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Iteratively Coupled Reservoir Simulation for Multiphase Flow

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Abstract

FIM (Fully Implicit Method) and IMPES (Implicit Pressure Explicit Saturation) are two of the most commonly used time-stepping schemes in present reservoir simulation. However, neither of them satisfies the requirements of accuracy and efficiency with increasing size and degree of complexity of highly heterogeneous reservoirs. In this paper, an iterative coupling scheme is developed and applied to multiphase reservoir problems, which aims to model and simulate realistic reservoirs accurately and efficiently.

Numerical examples reflecting major difficulties in treating heterogeneities and simulating complex reservoir phenomena such as coning and countercurrent flow problems are presented in comparison studies of iterative coupling, FIM and IMPES methods. Our results indicate that for the same accuracy the iterative approach can reduce computational time by 30%-40% or even more over the FIM. In comparing with the IMPES method, the iterative method shows better stability for taking larger time steps, and superior local mass balance. In this paper, the iterative approach is also shown to be scalable in parallel.

Another advantage of the iterative coupled approach over FIM is that different numerical schemes and even physical models can be incorporated into the algorithm thus allowing more flexibility in treating complicated problems, e.g. highly heterogeneous reservoirs with different subdomain stochastic properties.

Introduction

Reservoir modeling is essential for reservoir management where the primary goal is to determine optimum conditions required to maximize the economic recovery of hydrocarbons

from an operated field. Specific objectives of reservoir simulation include: (1) history matching and prediction of pressure and saturation values in the porous media; (2) understanding the fluid flow and oil recovery processes in the reservoir; (3) devising production strategies. The reservoir simulator is based on numerically approximating coupled nonlinear systems of partial differential equations described by conservation of mass and Darcy's Law. These equations are nonlinear and strongly coupled. In these systems one encounters elliptic, parabolic, and near-hyperbolic equations with complicated nonlinear behavior arising from fluid and rock properties. Additional computational complications arise from the geological media that exhibit a high level of spatial variability at a multiplicity of scales. This spatial variability, together with measurement limitations, lead to uncertainty in describing the properties of the media as well as interface relationships. Since numerically approximating subsurface phenomena is an intricate problem that is critical in the industry for accurate prediction of costly projects, our goal in this paper is to address the time-stepping issues for both minimizing computational cost (CPU time) and obtaining accurate solutions.

The two most widely used time-stepping approaches that have been applied for modeling multiphase flow are the FIM and IMPES methods¹⁻⁸. The first method solves for a reference pressure and saturations or concentrations simultaneously within a given time step. Because of the implicitness of the system, FIM is unconditionally stable but can be computationally costly. The IMPES method is based on operator time-splitting that involves solving for a reference pressure obtained by summing the mass balance equations. Saturation or concentration equations are obtained using total velocity and fractional mobility. The IMPES method while computationally inexpensive can exhibit oscillatory unacceptable solutions unless very small time steps are employed.

Several attempts have been made for combining the advantages of both FIM and IMPES to achieve better stability, accuracy and efficiency. Examples include the sequential and adaptive implicit methods⁹⁻¹⁶. However, small time steps are still required for the sequential approach and parallelization issues such as dynamic load balancing arise for the adaptive implicit approach. In this paper we discuss a new approach, the iterative coupling method, which shows major advantages over the FIM and IMPES that include both treating larger time steps and stable performance as well as scalable in parallel.