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Keynote Presentation: Scalable Reservoir Simulation and the Curse of Nonlinear Coupling

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SUMMARY

Reservoir Simulation (RS), which involves solving the equations that describe the dynamics of subsurface recovery processes numerically, is a primary tool for making predictions of reservoir performance. Quantification of the uncertainty associated with the RS predictions is usually performed in a probabilistic framework. The most common approach for Uncertainty Quantification (UQ) in the reservoir engineering community is Monte Carlo Simulation (MCS). The MCS procedure involves: (1) construction of an ensemble of Reservoir Characterization Models (RCMs), (2) running the reservoir flow simulator for each RCM realization, and (3) post-processing the results to compute the statistical moments of interest. Each RCM realization in the ensemble should be consistent with all available information. In large-scale developments, the available data include (1) static information (e.g., measurements of permeability at a few well locations; statistical moments of permeability - mean, variance, covariance), and (2) dynamic data, injection/production rates and well pressures as a function of time, transient well tests, and saturation changes from 4D seismic surveys).

It is becoming increasingly difficult to scale the Reservoir Simulation capabilities to keep up with the enormous growth in the complexity and resolution of the RCM. The “scalability challenge” associated with Reservoir Simulation comes from three primary sources: (1) the multiscale nature of the reservoir properties (e.g., permeability field), (2) the global nature of the interactions (e.g., pressure field), and (3) the nonlinear coupling of the conservation laws. We discuss the latest developments dealing with the first two sources, namely, the multiscale nature of the problem and global interactions. Specifically, we describe our Algebraic Multiscale Solver (AMS) framework and its implementation on emerging parallel architectures. As for the third source - nonlinearity - there is a great need for new ideas and approaches.

The nonlinear evolution of the coupled systems of equations (conservation laws, constitutive relations, and constraints) that describe multi-component, multiphase flow in large-scale subsurface porous formations is usually dealt with by marching forward in time using small increments (time steps). In essence, the governing equations are linearized around the latest estimate of the solution. The size of the time step that can be used depends strongly on the ability of the nonlinear solver, which is usually Newton-based, to converge for the specific problem of interest. Industrial reservoir simulators employ complex heuristics to guide the time-step choice. This standard nonlinear solution strategy has become a serious bottleneck in terms of scaling the computational efficiency of reservoir simulation with the increase in the size and complexity of the RCM. The severity of the nonlinear challenge increases dramatically as the spatial and temporal scales (associated with the physics that describes the subsurface flow processes) of interest increase in range and complexity. We describe a nonlinear solution strategy based on constructing trust regions for the nonlinear multiphase transport problem (evolution of the saturation field), and we show that unconditionally convergent iterative schemes can be obtained. We also discuss the connection between the trust-region approach and the continuation-Newton framework. We argue that while we have a long way to go, the curse of nonlinearity, as an obstacle to scalability, is being mitigated methodically.