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FEASIBILITY OF OIL RECOVERY BY POLYMER/ALKALINE FLOODING THROUGH HORIZONTAL WELL

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ABSTRACT

A laboratory study on Saudi oil recovery by polymer/alkaline flooding from a horizontal well in a scaled quarter five-spot model was conducted. Safaniya crude oil, obtained from Safaniya oil field operated by Saudi Aramco, was used in the displacement tests. Properties of different concentrations of polymer/alkaline solutions were experimentally determined to select the suitable ones for enhanced oil recovery processes. An economic model was also developed to investigate the effects of polymer/alkaline concentration, oil price, and cost of the horizontal well on the feasibility of the process.
Results are presented for selected concentrations of polymer/alkaline solutions for enhanced oil recovery experiments in the ratios of 0.05/1.0, 0.10/1.0, 0.15/1.0 and 0.20/1.0 by weight. Displacement results show that the best polymer/alkaline concentration that yields the maximum oil recovery from a horizontal well is 0.10/1.0. A good agreement exists between the optimum concentration of polymer/alkaline solution determined from the experimental results and that obtained from the economic model. This indicates that, with current oil prices, the reservoir engineering component of the economics (i.e. the amount and value of recovered oil) is more significant than all other factors and costs of the process.

NOMENCLATURE

a = well spacing, ft
b = vertical well penetration, ft
C_c = cost of chemical, $/bbl
C_h = depreciation of horizontal well, $/bbl
d = distance between vertical wells, ft
Dr = depreciation over the oil production period
Er = capital expenditure over the oil production period
h = formation thickness or model thickness, ft

Ir = well intangible over the oil production period
k = absolute permeability, darcy
k_h = horizontal permeability, darcy
k_v = vertical permeability, darcy
L = horizontal well length, ft
NCF = net cash flow, $
OP_c = operating cost of chemical, $/bbl
P_i = inlet pressure, psi
P_o = oil price, $/bbl
P_{out} = 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
R_o = oil recovery
S_o = recoverable oil saturation
S_{oi} = initial oil saturation
S_{wi} = initial water saturation
t = time
X_c = concentration of chemical, lb/bbl
Y = tax rate
μ = viscosity, cP
μ_o = oil viscosity, cP
μ_w = water viscosity, cP
σ = shear stress, psi
θ = contact angle

INTRODUCTION

The improvement in oil recovery and economics obtained with horizontal well results from extensive contact with the resevoir. This results in lower fluid velocities around the wellbore while providing total flow rates that are economical. Typical applications of horizontal wells include reservoirs where conventional wells have low productivity, reservoirs where recovery is limited by water coning or gas cupsing, reservoirs with typical fractures, and heavy-oil and tar-sands reservoirs [1]. Horizontal wells used in these applications have improved the oil recovey and extended the operating life of the reservoir. The horizontal well produces at a higher rate, a lower drawdown, and a lower gas-oil ratio which will extend the life of the field and result in higher recovery [2].

In 1990, Saudi Aramco commenced drilling of a long radius horizontal well in an offshore field in Saudi Arabia [3]. The main objective of the well was to test the potential of a horizontal well as an oil producer in the reservoir. It was drilled to a total depth of 3466 m (11371 ft) with a lateral departure of 1198 m (3930 ft). The field has an average permeability of 8.5 mD and an average porosity of 17%. The cost of the horizontal well was estimated to be 1.8 times as much as the average cost of a conventional well in the area. The production tests conducted indicated that the productivity was increased by three times. Following this, Saudi Aramco started an ambitious horizontal well drilling program involving producers and injectors, both onshore and offshore.

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, little information is available on horizontal well applications for enhanced oil recovery (EOR) methods [4]. Many published articles show that horizontal wells have been used so far primarily to solve specific production problems. These include low permeability formations especially fractured formations, low permeability gas reservoirs, unusual gas sources, gas or water coning, thin formations and viscous oil [5].

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 [6,7]. Published information on the use of horizontal injection wells, other than for thermal recovery, is scanty. However, several authors pointed to the need to study systems of both horizontal injection and vertical production wells, as means of increasing flooding rate in EOR [8-12]. Early laboratory work [13&14] showed that the use of a horizontal well as an injector in alkaline flooding increases oil recovery by a minimum of 8.5 percent of initial oil in place (IOIP) relative to a vertical injector well.

In the field of chemical flooding through linear and radial cores, Mihcakan and Van Kirk [15] reported that a chemical system of alkaline and polymer blended together yielded more oil recovery than either alkaline or polymer alone. They observed that Alkaline/polymer flooding provides better sweep effeciency than either alkaline or polymer alone. Also, a small residual oil saturation ring adjacent to the sandface was noted. This ring is much lower than that observed with either alkaline or polymer alone.

The present work investigates the polymer/alkaline flooding through a horizontal well in a horizontal-vertical scaled quarter of a five-spot model saturated with Safaniya crude oil . An economic model is also presented to show the feasibility of oil recovery by polymer/alkaline solutions through a horizontal well and to calculate the optimum polymer/alkaline concentration for Safaniya crude oil.

SCALING PARAMETERS CALCULATION

In designing bench-scale models for 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. [16] and Perkins et al. [17]. This involves the calculation 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 at. [15] is given in Table 1, which shows that the calculated scaling parameters are in agreement with the practical ranges. The vertical permeability is assumed to be 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 at. [11].

Table 1. Comparison between geometrical scaling parameters of used model and possible practical ranges recommended by Henley et al. [12].

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 / 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 = $Ah\phi[1-S_{wi} - S_{or})/Q_t]$	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 = not calculated

EXPERIMENTAL WORK

Experimental Apparatus

The experimental apparatus used in this study is shown in Fig. 1. The displacement model has a rectangular parallelepiped shape and is packed with sand. It is made of transparent perspex section with inner dimensions of 28.1 x 28.1 x 2.5 cm.

Perforated 0.5 cm outside diameter stainless steel tubing with 0.3 cm inside diameter was used as horizontal and vertical wells. The wells were enveloped with a 200 mesh screen to prevent sand production and ensure uniform flow.

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

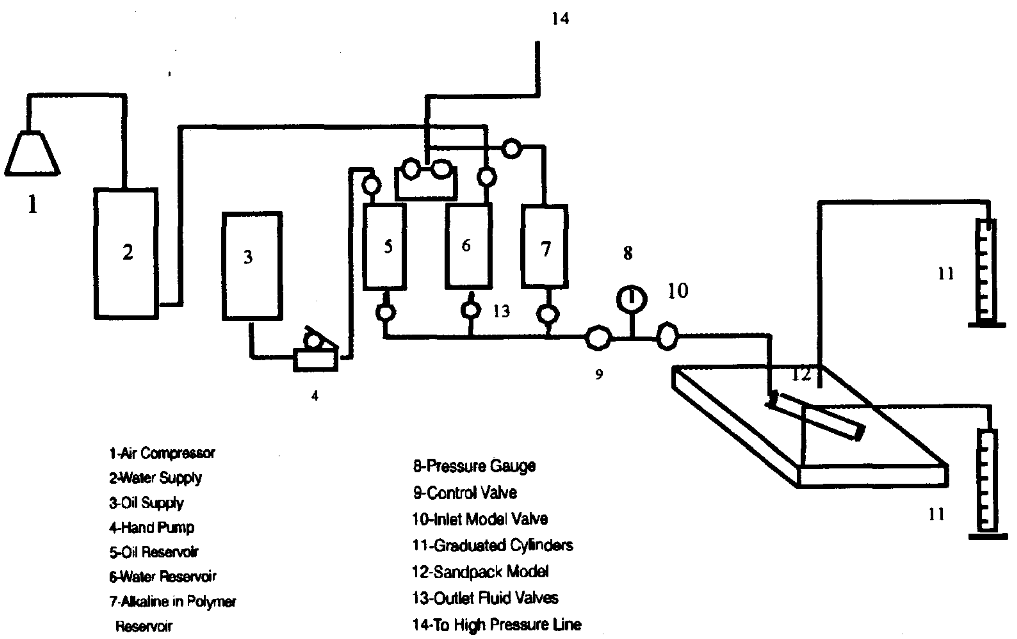

Fig. 1. Displacement Apparatus

Experimental Procedures

The model was packed with friable sand obtained from the Eastern Province, Saudi Arabia. The grain size distribution is given in Table 2. The grain sizes above 50- mesh number were used for packing purposes. The sandpack has an average porosity of 35% and an average 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 pressure drop across the sandpack using both vertical wells. The following equation was used to calculate the absolute permeability [18]:

$$Q = \frac{3.541kh(P_i - P_{out})}{\left\{\mu\left[\ell n\left(\frac{d}{r_w}\right) - 0.619\right]\right\}} \quad (1)$$

Table 2. Grain size distribution of sand used in packing process

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

Injection of oil was then carried out until complete oil saturation of the model was reached, corresponding to the initial saturation conditions. The polymer/alkaline solution was then continuously injected into the sandpack. 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 their use to avoid any air exposure or change in their properties because of aging. Nasr El-din et al. [19] report that the change due to aging depends on the type of chemicals used with sodium hydroxide/polymer solution suffering a properties change after 200 hours aging time.

RESULTS AND DISCUSSION

Fluid Properties

The fluids used in this study are Safanyia crude oil, biopolymer, sodium hydroxide (NaOH), and soduim chloride (NaCl) solutions. Safanyia crude oil has an acidic number of 1.4 mg KOH/gm crude. The biopolymer used is xathnan powder. It has a high molecular weight polysaccharide (M=9.6×10^6 Dalton). The length of the rodlike molecule is of the order of 1 μm and the diameter of the rod is 16.6 A. The polymer solution was prepared by dissolving the powder in 3.5% brine water and gently agitated by a magnitic stirrer. The polymer concentrations are 0.05, 0.10, 0.15 and 0.20% by weight. The applied alkaline is sodium hydroxide with concentration of 0.5, 0.1 and 0.15% by weight. Sodium chloride was used to prepare formation water and polymer and alkaline solutions. The viscosity of Safniyia crude oil and the chemical solutions were measured using a Brookfield viscometer, model LVT. The measurement of interfacial tension between different solutions and Safanyia crude oil were measured by digital Kruss tesiometer model K10.

The measurements of interfacial tension between crude oil and polymer/alkaline solutions are plotted in Fig. 2. This figure shows that, the interfacial tension increases with increasing polymer concentration for all concentrations of alkaline. It can also be observed that the interfacial tension decreases with increasing alkaline concentration from 0.5 to 1.0 % and then increases with increasing alkaline concentration from 1.0 to 1.5%. This means that, the lowest value of interfacial tension results from the use of alkaline concentrations of 1.0% within the polymer/alkaline solutions.

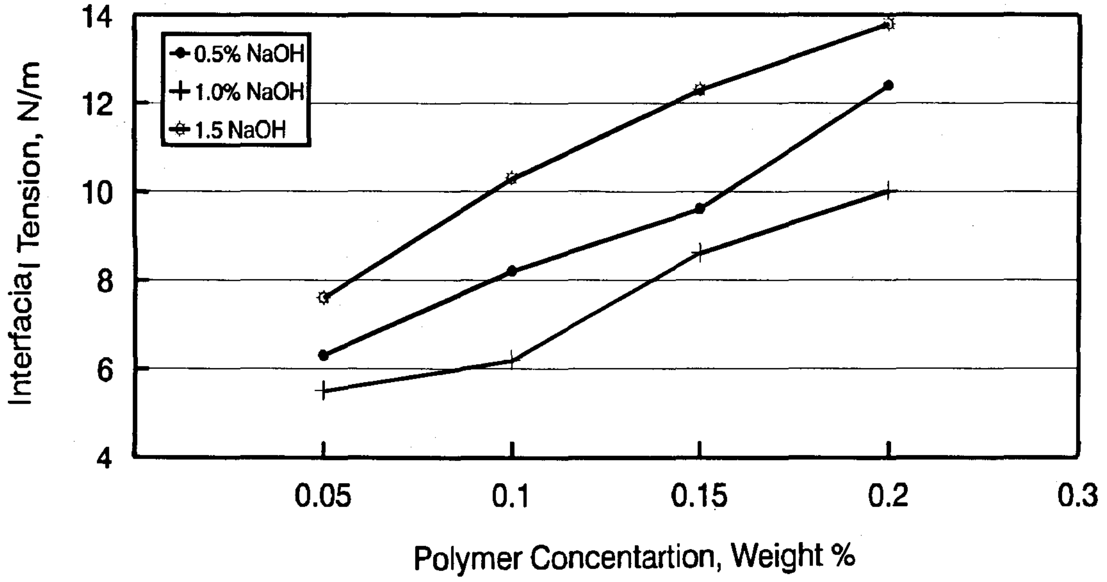

Fig. 2. Effect of alkaline concentration on interfacial tension between crude oil and polymer/alkaline solutions

Viscosity data are plotted in Fig. 3. This figure shows that the viscosity increases as the polymer concentration increases for all alkaline concentrations, and slightly increases with increasing alkaline concentration for all polymer concentrations. This means that adding alkaline to polymer has slight effect on its viscosity, a result consistent with tests on other crudes [20]. It is important to note here that the viscosity data were measured at a shear rate typical of rates existing in the porous media (82.5 s^{-1}).

The viscosity of crude oil is equal to 42 cP at a shear rate of 82.5 s^{-1}. From Figs. 2 and 3, one can estimate that practical polymer/alkaline concentrations suitable for enhanced oil recovery experiments are in the range 0.05/1.0, 0.10/1.0, 0.15/1.0 and 0.20/1.0. It is reported that the highest oil recovery by alkaline flooding can be achieved by injecting an alkaline solution that yields the lowest interfacial tension [20]. However, increasing polymer concentrations increases the oil recovery. Therefore, alkaline concentration of 1.0% mixed with the above mentioned concentrations of polymer are selected for the experiments to determine the best concentration for Safaniya crude oil by alkaline/polymer flooding.

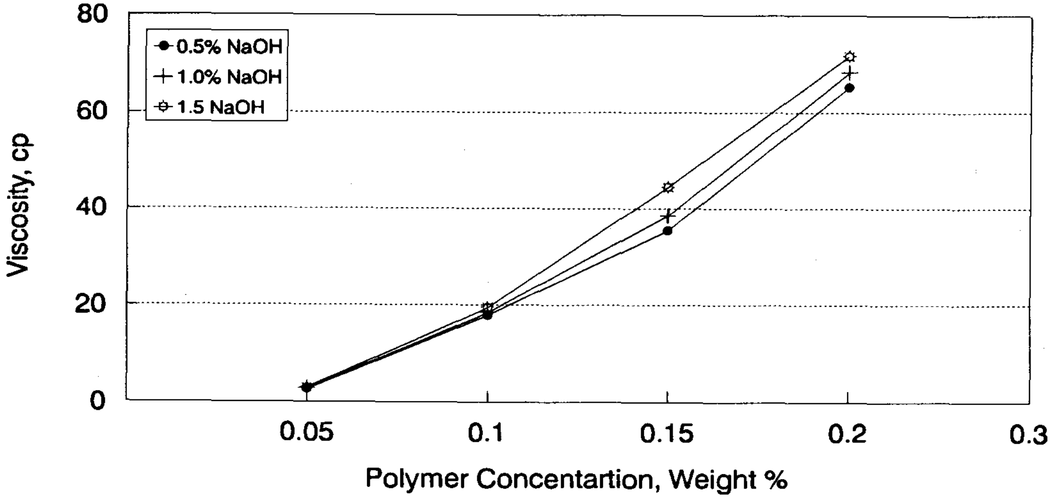

Fig. 3. Effect of alkaline concentration on viscosity of polymer/alkaline solutions

Displacement Tests

To confirm which concentration yields the highest oil recovery, displacement tests were conducted using the previous polymer/alkaline concentrations. The oil in sample and cumulative oil recovery obtained from the displacement tests are plotted in Figs. 4 and 5, respectively. Both figures show that the recoverable oil increases with increasing polymer/alkaline concentration from 0.05/1.0 to 0.10/1.0 and then decreases as polymer/alkaline concentration increases from 0.10/1.0 to 0.20/1.0. This means that the maximum oil recovery is obtained when the polymer/alkaline concentration of 0.10/1.0 is used. These results can be confirmed by explaining the effect of alkaline on interfacial tension between crude oil and polymer/alkaline solutions, as shown in Fig. 2. Since Safaniya crude oil has a high acidic number (1.4 mg KOH/gm crude) [13], the effect of alkaline on oil recovery is due to the chemical reactions between the alkaline and organic acids occurring in the crude oil. These reactions result in the formation of surface active compounds (soaps) whose absorption on the oil-water interfaces decreases the interfacial tension between oil and water, as one of the oil recovery mechnisms of alkaline flooding, thus yielding an oil-water emulsion [15]. This phenomina has been observered in the produced fluids where an oil in water emulsion produced after water breakthrough and a demulsifing agent was then added to separate oil from water. The addition of polymer to alkaline can improve the mobility control which in turn improves the displacement efficiency and enhances the oil recovery. This is evident from Figs. 4 and 5, in which the polymer/alkaline ratio increased from 0.05/1.0 to 0.10/1.0. In contrast, for polymer/alkaline concentration ranging from 0.10/1.0 to 0.20/1.0, the addition of polymer caused a reduction in oil recovery. As it was reported by Szabo [21, 22], this reduction is due to the retention and adsorption of the polymer in the formation as the polymer concentration increases. This retention results in an inaccessible pore spaces due to plugging. The plugging of these pores decreases the permeability as well as the recovered oil. Also, Mihcakan et al. [15] reported that alkaline/polymer flooding produces a visible residual oil saturation ring smaller than that observerd with both radial and linear core flooding. Therefore, one can conclude that the best polymer concentration mixed with 1.0% NaOH alkaline lies between 0.05 and 0.10% and can be considered as 0.10%.

Development of the Economic Model

The development of an economic oil recovery model is a key to recover a substantial portion of the oil. It determines the concentration of the chemical (polymer/alkaline solution) by knowing the cost of chemical, operating cost of chemical, oil price, and cost of horizontal well. This approach is analogous to that proposed by Al-Blehed et al. [23]. It can be expressed as follows:

Net cash flow = value of oil recovered - cost of chemical - cost of horizontal well + depreciation - capital expenditure + well intangible .. (2)

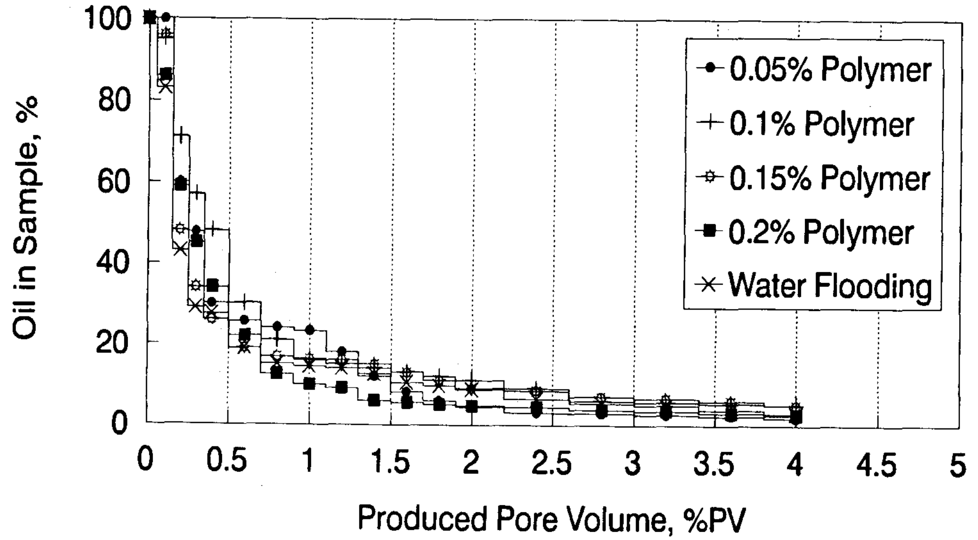

Fig. 4. Percentage oil in sample versus produced pore volume

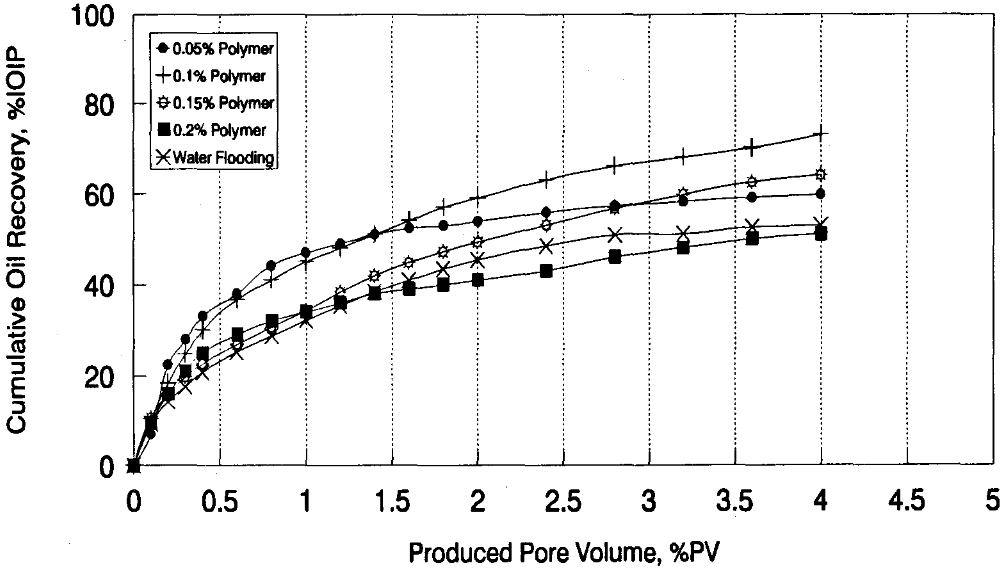

Fig. 5. Cumulative oil recovery versus produced pore volume

Based on the pore volume (PV) of the reservoir equals to one barrel, and in terms of reservoir parameters, Eq. 2 can be rewritten as follows:

$$NCF = S_o R_o P_o (1\text{-}Y) - X_c(C_c + OP_c) - S_o R_o P_o (1\text{-}Y)\, C_h + S_o R_o P_o (1\text{-}Y)(Dr\text{-}Er\text{+}Ir) \quad (3)$$

Arranging the variables, one obtains

$$NCF = S_o R_o P_o (1\text{-}Y)\,(1\text{-}C_h + Dr - Er + Ir) - X_c(C_c + OP_c) \quad (4)$$

Dividing each term by S_oP_o and differentiating the resulting equation with respect to X_c, the following equation is obtained:

$$(\partial/\partial X_c)(NCF/S_oP_o) = (\partial/\partial X_c)\,[R_o(1\text{-}Y)(1\text{-}C_h + Dr - Er + Ir) - X_c(C_c + OP_c)/\, S_oP_o \quad (5)$$

The net cash flow (NCF) can be maximized when [21]

$$(\partial/\partial X_c)(NCF/S_oP_o) = 0.0 \quad (6)$$

Substituting Eq. 6 in Eq. 5, one gets

$$\frac{\partial R_o}{\partial X_c} = \frac{C_c + OP_c}{(1-Y)(1-C_h + Dr - Er + Ir)(S_oP_o)} \quad (7)$$

Thus, the value of (NCF) is maximum when the slope of the oil recovery versus concentration of chemical curve is equal to right side of Eq. 7. This equation can be reduced to the well-known Stanley's equation (6) when the values of tax rate, cost of horizontal well, depreciation, capital expenditure, operating cost of chemical and well intangible equal to zero.

$$(\partial R_o) / (\partial x_c) = C_c / S_o P_o \tag{8}$$

According to Saudi regulations [24], the tax rate, depreciation, capital expenditure and well intangible should be neglected. Therefore, Eq. 7 can be reduced to

$$(\partial R_o) / (\partial x_c) = [(C_c + OP_c)] / [S_o P_o (1 - C_h)] \tag{9}$$

The cost of chemical (alkaline/polymer/brine solution) and operating cost of chemical were fixed at 0.40 and 0.15 \$/bbl, respectively. Therefore, Eq. 9 becomes

$$(\partial R_o) / (\partial x_c) = 0.55 / [S_o P_o (1 - C_h)] \tag{10}$$

Based on the experimental results obtained and the information given in ref. [25], the oil recovery (R_o) is plotted against chemical concentration (X_c) in Fig. 6. The oil recovery at zero chemical concentration is taken as the recovery obtained by water flooding. For our case, the data of this figure were correlated to the following equation with a correlation coefficient of 0.999.

$$R_o = 0.497 + 3.74\,X_c - 18\,X_c^2 \text{ for } 0.05 \;?\; X_c \;?\; 0.20 \tag{11}$$

Differentiating Eq. 11 with respect to X_c, one obtains

$$(\partial R_o) / (\partial x_c) = 3.74 - 36\,X_c \tag{12}$$

Substituting Eq. 12 in Eq. 10, the optimum chemical concentration (X_c) is given by

$$(X_c)_{opt} = 0.1038 - \{0.01528/[S_o P_o (1 - C_h)]\} \tag{13}$$

Based on oil price, cost of horizontal well and recoverable oil saturation above water flooding equal to \$20/bbl, \$0.8/bbl and 23% (bsed on IOIP per pore volume), respectively, the optimum chemical concentration is equal to 0.099. The value of the optimum chemical solution confirm what was obtained in experimental part (i.e. the highest oil recovery was obtained when the chemical concentration (polymer/alkaline) is equal to 0.10/ 1.0.

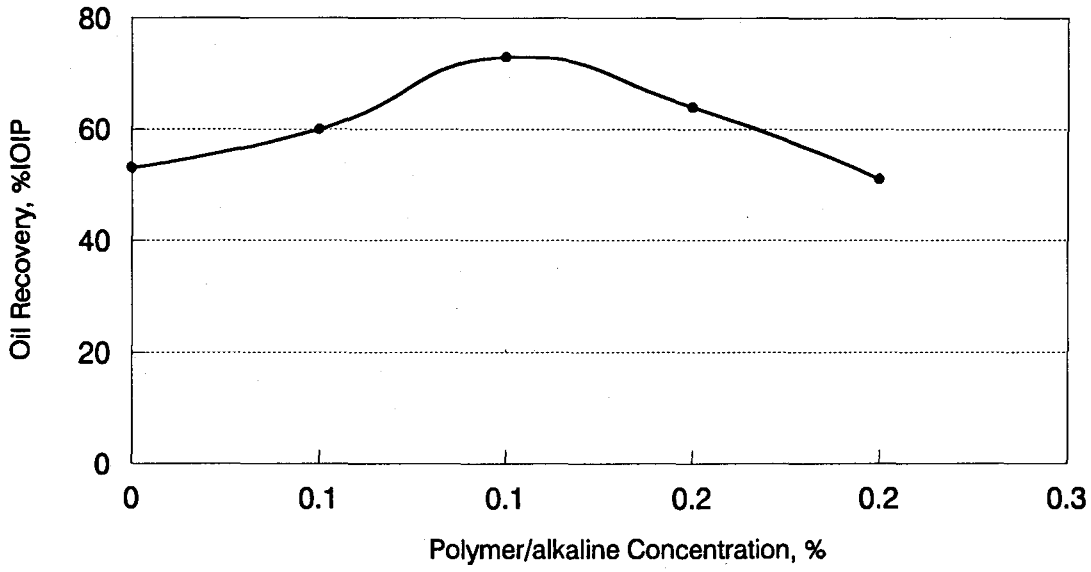

Fig. 6. Oil recovery versus polymer/alkaline concentration

This means that the economic polymer/alkaline concentration for flooding Safaniya crude oil is 0.10/1.0. The above model can be modified for any type of crude oil taking into considerations the experimental part and country regulations.

CONCLUSIONS

Based on the results of the experimental work and economic model, the following conclusions are obtained:

The best polymer/alkaline (Xanthan/NaOH) concentration to yield the maximum oil recovery of Safaniya crude oil through horizontal wells is 0.10/ 1.0.

Increasing polymer concentration from 0.10 to 0.20 in polymer/alkaline solutions causes a reduction in oil recovery by 29.63%.

An economic model was introduced to determine the optimum concentration of a polymer/alkaline concentration as a function of oil price, cost of horizontal well, and oil saturation after water flooding of Safaniya based on Saudi regulations.

Results of the economic model confirm those of experimental work for Safaniya crude oil indicating the importance of the reservoir engineering aspects on the feasibility of the process. This model can be applied for any crude oil taking into considerations the experimental part and the country regualtions.

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