Journal of Computational and Applied Mathematics 270 (2014) 417–432

Contents lists available at ScienceDirect

Journal of Computational and Applied Mathematics

journal homepage: www.elsevier.com/locate/cam

A fully coupled multiphase flow and geomechanics solver for highly heterogeneous porous media

Daegil Yang [a,*], George J. Moridis [b,c], Thomas A. Blasingame [c]

[a] Chevron Energy Technology Company, Houston, TX 77002, USA
[b] Earth Science Division, Lawrence Berkeley National Laboratory, Berkeley, CA 94720, USA
[c] Harold Vance Department of Petroleum Engineering, Texas A&M University, College Station, TX 77843, USA

ARTICLE INFO

Article history:
Received 30 September 2013
Received in revised form 7 December 2013

Keywords:
Coupled multiphase flow and geomechanics
Heterogeneous media
FEM

ABSTRACT

This paper introduces a fully coupled multiphase flow and geomechanics solver that can be applied to modeling highly heterogeneous porous media. Multiphase flow in deformable porous media is a multiphysics problem that considers the flow physics and rock physics simultaneously. To model this problem, the multiphase flow equations and geomechanical equilibrium equation must be tightly coupled. Conventional finite element modeling of coupled flow and geomechanics does not conserve mass locally since it uses continuous basis functions. Mixed finite element discretization that satisfies local mass conservation of the flow equation can be a good solution for this problem. In addition, the stabilized finite element method for discretizing the saturation equation minimizes numerical diffusion and provides better resolution of saturation solution.

In this work, we developed a coupled multiphase flow and geomechanics solver that solves fully coupled governing equations, namely pressure, velocity, saturation, and geomechanical equilibrium equations. The solver can deal with full tensor permeability and elastic stiffness for modeling a highly heterogeneous reservoir system.

The results of the numerical experiments are very encouraging. We used the solver to simulate a reservoir system that has very heterogeneous permeability and elastic stiffness fields and found that the numerical solution captures the complex multiphysics of the system. In addition, we obtained higher resolution of saturation solution than with the conventional finite volume discretization. This would help us make a better estimate of the numerical solution of complex multiphysics problems.

© 2013 Elsevier B.V. All rights reserved.

1. Introduction

A reservoir simulator is a sophisticated tool to describe flow physics in a reservoir and most oil and gas companies use reservoir simulators to design production and predict reservoir performance. Thus, reservoir simulation has become one of the important research areas in petroleum engineering. Over the years, there have been significant improvements in reservoir simulation, mostly focused on the aspects of flow physics in porous media. The geomechanical behavior of reservoirs had not received the same level of attention, and it is only recently that it has become an important issue as extension of production into reservoirs with significant geomechanical challenges (mainly unconventional) necessitated consideration and analysis of the matter. In reality, porous media are deformable, requiring consideration of the interrelation between fluid flow and rock deformation. In conventional reservoirs with consolidated/lithified media, low

---

* Corresponding author. Tel.: +1 9794226765.
E-mail addresses: daegil.yang@gmail.com, daegil.yang@chevron.com (D. Yang).

0377-0427/$ – see front matter © 2013 Elsevier B.V. All rights reserved.
http://dx.doi.org/10.1016/j.cam.2013.12.029

pore compressibility, stiff overburdens and mild pressure drops, full consideration of geomechanics may be unnecessary, and its effect can be adequately accounted for by adjusting the flow equation. This is not the case in unconventional reservoirs, unconsolidated media, large pressure drops and hydraulically-fractured systems, in which the interdependence of, and interaction between, flow and geomechanical properties is significant, affects production, and has to be explicitly described. To analyze such problems, coupled flow-geomechanical simulators are needed.

Most reservoir systems are by nature heterogeneous. As such, they are characterized by spatial variations in the distribution of their flow properties such as the intrinsic permeability, which is coefficient of Darcy's equation that controls the flow velocity. In this case, obtaining a more accurate velocity solution is very important since flow path will be determined by the direction of the velocity. In addition, obtaining better descriptions of the saturation solution is always very favorable.

Heterogeneous media contain anisotropic properties that should be considered in the flow and geomechanics equations by using full tensors. For an accurate description of the reservoir system, upscaled (coarse-scale) multiphysics models need to have the capability of full-tensor description of permeability and elastic stiffness.

Coupling a geomechanics simulator to a reservoir simulator has been investigated by a number of researchers [1–19]. Settari and Mourits [1,2] developed a modular approach to couple geomechanics code (stress code) with a commercial reservoir simulator. This is the so-called *iteratively coupled (IC)* approach in which each code solves its own governing equations and the two codes are coupled using a porosity correction term. The advantage of this method is that it does not require the development of a new multiphysics simulator (coupled flow and geomechanics), a very significant undertaking. Instead, currently available codes can be used, and are coupled them with a relatively simple interface. Later, Settari and Walters [5] showed the application of the iteratively coupled method for a full field reservoir model.

Gutierrez et al. [4] showed the importance of coupling geomechanical deformation to multiphase flow in porous media. In their approach, the fully coupled multiphase flow and geomechanics equations are discretized with the finite element method. The resulting fully implicit linear system of equations, which use displacement and fluid pressures as the primary variables, is solved simultaneously. Gutierrez et al. [4] mentioned that the iterative approach may not be sufficiently robust because there is no proof that the iterative algorithm guarantees a unique solution. One possible example is the case of shear dilation when the volume of the rock increases while the pore pressure decreases. This process would necessitate negative compressibility values in the reservoir simulation component of the coupled flow-geomechanics model, leading to numerical instability [4,16].

Several fully and iteratively coupled methods have been proposed by several researchers [6,10,14,16]. Wan [6] viewed the Jacobian matrix of the IC method as a modified Newton–Raphson approach to the fully coupled method, and noted that the number of iterations to reach convergence would be higher than in the fully coupled method because the Jacobian obtained from the iterative method is not exact. In addition, Wan [6] indicated that a certain mapping of solutions might be required because the discretizations of two separate modules might be different. Dean et al. [10] showed that the IC method would result in the same solution as the fully coupled method if it uses an adequately tight convergence criterion during the iteration process. They pointed out that the iterative method would provide a first-order convergence rate during the nonlinear iterations. This indicates that a large number of iterations would be needed to reach convergence in the simulation of difficult problems. In addition, Dean et al. [10] indicated that the fully coupled approach (a) is the most stable one of the three approaches (explicitly coupled, iteratively coupled, and fully coupled) that they investigated, and (b) it guarantees second-order convergence, but (c) it requires more effort to develop the code and (d) it may be computationally more expensive than the iterative method.

Wheeler and Gai [20] suggested that the convergence of the IC method is independent of permeability if the fluid is sufficiently compressible, and showed through numerical examples that the number of iterations depend on the values of permeability (more iterations for low permeability) only for lower fluid compressibility. Huang et al. [16] developed a fully coupled, fully implicit flow and geomechanics simulator to model injection into heavy oil reservoirs. Their simulator was reported to solve nonlinear geomechanics equations and multicomponent flow equations. Huang et al. [16] indicated that the IC method would be almost certain to face convergence challenges if it involves nonlinear flow and geomechanics problems because this scheme was shown to be equivalent to solving the equations without a consistent tangent matrix.

In petroleum engineering, finite-volume or cell-centered finite difference discretization is commonly used for simulating fluid flow in undeformable porous media because it can conserve mass locally [21]. For modeling solid deformation, the finite element is known to a better choice and is practiced by a number of researchers [1,2,5,22]. Therefore, many of the IC flow and geomechanics simulators used in reservoir simulation adopt a finite-volume or cell-centered finite difference formulation for the flow equations and a finite element formulation for the solid mechanics equation [1,2,5].

The mixed finite element method is known to satisfy local mass conservation and to provide a more accurate and continuous description of the velocity solution by solving the coupled mass balance and Darcy's equations simultaneously [23–26]. The fundamental difference of this method is that the formulation treats the velocity as a primary variable rather than obtaining from the pressure solution. In addition, this method can deal with discontinuous full tensor permeability and unstructured meshes [27–31].

Gai [8] used a mixed finite element formulation to model multiphase flow equations that are coupled with the geomechanical equilibrium equation. The formulation of the multiphase flow equations ended up using a cell-centered finite difference scheme that is only applicable to a directional permeability field and a structured hexahedral mesh. Thus,

Download English Version:

https://daneshyari.com/en/article/4638753

Download Persian Version:

https://daneshyari.com/article/4638753

Daneshyari.com