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# Advancing Reservoir Simulation: Reservoir-Wellhead Coupling in an Innovative Simulator Based on a Plugin Architecture

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**Abstract.** This paper presents an implicit reservoir-wellhead coupling methodology using vertical lift performance (VLP) tables in the GSIM simulator, developed through a Petrobras-PUC-Rio R&D partnership. Addressing critical production system pressure drops affecting hydrocarbon recovery. It is a first step in implementing integrated reservoir-surface simulation. By extending GSIM's plugin architecture, the work focused on the residual and Jacobian matrix terms in Newtonian iterations, making use of Inflow Performance Relationships (IPR) and Tubing Performance Relationships (TPR) for nodal analysis. The methodology introduces multidimensional VLP table interpolation validated against CMG's IMEX simulator. Single-layer cases showed excellent agreement with IMEX, while multilayer configurations exhibited small transient discrepancies resolving over time, confirming GSIM's system replication capability. The implementation enables accurate wellhead specifications while preserving GSIM's plugin-based flexibility. This advancement provides a robust platform for integrated reservoir-to-surface modeling, enhancing production system simulation accuracy and demonstrating how explicit tubing pressure loss consideration improves forecasting reliability in field development.

**Keywords:** Reservoir Simulation, Well Coupling, Simulator Development, Numerical Methods

## 1 Introduction

In petroleum reservoir development, engineers are faced with the task of selecting an appropriate production system, which encompasses all equipment from the bottom of the wells to the processing plant, in order to optimize the hydrocarbon recovery. Onshore projects typically involve simpler logistics, with wells connected to nearby facilities, while offshore operations present greater complexity, requiring wells to be drilled offshore and linked to platforms or directly to onshore facilities via subsea connections. Due to varying pressure drops, this selection requires thorough modeling, simulation, and comparative analysis. The fundamental equation governing fluid flow in pipes, derived from conservation principles, accounts for friction, elevation, and acceleration, dictating pressure drop along the pipe. However, applying it in reservoir simulation is complicated by temperature-induced fluid property changes and different flow regimes within the wellbore and pipes, which differentially impact pressure predictions, so the industry relies greatly on multiphase flow correlations (Brill and Mukherjee [1]; Hasan and Kabir [2]).

Integrated simulation is paramount for effective forecasting and management of complex petroleum production systems, offering a comprehensive understanding of interactions among the reservoir, wellbore, and surface facilities (Wang [3]). Traditionally, segregated simulation methodologies often fail to capture essential couplings, thereby limiting the accuracy of predictions concerning reservoir deliverability and hydrocarbon recovery optimization (Bik Deli [4]). By coupling these simulations, not only can variations in production strategies be better accommodated (Breaux et al. [5]), but also collaboration among multidisciplinary experts is fostered, improving overall efficiency and predictive accuracy (Hiebert et al. [6]).

The coupling of the reservoir to the surface simulator is essential for specifying pressure and flow rates under surface conditions, requiring the assessment of pressure drops across the tubing string. This can be achieved implicitly by simultaneously solving flow equations for porous media and tubing flow (Schiozer [7]]), or explicitly through an integrated computational code, or by using pre-calculated vertical lift performance (VFP) tables. Nev-

ertheless, challenges persist, including the intricate modeling of flow interactions and the substantial computational demands of full-field integrated models, which may necessitate a more cautious approach to integration (Schiozer [7]).

The GERESIM Simulator (GSIM), a collaborative effort by Petrobras and PUC-Rio, is a versatile reservoir simulator leveraging the modular, plugin-based architecture of TopSim (Duarte [8]). Initially focused on a black-oil model (Bastos [9]) and benchmarked against CMG's IMEX [10], GSIM has since been enhanced by Wang [11] to include compositional reservoir modeling for volatile oil and EOR processes, validated against CMG's GEM [12]. While initially lacking reservoir and surface facilities coupling, GSIM represents an evolving and adaptable tool, characterized by its validated performance and capacity to accommodate diverse simulation scenarios.

The general objective of this work is the implementation of a reservoir and surface coupled representation in the black-oil version of a simulator with a plugin architecture. More specifically, to implicitly implement the use of VLP tables, as a first step in integrated simulation, in GSIM black-oil to allow the specification of wellhead conditions for single-completion and multi-completion wells and compare the results with the commercial simulator IMEX.

## 2 VLP table interpolation

A VLP table represents the pressure drops along the production system by informing the bottomhole pressure (BHP) for a given combination of input variables. For a well injector, the variables are water (or gas) rate and wellhead pressure (WHP), while for a producer they are oil (or liquid or gas) rate, gas-oil ratio (GOR), water cut (WCUT), artificial lift quantity (ALQ), e.g. lift gas rate (LGR) and WHP.

Bigdeli et al. [13] explored interpolation functions when implementing the use of VLP tables in a different simulator and comparing to CMG's results, concluding that linear interpolation for WHP yielded the best results, although discrepancies remained due to the multidimensional nature of both injector and producer VLP tables. Because of these inaccurate results when picking only one of the dimensions to interpolate the tables, it was considered, for this work, that bilinear interpolation for injector tables and multidimensional (five dimensions) linear interpolation for producers were the natural choice. Figure 1 shows an example of a bilinear interpolation and an expression for the interpolated BHP can be given as

$$\begin{aligned} BHP_{Q,WHP} =& (1-W_Q)(1-W_{WHP})BHP_{1,1} + (1-W_Q)W_{WHP}BHP_{1,2} + W_Q(1-W_{WHP})BHP_{2,1} + \\ & W_Q W_{WHP} BHP_{2,2}, \end{aligned} \tag{1}$$

where $Q$ is the rate, $W_Q = (Q - Q_1)/(Q_2 - Q_1)$ and $W_{WHP} = (WHP - WHP_1)/(WHP_2 - WHP_1)$. Equation (1) computes the interpolation as a weighted combination of four corner values surrounding the desired point. This method allows for efficient computation and expansion, as it relies on reading $2^d$ BHP values from the VLP table and calculating $d$ dimension weights, where $d$ is the number of input variables. The producer table interpolation, with five input variables, leads to 32 surrounding values being read from the table and weighted.

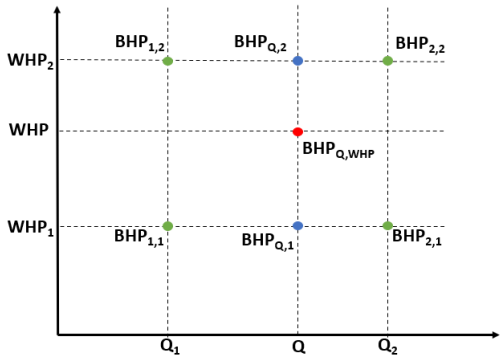



Figure 1. Example of a bilinear interpolation

The proposed interpolation functions were validated through a simulation case study involving a 5-spot configuration, as illustrated in Fig. 2, where a producer well was centrally located and surrounded by water and gas

injectors, so that water cut and gas-oil ratio would significantly vary along the simulation, impacting the pressure drops. Using VLP tables generated in PETEX's Prosper software [14] , the IMEX simulation results were compared against the interpolated BHP values obtained herein, using bilinear and multidimensional linear interpolation functions.

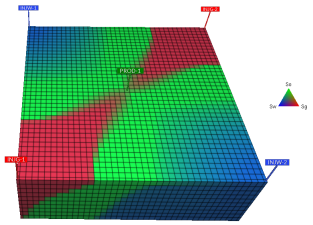


Figure 2. IMEX 3D model view with oil, water and gas saturations at the end of simulation. Center green well is the producer, while the blue wells are the water injectors and the red ones are the gas injectors

Table 1 shows the comparison between the IMEX's simulation results for the producer, with the simulation parameters in the first seven columns and the proposed multidimensional linear interpolation in the last column. The results indicated that the proposed method performed well, producing BHP values that closely matched those from IMEX. Although further testing may be conducted in the future, the current techniques were deemed sufficient for integration into GSIM's VLP table lookup functionality.

Table 1. Producer VLP interpolation

| Time | $Q_o$ | GOR | WCUT | LGR | WHP | BHP | Our results |
|---|---|---|---|---|---|---|---|
| $days$ | $m^3/d$ | $sm^3/sm^3$ | % | $m^3/d$ | $kPa$ | $kPa$ | $kPa$ |
| 5 | 947.4 | 84.4 | 0.05 | 75000 | 1200 | 15370.2 | 15370.17 |
| 481 | 596.5 | 378.7 | 12.12 | 75000 | 1200 | 14700.3 | 14700.29 |
| 640 | 337.6 | 632.6 | 48.07 | 75000 | 1200 | 15954.2 | 15954.18 |

## 3 Newton's method implementation

To implicitly implement reservoir coupling with the wellhead, adaptations to the solution of nonlinear reservoir equations are required in GSIM, which employs finite differences for discretizing nonlinear partial differential equations and Newton's method for linearization, i.e.

$$\mathbf{J}\delta\mathbf{X} = -\mathbf{R}, \tag{2}$$

where **R** is the vector of residuals, **X** is a vector that contains increments of primary variables, and **J** is the Jacobian matrix. In this context, the source and sink terms, representing wells, influenced by well specification are incorporated into the residual vector, with their derivatives represented in the Jacobian matrix. Given that the focus of this work is on implementing wellhead pressure specifications using VLP tables, new methodologies and updates to specific plugins are required for computing both the residual and derivative terms of grid cells containing well completions. It is important to note that both accumulation and flux terms, that are also a part of reservoir equations, are not impacted by this approach. The source and sink term of a completion $k$ from a producer well, for the oil phase, can be written as

$$Q_{o,k} = -J_{o,k}(P_{o,k} - P_{wf,ref} - \gamma_m \Delta Z_k), \tag{3}$$

where $Q_{o,k}$ is the completion's oil rate, $J_{o,k}$ is the oil productivity index of completion $k$, $P_{o,k}$ is the completion's cell oil pressure, $P_{wf,ref}$ is the reference layer´s bottomhole pressure, $\gamma_m$ is the mean well hydrostatic gradient,

and $\Delta Z_k$ is the height difference between the completion $k$ and the reference layer. Similar equations represent the water and gas rates for both producers and injectors.

The use of nodal analysis is necessary and in order for it to work, for a given reference depth, a well inflow pressure relationship (IPR) must be calculated and an intersection point with the tubing pressure relationship (TPR), that is represented by the VLP table, must be found. In the generic case of a multilayer producer well, the IPR equation for the oil phase can be expressed as (Ertekin et al. [15])

$$P_{wf} = \frac{Q_o^{well}}{J_o^{well}} + \overline{P_o}, \tag{4}$$

where $P_{wf}$ is the bottomhole pressure of the well, $Q_o^{well}$ is the oil well rate, $J_o^{well}$ is the oil well productivity index, represented by the sum of the oil productivity indexes of all completions, and

$$\overline{P_o} = \frac{\sum_{k=1}^{n} J_{o,k}(P_{o,k} - \gamma_m \Delta Z_k)}{\sum_{k=1}^{n} J_{o,k}}. \tag{5}$$

Having defined the table interpolation method and the IPR calculation, the following algorithm was implemented to define the well operating point, as shown in Fig. 3: Identify the type of well; in the case of a producer well, estimate the gas and water fractions based on the phases productivity indexes at the beginning of the Newton's iteration, and, if assigned, get the value of lift gas rate; WHP is given by the specification of the well; the correct phase IPR is selected corresponding to the phase rate informed in the VLP table and iterates sequentially through all the tabulated rate values, calculating the available pressure, using the IPR, and the required pressure, interpolating the VLP table, for each rate.

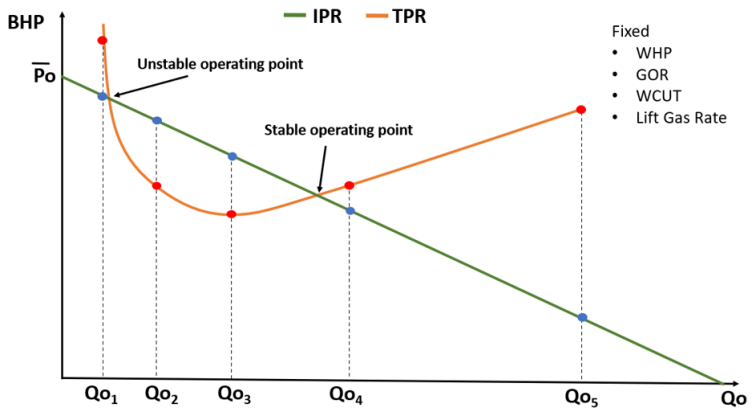



Figure 3. Example of a nodal analysis implemented in GSIM for a producer. $Q_o$ represents the well oil rate.

This procedure enables the comparison of available and required pressures for each rate, facilitating two key objectives: identifying the rate ranges where the Inflow Performance Relationship (IPR) and Tubing Performance Relationship (TPR) intersect, and determining the stability of the intersection point. By assuming linear behavior for the TPR between sequential rates and fixing all other inputs, the exact intersection point can be found by solving the linear equations of the IPR and TPR. With the bottomhole pressure (BHP) at the intersected reference layer established, the BHP for all completions can be calculated using the well's gradient, allowing computation of all completions rates.

Let $R_k$ represent the reservoir primary variables of completion $k$, which in GSIM black-oil are $P_{o,k}$ (oil pressure), $S_{w,k}$ (water saturation), and $P_{b,k}$ (bubble pressure) or $S_{o,k}$ (oil saturation). No additional well primary variable was added for implementing the wellhead pressure specification. The derivatives of eq. (3) with respect to $R_k$ need to be computed and are an important part of the Jacobian matrix. While different approaches in calculating them are possible, the numerical one is presented here:

$$\frac{\partial Q_{o,k}}{\partial R_k} \approx \frac{Q_{o,k}(R_k + \epsilon) - Q_{o,k}(R_k)}{\epsilon}, \tag{6}$$

with $\epsilon$ being a small perturbation to the primary variable $R_k$. The terms $J_{o,k}(R_k+\epsilon)$, $P_{o,k}(R_k+\epsilon)$ and $\gamma_m(R_k+\epsilon)$ are straightforward because they depend only on perturbations of pressure, relative permeability and fluid properties. The term $P_{wf,ref}(R_k+\epsilon)$ requires a new nodal analysis since the perturbation leads to a new IPR and hence a new intersection with the VLP table.

## 4 Case study

In order to assess and validate every stage of the proposed GSIM reservoir–wellhead coupling implementation, both a single-layer model and a multilayer model were developed, as shown in Fig. 4. The models were initialized with a typical black-oil fluid with no contacts present, with a solution gas-oil ratio of around $84\,sm^3/sm^3$ and a viscosity close to $1.7 \times 10^{-3}\,Pa.s$. A configuration of two diagonally opposed producer and water injector vertical wells was used with all layers perforated. Table 2 presents the dimensions and physical properties of each grid and for relative permeability, Corey correlations were used with the following parameters: Irreducible water saturation ($S_{wi}$) 0.2; Residual oil saturation ($S_{or}$) 0.3; Oil relative permeability @$S_{wi}$ 0.8; Water relative permeability @$S_{or}$ 0.3; Residual oil in gas saturation ($S_{org}$) 0.1; Gas relative permeability @($S_{wi} + S_{org}$) 0.9, and Corey exponents 2.0.

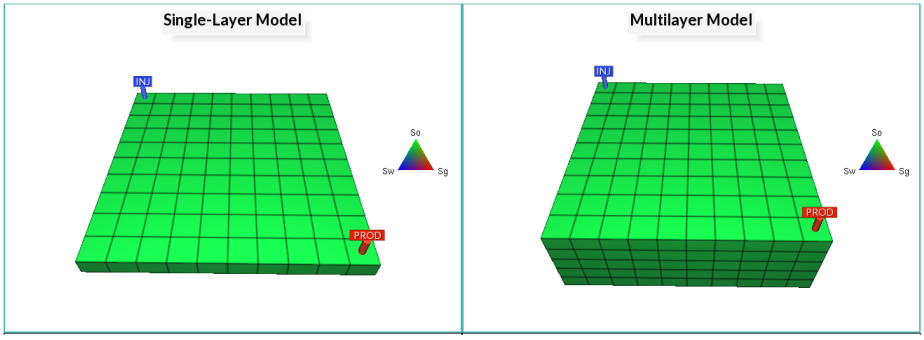



Figure 4. 2D and 3D models with initial fluid.

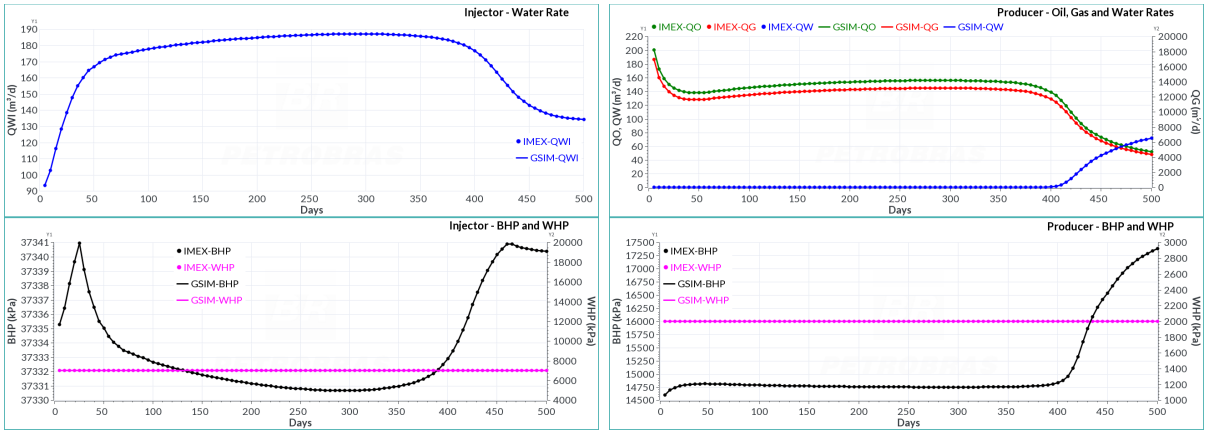
Table 2. Grid dimensions and physical properties

| Parameter | Values |
|---|---|
| Number of grid cells in x, y and z | $10 \times 10 \times 1$ ($10 \times 10 \times 5$, for multilayer) |
| Grid cell length in x and y ($m$) | $50 \times 50$ |
| Grid cell thickness ($m$) | 10 |
| Grid top ($m$) | 3000 |
| Porosity | 0.1 |
| Permeability ($m^2$) | $9.87 \times 10^{-14}$ |
| Rock compressibility ($kPa^{-1}$) | $5.1 \times 10^{-7}$ |
| Initial reservoir pressure at $3005\,m$ ($kPa$) | 30000 |
| Bubble Pressure ($kPa$) | 13000 |

In this scenario, the production system comprises offshore wells in $1000\,m$ of sea depth and vertical wells with $2005\,m$ tubing. For simplicity, the surface facility is assumed to lie directly above each well, resulting in $1000\,m$ vertical risers connecting each well to the plant. The producer was specified with a wellhead pressure of $2000\,kPa$ and operated with artificial lift via a constant lift gas rate of $50000\,m^3/d$. The injector well was set to a wellhead pressure of $7000\,kPa$, mirroring typical field operations in which well boundary conditions can be governed solely by surface limitations, such as water injection pump pressure and separator pressure. The VLP tables for both wells were generated in PETEX's Prosper software with Petroleum Experts 5 correlation.

Figure 5 demonstrates a strong agreement between IMEX and GSIM for single-layer producer and injector wells. Incorporating WHP specification into GSIM clearly shows its advantages when examining the dynamic

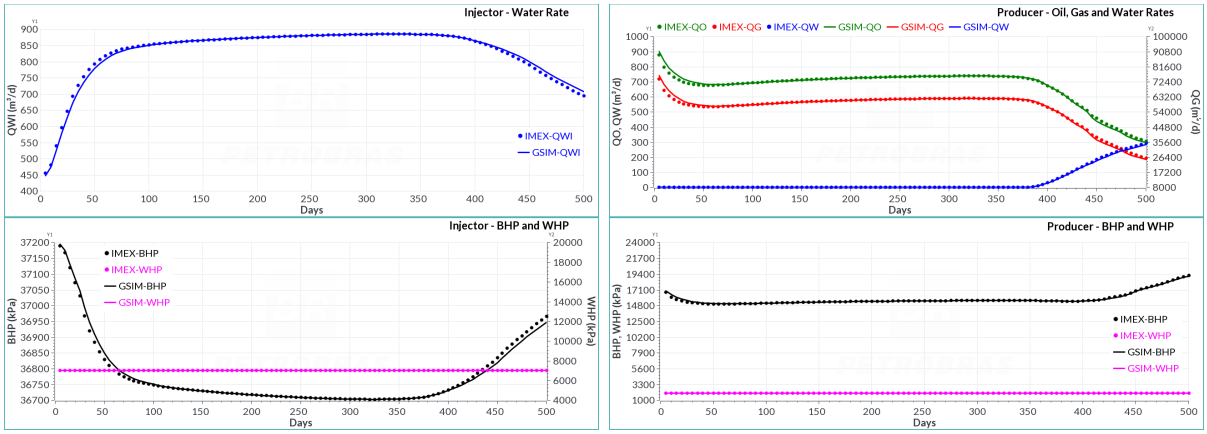
behavior of bottomhole pressure and well rates throughout the simulation. Under a fixed wellhead pressure, BHP and all flow rates fluctuate continuously, which other well specification methods cannot capture. GSIM accurately reproduced both the initial transient response and the water breakthrough observed in IMEX for each well.




(a) Injector (b) Producer

Figure 5. Single-layer simulation. On the left, the injector well with water rate - $QWI$ (top) and $BHP$ and $WHP$ (bottom). On the right, the producer well with oil, gas and water rates - $QO$, $QW$ and $QG$ (top) and $BHP$ and $WHP$ (bottom).

The results from the multilayer wells simulation can be seen in Fig. 6. GSIM was able to capture again the overall behavior of both the injector and the producer, with results closely aligned with those of IMEX, though minor discrepancies were observed. The small differences seem to happen during the initial transient and when injected water breaks through to the production and possible reasons include different number of Newton iterations for convergence in some time steps, different calculation methods between the simulators and different representation of wells, leading to slightly different productivity and injectivity indexes relating directly to perforated cells domain and short-term prediction.




(a) Injector (b) Producer

Figure 6. Multilayer simulation. On the left, the injector well with water rate - $QWI$ (top) and $BHP$ and $WHP$ (bottom). On the right, the producer well with oil, gas and water rates - $QO$, $QW$ and $QG$ (top) and $BHP$ and $WHP$ (bottom).

To calculate the numerical derivatives, the perturbation $\epsilon$ of $10^{-4}\,Pa$ was applied to the primary pressure variables, and $10^{-4}$ was used for the saturation variables. Reducing the perturbation size did not improve the results, while increasing it led to greater deviations from the IMEX response. Perturbation values significantly smaller than $10^{-4}$ caused convergence issues during simulation.

## 5 Conclusions

This study developed and validated a reservoir-wellhead coupling approach in GSIM that uses vertical lift performance (VLP) tables to specify wellhead pressure (WHP) and thus capture surface boundary conditions. By incorporating both reservoir behavior and production system pressure drops, the simulator's predictive power was enhanced. Bilinear interpolation schemes for injector tables and multidimensional linear for producer tables reproduced IMEX results accurately. Single-layer wells under WHP specification, whether water injectors, gas injectors, or producers, showed excellent agreement with IMEX, validating both the interpolation functions and the nodal analysis with numerical calculations of the Jacobian terms. Multilayer wells exhibited short-term differences during transients or fluid breakthroughs, but GSIM still reproduced the overall IMEX behavior.

Although a homogeneous and compact reservoir model with only two wells was used in the case study, the coupling implementation was considered successful. A large-scale simulation might provide additional insights into GSIM's stability and convergence, aspects not fully captured in this study. To focus on specifying wellhead pressure and eliminate any initial discrepancies between GSIM and IMEX, a simplification was made by using constant values for the wellbore fluid gradients. Extrapolation of the VLP table was also avoided, because IMEX calculations were not explicit.

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