SCALE-UP OF MISCIBLE FLOOD PROCESSES FOR HETEROGENEOUS RESERVOIRS

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Introduction

The current project is a systematic research effort aimed at quantifying relationships between process mechanisms that can lead to improved recovery from gas injection processes performed in heterogeneous Class 1 and Class 2 reservoirs. It will provide a rational basis for the design of displacement processes that take advantage of crossflow due to capillary, gravity and viscous forces to offset partially the adverse effects of heterogeneity. In effect, the high permeability zones are used to deliver fluid by crossflow to zones that would otherwise be flooded only very slowly. Thus, the research effort is divided into five areas:

- Development of miscibility in multicomponent systems
- Design estimates for nearly miscible displacements
- Design of miscible floods for fractured reservoirs
- Compositional flow visualization experiments
- Simulation of near-miscible flow in heterogeneous systems

The status of the research effort in each area is reviewed briefly in the following section.

Project Status

- **Development of Miscibility in Multicomponent Systems**

  In this area, we continue to make progress in creating a systematic theory of miscibility development in multicomponent systems. We have extended the four component theory to the displacement of an oil with an arbitrary number of components by a single gas component. We have constructed analytical solutions for a ten-component synthetic oil by CO_2 and compared the results to displacement experiments to demonstrate the generalization of the theory [6]. We also constructed solutions for displacement of mixtures of methane, butane and decane by nitrogen or by nitrogen/methane mixtures [2]. These solutions explain conflicting experimental observations concerning the sensitivity of minimum miscibility pressures to changes in the compositions of initial oil or inected gas. Ph.D student, Yun Wang, recently developed a closed-form mathematical representation of the solutions for two-phase flow of three- and four-component systems with constant equilibrium ratios (K-values). The analytical approach allows us to construct the whole solution without resorting to numerical calculation which might introduce error. Although the constant K-value assumption is valid only when the system pressure is low, the theory gives us the first complete description of the solution behavior. Because the solution structure for constant K-values is similar in its essential details to that for two-phase flow of multicomponent systems, the analytical solution with estimated average K-values can be used as a guide to construct solutions for systems with variable K-values.

  The solutions for gas displacements from the mathematical theory so far are obtained without considering gravity effects. Jichun Zhu, a master student, has recently joined the research group and started to construct solutions for gas injection processes under influence of gravity. He is also looking for solutions for the problems in which both gas and oil initially exist in the reservoir.

We also finished an analysis of rising bubble experiments for the determination of minimum miscibility pressure and/or minimum miscibility enrichment [12] for a gas injection process. Both our analysis and experimental observations for a three-component system indicates for vaporizing gas drives rising bubble experiments can accurately reflect the development of miscibility and falling drop experiments are good for condensing gas drives.

- **Design Estimates for Nearly Miscible Displacements**

In this area, Ph.D student, Akshay Sahni, is examining the effects of three-phase relative permeability behavior on the performance of gas injection processes in which all three phases (gas, oil and water) move. Combining a newly developed mathematical theory of three-phase flow [5] and experimental measurements, he is evaluating the efficiencies of nearly miscible gas injection processes at reservoir scale to examine whether the high oil recoveries measured in laboratories are achievable in the fields. At the present time, he is able to match laboratory experiments with different initial conditions using a single set of relative permeability curves for the same medium and fluid system, which suggests that the relative permeability curves used are sufficiently reliable. He will use this set of relative permeability to predict field scale problems to examine whether it is feasible to obtain laboratory measured high oil recovery in the field life time.

To understand the effects of spreading coefficient and pore geometries on relative permeability behaviors at low saturations, we conducted drainage experiments of hydrocarbons in noncircular capillaries. We also developed a closed-form solution for flow in corners, which is important for accurately predict relative permeabilities from network simulations. The new solution also highlight the effects of geometry on the behavior of relative permeabilities. We are extending this experiments to study the effects of boundary conditions at the water/oil and oil/gas interfaces.

Darryl Fenwick, a Ph.D student, continues constructing his three-dimensional network research simulator for three-phase flows and has been producing very interesting results[4]. He has found that spreading coefficients and saturation histories are among the most sensitive parameters in determining final oil recoveries from gas injections, which cannot be revealed by conventional capillary and relative permeability models. Combination of his network simulations and our laboratory measurements will enable us to obtain much better understanding relative permeability behaviors with changes in spreading coefficient, pore structures and wettability.

- **Design of Miscible Floods for Fractured Reservoirs**

We continue to extend our effort in understanding the effects of spreading coefficient and reservoir heterogeneity on final oil recoveries by gravity drainage. Our sand column experiments have shown that for water-wet media, the final oil saturation can be as low as 0.1% of pore volume for a spreading system, however, for nonspreading systems, the final oil saturation depends on the spreading coefficient and the pore geometry. We recently started to conduct visualization experiments to investigate the drainage mechanisms in pore spaces. In these experiments, we can observe the spreading process when gas contacts a water-trapped oil droplet in a glass-bead pack and the consequent drainage mechanisms between pores. The differences of this visualization experiments from other micromodels is that the glass-bead pack has significantly larger dimensions than micromodels so that gravity effects can been observed.

Our high pressure drainage experiment continues producing new data for the drainage of Means crude in the presence of CO_2. We have obtained results pressures of 900, 1500, and 1700 psia on two sandstone cores withe permeabilities of 100 and 500 mD. Our data show that increases in pressure (for the same temperature) result in increased oil recovery. This is a result, we believe, of the reduction in interfacial tension between gas and oil phases with increaseing pressure.

- **Flow Visualization Experiments**

  We have continued to conduct flow visualization experiments. We have performed two-phase displacements of matched viscosity but different densities to investigate gravity effects without the influence of stablizing or unstablizing created by viscous forces. The observations from those experiments will be reproduced by the particle-tracking simulator. Bradley Peters, a master student, continues his experiments to investigate the scaling parameters for gravity and viscous forces in layered systems, by comparing the fluid distributions on two models of same heights but different lengths.

- **Simulation of Flow in Heterogeneous Reservoirs**

  We have continued to investigate the streamline approach as a numerical alternative to conventional finite difference simulators to be used in predicting near-miscible gas injection in heterogeneous reservoirs. The streamline method has been generalized to include compositional effects and dispersion in three dimensions [1]. We have run multi-well tracer problems with one million blocks. More recently we have started looking at three-dimensional, first-contact miscible displacements. Detailed results about this work will be presented in the research result section that follows. The ultimate goal of this project will be to test the streamline simulator with real field data and compare against conventional simulators.

Research Results

In this section, we report some of the recent results from streamline simulations. This work is a joint effort by Ph.D student, Rod Batycky, and Prof. Martin Blunt.

Introduction

Recently *Thiele et. al* [10][11] have successfully used streamtubes to model flow in convection dominated two-dimensional displacements. They have shown that streamtube calculations combined with mapping of any one-dimensional solution onto the streamtubes, results in accurate performance predictions using between 10 and 10000 times fewer matrix inversions than conventional approaches. The main focus of our work here is to extend *Thiele's* streamtube methods to three-dimensional field scale systems with arbitrary well locations.

In this work, we trace streamlines in a three-dimensional flow field as opposed to calculating the streamtubes [1], although in 2-D our streamline method gives identical results to 2-D solutions from *Thiele*. As with the streamtube method, each streamline is treated as a one-dimensional homogeneous systems along which any one-dimensional solution can be mapped. The physics of the displacement is captured in the appropriate one-dimensional solution, while the effects of the heterogeneity are captured by the paths of the streamlines.

Tracing Streamlines and Mapping a One-Dimensional Solution

By definition, a streamline is a line in a velocity field that at any location is parallel to the local velocity vector. We trace streamline paths by a procedure similar to those documented in particle tracking and groundwater literature.

A summary of the streamline tracing and one-dimensional solution mapping method to arrive at a three-dimensional solution is shown below.

1. To begin we first solve the pressure equation,
$$\nabla \cdot \lambda_t \nabla P = 0, \tag{1}$$
on a conventional finite difference grid with appropriate well locations and noflow outer boundaries. Here λ_t is the total mobility at any point in the grid and P is the pressure.
2. Solve for the velocity field at each gridblock face using Darcy's Law.
3. Apply the method derived by *Pollock* [9] for the analytical definition of a streamline path within a gridblock. In *Pollock's* method, he defined a piecewise linear interpolation of the velocity field in each direction, within a gridblock, based on the values at the block faces.
4. Trace streamlines from injectors to producers using the analytical expressions within each gridblock. For each block that a streamline passes through, record the time-of-flight. *King et. al* [7] defined the time-of-flight, tof_s, to any location, s, as the time it takes to move along a given streamline from the injector to location s,
$$tof_s = \int_0^s \frac{1}{V(\zeta)} d\zeta. \tag{2}$$
Here $V(\zeta)$ is the local interstitial velocity along the streamline.
5. Map a one-dimensional solution along each streamline. These solutions (composition, saturation) typically scale by dimensionless velocity x_D/t_D. At any given elapsed time of the simulation, t_e, the following relationship holds,
$$\frac{tof}{t_e} = \frac{x_D}{t_D}. \tag{3}$$
So for a given elapsed time, any location along a streamline corresponds to a dimensionless velocity and hence, a unique composition and saturation.

We have integrated the above steps into a general 3-D streamline simulator, 3DSL, that can handle multiple wells in any location.

[1]Streamtubes do exist in 3-D, but calculating them can be quite involved (*Matanga* [8])

Current Results

In this section we use 3DSL for several simulations, and compare against ECLIPSE or analytical solutions where available. We look at tracer displacements, the application of 3DSL to multiple equiprobable realizations, and conclude with waterflood displacement comparisons on three different permeability fields.

Quarter Five-Spot Tracer Displacement

To validate our numerical method employed here, we first compare 3DSL results with the analytical solution of a tracer displacement in a quarter-five spot. The analytical streamline tracing technique combined with a 1-D tracer profile should yield "exact" results from 3DSL. The results on a 100X100 grid are shown in Figure 1 [2]. Also included are results from ECLIPSE for a diagonal and parallel grid. Clearly the 3DSL results are identical to the analytical solution and are free of numerical diffusion and grid orientation effects.

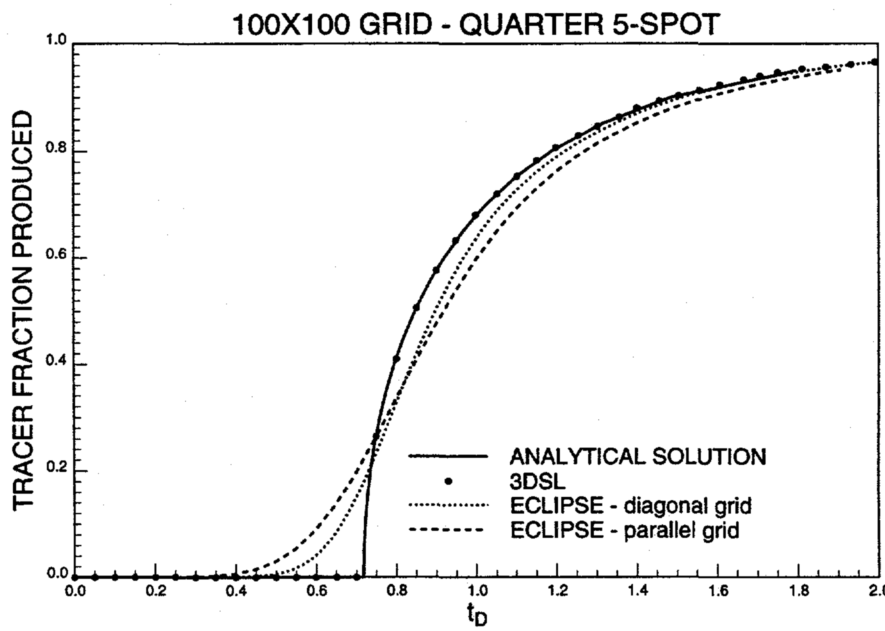

Figure 1: Tracer concentration at producer in a quarter-five spot.

Three-Dimensional Tracer Simulations

Because tracer results from 3DSL are exact, we can use this new simulator to quantify the level on numerical diffusion present in conventional ECLIPSE tracer simulations. Here we have generated a 40X40X10 permeability field using GSLIB. The field, as seen in Figure 2, is

[2] Similar results were presented by *Fay & Pratts* [3] in 1951 by numerically solving for the stream function directly, and then mapping a tracer solution to the calculated streamlines.

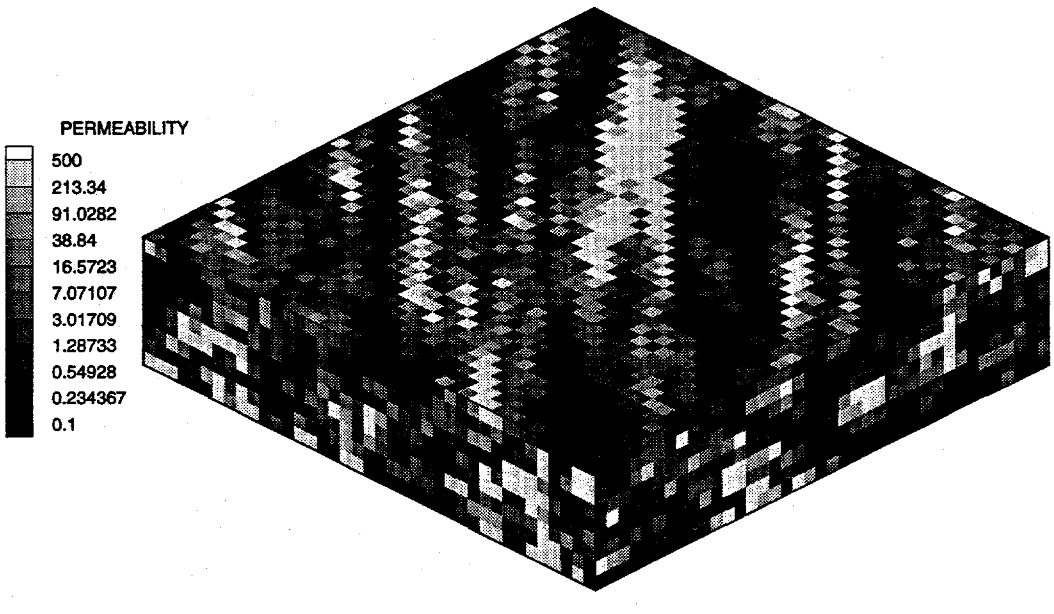

Figure 2: 40X40X10 correlated permeability field.

anisotropic with an on-trend correlation length of $\lambda_c = 0.5$ in the main horizontal direction, a transverse correlation length in the horizontal of $\lambda_c = 0.2$ and vertical correlation length of $\lambda_c = 0.1$.

We performed two quarter-five spot displacement experiments, one in the on-trend direction and one in the off-trend direction. The tracer recoveries for 3DSL and ECLIPSE are shown in Figure 3. The ECLIPSE results agree better with the actual solution (3DSL) when the main flow direction is off-trend as opposed to on-trend. The difference seen in the two solution methods is based strictly on the magnitude of numerical diffusion within ECLIPSE.

ECLIPSE has both longitudinal and transverse numerical diffusion while 3DSL has neither. Longitudinal diffusion along a streamline will smear the displacing tracer shock and act to reduce tracer recovery, while transverse diffusion will improve recovery. Clearly in the on-trend case transverse diffusion within ECLIPSE is more dominant than transverse convection. Tracer fingering through high permeability regions has the potential to diffuse into adjacent low permeability regions and remain there, giving overly optimistic recovery. When flow is off-trend the fluid takes a more tortuous path from injector to producer. Now transverse convective fluxes are large compared with transverse numerical diffusive fluxes, and the recovery curves are in closer agreement. However, there is still longitudinal diffusion that affects recovery during the first half of the displacement.

Using 3DSL with Multiple Realizations

The streamline method is suitable for quickly processing many equiprobable geological realizations generated using geostatistics. Here we show in Figure 4, the recovery curves from

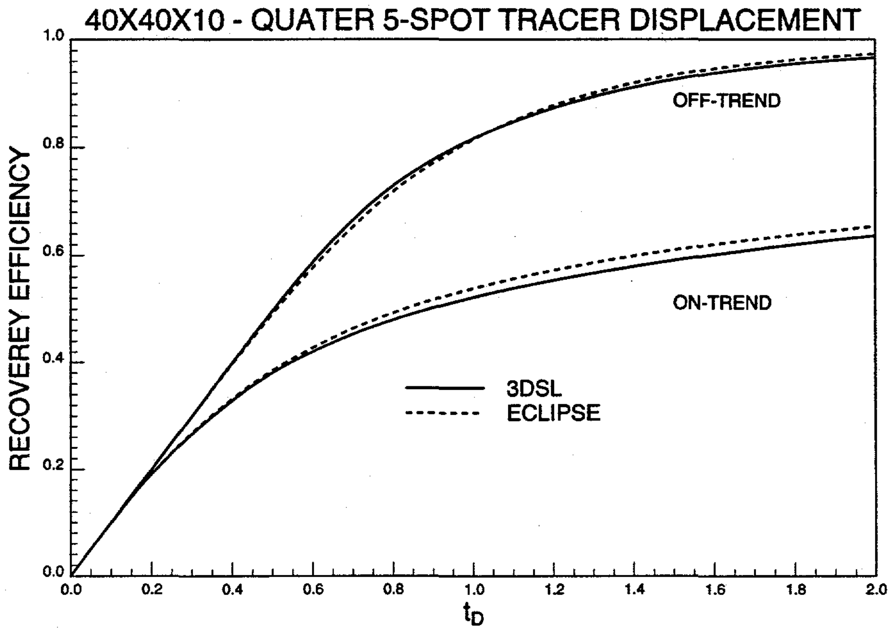

Figure 3: Recovery curves for tracer displacement in a quarter five-spot patter, for on-trend and off-trend directions.

3DSL for ten equiprobable geological models of a 200X200X10 ($4X10^5$ gridblocks) quarter five-spot tracer displacement. Note that it took less time to generate these 10 curves then is would have taken to generate one curve using a conventional finite difference approach. So by using 3DSL, one can quickly provide a distribution of recoveries based on the known uncertainty in any geological description.

Waterflooding in a Full Five-Spot Pattern

In the previous sections we mapped a one-dimensional tracer solution to each streamline. Here we map the Buckley-Leverett solution of a waterflood displacement to each streamline. Furthermore, to illustrate the generality of 3DSL, we consider a full five-spot pattern on a 50X50X20 grid with four corner producers and one central injector. The producers are completed in the upper 10 gridblocks while the injector is completed in the lower 10 gridblocks. We looked at three different fields with varying reservoir heterogeneity generated using GSLIB,

Case 1 A diagonally oriented permeability field with a correlation length of $\lambda_c = 0.3$ in the on-trend direction and $\lambda_c = 0.03$ in the off-trend direction. The vertical correlation length is $\lambda_c = 0.1$.

Case 2 An isotropic areal distribution with $\lambda_c = 0.4$ and a vertical correlation of $\lambda_c = 0.1$.

Case 3 A diagonally oriented field with $\lambda_c = 0.4$ in the main trend direction, an off-trend horizontal correlation with $\lambda_c = 0.1$, and a vertical correlation of $\lambda_c = 0.8$.

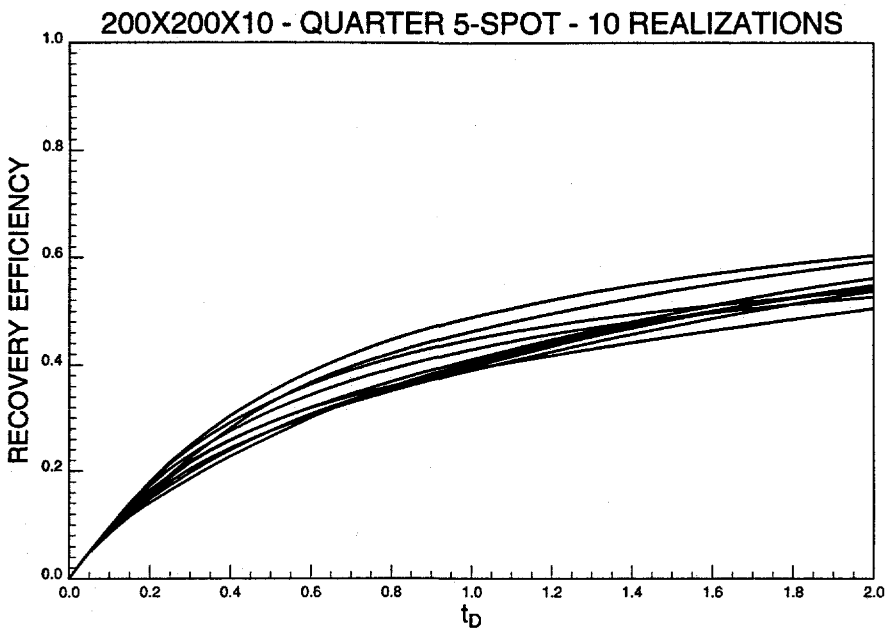

Figure 4: Recovery curves from 3DSL for ten equiprobable geological realizations of a quarter five-spot tracer displacement.

Figure 5 summarizes the oil recoveries under waterflooding for the three permeability fields. Clearly the results from the two simulation methods are in excellent agreement for all cases. Again ECLIPSE suffers from numerical diffusion which can lead to optimistic recoveries, depending on the interaction of major flow directions with permeability correlations. Note that the 3DSL solutions required between 10 and 20 times less CPU usage than the ECLIPSE solutions. So not only does 3DSL generate accurate results for waterfloods, but it does so in a fraction of the time.

Conclusions

We have successfully extended *Thiele et. al's* methods of calculating two-dimensional displacements to three-dimensional systems by tracing streamlines from injectors to producers. The above examples highlight the advantage of the streamline technique over conventional finite difference results. The advantages being, 3DSL gives fast accurate results, it is a useful tool for quantifying the effects of numerical diffusion in conventional simulations, and 3DSL provides a way to quickly analyze equiprobable geological models thereby giving a distribution of possible recovery curves.

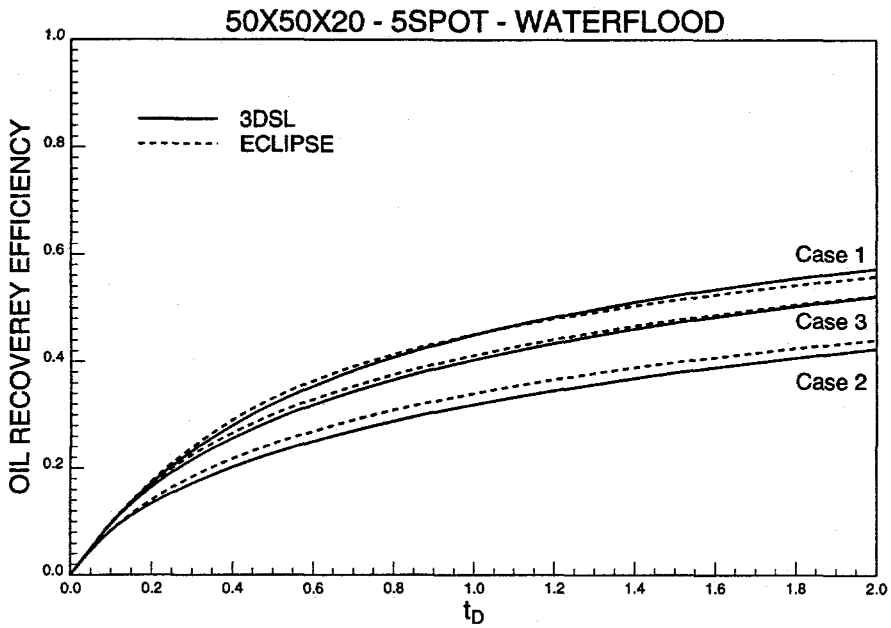

Figure 5: ECLIPSE and 3DSL recovery curves of a full five-spot waterflood displacement for three different permeability fields.

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