J. King Saud Univ., Vol. 8, *Eng. Sci.* (1), pp. 59–75 (A.H. 1416/1996)

PETROLEUM ENGINEERING

Laboratory Study on the Effect of Horizontal-vertical Well Configurations on Oil Recovery Using Sodium Hydroxide

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(Received 12/2/1994; accepted for publication 7/1/1995)

Abstract. This paper presents a laboratory-scale experimental investigation on the performance of horizontal-vertical well configurations in conjunction with oil recovery by alkaline flooding. Emphasis focuses on the effect of the horizontal well position and length on oil recovery. The effect of three alkali solution types, [i.e. sodium carbonate (Na_2CO_3), sodium ortho-silicate (Na_4SiO_4), and sodium hydroxide (NaOH)] on cumulative oil yield, in both secondary and tertiary recovery processes is also investigated, using a linear model and various horizontal-vertical schemes.

It was found that displacing Safaniya crude oil by a 1% NaOH solution results in higher oil recoveries in both linear and horizontal-vertical schemes. Moreover, the highest oil recovery through horizontal-vertical schemes was obtained by positioning the horizontal well perpendicular to the line connecting both vertical producing wells with a length that does not extend to the reservoir boundary. It was also found that the oil displacement efficiency in the tertiary process is much higher than that encountered in the secondary process. Also, increasing horizontal well length in a limited reservoir area does not increase the cumulative oil recovery.

Introduction

With the continuing progress in drilling techniques, the use of horizontal wells has been increasing very rapidly throughout the oil industry. However, in spite of a recent tremendous increase in published literature references, little information is available on horizontal well applications for enhanced oil recovery (EOR) methods [1]. Many published articles show that horizontal wells are used so far primarily to solve specific production problems. These include low permeability formations and especially fractured formations, low permeability gas reservoirs, unusual gas sources, gas or water coning, thin formations, and viscous oil [2,3].

Most horizontal applications of the EOR activity have been in the area of thermal recovery, primarily in conjunction with steam stimulation and steam drive operations [4,5]. Published information on the use of horizontal injection wells, other than for thermal recovery, is scanty. However, the need for systems of both horizontal injection and vertical production wells, as a means of increasing flooding rate in EOR, has been mentioned [6-9]. Early laboratory work [10] showed that the use of a horizontal well as an injector in alkaline flooding increases oil recovery by a minimum of 8.5 per cent of initial oil in place (IOIP) relative to a vertical injector well.

This paper investigates the effect of horizontal-vertical well configurations in a rectangular parallelepiped sand pack laboratory model on oil recovery by alkaline flooding. It also discusses the effect of alkali type and concentration on oil recovery in both the secondary and tertiary processes. Safaniya crude oil from Saudi Aramco was used to qualitatively investigate the effect of horizontal-vertical well configurations in a laboratory-scale rectangular block simulating a reservoir producing oil by alkaline flooding.

Scaling Parameter Calculations

In enhanced oil recovery, the scaling technique is usually adopted to interrelate the variables pertinent to fluid flow in porous media. The most comprehensive scaling technique treatment is given by Henley *et al.* [11] and Perkins *et al.* [12]. This involves the calculations of seven dimensionless groups: well spacing, well radius, well penetration, cumulative oil production, mobility ratio, gravity force to viscous force ratio and capillary force to viscous force ratio. Some of these parameters were calculated for the model used in this study. A comparison between the calculated scaling parameters and the practical ranges quoted from Henley *et al.* [11] is given in Table 1. This table shows that the calculated scaling parameters are in agreement with the practical ranges. The vertical permeability is assumed equal to the horizontal permeability. The seventh parameter is not calculated because of the difficulty to measure capillary forces in the model. The scale up parameters were originally conceived for vertical wells; the selected horizontal well has the same vertical well diameter, based on the modeling techniques suggested by Chang *et al.* [8].

Experimental Work

Fluid properties

The physical properties of the fluids used in this study are given in Table 2. The investigated Safaniya crude oil was obtained from Saudi Aramco. The alkali types

Table 1. Comparison between geometrical scaling parameters of used model and possible practical ranges recommended by Henley *et al.* [11].

Geometrical parameter	Possible practical range	Selected model
Dimensionless well spacing = $(a/h)\sqrt{k_v/k_h}$	2.0 – 20.0	15.896
Dimensionless well radius = $(r_w/h)\sqrt{k_v/k_h}$	0.0008 – 0.2	0.06
Dimensionless well penetration = b/h	0.0 – 1.0	1.0
Cumulative production parameter = $Ah\phi[1-S_{wi}-S_{or})/Qt]$	1.0	1.0
Mobility ratio = $k_o\mu_w/k_w\mu_o$	0.1 – 10.0	0.13
Gravity force / viscosity force= $kg\,\Delta P\,A/Q\mu_o$	0.0 – 1000	97.48
Capillary force / gravity force = $\sigma\cos\theta(\sqrt{kg})\Delta Ph$	0.0 – 15	NC*

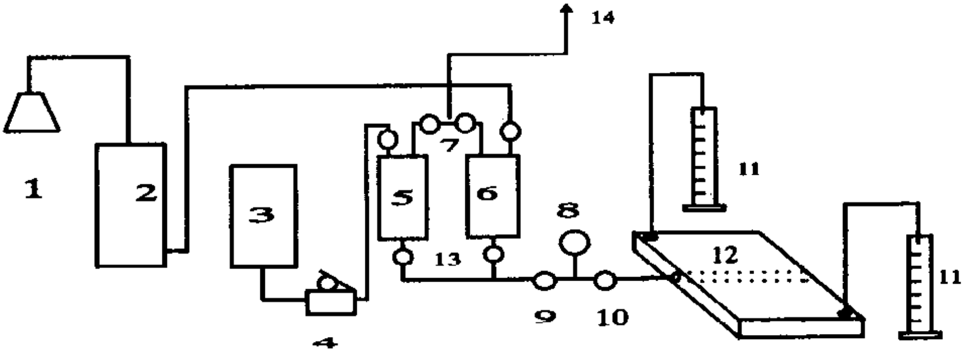
*NC = Non calculated

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	0.8
Total	100.00

used were sodium hydroxide (NaOH), sodium carbonate (Na_2CO_3) and sodium ortho-silicate (Na_4SiO_4).

The measurements of interfacial tension between different solutions and Safaniya crude oil were carried out by means of a digital tensiometer model K10, manufactured by Krauss, Hamburg, Germany. A Brookfield viscometer model LVT, manufactured by Brookfield Engineering Laboratories, Inc., USA, was used to measure liquid viscosities. The fluid acidity was determined by a 523 pH meter model manufactured by Wissenschaftlich Technische Werkstatten. Wilheim, Germany. Buffer solutions were used for calibration before measurements.



1. Air compressor
2. Water supply
3. Oil supply
4. Hand pump
5. Oil reservoir
6. Water reservoir
7. Inlet pressure valves
8. Pressure gauge
9. Control valve
10. Inlet model valve
11. Graduated cylinders
12. Rectangular parallelepiped sand pack
13. Outlet fluid valves
14. To high pressure line

Fig. 1. Displacement apparatus setup.

Experimental apparatus

The experimental apparatus is shown in Fig. 1. Two displacement models were used for experimentation; a linear model and a rectangular parallelepiped model. The linear model consisted of a steel tube with 5 cm diameter and 61 cm length. The rectangular parallelepiped sand pack model was a transparent perespex section with inner dimensions of 28.1 × 28.1 × 2.5 cm. Five configuration schemes of the sand pack model were investigated.

Well configurations

The selected well configuration simulate field applications of a horizontal injection well in conjunction with already existing production vertical wells. The investigated well configuration schemes are schematically shown in Fig. 2, and are described below:

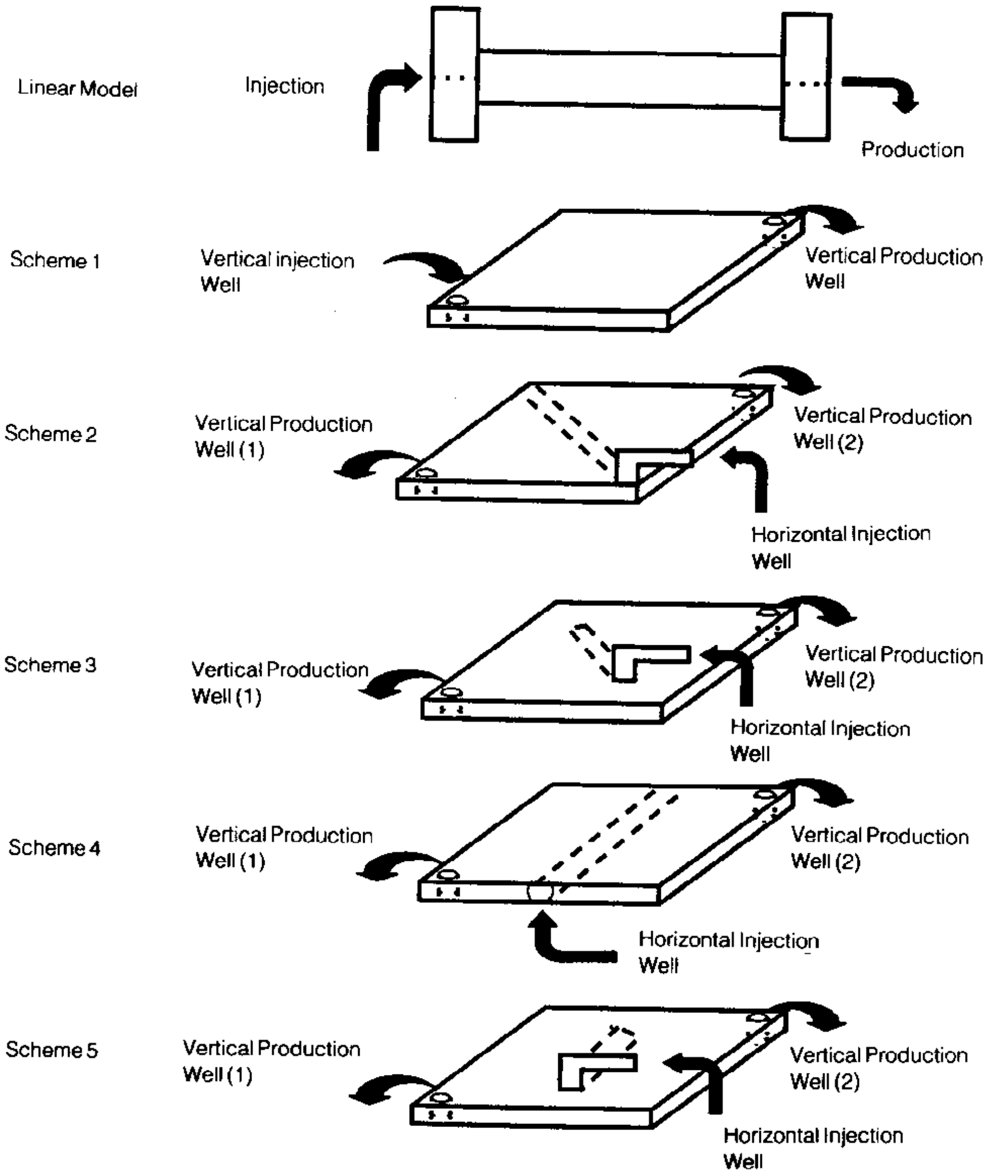


Fig. 2. Experimental well configurations.

1. Scheme 1 consists of a vertical injection well and a vertical production well. It is used for comparison as a conventional alkaline flooding case.
2. Scheme 2 is composed of a horizontal injection well and two vertical production wells. The horizontal well axis is a diagonal perpendicular to the line connecting the two vertical wells.
3. Scheme 3 is similar to scheme 2 with a reduction of the horizontal well length to half its value.
4. Scheme 4 consists of a horizontal injection well and two vertical production wells. The horizontal well axis forms a 45 degree angle with the line connecting both vertical wells.
5. Scheme 5 is similar to scheme 4 with a reduction of the horizontal well length to half its value.

Perforated 0.5 cm outside diameter stainless steel tubings with 0.3 cm inside diameter were used as horizontal and vertical wells. The wells were enveloped with a 200 mesh screen to prevent sand production and end effects.

A vacuum pump was used to evacuate the model and its connections before the start of each experiment. Three stainless steel tanks contained the oil, formation water, and alkaline solution. A high pressure feeding line was used to inject different liquids into the model. The pressure at the inlet was measured by a pressure gauge. The experiments were conducted at room temperature.

Experimental procedure

The models were packed with friable sand brought from Half Moon Bay (Eastern Province) located on the Arabian Gulf. The grain size distribution of the sand is given in Table 2. The sand pack had an average porosity of 34.26% and a permeability of 1.4 darcy. The experimental assembly was then completely evacuated from air by means of the vacuum pump. The model was then saturated with brine water. From the volume of water and the amount of sand, the experimental porosity was calculated. The absolute permeability value was obtained through circulating the formation water at a given pressure drop across the linear model or across the sand pack using both vertical wells.

The following equation was used to calculate the absolute permeability [13]:

$$Q = \frac{3.541\ kh\ (P_i - P_o)}{\left\{\mu\left[\ell n\left(\frac{d}{r_w}\right) - 0.619\right]\right\}}$$

Injection of oil was then carried out until complete oil saturation of the model was reached, corresponding to the initial saturation conditions. For the secondary displacement process, caustic solution was continuously injected either through the linear model or through the horizontal well from the beginning of the displacement process. A tertiary displacement process was performed through injecting alkaline solutions following secondary waterflooding. The products were collected from the two vertical wells and expressed as ratios of the model pore volume. The amount of oil produced was determined and recorded for each well for horizontal well displacement. All chemical solutions were freshly prepared just before use to avoid any air exposure or precipitation effects.

Results and Discussion

The main objective of this research is to evaluate the performance of horizontal-vertical well configurations in secondary and tertiary alkaline solution flooding, using a rectangular parallelepiped sand pack model. To achieve this objective, a linear model was first used to evaluate the displacement efficiency of alkaline solutions, namely, sodium hydroxide (NaOH), sodium carbonate (Na_2CO_3) and sodium ortho-silicate (Na_4SiO_4) to produce Safaniya crude oil from a sand pack laboratory model. The solution achieving the highest oil recovery in the linear model was used in the horizontal-vertical alkaline flooding processes.

Type of alkaline utilized

The selection of an alkali type was based on interfacial tension as well as surface tension of the solution [14-17]. Table 3 gives these properties for the three alkali materials. The plot of these properties in Fig. 3, indicates that the lowest viscosity results from the use of one per cent sodium hydroxide (NaOH). A one per cent sodium carbonate (Na_2CO_3) minimizes interfacial tension. Lowest surface tension occurs when using a 0.5% Na_2CO_3 concentration.

Linear model alkaline flooding experiments were run to categorize the alkaline type and alkaline concentration on displacement efficiency basis. The results are given in Table 4, and are graphically plotted on Fig. 4. It appears that the highest oil recovery is obtained when using a one per cent NaOH alkaline solution. This same NaOH concentration was, therefore, utilized in all displacement runs.

Oil recovery through vertical and horizontal wells

In order to differentiate between the performance of a vertical injector and that of a horizontal injector, the second model (scheme 1) was used to run displacements

Table 3. Physical properties of fluids used

Fluid type	**Concentration %**	**Viscosity mPa.s**	**Interfacial tension mN/m**	**Surface tension mN/m**	**pH value**
Crude oil	--	54.00	28.2	31.0	1.5
Brine	3.5 NaCl	1.26	9.1	66.5	9.5
Alkaline solution	0.5 Na_4SiO_4	1.25	0.3	41.1	10.8
"	1.0 Na_4SiO_4	1.185	0.5	42.0	10.9
"	1.5 Na_4SiO_4	1.267	0.3	42.5	11.1
"	0.5 NaOH	1.213	1.5	55.0	12.78
"	1.0 NaOH	1.107	0.4	55.4	13.07
"	1.5 NaOH	1.6	1.3	56.0	13.10
"	0.5 Na_2CO_3	1.15	0.3	34.8	10.6
"	1.0 Na_2CO_3	1.173	0.2	55.6	10.75
"	1.5 Na_2CO_3	1.228	0.5	42.2	10.8

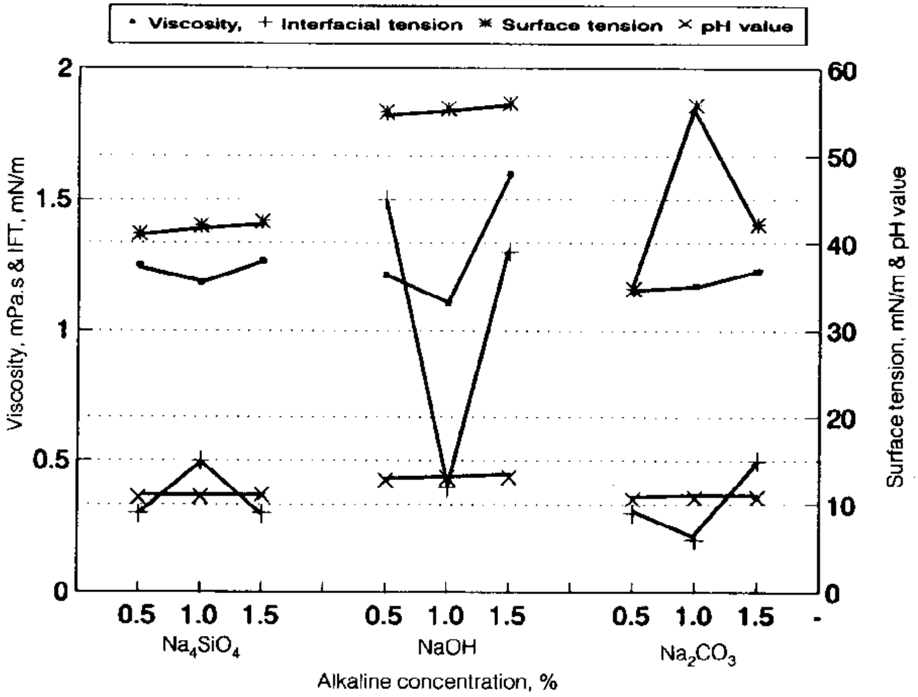


Fig. 3. Effect of alkaline type and concentration on physical properties of solution.

Table 4. Summary of displacement processes using the linear model

Run number	1	2	3	4	5	6	7	8	9
Initial oil saturation, %	87.4	86.4	89.2	87.4	85.68	88.6	90.0	86.76	88.54
Initial water saturation, %	12.6	13.6	10.8	12.6	14.32	11.4	10.0	15.34	11.46
Porosity, %	35.5	35.6	35.7	35.8	32.8	35.7	36.1	36.6	36.4
Permeability, darcy	3.2	3.179	3.33	3.33	3.33	3.33	3.33	3.33	3.33
Alkaline type	Na_4SiO_4	Na_4SiO_4	Na_4SiO_4	Na_2CO_3	Na_2CO_3	Na_2CO_3	NaOH	NaOH	NaOH
Alkaline concentration, %	0.5	1.0	1.5	0.5	1.0	1.5	0.5	1.0	1.5
Cumulative recovery, %	68.88	63.74	62.78	55.30	67.78	68.65	76.22	77.98	70.29

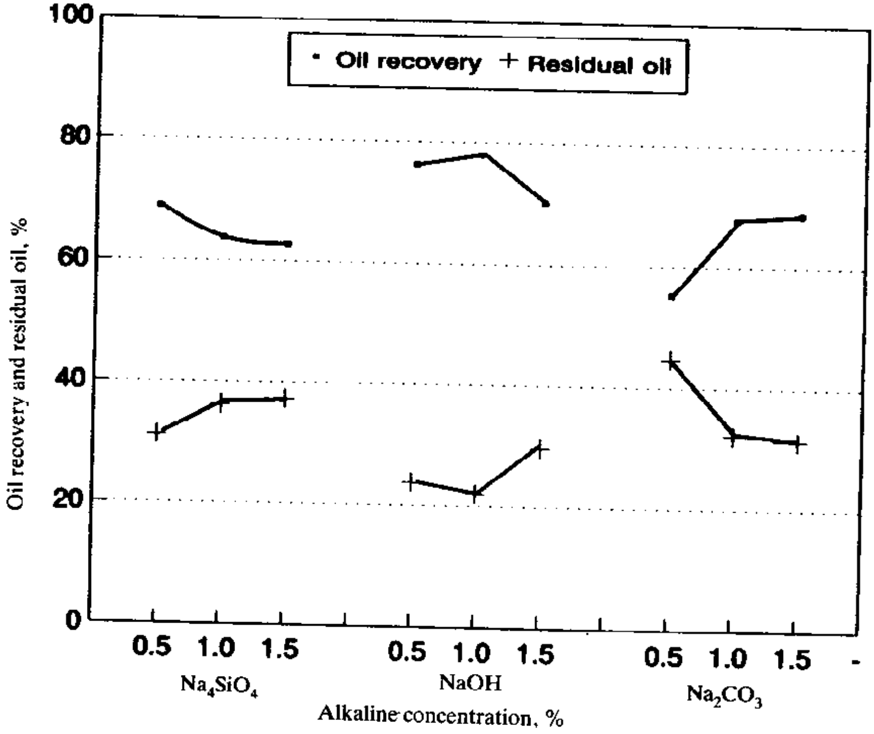


Fig. 4. Oil recovery and residual oil by alkaline flooding through linear model.

by alkaline solutions (a vertical injector well and a vertical producer well). The same experiments were run by introducing the alkaline solution through a horizontal injector well (scheme 2), being collected from two vertical production wells. These experiments were run with 0.5, 1.0 and 1.5% NaOH solutions.

The results are compiled in Table 5 and are plotted on Fig. 5. They indicate that horizontal wells increase oil recovery by a minimum of 8.5 per cent of the original oil in place and accelerate production. This is due to the fact that the horizontal well configuration results in the sweep of a larger portion of the reservoir. Figure 5 also compares between oil recoveries for the linear, vertical injector-vertical producer and the horizontal injector-vertical producer models at different sodium hydroxide (NaOH) concentration levels. It appears that the horizontal injector is better performing and that a one per cent NaOH concentration achieves the highest Safaniya crude oil recovery. The increase in oil recovery is attributed to an improved sweep pattern and to the formation of surfactants through combination of sodium hydroxide with organic acids naturally present in Safaniya crude oil.

Table 5. Summary of displacement processes using a rectangular parallelepiped sand packs

Run number	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17
Pore volume, cc	495	447	449	500	425	380	450	425	440	430	420	430	430	435	425	420	435
Porosity, %	35.1	35.8	37.45	35.6	34.5	32.2	34.82	33.25	34.15	33.52	33.9	33.63	33.33	33.5	33.8	33.8	34.1
Permeability, darcy	1.61	1.63	1.52	1.00	1.32	1.27	1.80	1.30	1.47	1.48	1.38	1.40	1.00	1.47	1.36	1.32	1.48
Initial oil saturation, %	83.76	81.74	87.30	82.00	86.00	87.00	87.33	86.75	87.12	85.34	87.38	87.20	88.83	85.30	86.40	86.51	85.21
Initial water saturation, %	16.24	18.26	12.70	18.00	14.00	13.00	12.67	13.25	12.88	14.66	12.62	12.80	11.17	14.70	13.60	13.45	14.75
Displacement process	Tertiary	Tertiary	Tertiary	Tertiary	Tertiary	Tertiary	Secondary	Tertiary	Secondary	Tertiary	Secondary	Tertiary	Secondary	Tertiary	Tertiary	Tertiary	Tertiary
Alkaline concentration, %	0.5	1.0	1.5	0.5	1.0	1.5	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0	1.0
Cumulative recovery, %	71.67	75.49	61.3	79.17	87.11	73.1	70.36	92.1	73.5	56.53	47.0	64.53	51.57	89.67	93.54	58.17	65.54
Residual oil saturation after secondary, %	38.91	40.19	41.67	31.4	30.3	32.0	---	27.2	---	44.06	---	42.67	---	31.30	28.10	45.40	43.50
Well configuration	1	1	1	2	2	2	2	3	3	4	4	5	5	2	2	4	4
Horizontal well length	---	---	---	L	L	L	L	0.5L	0.5L	L	L	0.5L	0.5L	0.75L	0.25L	0.75L	0.25L

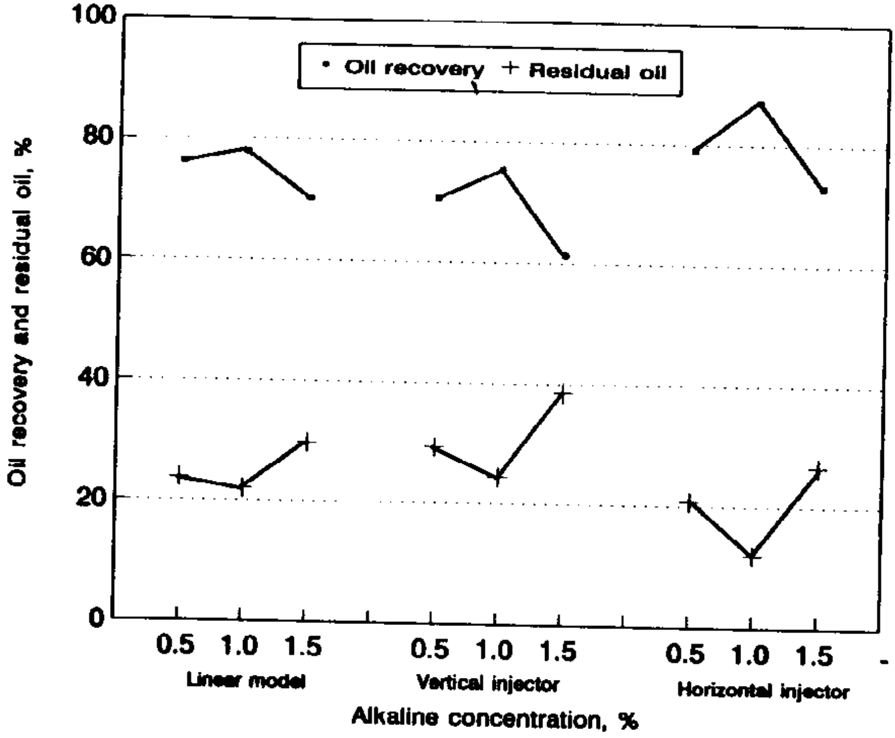


Fig. 5. Effect of model type on oil recovery by alkaline flooding.

Effect of well configuration schemes in secondary and tertiary processes

In order to investigate the effect of horizontal well configuration and length, displacement runs were conducted using the 5 schemes described before. The experiments were carried out for both secondary and tertiary production processes. Alkaline secondary recovery was achieved through alkaline solution injection from the beginning of the experiments, while in tertiary recovery, oil displacement with alkaline solution followed water-flooding. The results are given in Table 5 and are graphically represented in Fig. 6.

The results indicate that scheme 3 produces the best cumulative oil recovery among all investigated schemes. Scheme 5 also produces a higher cumulative oil recovery than scheme 4. Higher oil recoveries with a smaller horizontal well length can be attributed to better oil sweep patterns. It is believed that the smaller well length generates a uniform ellipsoidal flow pattern around the well and prevents fingering of the displacing fluid through the boundary. Horizontal wells not extending

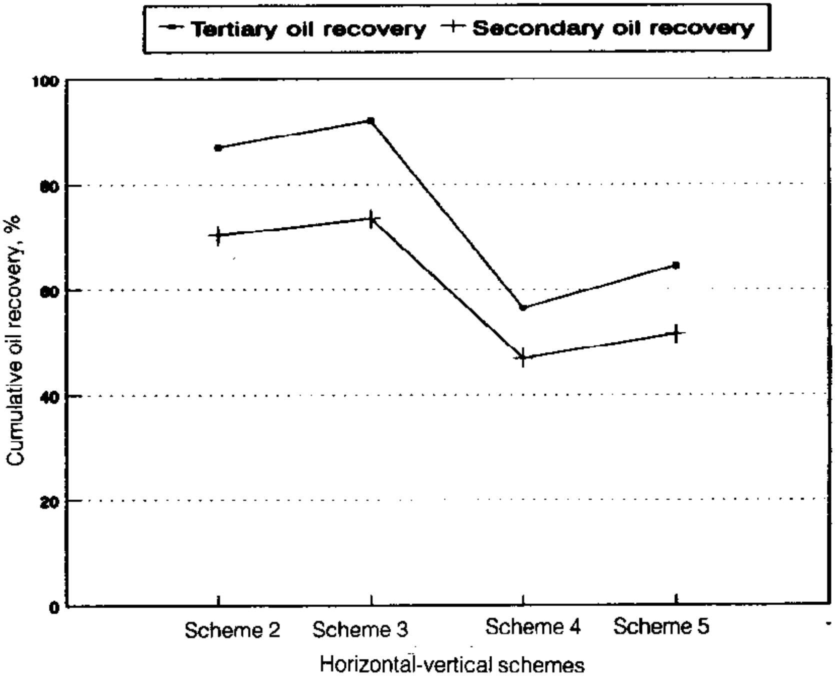


Fig. 6. Comparison of oil recovery in secondary and tertiary processes in horizontal-vertical schemes.

in length to the reservoir boundary thus increase oil recovery through sweep pattern inprovement.

Concerning the horizontal well layout, investigational results indicate that positioning the horizontal well perpendicular to the line connecting two vertical wells produce much more oil than a well inclined relative to mentioned position (schemes 2 and 4). This is because the perpendicular configuration divides the swept area into two equal triangles with both vertical producing wells located at the summit of each triangle. Such configuration minimizes the average flow path of swept oil between the horizontal injector and both vertical productors.

Figure 6 also reveals that the tertiary recovery process yields more oil than does the secondary process which indicates that alkaline solutions exhibit higher displacement efficiencies for Safaniya crude oil at higher water saturation levels.

Effect of horizontal well length on oil recovery

Four experiments were run with horizontal well lengths of 0.25 and 0.75 of the full length for each scheme. The results are plotted in Fig. 7, for horizontal injector

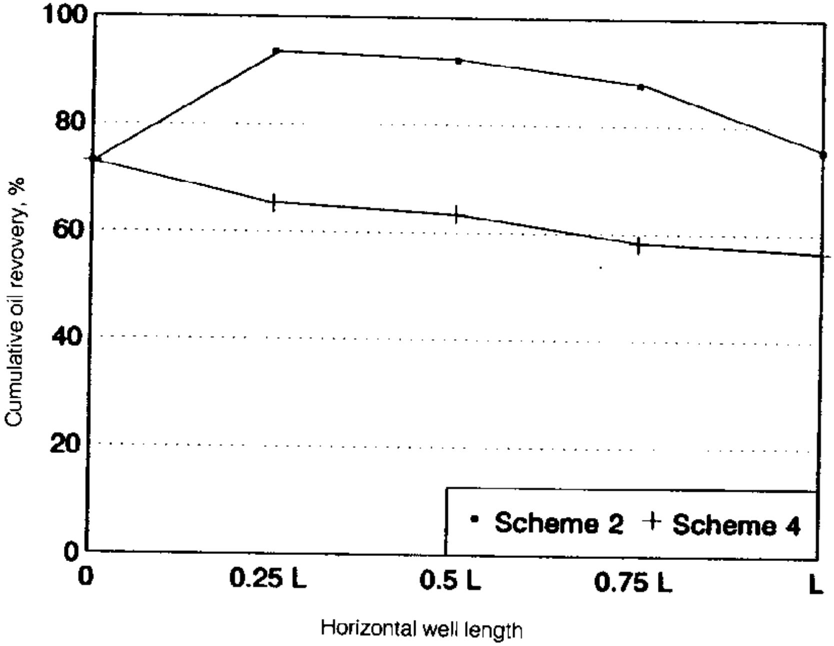


Fig. 7. Effect of horizontal well length on tertiary oil recovery for schemes 2 and 4.

lengths ranging from zero (vertical injector) to full value (L). It appears that 0.26 L achieves the highest oil recovery; later decreases gradually with increasing horizontal injection length.

Conclusion

The obtained experimental results lead to the following conclusions:

1. Safaniya oil recovery tests, through displacement with alkaline solutions, indicate that sodium hydroxide (NaOH) is better than sodium carbonate (Na_2CO_3) and sodium ortho-silicate (Na_4SiO_4). The highest recovery is obtained by injecting one percent NaOH solution.
2. The injection of alkaline solution through horizontal wells achieves a better sweep and a higher oil recovery than those experienced when using vertical wells or unidirectional displacement flow patterns.
3. Positioning the horizontal injector well perpendicular to the line connecting both vertical production wells achieves the highest oil recovery relative to other well configuratios. Injector well interference with the model or th reservoir

boundary should be avoided.

4. The use of alkaline flooding as a tertiary recovery process produces more oil than it achieves in secondary recovery process because of improved oil displacement efficiency at higher water saturation levels.
5. Increasing horizontal well length in a limited reservoir area reduces cumulative oil recovery.

Nomenclature

A = well production area, ft^2
a = well spacing, ft
b = vertical well penetration, ft
d = distance between vertical wells, ft
g = gravitational constant, 32.2
h = formation thickness or model thickness, ft
k = absolute permeability, darcy
k_o = effective oil permeability, darcy
k_w = effective water permeability, darcy
k_v = vertical permeability, darcy
k_h = horizontal permeability, darcy
L = horizontal well length, ft
P_i = inlet pressure, psi
P_o = outlet pressure, psi
ΔP = pressure difference, psi
Q = flow rate in equation, bbl/day or production rate in geometrical parameters, Table 1
r_w = well radius, ft
S_{oi} = initial oil saturation
S_{wi} = initial water saturation
t = time
μ = viscosity, cp
μ_o = oil viscosity, cp
μ_w = water viscosity, cp
σ = shear stress, psi
θ = contact angle

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دراسة معملية عن تأثير نظم الآبار الأفقية ـ الرأسية على إنتاجية النفط باستخدام محلول هيدروكسيد الصوديوم

عبدالعليم هاشم السيد، محمد بن سعود البليهد و عطية محمود عطية

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الرياض ١١٤٢١، المملكة العربية السعودية

(اسُتلم في ١٢/٢/١٩٩٤م؛ قبل للنشر في ٧/١/١٩٩٥م)

ملخص البحث. تقدّم هذه الورقة استقصاءً معمليًا تجريبيًا عن أداء نظم الآبار الأفقية ـ الرأسية وربطها بإنتاجية النفط بالغمر القلوي. فقد رُكِّز فيها علي إبراز تأثير مكان وطول البئر الأفقي على إنتاجية النفط. كما بحث أيضًا تأثير ثلاثة أنواع من المحاليل القلوية، ألا وهي كربونات الصوديوم (Na_2CO_3)، رباعي سليكات الصوديوم (Na_4SiO_4) وهيدروكسيد الصوديوم (NaOH) على إنتاجية النفط في كل من عمليات الإنتاج الثانوية والثلاثية مع استخدام نموذج خطي ونظم للآبار الأفقية ـ الرأسية.

وقد وجد أن إزاحة نفط سفانيا باستخدام ١٪ (واحد بالمئة) هيدروكسيد الصوديوم (NaOH) يعطي أعلى إنتاجية للنفط في كل من النموذج الخطي ونظم الآبار الأفقية ـ الرأسية، علاوة على ذلك فإن أعلى إنتاجية للنفط باستخدام نظم الآبار الأفقية ـ الرأسية تحققت بوضع البئر الأفقي في موضع عمودي على الخط الفاصل بين بئري إنتاج رأسيين وبطول لا يصل إلى حدود المكمن، كما وجد أيضًا أن كفاءة الإزاحة باستخدام العمليات الثلاثية للإنتاج أفضل بكثير من عمليات الإزاحة الثانوية، كما أن زيادة طول البئر الأفقي في مكمن محدود المساحة لا يزيد من كمية النفط المنتجة من المكمن.