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Viscous and gravitational fingering in multiphase compositional and compressible flow

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ABSTRACT

Viscous and gravitational fingering refer to flow instabilities in porous media that are triggered by adverse mobility or density ratios, respectively. These instabilities have been studied extensively in the past for (1) single-phase flow (e.g., contaminant transport in groundwater, first-contact-miscible displacement of oil by gas in hydrocarbon production), and (2) multi-phase immiscible and incompressible flow (e.g., water-alternating-gas (WAG) injection in oil reservoirs). Fingering in *multiphase compositional* and compressible flow has received much less attention, perhaps due to its high computational complexity. However, many important subsurface processes involve multiple phases that exchange species. Examples are carbon sequestration in saline aquifers and enhanced oil recovery (EOR) by gas or WAG injection below the minimum miscibility pressure. In multiphase flow, relative permeabilities affect the *mobility* contrast for a given viscosity ratio. Phase behavior can also change local fluid properties, which can either enhance or mitigate viscous and gravitational instabilities. This work presents a detailed study of fingering behavior in compositional multiphase flow in two and three dimensions and considers the effects of (1) Fickian diffusion, (2) mechanical dispersion, (3) flow rates, (4) domain size and geometry, (5) formation heterogeneities, (6) gravity, and (7) relative permeabilities. Results show that fingering in compositional multiphase flow is profoundly different from miscible conditions and upscaling techniques used for the latter case are unlikely to be generalizable to the former.

1. Introduction

Gravitational and viscous flow instabilities can occur both within a single phase or when multiple fluid phases flow through the same porous media. A few examples for single-phase flow are (1) the spreading of a contaminant or solvent that changes the density or viscosity of an aqueous phase upon dissolution [40,47], (2) enhanced oil recovery (EOR) by first-contact-miscible (FCM) gas injection [25], and (3) carbon sequestration in saline aquifers [33]. The latter only considers the local density increase in an aqueous phase upon CO_2 dissolution, which can trigger gravitational fingering throughout the aquifer.

Injection of low-viscosity, high-density water into a reservoir saturated with lighter but more viscous oil, is an example where both viscous and gravitational instabilities may occur for two-phase immiscible, and often incompressible flow. Migration of dense-non-aqueous-phase liquids (DNAPL) through groundwater is in a sense the opposite problem. Studies of water-alternating-gas (WAG) injection also often assume two-phase flow: the gas is FCM in the oil, while the aqueous phase is immiscible.

The most complicated processes susceptible to fingering involve multiphase compositional and compressible flow. Important examples are: (1) EOR by gas injection *below* the minimum miscibility pressure (MMP), (2) WAG below the MMP for the injected gas, (3) carbon sequestration, taking into account the CO_2-rich gas phase. Another example is injection of CO_2 on top of denser oil. This should be gravitationally stable, but when CO_2 *dissolves* it can increase the oil density in the top. This is unstable to gravitational fingering *within* the oil phase [2,43], similar to the driver of fingering in carbon sequestration.

It is hard to do justice to all important contributions in the vast literature on fingering behavior in porous media. The following review is intended to put this work into the context of earlier studies, which were mostly confined to single-phase flow.

Most studies were carried out in the 1980s and '90s for *miscible* (FCM) displacement, motivated by earlier Hele-Shaw experiments (e.g., [4,11,18,38]). Todd and Longstaff [54] proposed a correlated upscaling technique, which has been widely used in commercial reservoir simulators to mimic the effect of small-scale fingering behavior on coarse grids. Tan and Homsy [47–49] performed

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experiments, linear stability analyses, and some of the earliest numerical simulations of the non-linear instability regime (reviewed in [19]). Zimmerman and Homsy [58,60] also considered the effects of anisotropic (mechanical) dispersion, while the effects of formation heterogeneities were investigated in [3,50–53]. Moissis et al. [24,25] presented the state-of-the-art in numerical simulations at that time.

The above studies were mostly for two-dimensional (2D) flow. Early simulations of fingering in three dimensions (3D) were presented in [10,53,59]. *Gravitational* fingering, or density driven flow, impacting single-phase solute transport in groundwater was investigated by, among others, [39,40,45,57], using both experiments and numerical simulations.

Blunt and Christie [6] considered fingering in two-phase three-component flow. A solvent is still FCM in oil, but an immiscible aqueous phase is considered as well, and both phases are assumed incompressible. These assumptions form the basis for most studies of WAG injection to date (e.g., [21]). Blunt et al. [5] generalized the Todd and Longstaff [54] model to two-phase flow. A few more recent studies presented experiments of heavy oil displacement by solvent [12], higher-order finite element simulations of viscous fingering in single-phase flow [16,20,41,42], and experiments and stability analyses for forced imbibition [44].

Carbon sequestration in saline aquifers is one important application where *gravitational* fingering may be critical, particularly when CO_2 has accumulated in the top of the aquifer. When CO_2 dissolves into the brine, it can cause a small increase of the aqueous phase density in the top [13,15]. This can trigger gravitational fingering, which effectively mixes dissolved CO_2 throughout the aquifer, because the convective time-scales for high permeability formations are much shorter than for diffusive transport. The literature on this process is extensive and will not be reviewed in detail here (see, e.g., [8,14,33,36,37,56] and references therein). From a modeling perspective, the problem is similar to FCM flow of a solvent in a weakly compressible fluid.

This short literature review illustrates that both viscous and gravitational flow instabilities have been studied in great detail, through experimental, analytical (stability analyses) and numerical investigations. However, all the aforementioned studies assume that the adverse viscosity and density contrasts are caused by a solvent that is fully dissolved (FCM) in the displaced fluid, sometimes also considering an immiscible and incompressible second, aqueous, phase. Two studies of fingering in multiphase compositional flow were carried out by [5,7]. However, limitations in computational power at that time only allowed for simulations on relatively coarse grids, even on a Cray system. Chang et al. [7] found that fingering behavior in compositional multiphase flow is different from FCM displacement, due to relative permeability and phase behavior. The authors acknowledged that more detailed simulations are required on finer grids.

The objective of this study is to do just that: to investigate fingering in multiphase flow with considerable mass transfer between the phases on fine grids, taking advantage of increased computational power and advanced higher-order finite element methods. Three fully compositional multicomponent phases are considered: water, oil, and gas. The phase compositions and phase properties are derived from rigorous equation-of-state (EOS) based phase-stability analyses and phase-split computations. Hydrocarbon phases are modeled with the Peng-Robinson (PR) [35] EOS, and the aqueous phase with the cubic-plus-association (CPA) EOS [23]. Viscosities are determined by the Christensen and Pedersen [9] model. All relevant physical processes are taken into account: gravity, anisotropic mechanical dispersion, and Fickian diffusion. The latter is represented by a unique model for multicomponent multiphase flow [17,22,27].

Fingering behavior is expected to be different from single-phase flow because of (1) the effect of relative permeabilities, which changes the *mobility* contrast between two phases for a given adverse *viscosity* ratio, and (2) phase behavior effects, particularly local changes in densities and viscosities, which can either enhance or stabilize flow instabilities. The focus of this work is on applications where both of these effects are most pronounced: EOR by gas injection below the MMP, with or without the presence of an aqueous phase (e.g., in WAG).

In this work, a reservoir oil is considered, which upon mixing with injected CO_2 (at a given reservoir temperature and pressure) is near the critical point and exhibits significant species exchange and non-trivial phase behavior. Moortgat et al. [30], Shahraeeni et al. [43] were able the model the detailed results of experiments with gravitational fingering at the core scale, including Fickian diffusion but without mechanical dispersion. A single example of viscous fingering during WAG injection in this oil was presented in [31]. Results were compared to a commercial reservoir simulator, demonstrating that lowest-order numerical methods cannot resolved the fingers on feasible grid sizes due to numerical dispersion. By using higher-order FE methods the process can be captured on coarse grids suitable for large-scale domains. The aforementioned numerical issues are not revisited here. Instead the focus is on a range of physical processes that affect the character of fingering instabilities.

The sections that follow include a summary of the main governing equations for multicomponent multiphase compositional flow, a discussion of simulation results, and the key conclusions. The analyses themselves consider (1) the importance of anisotropic dispersion and Fickian diffusion as potential restoring forces, (2) the interplay between viscous and gravitational fingering, (3) effects of dimensionality, (4) permeability heterogeneities, and (5) rate and domain size dependencies. The assumptions for this study are: (1) high Péclet numbers (advection dominated flow), (2) mobility ratios that are unstable to viscous fingering, and (3) negligible initial gas-oil density contrast, such that gravitational effects are only due to local changes in density from phase behavior.

2. Problem set-up

Multiphase compositional flow in porous media is described by mass conservation (or transport) equations for each species i (or j) in a n_c-component mixture, Darcy velocities for each phase α (with $\alpha = g, o, w$ for gas, oil and water phases, respectively), and a pressure equation that involves the formation and fluid compressibilities C_r, and C_f.

2.1. Advection–diffusion–dispersion transport

The transport equations (molar balance) are given by

$$\phi \frac{\partial c z_i}{\partial t} + \nabla \cdot \mathbf{U}_i = F_i, \quad i = 1, \ldots, n_c \tag{1}$$

in terms of porosity, ϕ, molar density of the multiphase mixture, c, overall molar composition, z_i, and sink and source terms F_i that can represent production and injection wells. The divergence term includes advective, diffusive, and dispersive phase fluxes:

$$\mathbf{U}_i = \sum_\alpha (c_\alpha x_{\alpha,i} \mathbf{u}_\alpha + \mathbf{J}^{\rm diff}_{\alpha,i} + \mathbf{J}^{\rm disp}_{\alpha,i}), \quad i = 1, \ \ldots, \ n_c, \tag{2}$$

$$\mathbf{J}^{\rm diff}_{\alpha,i} = -\phi S_\alpha c_\alpha \sum_{j=1}^{n_c-1} D^{\rm Fick}_{\alpha,ij} \nabla x_{\alpha,j} = -\frac{\phi S_\alpha c_\alpha}{RT} \sum_{j=1}^{n_c-1} \mathcal{B}^{\rm M}_{\alpha,ij} \, x_{\alpha,j} \nabla \mu_{\alpha,j}, \tag{3}$$

$$\mathbf{J}^{\rm disp}_{\alpha,i} = -\phi S_\alpha c_\alpha \sum_{j=1}^{n_c-1} \mathbf{D}^{\rm disp}_\alpha \nabla x_{\alpha,j}, \tag{4}$$