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Integration of Streamline Simulation and Automatic History Matching
Célio Maschio, SPE, UNICAMP; Denis J. Schiozer, SPE, UNICAMP

Abstract

This paper presents an integration of different methodologies for history matching of complex fields. For such cases, a fine grid model is necessary and, therefore, the simulation time is high, yielding a constraining factor because the number of simulations must be limited in such cases in order to turn the process feasible. The proposed approach combines three fundamental steps: (1) a global history match; (2) the use of streamline simulation to determine flow path among producers and injectors or between an aquifer and a producer well to facilitate the choice of regions of interest to history match individual wells; and (3) the history match of wells through the modification of the properties of the regions of interest. The first and third steps are performed using an automated history matching methodology, which uses parallel computing and traditional simulation procedure.

The proposed approach is applied to a real case from an offshore field with 34 producer wells and 13 injector wells and a period of 22 years of production is available. Results showing the advantages and disadvantages of using an automated history matching in a complex field are presented. The use of streamline simulation as a support tool in such complex field history matching is also presented. Other aspects such as speedup of the process, using parallel computing, and high reduction rate of objective-function, by choosing correct regions for modification of the properties, are described in the paper.

The main contribution of this paper is to show a convenient form of combining two important tools: streamline simulation and automatic history matching of complex fields.

Introduction

Several sophisticated reservoir characterization techniques are available today yielding very detailed simulation models. These models can capture in great details heterogeneities in porosity, permeability, lithology, and others important properties that are critical to accurate reservoir simulation. However, despite the modern characterization tools, there is still a high level of uncertainties in the process. This is particularly aggravated in complex fields. Therefore, a continuous characterization process, including dynamic data to calibrate the model, is necessary.

History matching is the process that consists of incorporating the observed (or dynamic) data, such as pressure, seismic and production data, into the characterization process. The most important and influential properties of the reservoir are submitted to systematic and consistent changes and the objective is that the model reproduce the observed data. History matching is an inverse problem normally of difficult solution. Even considering only the most influential reservoir attributes, there are a large number of variables, principally in complex fields, with high heterogeneities, faults, complex structure, etc.; the possibilities of changes are very wide.

Traditionally, history matching is done manually. This signifies that each change must be implemented by interference of the professional responsible by the process. Manual process normally is a very time consuming task. Besides, due to the necessity of managing a large amount of data, such as many simulation runs and comparison between observed and simulation data, the manual process is more susceptible to errors. To circumvent these difficulties inherent to the manual process, many automatic history matching methodologies have been developed in the literature.

Despite a relatively large number of automatic history matching methodologies existing in the literature, its use is not very diffused in the industry mainly because most of these methodologies present some restrictions for application in complex cases. Some tools have a limited number of model parameters that can be changed for matching. This aspect imposes limitations in more general applications.

The experience and judgment of the professional involved is always necessary in several steps of the process. Assisted History Matching (AHM) makes it possible to integrate this experience with the automation of manual tasks. Therefore, AHM provides the advantages and benefits of automatic procedures, such as implementation of the changes in the simulation input data, running of simulations, analysis of objective functions, etc., and it allows the professional to conduct important decisions, such as selection of attributes, priorities, sequence of changes and objective functions and when to stop the process.

History matching can be divided, in a general manner, in two steps: a global matching, in which overall reservoir
properties are changed, and a local matching, in which local properties are changed. The definition of regions of the reservoir for local matching can be done using streamline simulation.

Streamline simulation has been used by several authors in the literature recently. According to Baker\textsuperscript{4}, assisted history matching with the aid of streamline technology may allow better convergence for fine tuning models, because it provides a way for identifying problem regions based on the streamlines and their associated producer/injector pairs. Caers\textsuperscript{2} applied the technique along with a geostatistical approach. The application consists of a local gradual deformation technique to adjust wells. To select the region of influence of each well, the author used the information provided by streamlines belonging to each region, in order to divide the reservoir. Several other works combine the use of streamline simulation with other techniques. Tran et al.\textsuperscript{5} applied a streamline-based inversion technique combined with a geostatistical downsampling algorithm. Ravalec-Dupin\textsuperscript{7} also used streamline simulation combined with geostatistical simulation and gradual deformation method.

Wang et al.\textsuperscript{9} applied streamline simulation for ranking reservoir models incorporating production data, using correlation between time-of-flight and water-cut. The authors utilized, besides the correlation mentioned earlier, the benefits of simulation time of the streamline simulator. But this was possible due to the characteristics of the model that falls in the category for which this type of simulation is normally faster, that is, heterogeneous models with low physical complexity. He et al.\textsuperscript{6} utilized generalized travel time inversion method for production data integration. The method was used specifically for fractional flow (water cut) history matching. Kulikarni et al.\textsuperscript{7} presented a more general methodology by introducing a diffusive time-of-flight term along streamlines. The method permitted the integration of transient pressure data for compressible flows under more general conditions. Kulikarni et al.\textsuperscript{8} have also used streamline approach for estimating relative permeabilities from production data. He et al.\textsuperscript{9} have used streamline simulation approach to identify reservoir compartmentalization and flow barriers based on computation of drainage volumes, utilizing well production and pressure response to infer the location and transmissibility of flow barriers.

Milliken et al.\textsuperscript{10} have used streamline simulation as simulation technique and also as supporting tool to determine flow paths. The main difference between the methodology used by Milliken and that used in the present work is the treatment of the change of streamlines configuration along the time. The time period selected by Milliken for generating the streamlines is an average over the history. That is, all wells in the model are represented with a voidage rate averaged over the production period. In this paper (and in another paper by the authors\textsuperscript{11}), several different times along the history period are chosen and streamlines in these times are considered. Other differences are related to the AHM design. For example, the AHM used here utilizes distributed computing to increase the efficiency of the optimization process.

The objective of this paper is to explore the potential of the streamline simulation in the history matching process and to show how it can be used in conjunction with an assisted history matching methodology. Other aspects approached are the treatment of the process using a complex field as example. The characteristics of the model, such as size (in terms of number of grid cells) and a relatively high simulation time imposes some limitations to the process, since the number of iterations (or simulations) can not be very high, because this could turn the process impracticable.

Methodology

The methodology presented in this paper consists of the integration of streamline simulation and assisted history matching. The methodology for assisted history matching (AHM) was developed by Schiozer and Sousa\textsuperscript{12} and Leitão and Schiozer\textsuperscript{13}. An important aspect of this methodology is the distributed computing. In order to improve the efficiency of the optimization process, the simulations are distributed in a network. The program responsible for this distribution executes several tasks such as determining the relative speed of the machines, the feasibility of the machines to perform more than one simulation at the same time, the number of licenses available and so on.

The simulations in the optimization process are done using a traditional simulator based on fine difference. The streamline simulation is incorporated into the process as a supporting tool.

The main steps of the methodology used in this paper are summarized in the next topics:

1) First, the history matching process is carried out in overall reservoir to adjust global pressure and production parameters, such as oil rate, water rate and average reservoir pressure;

2) The simulation model resulting from the first step is converted to a streamline simulator format. This conversion is relatively easy owing to the use of an automatic converter, however, after conversion it is necessary to check the consistency of the model. This simulation model is then run generating the streamlines map. The output containing the streamlines is post processed in order to map the grid blocks pertaining to the streamlines connecting a given producer well to one or more injector wells (Fig. 1);

3) The next step is to implement changes to the simulation model to achieve the history matching. These tasks are made through the AHM program, whose main tasks are to change the set of simulation models, submit it to run and apply the optimization algorithm to find the minimum of the objective function.

Optimization Algorithm

The optimization algorithm utilized in this work does not use the computation of derivatives of the objective function. The algorithm is based on direct search method and uses only the objective function value to determine new search directions in a space solution composed by grid points. Each axis in the space solution corresponds to a property that is being changed and each point in the grid corresponds to a set of property modifications. In order to avoid a high number of simulations, the properties assume discrete values, such that only points represented by the nodes of the space solutions are simulated.
Application

The methodology studied in this paper was applied to an offshore field with complex structural aspects and highly heterogeneous geological properties. The reservoir is formed by sandstone turbidites confined by faults with regions of good porosity and permeability. The STOIP of the field is approximately 150 MMM$^3$ and the main production mechanism is solution gas drive. It is a developed field, with 22 years of production history. The field is drained by 34 oil production wells and 13 water injector wells. The water injection began after 1500 days of primary production. The available data before production were composed of nine seismic lines, 8 perforated wells, 4 oil analyses (PVT), formation test analysis, interpreted electric logs and data cores from 3 wells. The data cores comprise porosity and permeability samples, 7 analyses of relative permeability, 10 of capillary pressure and rock compressibility. Datum depth is located at 3000 m, water oil contact is located at 3110 m and gas oil contact is located at 2900 m. A history production period of 22 years is available.

The simulation model is composed of a grid of 80 blocks in the x direction, 45 blocks in the y direction and 22 layers (80×45×22), discretized into a corner point grid. In Fig. 2 is presented a three-dimensional horizontal permeability map of the reservoir, with some wells placed on the model. For questions of visibility, not all wells were included. Simulation time is relatively high. Each run takes approximately 1 hour in a machine with 2 GB processor. For history matching, this run time is critical because a high number of simulations can turn the process prohibitive. Therefore, the changes must be carefully done to avoid excessive time consumption.

Results and Discussion

Global History Matching. The first step of the application of the methodology was a global history matching. In this step, four overall reservoir properties were chosen: porosity (POR), net to gross ratio (NTG), horizontal permeability (PERMI) and vertical permeability (PERMK). In Tab. 1, it is described how these properties were changed. The objective of this step was the history matching of field production parameters. Figs. 3, 4 and 5 show that mainly the field oil rate presented a considerable mismatch.

Oil Rate Well Matching. After field global matching, several wells were still presenting problems in reproducing historical oil rate. Therefore, the next step of the process was to match the oil rate of these wells. Seven wells were matched by changing porosity and horizontal permeability in completed blocks. Porosity was increased in 5 % to 20 % in average. Horizontal permeability was increased two times in well blocks in order to increase the productivity index. In Figs. 6 and 7, two of the most problematic wells (W-026 and W-050, respectively) and the resulting oil history match are presented. In this case, Base model is that which resulted from the global history match. A great difference between simulated and history data.

Water Rate Well Matching. After well oil rate matching, the next step of the work was the matching of well water rate. It is in this step that streamline simulation is used as a supporting tool. The first procedure was to identify the wells with greater difference between observed and simulation data. Six wells were identified with critical disagreement.

Two history matching strategies were adopted for this step. The first one was the selection of regular regions around the selected wells for the change of the properties, in this case, horizontal and vertical permeability. In this procedure, the regions are combined so that the modifiers are applied equally in the regions. The second strategy was the use of streamlines to map the most influent flow region.

Initially, the output of streamline simulation was post-processed in order to format the data, that is, select the streamlines correspondent to wells of interest and convert it in reservoir block coordinates. The region of interest for matching, in this way, was composed by the blocks pertaining to the streamlines connecting water injector wells and the selected producer wells. In the same way as the first strategy, the modifiers for horizontal and vertical permeability were applied over this region. In the two cases, the same extremes values (limits) and number of intervals were used in the AHM program.

The results comparing the history matching for three wells are shown in Figs. 8, 9 and 10. It is possible to note that the results obtained with the region mapped by streamlines (Match 1) is much better than the results obtained using the regular regions (Match 2).

In Fig. 11 it is presented the comparison of the reduction of objective function for the two matching strategies. For Match 1, which corresponds to the use of streamline to map block regions, a higher reduction with less simulation can be noted. The value of the objective function correspondent to initial model is 1. Values greater than 1 signify that the changes increase the distance between the simulated and history data.

Separated injector wells. It is common to have several injectors associated to a given producer well. A producer well (W-016) was selected and a test was carried out to compare the history matching of the producer well water rate, following two procedures. Fig. 12 shows the mapped blocks by the streamlines connecting two injector wells (W-006I and W-031I) and the producer W-016. In the first procedure, the blocks corresponding to the pairs of wells W-016/W-006 and W-016/W-311 were considered as one region in which the change of horizontal (PERMI) and vertical permeability (PERMK) was done. Multipliers in the range of 0.1 and 0.5 were adopted, with 12 intervals for PERMI and PERMK. In this case, the space solution was composed of 2 axes. In the second procedure, the blocks corresponding to each pair were considered as a separated region. The same properties and discretization used in procedure 1 were used in procedure 2, therefore in this case, the space solution was composed of 4 axes.

The evolution of the objective function along the simulations, for the two history matching, is shown in Fig. 13. Using the regions correspondent to the two injectors separately, the reduction of the objective function is greater.
compared to the reduction obtained with only one region. However, the number of simulations using two regions (4 properties) is practically two times the simulations for the process using two properties.

In Figs. 14, 15 and 16, field oil rate, field water rate and field average pressure are presented for the global matching and after wells matching. The results show that there was an improvement in the overall field match after wells matching. For oil rate, for example, it can be noted an additional decrease of the distance between the simulated and observed data in the period between 2500 and 6000 days. For water rate, the additional improvement can be noted practically between 4000 and 8000, except in a short period next to 6700 days. However, the history matching process must continue to improve oil rate and pressure matching. However, the main objective of this paper was to perform part of the matching process, showing the integration of two important tools and their application in the several steps of the process.

Speedup. It is important to observe the benefits of the distributed computing in the AHM methodology used in this work. In this case, four machines were utilized. For the global matching, for example, for which 45 simulations were necessary, the speedup factor was 0.65, that is, the time of the process using the parallel processing was 65% smaller compared to the serial process. This shows the importance of using this technique in the AHM process.

Conclusions
This paper presented an application of streamline simulation along with assisted history matching methodology. The results showed that the combination of these tools can improve the process. The use of regions of main flow path determined by streamlines provided better results compared to the use of regions defined using an intuitive procedure. The selection of the type and number of regions can be done with streamline simulation. The separation of each injector/producer pair increases the number of properties and, therefore, the number of simulations; however it improves the performance of the matching. Finally, assisted history matching can provide several benefits, because it is possible to incorporate the advantages of automatic procedures and to maintain the experience of the professional in the principal decision of the process.

References

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Table 1: Properties modifiers for global matching

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<th>PERMI</th>
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Figure 1: Schematic representation of streamlines mapped blocks

Figure 2: 3D reservoir horizontal permeability map (mD)

Figure 3: Field oil rate after global matching

Figure 4: Field water rate after global matching

Figure 5: Field pressure after global matching

Figure 6: Oil History Matching of well W026
Figure 7: Oil History Matching of well W050

Figure 8: Comparison of water history matching for well W007

Figure 9: Comparison of water history matching for well W038

Figure 10: Comparison of water history matching for well W050

Figure 11: Comparison of the reduction of objective function for wells water rate matching

Figure 12: Mapped blocks by streamlines connecting two injector wells and a producer well
Figure 13: Comparison of reduction of the objective function using one and two regions

Figure 14: Field oil rate after wells matching

Figure 15: Field water rate after wells matching

Figure 16: Field pressure rate after wells matching