A time marching scheme for injection in a deformable reservoir saturated by three immiscible fluids

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Introduction

Most of the improved oil recovery (IOR) methods involve the flow of three immiscible phases, with the typical injection of gas into a reservoir containing oil and water. Among the most established IOR methods are the so-called water alternating gas (WAG) injection process and steam assisted gravity drainage (SAGD, e.g. Butler, 1994). Furthermore, the co-existence of three immiscible fluids applies to a number of engineering problems ranging from CO_2 sequestration (Plug et al., 2008) to contamination of ground water by NAPL and decontamination techniques.

In the design process, reliable numerical algorithms are needed to simulate the three-phase immiscible fluid flow in deformable porous media, taking care of the complex, highly non-linear constitutive equations that relate macroscopic properties such as relative permeabilities to the capillary pressures and saturation degrees.

Computational strategy

Although significant progress has been recently made on the physical understanding of the three fluid phase law at the microscopic pore level, numerical simulations at the macroscopic level still need improvement. Two main approaches have been proposed in the literature. In the first one, the individual mass balance of each phase is considered. One of the first applications along this line is due to Faust (1985), who neglected gas pressure gradients and solid skeleton deformability. The second approach is based on a manipulation of the mass balance equations to obtain a global fluid pressure and a total flux. A fractional flow function is then used for deducing the flux of each phase.

Within the fractional flow approach, the governing equations are rewritten in terms of a global pressure and saturation (Chavent and Jaffré, 1978, Chen and Ewing, 1997). The fractional flow approach does not however appear directly applicable to the analysis of deforming porous media, in fact the solution provides the global pressure and not the single pressures of each fluid. Moreover, rewriting the governing equations in terms of a global pressure, a total flux and two saturations generally requires the satisfaction of a total differential condition, which is not usually satisfied by existing relative permeability and capillary pressure curves (Chen and Ewing, 1997).

In this work, a fully coupled, three-fluid, hydro-mechanical constitutive model based on the individual mass balance of each phase is developed, without resorting to specific simplifications that are usually required by standard numerical schemes based on fractional flow. As a key feature of this approach and at variance with current models, the capillary pressures are expressed in terms of the saturations of the three fluids. A domestic finite element formulation is thus presented (Gajo et al., 2017), in which the solid displacement and the pressures of the three pore fluids are considered as primary variables. Special convective boundary conditions are adopted for pressures to be consistent with the assumed rock wettability properties during co-current imbibition.

Computational simulations

The numerical issues that arise in this type of formulation are investigated, focusing on the injection and imbibition processes that are typically employed in laboratory core flooding tests. The time marching scheme (namely the numerical strategies used in the numerical integration) has a particular importance in the elimination of the numerical instabilities associated with the propagation of sharp saturation fronts that are typically induced in core flooding tests.

The effects of mesh refinement, time step amplitude, residual permeability, maximum values of saturation gradients, permeability model and boundary conditions are addressed. In particular, the different permeability models proposed in the literature can significantly influence the simulations, as can be appreciated from the oil saturation profiles shown as an example in Fig. 1. This figure concerns a 30 cm long core having the following initial saturations: Sw=0.110, So=0.512, Sg=0.378. The left hand side boundary of the sample (at the position of x=0 m) is put in contact with a water reservoir in a short time (50 s) whereas oil and gas can outflow from the right hand side boundary (at the position x=0.30 m), according to the capillary effects on this boundary. In this way, a co-current imbibition test is simulated.

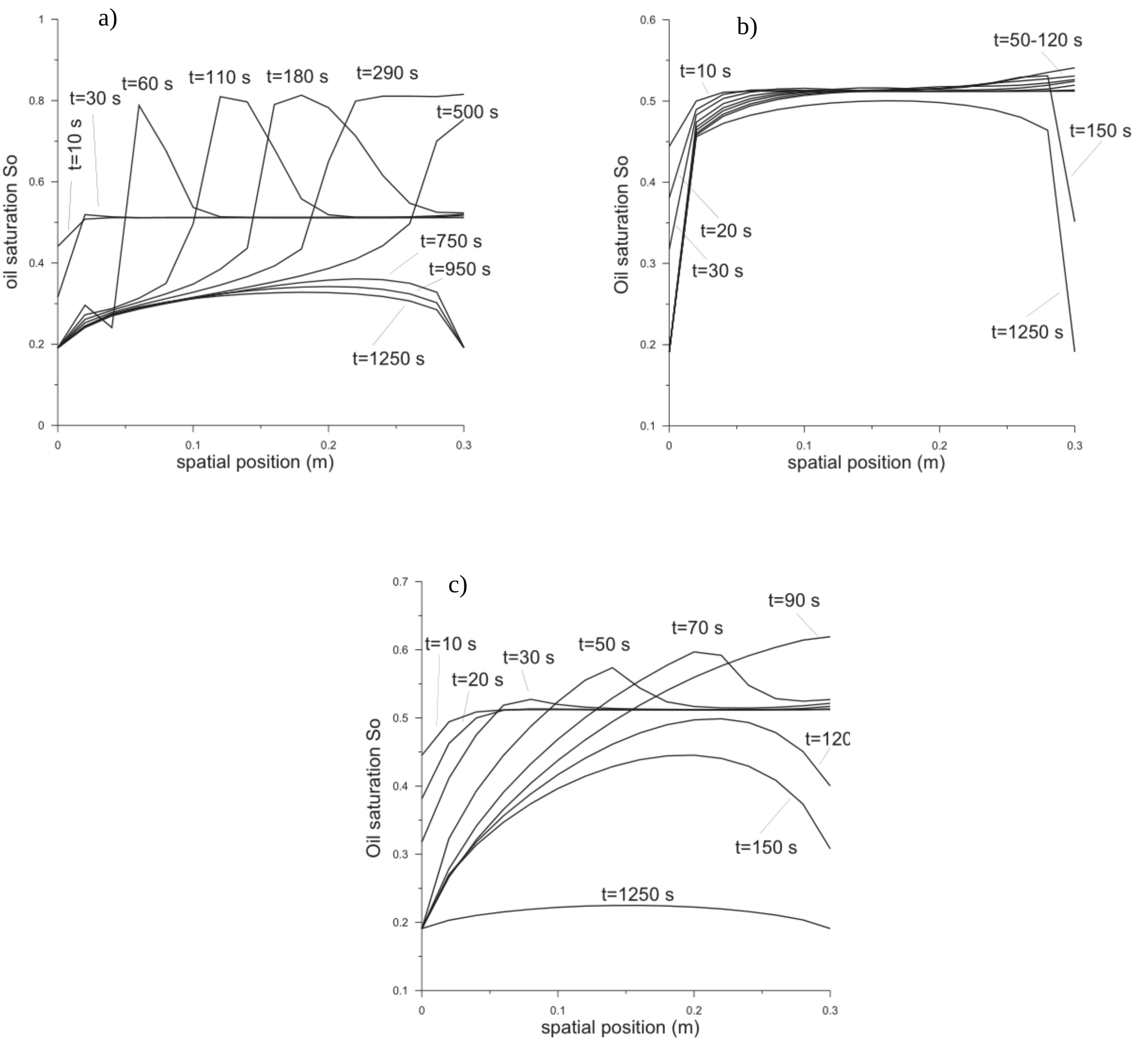

Fig. 1: Oil saturation profiles simulated with a) Brooks and Corey model, b) Stone model and c) Symmetric model with ω=1.

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