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FLUID DYNAMICAL AND MODELING ISSUES OF CHEMICAL FLOODING FOR ENHANCED OIL RECOVERY

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ABSTRACT

This paper evaluates the relevance of Hele-Shaw (HS) model based linear stability results to fully developed flows in enhanced oil recovery (EOR). In a recent exhaustive study [Transport in Porous Media, 93, 675-703 (2012)] of the linear stability characteristics of unstable immiscible three-layer "Hele-Shaw" flows involving regions of varying viscosity, an optimal injection policy corresponding to the smallest value of the highest rate of growth of instabilities was identified among several injection policies. Relevance of this HS model based result to EOR is established by performing direct numerical simulations of fully developed tertiary displacement in porous media. Results of direct numerical simulation are succinctly summarized including characterization of the optimal flooding scheme that leads to maximum oil recovery. These results have been compared with the HS model based linear stability results. The scope for potential application of the HS model based results to the development of fast methods for optimization of various chemical flooding schemes is discussed. Numerical experiments with more complex flooding schemes in both homogeneous and heterogeneous reservoir are also performed and results analyzed to test the universality of the generic optimal viscous families in a broader setting.

Introduction

Systems of nonlinear partial differential equations subject to appropriate initial and boundary data usually model complex fluid flows that occur in porous media during tertiary displacement process of chemical enhanced oil recovery. Solving such systems for quantities of interest (such as displacement efficiency, sweeping efficiency, net oil recovered, just to mention a few) requires fast, efficient and accurate numerical methods. Related optimization problems can be even more intensive computationally depending on the objective function. However, such numerical optimization process can be significantly enhanced by judicious choice for initial guesses of quantities of interest that are hopefully near optimal. For example, one of the objective functions in tertiary oil recovery by polymer flooding is the "optimal" viscous profile of the poly-solution (polymer in water) that leads to maximum oil recovery. Knowledge of this helps design optimal polymer injection policies.

In the context of EOR, it would seem difficult to solve for or even characterize the geometry (such as linear, exponential, etc.) of such "optimal" viscous profiles without considering the fully developed flow of tertiary displacement process which certainly occurs long before the displacing fluid (poly-solution) breaks through. It is well known from the abundance of existing studies on a variety of unstable immiscible interfacial fluid flows that certain types of undesirable patterns such as fingering in fully developed flows lead to poor displacement efficiency and ultimately poor oil recovery ([1], [4], [7]). There are two fundamental fluid dynamical mechanisms, among many others, by which the oil recovery can be improved: (i) delaying and slowing down the development of these instabilities that lead to fingers since there is always a finite reservoir area that needs to be swept; or/and (ii) completely arresting the development of such unwanted patterns. The later one is usually difficult because the displacement processes involved are usually unstable to begin with and secondly there are other non-fluid dynamic effects that play a role.

The goal here is then to design optimal flooding schemes that will slow down the development of these fingers "most" in the fully developed nonlinear flow. These nonlinear fingers develop from interactions of various nonlinear interfacial and layer modes as they evolve. But these nonlinear instabilities themselves evolve from "infinitesimal" interfacial hydrodynamic disturbances whose growth rates can be determined by linear analysis of the underlying system. Thus slowing down the development of nonlinear fingers in essence means controlling the growth rates of infinitesimal disturbances at early stages: what is sought is then the injection policy or equivalently the viscous profile of the displacing fluid that stabilizes (i.e. make less unstable) the instabilities most in the "linear regime". Such a viscous profile is called an optimal viscous profile. Whether an optimal profile determined this way, ignoring the effect that the nonlinear part of the instability as it evolves past linear regime may have, is also the optimal or even near optimal profile (corresponding to most oil recovery) for the fully developed flow requires validation of linear stability results against full direct numerical simulation of EOR flooding schemes.

Thus there are two separate problems that need to be solved to address the problem of relevance of linear stability results to EOR: (i) linear stability analysis of the mathematical model of EOR flooding schemes; and (ii) full direct numerical simulation of these flooding schemes. The first problem, as we will see, involves linear analysis of the flow model at the start of injection process when the interfacial disturbances are infinitesimal. The mathematical model of EOR at this stage is very close to immiscible flow in a Hele-Shaw cell such as the one shown in Fig. 1. In section 2, we briefly discuss this analogy. Linear stability of HS model has been studied in great detail in Daripa & Ding [3]. In this section, we highlight two key results from Daripa & Ding [3]: one has to do with the family (such as linear or exponential and so on) of the optimal viscous profiles; and the other has to do with the exact shape (function) of the optimal profiles. Relevance of these to tertiary displacement of chemical EOR is tested using full scale simulations in section 3. All possible simulations, similar to the ones reported there, of various chemical EOR flooding schemes in real porous media have been performed using STARS [9] simulator. Section 3 is a very compact summary of most pertinent technologically important results of full scale simulation that establishes the relevance of our study reported in [3]. This section also provides a procedure that can potentially improve the performance of some direct numerical optimization algorithms that seek to optimize viscous configuration of the displacing fluid in such EOR flooding schemes. In this section, limitations of the key results of [3] are also tested on more complex flooding schemes which are outside the scope of the flooding model used in Daripa & Ding [3]. Finally, we conclude in section 4.

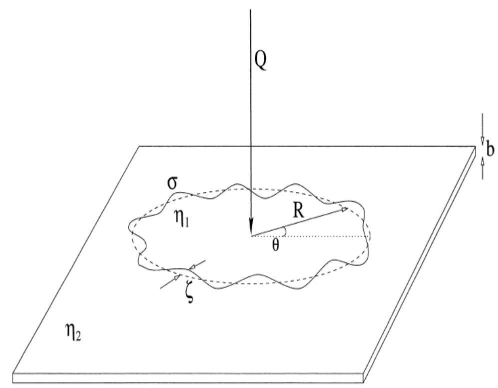


FIGURE 1. SCHEMATIC DIAGRAM OF RADIAL SOURCE FLOW IN A HELE-SHAW CELL.

Results from Linear Stability Analysis

System of partial differential equations that models displacement processes in porous media during enhanced oil recovery is a coupled set of Buckley-Leverett (BL) equations for saturations of various components and Darcy's Law (see [4]). For the purpose of linear stability of a uniformly moving basic state in which displacing fluid consists of an aqueous phase with a mobility gradient induced by polymer concentration profile, the Hele-Shaw model $\nabla \cdot \mathbf{u} = 0$, $\nabla p = -\mu\, \mathbf{u}$, $\mu_t + \mathbf{u} \cdot \nabla \mu = 0$ (see Daripa [2] for more details on this equation) is adequate as it retains all the important features of the Buckley-Leverett model. As is well known, the first equation is the incompressibility condition, the second one is the Darcy's law and the last equation above is the result of passive advection equation of polymer and assumption that the viscosity of poly-solution (aqueous solution containing polymer) is an invertible function of polymer. It has been argued in Daripa & Ding [3] and Daripa [2] that HS models with capillary interfaces and viscous profiles of the displacing fluids are reasonably good approximate models for unstable immiscible fluid displacements in porous media. Readers are referred to these articles for further details on this issue. Because of this analogy, the spectrum from the linear stability analysis based on HS model should be a good reflection of the same based on BL model of EOR.

In Daripa & Ding [3], linear stability of the above Hele-Shaw model involving regions of varying viscosity to provide a stabilizing mechanism was analyzed and the resulting eigenvalue problem was solved for different viscosity profiles to determine the optimal viscous profile corresponding to the smallest value of the highest growth rate of the disturbances. The optimal injection policy can be designed based on this optimal viscous profile. Many results on optimal profiles have been summarized in the last section of that paper. Only a few of these are relevant for this paper which are recalled below from this paper.

In Daripa & Ding [3], we found that the linear viscous profile of the poly-solution displacing oil is optimal unless the width of the middle layer is not small in which case the exponential viscous profile is the optimal one. Whether this linear stability result based on the HS model is the answer to the question posed earlier (i.e. does controlling growth rate of instabilities at early stages of displacement processes during EOR means more oil recovery ?) and thus relevant for EOR is questionable in the absence of direct numerical simulation of real porous media flow during EOR. The study below is designed to address this. Moreover, there is also the issue about whether the optimal profile based on linear stability analysis of HS model is truly the optimal profile for the full simulation or not. These questions will be answered by the results reported in the next section. As we will see, linear stability based optimal profile in the HS model can be a useful guide for the choice of close-to-optimal injection policy for the chemical EOR. It is likely that such a choice in an optimization process for the initial guess can improve computational efficiency of the optimization process. We discuss this issue in the last section.

Direct numerical simulation

Direct numerical simulations of various types of chemical EOR floods have been performed to identify optimal profiles of displacing fluids, i.e. profiles that lead to maximum oil recovery. All numerical simulations were performed using the commercial simulator STARS [9]. All equations of fluid flow solved by this simulator can be found in the documentation of the simulator and we refer to STARS [9] for this. The equations are similar to BL model discussed above briefly. The physical domain, shown in color Fig. 2, is discretized using $11 \times 5 \times 1$ Cartesian grid blocks with each grid block size of $0.55 \times 1 \times 0.55\ cm^3$. There are two wells, an injector and a producer as shown in the figure. For the homogeneous case below, the permeability is assigned a constant value of 2591 *md* and field porosity of 0.2494. For the heterogeneous case, permeability and porosity fields are chosen isotropic with their average values fixed at the same values as the homogeneous case which will be helpful for comparison of results. The color Fig. 3 shows the permeability and porosity distribution in the heterogeneous reservoir model. Uniformly distributed permeability, ranging from 600 *md* to 17,000 *md*, were assigned to the grid blocks with the average permeability of 2591 *md*. Uniformly distributed porosity, ranging from 0.17 to 0.4, were similarly assigned to these grid blocks with the average porosity of 0.2494.

Direct numerical simulations of several EOR flooding schemes in homogeneous and heterogeneous reservoirs have been performed by varying the concentration of polymer and

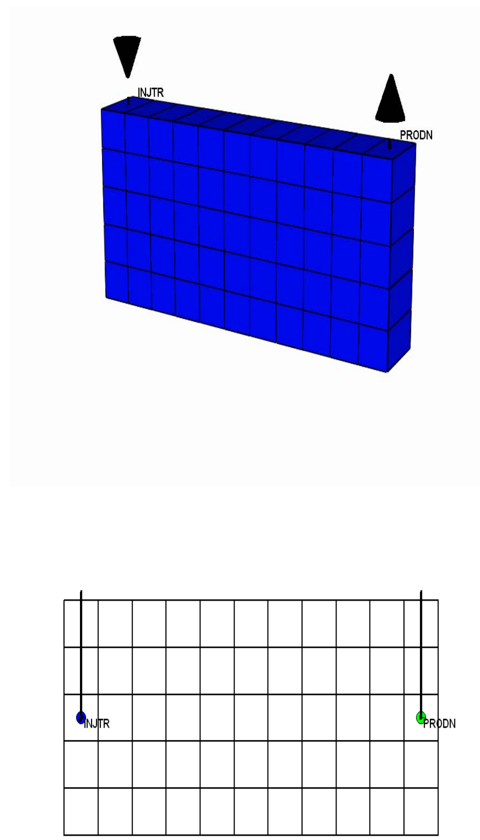


FIGURE 2. RESERVOIR MODEL - 3D VIEW (TOP) AND 2D VIEW (BOTTOM). THIS IS A COLOR FIGURE.

other additives in the poly-solution (which is polymer-thickened aqueous phase) as these are injected in a manner that leads to different viscous profiles of the displacing fluid. The viscosity of the dead oil in the reservoir is constant at 10.94 cp. The pressure and temperature of the system initially are 89 kPa and 31^0C respectively. In simulations with the polymer flood, the poly-solution is injected for three days followed by one day water flooding as seen in color Fig. 4. This figure shows four types (linear, exponential, sine and polynomial) of polymer concentration profiles in the poly-solution which is displacing oil. The concentration of the poly-solution at time $= 0$ (day) and time $= 3$ (day) are denoted by $c(T_0)$ and $c(T_3)$ respectively as shown in Fig. 4. The concentration value at any time during the injection period is determined by the profile used.

Using each of these profiles in both types of reservoirs, many simulations have been performed changing either $c(T_0)$ or $c(T_3)$ or both over a range $(0, 3.3)$ where viscosity of the polysolu-

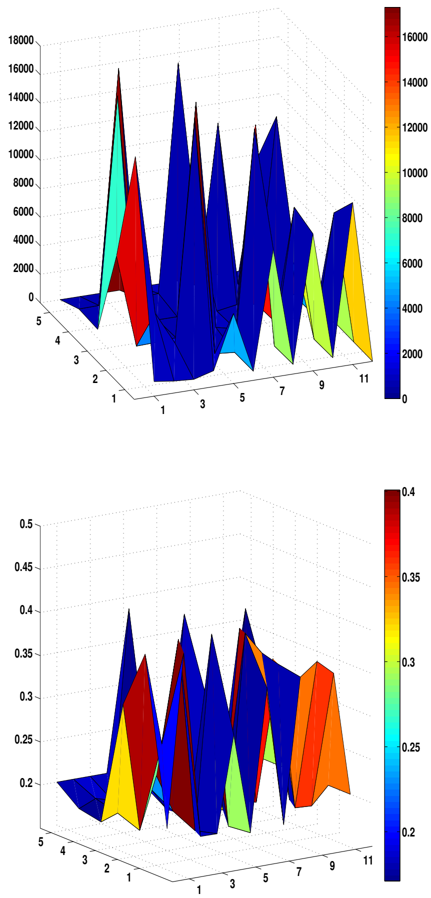


FIGURE 3. HETEROGENEOUS RESERVOIR - PERMEABILITY FIELD (TOP) AND POROSITY FIELD (BOTTOM). THIS IS A COLOR FIGURE.

tion corresponding to the highest value is closest but less than the viscosity of the oil being displaced. Figures 5(a) and 5(b) show plots of oil recovered (after four days of flooding as per the Fig. 4) in homogeneous reservoir for linear and exponential concentration profiles respectively (for other two profiles, results are similar and not shown for brevity). Similar plots for the heterogeneous case are shown in Fig. 6(a) and 6(b). Maximum oil recovered (shown within a red box in each of these figures) and the corresponding profile, so called optimal profile, are thus identified for all four families of profiles for both types of reservoirs. These results show that the maximum oil recovered at the end of four days of flooding for all four optimal profiles, one from each family, in each type of reservoirs are very close to each other though the linear profile is found to be marginally superior and thus the most optimal one for four days of flooding in both types of reservoir. However, Figures 5(a) and 6(a) show that the

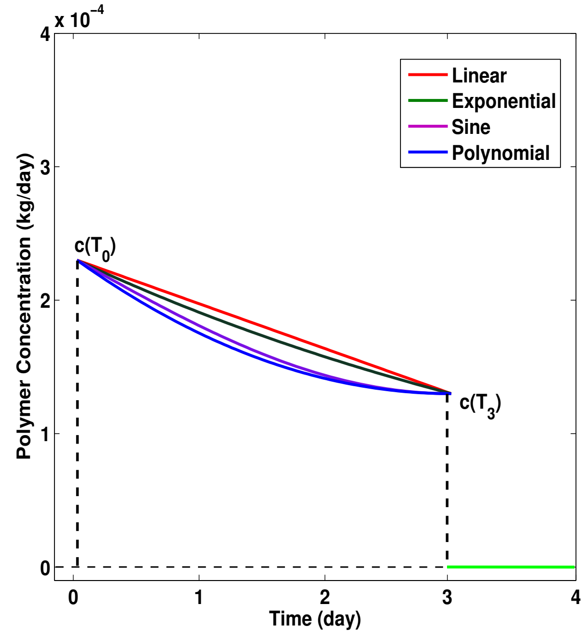
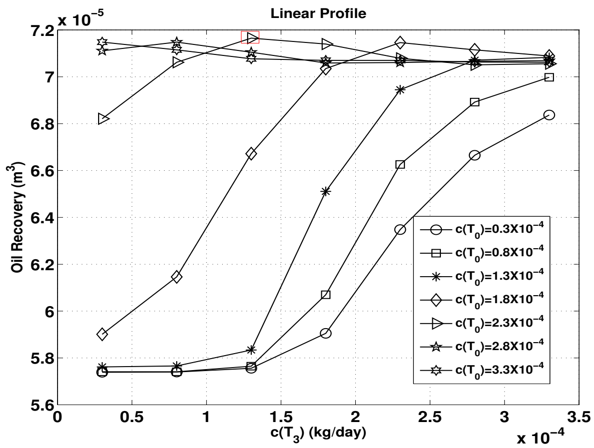


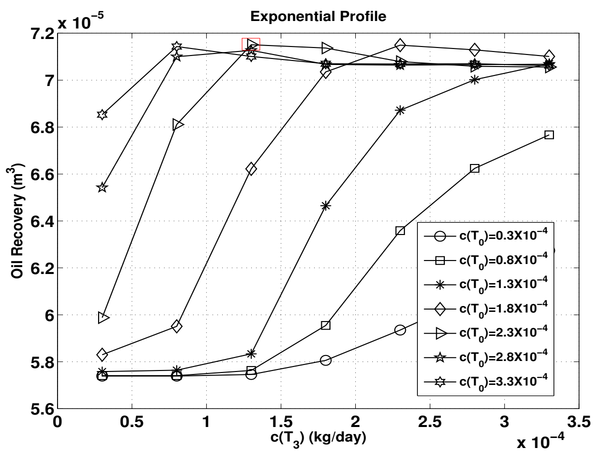
FIGURE 4. POLYMER FLOOD: POLYMER CONCENTRATION VERSUS TIME OF INJECTION. THIS IS A COLOR FIGURE.

optimal profiles (which are linear) for homogeneous and heterogeneous reservoirs are not same and the net oil recovered after 4 days of flooding with the optimal profile for the heterogeneous case is somewhat less than that for the homogeneous case.

The color figure Fig. 7 shows the percentages of oil produced corresponding to these four optimal profiles, one from each family, for the homogeneous reservoir. This figure shows a switch from exponential to linear optimal profile as the duration of flooding increases. In fact, the figure shows that for any duration of flooding there is little variation in the percentages of oil produced by the four profiles with either linear or exponential doing little better depending on the duration of flooding. In particular, the exponential profile performs the best up until little over two days of flooding and thereafter linear one takes over. Thus we notice the similarity between the behavior of optimal profiles from full direct simulation with that from linear stability of the HS model: recall from Daripa & Ding [3] that either the linear or the exponential profile depending on the length of the slug (equivalently duration of injection) was also found most stabilizing in the HS model. Figure 8 shows the water saturation at time = 0.30, 1.00, 2.00 and 4.00 days for polymer flooding with the optimal linear profile. Notice that severe fingering patterns do not appear because the instabilities at early stages are significantly suppressed by the choice of this optimal linear optimal profile. To test the limitation of the similarity result, direct numerical simulations were performed with other chemical flooding

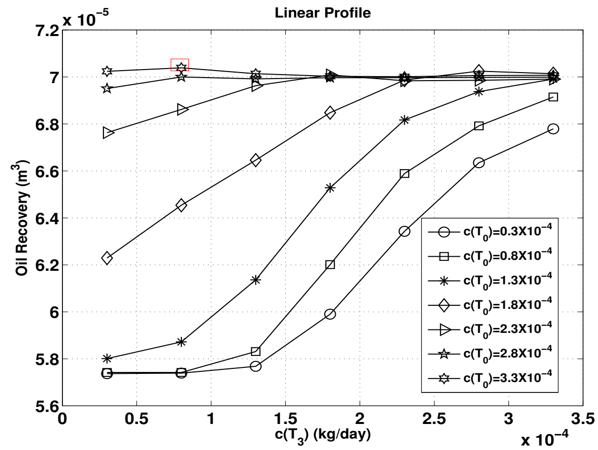


(a) Linear profile

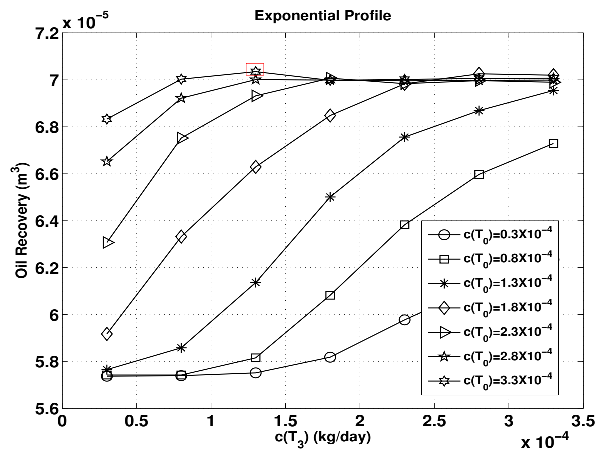


(b) Exponential profile

FIGURE 5. HOMOGENEOUS CASE: NET OIL RECOVERED FOR SEVERAL LINEAR AND EXPONENTIAL POLYMER CONCENTRATION PROFILES ((SEE FIG. 4) IN POLYMER FLOODING.



(a) Linear profile



(b) Exponential profile

FIGURE 6. HETEROGENEOUS CASE: NET OIL RECOVERED FOR SEVERAL LINEAR AND EXPONENTIAL POLYMER CONCENTRATION PROFILES ((SEE FIG. 4) IN POLYMER FLOODING.

schemes such as surfactant-polymer (SP) and alkali-surfactant-polymer (ASP) floods which are briefly discussed next.

We first show simulation results with surfactant-polymer (SP) flooding. Since optimal polymer concentration profile in the polymer flooding was found to be linear, numerical simulations with various linear profiles for both surfactant and polymer in surfactant-polymer flooding were performed for the same duration of flooding. For easy comparisons, concentration profile of polymer injected is kept same as in the polymer-flooding. The mass ratio of injected surfactant and polymer is 2.1 : 1. Plots similar to Fig. 5(a) are shown in the bottom panel of Fig. 9 for SP-flooding and compared with the polymer flooding results shown in the top panel of Fig. 9. Several observations can be made: (i) SP-flood, almost for all linear profiles except in a few cases, produces more oil than the polymer flood; (ii) the optimal linear profile for SP-flooding is different from that for the pure polymer flood; (iii) the net oil recovered corresponding to these optimal profiles are different with the pure polymer flooding doing little better than the SP-flood; and (iv) SP-flooding is better than the polymer flooding for almost all linear viscous profiles except for a few. The self-explanatory color grid plot Fig. 10 in which the color bar value refers to the difference between the net oil recovered by these two flooding schemes show that most of the grid cells' colors correspond to positive values meaning SP-flooding produces more oil than pure polymer flooding for most linear profiles.

Results with SP-flooding above shows that the surfactant in SP-flooding does not mobilize residual oil that much. This is due

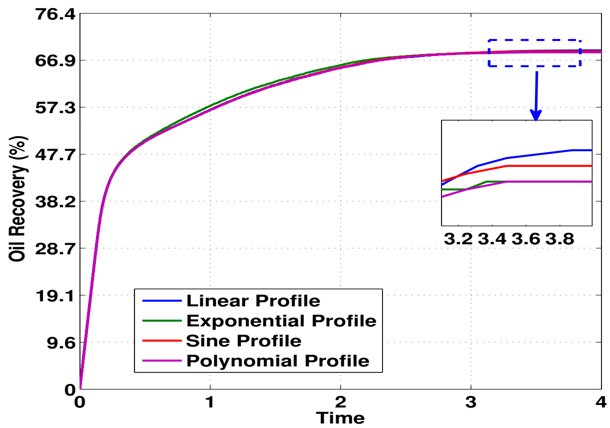


FIGURE 7. POLYMER FLOODING IN HOMOGENEOUS RESERVOIR: NET OIL RECOVERED VERSUS DURATION OF FLOODING FOR FOUR DIFFERENT CONCENTRATION PROFILES. THIS IS A COLOR FIGURE.

to severe surfactant retention. Since alkali reacts with the acids in the reservoir crude oil to generate additional surfactant in situ, adding alkali thus helps to overcome the surfactant depletion as next set of direct simulation results with ASP-flood shows. Again for easy comparison, concentration profile of polymer injected is kept same as in the polymer-flooding and SP-flooding with the mass ratio of alkali:surfactant:polymer=10 : 0.75 : 1. Figures 11(a) and 11(b) compare net oil recovered after four days of polymer-flooding and ASP-flooding respectively in homogeneous reservoir. It shows that ASP-flooding produces significantly more oil than polymer-flooding for every linear polymer concentration profile in the injected displacing fluid. The color figure Fig. 12 compares oil recovery percentage for ASP flooding and polymer flooding for both heterogeneous and homogeneous reservoirs. We see that the homogeneous one produces more oil than the heterogeneous one after 2 days of polymer flooding and little after 3 days of ASP flooding.

Discussions and Conclusions:

In conclusion, we have shown similarity in the shape (geometry) of the optimal profiles based on the linear stability of the HS model and the one based on the full direct simulation of the polymer flooding. In both cases, it is either the linear profile or the exponential profile depending on the number of days of flooding. Since the growth rate of instabilities at early stages is suppressed most by the optimal profiles in the HS model (see [3]), use of the optimal profile in the polymer flooding perhaps does the same because this would naturally lead to more oil recovery for reasons already mentioned earlier, namely suppression and delay in the development of fingers and other complex detrimental instabilities. This scenario is clearly supported by the Fig. 8 in which

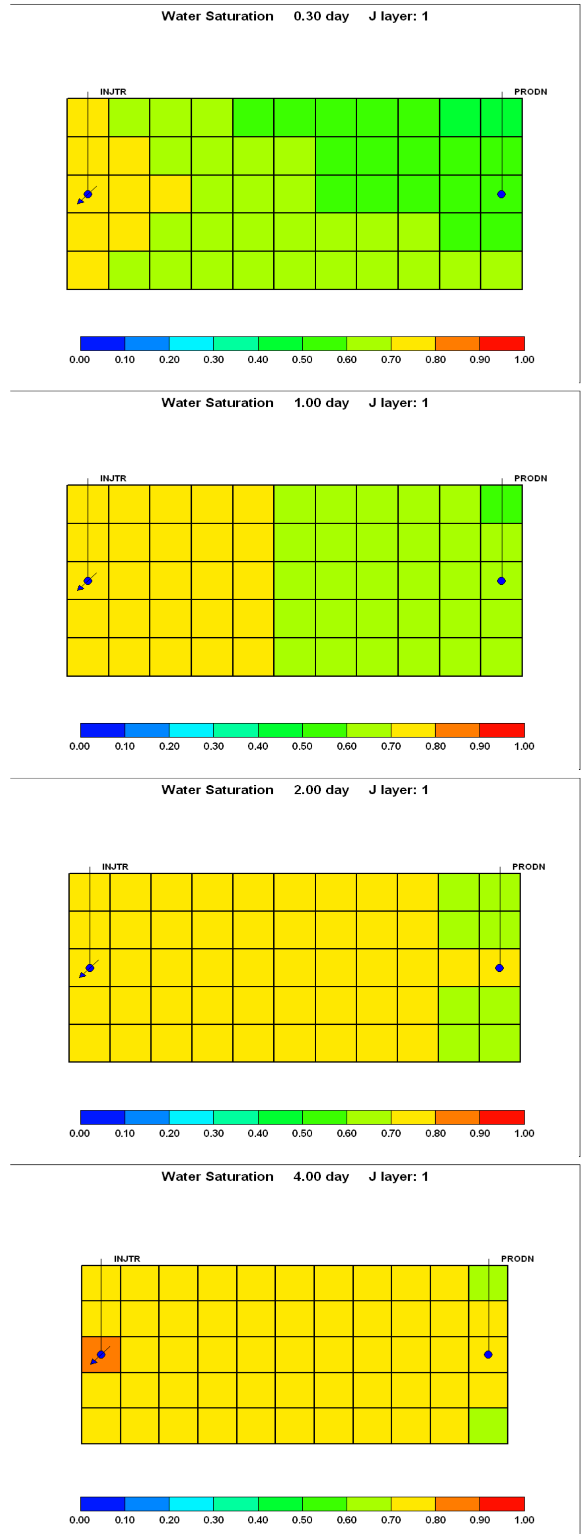


FIGURE 8. POLYMER FLOODING IN HOMOGENEOUS RESERVOIR: COLOR GRID PLOT OF WATER SATURATION AT DIFFERENT TIMES FOR THE OPTIMAL LINEAR PROFILE. LAYER 1 MEANS TWO DIMENSIONAL SIMULATION. THIS IS A COLOR FIGURE.

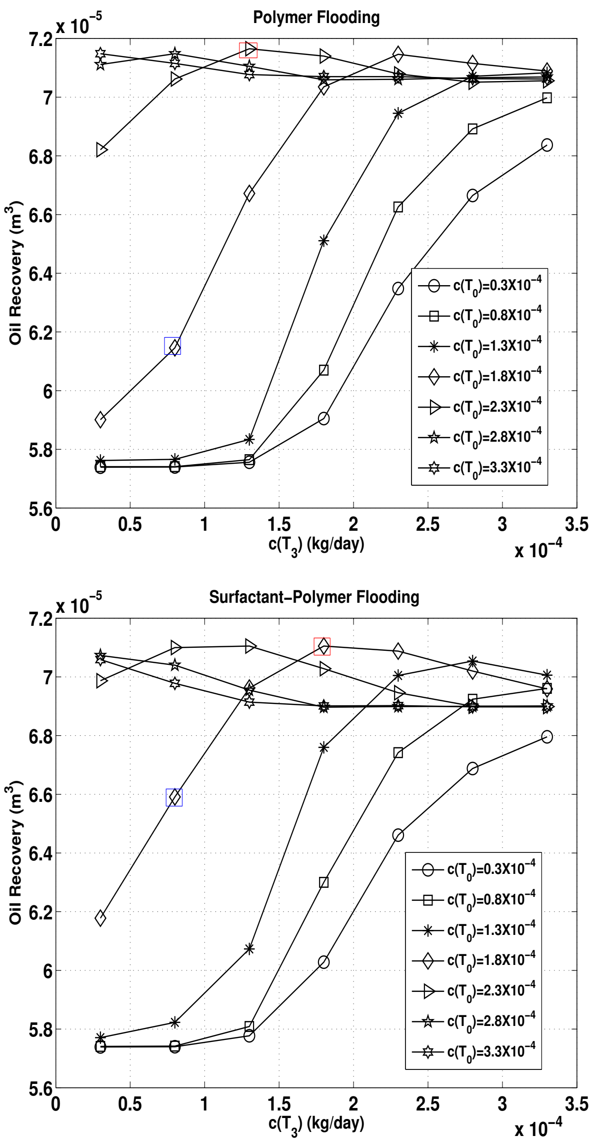


FIGURE 9. NET OIL RECOVERED FOR SEVERAL LINEAR POLYMER CONCENTRATION PROFILES USED IN POLYMER-FLOODING AND SP-FLOODING IN HOMOGENEOUS RESERVOIR. EACH MARKED POINT IN THESE PLOTS CORRESPOND TO A LINEAR PROFILE CONNECTING $c(T_0)$ AND $c(T_3)$ (SEE FIG. 4).

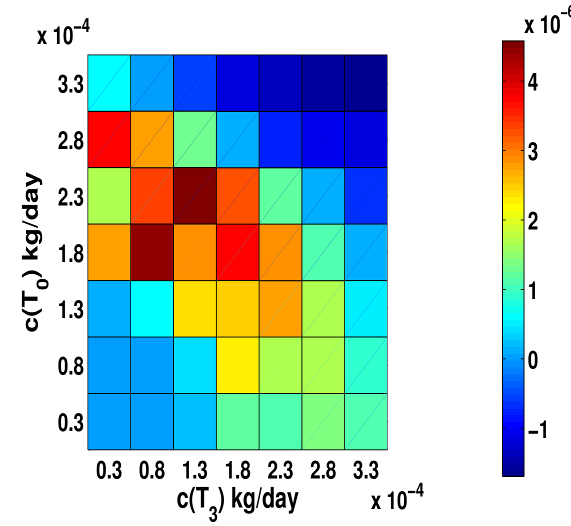


FIGURE 10. COLOR GRID PLOT OF THE DIFFERENCE BETWEEN THE NET OIL RECOVERED IN SURFACTANT-POLYMER FLOODING AND IN POLYMER FLOODING. THIS IS A COLOR FIGURE.

severe fingering patterns are absent. Interestingly, the present simulation as shown above shows linear profiles as optimal ones in SP-flooding and ASP-flooding. Moreover, the optimal profile for ASP flooding is shown to be significantly more effective than the optimal profiles for polymer-flooding and SP-flooding.

Another issue that we started out with to address is whether the optimal profile based on linear stability analysis of the HS model is truly the optimal profile for the full simulation or not. On the assumption that viscosity is a linear function of the polymer concentration which actually happens to be the case in our full scale simulation, correspondence between the linear optimal viscous profile in the HS model and the linear polymer concentration profile of the poly-solution is straight forward. This way the above issue can be settled if it were not for the other effects present in the porous media flow model of full scale simulation. However, the optimal linear viscous profile of the HS model which is computationally very inexpensive to obtain (see [3]) is likely to be an excellent initial guess for the true optimal profile for the polymer flooding. Such a guess is likely to significantly expedite the performance of any optimization algorithm that seeks such an optimal profile in polymer flooding. In fact, this procedure can be used even for other EOR chemical flooding schemes such as SP-flooding and ASP-flooding as the discussion above of the results obtained with these flooding schemes show. Though this procedure is partly speculative and partly supported by the simulation here, further work needs to be done in order to verify computational effectiveness of this procedure.

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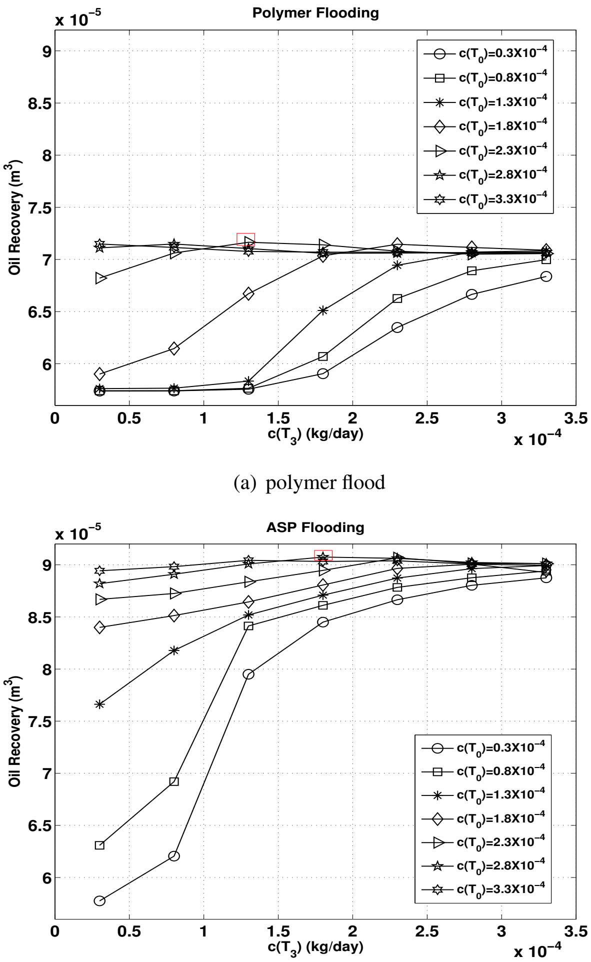

(a) polymer flood

(b) ASP flood

FIGURE 11. NET OIL RECOVERED FOR SEVERAL LINEAR POLYMER CONCENTRATION PROFILES USED IN POLYMER- AND ASP-FLOODS IN HETEROGENEOUS AND HOMOGENEOUS RESERVOIRS. EACH MARKED POINT IN THESE PLOTS CORRESPOND TO A LINEAR PROFILE CONNECTING $c(T_0)$ AND $c(T_3)$ (SEE FIG. 4). THIS IS A COLOR FIGURE.

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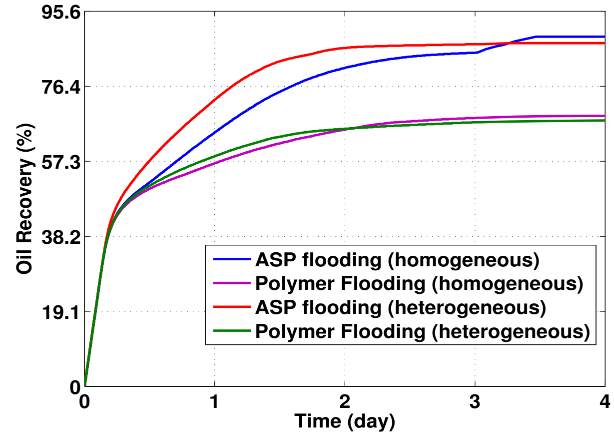

FIGURE 12. PERCENTAGE OF OIL RECOVERED VERSUS DURATION OF FLOODING FOR POLYMER- AND ASP-FLOODS IN HETEROGENEOUS AND HOMOGENEOUS RESERVOIRS. THIS IS A COLOR FIGURE.

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