

# Evaluating the Application of Nanoparticles to Reduce Surface Tension and Wettability Change in Surfactant and Polymer Flooding to Increase Oil Recovery Factor in Sarvak Reservoir

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## Abstract

Nowadays, the use of enhanced oil recovery methods, such as chemical flooding, is increasingly felt. Given the rapid developments in nanotechnology and its high efficiency, the rise of oil recovery through nanotechnology is the main idea of this research. Early water breakthrough in the producing well, and the unfavorable conditions of oil reservoirs such as high temperatures, the presence of different types of salts, incorporation of a variety of shear stresses into the polymer and the surfactants in the reservoir, limited the use of these solutions. In this study, the effect of silica nanoparticles on the performance of surfactant-polymer solution in the chemical flooding process was investigated. Two types of fluids including one solution of polymer-surfactant in water and another suspension of nanoparticles and a polymer-surfactant solution were evaluated using a physical model (sand pack) and flooding at different temperatures and salinities. The optimum concentration of the nanoparticle was determined (0.3). In addition to measuring the recovery factor, the main phenomena associated with flooding in the porous medium, including wettability and surface tension, were also investigated. The results of the experiments showed that flooding as 2PV with nanoparticle suspension increased 11% of oil production, compared to the non-nanoparticle polymer-surfactant flooding. It also converts the wettability of the reservoir rock from lipophilic to hydrophilic properties, due to the presence of nanoparticles. Also, measuring the interfacial tension showed that the solution with nanoparticles further reduce the interfacial tension between the water and the reservoir's oil, and consequently increase microscopic displacement efficiency.

**Keywords:** Silica nanoparticles, Polymer-surfactant, Sand pack, Surface tension, Flooding.

## Introduction

Since the discharge rate of petroleum extraction in the fields has begun to decline, and the rate of new discoveries is significantly lower, increasing the recovery factor is important. Many of the fields with the residual oil saturation more than 30% have been abandoned (Zang et al., 2008).

A few percent increase in the recovery factor may be worth billions of dollars. An enhanced or tertiary oil recovery technique has been developed to increase oil recovery higher than the secondary recovery. The thermal recovery, which uses heat to reduce viscosity, especially viscosity of heavy oils, and the miscible and non-miscible gas injection and chemical injections involving the use of polymers, alkaline and surfactants, all of them are the tertiary oil recovery techniques (Kong & Ohadi, 2010)

Injectable transporter fluids, such as water and CO<sub>2</sub>, and surfactant solutions are often less viscous than oil. With the increase of nanoparticles, the viscosity of the injected fluid can be increased and less mobility ratio can be obtained. A laboratory study carried out by Shah and Rusheet showed that either density or viscosity of CO<sub>2</sub> increase only by adding 1% of CUO nanoparticles. Viscosity of CO<sub>2</sub> Nano fluid reached about 140 times more than that of conventional CO<sub>2</sub> (Shah, 2009).

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Some articles also refer to experiments that tested the combination of nanoparticles and surfactant solutions. Le et al. studied a synthesized mixture of SiO<sub>2</sub> nanoparticles and surfactant for EOR in the reservoirs with high temperature. They designed experiments by mixing different types of surfactants with SiO<sub>2</sub> nanoparticles. Some compounds showed high potential for EOR applications due to their resistance to rock absorption and thermal resistance at 91 °C (Le et al., 2011).

Onyekonwu and Ogolo considered polysilicon nanoparticles (PSNP) as a general EOR. One of the most important features of silicon nanoparticles is their ability to convert the wettability of the rocks. Onyekonwu and Ogolo studied three types of PSNPs, which change the wettability of the rock in different ways. Their results showed that the NWP and HLPN flooding, produced by a simple layer of organic compounds, improved more than 50% in hydrophilic rock after the primary and tertiary recovery (Onyekonwu & Ogolo, 2010)

Ju and Fan mention the challenges related to the use of Nano-powder in oil fields to improve water injection by the effect of wettability through absorption in the walls of porous sandstone environments. Their results revealed that the wettability of the sandstone could be converted from lipophilic to hydrophilic by absorbing lipophilic and hydrophilic polysilicon nanoparticles (LHPN). Also, effective permeability of sandstone was improved, while decrease in absolute permeability was observed (Ju & Fan, 2008).

Nanoparticles have properties that are potentially useful for oil recovery processes. They are solid and 2 million times smaller than colloidal particles.

The stabilized emulsion droplets of nanoparticles are small enough to pass through empty spaces. They pass through the reservoir's rock without being kept too much (Zhang et al., 2010). Spherical evaporated silica particles ( $\geq 10\text{nm}$ ) have the most applications. Their wettability is controlled by the coverage of the silanol groups that are spread over the surface, and it is assumed that if 90% of the surface is covered with silanol groups, they are hydrophilic. With these hydrophilic properties, they can subsequently form an oil emulsion in water. Conversely, if Nano silica particles are coated with only 10% of silanol groups, they will be hydrophobic and form water emulsion in oil (Zhang et al., 2010).

Nano emulsions are stable over time, and resistant to coagulation and dispersion of phases between droplets (Kong & Ohadi, 2010) Particles are also able to sustain supercritical CO<sub>2</sub>-in-water emulsions (Dickson et al., 2004) as well as supercritical water-in-CO<sub>2</sub> emulsions (Adkins et al., 2007)

Kanj et al. determined the usable size of the particles in the reservoir's rock and their transfer potential (Kan et al., 2009). In another study, Skauge concluded that silica particles are readily distributed in an empty space system, and because of their performance in the reservoir, they do not harm or damage the environment. They also seem to be very small for blocking empty spaces, which also makes them relevant for EOR goals (Skauge, et al., 2010).

In addition to SiO<sub>2</sub>, recent studies determined the potential of MgO, AL<sub>2</sub>O<sub>3</sub>, and FE<sub>2</sub>O<sub>3</sub> nanoparticles. The results showed that some compounds have better efficiencies than SiO<sub>2</sub> (Ogolo et al., 212). Based on existing knowledge, it is expected that chemical EORs, especially micellar flooding, will benefit from nanotechnology and Nano emulsion (Mokhatab et al., 2006)

On the other hand, (Sharabadi et al., 2012) examined the effects of hydrophobic and lipophilic polysilicon (HLP) on various water injection processes from a mechanical perspective. The results of the research showed that HLP injection into a hydrophilic sandstone specimen led to an increase in crude oil production under two mechanisms of reducing surface tension and changing wettability.

(Ogolo et al. 2012) evaluated the mechanisms by which nanoparticles increase oil recovery including the change of wettability, the decrease of surface tension and mobility ratio. The results showed that the use of distilled water to prepare nanoparticle solution resulted in lower recovery, and also negative effect of nanoparticles in salt and ethanol solutions on the production of oil was observed.

(Bergland in 2006) evaluated the rheological behavior of Nano composites, composed of cellulose and laminated silicates. Studies have shown that the formation of non-movable polymer layers and the presence of large surface of silicate particles enhance the viscoelastic behavior of these composites and improve properties such as fire resistance.

In the methods of chemical recovery, two main goals of reducing the surface tension and increasing the viscosity of the injectable phase are followed to increase the microscopic and macroscopic efficiencies (volumetric), respectively. Nanotechnology can be effective on enhanced oil recovery through adjusting the physical properties of injectable chemicals by improving these two properties, and result in more petroleum extraction and more oil recovery factor.

Injection of nanoparticles into the reservoir lead to the deposition of the particles on the wall, reduction of the porosity and permeability of the medium, and consequently, reduction of the nanoparticle transfer into the depth of the reservoir. This case is one of the main challenges of the use of nanoparticles in improvement of enhanced oil recovery techniques. Porous environments are composed of very complex networks of vacant spaces, so that the deposition of nanoparticles not only affect porosity and absolute permeability, due to the presence of a considerable level of surface (in some cases, active surfaces with ion charges), but also it can change the physical and chemical properties of the porous medium, including wettability (Pourafshar et al., 2009).

In the oil industry, in order to increase the efficiency of technologies, nanotechnology appears to be efficient in various fields, such as drilling, exploitation, and enhanced recovery. The aim of this study was to evaluate the efficacy of polyacrylamide solutions in different temperatures and salinities of formation water, and also to investigate the effect of silica nanoparticles on the performance of these polymers under the conditions mentioned above. For this purpose, a series of flooding experiments were carried out to convert the wettability in the Sand pack system. Another goal was to study the effect of nanoparticles on reducing the desired surface tension. Regarding the application of nanoparticles in improving the performance of copolymers, it is possible that nanoparticles can be used to improve the resistance of solution polymers against heat and shear stresses introduced to the fluid, consequently, by increasing the viscosity of the injected phase by nanoparticles, increase in the production of crude oil can be resulted.

## Materials and Methods

In this research, oil and water from Sarvak reservoir, related to Darkhoein oil field and located in southwestern Iran, were used. The characteristics of the oil and water are given in the following tables.

**Table 1:** Characteristics of the oil from Sarvak reservoir

Result of experiment	Unit	Amount
Temperature	0 °C	25
Bubble point pressure	Psia	355
Ratio of gas to oil	SCF/STB	18
Density of residual oil at 60° F	g/cm <sup>3</sup>	0.9223
Special weight of residual oil at 60° F	-	0.9229
API degree of residual crude oil at 60° F	-	32
Special weight of gas in standard condition	Air=1	1.6488
Density of gas in standard condition	g/lit	2.0165

**Table 2:** characteristics of reservoir water (salty composition of forming water)

Type of salt	NaCl	MgCl <sub>2</sub>	CaCl <sub>2</sub>	Na <sub>2</sub> SO <sub>4</sub>
Percentage of salt	73.2	2.5	2.7	21.6

**Table 3:** characteristics of used surfactant

Name of surfactant	Type of surfactant	Abbreviated name	Chemical formula
Sodium dodecyl sulfate	Anionic	SDS	NaC <sub>12</sub> H <sub>25</sub> SO <sub>4</sub>

**Table 4:** Characteristics of the used polymer

Name of polymer	Molecular weight	Viscosity (c.p.)	Density (kg/m <sup>3</sup> )
Polyacrylamide	6×10 <sup>6</sup>	45	1744

**Table 5:** Characteristics of the used SiO<sub>2</sub>

Type of particle	Density of particle(g/m <sup>3</sup> )	Special surface (m <sup>2</sup> /g)	Size of particle (nm)
SiO <sub>2</sub>	0.048	210	20

The physical model used for flooding experiments in this research was sand pack, which was prepared using rock and fluid from Sarvak reservoir in Darkhoein oilfield.

A hand pump was used to provide the pressure above the floor to approach the reservoir conditions in the core holder. The pump is able to inject water into an intermediate space between plastic sheath and the metal body of the core holder, and apply pressures of up to 6,000 psi on the core. The rock sample from Sarvak reservoir in Darkhoein oilfield was washed by Soxhelt device and dried in Oven for 24 h. Then the sample is pulverized by the mill and then sieved with different mesh sizes. Next, 365 g of sieved particles, mixed in different sizes and weights, was weighted to be packed in sand pack cylinder pack.

The type of Sand pack cylinder is an anti-corrosion steel that is supplied by high pressure HPLC pump and 2 oil and gas transfer cylinders, one of which is for injection of water or polymer solution and another is for crude oil. Oil, forming water and injectable solutions are injected with a flow rate of 2.0 cc / min. After packing the sand, the cylinder containing sand was weighted (its weight before saturation was 12150 grams).

Sand pack cylinder was placed vertically in the oven and the saturation action begins with formation water at an injection rate of 0.2 cc /min. The injection was done vertically and from the bottom of the metal cylinder. This is to prevent channeling water inside sand pack and to saturate all the points inside the sand pack by water. The weight of sand pack after and before saturation was 12223 and 12100 grams, respectively. The water saturation stage is performed without temperature and pressure, with different weight of 73 grams.

Because water density was  $1\text{g/cm}^3$ , thus 73 grams are equivalent to 73cc, and the dead volume of the input and output ponds of sand pack is 20 cc. As a result, the volume of porous space inside the sand pack is 54 cc.

In the calculation of the permeability, the system is placed at back pressure of 50 bar and injected at ambient temperature. The five selected rates for injection are equal to 0.7, 0.6 and 0.4, 0.2, and 0.1 cc/min.

In these flooding experiments, 106 is equivalent to 2pv. Sand pack saturation is vertically carried out by the crude oil of Sarvak reservoir in the Darkhoein oil field, and the injection is carried out at a rate of 0/2cc/ min at ambient temperature and back pressure of 500 bar. When the water is no longer out of the model, the saturation process is completed and the amount of oil and water in the model is 52cc and 6cc, respectively.

$$Swc = \frac{6cc}{58cc} = 11\%, Scc = \frac{52cc}{58cc} = 89\%$$

To select the most stable concentration of nanoparticles, all 4 samples were sustained in distilled water. However, the samples with a concentration of 0.3 were more stable in water formation.

**Table 6:** Experiment of wettability conversion

Type of sample	Points		
	1	2	3
1) The part affected in nanoparticle suspension in the formation water	2	1.5	1.3
2) The part affected in formation water	78	65	73
3) The part affected in suspension of nanoparticles, polymer-surfactant and formation water	22	25	25
4) The part affected in the solution of polymer-surfactant and formation water	28	29	27.4
5) The part affected in reservoir oil	140	<b>153</b>	<b>145</b>

As it can be seen in table (6), the contact angle in the state, where the surface is covered with water-based suspensions containing nanoparticles, is approximately 1.5, which indicates the strong hydrophilic properties of the nanoparticles in the suspension.

*Evaluation of surface tension*

**Table 7:** The experiments of measuring surface tension between crude oil and prepared fluids.

Experiments phases	Interfacial tension (IFT) (dynes/cm)		
	Light phase	Heavy phase	
55	Reservoir oil	Formation water	
20	Reservoir oil	Surfactant solution (500ppm) and polymer in formation water	
27	Reservoir oil	The suspension containing silica nanoparticles and formation water (0.3% of nanoparticle weight)	
14.5	Reservoir oil	4-1: concentration of nanoparticles (0.01% of weight)	Suspension containing nanoparticles, surfactant, polymer and water
12	Reservoir oil	4-2: concentration of nanoparticles (0.1% of weight)	
9	Reservoir oil	4-3: concentration of nanoparticles (0.3% of weight)	
13	Reservoir oil	4-4: concentration of nanoparticles (0.5% of weight)	
17	Reservoir oil	5-5: concentration of nanoparticles (1% of weight)	

As it can be seen in the table (7), surface tension between oil and reservoir water is initially large (55dyne/cm), but surface tension between the suspension of nanoparticles and reservoir oil is 27 dyne/ cm and between surfactant and reservoir oil is 20 dyne/cm. The best concentration of nanoparticles is 0.3% of weight, which reduces surface tension to 9 dyne/cm.

*Injection experiments in the physical model*

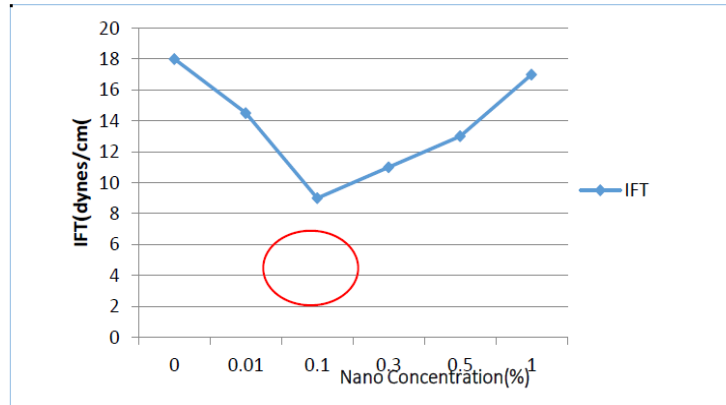
The experimental system in this study is the physical model of sand pack (sand bed). The characteristics of sand pack, are given in Table 8.

**Table 8:** Characteristics of 6 physical models (sand pack) to do flooding experiments of chemical solutions

Oil saturation (%)	Water saturation (%)	The volume of empty space (cc) pv	Permeability (md)	Porosity%	Sand pack ID (sand bed)
89	11	53	315	27	S1
91	9	55	298	25	S2
87	13	54	320	24.5	S3
90	10	62	310	27	S4
86	14	55.3	276	24	S5
89	11	54	295	23.5	S6

**Results and Discussion**

*Evaluation of surface tension (IFT)*



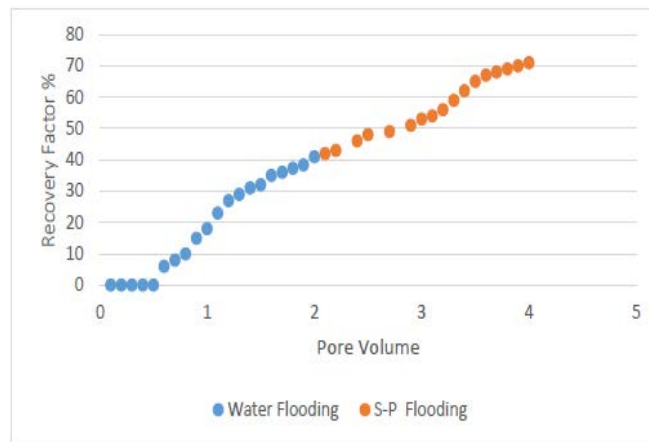
**Fig. 1:** surface tension based on different concentrations of suspension containing nanoparticles, surfactant and formation water.

As it is shown in figure (1), increasing the concentration of nanoparticles decreases the surface tension, and the least surface tension is observed in the concentration of 0.3, and after that increasing concentration of nanoparticles increases surface tension. Thus, optimal concentration of nanoparticles in this test was calculated as 0.3%. The suspension of the nanoparticles and the surfactant-polymer decreases surface tension between water and oil. Therefore, the decrease of the capillary force increases the tendency to mixing of oil and water at their contact surfaces, resulting in an increase in the microscopic displacement efficiency and oil sweeping in smaller paths inside the porous medium.

*Flooding experiments in physical models (sand pack)*

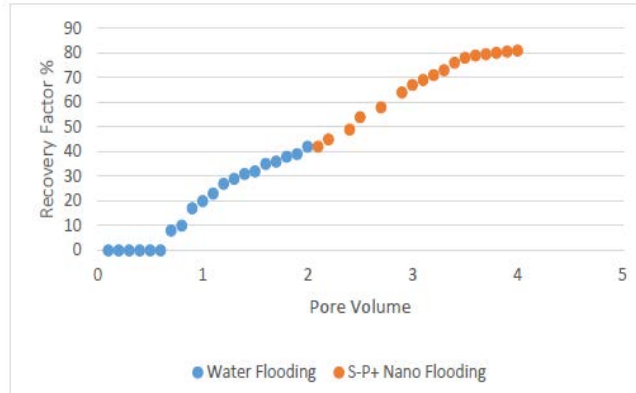
**Table 9:** Designing flooding experiment to evaluate the effect of temperature

Flooding experiment to evaluate effect of temperature (disregarding salt)	Flooding with polymer solution (2000ppm) and surfactant (1000ppm)	25 °C
		70 °C
		90 °C
	Flooding with polymer solution (2000ppm), surfactant (1000 ppm) and nanoparticles (0.3% of weight)	25 °C
		70 °C
		90 °C



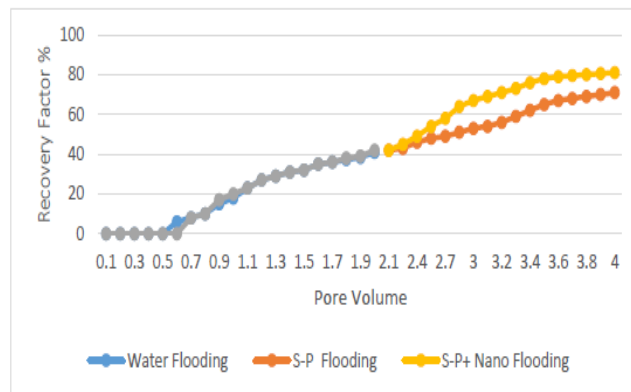
**Fig. 2:** Injection of water and surfactant- polymer solution at 25 °C without salinity.

As shown in figure (2), the oil starts producing with an appropriate gradient but after injection of about 1.5 PV, empty space of oil recovery factor did not change much and increased by 40% (section indicated in the Chart). Following injection of 2 PV, injecting solution of surfactant-polymer alone began and as expected, due to the effect on the level of surface tension and its reduction, as well as the fact that the polymer controls the mobility ratio, the oil production rate increased again by about 72%, after injecting about 3.6 PV.



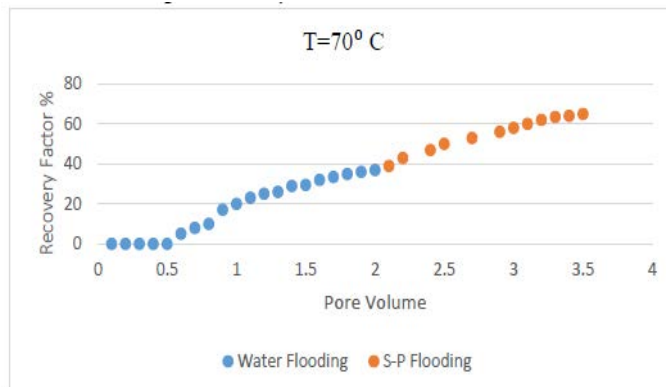
**Fig. 3:** injection of surfactant solution and polymer+ nanoparticles at 25 °C without salinity.

After maintaining all conditions including temperature at 20 ° C and zero salinity, the optimal concentration of nanoparticle (0.5%) was added into surfactant solution and polymer, and flooding is done. The final recovery factor was significant after the injection of 3.7% PV, and it increases by about 81% after reaching 10%.



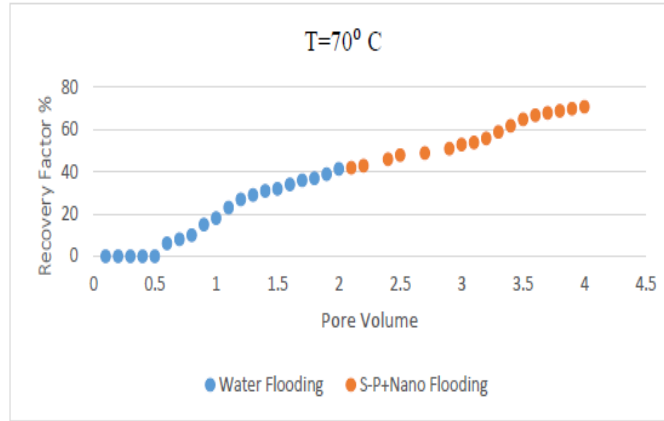
**Fig. 4:** comparison of oil production at 25 ° C and without salinity using injection of surfactant-polymer, nanoparticles and without nanoparticles.

Regarding figure 4, the line of surfactant injection data and nanoparticles is higher than the line of surfactant injection alone, indicating 10% increase of oil recovery factor by injection of nanoparticles in surfactant –polymer solution.



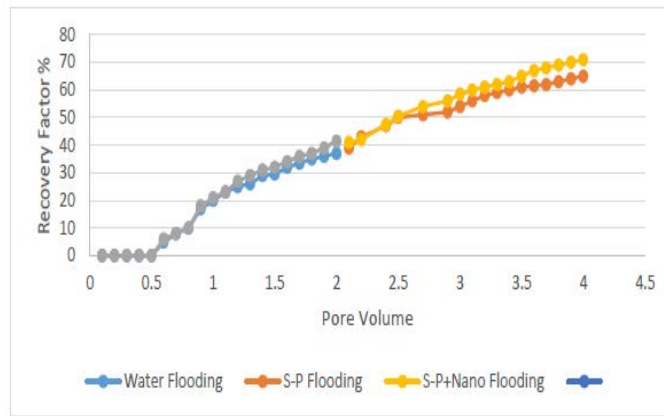
**Fig. 5:** flooding with polymer-surfactant solution at 70 ° C without salinity.

In this stage, the temperature condition of experiments was increased to 70 ° C, and oil recovery factor was obtained as 68.5%



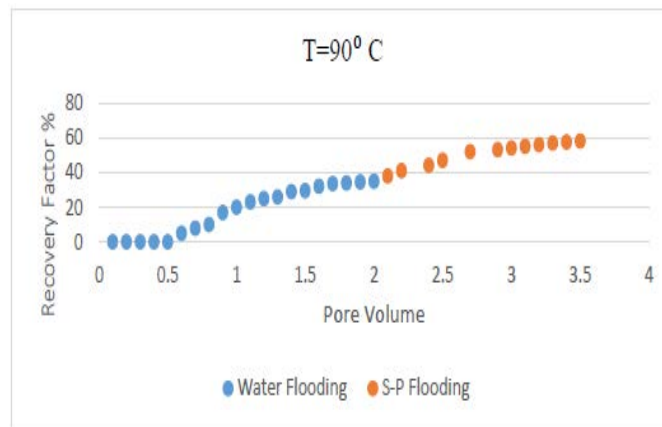
**Fig. 6:** Flooding with surfactant-polymer solution and nanoparticles at 70 ° C without salinity.

After injection of water as 2pv, the injection of the solution containing surfactant and the nanoparticles began and continued until 4 PV. The oil recovery factor increased by 73%.



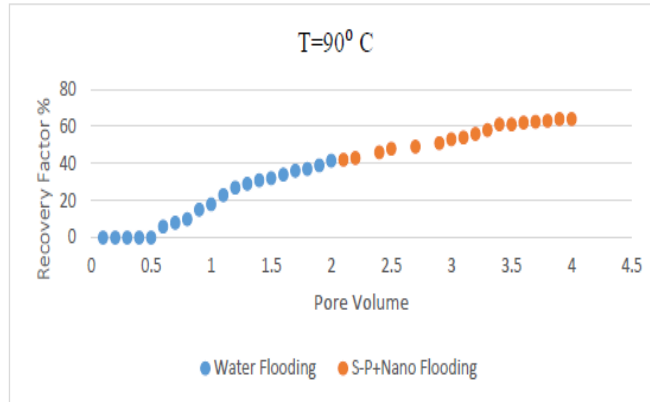
**Fig. 7:** comparison of oil production at 70 ° C and without salinity using the injection of surfactant-polymer, with and without nanoparticles.

As shown in figure 7, the effect of adding nanoparticles into the surfactant –polymer solution, results in 8% increase of oil recovery factors.



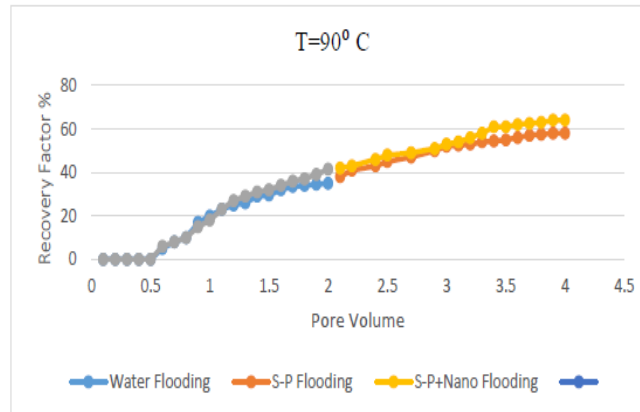
**Fig. 8:** flooding with surfactant –polymer solution at 90 ° C without salinity.

At this stage, the condition of temperature is changed and the temperature increased to 90 ° C. The oil recovery factor was obtained as 58%.



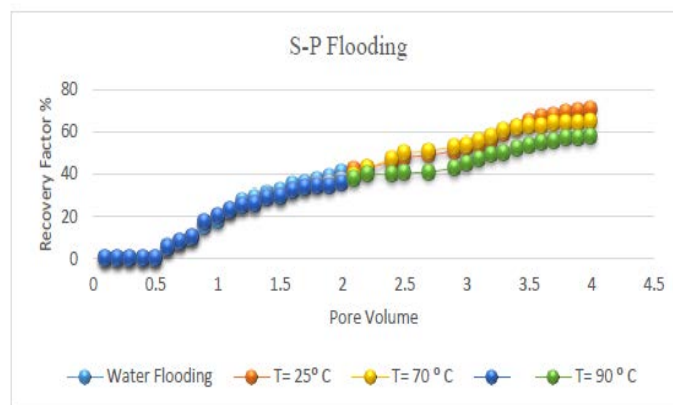
**Fig. 9:** flooding with surfactant –polymer solution and nanoparticles at 95 ° C without salinity.

In order to investigate the effect of increasing nanoparticles at 90 °C, flooding is carried out with the solution of surfactant-polymer together with nanoparticles. After injection of water as 2 PV, the injection of surfactant-polymer solution and nanoparticles begins and continues to 4 PV. Oil recovery factor increased by 64% (figure 9).



**Fig. 10:** comparison of oil production at 90 ° C and salinity of zero, using the injection of surfactant- polymer solution with and without nanoparticles.

To evaluate the results of flooding at this temperature, we draw the data in a graph (Fig. 10). The effect of adding nanoparticles to surfactant-polymer and the increase of 6% in the amount of oil recovery factor are observed.



**Fig. 11:** comparison of flooding with surfactant-polymer solution at 3 different temperatures.

As it can be observed in figure (11), with increasing temperature, the oil recovery factor decreases; the highest recovery factor (70%) at 25 ° C, and the lowest recovery factor (58 %) at 90 ° C are seen. The oil recovery factor is 65% at 70 ° C temperature. The results indicate the reduction of 6% in recovery factors by increasing the ambient temperature to 70 ° C and reducing the recovery factor by 13%, which is achieved by increasing the ambient temperature to 90 ° C.

**Table 10:** oil recovery factor at different temperatures and by flooding with the solution containing nanoparticles.

Injected fluid	T=25°C	T=70°C	T=90°C
Surfactant_Polymer	71%	65%	58%
Surfactant_Polymer+Nano	81%	73%	64%

As indicated in Table (10), the oil recovery factor decreases with increasing temperature, but the use of nanoparticles in flooding increases the recovery factor at all temperatures.

## Conclusion

1. Results showed that nanoparticles reduce surface tension, and optimal concentration of these nanoparticles was 0.3. Moreover, the concentration more than this amount in nanoparticle and polymer-surfactant suspension leads to the increase of surface tension.
2. The results of flooding experiments show that the amount of oil produced in flooding with polymer-surfactant solution of 2 PV decreased by 13% through increasing temperature from 25 ° C to 90 ° C.
3. The results of flooding in the Sarvak oil reservoir show that the amount of oil produced in flooding of 2 PV with the suspension, prepared by dispersion of polyacrylamide-surfactant and nanoparticles in distilled water, reduced by 8% by increasing temperature from 25 ° C to 90 ° C.
4. Results of flooding with nanoparticle suspension at 25 ° C show 10% increase in oil production relative to flooding with polyacrylamide-surfactant at the same temperature. 5) The results of flooding with nanoparticles suspension at 70 ° C show 8% increase in oil production compared to the flooding with polyacrylamide-surfactant at the same temperature. 6) The results of flooding with nanoparticle suspension at 90 ° C show 6% increase in oil production compared to flooding with polyacrylamide-surfactant at the same temperature.

## References

- B. Ju and T. Fan 2008, \Experimental Study and Mathematical Model of Nanoparticle Transport in Porous Media," Powder Technology, Accepted 22 December 2008.
- Berglund, L.A," Rheology of polymer nanocomposites – are there unique effects for exploitation? ", Annual Transacation of the Nordic Rheology Society, 14, 2006.
- J. Dickson, K. Johnston, and B. Binks 2004, \Stabilization of Carbon Dioxide in Water Emulsions with Silica Nanoparticles," Langmuir The Acs Journal Of Surfaces And Colloids, August 14 2004.
- L. Zang, J. Yyan, H. Liang, and K. Le 2008, \Energy From Abandoned Oil and Gas Reserves," SPE Asia Pacic Oil and Gas Conference and Exhibition,Perth, Australia, 20-22 October 2008.
- M. O. Onyekonwu and N. A. Ogolo 2010, \Investigating the Use of Nano-particles in Enhancing Oil Recovery," Nigeria Annual International Confer-ence and Exhibition, Tinapa - Calabar, Nigeria, 31 July - 7 August 2010.
- M. Y. Kanj, Z. AlYousif, and J. Funk 2009, \Nanoid Coreood Experi-ment in the ARAB-D," SPE Saudi Arabia Section Technical Symposium andExhibition, Aikhobar, Saudi Arabia, 9-11 May 2009.
- N. Le, D. K. Pham, K. H. Le, and P. T. Nguyen 2011, \Design and Screening of Synergistic Blends of SiO2 Nanoparticles and Surfactants for Enhanced Oil Recovery in High-Temperature Reservoirs," Advances in Natural Sciences: Nanoscience and Nanotechnology 2, Published 21 July 2011.
- N. Ogolo, O. Olafuyi, and M. Onyekonwu 2012, \Enhanced Oil Recovery Using Nanoparticles," SPE Saudi ARabia Section Technical Symposium and Exhibition, Al-Khobar, Saudi Arabia, 8-11 April 2012.
- Ogolo, N.A., Olafuyi, O.A and Onyekonwu, M.O, " Enhanced Oil Recovery Using Nanoparticles", SPE 160847, presented for presentation at the SPE Saudi Arabia Technical Symposiom and Exhibition held in Al-khobar, Saudi Arabia April 8-11 , 2012.
- P. Pourafshary, S. Azimipour, P. Motamedi, M. Samet, S. Taheri, H. Bargozin, and S. Hendi 2009, \Prior Assessment of Investment in Development of Nan-otechnology in Upstream Petroleum Industry," SPE Saudi Arabia Section Technical Symposium, AlKhobar, Saudi Arabia, 9-11 May 2009.
- R. D. Shah 2009, \Application of Nanoparticle Saturated Injectant Gases for EOR of Heavy Oil," SPE Annual Technical Conference and Exhibition, New Orleans, Louisiana, USA, 4-7 October 2009. 17
- S. Mokhatab, M. A. Fresky, and M. R. Islam 2006, \Application of Nanotechnology in Oil and Gas E&P," JPT, Society of Petroleum Engineers, April 2006.

- S. S. Adkins, D. Gohil, J. L. Dickson, S. E. Webber, and K. P. Johnston 2007, "Water-in-Carbon Dioxide Emulsion Stabilized by Hydrophobic Silica Particles," *Physical Chemistry Chemical Physics* Issue 48, November 8 2007.
- Shahrabadi, A., Bagherzadeh H., Roustaei A and Golghanddashti H, " Experimental Investigation of HLP Nanofluid Potential of Enhance Oil Recovery: A Mechanistic Approach", SPE 156642, presented for presentation at the SPE International Oilfield Nanotechnology Conference held Noordwilk, The Netherlands, June 12-14 2012.
- T. Skauge, K. Spildo, and A. Skauge 2010, "Nano-sized Particles For EOR," SPE Improved Oil Recovery Symposium, Tulsa, Oklahoma, USA, 24-28 April 2010.
- T. Zhang, A. Davidson, S. L. Bryant, and C. Huh 2010, "Nanoparticle- Stabilized Emulsions for Application in Enhanced Oil Recovery," SPE Improved Oil Recovery Symposium, Tulsa, Oklahoma, USA, 24-28 April 2010.
- X. Kong and M. M. Ohadi 2010, "Application of Micro and NanoTechnologies in the Oil and Gas Industry- An Overview of the Re-cent Progress," Abu Dhabi International Petroleum Exhibition & Conference, 1-4 November 2010. iii, vii, 16, 18