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Numerical Simulation of Compositional Flow in Porous Media under Gravity

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Abstract. This paper is concerned with the numerical simulation of multiphase, multicomponent flow in porous media. The model equations are based on compositional flow with mass interchange between phases. The compositional model consists of Darcy's law for volumetric flow velocities, mass conservation for hydrocarbon components, thermodynamic equilibrium for mass interchange between phases, and an equation of state for saturations. High-accurate finite volume methods on unstructured grids are used to discretize the model governing equations. Special emphasis is placed on studying the influence of gravitational effects on the overall displacement dynamics. In particular, free and forced convections, diffusions, and dispersions are studied in separate and combined cases, and their interplays are intensively analyzed for gravitational instabilities. Extensive numerical experiments are presented to validate the numerical study under consideration.

Key words: Compositional model; reservoir simulation; finite volume method; unstructured grids; gravitational effect; free and forced convections; diffusions; dispersions; numerical experiments.

1 Introduction

This paper is concerned with the numerical simulation of multiphase, multicomponent compositional model often used in petroleum reservoirs. This model incorporates compressibility, compositional effects, and mass interchange between phases. It consists of

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Darcy's law for volumetric flow velocities, mass conservation for hydrocarbon components, thermodynamic equilibrium for mass interchange between phases, and an equation of state for saturations. It models important hydrocarbon recovery processes such as natural depletion or gas cycling drive for gas condensate reservoirs and miscible flooding for volatile oil reservoirs. To understand complex thermodynamic and physical phenomena of multiphase flow in petroleum reservoirs, it has become increasingly important to simulate numerically such a realistic model.

A qualitative analysis of the compositional model under consideration was given in [6, 14]. The mathematical structure of the differential system describing this model was studied, and numerical results were given for a one-dimensional version of this model. Three-dimensional simulations of the compositional model using finite difference and finite element methods were presented in [4, 5]. In this paper, we present numerical results for the three-dimensional compositional model using high-accurate finite volume methods on unstructured grids, with an emphasis on the numerical study of interfacial instabilities under gravitational forces. An implicit second-order integration scheme is exploited for time differentiation terms, the Newton-Raphson iteration is utilized for linearization, and the BiCGSTAB (<u>bic</u>onjugate <u>g</u>radient <u>stab</u>ilized) iterative algorithm with ILU preconditioners is employed for the solution of linear systems.

Fluid flow models in porous media involve large systems of nonlinear, coupled, time-dependent partial differential equations. An important problem in reservoir simulation is to develop stable, efficient, robust, and accurate solution approaches for solving these coupled equations. Essentially, there are three types of solution approaches in reservoir simulation: the IMPES (implicit in pressure and explicit in saturation), the fully implicit, and the sequential. The fully implicit solution approach, which is also called the simultaneous solution approach [7], solves all of the coupled nonlinear equations simultaneously. This approach is stable and can take very large time steps, while its stability is maintained. However, due to a large number of partial differential equations to solve for the compositional model, this solution approach is computationally prohibitive, even on today's most powerful supercomputers. The sequential solution approach [10] splits the coupled system of nonlinear governing equations of reservoir simulation up into individual equations and solves each of these equations separately and implicitly. This approach is less stable but more efficient than the fully implicit approach for the compositional model, and will be investigated in our future study for this model. In the present paper, by a careful choice of the primary unknowns an *iterative* IMPES solution approach is employed to solve the system of the compositional governing equations.

As an application of the solution approach developed here, the stability of interfaces separating fluids of different densities and viscosities in porous media is studied. By means of experiments and, more recently, numerical simulations, the nonlinear interfacial dynamics has been studied using a variety of physical models and geometries [9]. In many reservoir applications, the basic instability is due to the density and viscosity contrast and permeability (conductivity) variations. In this paper, the nonlinear evolution of interfaces between miscible fluids of different densities is particularly analyzed. Both forced convec-