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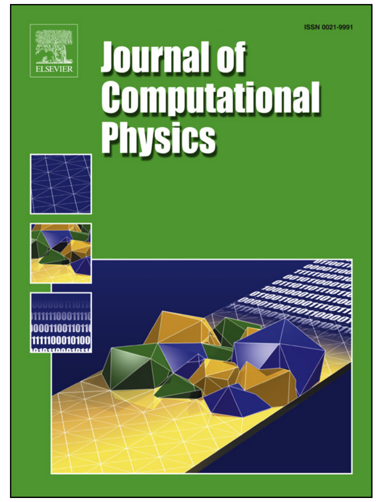

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Analytical Decoupling Techniques for Fully Implicit Reservoir Simulation

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Abstract

This paper examines linear algebraic solvers for a given general purpose compositional simulator. In particular, the decoupling stage of the constraint pressure residual (CPR) preconditioner for linear systems arising from the fully implicit scheme is evaluated. An asymptotic analysis of the convergence behavior is given when Δt approaches zero. Based on this analysis, we propose an analytical decoupling technique, from which the pressure equation is directly related to an elliptic equation and can be solved efficiently. We show that this method ensures good convergence behavior of the algebraic solvers in a two-stage CPR-type preconditioner. We also propose a semi-analytical decoupling strategy that combines the analytical method and alternate block factorization method. Numerical experiments demonstrate the superior performance of the analytical and semi-analytical decoupling methods compared to existing methods.

Keywords: reservoir simulation, fully implicit method, linear solver, preconditioner, decoupling

1. Introduction

Petroleum reservoir simulation is one of the most important tools for petroleum engineers to estimate, predict, and optimize oil and gas production. The black oil model and the compositional model have been the most popular models in petroleum engineering. The black oil model includes oil and gas pseudo-components and is widely used for immiscible displacement processes, such as water flooding. A compositional model, however, allows changes in phase compositions and models phase behavior through solving fugacity equations based on equations of state (EOS). The compositional model is preferred when significant mass transfer occurs between two hydrocarbon phases, such as in gas condensate reservoirs and miscible gas flooding processes [23].

In this paper, we consider a general purpose compositional formulation [13] that can be adapted to various fluid types, including the black oil model and the EOS compositional model. The fully implicit method (FIM) is employed where the time derivative is discretized with the backward Euler method and the spatial derivatives are discretized by a finite volume method. The nonlinear equation system is linearized by the Newton-Raphson method. Very often, the Jacobian matrix arising from FIM is non-symmetric and ill-conditioned, which often causes difficulties for linear solvers. Furthermore, the increasing demand for resolution in reservoir industry requires a larger number of grid cells, leading to slow linear solver convergence.

Iterative solvers are usually used for large-scale reservoir simulation, for which a significant portion of the simulation time is spent on linear solution of the Jacobian systems. In this paper, generalized minimal residual method (GMRES) is applied as the Krylov space iterative method because it monotonically decreases the l^2-norm of residual [29]. The reservoir simulation community has investigated various algebraic preconditioners and special preconditioners for FIM petroleum reservoir simulation. The purely algebraic preconditioners include incomplete LU factorization (ILU) [37], block ILU (BILU) [5], nested factorization [3], and singular value decomposition reduction [36]. The specialized preconditioners for reservoir simulation include the combinative method [5], constraint pressure residual (CPR) [34, 35, 22], auxiliary space preconditioner (ASP) [15, 16], and system AMG methods [9, 14].