipated applications of dielectric and magnetic NPs for improving trapped oil from a reservoir cannot be overemphasized, and a lot of effort has been made and different analyses are still ongoing. However, several challenges still need to be addressed so that the work will be more productive, efficient, and significant. Some of the challenges are as follows:

- I. Most of the experimental analysis using dielectric and magnetic nanofluids were laboratory-scale analysis, in the sense that they were conducted under ambient temperature and had no practical applicability.
- II. Field application has shown that direct heating of the reservoir via radio frequency EM heating has been executed with an essential outcome by improving the heavy oils. Such fieldwork was conducted for the first time in 1992 in the USA, Canada, and Russia, despite the limited work in that regard. However, EM-assisted nanofluids remain a great challenge in field application because most of the NPs studied so far cannot withstand the harsh situation of the reservoir. This will lead to a situation whereby EM wave propagation in nanofluids will get disturbed and be worthless.
- III. Another great challenge has to do with nanofluids responses under the influence of EM waves, which required potential computational techniques that demand numerical simulators that will be used to examine essential and analytical modeling that will provide accurate and perfect calculations concerning the heat disaffection and distribution to the reservoir. However, the success of the work is also accredited to the optimum selection and application of the required frequency and power needed by the experiment.
- IV. The high cost of nanoparticles remains problematic, because a huge amount of NPs is required for oil and gas industrial operation.

9. Future Outlook

Despite the challenges mentioned, there are ways forward that can provide an improvement in the subject matter, which need to be done in the prospective analysis by addressing such critical challenges as briefly discussed here:

- I. Reservoir conditions need to be taken into consideration while conducting experimental analysis in such a way that the laboratory experiment will comply with the field-scale applications. Consequently, proper selection of NPs that can withstand high temperature and high pressure is highly recommended for future analysis while conducting nanofluids flooding at reservoir temperatures, because most of the NPs are temperature sensitive. In addition to that, more nanofluids flooding experiments are required in an advanced manner, because the laboratory experiment is an output manifestation of the fieldwork.
- II. One of the significant ways to improve ahead of the existing experiment of the NPs on EOR is by modifying the surface of the particles, as a result of which the NPs' properties can be altered towards the worthy and eligible standard for a particular analysis. This can be achieved by attaching an appropriate polymer/surfactant to the surface of the NPs. However, there is very limited work on that, despite the reasonable outcome displayed, which was why the influential effect of NPs surface modification concerning EOR is not well known and not fully understood. Moreover, polymers or surfactant coating on the surface of the NPs can provide an advanced level of improvement in the reservoir in different ways, such as improving sweep efficiency, solubility, and stability of the nanofluids, smoothness mobility of the fluids in a porous medium, temperature tolerance, etc., which in turn improve the EOR. The NPs type, size, and concentrations played a significant role in this regard. Furthermore, the proper selection of polymer/surfactant is the most important factor by considering some environmental features like temperature, pressure, salinity, etc. Otherwise, the wrong selection of an appropriate

polymer/surfactant can lead to low recovery, and indeed it can be disadvantageous and extremely detrimental to the reservoir rocks, as they can block the reservoir rock pores.

- III. It is recommended to make further investigations with regards to the theoretical and analytical modeling to make accurate calculations concerning the required heat and frequency that favors the reservoir situation. Moreover, creating proper nanosensors that will be injected in the reservoir is also required which could help in creating optimum, significant, and effective signals to be applied during the exercise for the attainment of appropriate goals of improving oil productivity. It is also a logical and good idea to investigate the possible situation in which the sensors embedded with NPs can be used in that regard.
- IV. The high cost of the NPs issue can be tackled by improving the major sources of forming the particles, thereby creating innovative cheaper raw materials that are cost-effective, electromagnetic field responsive, and environmentally feasible.

10. Conclusions

The unique properties of the nanoparticles (NPs) and unprecedented development and progressiveness observed in the various application has made them become one of the most useful materials in modern science and technology. NPs played a decisive role in oil and gas industries, like drilling, refinery, transportation, moreover, employing them in oil production has been proposed and a lot of work has been done on that aspect with a profitable outcome for oil recovery better than the usual conventional process of oil production. This paper has specifically provided a critical review of a recently published experimental analysis using magnetic and dielectric NPs inform of EM assisted nanofluids for EOR. Significantly, providing comprehensive literature upon chemical flooding via EM assisted nanofluids is highly significant in enabling the researchers to make further improvements before the field application. Different characteristics of the NPs should be scrutinized before undertaking the chemical nano flooding for EOR, which include the type of NPs, particle size, concentrations, temperature tolerance, and injection rate. Recently, a lot of investigations have had a significant outcome for EOR prevail using metal oxide NPs; the metal oxides employed so far for EOR are ZnO, TiO₂, Al₂O₃, MgO, ZrO₂, CeO₂, and Fe₂O₃. However, MgO shows low recovery, and CeO₂ is not very effective. Some of the negative constraints that inhibit the performance of the NPs in stability, solubility, and mobility in the reservoir can be minimized or eliminated by embedding the surface of the particles with a required surfactant or polymer; however, extra precautions need to be taken during the polymer/surfactant selection. The technical review has shown that anionic surfactant was found to have performed positively in recovering residual oil in a sandstone reservoir; moreover, a lot of progressive reports toward chemical EOR were equally observed while employing cationic and nonionic surfactant in a carbonate reservoir. Notably, the comparative concentration ratio between the surfactant and NPs has to be considered because the surfactant would cover a small portion of the particles at low concentrations. EM-assisted nanofluids have shown a promising result in recovering oil from porous media. Some mechanisms that determine EOR, like IFT reduction, wettability alteration, and fluids viscosity change, were reported to be effective, consistent, and substantial when EM-assisted nanofluids were used.

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