OUR PAST RECORD

Over the past several years, Texas A&M University has been at the forefront of technologies related to dynamic data integration into high resolution reservoir models. As a result of our collaborative research with the Lawrence Berkeley Laboratory, an important development in this area has been rapid and robust history matching using trajectory-based (streamline) models. Briefly, our approach exploits an analogy between streamlines and seismic ray tracing to pose the history matching technique in a manner analogous to geophysical inversion. We can then utilize efficient and proven techniques from geophysics to perform the history matching exercise. Because the parameter sensitivities are defined along one-dimensional trajectories, the inverse problem scales very well with respect to model size. Our approach has resulted in a significant reduction in costs associated with the time and manpower involved in traditional history matching. We have successfully applied our technique to a large number of field cases in the continental U.S and also the Middle East.

Specifically, the following are the highlights of some of the new concepts related to data integration and model calibration that were the direct outcome of the collaborative research work between Texas A&M and Lawrence Berkeley Laboratory during past five years.

II.1 History Matching and Model Calibration

- *Rapid History Matching via Travel Time and Generalized Travel Time Inversion of Multiphase Data (SPEJ, December 2002): PHIS3D Software*

We introduced the concepts of travel time and generalized travel time inversion for field-scale production data integration. Our approach has been applied to numerous synthetic and field examples in North America and Middle East. The travel time approach has been shown to be robust and has quasi-linear properties that lead to rapid convergence during history matching via inverse modeling (see the attached paper in Appendix-A). A software, *PHIS3D*, has been developed to accomplish full-field history matching (both 'assisted' and 'automatic') via generalized travel time inversion. Most recently, we have collaborated with Saudi Aramco to apply our technique to integrate 30 years of waterflood production history into a geologic model for the Berri-Hanifa field (22nd largest in the world) with 2.6 million cells. To our knowledge, this is the largest such application anywhere to-date and took about 6 hours of CPU time in a PC (see the attached paper in Appendix-B). Also, in collaboration with Chevron-Texaco, we have linked our history matching software to commercial reservoir simulator such as *Frontsim*, making it suitable for routine field-scale history matching.

- *Streamline-based Analytic Sensitivity Computation of Multiphase Production Data(SPEJ, December 1999)*

One of the major developments in streamline-based history matching has been the analytic computation of sensitivities of multiphase production data. These sensitivities quantify the change in production response because of a small perturbation in reservoir properties and constitute an integral part of most inverse modeling algorithms. The analytic sensitivity computation is widely considered as the single-most important development in terms of making field-scale production data integration practically feasible. We can now routinely integrate production data into high-resolution geologic models consisting of multi-million cells in a few hours in a PC. We introduced the analytic computations in 1998 and further generalized to account for gravity and changing field conditions in 2002.

- *Travel Time Inversion of Transient Pressure Response(SPEJ, September 2001)*

Utilizing concepts from asymptotic ray theory in seismic and diffusive electromagnetic imaging, we generalized the streamline approach to transient pressure conditions. A 'diffusive' streamline time of flight was introduced for primary production and integration of transient pressure tests into reservoir models. The 'diffusive' time of flight allows us to visualize drainage areas and drainage volumes associated with primary production under most general conditions. Furthermore, we derived analytic sensitivity for the 'diffusive' time of flight with respect to reservoir properties. The outcome was an efficient and robust approach to integrate transient pressure response to field-scale geologic models. We have demonstrated the feasibility of our approach by characterizing the fracture distribution and orientation at the Fort Riley formation in Oklahoma using pressure interference tests. Our results were validated by independent geophysical experiments.

II.2 Fast Flow Simulation Using Streamline Models

- *Streamline Simulation in Naturally Fractured Reservoirs: S3D-FRAC Software (Al-Huthali, 2003)*

Current streamline simulators are limited to single-porosity systems and are not suitable for modeling fluid flow and transport in naturally fractured reservoirs. We generalized the streamline-based flow simulation to naturally fractured reservoirs whereby the fractures and matrix are treated as separate continua that interact through a transfer function, as in conventional finite difference simulators for modeling fractured systems. Using streamline time of flight as a spatial variable, we developed a general dual porosity dual permeability system of equations for saturation calculations in naturally fractured reservoirs. The transfer functions that describe the matrix-fracture fluid exchange simply appear as source terms in the transport equation. On comparison with a commercial finite-difference simulator, the streamline approach shows close agreement in terms of recovery histories and saturation profiles with a marked reduction in numerical dispersion and grid orientation effects. An examination of the scaling behavior of the computation time indicates that the streamline approach is likely to result in significant savings for large-scale field applications.

- *Time Step Selection via Transverse Flux Correction During Streamline Simulation: S3D Software (SPE 79668)*

Unlike conventional finite-difference simulators, no clear guidelines were available for the choice of time step for pressure and velocity updates during streamline simulation. This remained largely an uncontrolled approximation, either managed by engineering judgment, or by potentially time-consuming time step size sensitivity studies early in a project. We proposed a novel approach for time step selection during streamline simulation that is based on three elements. First, we reformulated the equations to be solved by a streamline simulator to include all of the three-dimensional flux terms – both aligned with and transverse to the flow directions. These transverse flux terms are totally neglected within the existing streamline simulation formulations. Second, we proposed a simple grid-based corrector algorithm to update the saturation to account for the transverse flux. Third, we provided a discrete CFL (Courant-Fredrich-Levy) formulation for the corrector step that leads to a mechanism to ensure numerical stability via the choice of a stable time step for pressure updates. All these concepts have been incorporated into the Texas A&M Streamline Simulation Software, *S3D*.

II.3 Data Correlation and Integration

- *Permeability Predictions in Complex Reservoirs Using Electrofacies Characterization and Non-parametric Regression: GRACE and EFACIES software(SPERE, June 2002)*

We introduced the use of optimal non-parametric transformations, specifically the Alternating Conditional Expectation (ACE) algorithm for data correlation and integration. A general-purpose software for data correlation, *GRACE*, was developed and is currently being used by over 50 organizations worldwide. A data partitioning software, *EFACIES*, was also developed based on multivariate statistical analysis (Principal Component and Cluster Analysis). All these led to a systematic procedure for permeability predictions from well logs in complex carbonate reservoirs based on electrofacies classification and non-parametric regression. We have successfully applied the proposed technique to the Salt Creek Field Unit (SCFU) and North Robertson Unit (NRU), both highly heterogeneous carbonate reservoirs in the Permian Basin, west Texas. Our approach consistently outperformed more traditional approaches to permeability predictions based on lithofacies and hydraulic flow units.