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DESIGN AND ECONOMICAL EVALUATION OF BIOPOLYMER INJECTION-DESIGN PROJECT

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Abstract

Throughout the life of a petroleum reservoir, the oil recovery passes through several stages, which are primary, secondary and tertiary recovery. At initial reservoir conditions, the production of the oil mainly depends on the natural existing pressure of the reservoir. However, after some time of production and the pressure becomes insufficient, other methods must be used to provide reinforcement and continue the production process. Therefore, many methods developed throughout the last decades to increase oil recovery. This research project investigates the application of biopolymer in the oil recovery process and how these biopolymers can increase the recovery of oil. The biopolymers used in the project are xanthan gum and starch where both of them are compared together by different experimental procedures. There are some physical properties that must be present in a polymer in order to guarantee good performance, which is high viscosities and having the tolerance to harsh reservoir conditions. Accordingly, the 2 biopolymers selected are compared together through firstly the rheological procedures using the 800 model 8-speed viscometer then carrying out flooding procedures by using the newly designed core flood system that was made by the students of this research project. After the experiments carried out, xanthan has reigned superior over starch when it comes to the viscosity and eventually having a better sweeping efficiency due to its higher viscosity, which makes it easier to sweep more portions of oil present in the core samples used during the flooding experiments. Furthermore, an economic study will be made to see how economically efficient those biopolymers are which is really important since any strategy made must consider the economic considerations.

Keywords*: Biopolymer injection; Enhanced oil recovery; Feasibility study; Relative permeability.*

1. Introduction

As the years pass, the demand for energy increases tremendously due to the abnormal increase in the world's population. Such increasing demand is too hard nowadays for the energy industry to keep up with it. Not because of the technological capabilities, but mainly because of the economic crisis that takes place every now and then. Concerning the oil industry, the duration of the production depends on several economic factors including the economic limit, which is the point where production from a reservoir is no longer economical. That is why several methods are used in trying to increase economic efficiency while producing as much oil as possible to keep up with the oil demand [1]. Polymer flooding has always been a trustworthy method of producing oil, due to its various advantages such as mobility control, improving the sweep efficiency and preventing water coning. Such method involves the process of injecting polymers into the target reservoir in order to sweep as much oil as possible to the surface. It was first discovered in 1949 that the mobility has an effect on the waterflood performance in which when the viscosity of the water is low, there is a high probability of water coning to take place, which will lead to an early water cut which is not the best economic scenario. This was when polymers started to be used with the water flooding process in order to reduce such problem and to be able to sweep as much oil as possible from the reservoir to the surface [2]. The main objective of this manuscript is to shed light on the application of biopolymers in the process of oil recovery. This is done by gathering various data from old sources to give a deep elaboration on how they were used in old experiments how effective they are in certain situations. As for the experimental work, 2 stages will be done, which are the rheology stage and the flooding stage, which help in determining important data such as the viscosity of the biopolymers and the maximum oil recovery achieved from the flooding procedures. After gathering the data from those 2 stages, a comparison will be made between xanthan and starch to see which one is better when it comes to the oil recovery and tolerance to harsh reservoir conditions such as high temperatures and salinities. The apparatus that will be used are the 800 model 8-speed viscometer for viscosity measurements and the core flood system that was designed by this project's team for the flooding procedures. The first part of the research project will provide various data from old research papers explaining how biopolymers are applied in the field and what the necessary factors are. As for the experimental work, specific procedures are followed in which in the rheology the values of the shear stresses are recorded to the corresponding values of the shear rates to be able to have graphical plots that are between the shear rate and the viscosity. As for the flooding stage, it will involve the usage of the newly designed core flood system in the process of polymer flooding, then the data gathered from the flooding such as the volume of oil and the volume of water and the initial oil in place would make it possible to calculate needed parameters such as the recovery of oil in order to have graphical plots between the pore volume injected and the cumulative oil recovery. From the experiments carried out, a comparison will be made between the 2 biopolymers used to identify the better candidate for polymer flooding. The annual increase in the demand for energy is a major issue nowadays since the demand must be kept up to achieve such thing; an economically efficient method must be present in order to produce the greatest amount of energy possible while maintaining the required economic balance. Thus, it is important to know that every strategy used should be compatible with certain situations and scenarios. This is because using an incompatible strategy would definitely cause financial losses in the future. When it comes to the biopolymer flooding, the biopolymer must be tolerant enough to handle reservoirs having very harsh conditions such as high temperatures and high salinities. This is why, in many cases, the biopolymers are modified in order to enhance their physical properties to be able to withstand the harsh reservoir conditions. Another problem that makes polymer a must to use is water coning [3]. Because when water is flooded into oil that is usually too viscous, the water would not be able to sweep the oil, thus, it goes through the oil and gets produced instead of the oil itself. This is where polymers are used to prevent such problems and to be able to sweep as much oil as possible with delayed water production. The energy production industry has always strived to maximize power production in the most economically and technically efficient manner. This is to keep up with the growing demand for energy that keeps increasing annually. Therefore, the oil industry played an important role in producing large amounts of hydrocarbons that are used in multiple applications such as car fuel and other mechanical demands [4]. However, it is quite hard to maintain a balance between the economic and technical considerations and the increasing global energy demand since it was predicted by BNEF that the demand for energy would increase to almost 30% in the year 2040 [5]. Initial conditions, the oil and gas production mainly depends on the natural forces that exist in the reservoir until a point where its pressure is sufficient. This is where reinforcement is needed to help in the recovery process. Therefore, different methods and techniques are proposed in order to achieve the balance of producing relatively large amounts of hydrocarbons while maintaining positive economic and technical scenarios. These methods include applying nanotechnology, injecting of polymer, gas injection, thermal recovery methods, and microbial recovery methods, which fall under the category of improved oil recovery, which are secondary and tertiary recoveries [6]. Figure 1 shows how the stages of the oil recovery from initial conditions until external forces are needed: -

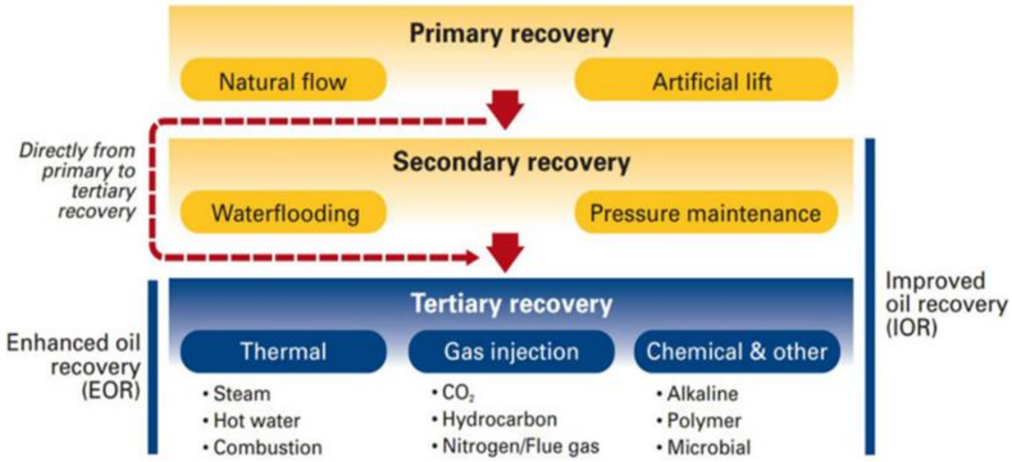

Figure 1. Stages of the oil recovery

One of the methods proposed was a biopolymer injection. Such a method is described as the usage of biopolymers with the water flooding in order to increase its viscosity. This is made in order to increase the sweep efficiency and displacement efficiency. There are multiple types of biopolymers that can be used in the process such as Xanthan gum, starch, and Schizophyllan biopolymers. Furthermore, it is important to select the optimum biopolymer that has a high tolerance for harsh reservoir conditions such as high temperatures and salinities in order to prevent problems in the future [7]. It was discussed that one of the applications of biopolymers is to improve the performance of water-based mud. Biopolymers like Scleroglucan are used in this task specifically due to their ability to clean holes, having a high tolerance to shale, and improving the rate of penetration. In addition, this type of biopolymer has shown to have high resistance to harsh conditions such as the existence of high temperatures, salinities, and shale presence. These physical properties would definitely maximize the efficiency of the drilling fluids used, thus, having an advantage and avoiding more potential problems [8]. El-hoshoudy [3] discussed the application of biopolymer flooding when dealing with horizontal wells that contain Safaniya oil. After carrying out several experiments to see the effect of the used biopolymers, much information was gathered regarding these biopolymers, such as having a maximum oil recovery of 30% when using a concentration of 0.15% in brine. Moreover, biopolymer flooding proved to be more effective when dealing with horizontal wells that are diagonally oriented rather than parallel oriented, and Figure 2 displays the difference in the looks of those two well patterns: -

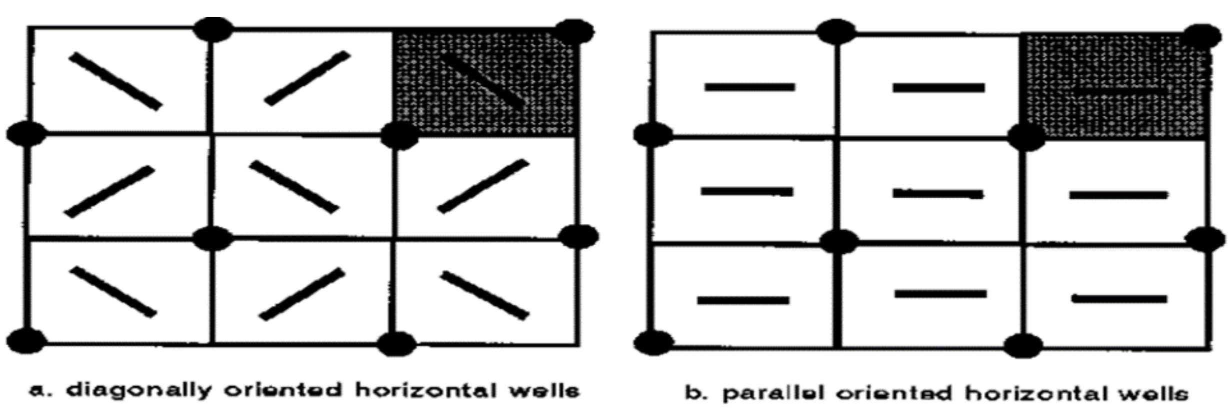

Figure 2. Diagonally oriented vs. parallel oriented horizontal wells

It was also shown that the sweep efficiencies were better in diagonally oriented wells, which lead to a higher recovery of oil in the early life of the reservoir. Al-Shalabi [9] shed-lighted on the application of Schizophyllan biopolymer in flooding of several carbonate core samples with high temperatures and salinities. Throughout this research paper, mathematical formulations and lab work was used to investigate the effect of such biopolymer on the recovery of oil. Evaluation of the oil recovery from Schizophyllan was done by UTCHEM simulator. This simulator produced various data that indicate the performance of the biopolymer. These data include that this Schizophyllan is better than the conventional water flooding, it reduces the mobility of the water phase and the most recommended concentration to produce oil at the highest efficiency is 800 ppm.

2. Biopolymer flooding

2.1. Xanthan biopolymer

Xanthan gum is considered a type of polysaccharides which has the chemical formula of $C_{35}H_{49}O_{29}$. Such a biopolymer was discovered in the second half of the 20th century (the 1960's) by the chemical researcher Allene Jeanes in the department of agriculture in the USA. It was discovered when the biopolymer itself was made from the bacteria Xanthomonas campestris through the fermentation process. Moreover, such biopolymer became used in various industrial uses such as being a food additive, water gel preparation, scaffolds construction, and can also be used in various medical applications such as being a substitute for saliva for patients who suffer from Sjogren's syndrome [10]. Lipton [11] explained various methods and techniques that could enhance the injectability of the xanthan biopolymer. These methods include using injection systems that are free of bacteria, using the most efficient mixing techniques, and preserving the surface adequately from microbial attacks. It was proved after laboratory work that the flow properties of the biopolymer can be significantly improved by various mechanical methods such as clay clarification, filtration, and enzymatic clarification. Moreover, it was also proved that increasing the viscosity and the injectability of the biopolymer could be achieved by proper mixing techniques such as by high shear hydration and the concentrate dilute method. Payton *et al.* [12] explained the application of xanthan biopolymer in low permeability reservoirs. The amount of xanthan that was used was limited to a certain amount since using it in low permeability formations may lead to injectivity problems that can arise from debris. This research paper wanted to point out that increasing the viscosity and improving the filterability could be attained from polymer pre-hydration using fresh water. Moreover, it was proved through lab procedures that the process of enzyme treatment has a high effect when it comes to debris reduction, and such treatment can be carried out in field conditions. Furthermore, such treatment also proved to have a positive effect on xanthan treatment to be injected in carbonate reservoirs with low permeabilities. Ash *et al.* [13] wanted to investigate the chemical stability of xanthan gum when dealing with the real-life operations where the biopolymer is injected into the reservoir to perform its tasks. Accordingly, the stability of the polymer is highly significant when it comes to the field operations since it will have to deal with relatively hard conditions where this stability is highly needed. An experimental approach was carried out to see the performance of xanthan and see how stable it is when exposed to certain conditions. Therefore, xanthan's stability was proven to depend on the salinity where it exhibited stable behavior when dealing with sea water at a temperature of 90°C. There are other important factors that must be considered such as the chemical hydrolysis, physical changes, free radical degradation, and enzymatic hydrolysis. Philips *et al.* [14] discussed the application of high-pyruvate xanthan for enhanced oil recovery. Several experimental procedures were carried out to show how such biopolymer affects the recovery of hydrocarbons from several core samples by the flooding process. After the experimental procedures, there are several pieces of information gathered, which are; the yield point and the viscosity of the high-pyruvate xanthan are lower than the conventional xanthan. When using high salinity brine solutions, the high-pyruvate xanthan has better injectivity than the conventional xanthan. Furthermore, the good injectivity of the HP xanthan can be maintained by the addition of $Fe^{+3}$and Ca^{+2} from non-ionic surfactants. HP xanthan is also proven to have compatibility with several materials such as biocides, surfactants and oxygen scavengers. Microbial control is a huge factor that must be taken into account since it contributes to also controlling the mobility of the HP xanthan biopolymer. Auerbach [15] predicted the changes in the viscosity of the xanthan in brine solutions have different salinities. It was discussed the reduction of the xanthan viscosity could be a major issue since it could have a negative effect on the mobility control, thus a decrease in the oil recovery. From experimental work, it was shown that the viscosity of the xanthan biopolymer having high pyruvate, in fact, increases when the concentration of the salt increases. In more detail, it was shown that high pyruvate xanthan's viscosity increases significantly when the salt concentration is above 3.5% total dissolved solids. In addition, it was also shown that multivalent cations do not exhibit a huge impact on the viscosity of the xanthan biopolymer. Lotsch *et al.* [16] carried out experiments in order to investigate the effect of the pore volume that is inaccessible in the core samples and how the xanthan solution performs throughout the entire experiment. Several correlations were used in calculating important parameters such as the mobility that has the following equation;

$$Mwo = \frac{\lambda w}{\lambda o} = \frac{Krw}{\mu w} \times \frac{\mu o}{Kro} \qquad (1)$$

Moreover, the resistance factor was also calculated by using the following equation;

$$RF = \frac{\lambda w}{\lambda p} = \frac{Krw}{\mu w} \times \frac{\mu p}{Krp} \qquad (2)$$

Furthermore, the residual resistance factor was calculated to see how much the permeability of the porous medium decreased from the xanthan polymer, and it is calculated using the following the equation;

$$RF = \frac{\lambda w1}{\lambda w2} = \frac{Krw1}{Krw2} \qquad (3)$$

After the experiment, it has been concluded that the inaccessible pore volume when xanthan was used is equal to 10%, the portion of the irreversibly retained polymer was set to be 0.5 mg/cm^{3,} and the equilibrium retention capacity of the xanthan is 1.0 mg/cm^3. Kohler *et al.* [17] discussed the process of improving the injectivity of the xanthan biopolymer by enzyme treatment. This treatment is carried out in order to eliminate microgels and bacteria that are insoluble. There were various ways that were discovered that can achieve the goal of injectivity improvement such as involving alkaline protease and cellulase that are responsible for destroying the insoluble bacteria. Moreover, it was mentioned that in order to reach maximum treatment efficiency, the treatment should take up to 4 hours maximum, and some parameters should be compatible with the treatment, such the temperature, the salinity of brine, and the Ph. Filterability tests were carried out to identify the best method for treatment; thus, the alkaline protease and cellulase were proven to be the most effective among other methods. Seright *et al.* [18] discussed in their paper the stability of the xanthan biopolymer when dealing with very high temperatures and discussed the factors that can lead to the xanthan degradation such as helix-coil transitions, the effect of oxidation and hydrolysis. After the experimental work, it was concluded that oxidation is not the main factor that affects the degradation of the xanthan biopolymer, but the hydrolysis has an observable effect. It was also shown that the xanthan could keep 50% of its original viscosity for half a decade if the conditions were optimum. These conditions include the Ph having a range from 7 to 8 and the temperature not exceeding 80°C. Littmann *et al.* [19] carried out various experimental approaches in order to check the stability of the xanthan in the reservoir. In other words, a polymer flooding pilot project was carried out in a sandstone reservoir located in Germany with a depth of 1150 feet, a thickness of 16.5 feet, a clay content of 10%, and other reservoir properties. The xanthan solution used had a concentration of 800 ppm and got injected into 2 wells in a 3-year span. After these procedures, it was concluded that the injection of the xanthan biopolymer into the pay zone encountered no difficulties, the project was marked successful from the economic and technical perspectives due to the oil recovery and the injectability of the xanthan biopolymer, there was a slight degradation in the xanthan and the chemical composition of the xanthan gum has not changed throughout the 3 year span of the project. Kolodziej [20] discussed in his research paper the use of xanthan biopolymer and its transport mechanisms, which are dispersion, inaccessible pore volume, and polymer adsorption. Moreover, this research paper focused primarily on evaluating the effects of these mechanisms of the biopolymer with residual oil and 100% brine. Furthermore, these transport mechanisms were explained in details where the polymer adsorption is basically the total amount of the polymer lost in the core samples during the injection process, and the inaccessible pore volume is defined as the fraction of the volume of the pore where flowing of the polymer is not possible and it can be classified into pore wall exclusion and total pore exclusion and finally. After carrying out the experimental procedures, it was concluded that the adsorption of the biopolymer was low when dealing with core samples that were acidized and fired. Moreover, it was found out the effects of the inaccessible pore volume were greater than the biopolymer adsorption effects. Furthermore, the dispersion of the biopolymer was found to be relatively large which resulted in a molecular diffusion coefficient that is very low in value. Guo *et al.* [21] elaborated in their research paper the application of xanthan biopolymer flooding Shengli oil fields that are located in China. Such biopolymer was picked as a candidate in the flooding process due to its characteristics, such as its resistance to shear and its durability to salinity. Therefore, after the injection process, it was found out that xanthan biopolymers succeeded in decreasing the water cut and increasing the recovery of oil. Moreover, it was observed that xanthan had the advantage of having a better thickening capacity than polysaccharides when dealing with high salinities. However, it was also shown that the xanthan biopolymer witnesses a loss in the viscosity by biodegradation when dealing with shear stresses, having a large difference in pressure. Accordingly, it was recommended to use biocide to xanthan to reduce the impact of such a problem. Navarrete *et al.* [22] explained how xanthan gum is used in the process of controlling fluid loss in damaged formations. In this research paper, it was explained how the rheology of this biopolymer affects the process of fluid loss control, and it was achieved using linear core flow tests. After lab work, some information was gathered regarding xanthan gum. This information includes that shear dominated the rheology of the xanthan in Berea cores, when the xanthan is combined with the fines of the formation it is going through is the best provision of fluid loss control and also a major factor of the formation permeability reduction process. Moreover, the skin factors caused by xanthan usage while drilling can be ignored due to the presence of the fines mentioned before, and because of these fines, the biopolymer only invades millimeters away from the wellbore, which is really a negligible amount. Fischer *et al.* [23] discussed the application of non-acetylated xanthan in the process of hydraulic fracturing. Such a variant of xanthan is made from combining the xanthan with guar; thus, very high viscosity is generated from the synergetic interaction that is developed. Moreover, it was found that crosslinking the non-acetylated xanthan fluids would enhance the viscosity at a high temperature. In addition to that, optimum ratios of non-acetylated xanthan would lead to the production of an enhanced proppant transport in comparison to guar fluids. The main objective of any fracturing fluid is proppant transportation through the height and the length of the existing fracture. El-hoshoudy *et al.* [24] carried out an experiment to investigate the correlation of the fluid characteristics of the xanthan biopolymer with various applications such as formational damage fixing and its usage in coiled tubing. After the experimental procedures, an inverse proportionality was found between the filtration rate of the xanthan and the concentration of the polymer. Moreover, it was also found that the extensional viscosity of the xanthan decreases when the elongation rate increases. Furthermore, it was explained that xanthan solutions should be used in an optimum amount since any unwanted increase in the amount of the biopolymer would result in loss of permeabilities of the porous media since adsorption occurs on the rock surfaces of the formations.

2.2. Starch biopolymer

Pledger *et al.* [25] discussed the application of starch-acrylamide for the EOR operations and using such biopolymer can enhance the production of oil in an efficient manner. Flooding operations were carried out inside the laboratory to investigate the effect of the biopolymer on the oil recovery and how its physical properties are altered when exposed to specific conditions. After the required lab work, it was discovered that the intrinsic viscosity of starch-acrylamide that has 18 grafts per one starch molecule is more than the acrylamide polymer alone by 3 folds. This indicates the positive effect of starch in the process of viscosity increasing. Moreover, it was also shown that the starch-acrylamide loses approximately 60% of its viscosity when getting exposed to a shear rate of 4300 s^{-1} if the molecular weight increases and the graft number decreases. Barrufet *at al.* [26] carried out studies to investigate the effect of starch on the permeability of the reservoir. This is important since permeability alteration is a major issue when it comes to oil recovery since a negatively affected permeability means less amount of oil that can travel to the surface. Therefore, modified starch was the biopolymer proposed for solving such problems because it can help in performing various tasks such as rock permeability improvement, increasing the sweeping efficiency, and maintaining stability when dealing with hard reservoir conditions. Experiments were carried out to see if this modified starch is compatible with the job; thus, it was shown that modified starch fits for the jobs of modifying permeabilities and a good agent of mobility control. In addition to that, the high viscosity of this biopolymer prevented the issue of water coning/fingering. Karmakar *et al.* [27] shed-lighted on the characteristics and synthesis of the starch biopolymer and its role in the process of oil recovery. These characteristics include being biodegradable-resistant and having intrinsic viscosity. An experimental approach has been made to see how using such biopolymer can affect the overall oil recovery. After the experimental approach, several conclusions were gathered regarding starch biopolymer. First of all, starch has a relatively high intrinsic viscosity in comparison to other types of polymers. Moreover, it was also proved that it had a higher resistance to biodegradation when compared with other polymer samples. Furthermore, the rheological procedures have shown that the starch solution exhibits pseudoplastic and non-Newtonian behavior. Simonides *el at.* [28] discussed the role starch plays in drilling and completion fluids design. Potato starch is chemically modified in order to be used in the design process, and experimental procedures were carried out to see how effective it is in the fluids design. After the procedures, it was observed that potato starch has very good properties when it comes to fluid design since it helps in optimizing rheological properties and also helps in reducing losses of fluids. Moreover, crosslinking the potato starch increases the biopolymer's ability to resist shear and heat. Leslie *et al.* [29] elaborated the usage of starch that is tailor-modified for the enhanced oil recovery stage. They also discussed how polymer, in general, is used in the process of controlling the production of water by reducing the permeability of the water. Experiments were carried out to see how the charge density and the molecular weight affects the adsorption. It was concluded that the adsorption of the polymer depends on several factors, such as the polymer-surface electric interaction and the size of the chains of the polymer. Moreover, it was also shown that the effect of the size of the pores is minor on high charge density starch; meanwhile, the pore size has a large effect on low charge density starch. Haicun *et al.* [30] studied the performance of the oil displacement when using cationic starch. Such type of starch consists of 70% amylopectin and 30% amylose. Flooding, operations were carried out at different salinities, and through graphical plots it was discovered that the oil recovery reaches 44% at low salinity and reaches 18% at high salinity. In addition, adsorption of the cationic starch on the oil droplets surface through the process of electrostatic interaction; thus, the zeta potential of the surface of the droplets is changed. This would improve the performance of oil displacement. Qu *et al.* [31] investigated the application of modified starch gel foam in carbonate reservoirs that are naturally fractured. This research paper is eager to replace gas flooding when dealing with fractured-vuggy reservoirs since one of the problems faced is the rapid channelling of the gas. In order to control the channeling, the gel is advised to be used. However, gel on its own would not be suitable for the harsh conditions of the reservoir. Thus, the modified starch gel foam was made in order to tolerate such harsh conditions. Laboratory work was done in order to see how tolerant such mixture is and how efficient it is in comparison to gel alone. After the required work, the modified starch gel foam has proven to be tolerant to high temperature and salinities and specifically in carbonate reservoirs that fractured-vuggy. Furthermore, it was also shown that the profile controlling can be attained through the modified gel foam by the process of secondary gelation. El-hoshoudy *et al.* [24] discussed the limitations that could be present from using starch in the process of oil recovery. These limitations such as degradation from bacteria in harsh conditions in the reservoir gave an idea of evolving the native starch used into a chemical that has a relatively higher functionality and efficiency. In more detail, Starch was functionalized with thiol derivative, and then the thiol is oxidized to sulfonic acids. After the oxidation, copolymerization of the starch derivative with monomers that contain vinyl occurs by redox emulsion in the existence of seeds of silica. Flooding procedures are carried out to test the modified version of starch and to see how the oil recovery is affected. After the procedures, it was shown that this modified version of the starch has proven to be more effective than regular starch in the oil recovery due to its better ability in withstanding harsh reservoir conditions such as the existence of high temperatures and salinities, and the recovery factor from the modified starch reached almost 40%. El-hoshoudy *et al.* [32] investigated the methods of improving the properties of the starch biopolymer for flooding. The starch's molecular structure makes it easier to be grafted with vinyl monomers. This is done while crosslinking agents are present. Such modification is made in order to make the starch used more resistant to the harsh conditions of the reservoir. Accordingly, the modified version is called acryloylated starch, and it exhibits a better behaviour and efficiency when different tests were carried out such as rheology. Furthermore, the results prove that the modified version of the starch tolerates very harsh reservoir conditions and the recovery factor increased up to 50% which is a good indicator that it is better than regular starch.

3. Experimental procedures

In the literature review, it was mentioned through many types of research that biopolymers play a huge role in the process of oil recovery. However, not all polymers yield the same oil recovery due to their different physical properties, such as viscosity or chemical stability. Accordingly, the experimental work of this research project will focus on comparing 2 types of biopolymers, which are xanthan gum and starch. First of all, the 2 biopolymers mentioned will be exposed to rheological procedures by using the 800 model 8-speed viscometer to compare the viscosities under different concentrations and temperatures. The second stage of the experimental work is designing a core flood system in the rock properties lab at the British University in Egypt. The raw materials were gathered and were taken into a specialized workshop, and the design of the core flood unit was made using the specific dimensions agreed on. This core flood unit design is highly significant since it will help in the stage of the polymer flooding and yields more accurate results in comparison to the sand pack model. The final stage of the experimental work is the flooding operations. These operations will be made by using several core samples and inject both xanthan gum and starch and monitor how the oil recovery is and compare them together. From the data gathered from the flooding, graphical plots will be made between the pore volume injected and the cumulative oil recovery in order to see the maximum recovery of oil reached when injecting the biopolymer into the core. After the experimental work mentioned, an economic evaluation will be made to see how economically efficient the polymers are. This evaluation made is extremely significant since the entire oil production process depends on the economic considerations since not being able to cover the expenses of production from the produced oil will cause major financial losses in the future, which is a very bad scenario. From the data mentioned above, all parameters gathered must coexist in order to guarantee a successful production operation in the most technically and economically efficient manner.

3.1. Rheological criteria

In this stage, the viscosity is measured by using the 800 model 8-speed viscometer that gives data related to the viscosity, such the shear stress and the speed rpm that is converted to shear rate through the conversion factor of 1.7. The procedures of the rheology should be followed strictly in order to guarantee accurate results and correct estimations. The procedure conducted as follow;

1. Brine preparation: distilled water is mixed with sodium chloride at a specific concentration, and the same goes with polymers used, and the entire mixture is made by the magnetic stirrer. Such a process is repeated several times when making new solutions with new concentrations whether in xanthan or in starch.
2. Connecting the viscometer to a power supply.
3. The viscometer has a viscometer sleeve where it should be filled till the fill line is reached.
4. The sleeve is then properly adjusted on the viscometer's platform to prevent falling of the sleeve while making the measurements.
5. The viscometer's platform is raised until the bob is reached.
6. The viscometer used in the experiments has 8 speeds that range from 3 sec^{-1} to 600 sec^{-1}. Therefore, the shear stresses corresponding to the speeds should be recorded.
7. The 8 speeds mentioned should be converted into shear rates by multiplying all these speeds by a conversion factor that has a value of 1.7.
8. After recording the important data, graphical plots should be made between the shear rate and the viscosity in a log-log scale.
9. The experimental procedures are repeated at the different concentrations and temperatures proposed.

Rheology is a very important stage since it is an indicator of how viscous the fluid is, and such physical property is important, especially for polymers since having a high viscosity means a higher overall oil recovery due to a better sweep efficiency. In other words, the xanthan and starch rheological data would give an estimation on which biopolymer is superior when it comes to the viscosity.

3.2. Experimental results

After the data gathered from the rheology, graphs were plotted between the shear rate and the viscosity on a log-log scale to estimate how viscous xanthan or starch when dealing with different concentrations and temperatures. The numerical data used will be presented in tables to make the results look clearer to the readers.

Case 1. A polymer concentration of 2.0 g/L at room temperature

Table 1. Rheological data for xanthan and starch at room temperature

		Xanthan		Starch	
Speed (rpm)	Shear rate (s^{-1})	Shear stress, Pa	Viscosity cP	Shear stress, Pa	Viscosity cP
3	5.1	1.5	29.4	0.5	9.8
6	10.2	1.6	15.7	0.5	4.9
30	51	1.8	3.5	0.5	0.98
60	102	2.0	2.0	1	0.98
100	170	3.5	2.06	1.5	0.88
200	340	4.5	1.3	2	0.60
300	510	5	0.98	3	0.58
600	1020	8	0.78	4	0.44

Case 2. Polymer concentration of 2.0 g/L at 50ºC

Table 2. Rheological data for xanthan and starch 50ºC

Speed (rpm)	Shear rate (s^{-1})	Xanthan Shear stress, Pa	Xanthan Viscosity cP	Starch Shear stress, Pa	Starch Viscosity cP
3	5.1	1	19.6	0.5	9.8
6	10.2	1.2	11.8	0.5	4.9
30	51	1.4	2.74	0.5	0.98
60	102	1.6	1.57	0.5	0.49
100	170	2	1.18	1	0.58
200	340	3	0.88	1	0.29
300	510	5	0.98	1.5	0.29
600	1020	6.5	0.63	2	0.19

Case 3. A polymer concentration of 4.0 g/L at room temperature

Table 3. Rheological data for xanthan and starch at room temperature

Speed (rpm)	Shear rate (s^{-1})	Xanthan Shear stress, Pa	Xanthan Viscosity cP	Starch Shear stress, Pa	Starch Viscosity cP
3	5.1	2	39.2	1	19.6
6	10.2	2.5	24.5	1	9.8
30	51	2.5	4.9	1	1.96
60	102	3	2.9	1.5	1.47
100	170	3	1.8	2	1.18
200	340	5	1.5	2.5	0.74
300	510	7	1.4	4	0.78
600	1020	10	0.98	5.5	0.54

Case 4. Polymer concentration of 4.0 g/L at 50ºC

Table 4. Rheological data for xanthan and starch 50ºC

Speed (rpm)	Shear rate (s^{-1})	Xanthan Shear stress, Pa	Xanthan Viscosity cP	Starch Shear stress, Pa	Starch Viscosity cP
3	5.1	1	19.5	0.5	9.8
6	10.2	1	9.8	0.5	4.9
30	51	1	1.95	0.5	0.98
60	102	1.5	1.47	1	0.98
100	170	2.5	1.47	1.5	0.88
200	340	3	0.88	2	0.59
300	510	4.5	0.88	3	0.59
600	1020	6	0.59	4.5	0.44

Case 5. A polymer concentration of 6.0 g/L at room temperature

Table 5. Rheological data for xanthan and starch at room temperature

Speed (rpm)	Shear rate (s^{-1})	Xanthan Shear stress, Pa	Xanthan Viscosity cP	Starch Shear stress, Pa	Starch Viscosity cP
3	5.1	4	78.4	2	39.2
6	10.2	4.5	44.1	2.5	24.5
30	51	5	9.8	2.5	4.9
60	102	5.5	5.3	4	3.9
100	170	6.5	3.8	4.5	2.6
200	340	8	2.4	6	1.8
300	510	9.5	1.9	7	1.4
600	1020	13	1.3	8.5	0.8

Case 6. Polymer concentration of 6.0 g/L at 50°C

Table 6. Rheological data for xanthan and starch 50°C

Speed (rpm)	Shear rate (s^{-1})	Xanthan Shear stress, Pa	Xanthan Viscosity cP	Starch Shear stress Pa	Starch Viscosity cP
3	5.1	3	58.8	1.5	29.4
6	10.2	3	29.4	1.5	14.7
30	51	3	5.88	2	3.9
60	102	4.5	4.41	2.5	2.5
100	170	5	2.94	3.5	2.1
200	340	6	1.76	5	1.5
300	510	7.5	1.47	6.5	1.3
600	1020	11	1.08	7	0.7

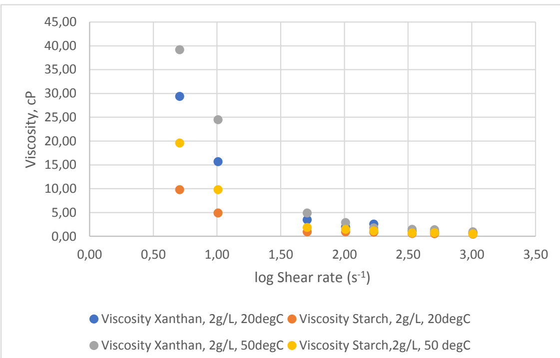

Figure 3. Comparison rheological data for xanthan and starch (2g/L) at room temperature and 50°C

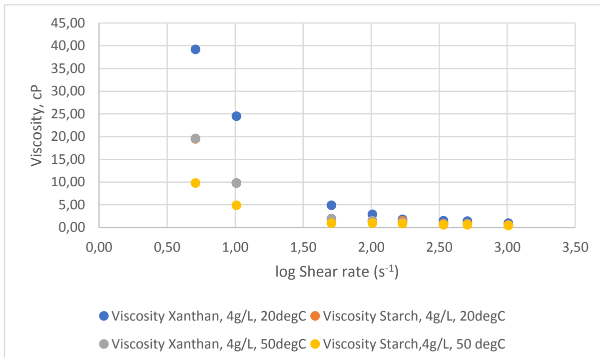

Figure 4. Comparison rheological data for xanthan and starch (4g/L) at room temperature and 50°C

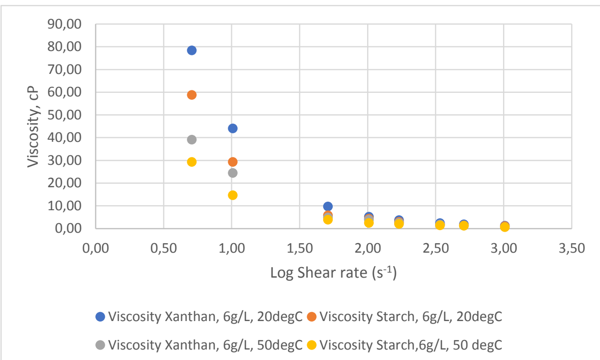

Figure 5. Comparison rheological data for xanthan and starch (6g/L) at room temperature and 50°C

4. Discussion and analysis

From the rheological data gathered for the xanthan and the starch biopolymer, it was shown that the viscosity of the xanthan is higher than starch at all proposed concentrations and temperatures. This can be an indicator that in a real-life operation, the xanthan biopolymer can be much more stable than a starch biopolymer when dealing with very harsh reservoir conditions such as high temperatures and high salinities. Moreover, the higher viscosity of the xanthan is favourable over the relatively lower starch viscosity since when trying to recover oil, the probability of water coning/fingering decreases since the viscosity of the xanthan is high enough to be able to sweep a large proportion of the oil present in the pay zone, thus, increasing the oil recovery. On the other hand, starch could be a weaker candidate for the polymer flooding operations since it lacks the viscosity that xanthan has, and it has less stability than xanthan when it comes to dealing with harsh reservoir conditions. That is why in most of the cases that deal with starch, modification of the starch itself is required in order to have more compatible physical characteristics and become more resistant to the relatively harsh conditions of deep reservoirs. In other words, the condition of the reservoir itself determines the best candidate for the flooding operations, since using the wrong candidate would lead to various problems in the future such as water coning, early water production, low sweeping and displacement efficiency and eventually a financial and economic crisis which is highly undesirable. That means that starch could be a good and more economically efficient candidate for the flooding operations if the reservoir conditions are not too harsh, which means no strong polymer is required for a job that does not require any. Meanwhile, in harsh reservoir conditions, choosing unmodified starch would be a really unwise and economic inefficient strategy. To summarize all the analysis regarding this part, the right materials should be picked for the right conditions to maintain a high technical and economic balance.

4.1. Secondary stage: flooding operations

This experimental stage is an extremely crucial part of this research project since it is the direct way of identifying the better polymer when it comes to oil recovery. Graphical plots between the pore volume injected and the oil recovery will be plotted to show the maximum oil recovery that can be achieved from those 2 polymers.

4.2. Core flood system design

A core flood system was designed in order to help in the process of the research project and in order to obtain relatively more accurate results in comparison to the sand pack model. The core flood unit was designed on a very accurate scale in a workshop to help in the flooding procedures. The parts of the core flood system are shown below: -

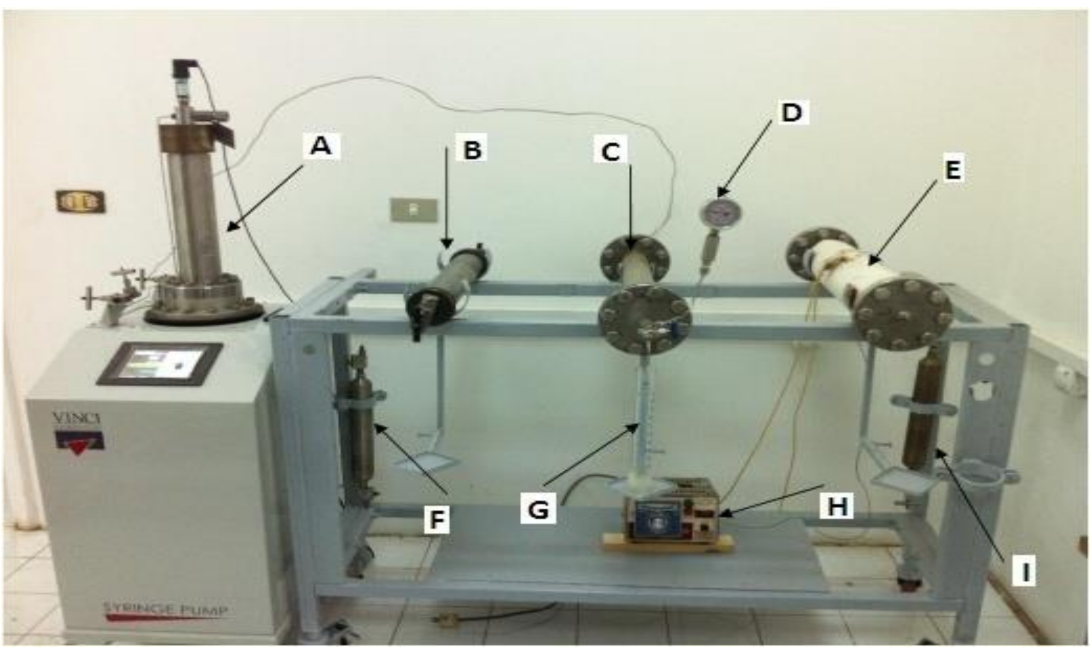

Fig.6. Core flood system (A: Pump; B: Brine solution; C: Sandstone holder; D: Pressure gauge; E: Sandstone holder with heating jacket; F: HAPAM-SiO_2 solution; G: Measuring cylinder; H: Electrical heating unit; I: HAPAM-SiO_2 solution) [33].

4.3. Methodology

After the rheological procedures that were carried out using the viscometer, the flooding operations are started to investigate the oil recovery from the core samples used from the xanthan gum and starch biopolymers. In order to start the flooding procedures, some steps must be carried out to start the experiment. These steps are: -

1) Brine preparation: like in the rheological procedures, a brine solution is prepared by using a certain concentration of sodium chloride and specific concentrations of both xanthan and starch.
2) Measure the dry weight of the core samples then saturate the cores with water then measure the saturated weight in order to identify the pore volume
3) Initiation: the core samples used must have reservoir characteristics, so oil is injected into the core samples to replace the water, then the connate water saturation and residual oil saturation is measured.
4) Flooding: the biopolymers to be used in the experiment are flooded into the core to see how the oil recovery is when they are injected. The procedure is done with the xanthan and done with the starch to be able to compare the overall recovery between them.
5) The volume of the oil is recorded until the breakthrough where only water is produced.
6) From the information gathered, a graphical plot between the pore volume and the cumulative oil recovery is made to see the maximum recovery reached.

4.4. Experimental results

After gathering the data related to the flooding procedures, graphical plots are drawn to investigate the recovery of oil after injecting xanthan and starch. This is done to compare between the two biopolymers and to estimate the better biopolymer that exhibits the better sweeping efficiency. In more details, the pore volume injected will be plotted against the cumulative oil recovery to have a better understanding and estimation of how the recovery is when dealing with both polymers. The tables below show the data gathered from the flooding operations.

Case 1. Flooding with xanthan gum

Table 7. Flooding data for xanthan biopolymer

P_v injected (cc)	V_{oil} (cc)	V_{water} (cc)	Δp (psi)	Time (sec)
0.2 (7.7)	7.7	0	43	560
0.4 (15.3)	15.3	0	43	912
0.6 (23))	11	12	43	1024
0.8 (30.6)	9.1	21.5	43	1114
1.0 (38.3)	0	38.5	43	1204

Case 2. Flooding with starch

Table 8. Flooding data for starch biopolymer

P_v injected (cc)	V_{oil} (cc)	V_{water} (cc)	Δp (psi)	Time (sec)
0.2 (5.5)	5.5	0	20	210
0.4 (10.9)	7.9	3	20	425
0.6 (16.4)	10.1	6.3	20	687
0.8 (21.9)	4.2	17.7	20	832
1.0 (27.3)	0	38.5	20	1013

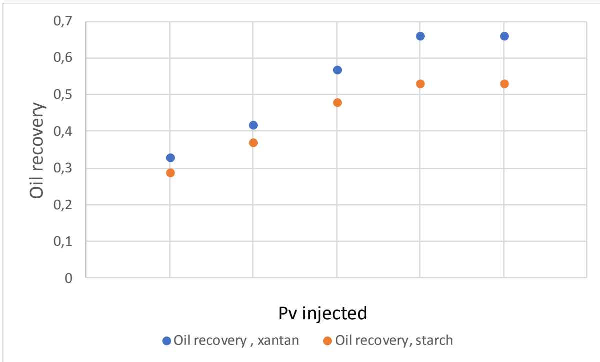

Fig. 7. Comparison of pore volume injected vs. oil recovery for xanthan and starch

From the core flooding data, it was shown that the oil recovery from xanthan gum is significantly higher than the recovery from starch. This is because of the better physical of the xanthan in comparison to starch, such as having a higher viscosity, which allows higher sweeping efficiency. Moreover, it is very important to use the compatible polymer according to the situation since using a biopolymer like starch that less tolerance to harsh temperature conditions would definitely lead to the rising of many problems such as water coning and early water production and earlier time of breakthrough.

Meanwhile, when xanthan was used, the situation was quite the opposite, since the time of water production was delayed in comparison to using starch biopolymer. Having a better sweeping and displacement efficiency means that the production process would also be economically efficient. As mentioned before, starch would have a better performance only if modified because modification would make the starch more tolerant of the harsh reservoir conditions. However, starch alone in real life operations would perform a poor job in the oil recovery process due to its low stability when dealing with high temperatures and salinities.

5. Preliminary economic considerations (feasibility study)

The development of economical EOR methods is the key to recover a substantial portion of the oil left after primary and secondary phases of production. The following material balance calculations are performed to determine the preliminary economic feasibility of the Xanthan for field flooding applications. Let us consider the application of the polymer flood to a sandstone reservoir having the following criteria, as illustrated in Table 9.

Pore volume injected vs. oil recovery

Table 9. Properties of a simulated reservoir for polymer flooding

Reservoir parameters	value
Area (A), acre spacing, five-spot pattern	20
Height (h), ft	20
Porosity% (Φ)	20 %
Initial water saturation% (S_{wi})	30 %
Residual oil saturation %(S_{or})	4 %
Initial oil saturation (S_{oi})	70 %
Oil formation volume factor (B_{oi}), bbl./STB	1.05
End-point relative water permeability (K_{rw}) at Sor	0.1322
End-point relative oil permeability (K_{ro}) at S_{wi}	1
Water Viscosity (μ_w), cP	1
Oil Viscosity (μ_o), cP	12.8
Darcy velocity (ν), ft/day	0.02
permeability (K), mD	400
Oil density, g/cc	0.874

An economical approach will be described here for determining the size of the chemical slug and how to estimate feasibility study;

1. Distance between the injector and producer (L) calculated by the following relation;

$$L = \sqrt{(20acres)(43560sqft/acre)/2} = 660 \text{ ft}$$

2. Mobility ratio (M) calculated by the following relation;

$$M = \frac{Krw/\mu w}{Kro/\mu o} = \frac{0.1322/1.0}{1.0/12.8} = 1.7$$

3. From Figure 4.5 of Green &Willhite at one pore volume of water injected and at a mobility ratio of 1.7, Areal sweep efficiency = EA= 0.85
4. Darcy velocity (ν) =0.02 ft/day= $0.02ft/D(\frac{1}{5.615ft^3/bbl})$ = 0.003561 B/D-ft^2.
5. Viscous to gravity ratio ($R_{v/g}$) = $\frac{2050\nu(B/D.ft^2)\mu o(cp)L(ft)}{K(md)\Delta\rho(gm/cc)h(ft)}=\frac{2050*0.0035618*12.8*660}{400*(1-0.874)*20}$= 61.2
6. From the Figure 4.17 of Green &Willhite, at $R_{v/g}$ of 61.0 and a mobility ratio of 1.7, Vertical sweep efficiency = E_H= 0.70
Volumetric sweep efficiency = E_V= $E_A \times E_H$ = (0.85) (0.70) = 0.60
7. Microscopic displacement efficiency = E_D= 0.94
Overall efficiency = E = $E_D \times E_V$= 0.564
8. Pore Volume (V_p)= AhΦ
$Vp = 20acres * 43560ft^2/acre * 20ft * 0.20 * 0.17809\,bbl/ft^3$ = 620608 bbl.
9. Initial oil in place(N) = $Ah\Phi Soi/Boi = (20acres * 43560ft^2/acre * 20ft * 0.20 * 0.7 * 0.17809\,bbl/ft^3)/1.05$= 413739 STB
10. Since incremental oil recovery by Xanthan copolymer flooding reach to 20.8%OOIP, so amount of recovered oil= 0.208*413739 = 86058 STB.
11. Assume that two pore-volume of water is injected at an optimum polymer concentration of 2000 ppm to achieve this incremental oil recovery;
Polymer consumption in case of Xanthan
$= (2 * 620608bbl) * (159liters/bbl) * (2000mg/L) * (10^{-6}kg/mg)$ =394706.70 kg= $(394706.7kg) * (2.2046\,lb/kg)$= 870170.4 lbs.
12. Assume oil price = $50 per bbl.
13. Income from additional oil recovery due to Xanthan flooding,
= 86058*($50) = $ 4302882.3
14. In this study, the cost of Xanthan copolymer dosage per barrel of oil at a concentration of 2000 ppm, = $1.17/bbl. of oil
15. HAPAM copolymer cost = $1.17*870170.4 lbs.= $ 1018156.03
16. *Net Cash Flow (NCF)* = [Value of Oil Recovered, bbl.] - [(Cost of Chemical, lb.) + (Depreciation) + (Capital Expenditure) + (Well Intangible)]
17. Since this polymer is readily soluble in water with minimal mixing. Therefore, it is reasonable to assume that facilities and operating expenses are negligible.
Net Cash Flow (NCF) in case of Xanthan *copolymer* = $ 4302882.3- $ 1018156.03= $ 3284726.32
18. Net profit per bbl. of incremental oil in case of Xanthan *copolymer = $3284726.32/ 86058= $ 38.16 per bbl.*
The previous feasibility study in the case of Xanthan can be summarized as in Table 10.

Table 10. Feasibility study summary

Constant parameters	Value
Initial oil in place(N), STB	413 739
Polymer consumption, lbs.	870 170.4
Oil Price, $/bbl.	50
Differential parameters	
Recovery factor, %OOIP	20.8
Incremental oil recovery, STB	86 058
Income from additional oil recovery, $	4 302 882.3
Cost of copolymer dosage $/bbl. of oil	1.17
Slug efficiency, lb./bbl. of oil	8.0
Polymer cost, $	1 018 156.03
Net Cash Flow (NCF), $	3 284 726.32
Net profit per bbl. of incremental oil, $/bbl.	38.16

The preliminary cost analysis indicates positive economics for enhanced oil recovery through Xanthan. According to Hartshorne and Nonchick [34] successful micellar-polymer field projects, producing 0.15 PV of tertiary oil and reducing the oil field residual oil saturation to less than 20% PV, the chemical cost of the recovered oil ranged from $10 to $45 per incremental barrel of oil. In this study the chemical cost = 1.17 $/bbl. of oil, in the case of Xanthan, which means high economic profits during sandstone flooding processes. According to El-hoshoudy *et al.* [33] who studied chemical methods for heavy oil recovery and found that an important process efficiency parameter in the enhancement of oil recovery by the use of surfactants is the surfactant consumption, in lb./bbl. of oil produced. They reported that the surfactant consumption would be in the range of 7 to 35 lb./bbl. In this study slug efficiency = 8.0 lb./bbl. of oil in case of Xanthan, which means high polymer performance during flooding processes.

6. Conclusion

This research project focused on the application of biopolymers in the process of oil production. General knowledge was provided about the biopolymer injection process regarding the required physical properties, and other important factors must be taken into account. Later, in the project, 2 types of biopolymers were focused on which are xanthan gum and starch. The main objective was to compare those biopolymers together regarding the viscosity and the sweep efficiency in the flooding operations. The experimental approach of the research project was classified into 2 stages. The first stage was the rheology stage, where the viscosities of the xanthan and the starch were measured at different concentrations of 2 g/L, 4 g/L, and 6 g/L and at different temperatures by using the available viscometer in the lab. Graphical plots between the shear rate and the viscosity were made, and it was shown that the xanthan was always superior when it came to the viscosity. The second stage of the experimental work was the flooding operations, which were carried out by the core flood system that was designed by the students of this research project to help in the flooding process and obtain accurate results. Moreover, the flooding data are gathered in order to plot graphs between the pore volume injected and the oil recovery. After the procedures, it was shown that the xanthan had a higher recovery factor than starch since its higher viscosity gave it the advantage of having a higher sweeping and displacement efficiency and avoiding problems like water coning/fingering.

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