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A new locally conservative numerical method for two-phase flow in heterogeneous poroelastic media

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ABSTRACT

We construct a new class of locally conservative numerical methods for two-phase immiscible flow in heterogeneous poroelastic media. Within the framework of the so-called iteratively coupled methods and fixed-stress split algorithm we develop mixed finite element methods for the flow and geomechanics subsystems which furnish locally conservative Darcy velocity and transient porosity input fields for the transport problem for the water saturation. Such hyperbolic equation is decomposed within an operator splitting technique based on a predictor–corrector scheme with the predictor step discretized by a higher-order non-oscillatory finite volume central scheme. The proposed scheme adopts an inhomogeneous dual mesh with variable cell size ruled by the local wave speed of propagation to compute numerical fluxes at cell edges. In the limit of small time steps the central scheme gives rise to a semidiscrete formulation for the water saturation capable of incorporating heterogeneous porosity fields and generalized flux functions including the water transport due to the solid phase velocity. Numerical simulations of a water-flooding problem in secondary oil recovery are presented for different realizations of the input random fields (permeability, Young modulus and initial porosity). Comparison between the accuracies of the proposed approach and the traditional one-way coupled hydro-geomechanical formulation are presented. The effects of the cross-correlation between the input random fields and compaction drive mechanism upon finger growth and breakthrough curves are also analyzed. A notable feature of the formulation proposed herein is the accurate prediction of the influence of geomechanical effects upon the unstable movement of the water front, whose evolution is dictated by rock heterogeneity and unfavorable viscosity ratio, without deteriorating the local conservative character of the numerical schemes.

1. Introduction

The study of the coupling between geomechanics and multiphase flows is becoming increasingly important in reservoir engineering as deeper formations are detected and explored. During secondary recovery of hydrocarbon fluid due to forced imbibition of water, changes in pore pressure trigger perturbations in the mechanical equilibrium of the porous medium leading to stress modifications which alter rock properties such as permeability and porosity. Applications are widespread and involve compaction drive mechanism, land subsidence, hydraulic fracturing, stress dependent permeability, pore collapse phenomena, caprock integrity, wellbore instability, casing damage, sand production, strain localization and fault reactivation [76].

The dynamics of hydromechanical coupling in multiphase flow involves highly complex physics associated with different patterns of chaotic fluid mixing and finger growth. Such complex behavior is strongly dictated by heterogeneity in the rock properties acting in conjunction with the unstable mechanism induced by unfavorable viscosity ratio and geomechanical effects [48]. Thermodynamically consistent models exhibiting varying degree of sophistication, with distinct versions of the effective stress principle, have been proposed to describe multiphase and unsaturated flows in shallow formations, where diffusion effects associated with capillary pressure play utmost role in the water movement [2,55]. On the other hand, for problems involving deep extraction of petroleum and gas, where diffusive capillary effects play secondary role, saturation-based formulations are widespread, where this quantity is included in the set of primary unknowns satisfying a hyperbolic equation in the limit of vanishing capillary pressure [28,9,56].

Historically, traditional reservoir models incorporate rock compaction through the well known definition of rock compressibility. Such single concept has a somewhat limited range of application

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