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Oil-recovery predictions for surfactant polymer flooding

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ABSTRACT

There is increasing interest in surfactant–polymer (SP) flooding because of the need to increase oil production from depleted and water flooded reservoirs. Prediction of oil recovery from SP flooding, however, is complex and time consuming. Thus, a quick and easy method is needed to screen reservoirs for potential SP floods. This paper presents a scaling model that is capable of producing reasonable estimates of oil recovery for a SP flood using a simple spreadsheet calculation. The model is also useful for initial SP design.

We present key dimensionless groups that control recovery for a SP flood. The proper physics for SP floods including the optimal salinity in the three-phase region and the trapping number for residual oil saturation determination has been incorporated. Based on these groups, a Box–Behnken experimental design is performed to generate response surface fits for oil recovery prediction at key dimensionless times. The response surfaces derived can be used to estimate the oil recovery potential for any given reservoir and are ideal for screening large databases of reservoirs to identify the most attractive chemical flooding candidates. The response function can also be used for proper design of key parameters for SP flooding. Our model will aid engineers to understand how key parameters affect oil recovery without performing time consuming chemical simulations. This is the first time that dimensionless groups for SP flooding have been derived comprehensively to obtain a response function of oil recovery as a function of dimensionless groups.

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1. Introduction

Surfactant–polymer (SP) flooding processes involve the injection of a surfactant–polymer slug followed by a polymer buffer and chase water injection. If designed correctly, the surfactant

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Nomenclature

C_{Brine}	brine salinity, meq/ml
C_{opt}	optimum salinity, meq/ml
C_{opts}	salinity of the brine divided by the optimal salinity, C_{Brine}/C_{opt}
C_s	surfactant concentration, volume fraction
C_{sel}	lower type III limit salinity, meq/ml
C_{seu}	upper type III limit salinity, meq/ml
H	height, L
$\overline{K}_{ij}$	permeability tensor for species i in phase j, L^2
k_{rl}^{o}	endpoint relative permeability of phase l
$k_{rl}^{o,H}$	endpoint relative permeability of phase l at high capillary number
$k_{rl}^{o,L}$	endpoint relative permeability of phase l at low capillary number
k_x	permeability in the x direction, L^2
k_z	permeability in the y direction, L^2
L	length, L
M_{o-w}^{o}	oil–water endpoint mobility ratio
M_{me-w}^{o}	microemulsion–water endpoint mobility ratio
N_B	bond number
N_{cij}^{H}	high capillary number between phases i and j
N_{Tl}	trapping number for phase l, $N_t = \lvert N_B + N_c \rvert$
ΔP	pressure difference between injector and producer, $m\,L^{-1}\,t^{-2}$
R_D	dimensionless recovery, fraction oil in place before SP flood
R_{D1}	dimensionless recovery at 0.75 PVI, fraction oil in place before SP flood
R_{D2}	dimensionless recovery at 1.5 PVI, fraction oil in place before SP flood
R_{D3}	dimensionless recovery at 2.25 PVI, fraction oil in place before SP flood
R_L	effective aspect ratio
S_j	saturation of phase j, fraction
$S_{l'r}^{H}$	residual oil saturation of phase l at high trapping number, fraction
$S_{l'r}^{H}$	residual oil saturation of phase l at low trapping number, fraction
S_{orw}	residual oil saturation to waterflood, fraction
S_{oi}	initial oil saturation, fraction
S_{wr}	residual water saturation, fraction
t_D	pore volumes of fluids injected
t_D^{o}	breakthrough time
t_{DPD}	polymer drive size, PVI
t_{DSP}	surfactant–polymer slug size, PVI
T_l	T parameter value for trapping of phase l
V_{DP}	Dykstra Parsons coefficient of permeability variation, $(k_{50}-k_{84.1}/k_{50})$
x_j	independent variables
$\vec{\nabla}$	gradient operator
β_{ij}	regression coefficients of interaction terms
β_j	regression coefficients
β_{ii}	regression coefficients of second order terms
β_o	constant term
ε	error term
μ_o	viscosity of oil, $m\,L^{-1}\,T^{-1}$
μ_{me}	viscosity of microemulsion phase, $m\,L^{-1}\,T^{-1}$
μ_p	viscosity of polymer solution, $m\,L^{-1}\,T^{-1}$
φ_l	fluid potential for phase l, $m\,L^{-1}\,t^{-2}$
ρ_j	density of phase j, $m\,L^{-3}$
$\Delta\rho_{ij}$	density difference between phases i and j, $m\,L^{-3}$
σ_{ij}	interfacial tension between phases i and j at the optimal salinity, MT^{-22}

increases the capillary number, which is crucial for the mobilization and recovery of tertiary oil. Polymer increases the sweep efficiency by lowering the mobility ratio. If the reservoir crude oil has sufficient saponifiable components, soap (surfactant) is generated *in situ* by the reaction of these components with the injected alkali, thus adding more surfactant to the flood (Lake, 1989).

Recovery predictions for SP floods involve numerous parameters and complex simulations. One way to simplify the process and predict oil recovery is to use a screening model based on a few key input variables or dimensionless groups. Dimensionless groups strategically combine properties so that their units cancel out. If done correctly, a reservoir with the same dimensionless groups should have similar dimensionless oil recovery curves. Dimensionless groups are typically attained in two ways: dimensional analysis and inspectional analysis (Shook et al., 1992). The dimensional analysis approach is based on Buckingham's π-theorem. Dimensional analysis is the only option in problems where equations and boundary conditions are not completely articulated. It computes sets of dimensionless parameters from given variables, even if the form of the equation is still unknown. However, the choice of dimensionless parameters is not unique: Buckingham's theorem only provides a way of generating sets of dimensionless parameters. Inspectional analysis takes advantage of the problem's full mathematical specification based on physical laws, and reveals a higher degree of similarity than dimensional analysis (Sonin, 2001). We use the University of Texas Chemical Flooding Simulator (UTCHEM, 2000) for our simulations, for a typical one dimensional surfactant–polymer flood UTCHEM requires around 170 parameters, carrying out Buckingham's dimensional analysis on this would result in over 160 groups. Using these 160 groups for creating a response surface for oil recovery in SP flood would be extremely time consuming and impractical. This was another reason why we chose inspectional analysis over dimensionless analysis as our method for obtaining dimensionless groups for SP flooding.

Previous screening models such as that of Paul et al. (1982) did not consider gravity and salinity effects. Pope et al. (1979) and Shook (1988) carried out sensitivity studies on SP floods and showed oil recovery as a function of R_L, N_g, and M, but did not attempt to correlate oil recovery to the parameters studied. Gupta et al. (1988) showed oil recovery as a function of R_L, N_g, M, T_{Ds}, and N_{TD}. Thomas et al. (2000) described scaling criteria for the micellar flooding process from the basic mass balance equations using inspectional and dimensional analysis. Micellar flooding experiments were carried out in sandstone cores of two different sizes, and the scaled up recovery curves were compared. The agreement

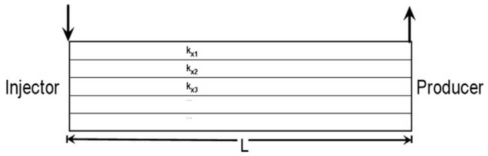

Fig. 1. Schematic representation of the reservoir and the wells.