Methodology for Water Injection Strategies Planning Optimization Using Reservoir Simulation

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This paper is to be presented at the Petroleum Society’s Canadian International Petroleum Conference 2002, Calgary, Alberta, Canada, June 11 – 13, 2002. Discussion of this paper is invited and may be presented at the meeting if filed in writing with the technical program chairman prior to the conclusion of the meeting. This paper and any discussion filed will be considered for publication in Petroleum Society journals. Publication rights are reserved. This is a pre-print and subject to correction.

ABSTRACT

The decision making process related to the recovery strategy during the development of a petroleum field is very complex because it involves a great amount of money and parameters and it is necessary to consider the risk associated with geological, economical and technological uncertainties.

An adequate choice of production strategy provides a satisfactory reservoir performance, improving the field recovery. Therefore, it is very important to have methodologies (1) to improve the quality of the results and (2) to accelerate the process.

This paper shows some optimization procedures applied to production strategy planning process. The procedure was developed for several types of reservoirs and includes producer and injector vertical wells. Furthermore, it uses reservoir simulation to improve the reliability of the prediction of production performance. The procedure was developed in a flexible way, allowing the application to different situations. The results of some of these cases are presented.

The methodology proposed does not provide a unique solution. It presents a set of alternatives that are analyzed in the decision making process for the planning of a recovery strategy, considering the objectives of the project.
INTRODUCTION

The planning of strategies for the development and management of petroleum reservoirs is one of the most important activities in reservoir engineering. The strategies are elaborated considering a previously defined objective, regarding physical, operating and economic restrictions. An adequate recovery strategy depends mainly on the geological characteristics of the reservoir and on the operational schedule defined for the field. A high number of parameters influence the decision making process. Therefore, it is not feasible to evaluate all possible combinations. It is necessary to evaluate the most important parameters related to the problem and develop an approach for this problem in order to achieve satisfactory solutions.

Petroleum reservoirs are very complex and there are great difficulties involved in proposing correct reservoir models. The use of numerical simulation provides a preview for the reservoir performance, considering a geological model previously prepared from several parameters obtained during the field appraisal. The use of numerical simulation is appropriate for the planning of strategies for the development of petroleum fields. It requires more time, however, it makes the process more reliable, leading to better results.

This work proposes a methodology containing an optimization procedure based on reservoir simulation that evaluates both individual well and field performance and the objective-function chosen was Net Present Value (NPV). The methodology helps managers to make decisions that lead to an adequate recovery for the reservoirs and to maximize profits and minimize risks associated to the investments. An example is presented where water injection strategy planning is performed with numerical simulation of an Atlantic offshore field in Campos Basin – Brazil. It can be shown the importance of reservoir simulation in the optimization of recovery strategies for petroleum reservoirs including water injection.

LITERATURE REVIEW

The planning of adequate recovery strategies for petroleum reservoirs has a great economic importance and several studies have been realized for the development of procedures applied to this problem.

Arps et alli [1967] participated of a study, organized by the American Petroleum Institute, with the objective of developing equations for the assessment of recovery factors for petroleum reservoirs. The well spacing was one of the most studied parameters. From the analysis of 312 reservoirs, they concluded that there was no mathematical relationship between recovery factor and well spacing. Their work had the purpose of developing a methodology for field recovery for an analysis preceding the stage involving simulation, but it was not possible to obtain satisfactory results.

Davis and Shepler [1969] verified that the well spacing initially used for the development of petroleum fields, in general, is not the most adequate spacing. The ideal well spacing depends on the characteristics of each reservoir. It is necessary to consider the uncertainties related to the geological model and the dynamic behavior of the economic and technological scenario.

The development of advanced technological resources, mainly in hardware and software, provided that numerical reservoir simulation became an important tool for the development and management of petroleum reservoirs. A prediction for the reservoir performance can be obtained through numerical simulation using a previously built geological model that presents several parameters obtained through reservoir characterization. The simulation model is the most important tool for the evaluation of an objective-function that represents the global objective of the project.

Using numerical simulation, Nystad [1985], Damsleth et alli [1992], Beckner and Song [1995] among others authors developed methods for the optimization of problems related to the development and management of petroleum reservoirs. These works presented the following common aspects: the problem was simplified and the number of simulations runs performed and of parameters evaluated was small. The main objectives of such works were: the evaluation of the most important parameters in the assessment of the objective-function and their optimization.
Bittencourt [1997] developed a hybrid algorithm based on direct methods, like genetic algorithm, Polytope method and Tabu Search, for the optimization of problems of development for petroleum reservoirs. The simulator was used as a data generator for the evaluation of the objective function, which involved an analysis of cash flows resulting from production predictions obtained from reservoir simulation.

Pedroso and Schiozer [2000] developed a methodology for the optimization of the number of producer wells and their location in a reservoir in development stage.

Cruz [1999] introduced the concept of "quality map", which is a bi-dimensional representation of the reservoir performance and its uncertainties. This concept can be applied to compare reservoirs, to classify stochastic realizations and to include uncertainties related to reservoir characteristics to the decision making process for the planning of a recovering strategy.

Mezzomo and Schiozer [2000] developed an approach for primary recovery strategies optimization, including only vertical producer well. In order to expand the scope of that procedure, compassing a greater number of reservoirs, this work developed a more extensive methodology, including water injection with producer and injector vertical wells.

METHODOLOGY

In order to develop a methodology to be applied for the planning of adequate recovery strategies for different reservoirs, it is necessary to include several parameters mainly related to the geological model, operational conditions and economic scenarios.

The objective of this work is to develop a methodology to support managers in the decision making process for the planning of a water injection pattern for oil recovery from fields under development stage.

Methodology Description

A general methodology proposed in this work is organized in several steps that will be described in the following paragraphs.

Depending on the characteristics of the problem, some of these steps can be simplified or discarded.

Step 1: Recovery Strategy Definition

The definition of a recovery strategy for a petroleum reservoir depends on several geological and physical characteristics, like reservoir geometry and structural framework, net pay and net gross, natural drive mechanism, permeability and porosity distribution and rock and fluid properties.

The first step of the proposed methodology consists of a study based on field data analysis for the definition of basic important parameters related to recovery strategy like well type (producer or injector) and geometry (vertical, horizontal or deviated). This study will also evaluate the necessity of a secondary recovery (water and/or gas injection) or an enhanced recovery method (thermal, chemical, etc).

Step 2: Evaluation of Production and Injection Patterns

The second step is an evaluation of several production/injection patterns regarding the recovery strategy method and the well type and geometry established in the previous step. The production/injection patterns are proposed based on the characteristics of the field and the technical and financial resources available.

During this stage, simulation runs can be performed for an assessment of recovery potential for each pattern proposed for the field. At this stage, all wells comprised by the proposed patterns must be opened simultaneously at the initial time of the simulation runs performed in this step in order to obtain a correct evaluation of their quality.

The best patterns are retained and submitted to an optimization procedure in the next step.

Step 3: Evaluation of the Approximate Number of Wells

This stage involves the application of an optimization procedure to the recovery patterns selected in Step 2.

The optimization procedure will provide the ideal number of wells for the indicated recovery patterns and it must be developed regarding the parameters related to the
recovery strategy, the number of required simulation runs and the desired quality for the results.

As in the previous stage, during the assessment of the ideal number of wells it is necessary to open all wells simultaneously in order to obtain a correct evaluation of the potential of each well and an accurate value for their objective-function.

The optimization of recovery strategies including secondary and enhanced recovery methods requires a more complex optimization procedure because it is necessary to consider a greater number of parameters.

**Step 4: Obligatory Optimization**

The optimization process is always restricted to operational restrictions and the economic model must consider investments and costs. These conditions always lead to a mandatory optimization.

Therefore, additional investments and restrictions in the operational scheduling must be included in Step 4. Others conditions may also be included depending on the case.

**Step 5: Optional Refinements**

The solution obtained after at the end of Step 4 is always an acceptable one. At this point, depending on the importance of the problem, desired accuracy and resources available (especially time and computer), several refinements can be applied to the solution. Such step will always increase the number simulation runs and therefore, it is important to have an automated procedure.

Some of the possible refinements for the solutions are: evaluation of completion intervals, individual analysis of well operational conditions, well position changes, well type modifications, etc.

**Step 6: Economic Sensitivity Analysis**

The economic scenario is very dynamic and is strongly influenced by technical and political circumstances. Therefore, parameters like oil price present substantial variations throughout the project life.

An economic sensitivity analysis is very important for a recovery strategy planning. The use of reservoir simulation allows a correct evaluation of the quality of each alternative comprised in the set of recovery patterns proposed by the methodology regarding different feasible economic scenarios, thus helping the reservoir managers to select the alternatives that present low financial risk and that are less influenced by economic scenario alterations.

**Case study**

The example defined for the validation of the methodology proposed in this work is water injection planning for an Atlantic offshore field in Campos Basin – Brazil. The reservoir comprises confined Albian-Cenomanian (Late Cretaceous) turbidite sandstone, with solution gas drive mechanism.

Because the field is in development phase, there is few data available and the knowledge of the reservoir is quite incomplete. Therefore, the proposed reservoir model was simple and the required simulations runs presented an adequate processing time. The model has six layers and the total number of blocks is 8568. The blocks were divided in three regions, considering the faults and the model presented solution gas drive. It used a Black-Oil system containing three phases: oil, gas and water.

It is important to notice that it is not necessary to perform all simulations presented here. They were performed only to test the methodology.

**RESULTS**

**Selecting the Objective-Function**

The net present value (NPV) was defined as the objective-function to be maximized. Two other indicators, cumulative oil production (Np) and rate of return (RR) were also analyzed for a better evaluation of the set of alternatives of water injection patterns. The objective was to identify, from graphs indicating the behavior of these indicators, strategies that maximize simultaneously the oil production, the return coefficient and the Net Present Value for the reservoir.

**Step 1:**

Considering the objective of this work that was to develop a methodology for optimization of recovery strategies including water injection, it was assumed that a geological study indicated recovery strategies comprising vertical producer and injector wells.
Step 2:
The water injection patterns evaluated in this study case were the most frequently used for secondary recovery of offshore fields: peripheral (with different ratios between producer and injector wells), 5spot, 7spot, 9spot, direct linedrive, alternate and combined.

The operational conditions for producer and injector wells were previously established and were the same for all the wells of each type.

The methodology developed in this work does not present a unique solution. Instead, it presents a set of alternatives that are analyzed to select the injection pattern that leads to the most adequate recovery for the reservoir, regarding the previously defined objectives for the project.

The cumulative oil production (Np), the cumulative water injection and production and the rate of return for the initially proposed injection patterns are presented in Figures 1, 2, 3 and 4.

These figures indicate the efficiency of the injection patterns for the selected field, with different well spacings and the comparison of the objective-function values obtained with each one of them. This is very important for the planning of a recovery strategy that provides a satisfactory oil production and a high NPV.

For this example, the best pattern was the peripheral, mainly for the 600 m spacing. This pattern presents a higher efficiency to displace the oil to the producer wells through water injection.

Step 3:
Two optimization procedures were developed in this work to obtain an estimative of the ideal number of producer and injector wells.

The initial stage of the first procedure used was the selection of a fine well spacing, which defined a high initial amount of producer and injector wells. This original model, containing this high number of wells, is simulated, providing an estimate of the best regions of the field. The individual contribution for each well and the objective-function for the field are calculated and the wells are ranked according to the descendent order of their objective-function values. An amount corresponding to 20% (example) of the initial total number of wells is excluded, regarding some restrictions that are case dependent. Then, a new simulation run for the reservoir is executed and the recovery scheme presents a reduced number of wells. The main restriction is not to exclude neighbor wells. This procedure is repeated until the value of the objective-function for the field diminishes.

The initial stage of the second optimization procedure was the evaluation of the best initial well spacing for the previously retained schemes. Then, this original model was simulated and the performance of each well was analyzed for the assessment of an adequate completion and then the evaluation of the ideal number of producer and injector wells was performed as described for the first procedure.

For the evaluation of the performance of the first optimization procedure, five injection patterns were selected. The initial well spacing for all these patterns was 450 m and the range for initial total number of wells was 89 to 109. Figure 5 indicates the NPV and the total number of wells for each of the simulation runs executed to obtain the ideal number of wells for the five selected schemes. The number of simulations runs required in this procedure varied from 10 to 12 and it is important to observe that the objective-function, due to its characteristics is non-linear, thus it presents local optimal values.

The ideal number obtained for patterns like peripheral and combined (35 to 42) was considerably higher than the ideal number obtained for patterns presenting similar amounts of producer and injector wells, like 5spot lead to a smaller ideal number (25 to 28).

Figure 6 indicates the values for the objective-function and for the cumulative oil production Np for each simulation run performed for the accomplishment of this optimization procedure. These values are compared with the values presented by initially selected water injection patterns. It can be noted a reduction in the cumulative oil production and a significant increase in the objective-function values.

This optimization procedure is simple and fast. The quality of the results depends mainly on the selected
initial well spacing and on the criteria applied to the wells during the simulation runs performed to achieve the ideal number of wells, thus requiring an evaluation of the performance of each well and of the reservoir for each simulation run.

For the assessment of the efficiency of the second optimization procedure, five injection patterns were selected. The initial total number of wells varied from 41 to 62 and all wells were opened simultaneously in the initial time for the simulation run.

Figure 7 indicates the NPV and the total number of wells for each of the simulation runs executed to obtain the ideal number of wells. The number of simulations runs required in this procedure varied from 8 to 10. The optimal total number of wells, varied from 40 to 43 for the injection patterns with 600 m well spacing and was 30 for the pattern with 750m well spacing. The NPV increased greatly in the first simulation runs in which the wells presenting the worst performances are excluded and became almost constant in the final runs.

Figure 8 indicates the values for the objective-function and for the cumulative oil production \( N_p \) for each simulation run performed for the accomplishment of this optimization procedure. These values are compared with the values presented by initially selected water injection patterns. It can be noted a reduction in the cumulative oil production and a significant increase in the objective-function values.

Like the previous optimization procedure, this one is also very simple and fast and the quality of the results obtained also depends on the criteria established for the wells during the simulation runs performed for the assessment of the ideal number of wells.

For large and homogeneous fields this second procedure involving a first stage for the assessment of the ideal initial well spacing reduces the number of required simulation runs, maintaining the accuracy for the results. However, for fields presenting a higher degree of heterogeneity the first procedure with the selection of a fine well spacing is more adequate to provide proper alternatives for field recovery.

**Step 4:**

In this work, this step was performed for the evaluation of the ideal well scheduling for the water injection patterns optimized in the previous stage using reservoir simulation and considering the production and injection performance presented by the well.

Five well scheduling were proposed for the selected patterns. It was established an interval of 2 months for the well scheduling according to the operational conditions.

Figures 9 and 10 indicate the results obtained for the objective-function and for the cumulative oil production \( N_p \) for each of the selected schemes.

These figures indicate that well scheduling is an important parameter with considerable effect over the results obtained for the objective-function. Selecting an adequate well scheduling provides a higher efficiency for the oil displacement to the producer wells and also a greater production time, leading to a increase in the recovery factor.

For the injection patterns applied to the selected reservoir model, the ideal well scheduling was to open the producer wells regarding the descendent order for their objective-function values alternating with the injector wells that should be opened according to the descending order of their water injected volumes values.

**Step 5 and 6:**

Considering the purpose of this work and the proposed type recovery, it was assumed that the results obtained after applying the four previous steps were satisfactory and it was not required the application of Steps 5 and 6.

**CONCLUSIONS**

1. The methodology developed in this work is very adequate for the planning of recovery strategies including water injection. It offers a direct evaluation of a high number of alternatives and provides a comparison of economic and technical indicators, allowing the selection of the most appropriate recovery strategy considering the previously defined objectives for the project.
2. The proposed methodology defines important parameters that must be evaluated for the planning of water injection patterns for petroleum reservoirs, including amount of producer and injector wells and its operational scheduling according to the technical and financial scenarios.

3. The methodology and the optimization procedures were developed in a flexible way, allowing its application to several different cases.

4. The steps 3 and 4 are the most important in the proposed methodology. The step 3 provides an approximate number of wells and depends on the field characteristics and step 4 is an obligatory optimization.

5. For the example studied in this work it was noted that the type of well pattern and the well spacing were parameters that presented a great effect on the results generated by the methodology.

6. The best water injection patterns for the reservoir studied in this work presented a high ratio between producer and injector wells like peripheral pattern.

REFERENCES


FIGURES

Figure 1: Step 1: NPV vs Np

Figure 2: Step 1: NPV vs Wp