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Experimental Study of Caustic Flooding through Horizontal Well

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The main objective of this study was to evaluate oil displacement by water and caustic flooding from a horizontal well as an injector in homogeneous two dimensional porous media. The oil used was Safaniya crude from Saudi Aramco.

It was found that oil recovery by tertiary caustic waterflooding increased with increasing caustic concentration from 0.5% to 1% NaOH. At 1.5% caustic concentration, it was found that the cumulative oil recovery decreased again. A comparison between horizontal and vertical wells shows that under the same conditions, horizontal wells yield higher cumulative oil recovery than vertical wells. The use of polymer in the caustic solution improves the tertiary oil displacement process.

1. Introduction

Horizontal technology is considered to be one of the most significant technological breakthroughs in the oil and gas industry of the 1980's[1]. The current focus on horizontal drilling began in the late 1970's. What was considered ten years ago as an exotic way of drilling, the economical applicability of which was contemplated with some skepticism by reservoir and production engineers, today it is a cost efficient tool for developing reserves whether new or old[1].

Early application of horizontal wells has been devoted to exploiting thin reservoirs, reservoirs suffering high tendency of water conning, and reservoirs of high vertical permeability. Recently, horizontal technology is applied for thermal recovery methods, gas injection, waterflooding, chemical flooding, and exploiting conventional reservoirs[2)~4)].

Laboratory studies on the recent applications of horizontal technology are rather scarce. However, the number of horizontal wells drilled worldwide has drastically increased. Also, laboratory studies on oil displacement by caustic flooding from vertical wells showed a greater increase in oil recovery than by waterflooding[5)~12)].

This paper studied the improvement in oil recovery using a horizontal well in the secondary and tertiary processes by caustic and caustic-polymer solutions. Also, a comparison between the recovery performance of vertical and horizontal wells under the same conditions was made.

2. Experimental Work

2. 1. Fluid Properties

The physical properties of the fluids used in this study are shown in **Table 1**. The crude oil is Safaniya crude taken from Saudi Aramco. The caustic and polymer fluids used are sodium hydroxide (NaOH) and pusher 500, respectively.

The measurements of interfacial tension be-

Table 1 Physical Properties of Fluids Used

Fluid type	Concentration [%]	Viscosity [cp]	Interfacial tension [dyne/cm]	Surface tension [dyne/cm]	pH value
Crude oil	—	54.00	28.2	31.0	1.5
Brine	3.5 NaCl	1.26	9.1	66.5	9.5
Caustic	0.5 NaOH	1.235	1.5	63.6	11.7
Caustic	1.0 NaOH	1.15	0.4	62.0	12.46
Caustic	1.5 NaOH	1.25	1.4	60.1	12.73
Caustic+Polymer	1.0 NaOH+0.5 pusher 500	2.7	5.7	55.0	13.07

API gravity of crude oil=26.8°.

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tween different solutions used and Safaniya crude oil were made by digital tensiometer model K10, manufactured by Kruss, Hamburg, Germany. A Brookfield viscometer model LVT, manufactured by Brookfield Engineering Laboratories Inc., U.S.A. was used to measure liquid viscosities. The fluid acidity was measured by 523 pH meter model manufactured by Wissenschaftlich-Technische-Werkstatten Wilheim, Germany. Buffer solutions were used for calibration before measurements.

2. 2. Experimental Apparatus

The experimental apparatus used in this work is shown in **Fig. 1**. The displacement model consists of quadrant which was made of transparent prespex. It has inner dimensions of 28.1×28.1×5 cm and contains one horizontal well on one diagonal with a length equals the model diagonal. On the ends of the second diagonal, two vertical wells are mounted. Screens are installed on the wells, both horizontal and vertical, to prevent sand movements and to minimize end effects. A vacuum pump was used to evacuate the model, and its connections were made before the start of each experiment. Three stainless steel tanks were used for the oil, formation water, caustic and caustic-polymer solution. A high pressure line was used to provide the pressure needed for the injection of different liquids into the model. The pressure at the inlet of horizontal well was measured by a

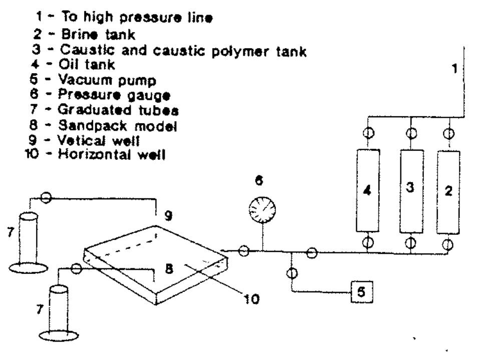

Fig. 1 Schematic Diagram of Displacement Apparatus

Table 2 Grain Size Distribution of Sand Used in Packing Processes

Mesh number	Weight percent
30	0.46
40	16.15
50	55.39
60	13.62
70	6.93
80	4.11
100	1.44
120	1.10
Pan	0.80
Total	100.00

pressure gauge. The experiments were conducted at room temperature.

The model was packed homogeneously with friable sand brought from Half Moon Bay (Eastern Province) area on the Arabian Gulf. The grain size distribution of the sand is given in **Table 2**. The sand has an average porosity of 34.04% and permeability of 1.65 darcy. The experimental system was then completely evacuated of air by using the vacuum pump. The model was then saturated with sea water. From the volume of water and the amount of sand, the experiment porosity was calculated. Absolute permeability was obtained by circulating the 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:

$$Q=\frac{[3.54\,kh(P_i-P_o)]}{\left\{\mu\left[\ln\left(\frac{d}{r_w}\right)-0.619\right]\right\}}$$

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 the production well, ft

The model was then saturated with oil by continuous injection of oil until complete oil saturation was produced. At that point, the initial saturation conditions were assumed to have occurred. For the secondary displacement process, the caustic or caustic-polymer solution was continuously injected through the horizontal well from the beginning of the displacement process. A tertiary displacement process was initiated by injection of caustic or caustic-polymer solution after the secondary waterflooding. The products were collected from the two vertical wells at ratios of the pore volume of the experiment. The amount of oil produced was determined and recorded for each well. All chemical solutions were freshly prepared just before use to avoid any effect of air exposure or precipitation.

3. Results and Discussion

The objective of this research was to evaluate the caustic flooding process through horizontal wells. A summary of the experimental results obtained are shown in **Table 3**.

Table 3 Summary of Displacement Processes

Run No.	Pore volume PV [cc]	Porosity ϕ [%]	Permeability k [darcy]	Initial oil saturation [%]	Connate water saturation [%]	Displacement process and caustic concentration	Cumulative oil recovery [%]	Residual oil after secondary process [%]
1	495	35.1	1.61	83.76	16.26	Caustic flooding 0.5% vertical well	71.2	—
2	500	35.6	1.0	82.0	18.0	Tertiary caustic flooding 0.5%	79.17	31.4
3	425	34.5	1.32	86.0	14.0	Tertiary caustic flooding 1.0%	87.11	43.3
4	380	32.2	1.27	87.0	13.0	Tertiary caustic flooding 1.5%	73.10	39.0
5	450	34.82	1.8	87.33	12.67	Secondary caustic flooding 1.0%	70.36	—
6	430	34.05	1.65	89.07	10.93	Secondary caustic+polymer flooding 1.0%+0.5%	60.57	—
7	410	33.04	1.15	89.27	10.73	Tertiary caustic+polymer flooding 1.0%+0.5%	70.82	28.6
8	415	33.48	1.68	89.39	10.61	Tertiary caustic 1.0%	60.57	28.4

Group of experiments 1 to 4 packed with 60 and 40 sand mesh sizes.
Group of experiments 5 to 8 packed with mixture of friable sand.

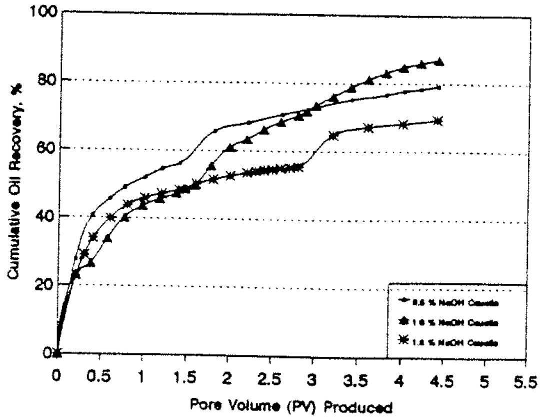

Fig. 2 Effect of Different Caustic Solutions on Oil Recovery

3. 1. Effect of NaOH Concentration on Oil Recovery

Figure 2 shows the cumulative oil recovery versus pore volumes (PV) of the fluids produced for three concentrations of caustic fluid. The caustic solution is injected in the tertiary phase. The effect of caustic solution is marked by a sudden increase in cumulative oils when the solution is injected. The figure shows that one percent concentration of NaOH resulted in an increase in oil recovery more than in the case of 0.5% and 1.5% concentrations. This behavior can be explained by the effect of caustic concentration on both interfacial tension and pH value of the solution as shown in **Table 1**. Since the Safaniya crude oil has a high acid number (1.4 mg KOH/gm crude), the effect of caustic on oil recovery is due to the chemical reactions between the caustic and organic acids occurring in the crude oil. These reactions result in the formation of surface active materials (soaps) whose absorption on the oil-water interfaces decreases the interfacial tension between oil and water, thus yielding an oil-water emulsion. Increasing NaOH concentration decreases the interfacial tension between Safaniya crude and caustic solution. The decrease reaches its maximum value at one percent NaOH concentration. From these results, it is clear that one percent NaOH concentration gives the highest oil recovery of Safaniya with horizontal wells. Moreover, the oil produced in the tertiary phase is equal to that produced in the secondary phase.

3. 2. Effect of Polymer Bank

The effect of polymer bank on cumulative oil recovery has been studied in both secondary and tertiary phases. The results are shown in **Figs. 3** and 4. **Figure 3** shows the effect of adding 0.5% polymer concentration (pusher 500) to 1% caustic

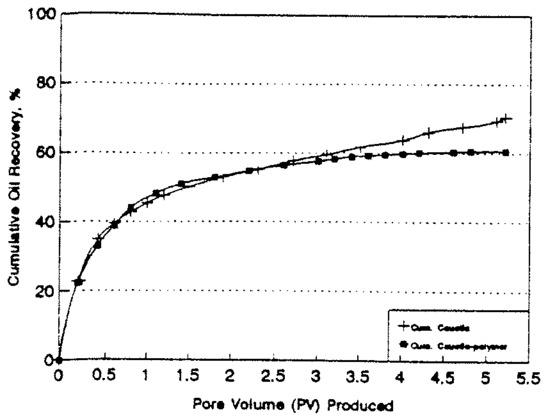

Fig. 3 Comparison between Secondary Caustic and Caustic-polymer Flooding

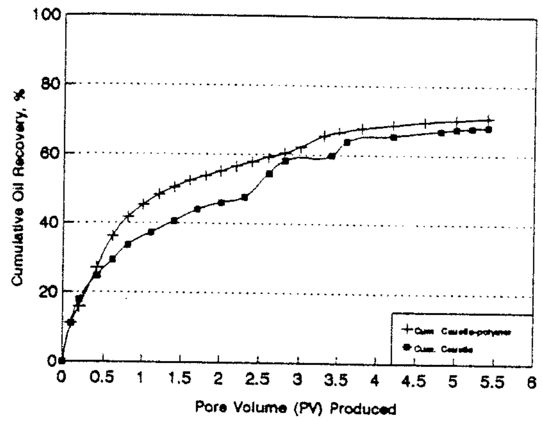

Fig. 4 Comparison between Tertiary Caustic and Caustic-polymer Flooding

solution in the secondary phase. The figure shows that addition of polymer to the caustic solution in the secondary phase does not affect cumulative oil recovery to a certain pore volume injected (2.5 pore volume). After that point, cumulative oil by caustic solution is higher than that produced by caustic-polymer. This can be explained by the decrease in the pH value of caustic solution after addition of the polymer as shown in **Table 1**. This decrease in pH value decreases oil recovery, in spite of the improvement in mobility control due to the addition of polymer. Lower pH values can cause the emulsion formed to be entrapped again into the caustic flow, resulting in better sweep efficiency. The entrainment or entrapment and the pore size distribution of the emulsions formed depend on the interfacial tension and on the applied pressure gradient during the displacement process.

The use of 0.5% polymer in 1% caustic solution in the tertiary phase is shown in **Fig. 4**. The result shows that the use of caustic-polymer in the tertiary is more effective than the use of caustic only. In spite of the minor difference in cumulative oil recovery, the caustic-polymer solution gives better production history than caustic alone. This stresses the use of caustic-polymer solution in the tertiary phase. The behavior observed in this case may be explained in terms of the improvement in mobility control due to the addition of polymer to the caustic solution and hence improvement in displacement efficiency.

3. 3. Comparison between Secondary and Tertiary

In order to compare the effect between caustic and caustic-polymer solutions on cumulative oil recovery using a horizontal well in both secondary and tertiary phases, part of the experiments was carried out under the same conditions. Some of these experiments were run by injecting the caustic solution and the caustic-polymer solution in the secondary phase. Others were completed by injecting the caustic solution and the caustic-polymer solution in the secondary phase. Others were completed by injecting the caustic solution and the caustic-polymer solution in the tertiary phase. The results are shown in **Figs. 5 and 6**.

The results of comparison between secondary and tertiary by caustic flooding are shown in **Fig. 5**. This figure shows no difference in the cumulative oil recovery. However, in the early stages, the cumulative oil recovery in the secondary is better than that in the tertiary. From the economical point of view, it is better to use caustic flooding in the secondary phase.

Figure 6 shows that, by injecting caustic-polymer solution, the cumulative oil recovery in the tertiary phase is higher than that in the secondary phase. This is marked by the polymer bank formed after injection of polymer solution. The reason can be attributed to the reduction in the

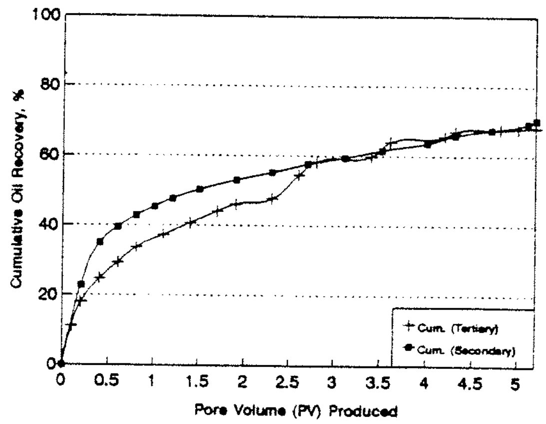

Fig. 5 Comparison between Secondary and Tertiary Caustic Flooding

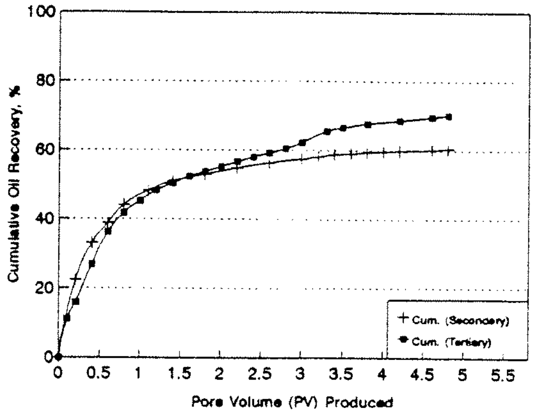

Fig. 6 Comparison between Secondary and Tertiary Caustic-polymer Flooding

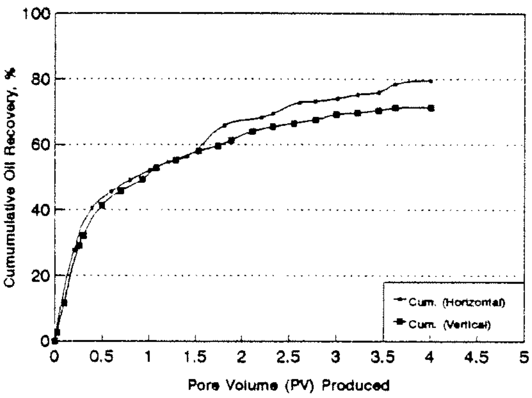

Fig. 7 Comparison between Oil Recovery from Vertical and Horizontal Well, 0.5% NaOH Concentration

pH value of the caustic fluid in the secondary stage. In case of the tertiary stage, the initial water saturation in the pores is high and will reduce the effect of polymer on the caustic solution. Moreover, the use of polymer in the tertiary will improve the mobility ratio better than its use in the secondary phase.

3. 4. Comparison between Vertical and Horizontal Wells

In order to investigate the effect of using a horizontal well on the cumulative oil recovery, the same model was used to run displacement by injecting the caustic solution from a vertical well, and production was carried out from the second vertical well while the horizontal well remained closed. The other experiments were run by injecting caustic solution from the horizontal wells, and production occurred from the two vertical wells.

The results shown in **Fig. 7** indicate that horizontal wells increase oil recovery by a minimum of 8.5% of the original oil in place. Moreover, the production rate in horizontal well is higher than that in vertical wells. This means that the use of horizontal wells increase and accelerate cumulative oil recovery and can be considered more economical than use of vertical wells. The main advantage of horizontal wells is that they contact a much greater portion of the reservoir and hence, they provide substantially higher production rates. Horizontal wells provide adequate productivity due to the vast area which is exposed to the reservoir[3),4)].

4. Conclusions

Based on the experimental conditions of this study, the following conclusions are obtained:
1) Horizontal wells increase and accelerate oil recovery.
2) The best caustic concentration to yield the maximum oil recovery from horizontal well is 1% (by measuring).
3) In comparison to vertical wells, horizontal wells yield 8.5% increase, as minimum, in oil recovery under the same conditions.
4) The use of polymer in caustic solution improves the oil displacement in the tertiary process. However, in the secondary stage the presence of polymer causes a decrease in oil recovery due to decrease in pH value.
5) Effects on the secondary and tertiary recovery processes of caustic solution are comparable. However, injection of caustic in the secondary stage reduces the cost and accelerates oil production.

Acknowledgment

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要　旨

水平坑井におけるアルカリ攻法の実験的研究

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この研究の主な目的は，二次元方向に均一な多孔質媒体を用いて，水平坑井からアリカリ溶液を注入して，油を回収する方法を調べることである。用いた油はサウジアラムコから得られたサファニヤ原油である。

アルカリ攻法による三次回収においてアルカリ濃度が 0.5% から 1% までは回収量が増加したが，1.5% では回収量は逆に低下した。水平坑井と垂直坑井を比較すると，水平坑井の方がより多く油が回収された。ポリマーを使うと三次回収量はさらに増加した。

Keywords

Horizontal well, Caustic flooding, Secondary recovery, Tertiary recovery, Polymer solution