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Research paper

Two- and three-hydrocarbon phase streamline-based compositional simulation of gas injections

P. Bhambri, K.K. Mohanty *

Department of Chemical & Biomolecular Engineering, University of Houston, 4800 Calhoun Road, Houston, TX 77204-4004, USA

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ABSTRACT

Up to three three-hydrocarbon phases can develop during gas flooding of oil reservoirs at relatively low temperatures. Very few reservoir simulators and none of the published streamline simulators can handle three-hydrocarbon phases. In this work, we have developed a four-phase (including water) compositional streamline module that works with an existing finite-difference simulator to study gas injections. Gravity effects are added using an operator splitting technique. TVD schemes are implemented to construct the numerical solution along streamlines for reducing the impact of numerical dispersion. Two- and three-hydrocarbon phase simulations of gas injections in quarter five-spot models have been demonstrated using this simulator. Breakthrough recovery efficiency increases with the viscous-to-gravity ratio in the range of 1–100. Gas injection simulation of the reservoir oil indicates that three-hydrocarbon phases exist only near the gas–oil displacement front. The gas phase is present in a few grid blocks while the second liquid phase is present in many grid blocks, under the conditions studied.

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1. Introduction

Miscible or near-miscible gas flooding can be considered for improving oil recovery if the waterflood recovery is small and solvents are available. For example, mixtures of natural gas liquid (NGL), lean gas (LG) and CO_2 are available and have been suggested for injection into a moderately viscous oil reservoir (Shraeder Bluff) in the North Slope of Alaska (Wang et al., 2003; McGuire et al., 2005). Laboratory studies conducted by Khatnair et al. (1999) show that mixtures of 85% CO_2–15% NGL or 60% LG–40% NGL develop miscibility at the reservoir pressure and temperature.

The temperature in most viscous oil reservoirs is low. When temperature <120 °F and pressure <2000 psi, oil and gas mixtures can form three-hydrocarbon (HC) phases (oil, gas and a second liquid phase, L2). This behavior has been shown for several West Texas oils and CO_2 (Orr and Jensen, 1984; Turek et al., 1988). Mohanty et al. (1994, 1995) have conducted slimtube/micromodel studies with some Alaskan oils and hydrocarbon solvents. They showed that three-hydrocarbon phases coexisted under reservoir conditions (totaling four phases if water is included) and condensation of solvent components into the oil and the resulting viscosity reduction improved oil recovery.

Mechanistic modeling of WAG processes in these reservoirs involves modeling of four fluid phases (water, oil, gas, and second liquid phase), which most commercial reservoir simulators are not designed to handle. There are two issues related to four fluid phases: computation of phase equilibrium of three-hydrocarbon phases and modeling of relative permeability of four phases. Many phase behavior packages have the capability of computing phase equilibria between three-hydrocarbon phases. Such computations are, however, much more computationally expensive than two-phase equilibrium calculations (Michelsen, 1982). Measurement of four four-phase relative permeability is difficult if not impossible; little experimental data is available on four-phase flow. Four-phase relative permeability models have been hypothesized in the past. Guler et al. (2001) have proposed a four-phase relative permeability model based on the Baker model (Baker, 1988) for three-phase flow for water-wet media. Li et al. (2003) have proposed a four-phase relative permeability model for mixed-wet reservoirs, which will be used in this work. UTCOMP is one of the finite-difference-based simulators which can handle three-hydrocarbon phases and water (Chang, 1990). Guler et al. (2001) and Li et al. (2003) have conducted compositional simulations of gas injection in typical patterns of viscous oil reservoirs involving four phases. These simulations are computationally very expensive primarily due to three-phase flash calculations, leading to the use of small number of grid blocks and high numerical dispersion. Thus, there is a need for more efficient computational techniques.

One way to minimize the computation time is by simplifying the phase behavior; Wang et al. (2003) have developed a three-phase behavior look up table method to substantially decrease the flash computation time. Another way is to use a streamline-based computational method to increase the computational time step. In this paper, we develop a streamline-based four-phase compositional simulation approach.

* Corresponding author. Tel.: +1 713 743 4331; fax: +1 713 743 4323.
E-mail address: mohanty@uh.edu (K.K. Mohanty).

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Even though stream tube concepts have been around for over sixty years, streamline-based 3D reservoir simulations have been developed only in the last 15 yr (Bratvedt et al., 1996; King and Datta-Gupta, 1998; Crane and Blunt, 1999; Cheng et al., 2004). Black oil streamline simulators have been developed to predict the performance of waterfloods as well as for reservoir characterization by history matching (Agarwal and Blunt, 2003). Thiele et al. (1997) have developed a streamline-based compositional simulator where transport equations are decoupled from the pressure equation on the underlying finite finite-difference grid. Fine-grid finite finite-difference method is used to solve the pressure field and determine the streamlines. All transport calculations are conducted along the streamlines. This method looks very attractive for large compositional problems where a huge amount of CPU time is spent on phase calculations in the finite-difference method. Recently, Yan et al. (2004) have developed a two-hydrocarbon phase compositional streamline simulator that can be used to study WAG processes.

Use of streamline-based methods involves many approximations which have not been as well studied as those for the finite-difference methods. Compressibility, capillarity, transverse dispersion, changing streamlines, and mapping do introduce errors to compositional simulation based on streamlines. Cheng et al. (2005) have described a generalized streamline formulation including compressibility effects for two- and three three-phase black oil simulation. Similar approach can be extended to compositional streamline equations with little modifications. Osako et al. (2004) have quantified transverse flux corrections due to large time steps in streamline-based black oil simulations. In fact, they showed that streamline simulation could be considered as a pre-conditioner to the routine finite-difference method. Jimenez et al. (2005) quantified the transverse and longitudinal spatial errors in streamline simulations. Jessen and Orr (2004) have presented a pseudo-immiscible approach to include gravity effects in streamline-based compositional simulators. This new approach is an extension of method proposed by Batycky et al. (1997) to include gravity in black oil streamline formulation. Mallison et al. (2004) have studied mapping errors in streamline simulations. None of the published compositional streamline simulators accommodate four fluid phases.

Gerritsen et al. (2005) have proposed a fully adaptive streamline framework for gas injection simulations. Higher order numerical schemes are implemented to accurately transport the fluids/components along the streamlines. Several investigators (Liu et al., 1994; Mallison et al., 2005) have studied the effect numerical dispersion on miscible displacement predictions. Thiele and Edwards (2001) have introduced and demonstrated the application of TVD schemes that is higher order in space and time. It has been shown that the use of lower order schemes produces lot of numerical dispersion which can have a significant impact on the performance prediction of gas injection simulations, particularly in miscible displacements.

In this work, a four-phase streamline module that works with a finite-difference simulator has been developed to study gas injections in low temperature reservoirs. The outline of paper is as follows. We start with a brief review of our streamline methodology. Inclusion of gravity effects in the streamline formulation is discussed in the next section. The simulator is used to model six example problems with two- and three-hydrocarbon phase systems and to illustrate the effect of gravity number on vertical sweep efficiency. The conclusions are summarized in the last section.

2. Streamline methodology

In this work, a compositional streamline module is developed and integrated with a finite-difference simulator. The streamline methodology is based on an IMPES formulation where pressure is solved implicitly and compositions/saturations are updated using an explicit method. The pressure equation is solved on the finite-difference grid. The velocity field is generated from the pressure field using Darcy's law as given by the equation,

$$u_j = -\frac{\vec{\vec{K}}k_{rj}}{\mu_j}\cdot\left(\nabla P_j + \rho_j g\nabla D\right). \tag{1}$$

Once the velocity field is generated, streamlines are traced based on the total velocity field. Streamlines are traced by using the analytical Pollock method (Pollock, 1988). The underlying assumption is that velocity changes linearly in each grid block in each coordinate direction. Streamlines are traced from injectors to producers and streamline path intersects with the underlying finite finite-difference cells. These intersection points are the streamline nodes and time of flight information is recorded for each streamline point for all the streamlines in the simulation domain. Note,

$$\tau(s) = \int_0^s \frac{\phi(x)}{|u_t(x)|}dx, \tag{2}$$

where τ is the time of flight, and u_t is the total velocity.

Information is mapped from the original finite-difference grid to the streamline grid. Three-dimensional material balance equation in the finite finite-difference form is transformed *approximately* to one dimensional equation along the streamline coordinates in terms of time of flight. Decoupling of flow from the underlying finite finite-difference grid allows us to take large time steps while updating compositions along the streamlines. Fluxes are calculated for all the components and concentrations are updated along each streamline using a 1-D solver.

Spatially accurate total variation diminishing (TVD) schemes are included in the flux calculations to eliminate spurious numerical oscillations while retaining higher order accuracy in smooth regions (Thiele and Edwards, 2001; Bhambri, 2007). Fluxes are computed at the interface by using higher order fractional flow, densities, and mole fractions.

$$F_{i,k+1/2} = \sum_{j=1}^{np} x_{i,j,k+1/2}\rho_{j,k+1/2}f_{j,k+1/2}. \tag{3}$$

The higher order fractional flow at the interface $f_{j,k+1/2}$ is estimated by

$$f_{j,k+1/2} = f_{j,k} + \frac{\phi(r)}{2}\left(f_{j,k+1} - f_{j,k}\right) \tag{4}$$

where

$$r(f) = \frac{f_{j,k} - f_{j,k-1}}{f_{j,k+1} - f_{j,k}} \tag{5}$$

and

Fromm limiter is used to eliminate all the unphysical oscillations, i.e.,

$$\phi(r) = \max\left[0, \min\left(2, 2r, \frac{1+r}{2}\right)\right]. \tag{6}$$

Similar formulations have been used to estimate higher order densities and mole fractions in Eq. (3).

Flux estimation at the streamline nodes is the most time consuming task due to repeated flash calculation procedures that are performed to determine the component distribution in hydrocarbon phases. The combination of accelerated successive substitution (ACSS) method with the Gibbs-free-energy minimization method is used for flash calculations (Chang, 1990). Flash is performed and phase densities and saturations are computed using updated values of phase mole fractions. Hydrocarbon phase viscosity is estimated using Lohrenz correlation (Lohrenz et al., 1964). Relative permeability and fractional flow of each phase are then calculated based on the updated phase saturation and viscosity. We have also incorporated a four-phase (three-hydrocarbon phases and water) relative permeability