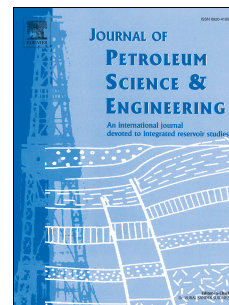


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# A computational framework for immiscible three phase flow in deformable porous media

Alessandro Gajo · Francesco Cecinato · Benjamin Loret

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**Abstract** Several soil decontamination processes and enhanced oil recovery techniques involve the co-existence of three immiscible fluids, such as water, a nonaqueous phase liquid and a gas. In this work, a computational framework based on the individual mass balance of each phase is developed, aimed at simulating three-phase flow in a deformable rock through the finite element method, without resorting to specific simplifications that are usually required by standard numerical schemes. Key ingredients of the model are: expression of the residual in terms of mass contents, consistent lumping of the storage terms in the residual and algorithmic (tangent) matrix, consistent integration rules, the use of a minimum relative permeability and a time marching scheme based on trapezoidal integration. Special convective boundary conditions are adopted for pressures to be consistent with the assumed rock wettability properties during co-current imbibition. The resulting numerical scheme can deal with arbitrary saturation and/or pressure boundary conditions. The model is tested by simulating gas injection tests, and both co- and counter-current water imbibition tests, in a deformable core. To assess the performance and robustness of the whole framework, sensitivity analyses are performed upon varying key constitutive, loading and numerical parameters.

**Keywords** Immiscible fluids · Capillary pressures · Relative Permeabilities · Gas injection · Imbibition · Finite Element · Time marching scheme

## 1 Introduction

A number of processes in civil, environmental and hydrocarbon engineering involve the co-existence of three non miscible fluids, typically water, a nonaqueous phase liquid (NAPL, e.g. chlorinated solvent, oil, supercritical CO<sub>2</sub>) and a gas (e.g. air, methane, etc.). Such situations arise for example in groundwater contamination problems (e.g. [1], [2]), in enhanced oil recovery techniques such as water alternating gas injection (WAG) or steam assisted gravity drainage (SAGD, e.g. [3]), and in CO<sub>2</sub> sequestration associated with coal-bed methane recovery [4].

The flow of three immiscible fluids in an undeformable porous medium has long been investigated (e.g., see [5] for an overview of this topic). The separate mass balance equations for each fluid in a three-fluid system can be found for instance in [6]. Three-phase flow models are usually obtained building up on two-phase models, for which two alternative approaches have been typically proposed. The first approach considers the individual mass balance of each phase, whereas the second one is based on a manipulation of the mass balance equations, to obtain a global fluid pressure and a total flux. The flux of each phase is then deduced from the total flux through a fractional flow function. While the former approach is typical of hydrology and of unsaturated soil mechanics, the latter approach was introduced in

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