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*"The sequential time step advances in explicit integration can cause errors or numerical deviations in model results."*

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## Correcting IPR Curves for Explicitly Coupling Reservoir and Production Systems

João Carlos Von Hohendorff Filho

Coupling reservoir and production facilities models can be used to integrate forecast of production of multiple reservoirs, which share production platforms (with limited production and injection capacity) and comprise complex production systems to collect and store fluids.

Explicit coupling simplifies the process of integrating reservoir and production systems simulations to model the whole system. It is also time efficient and can be applied using commercial software, allowing flexibility to assess alternatives in well management.

The sequential time step advances in explicit integration can cause errors or numerical deviations in model results, hinder a unified response and cause severe oscillations, especially in scenarios with highly productive producer wells. Iterative procedures could be used but they are not allowed by the commercial software in some cases and could increase computational time. These errors can be minimized by decreasing the time step but this significantly increases computational time, so the aim of this work is to improve reliability without dramatically increasing time consumption.

Proposed solutions in the literature to minimize these numerical instabilities and guarantee a unified response depend on code changing within the software.

To correct these problems, such as deviations occurring due to highly productive/injective wells, the simulated IPR curves can be adjusted.

In a first paper [1], the inflow performance relationship corrector (IPRc) correction methodology was created to correct IPR curves for water injector wells, which empirically correlates grid block pressure, injectivity index of injector well, water rate, and size of time step.

In a new paper [2], a theoretical background was formulated to support the created IPRc correction methodology, using observed well grid block pressure data for oil and water (two-phase), slightly compressible flow through porous media for three-dimensional flow from reservoir simulations.

### Theoretical Background

Initially, an equation was developed for 1-phase flow of a slightly compressible fluid in one direction using diffusivity equations, assuming some hypotheses. The main consideration for these hypotheses was the similarity of some parameters for consecutive time steps, as the coupling occurs in time steps small enough to disregard the small changes in fluid and pressure near wells:

(1) Transmissibility from neighboring blocks is similar in consecutive time steps.

(2) The difference in time for source term is bigger than for influx term.

(3) The volume compressibility term is bigger than the sum of influx term.

Then other formulas from other directions were combined to consider two-phase flow, incorporating more hypotheses:

(4) Fluid density changes are small during the time step.

(5) Total liquid effective permeability varies little.

(6) Minimal variation in the compressibility of each fluid.

(7) Minimal variation in capillary pressure between oil and water with saturation changes in all directions.

After creating Eq.1 to support the IPRc, the overall behavior of the derived term K for the correction method was studied, because this term involves intrinsic parameters that comprise: the drainage radius, reservoir porosity and thickness, rock and fluid compressibilities, fluid viscosities and saturations, and others that may vary over time during coupling.

$$p_i^{n+2} - p_i^{n+1} = \left(q_{lsc_i}^{n+1} - q_{lsc_i}^{n}\right)\left(\frac{\alpha_c B_l^o \Delta t}{V_b Ø c_l}\right)_i = \left(q_{lsc_i}^{n+1} - q_{lsc_i}^{n}\right)K \qquad \text{Eq. 1}$$

### Behavior of the term K

Obtaining the term K for the integrated simulation, linking pressure and fluid rate, is a challenge when using the IPRc methodology, as it is time dependent and could be influenced by factors that are oversimplified using the formulas.

To analyze the behavior of the term K, we developed four five-spot models based on the well logs of 4 wells, horizontally homogeneous, with four producers and one centered injector [2]. We used the default reference completion for injector well in these models to obtain their grid block pressure. So grid block pressure variations along consecutive time steps were calculated. The variation also was done with the water rate for the injector well. Linear correlations were observed in **Fig. 1** between in grid block pressure variations (ΔP) and variations in the water flow rate for all models. These linear correlations are indicative of the variations in value and signal, which represent the term K.

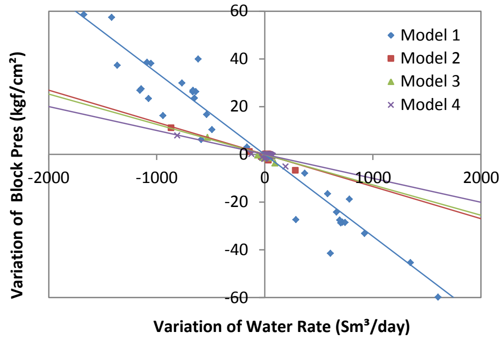


***Fig. 1:*** *Grid block pressure variation and water rate variation over consecutive time steps, for the injector well in each five-spot model, indicating linear correlations between variables.*

The evaluation test for a five-spot model, with IPR correction, implementing term K obtained automatically during time steps, did not show numerical instability (**Fig. 2**) for the water injector in the five-spot Model 1 with 2-day time steps, validating the developed equation.

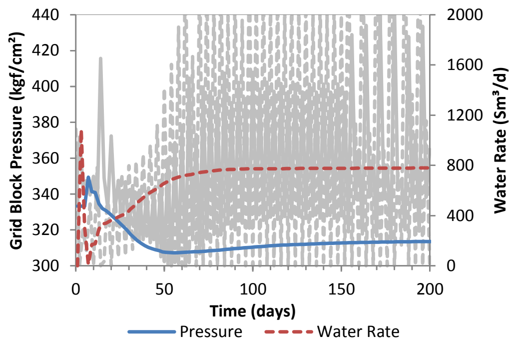


***Fig. 2:*** *Oscillatory behavior of grid block pressure and water rate in explicit coupling with IPRc correction, for the injector well in five-spot evaluation test for Model 1 (in grey is explicit coupling without correction).*

### Application in a Full Model

The application was divided into two case studies for base strategy E9 for UNISIM-I-D Benchmark [3] to assess results:

(1) Case 1: base strategy with bottom-hole restrictions for producers and injectors, to compare a standalone run (reference simulation) with coupled runs;

*"The developed formula represented flow behavior from reservoir simulation data for waterflooding, validate the IPRc methodology to correct IPR curves."*

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unisim@cepetro.unicamp.br

(2) Case 2: base strategy with wellhead restrictions for producers and bottom-hole restrictions for injectors, to compare a decoupled run (reference simulation) with coupled runs. Both case studies included different IPRc configurations for coupled runs.

A methodology for adaptive control of time step advance (ACET) [1] was revaluated, which verifies changes in pressures and flow rates of the previous time step and modifies the length of the next time step by a pre-established criterion.

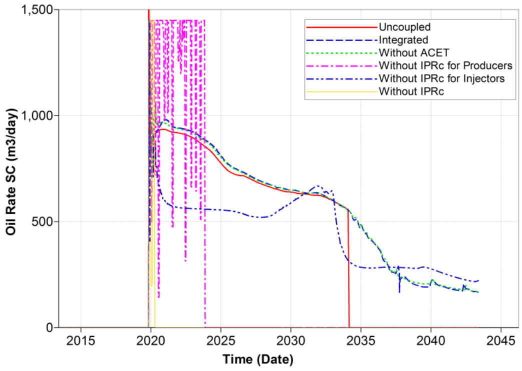


*Fig. 3: Oil production for PROD-026 (Case 1 – BHP restriction). Uncoupled is the standalone reservoir simulation. Others runs are coupled with bottom-hole conditions.*

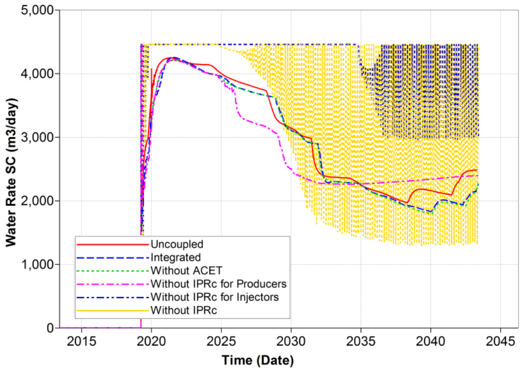


*Fig. 4: Water injection for INJ-022 (Case 1 – BHP restriction). Uncoupled is the standalone reservoir simulation. Others runs are coupled with bottom-hole conditions.*

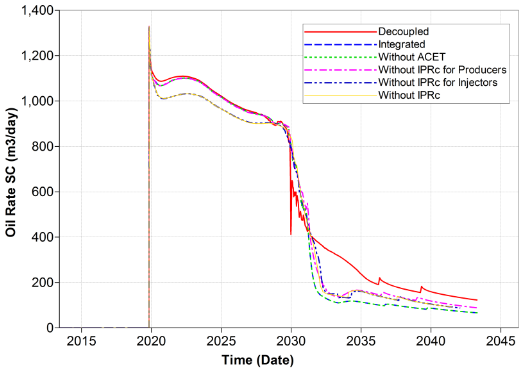


*Fig. 5: Oil production for PROD-026 (Case 2 – WHP restriction). Decoupled is the reservoir simulation with VLP tables. Others runs are coupled runs with VLP tables coupled explicitly.*

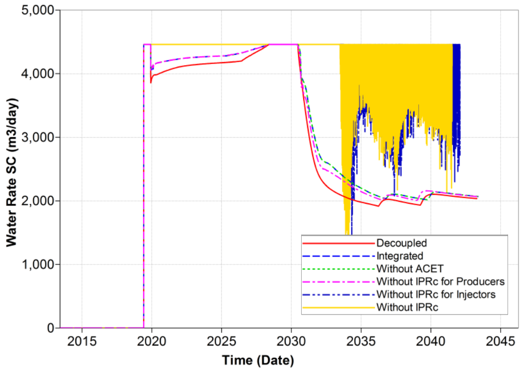


*Fig. 6: Water injection for INJ-006 (Case 2 – WHP restriction). Decoupled is the reservoir simulation with VLP tables. Others runs are coupled with VLP tables coupled explicitly.*

Explicit coupling with bottom-hole pressure restrictions (**Figs. 3** and **4**) produced less stable results for producer wells than with wellhead restrictions (**Figs. 5** and **6**). The bottom-hole pressure required by the production system increases as fluid rates increase, leading to more stable solutions (decreasing deviation) for operational rates, compared with constant bottom-hole pressure limits during the same time step.ACET did not improve results for the configuration 'Without IPRc', while demanding time steps shorter than 1 day, but showed small improvements for 'Integrated'.

Computational time with corrected explicit simulations results indicated a suitable time for explicit coupling applications.

**Conclusions**

The main advantage of IPRc is that it can be used in any reservoir simulator with an interface for IPR data exchange, without changing codes within the simulator. We defined suitable hypotheses and physics for the IPRc equation to assess adequately intrinsic parameters, defining term K based on correlation between water and/or oil rate and grid block pressure for injector or producer well. The IPRc becomes suitable for explicit coupling application in different scenarios as oil, water and gas production.

**References**

[1] HOHENDORFF FILHO, J. C. V., SCHIOZER, D. J., 2014, "Evaluation on Explicit Coupling between Reservoir Simulators and Production System", J. Energy Resour. Technol, v. 136(4), pp. 1-24. doi: 10.1115/1.4028860

[2] HOHENDORFF FILHO, J. C. V.; SCHIOZER, D. J., 2018, "Correcting Inflow Performance Relationship Curves for Explicitly Coupling Reservoir Simulations and Production Systems Simulations", J. Energy Resour. Technol, v. 140 (3), pp. 0320061-03200610. doi: 10.1115/1.4038045

[3] SCHIOZER, D. J., SANTOS, A. A. S., DRUMOND, P. S., 2015. "Integrated Model Based Decision Analysis in Twelve Steps Applied to Petroleum Fields Development and Management". Europec 2015, Madrid, Spain, 1-4 June, 2015, SPE 174370. doi: 10.2118/152860-MS.

**About the author:** João Carlos von Hohendorff Filho is graduated in Civil Engineering, specialized in Petroleum Engineering with emphasis on Reservoir Engineering, and master's in Petroleum Sciences and Engineering. He is a researcher at UNISIM/CEPETRO/UNICAMP since 2013, in the area of Simulation and Management of Petroleum Reservoirs.

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