Delivery of Remedial Amendments to Lower-Permeability Zones through Fluid Viscosity Modifications

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Abstract. Laboratory experiments and numerical studies have been conducted to investigate the use of a shear-thinning polymer (Xanthan gum) to improve access to low-permeability zones in heterogeneous systems. The impact of polymer concentration, fluid injection rate, and permeability contrast in the heterogeneous systems has been studied in a series of eleven two-dimensional flow-cell experiments. The Subsurface Transport over Multiple Phases (STOMP) simulator was modified to include polymer-induced shear thinning effects. The experimental and simulation results clearly show that using the polymer leads to an enhanced delivery of remedial amendments to lower permeability zones and an increased sweeping efficiency. The modified STOMP simulator was able to predict the experimental observed fluid displacing behavior well.

1. Introduction

Subsurface heterogeneity induces fluid bypassing by creating preferential flow channels in the high-permeability pathways during subsurface fluid flooding, leaving the low-permeability zones untouched (bypassed). Such a heterogeneity-induced bypassing phenomenon places certain contaminated areas inaccessible to the remedial fluids and remedial amendments, thus inhibiting the success of remedial operations. The adverse effect can considerably delay the completion and closure of a remedial operation and significantly increase the cost or simply make the remediation impossible to accomplish.

Methods of forcing fluids into low-permeability flow paths have been developed and widely implemented to solve the heterogeneity-induced bypassing problem encountered during oil recovery in the petroleum industry. Since the intent of petroleum reservoir engineers is to control the mobility of the injected fluid in the high-permeable zones so that the

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fluid can be pushed through the low-permeable zones to contact and mobilize the remaining oil in these zones, these methods are thus referred as "mobility controlled flood" (MCF) techniques in the petroleum engineering literature. The mobility ratio, *M*, is a key parameter that can be manipulated to achieve improved sweep efficiency of low-permeability zones. This ratio *M* is defined as the mobility of the displaced, or resident, phase over that of the displacing phase, where the mobility is equal to the effective permeability of each phase divided by the viscosity of that phase. The mobility ratio can be simplified as the ratio of the resident fluid viscosity, μ_R, to the displacing fluid viscosity, μ_D (e.g., Martel et al., 1998):

$$M = \frac{\mu_R}{\mu_D} \tag{1}$$

When the displacing fluid is more viscous than the resident fluid, $M < 1$, a flood is considered to be favorable and stable displacement is observed. When the displacing fluid is less viscous than the displaced fluid, $M > 1$, and the displacement is typically unstable and is considered to be unfavorable.

Mobility-controlled flooding using polymers may be applied to subsurface remediation to overcome heterogeneity-induced bypassing problems, so that amendments can be delivered to low permeability zones. The experiments conducted by Martel et al. (1998) provided a first systematic investigation of mobility control for environmental purposes, using Xanthan gum polymer for solution mobility control. Although Martel et al. (1998) investigated sweeping efficiency for heterogeneous sand packs, no remedial amendments were to the polymer solutions considered.

The flow cell experiments reported in this contribution were conducted to 1) demonstrate enhanced sweeping efficiency and remedial-amendment delivery, and 2) test and verify a modified version of the STOMP simulator (White and Oostrom, 2006) considering polymer shear-thinning behavior. The amendment used in the experiments was sodium mono-phosphate (NaH_2PO_4), a chemical that is currently evaluated to aid in the remediation of uranium [U(VI)] at the Hanford Site (Wellman et al., 2007).

2. Methods

2.1. Experiments

The experiments were conducted in a 0.5-m-long, 0.4-m-high, and 0.05-cm-wide flow cell. A schematic of the flow cell is presented in Fig. 1. Fluids were injected through eight evenly-spaced (0.05 m distance) inflow ports using separate Encynova (Broomfield, CO) high-precision piston pumps. The porous media used in the flow cell experiments were four grades of silica sand (20/30, 30/40, 40/50, and 70 mesh), obtained from Unimin Corporation (Le Sueur, MN). The main properties of the sands are provided by Schroth et al. (1996). Accusand 20/30 was used as the porous medium matrix in all experiments. Two-lower permeability zones were formed with Accusand 30/40, 40/50, or 70. The packed systems had an average porosity of approximate 0.35 and a total "pore volume" (PV) of 3.5 x 10^{-3} m^3.

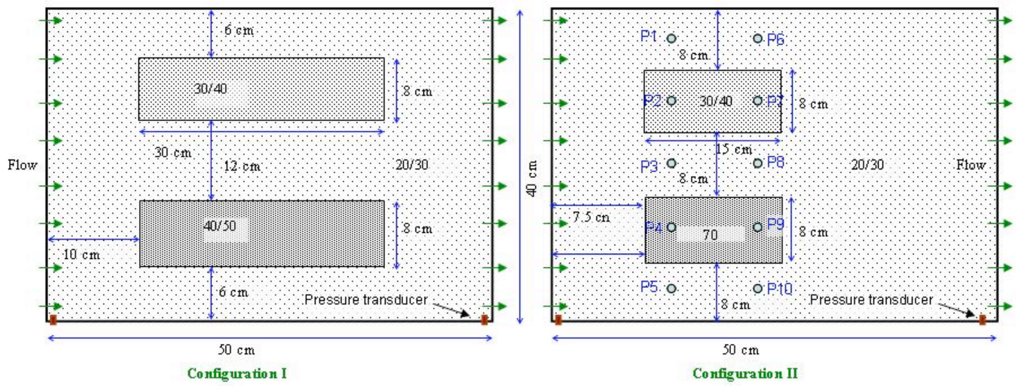

Figure 1. Flow Cell Configuration for the two Experimental Sets.

Details of the experiments are presented in Table 1. In experiment set I, no remedial amendment was used, while sodium mono-phosphate (NaH_2PO_4) was the remedial amendment used in experiment set II. Xanthan gum (Kelco Oil Field Group, Houston), a water-soluble biopolymer with shear-thinning properties, was used to modify the viscosity of the displacing fluids. All chemicals, except for the Xanthan gum, were obtained from Aldrich Chemical Company (Milwaukee, WI). Liquid samples were taken during selected experiments in experiment sets II and III using gas-tight syringes. Phosphate (PO_4^{3-}) concentrations were obtained using an ion chromatograph.

Table 1. Description of Experiments.

Name	Packing conf.	Flood type	Flow rate (ml/min)	Displacing fluid composition[1]
Exp-Ia-W	I	water	5	de-ionized water
Exp-Ib-W	I	water	50	de-ionized water
Exp-Ic-P	I	polymer	5	600 ppm Xanthan, 400 ppm NaCl
Exp-IIa-W	II	phosphate - water	5	de-ionized water
Exp-IIb-P	II	phosphate - polymer	5	200 ppm Xanthan, 400 ppm NaCl, 200 ppm NaH_2PO_4
Exp-IIc-P	II	phosphate - polymer	50	200 ppm Xanthan, 400 ppm NaCl, 200 ppm NaH_2PO_4
Exp-IId-P	II	phosphate - polymer	5	600 ppm Xanthan, 400 ppm NaCl, 200 ppm NaH_2PO_4
Exp-IIe-P	II	phosphate - polymer	50	600 ppm Xanthan, 400 ppm NaCl, 200 ppm NaH_2PO_4

2.1. Numerical Simulations

The water operational mode of the STOMP (Subsurface Transport Over Multiple Phases) simulator (White and Oostrom, 2006) with sequential electrolyte transport was used in this study. The applicable governing equations are the component conservation equations for water flow and electrolyte transport in the aqueous phase. In this STOMP mode, electrolyte concentrations do affect density and viscosity but the mass-conservation equation is not fully coupled with the water conservation equation. Instead, an operator splitting approach is used where the electrolyte transport equation is solved after convergence of the water conservation equation. The 50 x 40 cm computational domain was discretized into 8000 uniform (0.5 cm x 0.5 cm) grid blocks. Using Euler backward time differencing, yielding a fully implicit scheme, a series of nonlinear algebraic expressions is derived. A total-variation diminishing (TVD) technique (Datta Gupta et al. 1991) was used to minimize artificial diffusion, preserve sharp displacement fronts while avoiding oscillations that commonly affect classical higher-order schemes. Because of the use of the TVD schemes and the operator splitting approach, the maximum allowable time step in the simulations is 60 seconds.

Polymer fluid viscosity was computed as a function of shear rate and polymer concentration (Eq. 3), following a method outlined by Lopez et al. (2003) where the effective viscosity, μ_{eff} (Pa s), is a constant for the Newtonian ranges at low and high shear rates, and follows a power-law model for the range where shear-thinning occurs:

$$\mu_{eff} = \max\left[\mu_{\infty}; \min\left\{\left(a\frac{C}{C_o}\right)\gamma^{b}; \mu_0\right\}\right] \qquad (2)$$

where μ_{∞} and μ_0 (kg m^{-1} s^{-1}) are the fluid viscosity at high (> 100 s^{-1}) low (< 0.1 s^{-1}) shear rates, respectively, C/C_o is the normalized polymer concentration, a (kg m^{-1} s^{-1}) and b are power-law model constants. The used a, b, μ_0, and μ_{∞} values, derived from independent experiments, are listed in Table 2.

The shear rate in Eq. (2) is computed as

$$\gamma = \frac{\alpha q}{\sqrt{kn}} \qquad (3)$$

where α is a shape parameter constant, q is the Darcy velocity (m s^{-1}), k is the permeability (m^2), and n the porosity. For the simulations reported in this paper, an α-value of 2.37 is used, which is consistent with the value reported by Martel et al. (1998) for sands having similar diameter.

Table 2. Values of *a*, *b*, μ_0, and μ_∞ used to compute viscosity of Xanthan solutions.

Solution Name	***a*** (kg $m^{-1}s^{-1}$ x 10^{-3})	***b***	μ_∞ (kg $m^{-1}s^{-1}$ x 10^{-3})	μ_0 (kg $m^{-1}s^{-1}$ x 10^{-3})
polymer	27.83	-0.19	1.002	44.1
phosphate – 200 ppm polymer	8.71	-0.22	1.002	12.4
phosphate – 600 ppm polymer	27.83	-0.19	1.002	44.1

3. Results

3.1. Experiment Set I

The experiments in set I (Table 1) were conducted to investigate the effects of Xanthan injection on sweep efficiency, defined as the portion of a subsurface volume contacted by the injected fluid as any stage of the flood. Sweep efficiency is determined visually based on the swept area of the lower-permeability zones. Figure 2 shows a comparison at three times between a water flood (Exp-Ia-W) and a polymer flood (Exp-Ic-P) at flow rate of 5 ml/min. For the water flood, flow bypassing to the lower-permeability zones is considerable, especially in the 40/50 zone. During the polymer flood, the displacing front is straighter in the matrix sand. The simulated fluid displacing fronts, represented by the C/C_o = 0.5 isocontours of the dye for the water flood and the Xanthan gum for the polymer flood, are also included in Fig. 2. The simulations show a good match with the experimental results. The plots show that the sweeping efficiency is considerably better when the mobility-controlling fluid was used as the displacing fluid as opposed to a regular water flood.

Pictures and simulated result of the five phosphate delivery experiments (set II in Table 2) are shown in Figure 3 for three PVs. The pictures show that the displacement fronts of the four polymer-flooding experiments were straighter than the water-flooding experiment (Exp-IIa-W). The pictures do not clearly show a major improvement in sweeping efficiency for the 30/40 lower-permeability zones for the polymer floods. For the 70-mesh sand, improvements can be seen at 0.52 PV for both the 200 and 600 ppm flushes. The efficiency improvement is more pronounced for the 600 ppm polymer flood because of additional, viscosity-induced, penetration at the top and bottom of the zone. Visual differences in sweeping results between the two injection rates (5 ml/min for Exp-IIb-P and Exp-IIc-P; 50 ml/min for Exp-IIc-P and Exp-IId-P) are minimal. The simulation results for all five experiments are in good agreement with the experimental observations.

3.2. Experiment Set II

Quantitative information on sweeping efficiency for experiment set II is shown in Fig. 4. Fig. 4a indicates that differences in the 30/40-mesh zone are small but that for the 70-mesh zone, the sweeping-efficiency enhancement increased as a function of polymer concentration. Compared to the water flood, the swept area was more than doubled for the 200 ppm Xanthan flood (Exp-IIb-P) and more than tripled in the 600 ppm Xanthan flood (Exp-IId-P). The effect of flushing flow rate on the sweeping enhancement is shown in Fig. 4b. Again, it is obvious that the 600 ppm polymer solution improved the sweeping efficiency more than the 200 ppm polymer solution. However, increasing the flow rate from 5 ml/min to 50 ml/min had a minor effect on the swept areas.

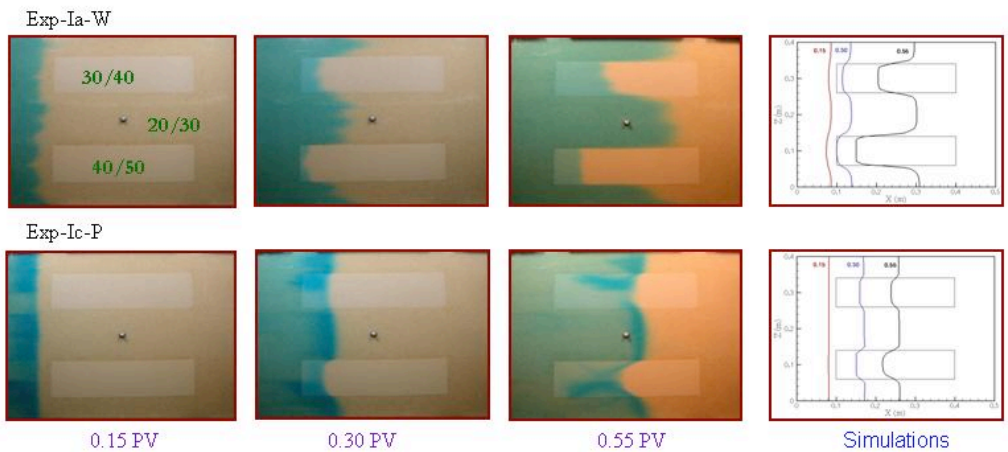

Figure 2. Displacement behavior of Exp-Ia-W and Exp-Ic-P at several pore volumes (PV) and comparisons with predicted $C/Co = 0.5$ isocontours. A PV is calculated based on the total pore volume of the flow cell.

4. Conclusions

A series of laboratory experiments have been conducted to investigate the use of a shear-thinning polymer to improve access to low-permeability zones in heterogeneous systems. Experimental variables were polymer concentration, fluid injection rate, and permeability contrast. The STOMP simulator was modified to include polymer-induced shear thinning effects. The experimental and simulation results clearly show that using polymer solutions leads to enhanced delivery of remedial amendments to lower permeability zones and increased sweeping efficiencies. The STOMP simulator was able to predict the experimental observed fluid displacing behavior well.

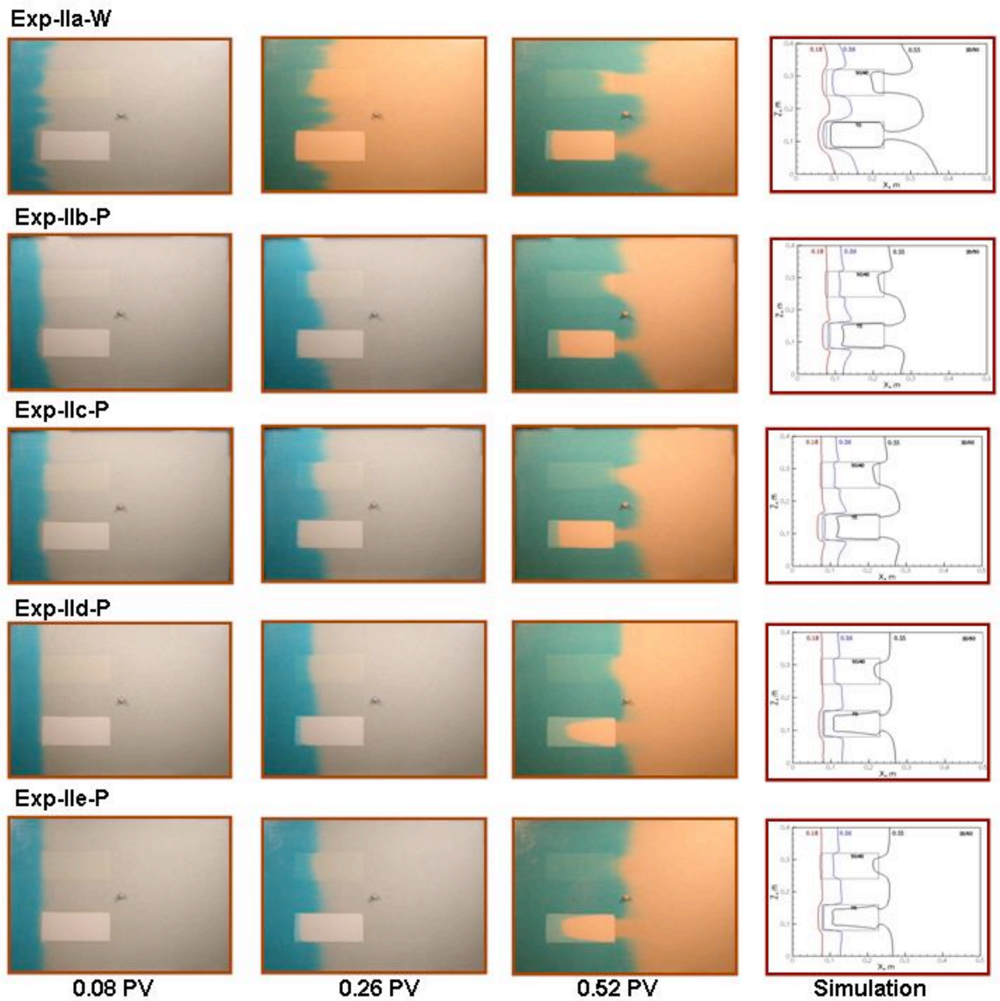

Figure 3. Fluid displacements for experiment set II at several pore volumes (PV) and comparisons with predicted *C/Co* = 0.5 isocontours.

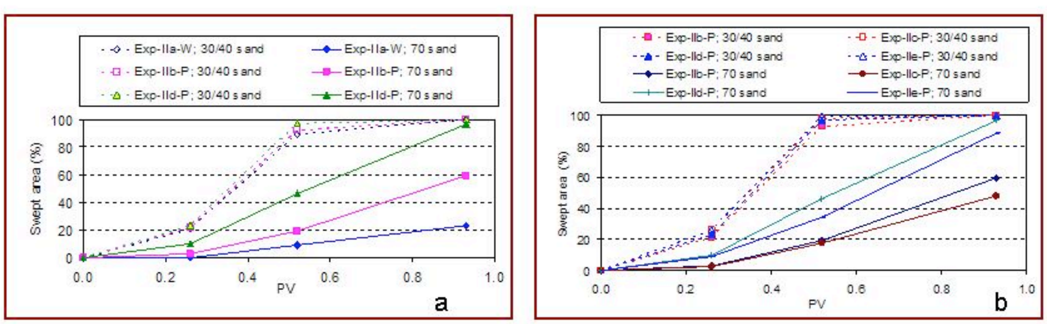

Figure 4. Influence of a) polymer concentration and sand type, and, b) flow rate on swept area (% swept of lower permeability zones) for experiment set II.

Acknowledgements. This study was performed under support provided by Pacific Northwest National Laboratory (PNNL) through the Laboratory Directed Research and Development (LDRD) program. PNNL is operated by the Battelle Memorial Institute for the Department of Energy (DOE) under Contract DE-AC06-76RLO 1830. The intermediate-scale experiments were performed in the Environmental Molecular Sciences Laboratory (EMSL), a national scientific user facility sponsored by the DOE's Office of Biological and Environmental Research and located at PNNL. Scientists interested in conducting experimental work in the EMSL are encouraged to contact M. Oostrom (mart.oostrom@pnl.gov).

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