Int. J. Nano Dimens., 6(5): 443-452, 2015 (Special Issue for NCNC, Dec. 2014, IRAN)
DOI: 10.7508/ijnd.2015.05.001

Review Paper

Effects of nanoparticles on wettability: A review on applications of nanotechnology in the enhanced Oil recovery

G. Cheraghian *

Young Researchers and Elite Club, Omidieh Branch, Islamic Azad University, Omidieh, Iran

Received 10 June 2015; revised 30 August 2015; accepted 10 September 2015; available online 02 December 2015

ABSTRACT: Recently, a renewed interest arises in the application of nanotechnology for the upstream petroleum industry. In particular, adding nanoparticles to fluids may drastically benefit enhanced oil recovery and improve well drilling, by changing the properties of the fluid, rocks wettability alteration, advanced drag reduction, strengthening the sand consolidation, reducing the inter-facial tension and increasing the mobility of the capillary trapped oil. In this study, we focus on roles of nanoparticles on wettability. This paper therefore focuses on the reviews of the application of nano technology in chemical flooding process in oil recovery and reviews the application nano in polymer and surfactant flooding on the wettability process.

Keywords: *Chemical flooding; Enhanced Oil recovery; Nano particles; Nanotechnology; Wettability.*

INTRODUCTION

Most of the oil fields around the world have reached or will reach soon the phase where the production rate is nearing the decline period. Hence, the current main challenge is how to delay the abandonment by extracting more oil economically. The latest worldwide industries innovation trends are miniaturization and nanotechnology materials. Nanotechnology is defined as the construction of functional materials, devices, and systems by controlling matter at the nanoscale level (one-billionth meter), and the exploitation of their novel properties and phenomena that emerge at that scale [1]. Nanofluid technology, as a part of nanotechnology, is a new interdisciplinary area of great importance where nanoscience, nanotechnology, and thermal engineering come across. It has developed largely over the past decade and revealed its potential applications in oil and gas industries [2]. Various nano-fluids can be designed by the addition of nanoparticles to different base fluids. The stability or dispersion of nanoparticles in solutions relies on the functionality (or surface activity) of the nanoparticles.

Nanotechnology in the petroleum industry has gained enormous interest the recent years [3]. Kanj *et al.* [4] identified the usable size of nanoparticles in reservoir rocks through Nano-fluid core flooding experiments. Adding nanoparticles to fluids may significantly benefit enhanced oil recovery and improve well drilling, such as changing the properties of the fluid, wettability alternation of rocks, advanced drag reduction, strengthening sand consolidation, reducing the interfacial tension and increasing the mobility of the capillary-trapped oil [5]. In the past decade, most investigations have shown that nanoparticles (NPs) offer promise for future enhanced oil recovery (EOR) processes where silica-based NPs have been most commonly used [6-10]. Although the oil displacement mechanism via NPs is not yet clearly understood [11-13]. The nanotechnology is now chosen as an alternative method to unlock the remaining oil resources and applied as a new enhanced oil recovery (EOR) method in last decade [2, 7, 8 and 14-17]. polymeric micro-spheres and nanospheres have been applied as water mobility control both as a pilot and full-field, and showed fantastic results in reducing water cut, increasing sweep efficiency and improving oil recovery [18-20]. Also, Tian *et al.* reported that polymeric microspheres and nanospheres can swell

---

*Corresponding Author: Goshtasp Cheraghian
Email: *g.cheraghian@srbiau.ac.ir*
Tel.: (+98) 21 44869627
Fax: (+98) 21 44869625

when meet with water and then reduce water permeability due to its ability of reducing the capillary force and change water flow path. Consequently water goes into bypassed area and enhances displacement efficiency. They also reported that polymeric microspheres and nanospheres have some advantages such as no degradation at high temperature and salinity. Some papers also address experiments where combinations of nanoparticles and surfactant solutions are tested. Li *et al.* studied synergistic blends of SiO_2 nanoparticles and surfactants for EOR in high-temperature reservoirs.

Hamedi Shokrlu and Babadagli, investigated the effects on nano metals on viscosity reduction of heavy oil and bitumen for thermal oil recovery applications. Based on their obtained results, various parameters such as nano particle types, size and concentration could affect on the mechanism of the viscosity reduction of heavy oil/bitumen [21]. In addition to previous applications of nanotechnology in petroleum upstreams, enormous researches have been made on the title of implementing of nano-particles on the enhanced oil recovery (EOR) from petroleum reservoirs [22]. Hence, in some studies the applications of nanoparticles in oil industry have been reported and classified based on priority. So, researchers have concluded that nanotechnology has the greatest usage in chemical EOR methods [23]. Therefore, in some studies, the role of nanoparticles in EOR operations has been reported [24-26]. Subsurface applications of nanotechnology seem to be promising in modifying and monitoring reservoir properties, such as wettability and interfacial tension between rock and fluids. For instance the capability of SiO_2 nanoparticles to alter the wettability of reservoir rock and reduce the interfacial tension between crude oil and brine phases has recently been actively investigated to find implementation in enhanced oil recovery (EOR) [27].

The objective of this paper is to investigate the potential of Nano particles in chemical flooding for oil recovery. This study reviewed and assessed some of the recent advances. Specifically, it aims to explain the contributions of Application Nano in the Polymer and Surfactant flooding on the Wettability process.

Chemical flooding

Oil production has three different stages; primary (production by natural reservoir energy), secondary (on the supply of external energy into the reservoir in the form of injecting fluids to increase reservoir pressure) and tertiary production (enhanced oil recovery methods increase the mobility of the oil in order to increase production). Chemical injection or usually known as chemical flooding was, up to 2000's, less common EOR method than thermal and gas but now, huge projects are initiated or revisited. This involves injection of three kinds of chemicals that are alkaline, surfactant and polymer. Each chemical has unique functions and usually isused coincide. Three methods involving these chemicals are polymer, surfactant-polymer (SP) and alkaline-surfactant-polymer flooding (ASP), and surely the most important substance in these methods is polymer [28].

Polymer

Polymer flood is the most widely used chemical EOR method. By adding polymers to water, the water–oil mobility is lowered. Such a change can lead to better sweep efficiency. It is generally believed that polymer flooding cannot reduce the residual oil saturation, but it can help to reach residual oil saturation in shorter time [29].

Polymer flood was proved technically and economically successful in many EOR projects worldwide [30-31]. In field applications, polymer floods increased recovery by 12–15% [32]. The field experiences in China showed that polymer flood was cheaper than water flood, due to increased oil output and reduced costs in water injection and treatment [33]. Currently, polymer flooding is considered as one of the most promising technologies in EOR process because of its technical and commercial feasibility. Particularly, the interest on polymer flooding applications worldwide has been stimulated by the outstanding results reported from the large-scale polymer flooding application in the Daqing oil field in China, with incremental oil productions of up to 300,000 barrels per day [34].

In practice, two commercial polymers, hydrolyzed polyacrylamides (HPAM) and xanthan gums, are commonly used in oil field applications. HPAM is a water-soluble polyelectrolyte with negative charges on the polymer chains. Xanthan gums, which are polysaccharides, show excellent viscosifying ability, high tolerance to salinity, and temperature [35].

However, the current widely used polymers, polyacrylamide (PAM) and partially hydrolyzed polyacrylamide (HPAM), cannot completely meet the requirements due to the hydrolysis, degradation, and others under high temperature or high salinity [36]. Furthermore, PAM and HPAM have poor shear resistance [37-40]. Polymer molecular chains will be cut off when polymer solution passes through the pump, pipeline, perforation, and porous medium at high speed, so the viscosity of polymer solution will be greatly reduced [40-41]. Polymer viscosity was seriously affected by salinity. The effect of shearing on polymer viscosity and oil recovery was significant. Thus, high concentration of polymer was utilized to maintain high viscosit [42].

Surfactant

The surfactant-based chemical flooding processes are normally employed to recover the trapped, residual oil after the waterflooding. Numerous patents exist on evaluating different factors, which may affect the performance of these processes [43].

Surfactant flooding is one of the main mechanisms of reducing interfacial tension between oil and water for the purpose of enhancing oil recovery. Essentially, two different approaches have been developed for using surfactants to enhance oil recovery.

In the first approach, a solution containing a low concentration of surfactant is injected. The surfactant is dissolved in either water or oil and in equilibrium with aggregates of the surfactant known as micelles. Large pore volumes (about 15–60% or more) of the solution are injected into the reservoir to reduce interfacial tension between oil and water and, thereby, increase oil recovery. Oil may be banked with the surfactant solution process, but residual oil saturation at a given position in the reservoir will only approach zero after passage of large volumes of surfactant solution. In the second approach, a relatively small pore volume (about 3–20%) of a higher surfactant concentration solution is injected into the reservoir. The high surfactant concentration allows the amount of dispersed phase in the micro emulsion to be high as compared with the low value in the dispersed phase of the micelles in the low concentration surfactant solutions. The infected slug is formulated with three or more components. The initial components (hydrocarbon, surfactant, and water) are sufficient to form the micellar solutions. A co-surfactant as the fourth component (usually alcohol) can be added. Electrolytes, normally inorganic salts, form a fifth component that may be used in preparing the micellar solutions or microemulsions. The high concentration surfactant solutions displace both oil and water. As the high concentration slug moves through the reservoir, it is diluted by the formation's fluids and the process reverts to a low-concentration flood. There are numerous mathematical modeling and experimental studies of various aspects of surfactant flooding in the literature [44-50].

Le and his colleagues performed experiments blending different types of surfactants with SiO_2 nanoparticles. Some of the blends showed great potential for EOR application because of their resistance to adsorption onto the rock surface, and thermostability at 91^{o}C [51]. Suleimanov *et al.* carried out experiments which showed how dispersed nanoparticels in an aqueous phase could modify the interfacial properties of a liquid/liquid system, if their surface were modified by the presence of an ionic surfactant. The application of nanosuspension in their study permitted significant increase in the efficiency of oil displacement flow rate. In homogeneous pore media, oil recovery before water breakthrough was increased by 51 % and 17 % for surfactant aqueous solution with nanoparticle addition respectively to water and surfactant aqueous solution [52].

Surfactant–polymer

Surfactant–polymer (SP) flooding processes involve the injection of a surfactant–polymer slug followed by a polymer buffer and chase water injection. If designed correctly, the surfactant increases the capillary number, which is crucial for the mobilization and recovery of tertiary oil. Polymer increases the sweep efficiency by lowering the mobility ratio. If the reservoir crude oil has sufficient saponifiable components, soap (surfactant) is generated in situ by the reaction of these components with the injected alkali, thus adding more surfactant to the flood [53]. Surfactant-polymer interactions in solution are important with regard to the flow behavior in the porous media and the potential to displace the oil [54, 55]. Furthermore, the surfactant-polymer interaction at the solid/liquid interface is extremely important with respect to the loss of chemicals by adsorption onto the minerals of the rock material. The loss of surfactant by adsorption is one of the main factors prohibiting, on economic grounds, the use of surfactants in field applications. In recent years, much attention, both experimen tal and theoretical, has been focused on surfactant- polymer interactions in solution, and several reviews have been published [56-59]. Alkali free SP flooding avoids the drawbacks associated with alkali. Surfactants with concentrations higher than the critical micelle concentration (CMC) can achieve ultra-low IFT. However, such surfactants are expensive. The use of a hydrophilic surfactant mixed with a relatively lipophilic surfactant or a new surfactant was also investigated [60-62]. However, studies on SP flooding only focused on the screening and evaluation of the polymer and surfactant and their interaction. Reduction in mobility ratio and IFT is influenced by reservoir brine salinity, reservoir temperature, concentration of chemical ingredients an oil components, and others [63-66].

Wettability

Wettability is defined as the tendency of one fluid to spread on, or adhere to, a solid surface in the presence of other immiscible fluids. This is a major factor controlling the location, flow, and distribution of fluids in a reservoir. Many investigations of wettability and its effects on oil recovery have come to the conclusion that there is a favorable reservoir wettability for operators to recover maximum crude oil from a given subterranean reservoir [67-77]. Also, wetting properties are fundamental for the understanding of multiphase flow in all aspects of oil formation and production, and can affect the production characteristics greatly during waterflooding. Due to this importance, many reviews of wettability and its effect on oil recovery have been published [78-79]. The wetting properties of a reservoir are determined by the interactions between rocks and fluids. The type of minerals, pore size distribution and pore surface area are believed to be important, as well as fluid composition and temperature. The wettability can vary from strongly water-wet to strongly oil-wet [80].

Effects of nanoparticles on Wettability

In recent years there has been an increasing interest in application of nanotechnology in petroleum industry. Reservoir engineering, however, have received the most attention for nanotechnology applications. Nanoparticles have been implemented in different enhanced oil recovery processes. Wettability alteration effects and considerable oil recovery were observed for hydrophilic poly-silicon nanoparticles [81]. Yu *et al.* [82] introduced iron-oxide cored particles with paramagnetic properties as potential EOR agents of which the behavior can be controlled by imposing an external magnetic field. Onyekonwu and Ogolo [83] studied capability of three different polysilicon nanoparticles as an agent for wettability alteration and oil recovery purposes. Skauge *et al.* investigated the oil mobilization properties of nano-sized silica particles and discussed the underlying mechanism of microscopic flow diversion by colloidal dispersion gels. Surface-coated silica nanoparticles have been used to stabilize both water-in-oil and oil-in-water emulsions (2010). Hendraningrat performed several experimental studies to investigate oil recovery using hydrophilic silica nanoparticle injection. Both secondary and tertiary processes were evaluated. Also Hendraningrat *et al.* determined the optimum nanoparticle concentration range for enhanced oil recovery purpose in low permeability sandstone reservoirs. Polysilicon nanoparticles (PSNP) have been considered as an EOR agent by Onyekonwu and Ogolo. One important characteristic of polysilicon nanoparticles is its ability to change rock wettability. Onyekonwu and Ogolo discuss three different PSNP which alter the rock wettability in different manners. Their results showed that silane treated NWPN, and hydrophobic and lipophilic polysilicon nanoparticle (HLPN) which is treated by a single layer organic compound, had an improvement of over 50 % after primary and secondary recovery on a water-wet rock [83]. Ju and Fan address the challenges relating to the application of nanopowder in oilfields to enhance water injection by the effect of changing wettability through adsorption on porous walls of sandstone. Their result revealed that wettability of surface sandstone can be changed from oil-wet to water-wet by adsorption of untreated polysilicon nanoparticle, lipophobic and hydrophilic polysilicon nanoparticle (LHPN). Furthermore, the sandstones' effective permeability of water was improved, while a decrease in absolute permeability was observed [81].

In Roustaei and Bagherzadeh work, the impact of SiO_2 Nanoparticles on the wettability of a carbonate reservoir rock was experimentally studied. Accordingly, SiO_2 Nanoparticles are wettability modifiers for carbonate systems, and they can change the wettability of carbonate rocks from strongly oil-wet to strongly water-wet condition [84].

Safari [85] investigated the effect of different concentration of lipophobic-hydrophilic polysilicon nanoparticles (LHPN) on rock surface. he used carbonate rocks in our experiments. The contact angle between oil droplet and rock surface was measured. Finally, results showed that the hydrophilicity and wettability will be increased with increasing nanoparticle concentration and also cores saturated with oil and water were initially mixed-wet, and nanoparticles injection made them water-wet. Water wettability increases at higher concentrations. The SEM image of the carbonate core after and before injecting with nanoparticles is shown in Fig. 1a and b. The pictures are taken with 10000 magnifications.

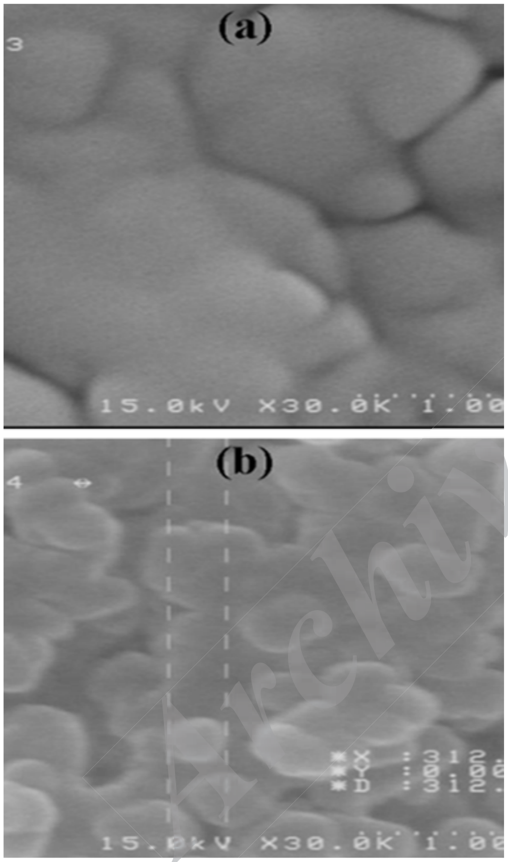

Fig. 1: (a). SEM images of carbonate cores before injecting with nanoparticles suspension, (b). SEM images of carbonate cores after injecting with nanoparticles suspension [85].

Nanoparticles have properties that are potentially useful for certain oil recovery processes, as they are solid and two orders of magnitude smaller than colloidal particles. The nanoparticle stabilized emulsions droplets are small enough to pass typical pores, and flow through the reservoir rock without much retention. Spherical fumed silica particles with a diameter in the range of several to tens of nanometers are the most commonly used. Their wettability is controlled by the coating extent of silanol groups on the surface, and are considered to be hydrophilic if over 90 % of the surface is covered by silanol groups. With these hydrophilic properties, they will consequently form a stable oil-in-water emulsion. Conversely, if the silica particles are coated with only 10 % of silanol groups on the surface, they are hydrophobic, and will form a water-in-oil emulsion [86]. The wettability of a formation can be changed by nanoparticles. The use of nanoparticles to alter rock wettability and its following effect on oil recovery has been published by several authors [81, 83, 87] . Ju *et al.* reported nanometer polysilicon materials that could change the wettability of porous surfaces. Polysilicon, of which SiO_2 is the main component, is obtained by adding an additive activated by γ-ray to form a kind of modified ultra-fine powder with particle size ranging from 10 to 500 nm [88].

A reason for fluid flow behavior during nanosurfactant flooding is the adsorption of ZrO_2 nanoparticles onto medium surface and their ability to change the surface wettability from oil-wet to water-wet. It is obvious that, among the many features affecting the fluid distribution and oil recovery in porous media, wettability is proven to be a crucial factor [89, 90]. Because of wettability alteration from oil-wet to water-wet by silica nanoparticles, oil recovery after dispersed silica nanoparticles in polyacrylamide solution flooding caused more of the pore space to become saturated with the dispersed silica nanoparticles in polyacrylamide solution resulting in 10% higher oil recovery than after polymer flooding.

In polymer flooding, adding silica nanoparticles to polymer solution can be an acceptable method to enhance oil recovery because besides increasing sweep efficiency by means of polymer, nanoparticles which are present in polymer solution can alter the surface wettability. The fluid behavior in porous media, especially in the wall of pores and throats shows medium wettability of the surface by the dispersed silica nanoparticles in polyacrylamide solution. In parts, the polymer phase has been trapped and oil on the wall of pores and throats has remained and the surface remains oil wet. In some parts, where the polymer phase existed on the wall of pores and throats, no significant oil is existent in pores and throats, and water-wet wettability is dominant [91].

Multi walled carbon nanotube (MWCNT)-Silica nanohybrid structures are very suitable material for enhanced oil recovery in order to their excellent interfacial activity. In the O/W interface, they could change the oil properties to mobilize the oil in the reservoir. The effect of nanofluid include MWCNT–Silica nanohybrid on the wettability of carbonate and sandstone rocks was investigated by Ershadi *et al.*. Results were shown that the nanofluid can significantly change the wettability of the rock from oil-wet to water-wet condition.

Fig. 2a and b show the XRD pattern and FE-SEM image of SiO_2 nanoparticles respectively and Fig. 2c and d show the XRD pattern and SEM image of MWCNT–SiO_2 nanohybrid respectively [92].

Modified silica nano fluid improved oil recovery through major mechanisms of interfacial tension reduction and wettability alteration toward oil-wet condition. Based on contact angle and interfacial experiments, the concentration of 3 g/L showed a significant share of interfacial tension reduction and high capability in the transformation of wettability toward oil-wet condition. It was considered as the optimum concentration and was employed in coreflood experiments for both light and intermediate oil systems. Modified silica nanoparticles are more capable in the reduction of interfacial tension and the alteration of wettability in the case of light oil reservoir [8].

Experimental unsteady state displacement tests of water/water saturated by dispersed nanopartcles-light crude oil systems were performed on a sandstone core sample and relative permeability curves of both water and oil phases were determined for two successive cycles of both imbibitions and drainage processes. Based on the results Nano-Particles additives have more effect on changing the non-wetting phase relative permeability curves than the wetting-phase [93-95]. The nanofluids change the rock wettability from water wet to neutral wet state and decrease oil-water interfacial tension [96]. γ-Al_2O_3 nanoparticles (Fig. 3) can be considered as an effective agent in the changing the wettability of carbonate rock surface from oil-wet to water-wet. Fig. 1 shows the construction of nanostructures on the rock surface, which changes the wettability to water-wet conditions [97].

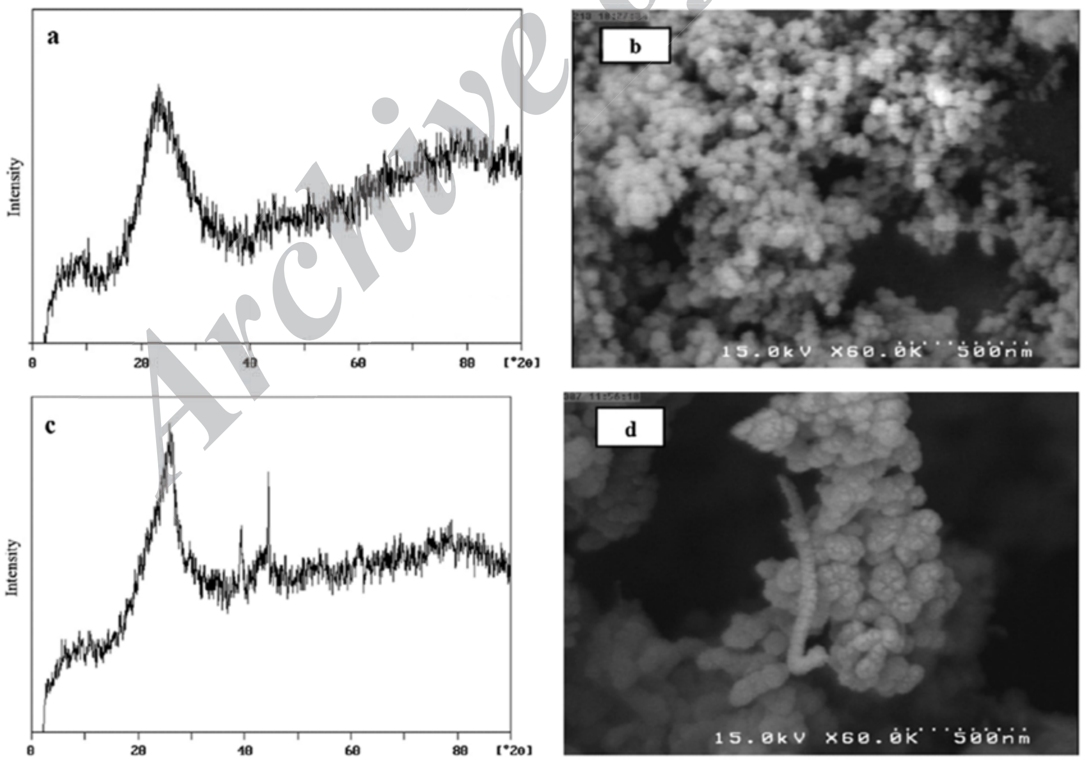

Fig. 2: (a and c) XRD patterns of SiO_2 nanoparticles and MWCNT–SiO_2 nanohybrid respectively (b and d) FE-SEM images of SiO_2 nanoparticles and MWCNT–SiO_2 nanohybrid respectively [92].

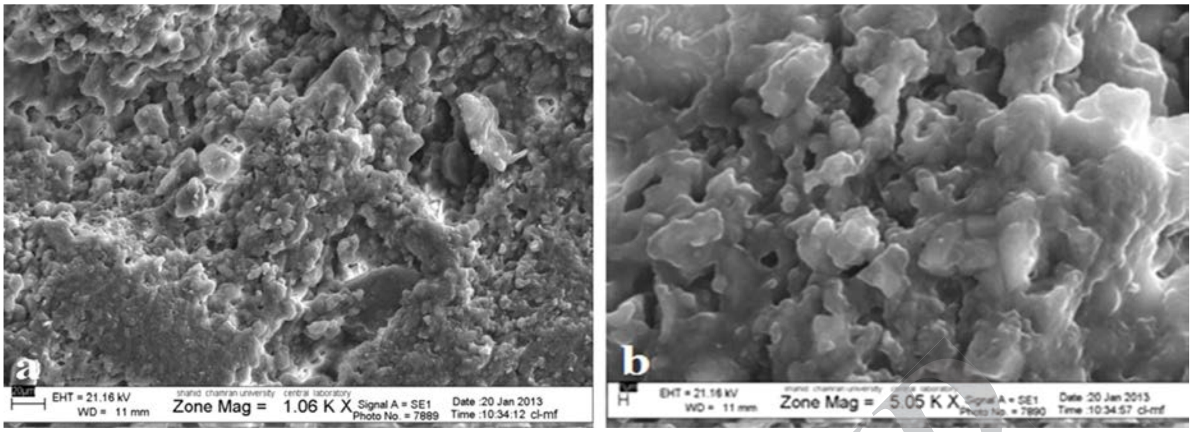

Fig. 3: SEM images γ-Al_2O_3 nanoparticles adsorption on calcite surface with a magnification of (a) 1000 and (b) 5000 [97].

CONCLUSION

A review of the effect of NPs on wettability for enhanced oil recovery processes have been presented. Several cases as well as laboratory studies were discussed. Nanotechnology has the potential to have a positive effect on the chemical EOR process. The aims of this paper were firstly to compilean up-to-date data base for wettability with NPs projects reported in the literature over the last 15 years. Altogether, nanotechnology can be an effective enhancement option for an oil recovery method in a oil reservoir which is technically sensitive to the chemical recovery method. Although the future of nanotechnology is completely uncharted territory, but certainly nanotechnology will revolutionize the oil industry in several important ways.

REFERENCES

[1] Das S. K., Choi S. U. S., Yu W., Pradeep T., (2008). Nanofluids Science and Technology. John Wiley & Sons, *Inc Publishing, Hoboken*, NJ, ISBN: 0470074736.

[2] Hendraningrat L., Li S., Torsæter O., (2013) A coreûood investigation of nanofluid enhanced oil recovery. *J. Petrol. Sci. Eng.* 111: 128-138.

[3] Engese B., (2012), The Potential of Hydrophilic Silica Nanoparticles for EOR Purposes: A Literateur Review and an Experimental Study. Norway: Department of Petroleum Engineering and Applied Geophysics, Norwegian University of Science and Technology.*Trondheim , Master thesis*.

[4] Kanj M. Y., Funk J. J., Al-Yousif Z., (2009), Nanofluid coreflood experiments in the ARAB-D, SPE Saudi Arabia Section Technical Symposium and Exhibition, AlKhobar, Saudi Arabia.

[5] Cheraghian G., Khalili Nezhad S., Kamari M., Hemmati M., Masihi M., Bazgir S., (2014), Adsorption polymer on reservoir rock and role of the nanoparticles, clay and SiO_2. *Int. Nano Lett.* 4: 114-117.

[6] Ju B., Fan T., Ma M., (2006), Enhanced Oil Recovery by Flooding with Hydrophilic. *Nanop. China Partic.* 4: 41-46.

[7] Miranda C. R., De Lara L. S., Tonetto B. C., (2012), Stability and mobility of functionalized silica nanoparticles for enhanced oil recovery application. *Soc. Pet. Eng. SPE* 157033-MS.

[8] Roustaei A., Saffarzadeh S., Mohammadi M., (2013), An evaluation of modified silica nanoparticles' effciency in enhancing oil recovery of light and intermediate oil reservoirs. *Egyp. J. Petrol.* 22: 427–433.

[9] Cheraghian G., Tardasti S., (2012), Improved Oil Recovery by the Efficiency of Nano-particle in Imbibition Mechanism. 74th EAGE Conference and Exhibition incorporating EUROPEC.

[10] Hendraningrat L., Li S., Torsæter O., (2013), Enhancing oil recovery of low-permeability berea sandstone through optimised nanoûuids concentration. In: SPE enhanced oil recovery conference, Kuala Lumpur, Malaysia.

[11] Wasan D. T., Nikolov A., (2003), Spreading of nanofluids on solids. *Nature.* 423: 156-159.

[12] Wasan D. T., Nikolov A., (2011), Kondiparty, K. The wetting and spreading of nanofluids on solids: Role of the structural disjoining pressure. *Curr. Opin. Colloid Interf. Sci.* 16: 344-349.

[13] Chengara A., Nikolov A., Wasan D. T., Trokhymchuck A., Henderson D., (2004), Spreading of nanofluids driven by the structural disjoining pressure gradient. *J. Colloid Interface Sci*. 280: 192-201.

[14] Ju B., Tailiang F., Mingxue M., (2006), Enhanced oil recovery by flooding with hydrophilic nanoparticles. *China Partic*. 4: 41-46.

[15] Ogolo N. A., Olafuyi O. A., Onyekonwu M. O., (2012), Enhanced oil recovery using nanoparticles. *Soc Pet. Eng. SPE.* 160847-MS.

[16] Hendraningrat L., Torsæter O., (2014), Metal oxide-based nanoparticles: revealing their possibility to enhance the oil recovery at different wettability systems. *Appl. Nano Sci*. Springer.

[17] Torsater O., Li S., Hendraningrat L., (2013), Effect of Some Parameters Influencing Enhanced Oil Recovery Process using Silica Nanoparticles, SPE Reservoir Characterization and Simulation Conference and Exhibition.

Abu Dhabi, UAE, 16-18 September.

[18] Yuan W., Liu X., Wei H., Liu J., Yang H., Hu S., Li Y., Wang D., (2010), Research and application effect of polymeric microsphere in Wen-10 of Sinopec Zhongyuan Oil field. *Inner Mong. Petrochem.* 12: 122-126.

[19] Li X., Ying Z., Jia Y., Liu X., Yang T., Ma L., (2012), Application of nanosphere deep profile control and displacement technology in Chanqing oil field. *Oil Field Chem.* 29: 13-16.

[20] Tian Y., Wang L., Tang Y., Liu C., Ma C., Wang T., (2012), Research and application of nano polymer microspheres diversion technique of deep fluid. *Soc. Pet. Eng. SPE.* 156999-MS.

[21] Hamedi Sh. Y., Babadagli T., (2010) Effects of nano sized metals on viscosity reduction of heavy oil/bitumen during thermal applications, Canadian Unconventional Resources & International Petroleum Conference Held in Calgary, Alberta, Canada, 19-21 October.

[22] Hendraningrat L., Engeset B., Suwarno S., Torsæter O., (2012), Improved oil recovery by nanofluids flooding: an experimental study. In: SPE Kuwait international petroleum conference and exhibition Kuwait city, Kuwait.

[23] Pourafshary P., Azimipour, S. S., Motamedi P., Samet M., Taheri S. A., Bargozin H., Hendi S. S., (2009), Priority assessment of the investment in development of nanotechnology in upstream petroleum industry. In: Proceedings of the Saudi Arabia Section Technical Symposium and Exhibition. A1Khobar, Saudi Arabia, SPE No. 126101-MS.

[24] Skauge T., Hetland S., Spildo K., Skauge A., (2010), Nano-Sized Particles for EOR , SPE 129933 , SPE Improved Oil Recovery Symposium, Oklahoma, USA, 24–28 April.

[25] Cheraghian G., (2015), Thermal Resistance And Application of Nanoclay on Polymer Flooding in Heavy Oil recovery. *Petrol. Sci. Tech.* 33: 1410-1413.

[26] Cheraghian G., Khalili Nezhad S., Kamari M., Hemmati M., Masihi M., Bazgir S., (2014), Effect of nanoclay on improved rheology properties of polyacrylamide solutions used in enhanced oil recovery. *J. Petrol. Explor. Prod. Tech.* 5: 189-196.

[27] Le N. Y. T, Pham D. K., Le K. H., Nguyen P. T., (2011), Design and screening of synergistic blends of SiO_2 nanoparticles and surfactants for enhanced oil recovery in high-temperature reservoirs. *J. Adv. Nat. Sci.* 2: 35013–35019.

[28] Abidina A. Z., Puspasaria T., Nugroho W. A., (2012), Polymers for Enhanced Oil Recovery Technology. *Proced. Chem.* 4: 11-16.

[29] Du Y., Guan L., (2004), Field-scale polymer flooding: lessons learnt and experiences gained during past 40 years. SPE 91787 presented at SPE international petroleum conference, Puebla, Mexico, 8–9 November.

[30] Wang J., Dong M., (2009), Optimum effective viscosity of polymer solution for improving heavy oil recovery. *J. Petrol. Sci. Eng.* 67: 155–158.

[31] Sheng J., (2011), Modern chemical enhanced oil recovery. Gulf Profession Publishing. 101–206.

[32] Wang D., Cheng J., Wu J., Wang Y. (2002), Producing by polymer flooding more than 300 million barrels of oil what experiences have been learnt. SPE 77872 presented at Asia Pacific oil and gas conference and exhibition, Melbourne, Australia.

[33] Wang D., Zhao L., Cheng J., Wu J., (2003), A, ctual field data show that production costs of polymer flooding can be lower than water flooding. SPE 84849 presented at improved oil recovery conference in Asia Pacific, Kuala Lumpur, Malaysia, 20–21 October 2003. Publishing 101–206.

[34] Wang D. M., Xia H. F., Liu Z. C., Yang Q. Y., (2001), Study of the mechanism of polymer solution with viscoelastic behavior increasing microscopic oil displacement efficiency and the Forming of Steady "Oil Thread" Flow Channels, SPE Asia Pacific Oil and Gas Conference and Exhibition, 17-19 April, Jakarta.

[35] Guo X. H., Li D. W., Tian J., Liu Y. Z., (1999), Pilot test of xanthan gum flooding in Shengli oilfield. In: SPE 57294 presented at SPE Asia Pacific improved oil recovery conference, Kuala Lumpur.

[36] Ye Z. B., Gou G. J., Gou S. H., Jiang W. C., Liu T. Y., (2013), Synthesis and characterization of a water-soluble sulfonates copolymer of acrylamide and N-Allylbenzamide as enhanced oil recovery chemical. *J. Appl. Polym. Sci.* 128: 2003–2011.

[37] Shiran B. S., Skauge A., (2013), Enhanced oil recovery (EOR) by combined low salinity water/polymer flooding. *Energy Fuels.* 27: 1223–1235.

[38] Zhong C., Huang R., Zhang X., Dai H., (2007), Synthesis, characterization, and solution properties or an acrylamide-based terpolymer with butyl styrene. *J. Appl. Polym. Sci.* 103: 4027–4038.

[39] Ye Z., Qin X., Lai N., Peng Q., Li X., Li C., (2013), Synthesis and Performance of an Acrylamide Copolymer Containing Nano-SiO_2 as Enhanced Oil Recovery Chemical. *Hind. Pub. Corp. J. Chem.* Volume 2013, Article ID 437309, 10 pages.

[40] Chang S. H., Chung I. J., (1991), Effect of shear flow on polymer desorption and latex dispersion stability in the presence of adsorbed polymer. *Macromol.* 24: 567–571.

[41] Xue L., Agarwal U. S., Lemstra P. J., (2005), Shear degradation resistance of star polymers during elongational flow. *Macromol.* 38: 8825–8832.

[42] Wu Z., Yu J., Cheng T., Yue X., Yang H., (2014) Effect of viscosity and interfacial tension of surfactant–polymer flooding on oil recovery in high-temperature and high-salinity reservoirs. *J. Petrol. Explor. Prod. Technol.* 4: 9–16.

[43] Yadali Jamaloei B., Kharrat R., Ahmadloo F., (2009), Selection of proper criteria in flow behavior characterization of low tension polymer flooding in heavy oil reservoirs. SPE Kuwait international petroleum conference and exhibition. Kuwait City, Kuwait.

[44] Raterman K. T., Kremesec Jr. V. J., Suffridge F. E., (1988), Evaluation of low-concentration surfactant flooding in the absence of mobility control agents. SPE/DOE Paper No. 17394. SPE/DOE Enhanced Oil Recovery Symposium, Tulsa, Oklahoma, April 17–30.

[45] Sanz C. A., Pope G. A., (1995), Alcohol-free chemical flooding: From surfactant screening to coreflood design. SPE Paper No. 28956. SPE International Symposium on Oilfield Chemistry, San Antonio, Texas, February 14–17.

[46] Yang H. D., Wadleigh E. E., (2000), Dilute surfactant IOR—Design improvement for massive, fractured carbonate applications. SPE Paper No. 59009. 2000 SPE International Petroleum Conference and Exhibition, Villa Hermosa, Mexico, February 1–3.

[47] Sanele S., Yortsos Y. C., (1986), A note on the application of the theory of coherence to surfactant flooding. *SPE Reserv. Eng.* 1: 23–28.

[48] Hornof V., Morrow N. R., (1987), Gravity effects in the displacement of oil by surfactant solution. SPE Paper No. 13573. *SPE. Reserv. Eng.* 2: 627–633.

[49] Hematpour H., Arabjamloei R., Nematzadeh M., Esmaili H., Mardi M., (2012), An Experimental Investigation of Surfactant Flooding Efficiency in Low Viscosity Oil Using a Glass Micromodel. *Energy Sour. Part A. Recov. Utiliz., Environm. Effects.* 34: 1745-1758.

[50] Esmaeilzadeh P., Hosseinpour N., Bahramian A., Fakhroueian Z., Arya S., (2014), Effect of ZrO_2 nanoparticles on the interfacial behavior of surfactant solutions at air–water and n-heptane–water interfaces. *Fluid Phase Equilibria.* 361: 289- 295.

[51] Le N., Pham D. K., Le K. H., Nguyen P. T., (2011), Design and Screening of Synergistic Blends of SiO_2 Nanoparticles and Surfactants for Enhanced Oil Recovery in High-Temperature Reservoirs. *Adv. Natural Sci.: Nanosci. Nanotech.* 2: 17: 45-49.

[52] Suleimanov B. A., Ismailov F. S., Veliyev E. F., (2011), Nanofluid for Enhanced Oil Recovery. *J. Pet. Sci. Eng*. 78: 431–437.

[53] Lake L. W., (1989), Enhanced Oil Recovery. Prentice-Hall, Inc., Upper Saddle River, New Jersey.

[54] Austad T., Fjelde I., Veggeland K., Taugbol K., (1994), Physicochemical principles of low tension polymer flood. *J. Petrol. Sci. Eng*. 10: 255-269.

[55] Taugbel K., Ly T. V., Austad T., (1995), Chemical flooding of oil reservoirs 3.Dissociative surfactant-polymer interaction with a positive effect on oil recovery. *Colloids Surf. A: Physicochem. Eng. Aspects*. 10: 83-90.

[56] Breuer M. M., Robb I. D., (1972), Interactions between macromolecules and detergents. *Chem. Ind.* 54: 530-535.

[57] Goddard E. D., (1986), Interactions between macromolecules and detergents. *Colloids Surf.* 1: 255-300.

[58] Piculell L., Lindman B., (1992), Association and segregation in aqueous polymer/polymer, polymer/surfactant. *Adv. Colloid Interf. Sci.* 4: 149-178.

[59] Lindman B., Thalberg K., Goddard E. D., Ananthapadmanabhan K. P. (Eds.), (1993) ,Interactions of Surfactants with Polymers and Proteins, CRC Press, Boca Raton. 203-276.

[60] Aoudia M., Al-Shibli M. N., Al-Kasimi L. H., Al-Maamari R., Al-Bemani A., (2006), Novel surfactants for ultralow interfacial tension in a wide range of surfactant concentration and temperature. *J. Surfac. Deterg.* 9: 287-293.

[61] Cui Z., DU X., Pei X., Jiang J., Wang F., (2012), Synthesis of didodecylmethylcarboxyl betaine and its application in surfactant–polymer flooding. *J. Surfac. Deterg.* 15: 685-694.

[62] Rosen M. J., Wang H., Shen P., Zhu Y., (2005), Ultralow interfacial tension for enhanced oil recovery at very low surfactant concentrations. *Langmuir.* 21: 3749–3756.

[63] Ferdous S., Ioannidis M. A., Henneke D. E., (2012), Effects of temperature, pH, and ionic strength on the adsorption of nanoparticles at liquid–liquid interfaces. *J. Nanopart. Res.* 14: 850-855.

[64] Gong H., Guiying X., Zhu Y., Wang Y., Dan W., Niu M., Wang L., Guo H., Wang H., (2009), Influencing factors on the properties of complex systems consisting of hydrolyzed polyacrylamide/triton x-100/cetyl trimethylammonium bromide: viscosity and dynamic interfacial tension studies. *Energy Fuels.* 23: 300-305.

[65] Cao Y., Zhao R., Zhang L., Xu Z., Jin Z., Luo L., Zhang L., Zhao S., (2012), Effect of electrolyte and temperature on interfacial tensions of alkylbenzene sulfonate solutions. *Energy Fuels*. 26: 2175–2181.

[66] Zhang H., Dong M., Zhao S., (2012), Experimental study of the interaction between NaOH, surfactant, and polymer in reducing court heavy oil/brine interfacial tension. *Energy Fuels.* 26: 3644–3650.

[67] Morrow N. R., Lim H. T., Ward J. S., (1984), Effect of crude-oil-induced wettability changes on oil recovery. 59th Annual Society of Petroleum Engineers of AIME Technical Conference, Houston, Texas (paper SPE 13215).

[68] Morrow N. R., (1990), Wettability and its effect on oil recovery. *J. Pet. Tech.* 24: 1476-1485.

[69] Anderson W. G., (1987), Wettability literature survey-Part 6: The effects of wettability on waterflooding. *J. Pet. Tech.* 39: 1605-1622.

[70] Rao D., Girard M., Sayegh S., (1992), The influence of reservoir wettability on waterflood and miscible flood performance. *J. Canad. Petrol. Tech.* 31: 47-55.

[71] Jadhunandan P. P., Morrow N. R., (1995), Effect of wettability on waterflood recovery for crude-oil/brine/rock systems. *SPE Reservoir Eng.* 10: 40-46.

[72] Zhou X., Morrow N. R., Ma S., (2000), Interrelationship of wettability, initial water saturation, aging time, and oil recovery by spontaneous imbibition and waterflooding. *SPE Journal.* 5: 199-207 .

[73] Dwarakanath V., Jackson R. E., Pope G. A., (2002), Influence of wettability on the recovery of NAPLs from alluvium. *Environm. Sci. Tech.* 36: 227-231.

[74] Hatiboglu C., Babadagli T., (2006), Primary and secondary oil recovery from different-wettability rocks by countercurrent diffusion and spontaneous imbibition. S*PE/ DOE Symposium on Improved Oil Recovery*, Tulsa, Oklahoma (paper SPE 94120).

[75] Johannesen E. B., Graue A., (2007), Mobilization of remaining oil—Emphasis on capillary number and wettability. *Int. Oil Conf. Exhibition in Mexico*, Veracruz, Mexico (paper SPE 108724).

[76] Johannesen E., Graue A., (2007), Systematic investigation of waterflood reducing residual oil saturations by increasing differential pressures at various wettabilities. *Offshore Europe*, Aberdeen, Scotland, UK. (paper SPE 108593).

[77] Yefei W., Huaimin X., Weizhao Y., Baojun B., Xinwang S., Jichao Z., (2011), Surfactant induced reservoir wettability alteration: Recent theoretical and experimental advances in enhanced oil recovery. *Pet. Sci.* 8: 463-476.

[78] Morrow N. R., Lim H. T., Ward J. S., (1986), Effect of crude-oil-induced wettability changes on oil recovery. *SPE Form. Eval*. (Feb.), 89–103.

[79] Cuiec L. E., (1990), Evaluation of reservoir wettability and its effect on oil recovery. In: Morrow, N.R. (Ed.), Interfacial Phenomena in Oil Recovery. Marcel Decker, New York, 375– 391.

[80] Kowalewski E., Holt T., Torsaeter O., (2002), Wettability alterations due to an oil soluble additive. *J. Petrol. Sci. Eng*. 33: 19–28.

[81] Ju B., Fan T., (2009), Experimental study and mathematical model of nanoparticle transport in porous media. *Powder Technol.* 192: 195–202.

[82] Yu H., Kotsmar C., Yoon K. Y., Ingram D. R., Johnston K. P., Bryant S. L., Huh C., (2010), Transport and retention of aqueous dispersions of paramagnetic nanoparticles in reservoir rocks. In: SPE improved oil recovery symposium, Tulsa, OK, USA.

[83] Onyekonwu M. O., Ogolo N. A., (2010), Investigating the use of nanoparticles in enhancing oil recovery. Paper No. 140744-MS, Nigerian Annual International Conference and Exhibition, Tinapa-Calabar, Nigeria, July 31–August 7.

[84] Roustaei A., Bagherzadeh H., (2015), Experimental investigation of SiO_2 nanoparticles on enhanced oil recovery of carbonate reservoirs. *J. Petrol. Explor. Prod. Tech.* 5: 27–33.

[85] Safari M., (2014), Variations in Wettability Caused by Nanoparticles. *Petrol. Sci. Tech.* 32: 1505-1511.

[86] Zhang T., Davidson A., Brytant S. L., Huh C., (2010), Nanoparticle-Stabilized Emulsions for Application in Enhanced Oil Recovery, SPE Improved Oil Recovery Symposium, Tulsa, Oklahoma, USA, 24-28 April 2010. 18.

[87] Bishan J., Tailang F., Mingxua M., (2005), Enhanced oil recovery by uooding with hydrophilic nanoparticles. *China Particuol*. 4: 41–46.

[88] Ju B., Luan Z., Wu Z., Lü G., (2001), A study of removal of organic formation damage by experiments and modeling approaches. Proceedings of the SPE Asia Pacific Oil and Gas Conference and Exhibition. Jakarta, Indonesia.

[89] Van Oss C. J., Giese R. F., (1995), The hydrophilicity and hydrophobicility of clay minerals. *Clays Clay Miner.* 43: 474-477.

[90] Wu S., Firoozabadi A., (2010), Permanent alteration of porous media wettability from liquid-wetting to intermediate gas-wetting. *Transp. Porous. Media.* 85: 189–213.

[91] Maghzi A., Mohebbi A., Kharrat R., Ghazanfari M. H., (2011), Pore-Scale Monitoring of Wettability Alteration by Silica Nanoparticles During Polymer Flooding to Heavy Oil in a Five-Spot Glass Micromodel. *Transp Porous Med.* 87: 653–664.

[92] Ershadi M., Alaei M., Rashidi A., Ramazani A., Khosravani S., (2015), Carbonate and sandstone reservoirs wettability improvement without using surfactants for Chemical Enhanced Oil Recovery (C-EOR). *Fuel.* 153: 408-415.

[93] Parvazdavani M., Masihi M., Ghazanfari M. H., Sherafati M., Mashayekhi L., (2012), Investigation of the Effect of Water Based Nano-Particles Addition on Hysteresis of Oil and-Water Relative Permeability Curves. SPE 157005. The SPE International Oilfield Nanotechnology Conference held in Noordwijk, The Netherlands, 12–14 June.

[94] Cheraghian G., Khalili Nezhad S., (2015), Effect of Nanoclay on Heavy Oil Recovery during Polymer Flooding. *J. Pet. Sci. Tech.* 33: 999-1007.

[95] Cheraghian G., (2015), An experimental study of a surfactant polymer for enhanced heavy-oil recovery using a glass micromodel by adding nanoclay. *J. Pet. Sci. Tech.* 33: 13-14.

[96] Joonaki E., Ghanaatian S., (2014), The Application of Nanofluids for Enhanced Oil Recovery: Effects on Interfacial Tension and Coreflooding Process. *J. Pet. Sci. Tech.* 32: 2599-2607.

[97] Mohammadi M., Moghadasi J., Naseri S., (2014), An Experimental Investigation of Wettability Alteration in Carbonate Reservoir Using γ-Al2O3 Nanoparticles . *Irani. J. Oil & Gas Sci. Tech.* 3: 18-26.

[98] Alvarado V., Manrique E., (2010), Enhanced Oil Recovery: *An Update Revi. Energ.* 3: 1529-1575.

How to cite this article: (Vancouver style)
Cheraghian G., (2015), Effects of nanoparticles on wettability: A review on applications of nanotechnology in the enhanced Oil recovery. *Int. J. Nano Dimens.* 6(5): 443-452.
DOI: 10.7508/ijnd.2015.05.001
URL: http://ijnd.ir/article_15159_1117.html