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METHODOLOGY TO ACCELERATE EXPLICIT INTEGRATION BETWEEN RESERVOIR AND PRODUCTION SYSTEM SIMULATORS

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Abstract. Integrated models are needed in some situations to analyze the interaction between reservoirs and production system models. However, the dynamics of the two systems is different and there are situations in which the production system response is very similar over time. The aim of this work is to propose a more efficient interaction between the simulators, avoiding repetitions, reducing the total time of the numerical coupling and accelerating the decision making process for the field. The methodology of this work proposes a proxy model for the production system, similarly to that done in decoupled approach with VLP (Vertical Lift Performance) tables previously generated, but with the proxy model being generated during the integrated simulation using explicit coupling. Integration with proxy model obtained total time values close to those obtained with the use of VLP tables previously generated, showing an efficient way of efficient interaction between the reservoir and production system simulators for the explicit coupling approach, without the need to run unnecessary values, as done in the generation of VLP tables.

Keywords: Proxy model, reservoir, production system, simulation, coupling

1 Introduction

In a process of development and management of reservoirs in closed loop, the integration between reservoirs and production systems is closely related to steps features within any proposed workflow. Following a consolidated methodology for integrated decision analysis in the development and management of petroleum fields [1], the integration relates to all steps provided in this approach: construction of simulation models, data assimilation for model calibration, long-term decisions under uncertainties, and implementation of long-term and short-term decisions.

It is an appropriate practice to use robust models to represent the behavior of the whole system, in order to allow the most appropriate evaluations of project parameters for field development, production management rules, expansions of the current production strategy, among other items of interest. These models describe the behavior of petroleum reservoirs connected to a production system, which require well, gathering system and surface facilities models [2].

Integrated models are needed in some situations to analyze the interaction between reservoirs and production system, using numerical simulation to forecast production, decision making based on economic indicators. A methodology to improve coupling reservoir models and production system models to accurately and reliably simulate integrated solutions representing fluid flow through the reservoir to the surface is explicit coupling, where different simulators are coupled and solved separately at each time step, exchanging boundary conditions sequentially at the integration point [3].

Integrated simulation is time consuming, for demand a rigorous calculation of mass, pressure drop and fluid state through the whole system. This question is especially important for explicit methodology, due extra time during exchange data between simulators [4].

Dynamics of the systems is different and there are situations in which a particular system response is very similar or well know over time, indicating the possibility of incorporate simplified models as proxy models, reduced models or data-driven models.

Proxy models are based on the integration of statistical methods, such as experimental design theory and response surface methodology, which allows the definition of a production strategy and the economic evaluation. The response surface methodology allows substituting the simulator by an analytical model (proxy model) in one part of the process [5]. Polynomial regression models, multivariate kriging models, thin-plate splines models or artificial neural networks are commonly used as a proxy-model for reservoir simulation [6].

Reduced Order Models reduce the order of the numerical simulation models in order to overcome the long computational overhead. This approach concentrates on the physics of the problem or in the space and time resolution of the reservoir numerical solution [7]. Examples in literature are material balance (tank model) [8, 9] and pseudo-state state [9], capacitance-resistance models [10], and upscale coarse grid model with pseudo properties and history matching [11].

Data-driven models use data in order to build models trained (using regression techniques or machine learning) to learn and mimic the forecast behavior of reservoir. Examples are time dependent type curve (decline) models [9] and surrogate reservoir models trained with machine learning [7].

We found references of proxy models for design or operation optimization of production systems [12, 13]. We didn´t find references for reduced models, although space and time reductions can be applied in models and some simplifications of black-box pressure drop models can be used to accelerate simulation time. For data-driven models, efforts are directed to incorporate basic parameters of production system and real time production data [14].

But, because production system response is very similar over time, some data reuse can be useful. For production system integrated with reservoir simulation, is commonly used hydraulic tables (Vertical Lift Performance – VLP) to represent well and gathering systems in decoupled simulations [15]. These tables are usually produced for wells in different reservoir areas using a standalone well simulator considering some production scenarios, and afterwards included in reservoir simulator dataset. There is not direct connection between simulators, thus drawback inaccuracies can be introduced in the calculations because of the possibility of interpolation or extrapolation of insufficient tabulated data [4]. But this ability for data persistence for integrated simulation is noteworthy.

2 Objective

This work aims to find an efficient interaction between the reservoir and production system simulators, proposing a proxy model for production system in an integrated explicit simulation, avoiding repetitions, reducing the total time of the numerical explicit coupling and accelerating the decision making process for the field.

3 Methodology

This work proposes a proxy model for the production system, in a similar way to that applied in decoupled simulation approach with VLP tables previously generated, but applicable for explicit coupling. The methodology is based on consolidate proxy-modeling workflow for reservoir proxy modelling [6].

The proposed methodology consists of the following sequential steps: (1) input variables selection, (2) proxy model estimation, (3) proxy model verification, and (4) proxy model employment.

3.1 Input Variables Selection

This step is related to selection of input variables that depends of intrinsic characteristics of production system, knowledge of engineer and data availability from/to coupler software. Also includes the selection of input dataset limits for each variable.

Sensitivity analysis can be useful to quantify the impact of input variables to eliminate those with insufficient impact in production system simulation results.

3.2 Proxy Model Estimation

Multiphase pressure drop along pipes results in a non-linear equation with n-dimensional parameters. Some strategy is needed to maintain prediction accuracy, flexibility and computational efficiency for a proxy model.

In this step we propose as estimator for regression model a modified case of multidimensional segmented linear (piecewise) regression to maximize the proxy quality. Segmented equation allows linearizing the regression in predefined one-dimensional segments, best fitting non-linear data. For illustration, equation (1) represents a piecewise linear regression [16] equation for two linear pieces or segments:

$$Y_i = \propto_1 + \beta_1 X_i + \beta_2 (X_i - X^*) D_i + u_i \tag{1}$$

where Y is dependent variable; X is independent variable; $\propto_1$, β_1 and β_2 are model parameters; X^* is threshold value; $D = 1$ if $X > X^*$ or $D = 0$ if $X < X^*$; u = disturbance term; and i the ith observation.

Expanding the linearity for two dimensions assuming 2 independent variables, equation (1) is updated in equation (2). It can be expanded for n-variables, capturing adequately the equation response in n-dimensional space.

$$Y_i = \propto_1 + \beta_{11} X_{1i} + \beta_{12} (X_{1i} - X_1^*) D_{1i} + \beta_{21} X_{2i} + \beta_{22} (X_{2i} - X_2^*) D_{2i} + u_i \tag{2}$$

How term D acts as a “segment selector”, the segmentation allows bypass initial data sampling to fill the whole input dataset, interesting for highly nonlinear multidimensional spaces. The sampling and regression will occur during the integrated simulation using explicit coupling data sharing, when demanded for our methodology.

3.3 Proxy Model Verification

This step evolves the process of assessment of prediction accuracy. Response values predicted by a proxy model are compared to numerical simulation for a set of experiments not included in the input dataset to verify quality.

For our piecewise linear regression, to define threshold values for each segment of n-dimensional variables is a main point to verification, because affects directly the quality of proxy models. Their evaluation is similar to define range values for VLP table generation. But how sampling occurs during integrated simulation, a higher number of segments are allowable with little efficiency loss, as commented above.

If proxy model quality is not sufficient, an input dataset improvement is required.

3.4 Proxy Model Employment

Efficiency of proxy model in forecast prediction is tested with different approaches in this step. Three approaches are defined to evaluate proxy model efficient avoiding repetitions and reducing the total time of the numerical explicit coupling:

Approach 1: reservoir and production system simulations coupled with explicit methodology directly via coupler software, where the production system simulator is demanded in every integration time step to obtain the operation point for each well using secant method [3,17];

Approach 2: explicit methodology with use of VLP tables previously generated via production system simulator. VLP tables are incorporated in coupler and operation point for each well is determined using a combination of Newton-Raphson and bisection [17];

Approach 3: explicit with production system proxy model, with sampling occurring during the integrated simulation using production system simulator data and operation point for each well is determined using a combination of Newton-Raphson and bisection.

All approaches are compared about production field forecast results and time performance.

4 Application

This work compared proxy model for two offshore field benchmarks with satellite wells, yielding 3 proxy evaluation cases.

Case 1 tested the approaches for production of a sandstone reservoir (UNISIM-I-D) in a numerical model with black oil fluid [1] with production strategy for water flooding recovery method defined with 20 wells. The reservoir model is represented by a corner point grid with 33,400 active cells.

This work uses the production strategy E9 optimized after 10 steps considering several types of uncertainties [18]. UNISIM-I-D was built to represent the field for a project in the initial stages of field management planning under uncertainties. After selecting some representative models (RM) to check the quality of decisions considering uncertainties, the production strategy of each RM is defined. E9 was the best production strategy for RM9 from which production systems were defined to determine the new project and operational variables. E9 was then considered the best strategy considering uncertainties to apply in this study.

Case 2 tested the approaches for production of a carbonate reservoir (UNISIM-II-D) in a numerical model with light oil fluid [19] with production strategy for water flooding recovery method previously optimized with 20 wells. The reservoir model is represented by a corner point grid with 65,000 active cells.

UNISIM-II-D was built to represent the field for a project in the initial stages of field development planning under uncertainties. After geological scenarios generation considering all possible scenarios and their reduction with dynamic data, a representative model was selected to define the production strategy.

Case 3 tested the approaches for both reservoirs sharing the same surface facility, selecting 19 wells from sandstone reservoir and 13 from carbonate reservoir, suiting 32 platform well slots.

The production system defined well and gathering systems as a satellite well [20] with pipe diameters for production/injection columns: 5”, flow lines: 6” and risers: 6”. Beggs and Brill multiphase flow empirical correlations were used to model pressure drop inside pipes [21] and Standing correlations [22] to model the fluid. In Case 3, a gas lift injection rate of 200,000 m³/day was assumed to maximize oil recovery [23].

Table 1. Platform capacities for each case

Case	Oil Production (m³/day)	Water Production (m³/day)	Liquid Production (m³/day)	Gas Production (m³/day)	Water Injection (m³/day)
1	20,150	9,765	20,150	-	28,210
2 - 3	28,617	38,156	28,617	4,000	38,165

The production system defined surface facility as a simplified offshore platform, represented only by production and injection capacities applied in each case are shown in Table 1.

Table 2 shows variables selected for proxy modeling (water cut rate, liquid rate, lift gas rate, gas liquid ratio and wellhead pressure) with input dataset limits and segments for each variable in multidimensional piecewise regression proxy model. The same values were used for VLP table generation using production system simulator. We restricted two samplings only in each segment for proxy model sampling, obtaining a similar behavior of VLP tables. For lift gas rate, data set limits are considered full due operational restrictions.

Table 2. Input dataset limits and segments for variables

Variable	Units	Values							
Water Cut Ratio	fraction	0	0.10	0.30	0.50	0.70	0.90	-	-
Liquid Rate	m³	100	200	400	500	800	1,600	2,400	3,200
Lift Gas Rate	10³m³	0	100	200	-	-	-	-	-
Gas Liquid Ratio	m³/m³	10	30	50	70	90	110	120	-
Wellhead Pressure	kPa	981	1,961	-	-	-	-	-	-

Output parameter selected for our production system proxy model is bottom-hole pressure (BHP) for each well. In explicit coupling for Approaches 1 and 2, well bottom-hole was determined as the integration point for reservoir and production system. We run comparison approaches using reservoir simulator IMEX™ 2014 and production system simulator PTUBE™ 2014 from CMG. The explicit coupler [24] assumes wellhead and bottom-hole restrictions in coupled runs. In explicit coupling for Approach 3, the production system simulator was replaced by proxy model to determine well bottom-hole pressure. For Approach 2, VLP tables were generated using same tubing simulator.

For verification of proxy model quality, we compared BHP results for a representative well (Prod-021) simulating a number of 2,000 aleatory experiments and comparing with proxy model response.

5 Results

5.1 Proxy Model Verification

Figure 1 shows cross-plot between production system simulation results and proxy model results for same surface conditions for BHP output variable in well Prod-021. The quality indicator was R^2 = 0.999, indicating a good fitting of proxy model and simulation results.

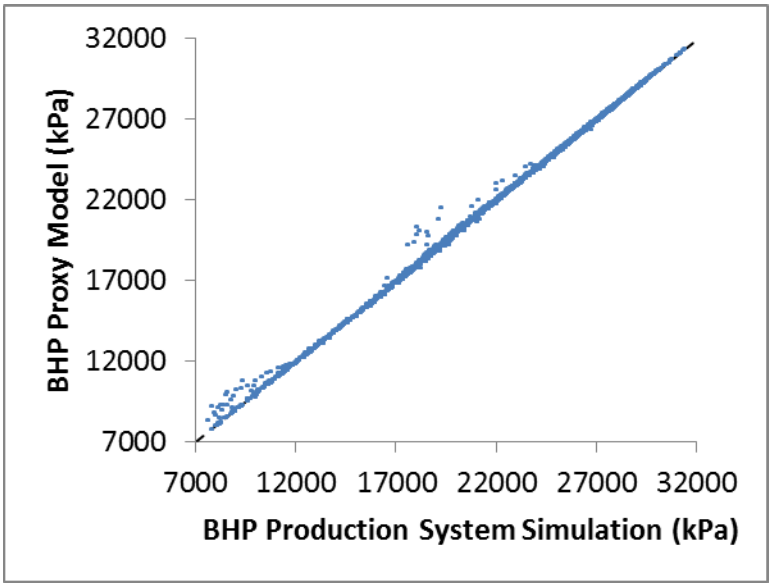

Figure 1. Cross-plot between production system simulation results and proxy model results for same surface conditions for BHP output variable in well Prod-021 (R^2 = 0.999)

5.2 Case 1 – UNISIM-I-D

Figures 2 to 4 show production curves for oil, water and liquid in sandstone reservoir. Figure 5 shows water injection for the reservoir.

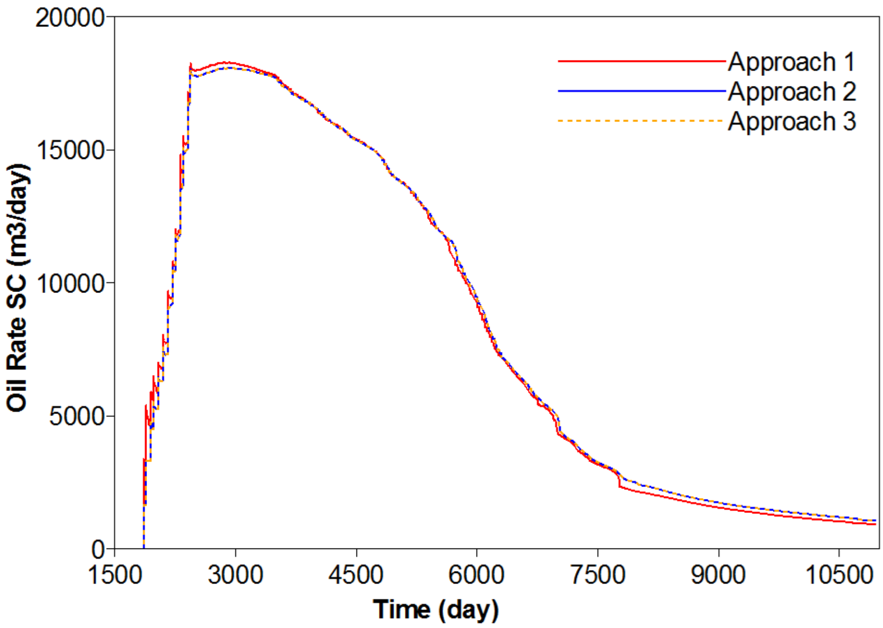

Figure 2. Oil production from field in sandstone reservoir

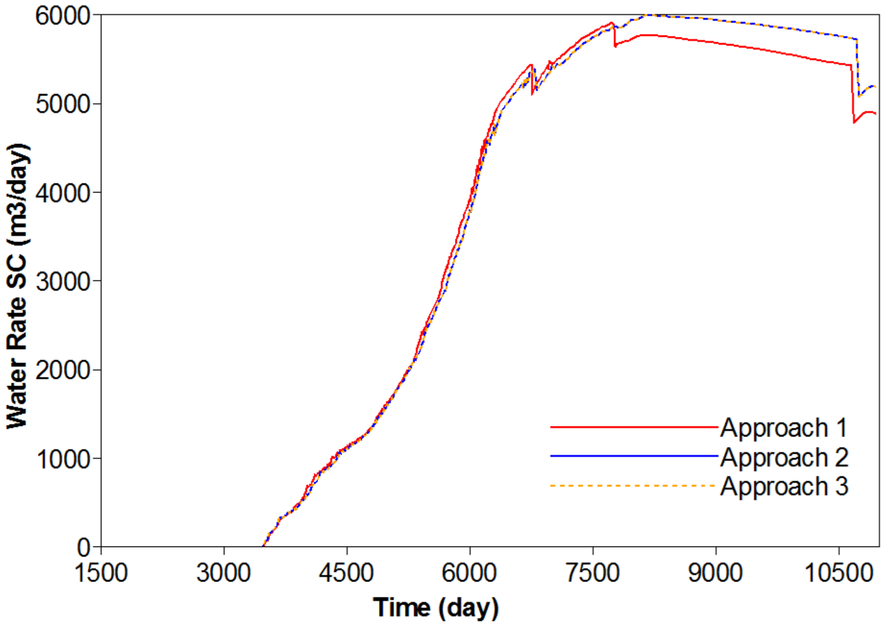

Figure 3. Water production from field in sandstone reservoir

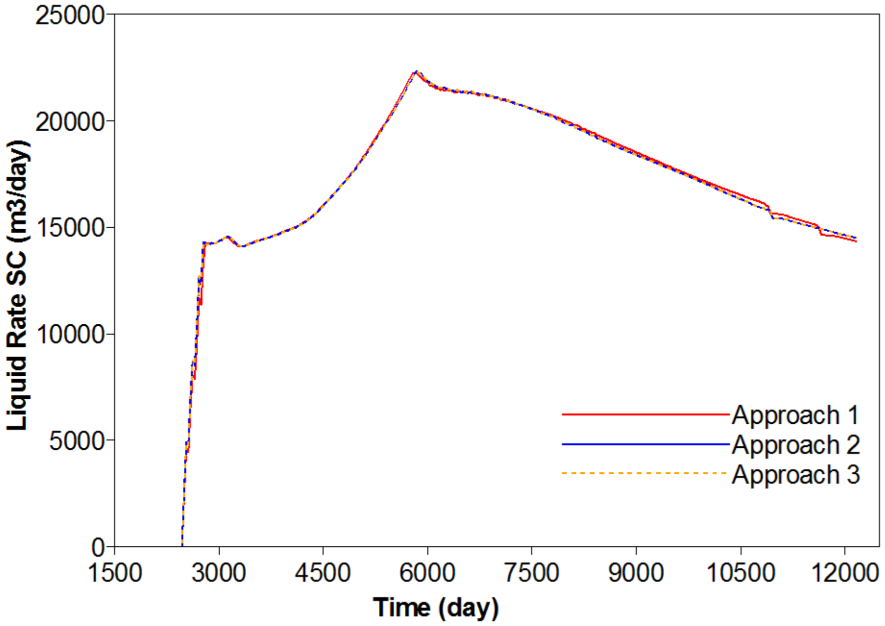

Figure 4. Liquid production from field in sandstone reservoir

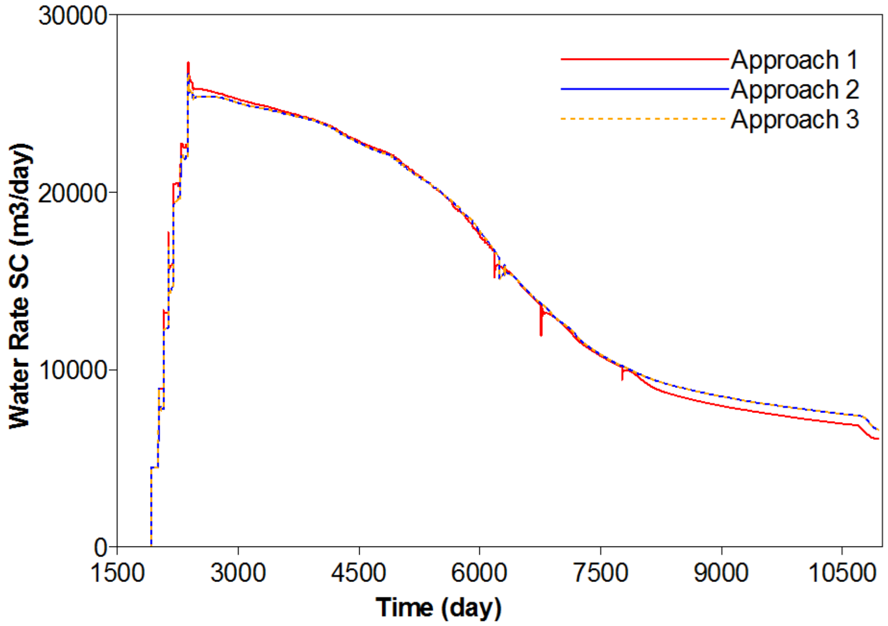

Figure 5. Water injection from field in sandstone reservoir

Table 3 summarizes time consuming for integration approaches and their respective reservoir and production system models, and total of iterations (integrated time steps) demanded.

Table 3. Time consuming for integration approaches and their respective reservoir and production system models, and total of iterations demanded for Case 1

Approach	Total(s)	Reservoir(s)	Production System(s)	Iterations
1	3.033	896	2.025	611
2	1.074	896	151	600
3	1.081	892	158	600

Table 4 shows comparison of production system simulator requesting for bottom-hole pressure calculation for all wells during the integrated simulation.

Table 4. Production system simulator requesting for bottom-hole pressure calculation for all wells during the integrated simulation for Case 1

Approach	Calls	Points/Call	Total
1	24.343	1	24.343
2	13	2.016	26.208
3	1.876	2	3.757

5.3 Case 2 - UNISIM-II-D

Figures 6 to 8 show production curves for oil, water and liquid in carbonate reservoir. Figure 9 shows water injection for the reservoir.

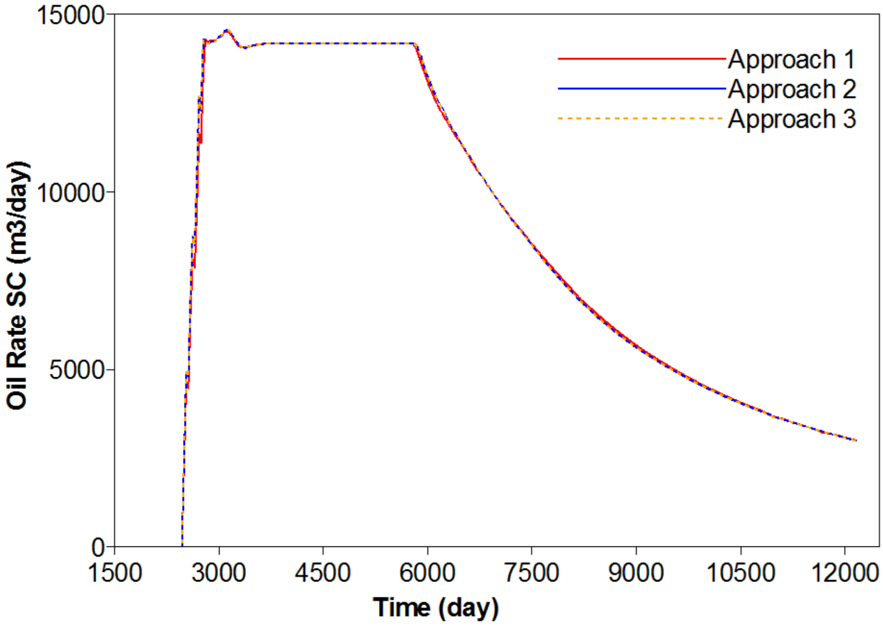

Figure 6. Oil production from field in carbonate reservoir

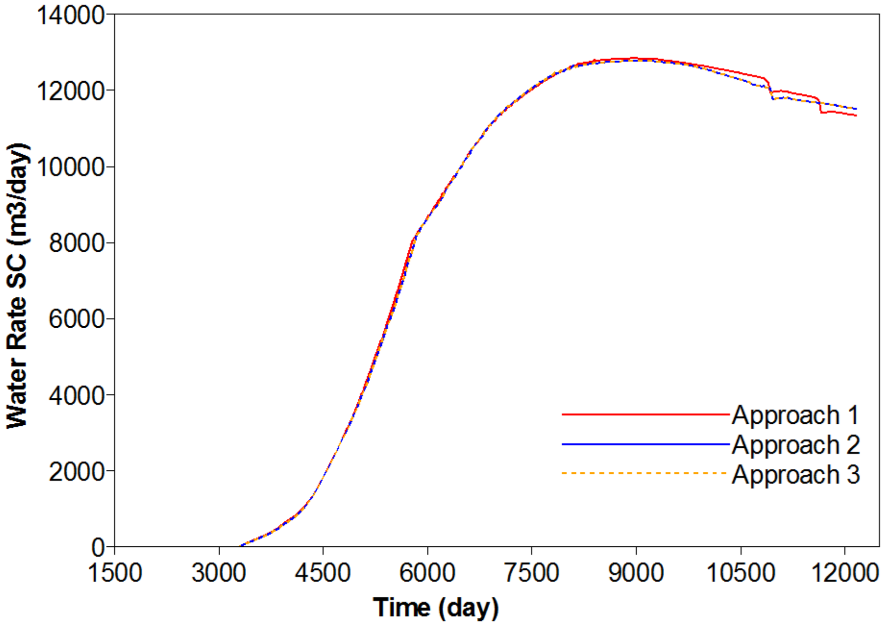

Figure 7. Water production from field in carbonate reservoir

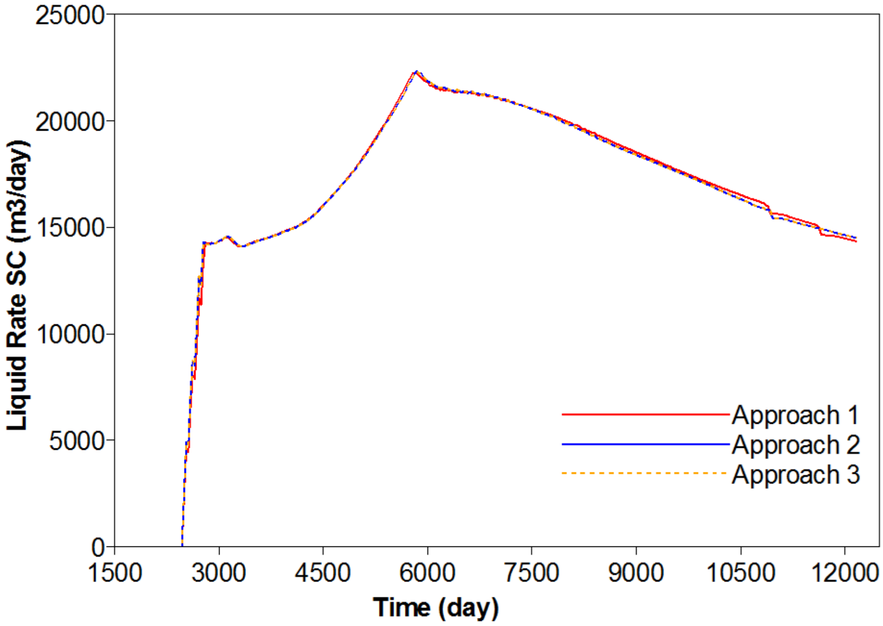

Figure 8. Liquid production from field in carbonate reservoir

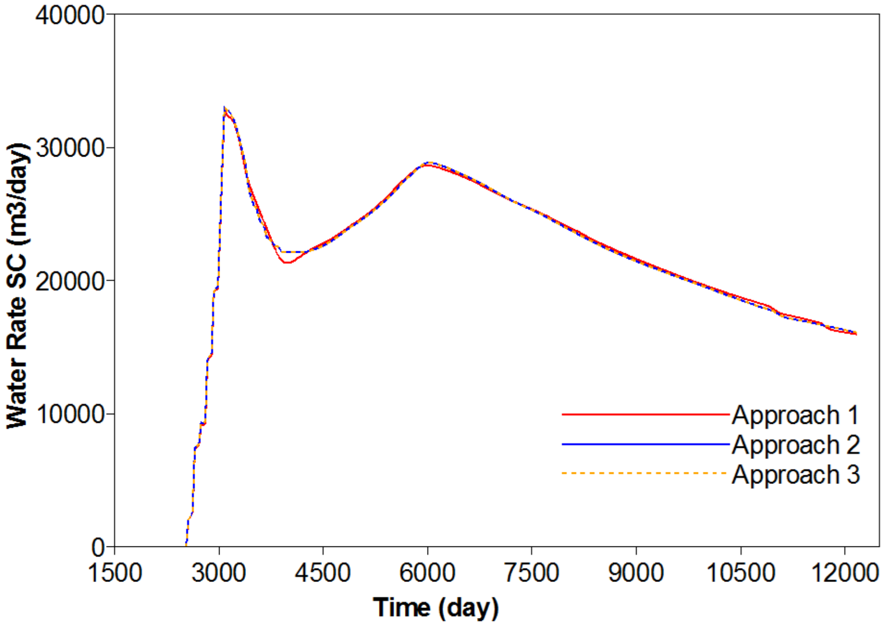

Figure 9. Water injection from field in carbonate reservoir

Table 5 summarizes time consuming for integration approaches and their respective reservoir and production system models, and total of iterations (integrated time steps) demanded.

Table 5. Time consuming for integration approaches and their respective reservoir and production system models, and total of iterations demanded for Case 2

Approach	Total (s)	Reservoir (s)	Production System (s)	Iterations
1	2.983	1.195	1.674	482
2	1.430	1.248	141	505
3	1.413	1.248	124	505

Table 6 shows comparison of production system simulator requesting for bottom-hole pressure calculation for all wells during the integrated simulation.

Table 6. Production system simulator requesting for bottom-hole pressure calculation for all wells during the integrated simulation for Case 2

Approach	Calls	Points/Call	Total
1	20.188	1	20.188
2	12	2.268	27.216
3	1.552	2	3.104

5.4 Case 3 - UNISIM-I-D & UNISIM-II-D

Figures 10 to 13 show production curves for oil, water and liquid in whole field. Figure 13 shows water injection for the whole field.

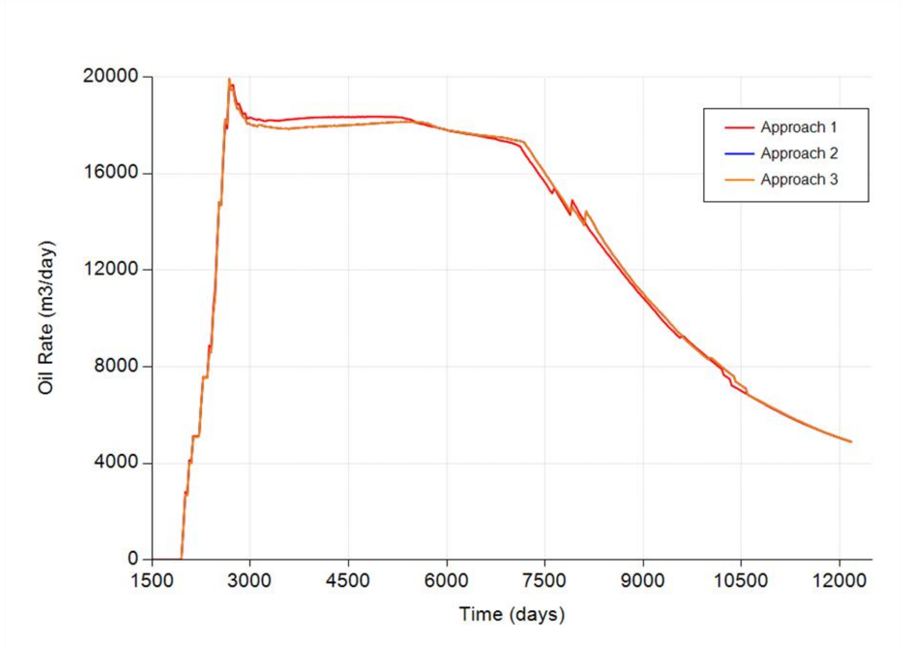

Figure 10. Oil production from field in whole field

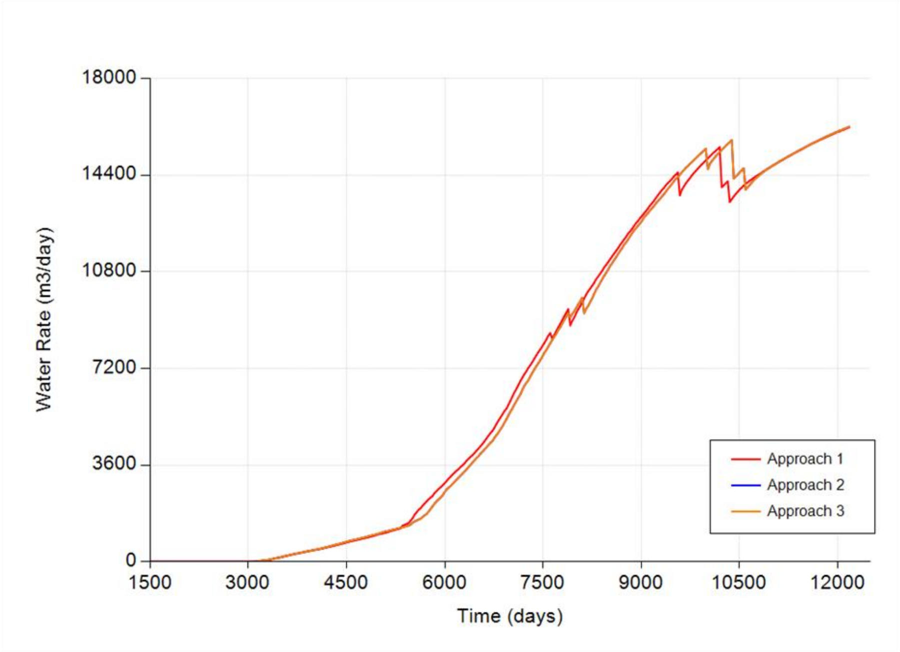

Figure 11. Water production from field in whole field

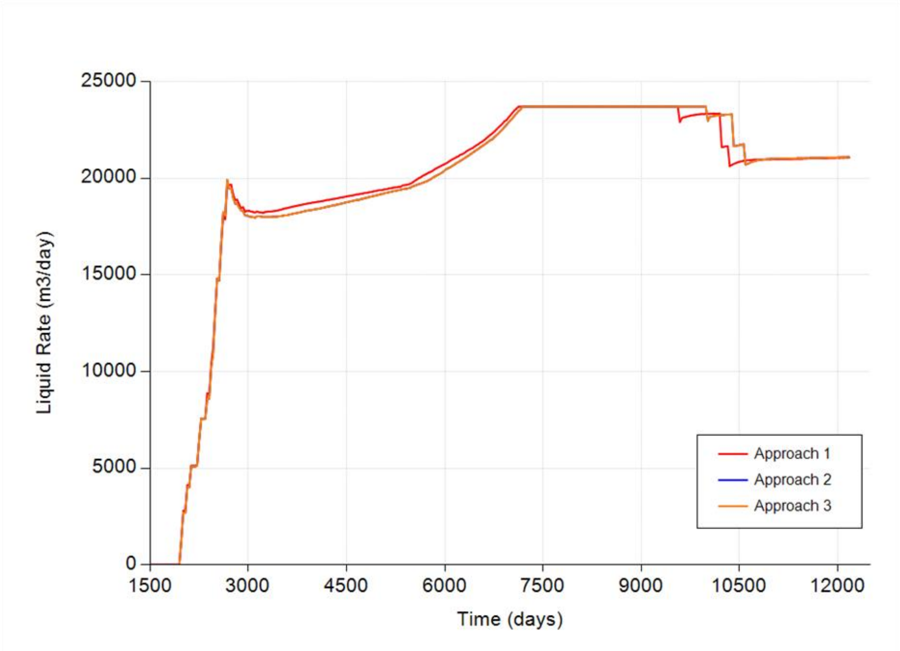

Figure 12. Liquid production from field in whole field

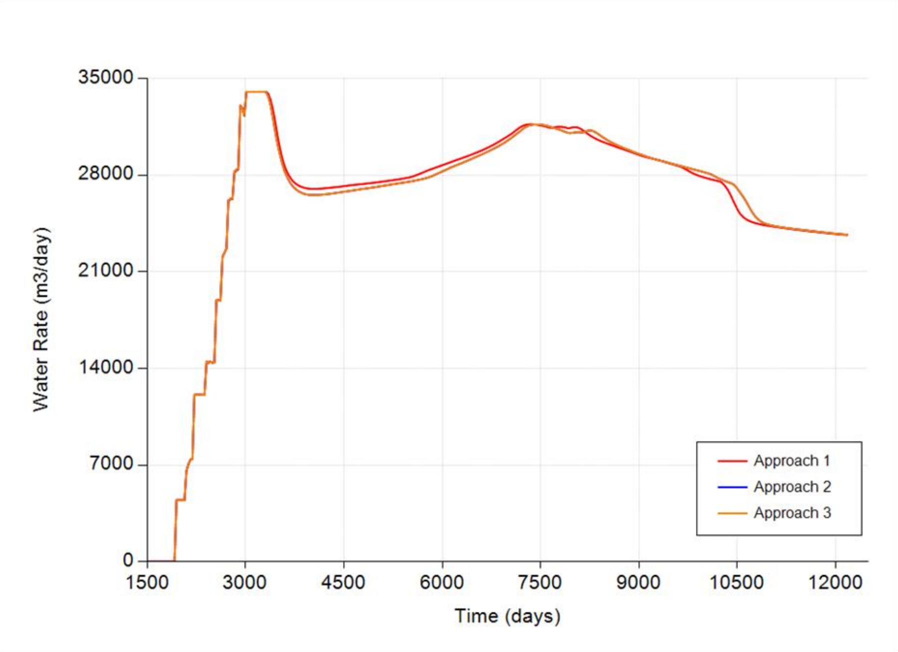

Figure 13. Water injection from field in whole field

Table 7 summarizes time consuming for integration approaches and their respective reservoir and production system models, and total of iterations (integrated time steps) demanded.

Table 7. Time consuming for integration approaches and their respective reservoir and production system models, and total of iterations demanded for Case 3

Approach	Total (s)	Reservoir (s)	Production System (s)	Iterations
1	4.734	1.314	3.224	531
2	1.537	1.315	170	522
3	1.556	1.315	189	522

Table 8 shows comparison of production system simulator requesting for bottom-hole pressure calculation for all wells during the integrated simulation.

Table 8. Production system simulator requesting for bottom-hole pressure calculation for all wells during the integrated simulation for Case 3

Approach	Calls	Points/Call	Total
1	35.942	1	35.942
2	19	2.268	43.092
3	2.174	2	4.348

6 Discussion

We obtained a proxy model for production system model yielding a more efficient integration with the reservoir. We compare results for a generic well after simulating a number of aleatory experiments. Piecewise regression model obtained a good quality for bottom-hole pressure. In terms of production forecast, all approaches had similar responses.

For the benchmark cases studied, Approach 1 demanded a computational time much larger compared to other approaches. There was a higher time consumption of production system simulator in relation to reservoir simulator.

Approaches 2 and 3 lower times compared to Approach1, with time reduced in 52% to 68% of the total time. As Approaches 2 and 3 obtained similar time and responses, previous generation of input dataset or VLP tables would not be necessary.

Time used in the production system simulator in Approaches 2 and 3 were lower than required by the reservoir simulator, indicating that the reuse of simulation results with piecewise proxy model gave considerable gains for the explicit integration.

7 Conclusions

Direct integration has a great computational time consuming, even using an efficient operation point algorithm in integrated simulation process.

It is possible to accelerate explicit integration between reservoir and production system simulators using a proxy model. A multidimensional piecewise regression represented adequately the bottom-hole pressure behavior, determined as the integration point for reservoir and production system.

Integration with proxy model obtained total time values close to those obtained with the use of VLP tables previously generated, showing an efficient way of efficient interaction between the reservoir and production system simulators for the explicit coupling approach.

It allows integrated without the need to run unnecessary values, as done in the generation of VLP tables.

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