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PETROLEUM ENGINEERING

Laboratory Study of Secondary Biopolymer Flooding of Safaniya Crude Oil Through Horizontal Well

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Abstract. This paper presents an experimental investigation of the biopolymer flooding of Safaniya crude oil through horizontal well in a laboratory scaled models. Two models were scaled according to two possible horizontal and vertical field arrays. Different biopolymer concentrations were used to determine the effective concentration for Safaniya crude oil biopolymer flooding. Oil recovery and oil cut from horizontal and vertical injectors were compared.

The results showed that displacing Safaniya crude oil with 0.15% concentration yielded the highest oil recovery. Diagonally placed horizontal well in the mixed arrays resulted in more oil recovery than vertical injector and parallel placed horizontal well. Parallel placed horizontal well resulted in a higher unswept area by the biopolymer which reduced oil recovery.

Introduction

Horizontal technology is considered to be the most significant technology in the oil and gas industry of the 1980's [1]. Early application have been devoted to exploiting thin reservoirs, reservoirs suffering high tendency of water conning, and reservoirs of high vertical permeability. Recently, horizontal technology was applied for thermal recovery methods, gas injection, waterflooding, chemical flooding, and exploiting conventional reservoirs [2-4].

Chemical flooding methods for enhanced oil recovery have long history, but in the last decade they have received an ordinate amount of attention from researchers and operators alike. Polymer flood is one of such methods which has been tested and developed for conventional as well as heavy oil recovery [5]. Polymer flooding involves the addition of high molecular weight polymers to the injection water to improve the mobility ratio by increasing the viscosity of water and by reducing the effective permeability of water. This paper addresses the use of biopolymer solution for the recovery of Safaniya crude oil, which is considered as heavy crude.

Literature Review

The application of polymer flooding has been well established, not only in the laboratory studies but also in field application long ago. This history of polymer flooding goes back to the year 1964 when Pye [6] and Sandiford [7] demonstrated that the injection water mobility can be significantly reduced by the addition of small amount of a water soluble polymer. In 1966, Mungan et al. [8] studied the rheological properties of the flow characteristics of polymer solutions and classified them as pseudoplastic fluids. Later research by Mungan [9] in 1968 found that the apparent viscosity of partially hydrolyzed polymer solutions was affected by temperature: Thermal degradation occurred between 135°C and 300°C. Also, he reported that adsorption was lower in more diluted solution and polymer loss was higher in unconsolidated sand than in consolidated porous media.

An investigation of the mobility control conducted by Gogarty [10] in 1967 showed that the apparent viscosity of polyacrylamide solution decreased when salt was added to the solution resulting in a reduction in permeability due to polymer retention. Maeker [11] in 1973 reported that the increase in polymer solution flow rate increased the polymer retention in the core and resulted in lower solution viscosity and hence, lower mobility reduction.

Field results showed that polymer flooding may be employed in reservoirs with crude oils that have viscosities in the range 10 to 150 cp. Reservoir temperature should be lower than 93°C to minimize polymer degradation [5]. More effective results were obtained when polymer flooding was applied in the early stages of a water flood [11]. Polymer concentration may range from 250 to 20000 mg/L. The main operational problems encountered in polymer flooding is the reduced injectivity. Other problems include loss of polymer to the rock, and formation of tight emulsion [12].

Proposed horizontal-vertical arrays

In this study, the reservoir is viewed as a large area which will be divided into rectangles having the same shape and size. The vertical wells are distributed in the field using the 5-spot techniques. The horizontal wells are to be drilled in arrays either diagnoal or parallel to the rectangle sides (see Fig. 1). The horizontal well length is taken as the half length of the width to provide an optimum performance. The center of the horizontal well coincides with the center of the rectangle. Due to the array symmetry, one rectangular block was taken for the design of the laboratory models (the shaded areas in Fig. 1). The models contain two vertical wells located on opposite sides of one diagonal and one horizontal well located either on the other diagonal or parallel to the rectangular block. The models are scaled to a proposed prototype for these laboratory experiments.

Models Scaling

Scaling the models was based on the scaling criteria proposed by Islam and Farouq Ali [13,14] for polymer flooding where the scaling equations are driven and listed. In these publications they mentioned that there are four approaches to satisfy the scaling parameters between the models and the prototype to scale the actual process. Each approach has to relax some parameters to satisfy others depending on the phenomena taking place in the process. First approach is proposed for same reservoir fluids, different porous media, and different pressure drops. The second approach uses the same reservoir fluids, same porous media, same pressure drop, and geometric similarity. The third approach is applied for same reservoir fluis, same porous media, same presure drop, and relaxed geometric groups, and in the fourth approach same reservoir fluids, different porous media and different pressure drop, and geometric similarity is applied.

By examining this study, approach numner one has been selected which is for the same reservoir fluids, different porous media, and different pressure drop. According to this approach the implementation of the scaling criteria resulted in representing the model dimensions by a scaling factory "a". Porosity, oil saturation, and irreducible water saturation remains the same as in the prototype. Height, width, reservoir pressure, injection pressure, and injection rate of the prototype must be reduced by the scaling factor. The permeability of the prototype must be increases by the scaling factor while the time of the process will be reduced by the square of the scaling factor. Therefore, a scaling factor of 81.5 has been selected for our study and the scaling parameters for the model are calculated and listed in Table 1.

Experimental work

The experimental apparatus used in this wok is shown in Fig.2. The displacement models consist of quadrants that were made of transparent plexiglass. They have inner dimensions of 28.1 x 28.1 x 2.5 cm and containing one horizontal well on one of the diagonals with a length equals half value of the model diagonal. On the ends of the second diagonal, two vertical wells are mounted. In the other model, the horizontal well

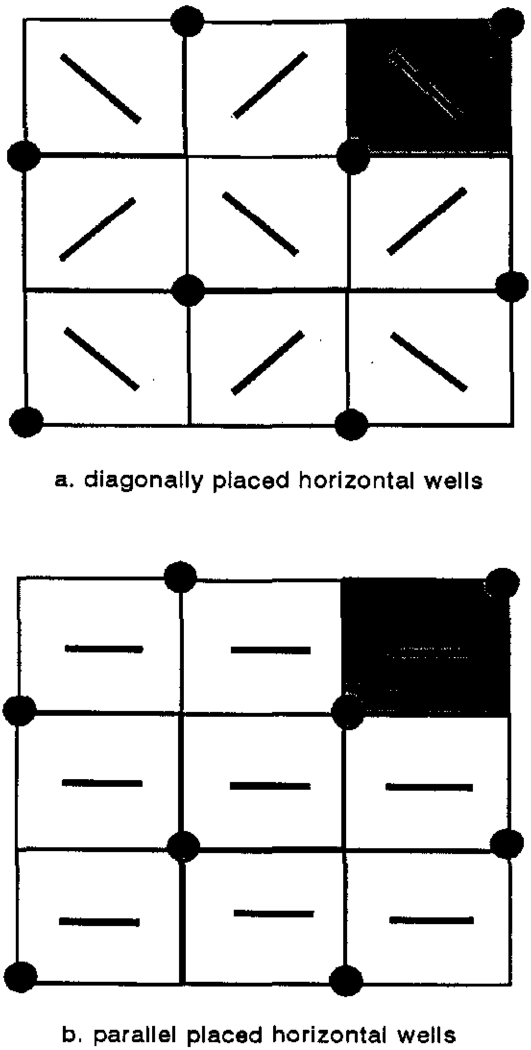

Fig. 1. Proposed field arrays of horizontal-vertical wells.

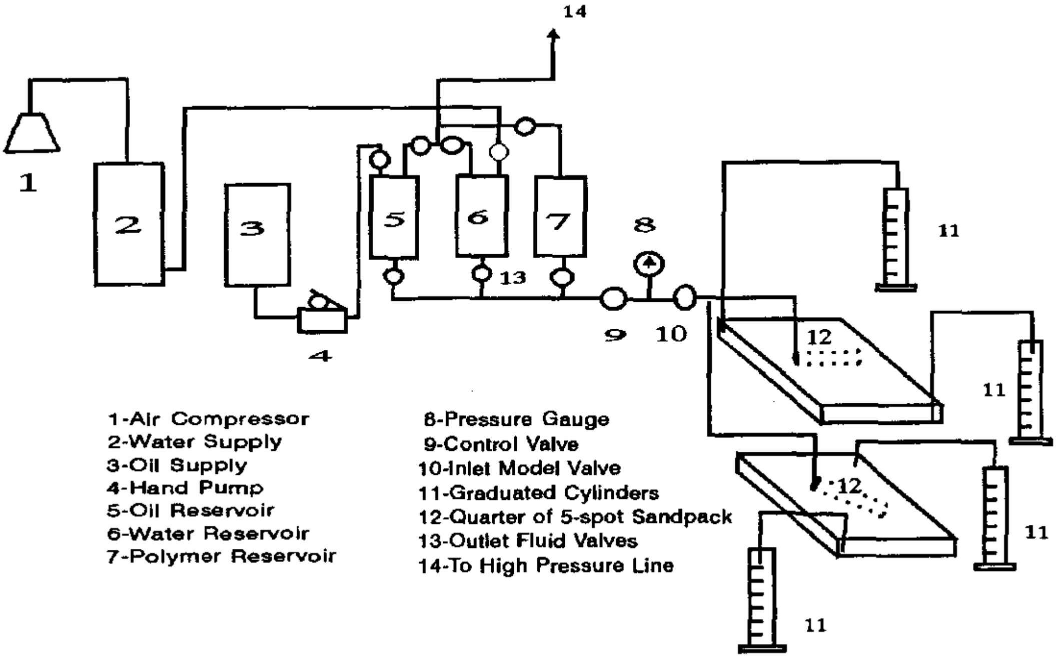

Fig. 2. Displacement apparatus setup.

Table 1. Summary of scaling parameters for selected models and prototype.

Property	Model	Prototype
Scaling factory	1.0	81.50
Permeability, darcy	2.883	0.496
Reservoir pressure, psi	5.0	2370.00
Pressure drawdown, psi	5.0	2370.00
Legth, ft	0.92	75.00
Width, ft	0.92	75.00
Thickness, ft	0.082	6.70
Well diameter, in.	0.118	9.675
Oil viscosity, cp.	17.00	17.00
Oil gravity	0.8624	0.8624
Formation water salinity, %	3.5000	3.5000

was placed parallel to two sides of the quadrants with a length equals the half length of the side and two vertical wells were placed on a diagonal of the quadrant. In both models the center of the horizontal wells coincides with the center of the quadrant. Screens were installed on the wells, both horizontal and vertical, to prevent sand movement and to allow uniform flow around the wells. A vacuum pump was used to evacuate the model and its connections before the start of the experiment. Three stainless steel tanks were used for oil, formation water, and biopolymer solution. A high pressure line was used to provide the necessary pressure to inject any of the different liquids into the model. The pressure at the inlet of the horizontal well was measured by a pressure gauge and was kept at 5 psig during polymer flooding runs. The output pressure was monitored at atmospheric pressure. The experiments were conducted at laboratory temperature.

The model was packed homogeneously with 40 mesh friable sand brought from Half Moon Bay (Eastern Province) area on the Arabian Gulf. The displacement system was then completely evacuated from air by the use of the vacuum pump. The model was then saturated with brine water 3.5% NaCl concentration and its porosity was calculated. Absolute permeability was obtained by circulating formation water at a given pressure drop across the sand pack using the two vertical wells. The following equation was used to calculate the absolute permeability [15, pp 118 and 192].

$$\frac{Q\{\mu[\ln(d/r_w) - 0.619]\}}{\{3.54\, h\, (P_i - P_o)\}}$$

Where,

Q = flow rate, bbl/day

k = absolute permeability, darcy

h = thickness of the model, ft

P_i = inlet pressure, psi

P_o = outlet pressure, psi

μ = viscosity, cp

d = distance between two vertical wells, ft

r_w = radius of production well, ft

The model was then saturated with oil by displacing the water with continuous injection of oil until 100% oil (no water) was produced in the effluent fluids. After that one pore volume of oil was injected to assure a complete saturation of the model. At this point, the initial oil saturation was irreducible water saturation were assumed to occur. For displacement process biopolymer solution was continuously injected through the horizontal well from the beginning of the experiment. The production was collected from the two vertical wells. The oil production from each well was determined and recorded. All chemical solutions were freshly prepared just before using them to avoid any effect of air exposure or precipitation.

Results and Discussion

Effect of polymer concentration on oil recovery

Figures 3 and 4 illustrate the oil recovery versus pore volume injected for a set of experiments conducted with the two models. The data of these runs are depicted in Table 2. Figure 3 demonstrates the production history of the runs conducted using waterflooding and biopolymer flooding through diagonally placed horizontal well. The polymer concentrations were 0.1%, 0.15% and 0.2% by weight dissolved in brine water 3.5% NaCl. The figure shows that there is an increase in oil recovery resulting from the use of biopolymer in displacing Safaniya crude oil. This additional oil ranges from 5% to about 30% from the original oil in place. The figure also shows that increasing the biopolymer concentration from 0.1% to 0.15% increased the incremental oil recovery by about 18% of the original oil in place while increasing the concentration to 0.2% resulted in lower cumulative oil recovery than that have been yielded by 0.15% concentration. This means that increasing biopolymer concentration from 0.15% to 0.2% has an opposite effect on the oil recovery. This gives an indication that the optimum mobility ratio between biopolymer solution and Safaniya crude oil was achieved by 0.15% biopolymer concentration. This optimum value was overridden by adding 0.2% biopolymer to the brine. The figure also shows that the highest value of incremental oil was achieved between 0.5 and 2.5 pore volume injected which could be considered as the optimum pore volume injected.

Figure 4 illustrates the run conducted through parallel placed horizontal wells. The cumulative recovery curves shows small amount of incremental oil between waterflood and bioplymer flood. Theses results can be attributed to the effect of the horizontal well

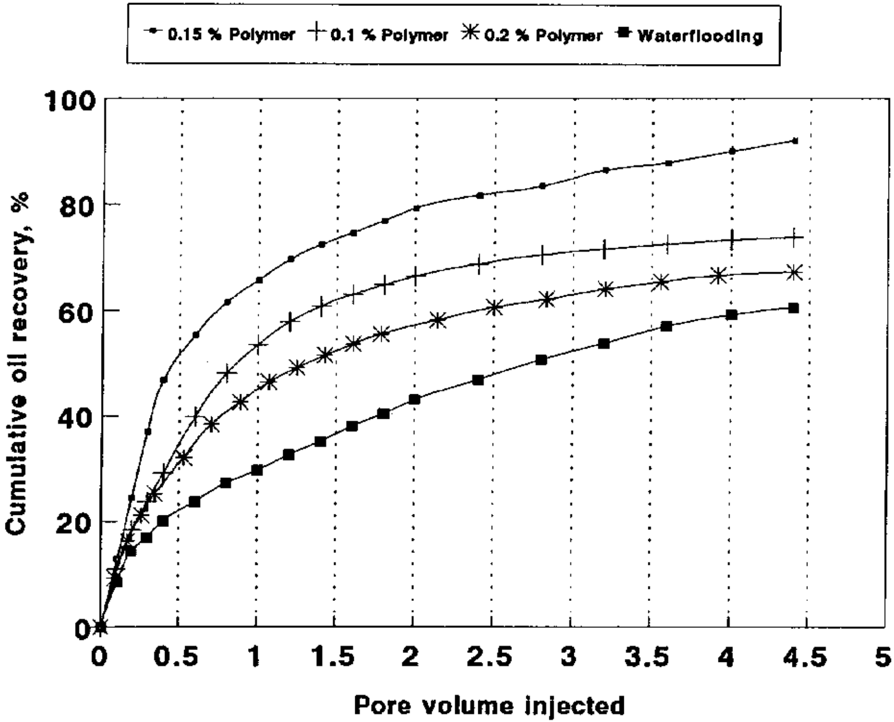

Fig. 3 Effect of polymer concentration on oil recovery through diagonally horizontal well.

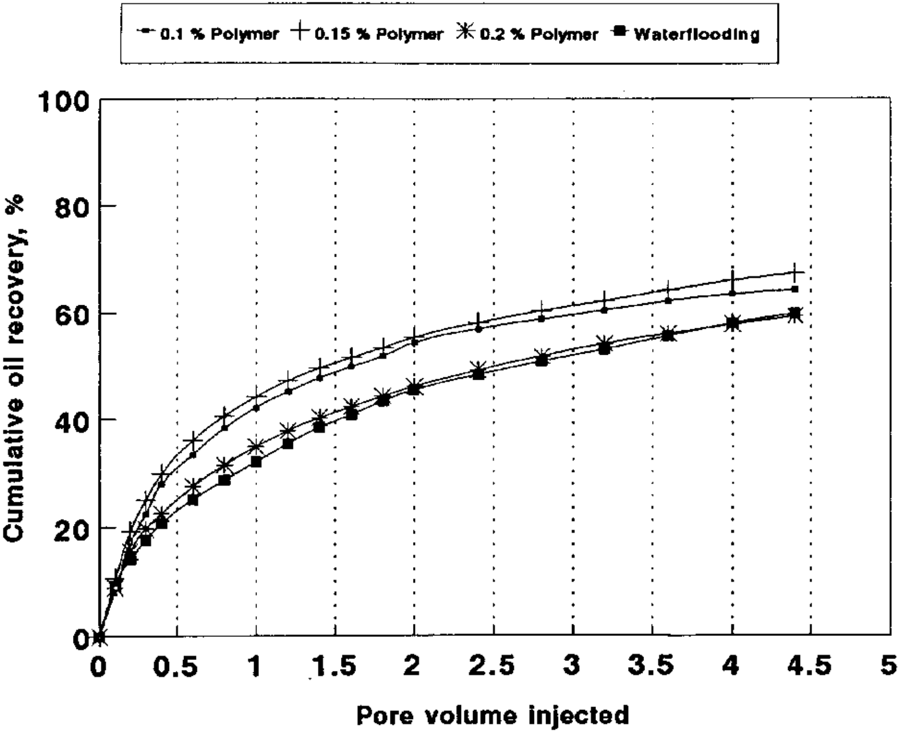

Fig. 4 Effect of polymer concentration on oil reco9very through parallel horizontal well.

Table 2. Sumary of experimental results

Run number	1	2	3	4	5	6	7	8	9	10
Pore volume, cc	450	460	450	417	425	425	410	450	440	430
Porosity	0.329	0.33	0.324	0.34	0.317	0.32	0.319	0.33	0.336	0.318
Permeability, darcy	2.858	2.928	2.912	2.941	2.837	2.916	2.814	2.893	2.918	2.817
Oil saturation, %	0./88	0.89	0.89	0.89	0.88	0.89	0.875	0.87	0.881	0.883
Water saturation, %	0.12	0.1	0.11	0.11	0.12	0.11	0.125	0.13	0.119	0.117
Polymer concen., %	0.01	0.01	0.15	0.15	0.2	0.2	WF.	WF.	WF.	0.15
Well layout	Diag.	Par.	Diag.	Par.	Diag.	Par.	Diag.	Par.	Vert.	Vert.
Cumulative oil, %	73.809	64.163	92.045	67.272	66.60	59.262	61.46	59.80	67.272	90.404

Diag. = diagonal placed horizontal well; Par. = parallel placed horizontal well; Vert. = vertical well; WF = waterflooding.

position in the model which will be discussed later. However, the figure also shows that 0.15% biopolymer concentration yielded the highest incremental oil recovery with these runs in comparison to waterflooding.

Regarding the oil cut in the produced samples which is defined as the percent of oil in the effluent, Figs. 5 and 6 depict the results of the two models with waterflooding and biopolymer flooding. It was noted that the amount of pore volume injected had markedly different effects in the waterflooding and 0.15 biopolymer concentration cases. The 0.15% biopolymer concentration resulted in late breakthrough and high oil cut at the beginning of the displacement process. After 2.5 pore volume injected the oil cut was lower than that with water flooding. This attributed to the difference in displacement mechanisms for the biopolymer solution. Also, the crossover in the curves shows that in the early life of displacement the biopolymer was superior and accelerated the oil production.

Figure 6 illustrates the results for parallel positioned horizontal well model. It shows low extent in the values than that shown in Fig. 5. These lower values are mainly due to the effect of horizontal well pattern and layout.

Effect of well pattern

Figure 7 and 8 illustrate the comparison of horizontal well patterns shown in Fig. 1 and their effects on cumulative oil recovery and oil cut in comparison to vertical well injector using 0.15% biopolymer concentration. In this figure, it is clear that diagonally placed horizontal well yielded about 25% incremental oil more than parallel placed well at the end of flooding experiments (4.4 pore volume injected). This is because the diagonally placed horizontal well divides the swept area into two identical triangles with a vertical well placed on the summit of each triangle having that largest distance to the horizontal well position. This symmetry as well as the flow pattern around the horizontal well which is ellipsoidal flow allow uniform swept areas around the horizontal well and delay the breakthrough at the vertical well. In case of parallel placed horizontal well the area was divided into two rectangles having a vertical well on the corner of each. This position allows early breakthrough to the vertical well resullting in unswept area on the other sides of the rectangles. This unswept area yielded tot oil in the model that could not be displaced by the injected fluid. In comparison to biopolymer flooding through vertical well, the curve also shows that diagonally placed horizontal well accelerated and increased the cumulative oil recovery especially at low pore volume injected. At large pore volume injected the incremental oil can be neglected. In field cases, the pore volume injected lies between 2.0 and 2.5 pore volume which means that diagnonally placed horizontal well accelerates and increases the recovery of Safaniya crude oil by biopolymer flooding.

Regarding the oil cut, Fig. 8 presents the oil cut in relation to pore volume injected for

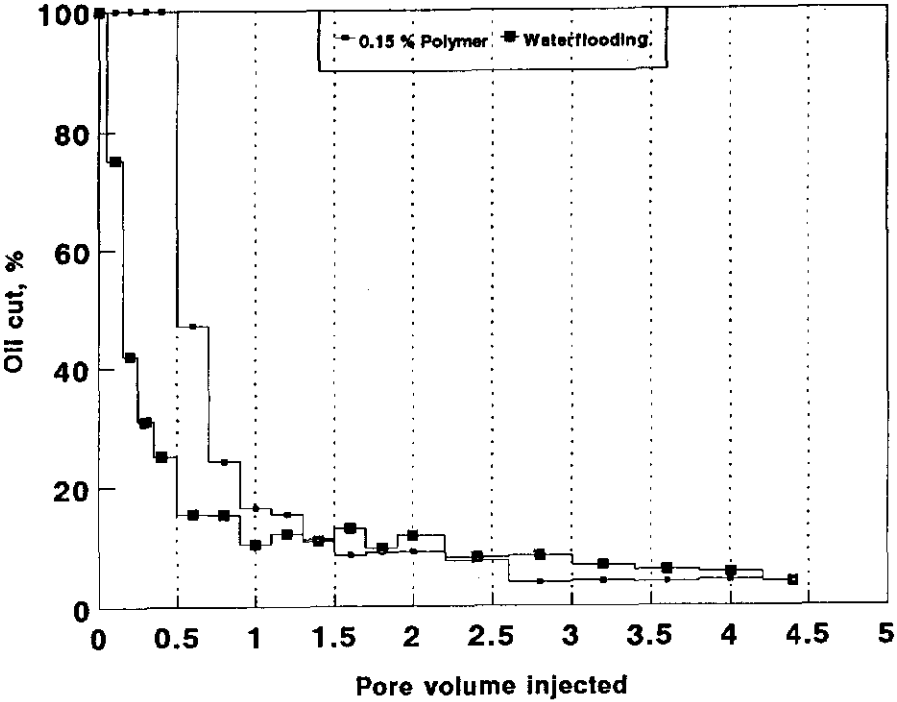

Fig. 5. Comparison of oil cut for waterflooding and 0.15% polymer concentration, diagonal model.

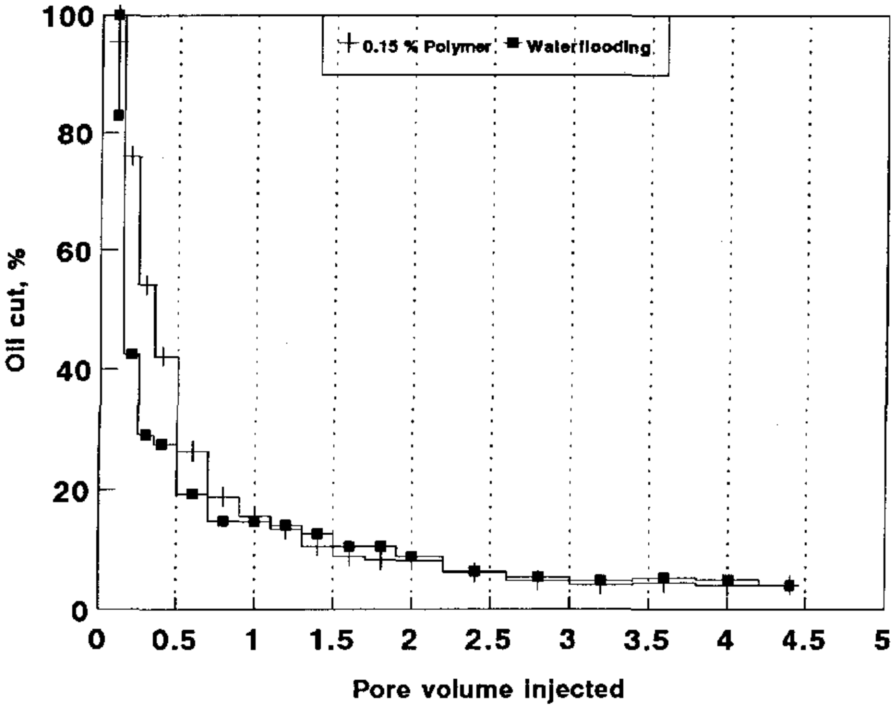

Fig. 6. Comparison of oil cut for waterflooding and 0.15% polymer concentration, parallel model.

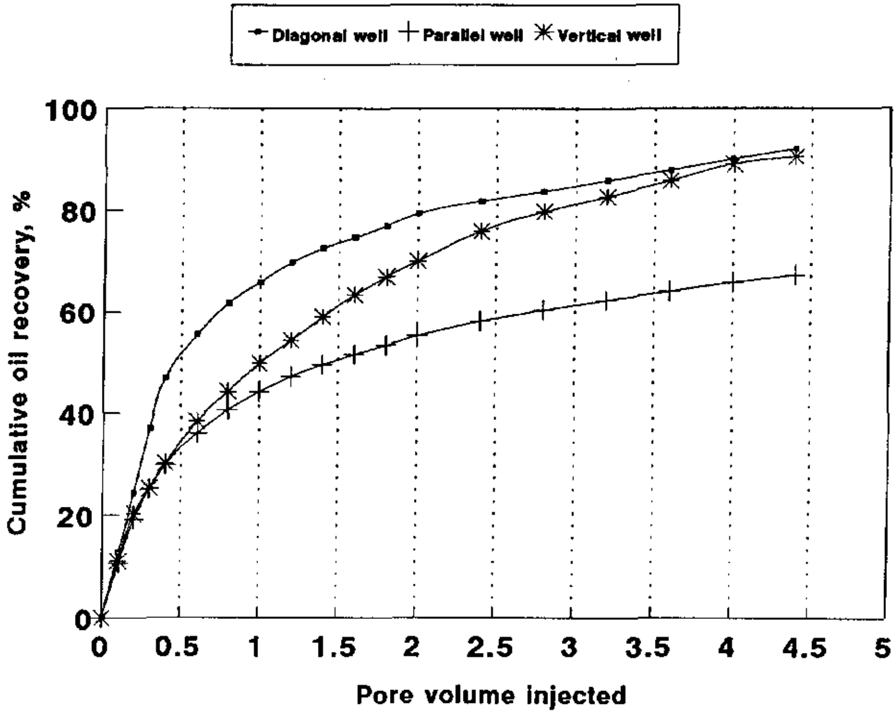

Fig. 7. Comparison of cumulative oil recovery between paralle, diagonal and vertical injectors (polymer concentration 0.15%).

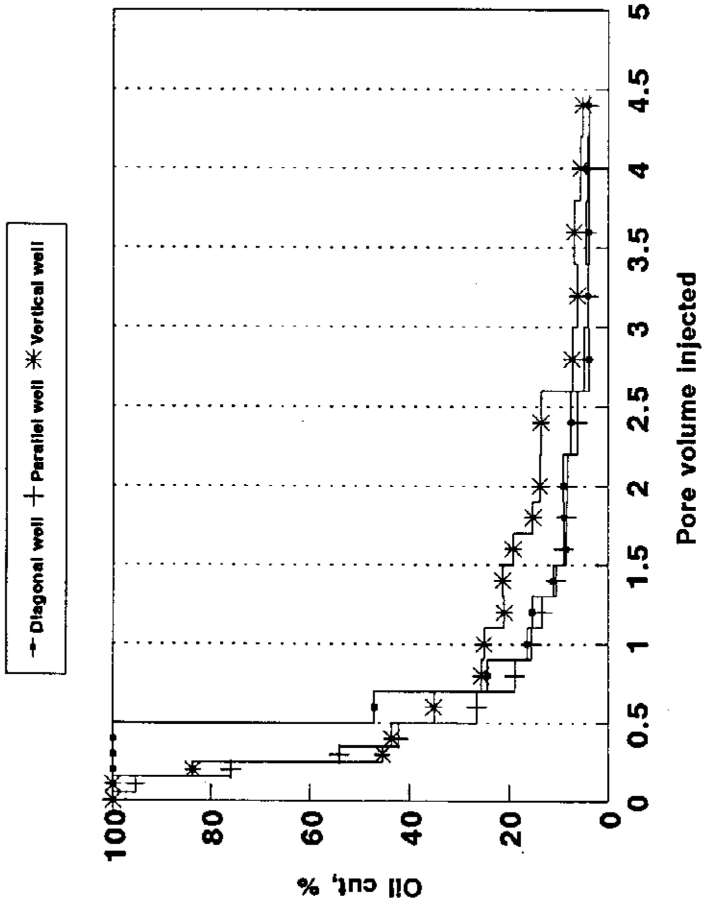

Fig. 8. Comparison of oil cut for diagonal, parallel and vertical injectors (polymer concentration 0.15%).

biopolymer flooding through diagonally placed, parallel placed horizontal wells and vertical well. The figure shows that diagonally placed well delays the breakthrough and yielded a high oil cut in the early life of injection. At about 0.75 pore volume injected the vertical injector curve crossed the diagonally placed well curve and override it till the end of experiment. This override is mainly due to the amount of residual oil in the model. Also, the difference decreases with the pore volume injected. A comparison of cumulative oil production of vertical well injector with parallel placed model shows that at the beginning of displacement the oil cut was high which was produced by biopolymer injection through horizontal well. At about 0.4 pore volume injected a crossing of the vertical injector curve had occurred and stayed overriding till the end of experiment. Also, the oil cut in the sample resulting from injection through diagonally placed and parallel placed horizontal well was identical after 1.5 pore volume injected. This means that the diagonally placed horizontal well yielded high oil cut in the first 0.8 pore volume injected resulting in about 65% cumulative oil production of the original oil in place in comparison 49% yielded from vertical injector and 43% from parallel placed horizontal well.

Conclusions

Based on the experimental results obtained from laboratory scaled experimental models of biopolymer flooding for Safaniya crude oil through horizontal well, the following conclusions are reached:

1. The highest oil recovery of Safaniya crude oil by biopolymer flooding was achieved by injecting a biopolymer solution (0.15% concentration). It was about 30% incremental oil produced.
2. In a mixed horizontal-vertical patterns, diagonally placed horizontal well is more efffective in biopolymer flooding of Safaniya crude than parallel placed one.
3. Diagonally placed horizontal well yielded better sweep efficiency and high oil cut in the early life of displacement, while parallel placed resulted in a tot oil in the model.
4. In comparison to vertical injector diagonally placed horizontal well accelerated and increased the cumulative oil recovery specially in the early life of the well.
5. Positioning the horizontal well parallel to pattern should be avoided because it gives the least recovery.

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دراسة معملية للغمر بالبوليمر الحيوي في المرحلة الثانوية لزيت خام السفانية خلال البئر الأفقي

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(استُلم في ١٦/ ٩/ ١٩٩٥م؛ قبل للنشر في ٦/ ٣/ ١٩٩٦م)

ملخص البحث. تقدم هذه الورقة إيضاحا تجريبيا للغمر بالبوليمر الحيوي لزيت خام السفانية خلال البئر الأفقي في نماذج معملية محاكاة، وقد استخدم نموذجان محاكيان لعملية صف الآبار الأفقية والرأسية في الحقل، كما استخدمت عدة تراكيز لتحديد التركيز الفعّال للغمر بالبوليمر الحيوي لزيت خام السفانية، وأجريت مقارنة للزيت المستخلص وكمية الزيت في العيّنات المنتجة من استخدام الآبار الأفقية الرأسية كحاقن للبوليمر الحيوي.

أوضحت النتائج أن إزاحة زيت خام السفانية بتركيز ١٥, ٠٪ (خمسة عشر من مائة في المائة) أعطى أعلى استخلاص للزيت. كما أعطى الوضع القطري للبئر الأفقي في المصفوفة المختلطة للآبار الأفقية والرأسية استخلاصا للزيت أكبر من الوضع المتوازي والبئر الرأسي، كما نتج عن الوضع المتوازي مساحات غير مكتسحة بالبوليمر الحيوي والتي أدّت إلى تقليل استخلاص الزيت.