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MODIFICATION OF MAINFRAME BOAST II

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ABSTRACT

BOAST II is a black-oil, applied-simulation tool used routinely for performing evaluation and design work in modern petroleum reservoir engineering. Personnel from the Louisiana State University Computer Science Department worked on modifying the mainframe version of this program through the simulation of two-phase flow of slightly compressible fluids in a three-dimensional porous medium. This included the construction of a FORTRAN program that uses 3-D finite elements to approximate the governing equations.

The existing finite element code was adapted so that virtually any size of element could easily be incorporated into the solution scheme. This gave increased flexibility and made it possible to utilize mesh refinement techniques. Modifications to the mainframe version also involved the development and integration of radial grid systems suitable for the investigations proposed in the project.

EXECUTIVE SUMMARY

BOAST II, released in 1987, was designed to provide more flexibility and to overcome some of the limitations of the original BOAST. Modifications to the mainframe version involved the development and integration of radial grid systems suitable for the investigations proposed in the project.

MAINFRAME BOAST Personnel from the Louisiana State University Computer Science Department worked on the simulation of two-phase flow of slightly compressible fluids in a three-dimensional porous medium. This included the construction of a FORTRAN program that uses 3-D finite elements to approximate the governing equations.

The existing finite element code was adapted so that virtually any size of element could easily be incorporated into the solution scheme. This gave increased flexibility and made it possible to utilize mesh refinement techniques.

This is a 3-D, two-phase model that includes capillary and gravity forces. The near wellbore region simulation models had to properly represent the near wellbore reservoir properties, the completion interval, and the multiphase flow into the well, especially coning and stratified flow. Modeling this region required an extremely fine grid in the neighborhood of the well, and this rapidly became a large scale computer problem. An accurate near wellbore regional simulator can be used for better well management. Well management can include setting of well rates or pressures, operating policies, production levels, etc. An accurate simulation can influence the decision to work-over or recomplete a well, to install artificial lifts, and/or to control water and gas production rates.

The need for an accurate and feasible way to model the simulation of flow near the well led to the development of this hybrid approach to reservoir simulation (finite elements in the wellbore region and finite differences everywhere else). In this technique, a Cartesian grid is used for the entire reservoir with arbitrary fine meshes for the finite elements in the near wellbore regions that can include one or more blocks of the Cartesian grid.

Multiphase flow near the well can be more accurately modeled with finite element methods coupled with adaptive, dynamic grid refinements in the region of high activity (maximum change). Timed portions of the finite element program on large-scale problems, have shown that the mesh refinement algorithms require an extremely small amount of time while the solution of the systems of equations consumes approximately 90% of the total computation time. To use dynamic grid refinement techniques in three dimensions, it was necessary to construct a unique finite element which, apparently, has not been developed previously.

Finite element methods (FEM) are very useful in solving problems in which the unknown function varies sharply in a localized region. FEM meshes are constructed so that smaller elements are placed in regions of high activity while larger elements are placed in regions where there is little activity. An adaptive refinement technique was developed that automates the process of refining the mesh where it is needed most and, in transient problems, allows mesh refinement to occur in different regions near the well as the solution evolves. The use of FEM with adaptive refinement techniques permits radial flow results near the well because of the fineness of the grid.

The implementation of the dynamic mesh routines on the parallel architectures were studied, recognizing the fact that efficient load-balancing would become a major issue. Much of this work from the past few years has been compiled as a doctoral dissertation. Parts of the dissertation, particularly parallel implementation, were intended for publication.

INTRODUCTION

BOAST II is a black-oil, applied-simulation tool used routinely for performing evaluation and design work in modern petroleum reservoir engineering. In 1982, the U.S. Department of Energy released the original black oil model called BOAST[1]. BOAST II[2], released in 1987, was designed to provide more flexibility and to overcome some of the limitations of the original BOAST. Modifications to the mainframe version involved the development and integration of radial grid systems suitable for the investigations proposed in the project.

The mainframe version of BOASTII, the PC version of BOASTII and the PC version of MASTER (all originally developed by the Department of Energy and in the public domain) were modified. All reservoir analysis for the "Assist in the Recovery of Bypassed Oil from Reservoirs in the Gulf of Mexico" were performed using the modified version, BOAST3-PC, of the PC version of BOASTII.

MODIFICATION OF MAINFRAME VERSION OF BOAST II

Personnel from the Louisiana State University Computer Science Department worked on the simulation of two-phase flow of slightly compressible fluids in a three-dimensional porous medium. This included the construction of a FORTRAN program that uses 3-D finite elements to approximate the governing equations. Although the solutions showed numerical stability, minor oscillations inherent in the transient finite element methods were discovered. The fact that the equations are highly nonlinear, along with the fact that the model typically contains a sharp front (or discontinuity), magnified these problems so that the resultant solutions were sometimes unsatisfactory. These problems of oscillations are traditionally resolved by refining the mesh, as in finite difference methods. However, in order to obtain acceptable answers, the refinement would have had to have been to such a degree that it would result in unacceptable memory and time requirements. Through further investigation, it was believed that the use of a better time integration would significantly reduce the oscillations.

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[1] Franchi, J.R., Harpole, K.J., and Bujnowski, S.W., "BOAST: A Three-Dimensional, Three-Phase Black Oil Applied Simulation Tool," U.S. Department of Energy Report Contract Number DOE/BC/1033-3, Volumes 1 and 2: 1982.

[2] Franchi, J.R., Kennedy, J.E., and Dauben, D.L., "BOAST II: A Three-Dimensional, Three-Phase Black Oil Applied Simulation Tool," U.S. Dedpartment of Energy Report Contract Number DOE/BC-88/2/SP: 1987.

To determine the source of the oscillation problem, considerable improvements were added to the program, and the code was scrutinized so that confidence of its correctness could be achieved. In addition, extensive information was gathered concerning Darcy-flow simulations when they are discretinized with finite element techniques. It was believed that an acceptable solution with the model was obtainable and would be reached with one of the time integration schemes. There was a high degree of confidence that these techniques would be easily extended to a large collection of simulation problems.

The existing finite element code was adapted so that virtually any size of element could easily be incorporated into the solution scheme. This gave increased flexibility and made it possible to utilize mesh refinement techniques.

Code was created that refines and unrefines arbitrary elements in a mesh of bilinear quadrilateral elements. This code was tested and appears to be robust. The next step was to incorporate this mesh refinement code into the finite element program to provide a tool that dynamically constructs small elements in regions of activity and coarse elements elsewhere.

This is a 3-D, two-phase model that includes capillary and gravity forces. The near wellbore region simulation models had to properly represent the near wellbore reservoir properties, the completion interval, and the multiphase flow into the well, especially coning and stratified flow. Modeling this region required an extremely fine grid in the neighborhood of the well, and this rapidly became a large scale computer problem. An accurate near wellbore regional simulator can be used for better well management. Well management can include setting of well rates or pressures, operating policies, production levels, etc. An accurate simulation can influence the decision to work-over or recomplete a well, to install artificial lifts, and/or to control water and gas production rates.

The need for an accurate and feasible way to model the simulation of flow near the well led to the development of this hybrid approach to reservoir simulation (finite elements in the wellbore region and finite differences everywhere else). In this technique, a Cartesian grid is used for the entire reservoir with arbitrary fine meshes for the finite elements in the near wellbore regions that can include one or more blocks of the Cartesian grid.

Multiphase flow near the well can be more accurately modeled with finite element methods coupled with adaptive, dynamic grid refinements in the region of high activity (maximum change). Timed portions of the finite element program on large-scale problems, have shown that the mesh refinement algorithms require an extremely small amount of time while the solution of the systems of equations consumes approximately 90% of the total computation time. To use dynamic grid refinement techniques in three dimensions, it was necessary to construct a unique finite element which, apparently, has not been developed previously.

The number of elements required for the near well portion of the reservoir using this approach can be very large. However, this approach is intended to improve the treatment of wells by use of this fine mesh in the well region and a normal (large) rectangular grid elsewhere in the reservoir. This substantially improved the treatment of wells in BOAST II. The rectangular grid that was currently used in BOAST II remains. The flow equations for the two regions are solved with different levels of implicitness; the simultaneous solution (implicit) method is applied to the well regions and the explicit saturation (IMPES) technique that is in the current version of BOAST II remains in the reservoir region.

The use of a hybrid grid scheme in reservoir simulation was introduced by *Pedrosa and Aziz*; however, their scheme was also to improve the treatment of wells. LSU's scheme is different because it uses BOAST, finite element methods in the well region, adaptive grid refinements in the region of high activity, and modern PDE solvers for the well region.

Finite element methods (FEM) are very useful in solving problems in which the unknown function varies sharply in a localized region. FEM meshes are constructed so that smaller elements are placed in regions of high activity while larger elements are placed in regions where there is little activity. An adaptive refinement technique was developed that automates the process of refining the mesh where it is needed most and, in transient problems, allows mesh refinement to occur in different regions near the well as the solution evolves. The use of FEM with adaptive refinement techniques permits radial flow results near the well because of the fineness of the grid.

A program for water and oil FEM with adaptive refinement techniques for the well region was tested against experimental results obtained *by Lance Hebert* in the LSU Department of Petroleum Engineering for coning and sweep efficiency problems. An excellent match was obtained between the program and the experimental results.

Although coning traces were produced similar to those in the Lance Hebert thesis, oscillations after breakthrough of the second fluid were still a problem. Testing on much simpler hypothetical problems produces oscillation-free results, but at the expense of heavy mesh refinement along the oil-water interface.

It was believed that extensive mesh refinement in the Hebert problem would also produce oscillation-free results, but calculations needed to be quicker and memory requirements need to be reduced. Distribution of the workload and memory across a cluster of RS6000's was accomplished, utilizing PVM for interprocess communication. On an 'unloaded' system, the speed-ups were excellent. However, because of the limitation to four nodes on the cluster at a time, usually sharing the nodes with other users, it was difficult to achieve any speed-up under these conditions. Because of this, it was ported to a 128-node Cray T3D for testing in an MPP environment. The parallel version of the code is suitable for 1, 2, and 3D problems using static meshes.

The implementation of the dynamic mesh routines on the parallel architectures were studied, recognizing the fact that efficient load-balancing would become a major issue. Much of this work from the past few years has been compiled as a doctoral dissertation. Parts of the dissertation, particularly parallel implementation, were intended for publication. The four publications and the dissertation present the results of this research. They are as follows:

- Morton, J.M. Tyler, A.T Bourgoyne, P.A. Schenewerk, "An Adaptive Finite Element Methodolgy for 2-D Simulation of Two-Phase Flow Through Porous Media," Proceedings of the ACM Symposium on Applied Computing, pp. 357-362, (1994).
- Morton, J.M. Tyler, J.R. Dorroh, "A New 3-D Finite Element for Adaptive h-Refinement in 1-Irregular Meshes, "International Journal for Numerical Methods in Engineering, accepted for publication (1995).
- Morton, J.M. Tyler, A.T. Bourgoyne, P.A. Schenewerk, "A Distributed Implementation of a Finite Element Approach for the Simulation of Two-Phase Flow Problems," Third SIAM Conference on Mathematical and Computational Issues in Geosciences, (1995).
- Morton, J.M. Tyler, A.T. Bourgoyne, P.A. Schenewerk, "Analysis and Implementation of a Portable and Versatile Approach for Distributing Transient and Nonlinear Finite Element Computations in Multiprocessor Environments," Computer Methods in Applied Mechanics and Engineering, submitted for publication (1995).
- Morton, Donald J., "An Adaptive Finite Element Methodology for the High-Performance Computer Simulation of Multiphase Flow Processes," Dissertation/Louisiana State University, Baton Rouge, Louisiana, 1994

Copies of these papers have been included in Appendix A.

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- Franchi, J.R., Kennedy, J.E., and Dauben, D.L., "BOAST II: A Three-Dimensional, Three-Phase Black Oil Applied Simulation Tool," U.S. Dedpartment of Energy Report Contract Number DOE/BC-88/2/SP: 1987.

APPENDIX A
Publications Concerning Modification of Mainframe Version of BOASTII

reprints and preprints
removed;
copyrighted thesis
cycled separately.