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An engineering-economic evaluation of enhanced recovery of Saudi crudes by chemical flooding

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Abstract

An approach for economic evaluation of crude oil displacement by chemical solutions (surfactant and/or alkaline) was developed. The approach developed is based on a probability distribution of escalating prices of oil, chemicals, polymers and brine, operating and capital costs. Experimental data from an actually existing Enhanced Oil Recovery (EOR) study of Safaniyah oil field using surfactant solution as chemical were used to assess the validity of the proposed approach. The optimum surfactant slug size for the displacement process under test conditions was determined. The effects of residual oil saturation, and oil and surfactant prices on the determination of optimum slug size were investigated. The results showed that these three parameters have a great effect on the decision of applying a more economical recovery process.

Nomenclature

C_b = cost of brine, \$/bbl (=dollar/barrel)
C_c = cost of chemical, \$/bbl
C_{pl} = cost of polymer, \$/bbl
D_r = depreciation over the oil production period
E_r = capital expenditure over the oil production period
I_r = well intangible over the oil production period
OIP = oil in place
OP_b = operating cost of brine, \$/bbl
OP_c = operating cost of chemical, \$/bbl
OP_{pl} = operating cost of polymer, \$/bbl
P_o = oil price, \$/bbl
PV = the volume of opening or space within a mass of reservoir rock
R_o = oil recovery, ratio between cumulative oil produced and recoverable oil
S_o = oil saturation, ratio between oil volume and pore volume
S_{or} = residual oil saturation (fraction), the amount of oil left in the reservoir to the initial oil in place
V_b = brine volume, fraction of reservoir pore volume
V_{opt} = optimum slug size, fraction of reservoir pore volume
V_{pl} = polymer volume, fraction of reservoir pore volume
V_s = surfactant volume, fraction of reservoir pore volume
x = tax rate
γ_s = specific gravity of sulfonates
γ_{ss} = specific gravity of surfactant slug
γ_o = specific gravity of oil

Introduction

Chemical flooding has received considerable attention in laboratory studies and field tests. This process is attractive because the displacement efficiency of an effective chemical flood can be almost 100% in zones swept by surfactant [1]. Displacement of oil by chemical solutions involves sequential injection of a chemical slug, a polymer slug for mobility control and a brine to drive these solutions.

Generally, enhanced oil recovery methods using chemical flooding require the injection of rather expensive fluids (such as surfactants) into oil bearing reservoir formations. Commercial application of any enhanced oil recovery process relies on its economical feasibility. The key factors in an economic projection for emerging tertiary oil recovery processes are investment requirements such as chemical and development costs, oil recovered, time required to obtain the oil, oil price and tax rate [2].

Because of high chemical costs, it is important to optimize their use to provide the greatest recovery at the lowest cost. The objective is to determine a theoretical basis for computing the best way of injecting an EOR fluid into a reservoir formation. Numerous mathematical models have been formulated for the economical evaluation of EOR projects. The pioneers in this field of research work are Stanley [3], Ramey and Brigham [4], Matheny [5], Richard et al. [6], Ramirez et al. [7] and Sayyouh et al. [8]. Practical applications of those models depend on whether economic projections indicate a decent return on investment or not.

In the present study, an approach for economical evaluation of crude oil displacement by chemical solutions was developed. The approach developed was applied to laboratory studies of Safaniyah oil field in Saudi Arabia.

Development of the economical approach

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. An economical approach will be described here for determining the size of the chemical slug. This approach is analogous to that proposed by Richard et al. [6]. It can be expressed as follows:

$$\begin{aligned}\text{Net cash flow} = {} & [\text{value of oil recovered}] \\ & - [\text{cost of chemical, polymer and brine}] \\ & + [\text{depreciation}] - [\text{capital expenditure}] \\ & - [\text{well intangible}] \end{aligned} \tag{1}$$

Based on the pore volume (PV) of the reservoir equal to one barrel, and in terms of reservoir parameters, eqn. (1) can be rewritten as follows:

$$\begin{aligned}\mathrm{NCF} = {} & S_o R_o P_o (1-x) - V_c (C_c + \mathrm{OP}_c) \\ & - V_{pl}(C_{pl} + \mathrm{OP}_{pl}) - V_b (C_b + \mathrm{OP}_b) \\ & + S_o R_o P_o (1-x)(D_r - E_r - I_r) \end{aligned} \tag{2}$$

where NCF is the net cash flow ($). Dividing each term of eqn. (2) by (S_oP_o) and differentiating with respect to V_c, the following equation can be obtained:

$$\begin{aligned}(\partial/\partial V_c)(\mathrm{NCF}/S_oP_o) = {} & (\partial/\partial V_c)[R_o(1-x)] - (1/S_oP_o) \times \\ & [C_c + \mathrm{OP}_c + (C_{pl} + \mathrm{OP}_{pl})(\partial V_{pl}/\partial V_c) \\ & + (C_b + \mathrm{OP}_b)\partial V_b/\partial V_c] \\ & + (\partial/\partial V_c)[R_o(1-x)(D_r - E_r - I_r)] \end{aligned} \tag{3}$$

The maximum net cash flow occurs when,

$$(\partial/\partial V_c)(\mathrm{NCF}/S_oP_o) = 0 \tag{4}$$

Substituting eqn. (4) in eqn (3), one gets

$$\begin{aligned}(\partial R_o/\partial V_c) = {} & \frac{[C_c + \mathrm{OP}_c}{\{S_oP_o(1-x)[1+(D_r - E_r - I_r)]\}} \\ & + \frac{(C_{pl} + \mathrm{OP}_{pl})(\partial V_{pl}/\partial V_c)}{\{S_oP_o(1-x)[1+(D_r - E_r - I_r)]\}} \\ & + \frac{(C_b + \mathrm{OP}_b)(\partial V_b/\partial V_c)}{\{S_oP_o(1-x)[1+(D_r - E_r - I_r)]\}} \end{aligned} \tag{5}$$

That is, net cash flow is maximum when the slope of the oil recovery versus chemical slug size curve is equal to the right hand side of eqn. (5). This equation can be reduced to the well-known Stanley's equation (3) when the values of tax rate, cost of polymer and brine, depreciation, capital expenditure and well intangible equal to zero. Thus,

$$(\partial R_o/\partial V_c) = (C_c/S_oP_o) \tag{6}$$

Application to Safaniyah oil field

Laboratory studies were carried out for Safaniyah oil field to study the application of surfactant/polymer flooding under the reservoir conditions [9]. The reservoir was characterized by high salt concentration in the associated water, usually in the range of 20% by weight. The surfactants used and their composition are given in Table 1. It was found that Petrostep-420 improves miscibility under the reservoir conditions better than others. The miscibility depends upon salt concentration, temperature, and the presence of Ca^{++} ions in water. Polymer was found to improve miscibility at low salt concentration.

TABLE 1

Composition of surfactants

	Petrostep 420	Petrostep HMW	Petrostep 465
Sulfonate actives	61.5%	50.7%	47.0%
Free oil	19.6%	24.4%	12.9%
Water	14.5%	22.1%	34.3%
Inorganic salt	4.4%	2.8%	4.0%
Equivalent weight range	410–430	500–530	440–465
Density (lbs/gal. @ 120F°)	9.0–9.4	9.0–9.4	9.0–9.4

The interfacial tension of surfactant solutions is markedly affected by salinity of formation water and temperature.

In the present work, it was proposed to use eqn. (5) to determine the optimum surfactant slug size for Safaniyah oil field. According to Saudi regulations, the tax rate and the second term in denominator of the right hand side of eqn. (5) should be neglected. Since the cost of the brine is too small as compared to the others, the fourth term in nominator of the right hand side of eqn. (5) will also be neglected. Therefore, eqn. (5) can be reduced to

$$(\partial R_o/\partial V_s)=(1/S_oP_o)[C_s+\mathrm{OP}_s+(C_{pl}+\mathrm{OP}_{pl})(\partial V_{pl}/\partial V_s)] \quad (7)$$

where V_s is the volume of surfactant slug and is equal to the volume of chemical slug (V_c) in eqn. (5).

On the basis of the active components, the composition of the surfactant slug in weight % should be the following: (1) $S\%$ active sulfonate; and (2) $O\%$ crude oil.

The cost of surfactant slug can be expressed in terms of the component densities as follows:

$$C_s=S\%(\gamma_{ss}/\gamma_s)P_s+O\%(\gamma_{ss}/\gamma_{so})P_o \quad (8)$$

The volume of the polymer slug was equal to half of the pore volume (i.e. 0.5 bbl). Thus

$$C_{pl}=0.5P_{pl} \quad (9)$$

The operating cost of surfactant and polymer slugs were fixed at 0.4 and 0.15 $/bbl, respectively (6).

Substituting eqns. (8) and (9) in eqn. (7), one gets

$$(\partial R_o/\partial V_s)=[S\%(\gamma_{ss}/\gamma_s)P_s+O\%(\gamma_{ss}/\gamma_o)P_o+0.4]/S_oP_o+[(0.5P_{pl}+0.15)(\partial V_{pl}/\partial V_s)]/S_oP_o \quad (10$$

Using the date reported in Ref. [9] as shown i Table 3, eqn. (10) can be rewritten as follows:

$$(\partial R_o/\partial V_s)=[1.15+0.0843P_s+0.558P_o+2.5P_{pl}]/S_oP_o \quad (11$$

The oil recovery was plotted against surfactan slug size in Fig. 1. The data of this figure wer correlated to the following equation with a cor relation coefficient of 0.976.

TABLE 2

Cost of EOR materials

Material	Material price, ($/bbl)	Handling cost, ($/bbl)
Surfactant	189.196	0.4
Polymer	0.3316	0.15
Oil	20.000	–

TABLE 3

Data of surfactant solution (Petrostep-420)

Component	Composition weight (%)	Specific gravity
Sulfonate active	10.00	1.103
Safaniyah oil	51.96	0.865
Brine	41.89	1.10

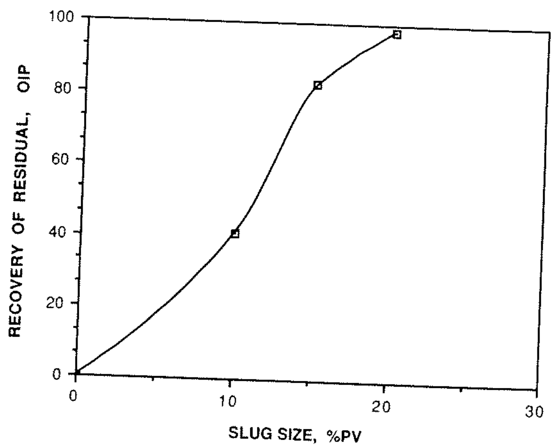

Fig. 1. Recovery of residual vs. slug size.

$$R_o = 3.563\, V_s^{1.126} \qquad (12)$$

Differentiating eqn. (12) with respect to V_s, one gets

$$(\partial R_o/\partial V_s) = 4.012\, V_s^{0.126} \qquad (13)$$

Substituting eqn. (13) in eqn. (11), the optimum slug size (V_{opt}) formula is given by

$$V_{opt} = [(1.15 + 0.0843P_s + 0.558P_o + 2.5P_{pl})/4.012S_oP_o]^{7.937} \qquad (14)$$

Based on the price given in Table 2 and residual oil saturation of 0.297, the optimum slug size was found to be 4.87% PV.

Effect of oil saturation

The effect of residual oil saturation on the determination of the optimum slug size for Saudi EOR project was studied. The results are given in Fig. 2. This figure shows that the increase in the residual oil saturation decreases the optimum slug size.

Effect of oil price

The effect of the change in oil price on the economical evaluation of the Saudi EOR project was investigated. The evaluation was carried out at initial oil saturation of 0.297. The results are plotted in Fig. 3. It can be observed that the optimum slug size decreases as the oil price increases.

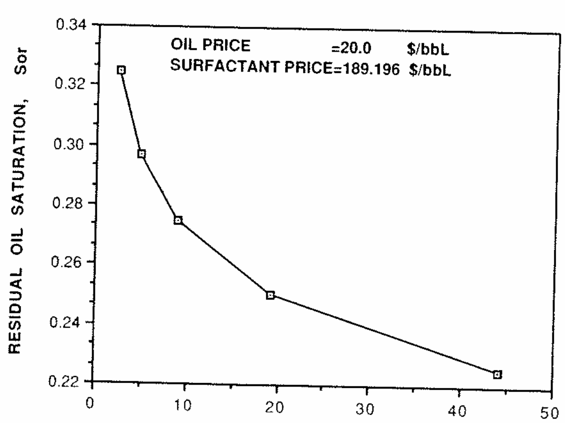

Fig. 2. Effect of residual oil saturation on the optimum slug size.

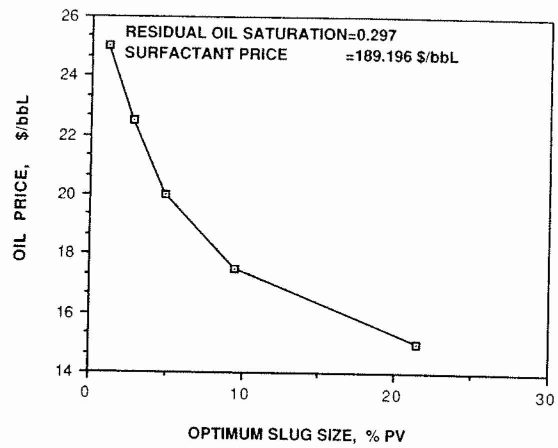

Fig. 3. Effect of oil price on the optimum slug size.

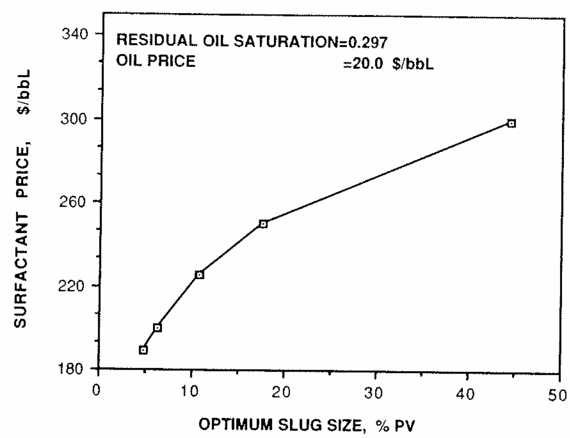

Fig. 4. Effect of surfactant price on the optimum slug size.

Effect of surfactant price

Since the surfactant price is much higher than polymer, its effect on the determination of the optimum slug size for the case study was considered. The calculations were performed at residual oil saturation and oil price of 0.297 and $20/bbl, respectively. The results calculated from eqn. (14) are plotted in Fig. 4. This figure shows that the cost of surfactant slug increases as the optimum slug size increases.

Conclusions

(1) An approach for economical evaluation of EOR projects using chemical flooding was developed.
(2) Based on the prices of surfactant, polymer, and oil used in the present study, application of the approach developed to Safaniyah oil field shows that the optimum slug size was 4.87% PV.
(3) For EOR projects of any oil field, the optimum size of the surfactant slug decreases as the residual oil saturation or oil price increases. However, it increases as the price of surfactant increases.

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