DOE/BC/14651--T7

Reservoir Characterization of Pennsylvanian Sandstone Reservoirs

(Contract No. DE-AC22-90BC14651)

Submitted by

University of Tulsa
Tulsa, OK 74104

Principal Investigator : Balmohan G. Kelkar

Contract Date : August 9, 1990

Completion Date : August 8, 1993

Reporting Period : April 1- June 30, 1993

Government Award : \$ 108,207

Contracting Officer's Representative

Ms. Rhonda P. Lindsey
U.S. Department of Energy
Bartlesville Project Office
P. O. Box 1398
Bartlesville, OK 74005

DISCLAIMER

This report was prepared as an account of work sponsored by an agency of the United States Government. Neither the United States Government nor any agency thereof, nor any of their employees, makes any warranty, express or implied, or assumes any legal liability or responsibility for the accuracy, completeness, or usefulness of any information, apparatus, product, or process disclosed, or represents that its use would not infringe privately owned rights. Reference herein to any specific commercial product, process, or service by trade name, trademark, manufacturer, or otherwise does not necessarily constitute or imply its endorsement, recommendation, or favoring by the United States Government or any agency thereof. The views and opinions of authors expressed herein do not necessarily state or reflect those of the United States Government or any agency thereof.

DISTRIBUTION OF THIS DOCUMENT IS UNLIMITED *nwn*

MASTER

DISCLAIMER

Portions of this document may be illegible in electronic image products. Images are produced from the best available original document.

Objectives

The overall objectives of this work are : (i) to investigate the importance of various qualities and quantities of data on the optimization of water flooding performance; and (ii) to study the application of newly developed, geostatistical techniques to analyze available production data to predict future prospects of infill drilling.

Specifically, to satisfy our first objective, we will study the feasibility of applying fractal geometry concepts to characterize individual formations; develop a three-dimensional conditional simulation program to define reservoir properties at various scales; establish a method to integrate the data collected at various scales including the well test and the core data; and to investigate the utility of outcrop data in describing subsurface reservoir details. To satisfy the second objective, we will investigate various techniques to utilize the production data, including initial potential and the production decline, in proposing a possible location for a future infill well. The techniques investigated will include geostatistical analyses. The study will be restricted to Pennsylvanian sandstone reservoirs commonly found in Oklahoma.

Summary of Technical Progress

The technical progress is subdivided into several sections based on the tasks in the original project.

1. Collection of Data

The data collection phase is complete and has been described in the previous reports.

2. Water flooding Optimization

This section is subdivided into several sub-tasks and is discussed separately as follows:

A. Characterization using Fractals

The primary goal of this work is to study the feasibility of applying fractal geometry technique to characterize producing formations. This work has been completed. The main conclusions of this work can be summarized as follows:

A. Based on our results, R/S analysis and box- counting are the two most reliable methods in determining the intermittency exponent, H .¹ Out of these two methods, box counting method seems to fit the variogram data the best. As a result, we recommend the box counting method for analyzing vertical well bore data.

B. Most of the well bore data include the effect of geological environment indicated by localized trends in the data. Before analyzing the vertical data, if the trends are removed, the analysis indicates much more consistent trend for intermittency exponent values. The typical values for both the carbonate and the sandstone fields lie between 0.75 and 0.8.^{2,3}

C. Based on exhaustive comparisons between the field well bore data and the simulated well bore data (using the method of conditional simulated annealing), we observed that, in general, fGn models do a better job in describing the areal heterogeneities in carbonate reservoirs; whereas, fBm models adequately describe the sandstone reservoirs. This observation may be important in constructing three dimensional reservoir descriptions when we have very limited data available.

B. Three Dimensional Conditional Simulation

To describe the reservoir in three dimensions, we have selected a method of simulated annealing. Originally proposed by Farmer,⁵ the method is based on the principle of swapping randomly generated values having the same histogram as the sampled values. After every swap, a predefined energy function is calculated and compared with the energy function in the previous step. If the new function is smaller, the swap is accepted. If the new energy function is greater, the swap may still be accepted depending upon the probability of acceptance. The process of swapping will continue till a desired level of energy function is reached. The method is flexible and allows incorporation of various constraints in generating the reservoir properties.

Although the technique of annealing is robust, one of the potential problems in using annealing simulation is its speed. Compared to other simulation programs, the program of annealing is relatively slow. One of the alternatives to speed up the algorithm is to use an initial distribution based on simple linear interpolation. Using this distribution followed by greedy algorithm results in significant savings in CPU time. This approach has been discussed in detail in the previous report.⁷ Another approach to speed up the annealing procedure is propose a better way of efficiently updating the variogram computations. Previous results have indicated that more than 90 % of the computation time is spent in updating the variogram values after each swap. If the updating process is made faster, substantial savings in the computation time may result. One option was to create a fictitious grid outside the domain of interest such that the updating of variogram can be done in a one simple test rather than through series of logical IF statements. We attempted this approach. Although the preliminary results were encouraging, further implementation revealed that it did not substantially improve the speed of the computation. Therefore, we decided to abandon that approach.

To make the program more flexible, we are also investigating the possibility of incorporating other types of data in describing reservoir characteristics. In addition to conditional data and the variogram models, another important input data that can be used for reservoir description is the well test data. Well test data are collected over a much larger volume than the core data, and is much closer representation of the grid block values than the core data. Unfortunately, conventional kriging and associated conditional simulation methods can not incorporate the well test data in reservoir description. Simulated annealing is flexible enough to accommodate the well test data through an appropriate objective function. This objective function should include the well test data as some representative average of nearby well bore data.

Before using the representative average as an objective function, we first need to determine the type of average the well bore data represents. Oliver⁶ has presented analytical technique to estimate well test permeability value for heterogeneous reservoirs. As indicated in the previous report⁷, using the Oliver solution, we compared the instantaneous permeability determined from the well test data with different averaging schemes to calculate effective permeability from small scale heterogeneities. For these purposes, we used ECLIPSE 100 simulator. The results indicate that Oliver's method is valid if we use the geometric average in theta direction and harmonic average in radial direction of the permeability values. In most cases, the difference between the well test value and the average value was less than 10 %.

Using Oliver's solution, we have implemented the well testing constraint in the simulated annealing program. The program requires the input of instantaneous well test permeability values at various times. Using that as a constraint, the simulated annealing program is run which honors the well test data. To validate the utility of the program, using the generated distribution, we flow simulated the well test, and compared the pressure and the pressure derivative data of the "truth" case with the simulated data. So long as early time data are included as a constraint, the comparison between the two data sets was very satisfactory.

We are in the process of optimizing this program by investigating the minimum number of times at which the well test values need to be defined. Also, since the last report, we have improved the implementation of Oliver's algorithm in the simulated annealing algorithm. Oliver's algorithm requires that the well test permeability be related to a weighted average of small scale permeability values in certain cylindrical region. Previously, we were computing the values for each time step by defining separate radial regions. At present, we have uniformly divided the region of interest in several radial, cylindrical, regions. As a result, we do not have to independently account for different regions at different times. Depending upon the time at which we are comparing the well test permeability values, we weigh various radial regions. At various times, many of the radial regions overlap. Therefore, we need not repeat the updating calculations for those regions every time. This saves memory requirements as well as computation requirements. We have tested the technique for several synthetic data sets. Before the end of the project, we will apply our technique to extended five spot pattern to study the usefulness of well test data in evaluating water flood performance. In addition, we will also study spatial anisotropic systems to investigate the applicability of the proposed method.

C. Effective Properties for a Grid Block

Reservoir properties are measured on various scales. Core data are collected on a size of two inches, whereas the well test data are collected on a reservoir size of thousands of cubic feet. From simulation point of view, we are interested in determining the grid block properties. A typical grid block size may vary between ten to thousand feet in size.

We are investigating the estimation of an effective property of a grid block by using both analytical and numerical methods. On analytical side, we have developed a method to predict an effective tensor of a grid block using the small scale heterogeneities present in the grid block for two dimensional distributions. The method is fast and flexible and compares very well with the numerical results. When compared to other literature methods such as power averaging and renormalization methods, the effective tensor method predicts the miscible displacement performance much better than any other method.

The method has also been tested for immiscible displacements. Again, compared to other literature methods, the effective tensor method predicts the effect of small scale heterogeneities on up scaling much more consistently than other methods..

As an extension of this work, we have also developed a scheme to incorporate the permeability tensor in conventional reservoir simulators. The scheme is based on finite element principles. The method is generalized, and it reduces to the methods proposed in the literature under certain simplified conditions. The method has been tested by incorporating it in a black oil simulator. A good comparison between simulated results using detailed heterogeneity model and the simulated results using up scaled heterogeneity model indicates the usefulness of the method.

Currently, we are in the process of extending the method to three dimensional grid blocks. We have already completed the analytical development of a estimation of effective permeability for a three dimensional grid block. The method assumes that the small scale permeabilities can be represented by isotropic permeability tensor with non-diagonal elements equal to zero. The analytical method is an extension of the two dimensional method and uses a combination of parallel and series grid blocks to define the effective properties in each direction. Presently, we are comparing the analytical results with the numerical results based on a finite element simulator. The diagonal elements of effective tensor from the analytical method match reasonably well with the diagonal elements using the numerical method. The non diagonal elements are off by less than 10 % indicating the ability of the analytical method to reproduce the numerical experiments. Currently, we have been able to use only limited number of elements in our simulator due to memory limitations. We believe that by using more finite elements, we will be able to further reduce the difference between the analytical and numerical results. Currently, we are extending the up scaling techniques to small scale, fully anisotropic systems. We hope to have some results before the final report.

3. Outcrop Studies

We continue to work on analyzing the outcrop data. In addition to collecting permeability data from the outcrop, we have also drilled 12 wells behind the outcrop. A typical distance between two wells is less than 50 feet with an exception of one well which is drilled about 400 feet away behind the outcrop to get complete geological section. Typical depth of well is in the range of 50 to 80 feet. All these wells have been cored and suite of logs have been run in these wells including gamma ray and neutron density. In addition, we have run FMS (Formation Micro-Scanner) log through one of the wells.

The whole cores have been slabbed and photographed. The cores have also been logged using gamma ray device. In addition, more than 1,000 minipermeameter readings have been taken to quantify the vertical variability of permeability distributions. Approximately 200, one inch, core plugs, some of them vertical, have been taken. Additionally, we have collected large number of minipermeameter readings on the outcrop by investigating several vertical and the horizontal transects.

To validate the minipermeameter results, we compared the permeability values using the conventional core analysis with the permeability values measured using the minipermeameter. The results indicate an excellent match. We have also generated vertical variograms for each well using the minipermeameter readings as well as the gamma ray logs. The results indicate that the average dimension of geologic unit can be estimated using the variogram structure as a basis. If we observe the hole effect in the variogram structure and compare the distance at which the minimum value is reached in the hole, that distance correlates very well with the average geological unit as described by the geologist. This method may provide to be useful in quantifying and validating the geological interpretation of a well log.

Using the data from the well bores, we have constructed a three dimensional facies description for the outcrop. Treating the description as a real reservoir, we intend to conduct water flooding simulations to understand the impact of small scale heterogeneities on reservoir flow performance.

4. Infill Drilling

To develop a procedure to locate infill drilling prospects, we have decided to start with a synthetic reservoir. The main advantage of using a synthetic reservoir is that we do not have to be concerned with production and operational constraints imposed upon the actual production. Further, we can control drilling and location of the wells.

In the previous reports^{2,3,7} we explained the use of various constraints in modeling the secondary performance. We have conducted several simulation runs using synthetic data. We related some of the performance parameters to the continuity functions. Results indicate that the continuity function is closely related to the performance of the reservoir. Also, if we incorporate the continuity function in the annealing program, we can reduce the level of uncertainty in the reservoir performance. Such function has been incorporated in simulated annealing program. The comparison between the "truth case" simulation and the simulation carried out using alternate images of the reservoir indicates that the continuity function is extremely important in characterizing flow behavior of the reservoir.

We also investigated the primary performance of the reservoir using synthetic data. We have used the variogram, the well test at the producing well and pore volume near the well bore as our primary constraints. Using these constraints, we have observed that we can obtain extremely good reservoir description to the truth case. Using the constraints developed using primary performance, we tried to simulate the water flooding performance. Our observations indicate that, although the constraints based on primary performance result in a better prediction of secondary performance compared to simply using variogram as a constraint, the interwell continuity cannot be well described by the primary performance. Unless we have some secondary performance data, it is very hard to precisely predict the reservoir description.

References

1. Hewett, T.A.: "Fractal Distributions of Reservoir Heterogeneity and Their Influence on Fluid Transport," paper SPE 15386 presented at the 1986 SPE Annual Technical Conference and Exhibition, New Orleans, LA (Oct. 5-8).
2. Quarterly DOE Report, Reservoir Characterization of Pennsylvanian Sandstone Reservoirs, (Contract No, DE-AC22-90bc14651) Jan. 1 - March 31, 1992.
3. Quarterly DOE Report, Reservoir Characterization of Pennsylvanian Sandstone Reservoirs, (Contract No, DE-AC22-90bc14651) July 1 - September 30, 1992.
4. Feder, J. : Fractals, Plenum Press, New York (1988) Chapter 10.
5. Farmer, C.L. : "Numerical Rocks," paper presented at the joint IMA/SPE European Conference on the Mathematics of Oil Recovery, Robinson College, Cambridge University (July 25-27, 1989).
6. Oliver, D.S., " Estimation of Radial Permeability Distribution from Well Test Data," paper 20555, presented at 1990 SPE Ann. Tech. Conf. and Exhibition, New Orleans, LA (Sept. 23-26).
7. 2. Quarterly DOE Report, Reservoir Characterization of Pennsylvanian Sandstone Reservoirs, (Contract No, DE-AC22-90bc14651) October 1- December 31, 1992.