Investigating The Application of Nano Particles for Enhanced Oil Recovery

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Abstract— Through this century, exponential increase of consumption of oil and gas worldwide is very clear trend and the world will need more energy under all scenarios. To meet the energy demand for the next decades, methods for extracting residual hydrocarbon trapped in reservoir need to be developed economically. The major challenge is to increase recovery simultaneously at all scales; increase microscopic pore scale recovery and macroscopic field scale sweep and vertical efficiencies. The goal of enhanced oil recovery is to manipulate the fluid-fluid properties (interfacial tension, viscosity), and fluid-rock properties (contact angle, relative permeability) to improve pore scale recovery efficiency. Nanoparticles have been considered as potential agents to enhance oil recovery as they have some unique properties, such as ultra-small size, very high surface to volume ratio, low costs and environmental friendliness. Researchers are now investigating whether nanotechnology can be applied to enhance oil recovery . This paper presented a critical review of the most recent research progress in the application of nanoparticles for enhanced oil recovery and paves the way for researchers who are interested in the integration of these progresses.

Index Terms— Nanoparticles, Nano fluids, Emulsion, Disjoining pressure, Interfacial tension, Wettability alteration, Core flooding , Micro models .

1. INTRODUCTION

The fact that finding a new source of hydrocarbon is difficult and most of the oil field have 60 to 70 % of non-producible hydrocarbon in place.[1] To meet the energy demand for the next decades, methods for extracting residual hydrocarbon trapped in reservoir need to be developed economically. There are various enhanced oil recovery (EOR) technologies which have been applied and were proven to increase hydrocarbon recovery significantly such as thermal methods, miscible methods, chemical methods, as well as some new technologies (microbial, low salinity flooding).

The major challenge is to increase recovery simultaneously at all scales; increase microscopic pore scale recovery and macroscopic field scale sweep and vertical efficiencies.

The amount of the oil recovery in a reservoir is mainly affected by the volume of the oil contacted by the injected fluid or fluids. Pore scale mobilization or displacement of the oil is considered as the microscopic sweep efficiency. Microscopic efficiency depends on the factors such as interfacial tension between the reservoir and injected fluid/fluids, wettability of the reservoir rock, capillary pressure, and relative permeability. Macroscopic sweep efficiency controls the effectiveness of the displacing fluids to recover the reservoir oil in volumetric scale. Heterogeneities and anisotropy of the reservoir, mobility ratio (the mobility of the displacing fluid compared with the mobility of the displaced fluids), injection and production well locations, and the type

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of the rock reservoir are the factors that limit the macroscopic sweep efficiency.

Nano technology is defined as the science of generating using and employing materials that have size below 100 nm. Researchers are now investigating whether nanotechnology can be applied to enhance oil recovery. The goal of enhanced oil recovery is to manipulate the fluid-fluid properties (interfacial tension, viscosity), and fluid-rock properties (contact angle, relative permeability) to improve pore scale recovery efficiency.

2. Nanoparticles Synthesis Process

Nano fluids are made by dispersing the nano scale materials in a specific fluid called base fluid which may be polar like water or non-polar like oil or toluene .[1]The prosperities of nano fluids as thermal conductivity , diffusivity, viscosity and heat transfer will not be similar to its pure base fluid .[2]Nano particles can be fabricated by two different ways which are the top-down and bottom-up process.[3]In the top-down process,the original solid materials are broken down into the smaller particle size by any external forces ,while , bottom-up process form nanoparticles by the coalition of atoms based on molecular condensation or atomic transformation .The typical methods used in the top-down process and bottom-up process are shown on Fig.1.

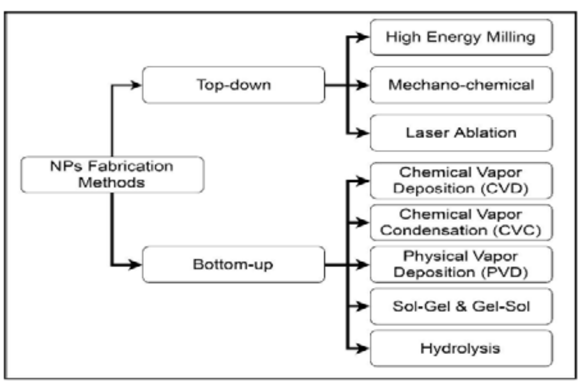
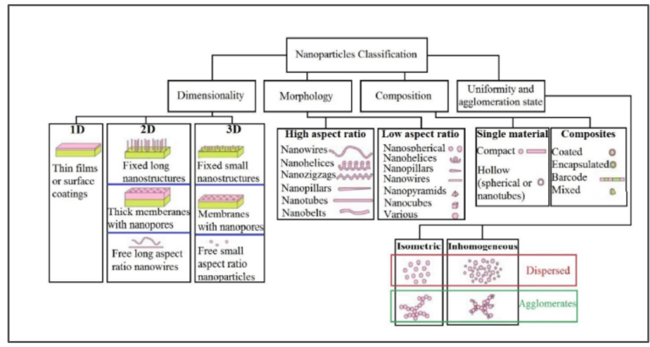


Fig.1 -Nanoparticle fabrication methods .[3]

3. Composition of nano particles

Nanoparticle consists of several layers, the core, a surface and an additional shell as shown on Fig.2. The core of a nanoparticle is located at the center of its structure, and it is used to identify the type of nanoparticles .The molecular shell consists of three different groups which are, the tail group, the hydrocarbon chain and the active head group .[4]

4. Composition of nano particles



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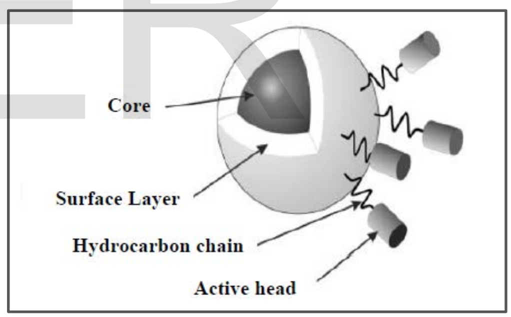

Fig.2- A nanoparticle structure .[4]

5. Types of nano particles

Nanoparticles can be discussed with respect to two major categories which are inorganic and organic nanparicles .[5]Inorganic nanoparticles include but not limited to Silica-based nanoparticles and other metal oxides like Aluminum oxides ($Al2O3$), iron oxides ($Fe2O3/Fe3O4$), Nickel oxides ($NiO/Ni2O3$), titanium oxidesTiO2, Zinc oxides (ZnO), Zirconium oxide / zirconia ($ZrO2$) .While organic nanoparticles include Polymer and polymer-coated, Carbon Nanotube (CNT), single-walled carbon nanotube (SWCNT) and multi-walled carbon nanotube (MWCNT) as shown on **Fig.3** .[6]

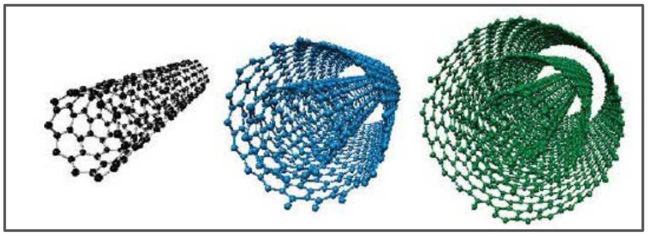

Fig.3-Single-walled carbon nanotube (SWCNT) (left), double & triple walled carbon nanotube (MWCNT) (mid and right) .[6]

Nanoparticles can be classified also based on their dimensionality, morphology, composition, and uniformity and agglomeration as shown on **Fig.4** .[7]

Fig.4- Nanoparticles classification .[7]

6. Properities of nanofluids

6.1. Ultra-small size:

Nanoparticles are are in the order of 1 nm–100 nm which is smaller compared to pore and throat sizes .[8] Due to this ultra small pore size , they can easily flow through porous media without permeability reduction and becoming trapped which increases the EOR effectivity of the injection fluids. Nanoparticles can increase the microscopic sweep efficiency due to their ability to penetrate some pores where traditional injection fluids are unable to

6.2. Very high surface to volume ratio:

Nanoparticles have a very high surface to volume ratio due to their small particle size as show on **Fig.5.** The large surface area increases the proportion of atoms on the surface of nanoparticle .[9]

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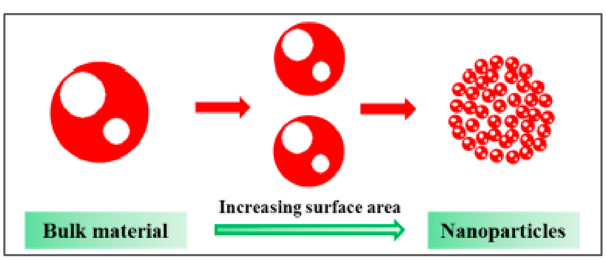


Fig.5-A schematic diagram of nanoparticles with high surface to volume ratio.[9]

6.3. Low costs and environmental friendliness:

Nanoparticles are usually cheaper than chemicals so that they can be widely applied for EOR at oil fields .In addition nanoparticles are environmentally friendly materials compared to chemical substances. For example, most of the silica based nanoparticles are silicon dioxide, which is the main component of sandstone. In brief nanoparticles are very cost effective and environmentally friendly.

7. Preparation of Stable Nanofluids

preparing stable nanofluid is a challenging task since nano particles tend to aggregate to make bigger particle .[10] when the nanoparticles are dispersed in the base fluid they tend to be stabilized by agglomerating into bigger particles due to their high surface energy as shown on **Fig.6** . Stable condition is achieved when the repulsion forces are greater than the attractive force once the attraction force starts to overcome the repulsion, the particles will stick to each other and finaly sedimentation occurs .In general,

nanofluid can be prepared by using two different methods, one-step and two-steps .[11,12]

The two-step method is the most common process that has been used to prepare nanofluids. In this process, dry nanoparticles powders produced from mechanical or chemical synthesis are dispersed in a base fluid .[13] The stability of the dispersion can be improved by adding asurfactant but this method is limited to hig tempreture but more economic on the larger scale production . On the other hand in one step process the nano particles and nanofluids are simultaneously synthesizes.[13] The processes such as drying, storing and transporting process associated with nano-powder fabrication are removed, minimizing the agglomeration and improving the fluid stability. By using one-step process, the uniformity of the dispersed particle and the stability became higher. However, this is limited to the small scale production.

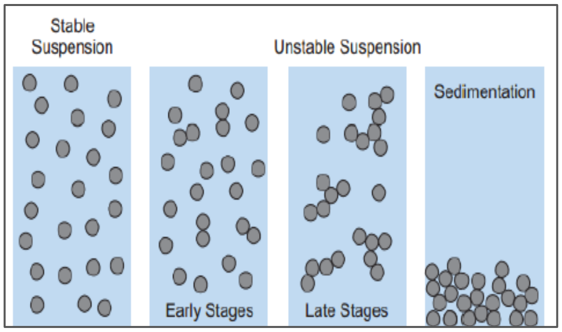


Fig.6- Stable and unstable suspension .[11]

8. EOR Mechanisms

The EOR mechanisms of nanofluids have already been investigated in literatures, which mainly includes disjoining pressure, pore channels plugging, viscosity increase of injection fluids, interfacial tension reduction, wettability alteration and preventing asphaltene precipitation. The schematic of the EOR mechanisms of nanofluids is shown on **Fig.7.** However, the detailed mechanism on how nanoparticle could increase the oil recovery is not clearly understood yet.

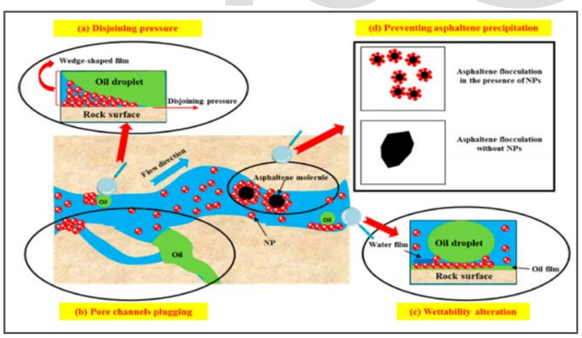
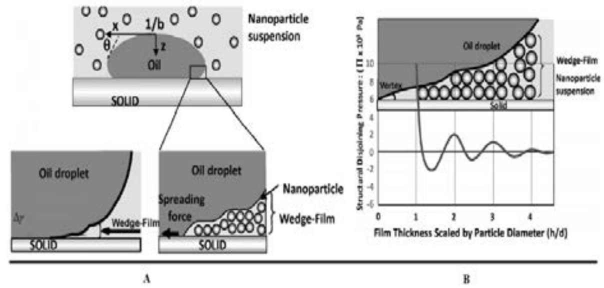


Fig.7- The schematic of the EOR mechanisms of nanofluids.

8.1. Disjoining Pressure

Disjoining pressure is defined as the attractive and repulsive forces between two thin layer of fluid surfaces .[14] The injection pressure of nano fluids exert apressure forcing the nanoparticles into the confined region forming a self-assembled wedge-shaped film on contact with oil phase as shown on Fig.8 . This film seperates the oil droplet from the rock surface .Disjoining pressure is affected by nanoparticle size, amount of the NPs, temperature, salinity of the base



fluid, and the characteristics of the rock surface .

Fig.8- Nanoparticle wedge shape structuring and the forces (A), Wedge contact pressure (B) .[14]

8.2. Pore Channels Plugging

Pore channel plugging can be caused by two mechanisms: mechanical entrapment and log-jamming as shown on Fig.9.[15] Mechanical entrapment occurs because the diameter of injected components is larger than pore channels that they flow through as shown on Fig.9(a).

Log-jamming is plugging of pore channels that are larger than each nanoparticle. Due to the small diameter at the entrance of the pore throat the small H2O molecules will flow faster than the nanoparticles causing accumulation of NPs at the entrance of the pore throats as shown on Fig.9(b) .Blocking the pore throat by log jamming makes pressure buildup in the adjacent pore throat forcing the traped oil out. Once the oil is freed, the surrounding pressure drops and the plugging gradually disappears and the NPs start to flow with the water. This phenomenon is mainly governed by the concentration and size of NPs, flow rate and the diameters of pore throats.

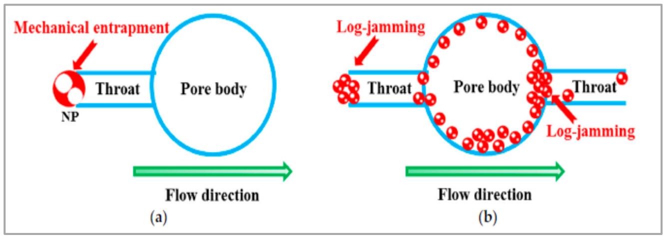


Fig.9- The schematic of two mechanisms causing pore channels plugging: (a) mechanicalentrapment; (b) log-jamming .[15]

8.3. Decreasing the Mobility Ratio of Injected Fluids

It is necessary to control the mobility of the injected fluid to achieve better sweep efficiency for higher oil recovery as high mobility of displacing fluid often results in viscous fingering which leads to poor sweep efficiency .The mobility ratio of the displacing fluid and reservoir fluid is the function of permeability and viscosity, and can be expressed by Eq.1 .[16]

$$M = \frac{kri*\mu_o}{kro*\mu_i} \quad \text{...Eq.1}$$

Which M is the mobility ratio; kri and kro are relative permeability of injection fluid and oil; μ_i and μ_o are the viscosities of both injected fluid and oil respectively . The mobility ratio can be decreased by viscosity reduction of oil phase or viscosity enhancement of injected fluids. Nanofluids can solve the above mentioned problem because adding nanoparticles in traditional fluids can increase the effective viscosity of injected fluids. Furthermore, the viscosity of nanofluids increases with increasing nanoparticles concentration and brine salinities. The type of nanoparticles also affects the viscosity of nanofluids.

8.4. IFT Reduction

Capillary force is one of the most essential forces in reservoir system which determine the fluid distribution and movement in the porous media and restricts the oil recovery .[17] Capillary pressure can be reduced by reducing interfacial tension and altering the rock wettability.[18]

Nanoparticles can decrease the IFT during EOR processes with or without surfactant. The presence of nanoparticle in surfactant mixture can improve the rheology of the solution and enhance the surfactant effect on IFT reduction .[19] Adsorption of nanoparticles onto the surface of the fluid will effectively reduce the interfacial tension between those fluids .[20]

8.5. Wettability Alteration

Wettability is defined as the tendency of a certain fluid to spread on the solid surface in the presence of other immiscible fluid in the same system .[21] It is very important parameter that govern oil recovery by affecting capillary pressure, fluids saturation, and relative permeability.

Wettability can be determined by three main experimental methods, the contact angle method, the Amott test and the core displacement test .[22:26] Among them, the contact angle method is the most universal used approach to determine wettability. Recent years, nanofluids have been considered as potential agents to alter wettability The wettability can be easily obtained by the rules shown on Fig.10.[27] Many researchers proposed nanoparticle to be used in EOR fluid as alternatives of wettability alteration agents. Actually, the wettability alteration caused by nanofluids can be affected by many factors, such as nanoparticles concentration and size and water salinity.

Fig.10- Wettability variation on oil-water system .[27]

8.6. Preventing Asphaltene Precipitation

Significant asphaltene precipitation may occur during EOR such as Co2 flooding . , which leads to wettability alteration, formation permeability reduction, and transportation pipelines blockage, etc. .[28:30] Some researchers proposed that nanoparticles can solve the asphaltene problems effectively and not cause environmental hazards .As the nano fluid concentration increased, asphaltene precipitation was delayed .the presence of the nanoparticles leaded to the adsorption of the nanoparticles onto the asphaltene molecules surface, which significantly reduced the asphaltene flocculation in the porous media.

9. Experimental work.

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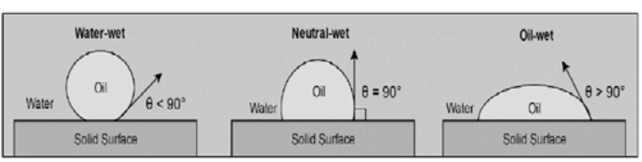
Several laboratory experiments on the application of nano particles in enhanced oil recovery have been conducted in past few years .in the following section we will review the experimental work done to understand how nanoparticles alter the main rock and fluid properties to enhance oil recovery.

9.1. Core Flooding Studies

Core flooding is approximate one dimensional flooding of real reservoir rock at reservoir conditions. There are many experimental investigations in literature studying the effect of nanoparticles on oil recovery using a core flooding process. **Table 1** summarizes the research that has been done to investigate the effect of Nano-EOR techniques on core flooding experiments.

Rodriguez et al (2009)[31] used a surface modified silica nanoparticles to perform a series of core flooding experiments to investigate the transport mechanism of nanoparticles and measure its retention in core plugs .this study shows that the transport of nanoparticles in porous media is less challenging in comparison with other colloidal dispersions .this experimental work also indicates that nanoparticles retention isn't significant due to the small size of nanoparticles in comparison with pore size and the surface modification of these nanoparticles causing them to stay uniformly dispersed during the core flooding . parameters such as flow rate, salinity and pH value of the injected fluid can affect the homogeneity and agglomeration state of nanoparticles in the injected fluid .



Onyekonwu and Ogolo (2010)[32] studied the effect of using polysilicon nanoparticles on oil recovery in core flooding experiments. The reported oil recovery efficiency was in range of 50 to 80 percent. They demonstrated that Wettability alteration and interfacial tension reduction were the two main mechanisms of improving oil recovery. they recommended using concentrations of lower than 3 grams of nanoparticles per liter of injected fluid for core flooding experiments.

Espinosa et al. (2010)[33] investigated the stabilization of CO_2 in water foam by using silica nanoparticles .the results of core flooding experiments indicated that promising mobility control method while using CO_2 as injected gas when nanoparticles are used in addition gravity overriding can be avoided.

Metin et al. (2012)[34] Silica nanoparticles were used to studied the dynamic viscosity of nanofluids during core flooding experiments. The experiments of coreflooding indicated that the viscosity of the nanoflooding strongly dependent on the concentration of the nanoparticles also Newtonian behavior of nanofluids was found during flooding. In sandstone core plug cases, significant amount of nanoparticle retention was observed due to clay swelling.

Hendraningrat et al. (2013)[35] studied the effect of important factors such as particle size, rock permeability, wettability, injection flow rate, and temperature by water flooding enriched with hydrophilic silica nanoparticles . They indicated that the highest recovery was obtained from cores with initial wettability of intermediate/oil wet after flooding with nanofluid due to the ability of hydrophilic silica nanoparticles in changing the wettability state of the rock from intermediate/oil wet to water wet. Approximately 5 to 10 % improvement in oil recovery.

Li et al. (2013)[36] used hydrophilic silica nanoparticles (7 nm) in core flooding experiments using Berea sandstone core . Approximately 4 to 5 % improvement in oil recovery. using silica nanoparticles in brine compared to waterflooding.

Zaid et al. (2014)[37] studied the ability of nano paritcles to creat astable emulsion by using using aluminum oxide (Al_2O_3) and zinc oxide (ZnO) nanoparticles. The emulsions created between oil and water interface have significantly higher viscosity, providing more force to push residual oil to the outlet. Asignificant IFT reduction using nanoparticles is also indicated. They observed 117 % increase in the oil recovery of residual oil in place using nanoparticles compared to surfactant. They suggest that this oil recovery improvement using nanoparticles might be due to emulsion generation. Moreover, aluminum nanoparticles were found to be more efficient compared to zinc oxide in terms of oil recovery improvement.

Sharma et al. (2014)[38] investigated the effect of using nanoparticles on emulsion generation at high pressure (13.6 MPa) and four temperatures (313, 333, 353, and 363 K).they suggested that stabilized emulsion created by nanoparticles can improve the oil recovery by two mechanisms of thermal stability and stabilized flow behavior. They observed a 23 % increase in oil recovery using nanoparticles compared to water flooding (core flooding experiments).

Esfandyari Bayat et al. (2014)[39] used intermediate wet limestone core and three different types of nanoparticles aluminum oxide (Al_2O_3), titanium dioxide (TiO_2), and silicon oxide (SiO_2). Core flooding experiments were performed in different temperatures. Wettability alteration from intermediate oil wet (θ = 90°) to water wet condition . The contact angle measured for Al_2O_3, TiO_2, and SiO_2 cases were 71°, 57°, and 26° respectively. Considerable oil viscosity reduction was observed after flooding with nano fluid due to thermal conductivity enhancement of the injected fluid.

Sun et al. (2014)[40] investigated the effect of using modified hydrophobic silica nanoparticles on oil recovery and nitrogen foam stability .They indicated that nitrogen foam stabilized by silica nanoparticles has a high temperature tolerance compared to foam stabilized by surfactant. The optimum concentration of nanoparticles was found to be 1.5 wt% in brine for core flooding.

Nguyen et al. (2014)[41] investigated the effect of nanoparticles on CO_2 foam stability. The foam stabilized by nanoparticles was found to be stable after 10 days while Surfactant based foam was found to stay stable only for 1 day. Improved 15% oil recovery was observed using nanoparticle stabilized foam.

Mo et al. (2014)[42] studied the effect of using nanosilica stabilized foam on oil recovery of core flooding experiments. They indicated that oil recovery increased approximately 30 % by using nanofluids compared to water flooding (pressure from 1200 psi to 2600 psi, and temperature from 20 °C to 60 °C).

Singh and Mohanty (2014)[43] reported 20 percent oil recovery improvement by using hydrophilic nanoparticles stabilized foam in core flooding experiments.

Joonaki and Ghanaatian (2014)[44] used SiO_2 and Al_2O_3 as nanoparticles EOR agents. They observed IFT reduction (from ~6 to ~2 dyne/cm) and wettability alteration (from ~130° to ~90°) .Approximately 20 % increase oil recovery was reported .

Roustaei and Bagherzadeh (2015)[45] used silica nanoparticles to run aseries of core flooding experiments using oil wet carbonate rock as porous media . Approximately 10 to 20 % increase in oil recovery using silica nanoparticles was reported due to wettability alteration of the rock from oil wet to strongly water wet after flooding with the nanofluid. They suggested 4 grams/liter as the optimum concentration of nanoparticles in brine for core flooding.

Nazari Moghadam et al. (2015)[46] investigated the effect of a wide range of nanoparticles on enhanced oil recovery (ZrO_2, $CaCO_3$, TiO_2, SiO_2, MgO, Al_2O_3, CeO_2, and carbon nanotube). They reported approximately 9 percent oil recovery improvement by using nanoparticles in core flooding experiments

Jafari et al. (2015)[47] investigated the effect of silica nanoparticles on heavy oil recovery during water alternating CO_2 core flooding experiments. They demonstrated that the efficiency of oil recovery was increased by approximately 5 % by using silica nanoparticles.

Adel et al. (2015)[48] studied the effects of SiO_2 and Al_2O_3 nanoparticles on IFT at ambient pressure and temperature. A significance decrease in IFT was reported when nanoparticles are used . The SiO_2 nanofluid has a lower IFT value than the Al_2O_3 nanofluid. Therefore, SiO_2 nanofluid able to produce more oil from reservoirs.

Adel et al. (2015)[49] performed several flooding experiments to study the effect of nanoparticle size on oil recovery. They found that smaller size nanoparticles have higher final recovery factors .

EI-Diasty (2015)[50] investigated the effect of NP size (5 to 60 nm) on SiO2 nanofluid flooding on Egyptian sandstones .

Ahmadi (2016)[51] reported 25% additional oil recovery when silica nanoparticles dispersed with surfactant fluid for carbonate core flood .

Jafarnezhad et al.(2017)[52] studied the impact of silica nanoparticles in heavy oil recovery on carbonate rock. Using silica nanoparticles dispersed in brine with concentration no more than 0.5 wt. % could improve heavy oil recovery by by 39 to 61%.

9.2. Micro model Studies.

Physical pore network micromodels are used for the visualization of mechanisms of multiphase fluid flow in porous media. The experimental data from physical micromodels can be used for validation of numerical simulators .In EOR studies, an appropriate micromodel represents a reservoir rock with specific characteristics such as the scale of the homogeneity and state of wettability. Further, micromodels have been used for studying the effects of nanoparticles in multiphase flow, and in water alternating gas injection . **Table 2** shows the summary of research done on the application of nanotechnology in EOR using pore network micro models.

Maghzi et al. (2011)[53] studied the effect of nanoparticles on oil recovery in micromodel injection by using silica nanoparticle in a polymer solution. The experimental work shows that nanoparticles changed the wettability of micromodel to strong water wet condition. Oil recovery was enhanced by 10 % using silica nanoparticles.

Maghzi et al. (2012)[54] studied the effect of nanoparticle concentration in deionized (DI) water on oil recovery during micro model flooding. Oil recovery improvement of 8.7 and 26 % for concentrations of 0.1 and 3.0 wt%. he reported that concentration of 3 wt% was the optimum concentration of nanoparticles in DI water. Strong water –wetness was found after nanoflooding

Hendraningrat and Shidong (2012)[55] investigated the effect of using hydrophilic nanoparticles in brine on IFT reduction, nanoparticles retention in the porous media and permeability impairment during micromodel injection. Permeability reduction was reported due to pore blockage which caused by nanoparticles agglomeration in the injected fluid, . This agglomeration can be avoided by uniformly dispersing nanoparticles.

Li et al. (2013)[56] Studied the effect of concentration of nanoparticles on emulsion generation by using hydrophilic silica nanoparticles (7 nm) . stable oil in water emulsion was created using nanoparticles.

Sun et al. (2014)[57] studied the effect of using partially hydrophilic modified SiO2 nanoparticles on nitrogen foam micromodel injection.

Nguyen et al. (2014)[58] studied the effect of using nanoparticle-stabilized CO2 foam during micromodel injection experiments. They found that the size of oil in water emulsion was decreased significantly by using nanoparticle in the foam. They indicated that the area which the foam is in contact with the oil is larger compare to water flood. They observed that viscous fingering is dampened by using nanoparticle stabilized foam as mobility control. They reported 15% oil recovery improvement.

Khezrnejad et al. (2014)[59] studied the effect of nanoparticles on oil recovery efficiency by two different types of nanoparticles (SiO2 and Al2O3).. They investigated the effect of different factors such as WAG ratio and nanoparticle concentration on oil recovery was studied. Significant IFT reduction was reported using nanoparticles in brine. Silica nanoparticles shown to be more efficient in terms of oil recovery compared to alumina nanoparticles. Oil recovery can be improved by 15 to 20 % using nanoparticles.

Hamedi-Shokrlu and Babadagli (2014)[60] investigated the stabilization and transportation of nanonickel particles in micromodel injection process. Nickel nanoparticles were used due to their high thermal conductivity, which make them perfect to be used as catalyst.

Gharibshahi et al. (2015)[61] used Silica nanofluid was used as injected fluid. They compared the results of experimental micro model injection with simulation. They indicated that nanoparticles can be used to prevent viscous fingering. Factors as pore heterogeneity and connectivity, tortuosity, , pore shape, breakthrough time and fluid trapping were studied .

Mohebbifar et al. (2015)[62] studied Wettability alteration (from oil wet to water wet), thinning oil film, IFT reduction, and emulsion generation using nanoparticles in micro models flooding .They reported 78 % recovery by using nanoparticles in micromodel flooding experiments. They indicated that nano particle can be highly efficient for improving the microscopic sweep efficiency.

Mohajeri et al. (2015)[63] reported 40 % oil recovery improvement over the water by using ZrO_2 nanoparticles .

Alnarabiji et al.(2017)[64] reported 31.8% improvement on heavy oil recovery by using Multi-walled Carbon Nanotube (MWCNT).

10. Conclusion

1. The reviewed literature shows that NPs have been considered as potential agents to enhance oil recovery as they have some unique properties, such as ultra-small size, very high surface to volume ratio, low costs and environmental friendliness.
2. Although nanoparticles are proved to be potential candidates as the agent in many EOR processes, most of them are limited to laboratory research and not suitable for field scale applications.
3. the detailed mechanism on how nanoparticle could increase the oil recovery is not clearly understood yet.
4. It is favorable to use mixtures of nanofluids for increasing the recovery since they combine the advantages of different NPs as a single nanofluid does not possess all the favorable characteristics required for a particular EOR.
5. The perforemance of anano fluid is greatly affected by types and sizes of NPs, temperature, injection time.
6. Preparation of astable emulsion is asignificant challenge as always tend to aggregate at the results of the strong VanderWaals interactions under the harsh reservoir conditions.
7. Performing accurate calculations and comprehensive modeling is needed to under stand of various nano-assisted EOR methods.

11. Recommendations

1. Further experimental work is still required to improve the nanofluid stability , understanding the EOR mechanisms of the nano-assisted EOR methodsand application of nanofluid mixtures .
2. Mathematical models and theortical studies are urgently needed to under stand the fundamental mechanisms of EOR process and reduce the risks for application on field scales.
3. Exploring the ability of application of nano-assisted EOR in pilot projects and oilfields in the near future .

Nomenclature

IFT : interfacial tension

M: Mobility ratio.

kri : relative permeability of injection fluid.

kro :relative permeability of oil.

μ_i :viscosity of injection fluid

μ_o: viscosity of oil.

θ : Contact angle .

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Table 1: Research summary of Nano-EOR techniques in core flooding experiments.

Author (year)	Nanoparticle type	Nanoparticle size	Base fluid	Nanoparticle concentration	Core sample	Oil properties	Flooding type
Rodriguez et al. (2009)	Surface treated SiO2	5 or 20 nm	NaCl brine	Up to 20 wt%	Limestone, Berea and Boise sandstone	_	Waterflooding
Onyekonwu and Ogolo (2010)	Polysilicon nanoparticles	10 – 60 nm	Brine 30000 ppm	2 – 3 g/L	Sandstone	28 °API 41 cP	Waterflooding
Espinosa et al. (2010)	Surface treated silica	5 nm	DI water and 4% NaCl brine	0.05 – 0.50 g/L	-	-	CO2 foam flooding
Aminzadeh et al. (2012)	Surface treated silica	5 nm	2 wt% NaBr brine	5 wt%	Boise sandstone	-	Stabilized CO2 in water foam flooding

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Metin et al. (2012)	SiO2	5 – 25 nm	0.05 NaCl brine	1 – 35 wt%	Berea sandstone, Limestone	-	Waterflooding
Hendraningrat et al. (2013)	Hydrophilic SiO2	7 – 40 nm	3 wt% NaCl brine	0.05 wt%	Berea sandstone	0.826 g/cm3 – 5.1 cP	Waterflooding
Li et al. (2013)	Hydrophilic SiO2	7 nm	3 wt% NaCl brine	0.01, 0.05, and 0.10 wt%	Berea sandstone	0.826 g/cm3 – 5.1 cP	Waterflooding
Sharma et al. (2014)	Hydrophilic SiO2	15	10.3 g/L brine	1 wt%	Berea sandstone	33.03 °API	Waterflooding
Esfandyari Bayat et al. (2014)	Al2O3 – TiO2 – SiO2	40 nm 10 – 30 nm 20 nm	DI water	0.005 wt%	Limestone	0.863 g/cm3 – 21.7 cP	Waterflooding
Sun et al. (2014)	Partially hydrophobic modified SiO2	14 nm	0.5 wt% NaCl brine	0.5 wt%	Sand pack	0.9139 g/cm3 – 413 mPa.s	Nanoparticle stabilized foam flooding
Nguyen et al. (2014)	Coated silica	12 nm	Ethanol – DI water	1 % (w/v)	Berea sandstone	14, 24, and 37 °API	Nanoparticle stabilized foam flooding
Ehtesabi et al. (2014)	TiO2	_	5000 ppm brine	0.01 and 0.05	_	0.92 g/cm3 – 41.21 cP	Waterflooding
Mo et al. (2014)	SiO2	17 – 20 nm	2% NaCl	_	Dolomite, Berea, Limestone	-	Nanoparticle stabilized CO2 foam injection
Singh and Mohanty	Alumina coated silica	20	Ultra-pure	1 wt%	Berea sandstone	30 cP	Foam injection

(2014)	nanoparticles		water				
Joonaki et al. (2014)	Al2O3, Fe2O3, and SiO2	40, 20 – 35, 10 – 30 nm	25000 ppm Brine	0 – 4 g/L	Sandstone	29.56 °API – 40.38 cP	Waterflooding
Roustaei et al. (2015)	SiO2	20-70	5 wt% NaCl	1 – 6 g/L	Carbonate rock	33 °API – 11.014 cP	Waterflooding
Jafari et al. (2015)	SiO2	14 nm	5000 ppm NaCl brine	700 ppm	Berea sandstone	0.8845 gr/cm3 – 10.07 cP	WAG injection
Adel et al. (2015)	SiO2, Al2O3	7.20-2.50	brine	-	Sandstone	0.85gr/cm3 75cp	Waterflooding
El-Diasty (2015)	SiO2	76.97/25.23	Brine	0.01; 0.5 and 3 wt.%	sandstone core	0.89gr/cm3	Waterflooding
Ahmadi (2016)	SiO2	-	water and surfactant	5 wt%	carbonate core	-	Waterflooding
Jafarnezhad et al.(2017)	SnO2	-	brine	0.1 wt%	carbonate core	-	Waterflooding

Table 2: Research summary of Nano-EOR techniques using micromodels

Author (year)	Nanoparticle type	Nanoparticle size	Base fluid	Nanoparticle concentration	Micromodel type	Oil properties	Flooding type
Maghzi et al. (2011)	SiO2	14 nm	DI water	1000 ppm	Glass	1400 (kg/m3), 85 cP	Polymer flooding
Maghzi et al. (2012)	Hydrophilic SiO2	14 nm	200000 ppm brine	0.1 to 5 wt%	Glass	19 °API 870 mPas	Water flooding
Hendraningrat and Shidong (2012)	Hydrophilic SiO2	15 to 50 nm	3 wt% NaCl brine	0.1 to 1.0 wt%	Glass	0.806 (gr/cm3), 2	Water flooding
Maghzi et al. (2013)	SiO2	14 nm	DI water	1000 ppm	Glass	840 (kg/m3),	Polymer flooding

						85 cP	
Li et al. (2013)	Hydrophilic SiO_2	7 nm	3 wt% NaCl brine	0.01, 0.05, and 0.10 wt%	Glass	0.826 (gr/cm3), 5.1 cP	Water flooding
Maghzi et al. (2014)	Hydrophilic SiO_2	14 nm	1400 to 84000 ppm brine	0.1 to 5 wt%	Glass (laser etching)	25 °API, 1000 cP	Polymer flooding
Sun et al. (2014)	Partially hydrophobic SiO_2	14 nm	0.5 wt% NaCl brine	0.0 to 2.0 wt%	Glass etched micromodel	0.913 (gr/cm3), 413 mPas	Foam Flooding
Nguyen et al. (2014)	Silica coated nanoparticles	7 nm	DI water	1% (w/v)	Glass	Light (37 °API), Medium (24 °API), and Heavy (14 °API)	Nano stabilized CO_2 foam flooding
Khezrnejad et al. (2014)	SiO_2 and Al_2O_3	5 to 100 nm	36000 ppm brine	0 to 1000 ppm	Glass	~0.85 (gr/cm3), ~25 cP	Water alternating gas injection
Hamedi-Shokrlu and Babadagli (2014)	Nickel nanoparticles	20 – 100 nm	DI water	0.05 wt%	Glass	Kerosene	Water flooding
Gharibshahi et al. (2015)	SiO_2	14 nm	Water	4 wt%	Glass	933 (kg/m3), 870 mPas	Water flooding
Mohebbifar et al. (2015)	SiO_2 and TiO_2	7 and 21±5 nm	Synthetic brine	0 to 3000 ppm	Glass	21 °API, 200 cP	Water flooding

Mohajeri et al. (2015)	ZrO2 nanoparticles	14 nm	_	100 ppm	Glass	21.2 °API, 130.4 cP	Water flooding
Alnarabiji et al.(2017)	MWCNT	-	MWCNT fluid	0.01; 0.05 and 0.10 wt%	Glass	Heavy oil	Water flooding