EVALUATION ON EXPLICIT COUPLING BETWEEN RESERVOIR SIMULATORS AND PRODUCTION SYSTEM

João Carlos von Hohendorff Filho
PETROBRAS
Campinas, São Paulo, Brazil

Denis José Schiozer
UNICAMP
Campinas, São Paulo, Brazil

ABSTRACT

Various methodologies to model the coupling of reservoirs and production systems have been applied in the oil industry in recent years due to the need to model properly the integrated solution of models that represent the flow of fluids through the reservoir to the surface.

These methodologies are used to solve the production forecast of multiple reservoirs, sharing production platforms with limited production and injection capacities ruled by complex production systems. They can be grouped into two basic types: implicit and explicit coupling methodologies.

Explicit methodology can be an efficient choice to integrate simulations because allows coupling adequate simulators to model the whole system and also to grant flexibility in study of well management alternatives. However, it is necessary to test this type of procedure to check the quality of the results. Therefore, a validation study of explicit coupling methodology is presented in this work where the production system is tested on common operating conditions during production and injection of fluids, verifying benefits and limitations of explicit methodology. Some methods for improving the explicit response are proposed and evaluated.

An example of application verifies the gain of flexibility in well prioritization by the group management obtained by use of an external methodology for reservoir simulator.

The explicit coupling, as implemented, has shown a satisfactory result for the integration between the simulators, honoring all operating constraints set in evaluation cases. Some correction methodologies are necessary to obtain stabilized results.

INTRODUCTION

There are oil fields production scenarios where the traditional reservoir simulation cannot adequately represent the behavior of complex production systems. As an example, multiple reservoirs in separate simulations sharing production platforms with limited capacity.

In the same example, a complex model of production system would get their boundary conditions from the reservoirs, which would be subject to operational restrictions varying in time, dependent on the production itself shared by the field.

Barroux et al (2000), Bento (2010), Cotrim et al (2011), Haugen et al (1995) and Kosmala et al (2003) show the necessity of integrated methodology between the simulators to obtain more reliable results because the current reservoir simulators don’t properly model the operational conditions of complex production systems. These authors have their definitions of coupling methodologies which may be divided mainly into two categories: implicit methodologies, where the reservoir simulation and production system simulations converge to the same result in the integration point (usually producing and injector wells) and explicit methodologies, where the systems are solved separately at each time step exchanging boundary conditions explicitly.

MOTIVATION

This work aims to investigate the implications in the use of one of the methodologies presented in the literature and available in many programs to integration between reservoir and production systems: the explicit coupling, firstly because the increasing use of this methodology in recent production projects in oilfield industry.

An advantage of explicit coupling is its flexibility to integrate several reservoir simulators and independent production systems, as well as enable the evaluation of routines of well control management by the user, as verified by Cotrim et al (2011).

Ghorayeb et al (2003) and Schiozer (1994) have shown the limitations of explicit methodology coupling reservoirs and production systems, such as errors due to the inadequate choices of time step and boundary conditions.

However, there are many publications that use this form of coupling (Rotondi et al, 2008, Cotrim et al, 2011) because formulation in implicit methodology is complex and involves modeling of two systems with different characteristics,
sometimes hard to obtain a unique solution to whole system. Further investigation is required to validate application of explicit methodology in the industry.

**OBJECTIVES**

This work seeks to validate the methodology of explicit coupling to cases of known response in common situations of well operation in production and injection of fluids. The results are compared with the response of the implicit coupling methodology to check the quality of numerical solution.

After validated the coupling methodology, a case with a more elaborated well management routine is evaluated, which cannot adequately represented by the reservoir simulator. This case shows that the flexibility of the application of external well prioritization methodologies at reservoir simulator can provided better reservoir management decisions.

**COUPLING METHODOLOGIES**

The coupling between the reservoir and the system of production involves the modeling of fluid flow through three interdependent systems:

a) The reservoir model, represented by the hydraulic diffusivity equation, which describes the flow of the fluids inside the porous medium, which is inserted within the reservoir simulator;

b) Well model, represented by the equation of well productivity, usually implemented within the reservoir simulator;

c) Production system model, represented by the equations of hydraulic flow in pipes, chokes, networks etc. Complex models that resolve several networks are implemented within production systems simulators.

There is no consensus on the definitions of coupling methodologies but they can be grouped by the numerical solution, at implicit or explicit forms.

In implicit methodology, coupling equations of flow of fluids involved in the production systems are resolved simultaneously or sequentially with the system of equations used to obtain the flow between the grid blocks of the model that represents the porous medium of reservoir and the equations that model the flow to the bottom of the well at the end of a time step.

In the explicit coupling methodology, calculations of production system are performed sequentially only at the beginning of time step, being held fixed until the end of time, as shown in Figure 1. The methodology chosen for the integration between the simulators of this work is based on Ghorayeb et al (2003) and Schiozer (1994).

This work seeks to validate the methodology of explicit coupling to cases of known response in common situations of well operation in production and injection of fluids. The results are compared with the response of the implicit coupling methodology to check the quality of numerical solution.

![Figure 1 - Explicit coupling methodology flowchart.](image)

In sequential algorithms, it is necessary that the reservoir simulator provide influx performance relationship curves (IPR) representing properly the fluids deliverability of each well. This curve is compared to the well tubing performance relationship curve (TPR), calculated by the production system model in order to find the operating point of well within the production system. This procedure is generally known as production system balancing.

The main limitations of explicit methodology reported in the literature are numerical instability of the solution and not guarantee of uniqueness of the response between reservoir and production system models. In this work, some proposals are presented to minimize these problems.

The flexibility inherent in the sequential coupling allows application of predefined wells managing rules, which could obtain gains to the field exploitation project, different of the well management implemented in many commercial reservoir simulators, where the flow restrictions in the surface installations are applied sequentially through predefined rules (Denney, 2003).

**METHODOLOGY**

The methodology starts with the development of a controller program that allows coupling explicitly a commercial reservoir simulator and an simplified production system simulator, used to test the explicit methodology. The coupled reservoir simulator only allows well control by one boundary condition that is the main fluid rate (water, oil or gas).

The response obtained by explicit methodology is compared with the results obtained by implicit methodology for some cases with known behavior. There was evaluates the pressures and flow rates behavior from the wells by successive
analyses at different levels of management control of reservoir wells by the production system simulator.

As some limitations in results are reported in literature, some modifications are proposed to enhance results from explicit methodology.

For situations with small variations in pressure and flow, which can be obtained with time step controlled advances, the explicit solution can be applied without coarse errors (Rodonti, 2008). It is proposed in this work the evaluation of a methodology for adaptive control of time step advance (ACET), which verifies changes in pressure and flow rate of the previous time step and modifies the length of the next time step by a pre-established criteria.

The ACET methodology initially calculates the differences of bottom-hole pressure and fluid flows for all coupling wells in relation to the previous time step. The current time step is then divided by the ratio between maximum allowed differences and the values obtained previously. The value is then compared with the minimum and maximum limits allowed.

There are also problems that occur due to the high productivity of wells. IPR curves provided by reservoir simulator are calculated from the initial average pressure of grid blocks where the wells are completed, and not from the final average pressure of wells grid blocks. This difference is the likely cause of numerical instabilities that hollow in the explicit methodology. A approach for the problem should be a IPR correction (IPRC) provided by reservoir simulator.

This work has adopted IPR curves correction for injector wells using a methodology that uses information from the previous time step, based in equation:

$$\frac{\partial P_{Iw}}{\partial P} (P_n^{n+1} - P^*)^2 + \left[ P_{Iw} + \frac{Q_w}{P_{Iw}^*} \frac{\partial P_{Iw}}{\partial P} \right] (P_n^{n+1} - P^*) - \frac{1}{K \Delta t} \left( P_n^{n+1} - P^* \right) + Q_w^n - Q_{w}^{n-1} = 0$$

(1)

where P is gridblock pressure, PI is productivity index of injector well, Qw is water rate, Δt is size of time step, n index is the beginning of time step, n+1 is the end of time step, n-1 is the end of last time step and K is a constant obtained in function of P and Qw.

To evaluate a complex application, this work explores the flexibility of using pre-defined wells management rules by the user, important item in cases with group operating restrictions, where the explicit methodology is compared with the methodology available in reservoir simulator. The wells prioritization methodology is based on work of Cotrim et al (2011), where the wells are prioritized according to their fluids production. This prioritization methodology (WellPrior) can be configured to follow the same rules used by the reservoir simulator.

**APPLICATION**

The validation model is a five-spot with 10x10x6 grid (100x100x10m gridblocks), 20% porosity, horizontal permeability 100 mD, vertical permeability 10 mD, with fluid and relative permeability curves and FVM tables from Namorado Field (Bento, 2010). There are 4 vertical oil producers and 1 vertical water injector. All wells are satellites connected to the surface. A quadrant of reservoir has increased permeability five times in order to assess the different water breakthrough in well PV-001.

Validation cases for analysis at different levels of coupling and management of reservoir wells by production system are:

a) Wells control by the controller at bottom-hole level (BHP and rates of production and injection operational limits), with different time steps, without group restriction. The operational constraints of producing wells are bottom-hole pressure of at least 100 kgf/cm² and production rate of liquid exceeding 1500 m³/d. For the injector well, a maximum bottom-hole pressure of 400 kgf/cm² and maximum injection flow rate of 8500 m³/d.

b) Control wells by production system simulator at surface level, without group restriction (only WHP operational limits), with different time steps. The operating constraint for producing wells is minimum well-head pressure of 17 kgf/cm².

Application case of explicit methodology and evaluation of the flexibility of the explicit approach is described below:

c) Same reservoir with wells control by the controller at bottom-hole level (BHP and rates of production and injection operational limits), with group restrictions (total production and injection). Different well management methodologies are used (WellPrior 1 reproduces the reservoir simulator methodology and WellPrior 2 prioritizes the production wells with less watercut). The group restriction applied is maximum liquid of 5000 m³/d. The IPR correction is applied in this case.

**RESULTS AND DISCUSSION**

For initial evaluation of explicit coupling, initial runs were made with variations in production and injection rates and time step size.

**Five-spot case ruled by controller, with liquid flow rate and bottom-hole pressure restrictions**

Figure 2 and Figure 3 show the behavior of bottom-hole pressure and flow rates for PV-001 and PV-003 oil producer wells, for implicit and explicit methodologies with 1 and 10 days time steps, as the results of IPR correction methodology. PV-001 is located in high permeability area and PV-003 is the more distant well, and both are more representative wells. The application of ACET methodology with IPR correction shown better control in well bottom-hole pressure.

Figure 4 shows the behavior of bottom-hole pressure and water rate for IV-001 water injector well. It is noticed great instability in injector well for explicit run without IPR correction, because IPR curves provided by reservoir simulator are calculated from the initial average pressure of grid blocks where the well is completed, and not from the final average pressure of grid blocks, that is dependent of injection rate during time step.

Cumulative production and injection values are shown in Table 1.
Figure 2 - Produced oil and water rates.

Figure 3 – Well bottom-hole pressure.

Figure 4 - Injected water rate and well bottom-hole pressure.

Table 1 - Cumulative oil and water production and cumulated water injection.

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F
Explicit coupling response was similar to that obtained by implicit coupling. The models have shown numerical instability in injector wells, when controlled by bottom-hole pressure. The use of methodology for correction (IPRc) improved the results presenting less instability. The producing well had instability problems in high water-cuts, caused by sequential opens and shut-ins, which was minimized by ACET methodology.

Five-spot case ruled by controller, with restricted production system via well management methodologies

Figure 8 and Figure 9 show the behavior of bottom-hole pressure and flow rates for PV-001 and PV-003 oil producer wells during the production, for implicit and explicit methodologies with 10 days time step. Figure 10 shows the behavior of bottom-hole pressure and water rate for water injector well, and Figure 11 shows group liquid, oil and water production rates. Cumulative production and injection values
are shown in Table 3.

Figure 8 – Produced oil and water rates.

Figure 9 – Well bottom-hole pressure.

Figure 10 - Injected water rate and well bottom-hole pressure.

Figure 11 - Liquid, oil and water group production rates.
The first application of external well management methodology presented similar production and injection results that provided by reservoir simulator. Explicit coupling are able to obtain same results those from reservoir simulator, useful for multiple reservoirs simulation runs.

The second application controlled the producing wells to prior low water-cut producer wells, generate a great delay in the arrival of water in PV-001 oil producer well and a small advance in PV-002, PV-003 and PV-004 wells, that reflected in a better oil recover from reservoir.

How verified, an external well management routine could manage better the displacement inside the reservoir and the arrival of fluids into wellbores, evaluating and redirecting well fluid rates based on more elaborated algorithms. Both applications honored the maximum well and group restriction, showing that any other methodology defined by user could be applied to well management.

**CONCLUSIONS**

The explicit coupling between a reservoir simulator and production systems was implemented obtaining satisfactory results when compared with implicit methodology. All well and group operating constraints defined were honored.

Both the producing and injection wells presented numerical instability problems, indicating the necessity of correction methodologies for explicit methodology. Both methodologies applied could minimize numerical instabilities. The controller and the production system simulator have practically the same result as the reservoir simulator.

The flexibility in the choice of managing wells methodology allowed by sequential approach proved to be advantageous to allow the use a methodology which brought a better management of production to its study. This flexibility opens opportunities to find better ways to improve well management in oilfield fluids production and injection.

The reservoir simulator interface used only allows wells to be controlled by one boundary condition of rate (water, oil or gas), supposedly done to ensure the mass balance of that fluid in the complete system, even if there is a discrepancy between the results of the well and the system of production (characteristic of explicit methodology) at the end of timestep. It is a cause of instabilities of producers when bottom-hole multiphase flow occurs. The same problem occurs when main fluid rate is small than other phases (per example high water-cut). Any small perturbation in main fluid rate multiplies the rate of other phases.

For future work, it is suggested for the methodology implemented in reservoir simulator to include the possibility to define the boundary condition for the operation of the well (pressure or flow), to provide an IPR curve calculated within a subdomain (in the area near the well, for example), as based on work by Schiozer (1994) or allow to repeat the time step by some convergence criteria.

**ACKNOWLEDGMENTS**

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**REFERENCES**


**Table 3 - Cumulative oil and water production and cumulated water injection.**

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<td>0.3%</td>
<td>2677.0</td>
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