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APPLICATION OF ACRYLAMIDE POLYMER GRAFTED WITH SiO_2 NANOPARTICLES IN ENHANCED OIL RECOVERY- DESIGN PROJECT

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Abstract

The recovery of oil passes through several stages, which are primary, secondary and tertiary recoveries. At initial conditions, the production of hydrocarbons is carried out from the natural forces of the reservoir. However, after a specific period of time of production, the natural pressures available become insufficient in applying the required reinforcements in pushing the oil into the surface. Accordingly, there are multiple methods that help in pushing the oil into the surface facilities including the polymer injection. This is until the field of nanotechnology stepped foot in the industrial field, especially the petroleum industry. Nanotechnology, in general, helped in making the production process easier by enhancing properties of the fluids and rocks, such as wettability, interfacial tension, and viscosity. The objective of this research project is to have a deeper understanding of how the recovery of oil can be enhanced by using nanotechnology. Moreover, the polymer that is used is the polyacrylamide, and the nanoparticles that are used are the silica nanoparticles. The experimental work has 2 stages, which are the rheology stage and the flooding stage. The rheology stage involves the process of measuring how the viscosity of the acrylamide polymer increases when it is grafted with the silica nanoparticles, which is an advantage since an increase in the viscosity of the polymer means that the sweeping efficiency is going to improve. The viscosity was measured by using the 800 model 8-speed viscometer, and 4 concentrations of 250 ppm, 500 ppm, 1000 ppm, and 2000 ppm were used. The core flooding stage was carried out using the core flood system that was constructed in the core analysis lab for the research work and for the future work of future students in the petroleum engineering department. The experimental work indicates that 200 ppm of polyacrylamide and silica nanoparticles is the optimum concentration for the best recovery of oil.

Keywords: *Polyacrylamides; SiO_2 Nanoparticles; Enhanced Oil Recovery; and Flooding displacement.*

1. Introduction

The demand for energy is increasing at a greater rate annually due to the observable increase in the global population and due to industrial reasons [1]. These facts resulted in various problems such as energy that is not sufficient to put up with the increasing demand. It was also mentioned by different international energy organizations that the energy shortage will increase by 50% every decade. In order to minimize the impact of such issue, several scientific types of research were carried out in different parts of the world to come up with several methods to increase the energy produced and keep up with the global energy demand [2]. Concerning the oil industry, most of the heavy crude oil is produced from the reservoirs by enhanced oil recovery techniques. However, the oil production process highly depends on 2 important factors, which are the economic and technical considerations [3]. Those 2 factors also depend on different factors such as lithology, reservoir rock types and fluid properties such as viscosity, mobility. The moment these factors are managed well, the technical and economic efficiencies will increase, thus, increasing the hydrocarbon recovery. In order to enhance the properties of the rocks and the fluids in the target reservoir, it was discovered that nanotechnology could play a vital role in achieving that. In other words, different Nano particles can lead to positive changes to the hydrocarbons such as reducing the viscosity, which leads to the increasing of the displacement efficiency, thus, enhancing the hydrocarbon recovery. Nanoparticles are also involved in changing other properties such as the wettability and the interfacial tension. Furthermore, the nanoparticles to be used should be suitable for the types of rocks or fluids. That is why different experiments are carried out using different apparatus such as the sand pack or the core flood system and using different concentrations of nanoparticles. This is in order to identify the right nanoparticles and the right concentration to be used for different types of hydrocarbons.

1.2. Objective

The main objective of this research paper is to shed light on the impact of using nanoparticles on oil recovery. This is done by the process of Nano flooding that is carried out by using several samples of nanoparticles that are injected into several core samples by using the core flooding system that was constructed in the core analysis laboratory at the British University in Egypt. The experiment is carried out in order to know how the viscosity, interfacial tension, and the wettability change when those nanoparticles are injected. By doing that experiment, it will be known what the best nanoparticle is to be used for a specific lithology and hydrocarbon. Moreover, having sufficient information regarding the right nanoparticles to be used and its concentration will definitely lead to increasing the recovery factor, and consequently the hydrocarbon recovery.

1.3. Problem statement

The main problem that should be taken into account is the energy demand that keeps increasing year after year and the insufficient amount of energy that is present to keep up with it. The shortage of energy that the world suffers from can lead to catastrophic consequences in the future, such as the closing of factories, reduction in the working force due to reduced industrial performance, and other global crises that can hinder the progress of the nations. The main problem in the oil industry, in general, is trying to maintain an economic balance with hydrocarbon production. That is why the concept of the economic limit was invented. This concept was made in order to know the point where if the hydrocarbon production continued, the net cash flow would give a negative value, which indicates that the expenses of producing the hydrocarbons are higher than the revenues gained from the hydrocarbons produced [4]. Moreover, the expenses of producing the hydrocarbons come from different sources including fluid properties such as high viscosity that can make the production process a lot harder. Furthermore, the world has to put more effort into coming up with different ways of producing energy in a time and cost-efficient manner and to prevent the occurrence of any further global crisis.

1.4. Methodology

In the experiment, several nanoparticle samples were investigated using the core flooding system that is constructed in the core analysis lab. This system that is built is used in determining which nanoparticle is compatible with each type of hydrocarbon. Moreover, different core samples are chosen in order to carry out the experiment. The nanoparticles are firstly put inside the crude oil then the physical parameters such as the wettability, viscosity, and interfacial tension are checked. These parameters should change in a way that helps in increasing the displacement efficiency, thus, enhancing the oil recovery. Furthermore, there are several steps that will be carried out in the experiment, such as putting the core samples inside the core holder and other steps that will be carried out using different parts of the core flood system that will be explained later in the research project in details.

2. Literature review

2.1. Overview

Due to the increasing demand for oil globally, petroleum companies tend to make huge efforts in increasing the productivity of oil and gas in a time and cost-efficient manner. Accordingly, different recovery methods are used in hydrocarbon production while maintaining a technical and economical balance [5]. As the technology got more advanced starting the 20th century, nanotechnology as a science started to be used in the recovery methods in order to improve the performance and take the hydrocarbon productivity into a new level of economic and technical efficiency. The oil recovery methods are classified into primary, secondary and tertiary recoveries and these methods depend on several factors such as the hydrocarbon nature present in the pay zone and hydrocarbon quantity to be produced. Fig. 1 gives a description of the 3 recovery stages:

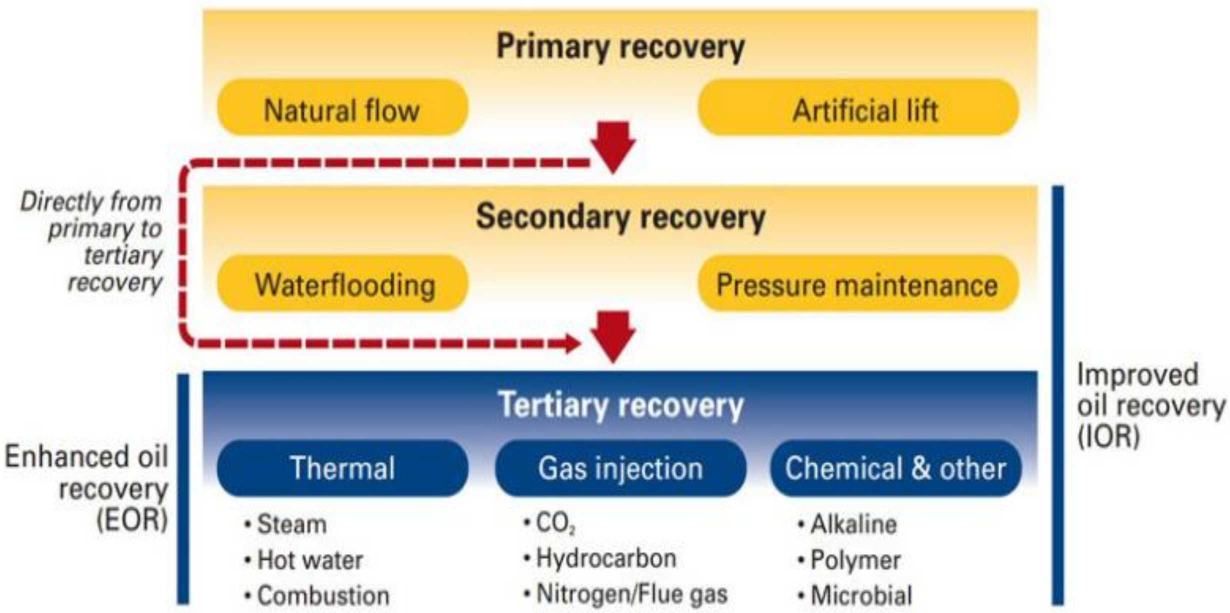

Fig. 1. The three oil recovery stages

All these recovery methods have their periods of time, depending on the reservoir pressures and the optimum time where the next recovery method is used as Fig. 2.

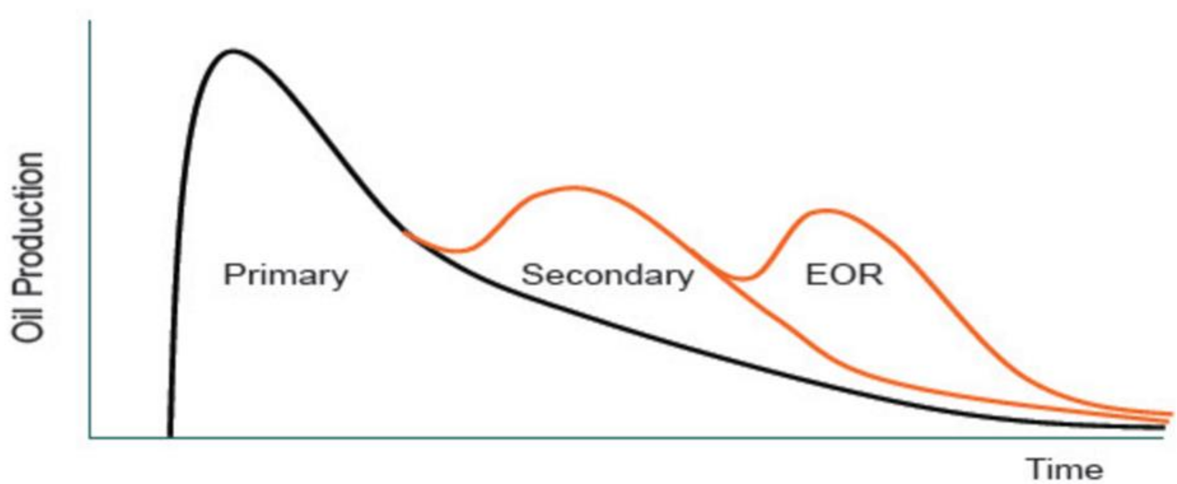

Fig. 2. The oil recovery methods performance vs. time

2.2. Oil recovery methods

2.2.1. Primary recovery

Primary recovery is the process where the hydrocarbon is produced from the reservoir by the natural forces existing and such forces depend on the reservoir's driving mechanism. The primary recovery mechanisms are classified into rock and fluid expansion drive, depletion drive, gas cap drive, water drive, combination drive, and gravity drainage drive mechanisms. These drive mechanisms differ due to several factors present in the reservoir such as the presence of gas cap and the properties of the rocks and fluids present. Artificial lift is also used in the primary recovery to maintain the pressure of the reservoir without any external force [6].

2.2.1.1. Depletion drive reservoir

Depletion (solution gas) drive reservoirs are the types of reservoirs where their internal forces that are providing energy for the production of oil are from the expansion of the gas dissolved inside the oil [7]. At initial conditions, the reservoir is undersaturated in which the reservoir pressure is greater than the bubble point pressure where no gas is released yet. As the reservoir keeps producing oil, the reservoir pressure keeps decreasing until the bubble point pressure is reached where the dissolved gas starts to get released. When the reservoir pressure is less than the bubble point pressure, this is where the reservoir is called a saturated reservoir. The average oil recovered in this drive mechanism ranges from 10% to 20% of the OOIP.

2.2.1.2. Water drive reservoir

Water drive reservoirs receive their natural force from the water aquifer below the reservoir. The water aquifer present is either a bottom aquifer or an edged aquifer. In this reservoir drive, the oil is produced from the expansion of the water aquifer which displaces the produced oil. The amount of oil recovered from water drive reservoirs ranges from 30% to 40% [5].

2.2.1.3. Gas cap drive reservoir

The reservoirs that produce the oil due to the expansion from the gas cap above the oil [8]. It is known that the gas cap reservoir pressure decline is slower than the pressure declines of the depletion (solution gas) drive reservoir. The average oil recovery ranges from 20% to 30%.

2.2.1.4. Combination drive reservoir

Combination drive reservoirs can contain both a gas cap above the oil zone and a water aquifer below the oil zone [9]. The average oil recovery of such drive mechanism is higher than the oil recovery of the depletion drive reservoirs and has a lower average oil recovery than the gas cap reservoirs and water drive reservoirs. Usually, the average recovery of the combination drive highly depends on the sizes of the gas cap and water aquifers present.

2.2.1.5 Gravity drainage drive reservoir

The production of oil in the gravity drainage reservoirs is due to the fluid density difference in the reservoirs. This will lead to a large gravitational force. The recovery of the oil in this drive mechanism can exceed 50% of the OOIP. This is if the reservoir itself has a high dip angle or steeply dipping and has a relatively high vertical permeability [10].

2.2.1.6 Artificial lift

This primary recovery method is used when the reservoir pressure is not strong enough to produce the oil to the surface. Accordingly, a pump is equipped down into the well to be able to pump the oil up to the surface [11]. There are various types of artificial lift systems such as the sucker rod pump, electrical submersible pump, gas lift, plunger lift, jet hydraulic pumping systems, and the progressive cavity pumps.

2.2.2 Secondary recovery

After some oil production, the natural forces present in the reservoir starts to decrease. Accordingly, this is the time when secondary recovery is used to compensate for the loss in the natural forces [12]. Secondary recovery helps in continuing oil production by external forces by using several methods. The 2 common methods in secondary recovery are the gas injection and water flooding. Those methods help in increasing the oil recovery by 15% of the initial oil in place [13-15].

2.2.2.1 Gas injection

Gas injection is a well-known pressure maintenance program in which the reservoir pressure is enhanced when the gas is injected, which helps in sweeping the oil present efficiently, boosting the production process. Moreover, the gas should be injected into the gas cap to provide more gas pressure that pushes the oil more. That is why having a gas cap is very crucial if the gas injection will be used [16].

2.2.2.2 Waterflooding

Water flooding is used in the process of maintaining the pressure of the reservoir by injecting water into the reservoir from injection wells. This method tries to restore the initial pressure of the reservoir as much as possible. Water flooding is highly important in the production process since it is used in displacing the hydrocarbons to the producing wells and the permeability of the formation is one of the factors that controls the injection pressure. Water flooding passes through several stages which are starting of the flood, the fill-up stage, breakthrough stage, and the stage after the breakthrough [17].

2.2.3 Tertiary recovery

The tertiary recovery method is used when the first 2 stages of the oil recovery do their jobs in producing their average oil recovery. The tertiary recovery is also known as the enhanced oil recovery where the oil recovery is increased at a range of 60% to 80% of the initial oil in place while maintaining the economic balance. Furthermore, the enhanced oil recovery techniques tend to enhance various factors such as the injection fluid properties and the reservoir rock and fluid properties in order to increase the recovery factor, thus, maximizing the economic efficiency and the productivity and improving the overall performance.

In addition, it is explained that the EOR method is different from the primary and secondary recovery regarding the average recovery and the way oil is produced, like the natural forces used in the primary recovery, external forces for the secondary and finally the enhanced oil recovery method which mainly focuses on positively altering different properties down into the formation to ensure maximum efficiency and a satisfyingly high hydrocarbon recovery. The improved oil recovery (IOR) is a terminology that is used both on the secondary recovery and the tertiary recovery. The Fig. 3 explains how the EOR process affects oil production by producing an incremental amount of oil.

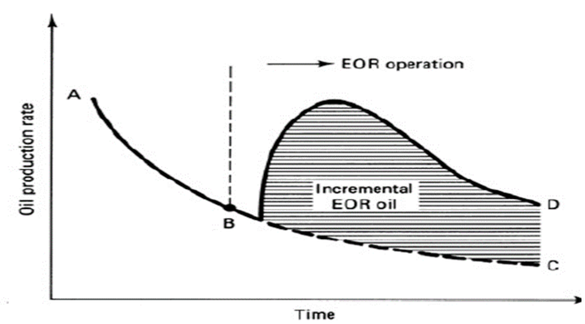

Fig. 3. The incremental oil produced from the EOR process

2.2.3.1 CO_2 injection

When carbon dioxide is injected into the reservoirs, a lot of positive outcomes will occur such as the swelling of oil that will make the oil change from the discontinuous phase to the continuous phase [18]. In addition to that, carbon dioxide can reduce the viscosity of the oil due to the fact that it can dissolve in the oil. This will increase the mobility ratio, thus, increasing the sweep efficiency. Moreover, carbon dioxide can have a chemical advantage since it can react with carbonate rocks, dissolving them and leading to an enhanced permeability. Another chemical advantage is the fact that the carbonic acid produced from the reaction of the carbon dioxide with the carbonate rocks tends to reduce the PH of the shale available. This will reduce the probability of swelling of the shale, therefore, the probability of shale blocking will also decrease.

2.2.3.2 Microbial enhanced oil recovery (MEOR)

This method involves the process of injecting bacteria into the reservoir. Due to the very small size of these bacteria, they can penetrate pores available in the rock. This penetration is required since many positive alterations take place [19]. This is due to the fact that the bacteria injected lead to the production of various gases hydrogen and carbon dioxide that do many property changes to the oil down at the reservoir such as viscosity reduction, oil swell increasing, changing the reservoir from the discontinuous to the continuous phase, increasing the sweep efficiency, decreasing the amount of the residual oil and other features that will definitely enhance the oil recovery. As for the properties of the formation itself, the bacteria injection helps the reservoir to produce acids that help in improving the formation features such as the effective permeability and the effective porosity. These formation features will obviously make the fluid flow easier and more efficient, thus, saving time and money and meeting the required specifications.

2.2.3.3 Thermal recovery (steam injection)

Thermal recovery involves the process of steam injection into the reservoir in order to produce thermal energy down there. This method is used for shallow reservoirs that contain oil with a very high viscosity. Moreover, steam injection as a thermal recovery method is considered a very popular method since it accounts for more than half of the total enhanced oil recovery market. Furthermore, steam injection is done in order to alter the characteristics of the oil in the reservoir such as reducing the viscosity of the oil, increasing the mobility ratio, increasing the relative permeability ratio, reducing surface tension and also generating the process of oil thermal cracking [20]. In addition to that, this thermal recovery method is also responsible for partially restoring the initial conditions of the reservoir since the steam injected can activate the depletion drive increasing the reservoir pressure. It is also known that using steam injection recovery method is an environmentally friendly process.

2.3. Application of nanotechnology

Nanotechnology is the science that deals with particles having a nanoscale; usually varying in size from 1 to 100 nanometers. The concept of the nanometer scale has spread widely ever since the Nobel prize was won by Richard Zsigmondy for introducing that scale after measuring the gold colloid particles under the microscope. Moreover, the term "Nano-technology" developed in 1974 by Norio Taniguchi [21]. At the time, Nano-technology was discussed in different scientific conferences and organizations to understand how the concept of nanoparticles can be used to evolve all the technological world. When it comes to the oil industry, the nanoparticles used can alter some of the properties of the reservoir fluids that can improve production performance. In other words, the injection of nanofluids into the formation get involved in a chemical mechanism that alters the physical properties of the rocks and fluids in the target reservoir such as the wettability, mobility. Ogolo *et al.* [22] made an experimental elaboration of how the oil recovery is enhanced using different nanoparticle samples that range in size from 20 nanometers to 100 nanometers. These particles include aluminum oxide, magnesium oxide, iron oxide, and zinc oxide. Firstly, fluids without nanoparticles are injected into core samples and then the displacement efficiency is calculated by using the following equation

$$ED = \frac{\overline{Sw} - Swi}{1 - Swi} * 100\% \quad (1)$$

After calculating the displacement efficiency, it should be calculated again while the nanoparticles are present within the fluids injected into the core samples then the 2 displacement efficiencies are subtracted to each other to identify the difference. If the difference gives a positive value, then there is a monitored increase in the displacement efficiency, if otherwise, then the efficiency decreased which is a very undesirable case. It was concluded that magnesium oxide and zinc oxide lead to permeability problems to the core samples, and aluminum oxide had a very good tendency for improving the oil recovery.

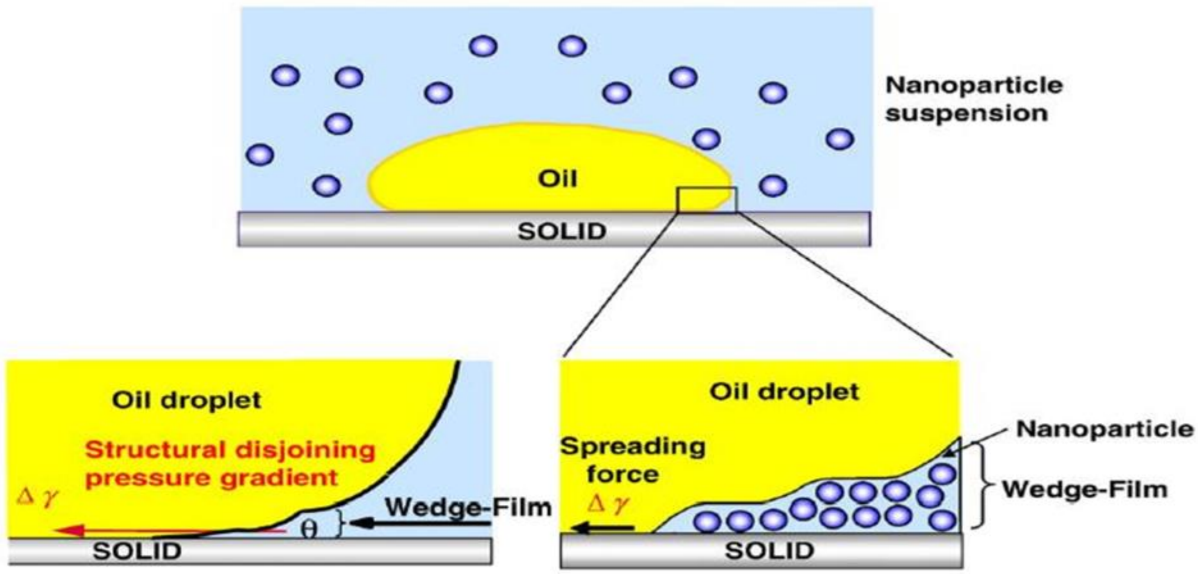

Fig. 4. Disjoining pressure caused by the nanoparticles

It was discussed in an article by Chegenizadeh *et al.* [23] that different types of nanoparticles contribute in performing different jobs that eventually enhance the oil recovery. Aluminum oxide, copper (II) oxide, iron oxide, and nickel oxide are responsible for reducing the viscosity. Moreover, tin oxide, silicon oxide and nanoparticles coated with polymer are used in alerting the wettability of the cores by making them more water-wet thus making it easier to produce oil. Increasing the sweep and displacement efficiencies are also jobs carried out by polymer-coated nanoparticles to make the water injection procedures more effective in sweeping a relatively large portion of the hydrocarbons present in the pay zone. However, it was also mentioned in the article that the application of nanotechnology may come with potential health drawbacks. For example, it was recently argued that there might be a relationship between using nanoparticles and lung diseases and other health problems linked with the DNA and chromosomes. Nevertheless, such claims aren't ensured yet and medical researchers are continuing to have a deeper understanding of how effective such technology is on human health. Lezorgia [24] discussed in his research the application of correlations like the known wettability fundamentals such as Young's equation, Wenzel model and the Cassie-Baxter Models. Firstly, Young saw the proportionality between the surface tension and the contact angle in 1805. It was observed by him that the liquid that is contacted with the solid surface ends up making 3 interfacial tensions. Accordingly, the wettability can be identified through the correlation shown below:

$$\sigma sg = \sigma sl + \sigma lg \cos\theta \quad (2)$$

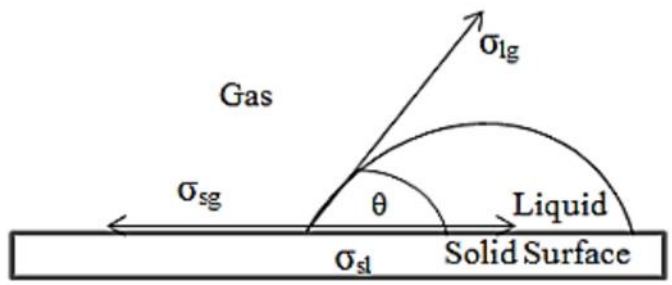

Fig. 5. 3-phase contact explanation from young's equation

Moreover, the Wenzel model focuses on measuring the homogeneity of the surface wetting. This model is known for putting the rough surface chemical homogeneity into account, unlike the Cassie-Baxter model. Thus, a correlation is made indicating how much the contact angle is affected by the surface roughness as shown in the equation below:

$$\cos\theta = r \cos\theta Y \quad (3)$$

As for the Cassie-Baxter model, it focuses on the chemical heterogeneity relative to flat surfaces. One of the limitations of the Wenzel model is that it focuses mainly on homogeneous surfaces. Accordingly, a more complicated model is required in order to detect the change in the contact angle during the involvement of different materials. The correlation made by Cassie and Baxter is shown and the graphical explanation is shown in the Figure 6:

$$\cos\theta = r_f f \cos(\theta_Y) + f - 1 \quad (4)$$

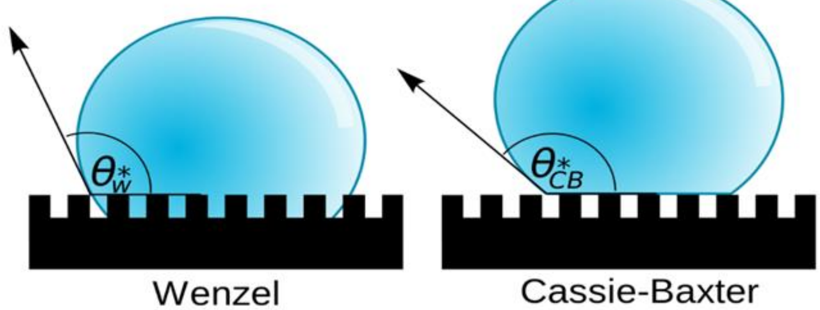

Fig. 6. The difference between the Wenzel and the Cassie-Baxter models

All those correlations are used in monitoring the wettability alteration as the nanoparticle samples are injected within the core samples tested. This shows how oil recovery changes after the nanoparticle injection process. Kumar *et al.* [25] explained that the 31 API oil recovery witnesses a significant improvement from the addition of nanoparticles by showing that experimentally. In their paper, the equipment used in their experiments were mentioned such as the reservoir permeability tester which is the equipment used in monitoring the permeability changes in the core samples after adding the nanoparticles and used as a core flooding system. Moreover, the Soxhlet extractor which is used in the oil and water removal from the core samples tested to make them return to their original state to calculate more properties needed. The manual extractor was also used whereas it is needed in the process of drying the core samples which is done by different parts in the equipment such as the pressure cell, the pressure pump, the liquid tank, the moisture trap, and the vacuum pump. Other equipment was also used such as the glass capillary viscometer and the desiccator. The experimental procedures were carried out such as cleaning of the core samples tested, preparing the brine water, determining the core properties such as the porosity and permeability, and finally prepare the nanoparticles to be used. Graphical interpretations were made showing the change in the oil recovery with and without nanoparticles after the addition of nanoparticles. The numerical parameters were also recorded showing how there is a decrease in the oil viscosity and an increase in the sweeping efficiency of the waterflood, thus, enhancing the oil recovery. Advanced microscopes were used in order to show a clear magnification of the insides of the core after the process of Nano flooding.

3. Experimental work

3.1. Overview

It was mentioned previously that the main objective of this research project is to shed light on the significance of nanotechnology in the enhanced oil recovery stage. Moreover, silica nanoparticles would be used in polyacrylamide to test its effect on it regarding the viscosity and the oil recovery. The main priority of using nanoparticles is to help in improving the fluid properties of the crude oil in order to make the production process easier and enjoy technical and economic efficiency. The experimental work would be classified into 2 stages. The first stage would be the rheology stage which was carried out in the drilling fluid laboratory in the BUE using the viscometer. The viscometer is designed in order to determine the viscosity of the solution by identifying the shear stresses under different shear rate rpm. The addition of the silica nanoparticles would show a change in the viscosity of the polyacrylamide. The second stage of the experimental work is the flooding stage. First of all, a core flood system was constructed by me and 2 of my colleagues and was put in the core analysis laboratory in the BUE for project use and for later use by future students. This core flood system is mainly designed to make the flooding procedure easier and its results contain fewer errors than the sand pack model. Several core samples were used in the experimental work where some of these cores were flooded with polyacrylamide on its own and the others were flooded using the polyacrylamide that is grafted with the silica nanoparticles. This is done in order to investigate the effect of the nanoparticles on the recovery of the oil inside the core samples. The main objective of experimental work is to understand the concept behind the theoretical understanding of the project and see how the nanoparticles used to affect the recovery factor and the overall performance of the production process. Accordingly, the experimental work is divided into 2 stages; rheology and core flooding. These are done to see how silica nanoparticles alter the physical properties of the polyacrylamide, thus, improving the recovery of oil.

3.2. First stage: rheology

3.2.1. Methodology

This stage involves the process of understanding how the nanoparticles affect the viscosity of the polyacrylamide at different concentrations and at different temperatures. Moreover, such a process requires several procedures that must be followed in order to attain the required results. The entire rheology process was made using the model 800 8-speed electronic oil field viscometer which designed and manufactured by OFI Testing Equipment, Inc.

3.2.1.1 Brine preparation

The first procedure to be done is to prepare the brine solution that will be used throughout the experiment. First of all, sodium chloride salt is added to 200 ml of distilled water having a concentration of 40,000 ppm (40 g/L). Moreover, this brine solution is the sample where the polymer samples would be used. In more details, this brine solution would be prepared several times but with several concentrations of polymer alone and the same concentrations with the polymer grafted with the silica nanoparticles. The salt and the polymer are mixed with the distilled water through the INTTLAB magnetic stirrer. It is very important to know that the polymer added to the brine solution should be added slowly through a period of time in order to prevent polymer problems that can negatively affect the entire solution.

It is very important to know that the polymer added to the brine solution should be added slowly through a period of time in order to prevent polymer problems that can negatively affect the entire solution.

3.2.1.2 Rheological measurements by Viscometer

Rheological properties of the solutions conducted by viscometer. The procedures are repeated several times at different temperatures and different concentrations of the polymers. Rheological procedures are extremely crucial in order to understand the behavior of polymers when grafted with the nanoparticles. The best scenario would be that the nanoparticles would help in increasing the viscosity of the polymer. This is in order to maximize the sweep efficiency, thus, increasing the oil recovery.

3.3. Results of rheology

After carrying out the rheological procedures, the graphical plots were drawn to understand the viscosity alteration that occurred in the polyacrylamide after being grafted with the silica nanoparticles. The data involves rheology of the acrylamide polymer alone and the acrylamide polymer grafted with the silica nanoparticles at different concentrations and at different temperatures as shown in the Tables 1 and 2.

Case (1): A concentration of 250 ppm and at room temperature (25°C)

Case (2): A concentration of 250 ppm and at a temperature of 50°C

Case (3): A concentration of 500 ppm and at room temperature

Case (4): A concentration of 500 ppm and at a temperature of 50°C

Case (5): A concentration of 1000 ppm and at room temperature

Case (6): A concentration of 1000 ppm and at a temperature of 50°C

Case (7): A concentration of 2000 ppm and at room temperature

Case (8): A concentration of 2000 ppm and at a temperature of 50°C

Table 1. Shear rate vs shear stress for polyacrylamide for cases 1-8

Speed (rpm)	Shear rate (1/sec)	Shear stress Case 1	Shear stress Case 2	Shear stress Case 3	Shear stress Case 4	Shear stress Case 5	Shear stress Case 6	Shear stress Case 7	Shear stress Case 8
3	5.1	0.5	0.5	1	0.5	1	0.5	1	0.5
6	10.2	0.5	0.5	1	1	1.5	1	1.5	1
30	51	1	1	1.25	1	2	1	1.5	1
60	102	1.5	1	1.5	1.25	2.5	1.5	3	1.5
100	170	2	1.25	2	1.5	3	2	4.5	2
200	340	2.5	2	2.5	2	5.5	3.5	6	4.5
300	510	3	2	3.5	2.5	7	4.5	8	5.5
600	1020	3.5	2.5	5	4	9	7	12	8.5

Table 2. Shear rate vs shear stress for polyacrylamide grafted with silica nanoparticles for cases 1-8

Speed (rpm)	Shear rate (1/sec)	Shear stress Case 1	Shear stress Case 2	Shear stress Case 3	Shear stress Case 4	Shear stress Case 5	Shear stress Case 6	Shear stress Case 7	Shear stress Case 8
3	5.1	1	0.5	1	0.5	1	1	2.5	1
6	10.2	1.25	1	1.5	1.25	2	1.5	3	1.5
30	51	1.5	1	1.5	1.5	3	2	3.5	2
60	102	2	1.25	2	1.5	3.5	2.5	5	3
100	170	2.5	1.5	2.5	2	5	3	7	5
200	340	3	2.5	3.5	2.5	7	5.5	9	7
300	510	3.5	3	5	3	9.5	7	14	9
600	1020	5	3.5	9	6	13	9	17	13

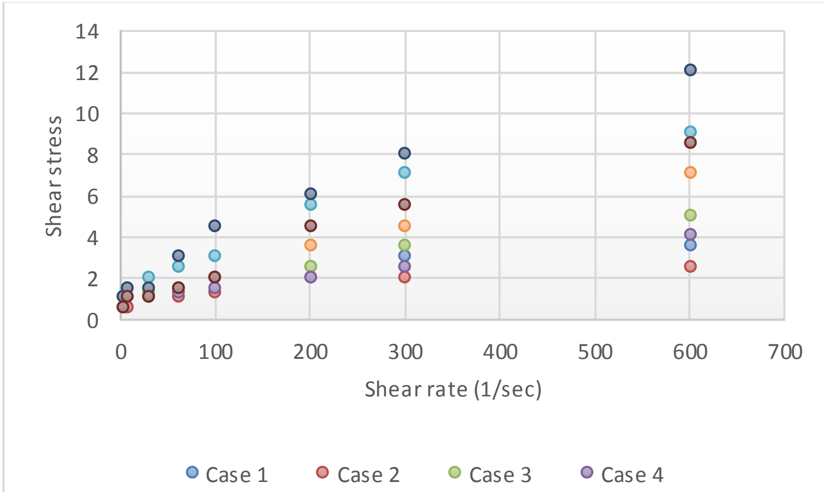

Figure 7. Comparison shear rate vs shear stress for polyacrylamide for cases 1-8

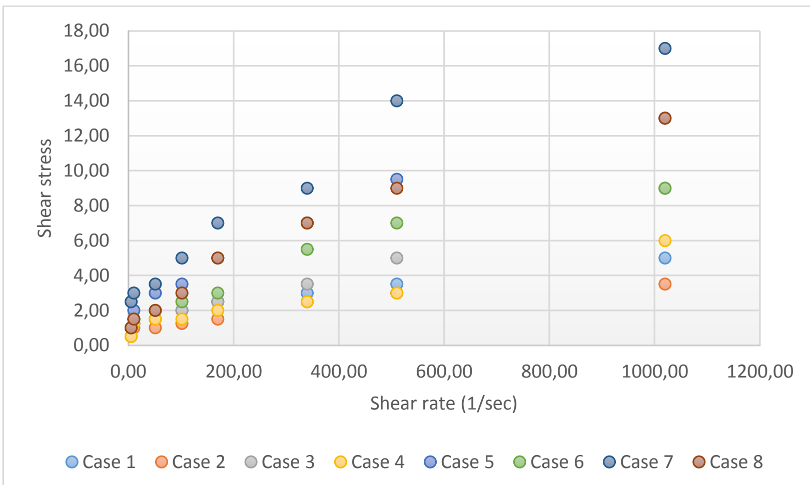

Figure 8. Comparison shear rate vs shear stress for polyacrylamide grafted with silica nanoparticles for cases 1-8

3.4. Discussion of rheology

The Figures 7-8 plotted indicates that silica nanoparticles play a major part when it comes to increasing the viscosity of the polyacrylamide. This is an advantage since such polymer grafted with the nanoparticles means that when injected into the reservoir, the sweep efficiency would be higher in value than using the polymer without the nanoparticles. Moreover, it was also shown that the polymer grafted with the silica nanoparticles show a resistance to viscosity reduction in higher temperatures which is a good indicator in real-life situations since the pay zone usually exist thousands of feet below the surface and such place has very harsh conditions such as the existence of extremely high temperatures. Accordingly, the nanoparticles are used to make the polymer used in the flooding process less resistant to the viscosity reducing temperatures. In more details, the nanoparticles increased the viscosity of the polyacrylamide by a known mechanism which is called irreversible bridging. This mechanism involves the process of the adsorption of the polyacrylamide on the surface of the silica nanoparticles. As for the motion of the polymer grafted with the nanoparticles, it was shown that its behavior is non-Newtonian and shear thinning. Such shear thinning behavior exists since the polymer and the nanoparticles exhibit a strong interaction in the water. Furthermore, such strong interaction is present due to the hydrogen bonds in the water.

4. Second stage: flooding

4.1. Methodology

After carrying out the rheology procedures, the flooding process is started. In order to investigate the impact of the nanoparticles on the oil recovery, the flooding is done by using the polyacrylamide alone and done also by the polyacrylamide that is grafted with the silica nanoparticles. A core flood system was designed and constructed by me and some colleagues in the core analysis laboratory in the BUE. The concentrations used were at 250 ppm and at 500 ppm both for the polymer and the polymer with the nanoparticles.

4.1.1. Brine preparation

Brine is also prepared in this experiment by using sodium chloride having a concentration of 40,000 ppm (40 g/L) and 500 ml of distilled water. The brine solution would be prepared several times like the previous experiment since different concentrations would be used throughout the flooding concentration in order to know the optimum concentration. The solution is also mixed using the magnetic stirrer to dissolve the salt and the particle into the distilled water.

4.1.2 Core flood system

In the core analysis laboratory, a core flood system was designed by me and several other colleagues to help in the process of core flooding in the research projects and for future use for other new petroleum engineering students. The most important part of the system to be manufactured was the core flood unit where the cores settle in during the flooding process. The core flood system consists of the core flood unit, the gas cylinder for pressure and the glass pipe for the fluids used for injection as shown in the Figure 9.

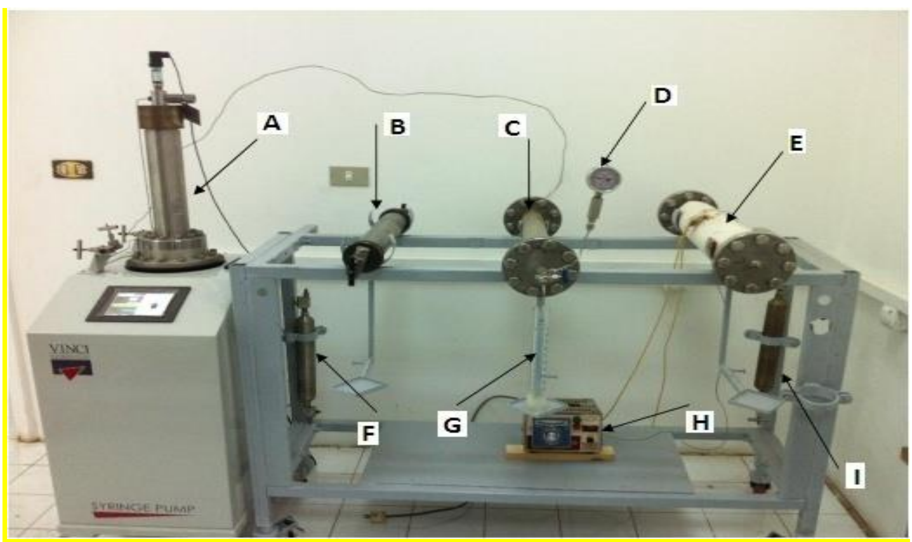

Fig.9. Core flood system (**A:** Pump; **B:** Brine solution; **C:** Sandstone holder; **D:** Pressure gauge; **E:** Sandstone holder with heating jacket; **F:** HAPAM-SiO_2 solution; **G:** Measuring cylinder; **H:** Electrical heating unit; **I:** HAPAM-SiO_2 solution) [3]

4.1.3. Initiation

The initiation process means that the core samples used in the experiment must have the reservoir characteristics which is having both water and oil in their pore spaces. As for the water saturation procedure, the cores are left inside brine solution for 24 hours to have sufficient time to be saturated. After this process, the oil should also be injected into the core in order to replace some of the water so that the core samples have both water and oil inside in order to start the core flooding procedures. The oil used had an API of 38° and 4 core samples were used.

4.1.4. Core flooding procedures

After preparing the core samples for use, flooding is carried out on the samples. Polymer without the nanoparticles is used first in the flooding, then the polymer with the nanoparticles will be used [14, 26-30]. This is done in order to show how the oil recovery is affected when the nanoparticles are with the polymer. Different concentrations were used in order to know the optimum concentration of the nanoparticles to be used that is the most efficient when it comes to flooding. Moreover, there are several procedures that are followed in order to carry out the experiment:

1. Get the dry weight of the core samples tested.
2. After saturating the cores with the brine, calculate the pore volume by subtracting the dry and wet weights.
3. The dimensions of the core like the length of diameter are determined using the digital Vernier caliper.
4. Insert the core into the core flood unit.
5. Inject brine into the core in order to calculate the absolute permeability.
6. Initialization process is made to make the core have the reservoir characteristics.
7. Start the process of flooding by injecting the mixture of brine with the polymer.
8. Record the volume of oil and gas produced from the injection till breakthrough where water is only produced.
9. Graphical plots concerning the data calculated will be made.

4.2. Results of flooding

After the core flooding process, some data are computed such as the pore volume injected, the amount of oil and water produced, what pressure was used, the amount of time taken and eventually the recovery of oil was calculated. Graphs of the pore volume injected vs. the oil recovery and the relative permeabilities of oil and water vs. the water saturations were plotted in order to see the wettability and the recovery as in the cases 1 to 3: -

Case (1): A concentration of 250 ppm of polyacrylamide

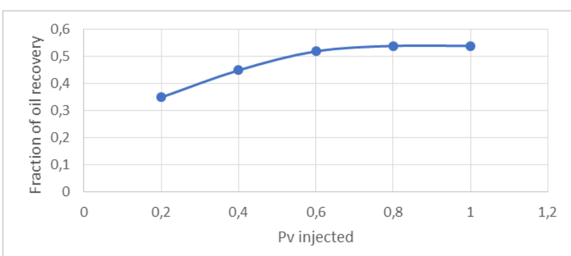

Fig. 10. Pv injected vs. fraction of oil recovery of polyacrylamide

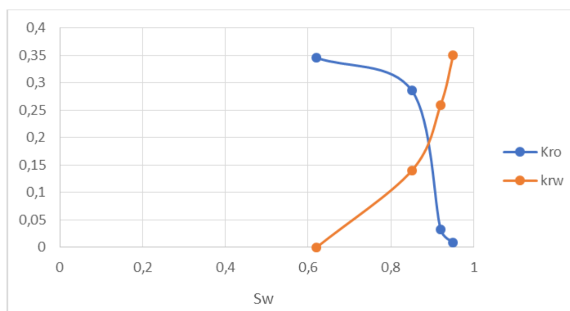

Fig. 11. Relative permeability curve of polyacrylamide

Case (2): A concentration of 250 ppm of polyacrylamide with silica nanoparticles

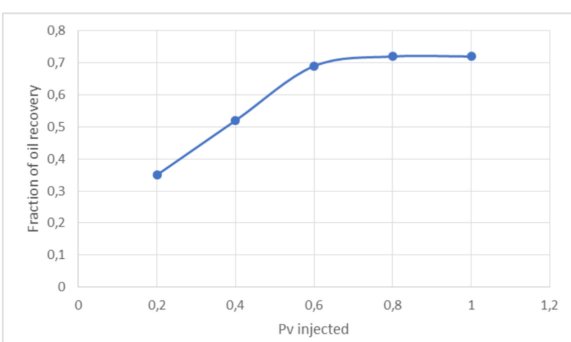

Fig. 12. Pv injected vs. fraction of oil recovery of polyacrylamide with silica nanoparticles

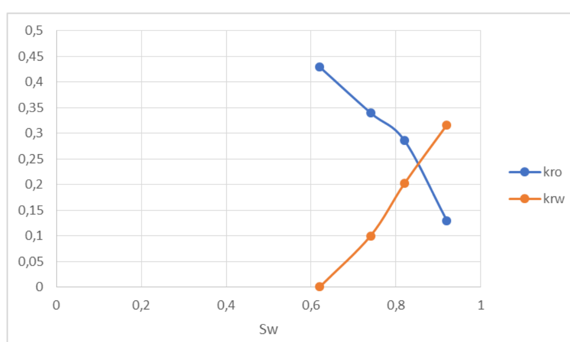

Fig. 13. Pv injected vs. fraction of oil recovery of polyacrylamide with silica nanoparticles

Case (3): A concentration of 500 ppm of polyacrylamide with silica nanoparticles

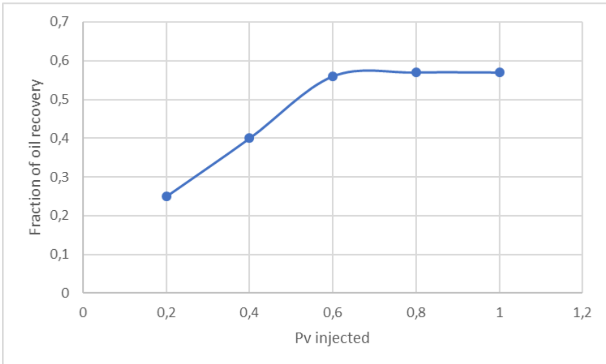

Fig. 14. Pv injected vs. fraction of oil recovery of polyacrylamide with silica nanoparticles

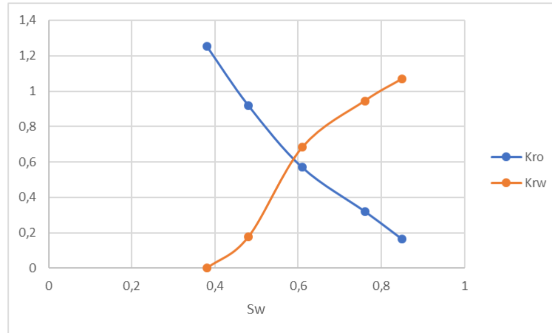

Fig. 15. Relative permeability curve of polyacrylamide with silica nanoparticles

4.3. Discussion of flooding

From the flooding data and the plots drawn, it was shown that the optimum concentration for producing the highest recovery is 250 ppm of the polyacrylamide grafted with the silica nanoparticles since the higher concentration of 500 ppm produced fewer hydrocarbons. This explains that the concentration of the nanoparticles to be used must be taken into account since the proportionality between the oil recovery and the amount to be nanoparticles to be used is not always a direct proportionality. Furthermore, that is why multiple samples of different concentrations must be tested in order to have more knowledge of the required concentration to be used in the flooding process. Some errors may be present throughout the experiments such as the time of starting the stopwatch due to the reaction time, parallax error and making readings and other errors that may cause minor fluctuations to the results presented. However, the accuracy of the results is sufficient to give a representation of how the oil recovery increased when the optimum concentration of the polyacrylamide with the silica nanoparticles were used in the flooding operations.

5. Economic study

When applying the project in real life, it is extremely important to take economic factors into consideration. In other words, the production performance of the reservoir depends on the cash flow, which means that the production continues until the production of the hydrocarbons is no longer economical. When it comes to the case here in the project, it is important to see the price of the polyacrylamide and the silica nanoparticles when carrying out a flooding project in real life. In any economic analysis, there are some parameters that need to be known such as the net present value, the price of the oil barrel and other economic parameters. This is to ensure that the entire process of the oil recovery is economically efficient enough to maximize the oil production, thus, the revenue. It must also be known that the nanoparticles are expensive in price, so it must be known that every type of nanoparticles and specific concentrations of these nanoparticles have a specific effect on the hydrocarbon recovery. That is why multiple experiments are carried out all around the world to understand which type of nanoparticles is compatible with which case because understanding this would decrease the risk of ending up having an economic crisis during the production process.

6. Conclusion

This research project discussed the usage and application of nanotechnology for enhanced oil recovery. Such technology was introduced in the 20th century to increase the recovery of oil and improve properties of the crude oil and the rocks such as wettability alteration, viscosity reduction and also the reduction of the interfacial tension. Moreover, in this project, several data were gathered by different authors explaining the impact of nanotechnology on oil production by different experimental approaches and in different cases. Polyacrylamide was the chosen polymer to be used in the experiment and silica nanoparticles were used as the nanoparticles to be mixed with the polymer. As for the experimental work in this project, it was classified into 2 stages which were the rheology stage and the core flooding stage. The rheology stage basically was measuring how the viscosity of the polyacrylamide increased when the silica nanoparticles were added. Moreover, the viscometer was used in the experiment to give different values of the shear stresses and shear rates and the concentration used in the experiment were 250 ppm, 500 ppm, 1000 ppm, and 2000 ppm, and as for the temperature, they were at room temperature (25°C) and at a temperature of 50°C. When the brine solution was prepared, the concentration of the sodium chloride salt that was used was 40,000 (40 g/L). The core flooding stage was about how the nanoparticles mixed with the polymer improves the recovery of oil. A core flood system was constructed by me and a number of colleagues in the core analysis lab in the BUE. The process of flooding had several important procedures that must be followed such as measuring the dry weight of the cores, saturating the cores with brine, then measuring the wet weight then calculate the pore volume from the previous values. Other important parameters were calculated such as the absolute permeability. Initiation of the cores was the first step to be done in order to make the core samples have reservoir characteristics which are having both oil and water inside the pore spaces. After preparing the cores, flooding should be done with the polymer alone then the polymer with the silica nanoparticles to compare the changes that occurred in the flooding. After the experimental procedures, it was found out that the optimum concentration of the polyacrylamide and silica nanoparticles mixture is 200 ppm.

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