Application of Sequential Explicit Coupling of Reservoir, Well, and Surface Facilities for 3D Compositional Simulation Models

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Abstract. The assessment of hydrocarbon production systems requires the utilization of a simulator with the capability of handling different scenarios, such as the simulation of fluid flow in porous media and also in pipelines, at steady-state and unsteady-state conditions. Recently, there have been efforts in the development of reliable simulators, which are capable of accurately modeling surface and subsurface environments simultaneously through the usage of flow tables. In this paper, first, we discuss the importance of nodal analysis and different wellbore boundary conditions. Based on the foregoing, we introduce a new approach for our in-house simulator UTCOMPRS. The new approach further extends the previously developed flow table algorithms for 3D reservoir models. We also compare the results of two case studies with a commercial compositional simulator. The operational parameters, such as bottom hole pressure, injection pressure, oil, gas, and water rates, among others, are in good agreement with both UTCOMPRS and the commercial simulator. Herein, we also show the importance of controlling well constraints. The results showed that the developed framework was successfully implemented and validated for 3D reservoirs. It enables the simulator to handle more realistic conditions, advancing its flexibility and providing an infrastructure for the coupling of the reservoir, well, and surface facilities.

Keywords: Surface Facility; Coupling of the reservoir, wells, and surface facilities; 3D Compositional reservoir simulation; Flow tables.

1 Introduction

By increasing global energy demand, conventional hydrocarbon resources are still the main source of energy. In reality, the continuing production of hydrocarbon resources is extremely dependent on the value of the recovery factor and technology development.

The recovery factor of oil and gas is a measure of hydrocarbon reservoir productivity. In general, there are three techniques for estimating the recovery factor: 1) field analogs, 2) analytical models (displacement calculation or material balance), and 3) reservoir simulation. The development of integrated models for simulating both sub-surface and surface conditions is a challenging task. However, an accurate forecast of the profitability of the project highly depends on the simulation packages that enable the coupling of the reservoir, wells, and surface facility equipment.

Previously, we had reported a general framework (Bigdeli *et al.* [1], Bigdeli *et al.* [2]) for coupling reservoir, well, and surface facility equipment for the 2D reservoirs. As the main objective of this paper, we are reporting an extension of the previously developed algorithms for 3D reservoirs.

2 Importance of nodal analysis

Petroleum Production Systems (or PPS) are referred to the systems that consist of the reservoir, wells, and surface facility equipment. According to the nodal analysis of PPS, each section of the PPS model can be treated as a node of pressure and flow rate. Hence, the coupling point refers to the point in which the total PPS is divided into two sub-systems for analysis of the inflow and outflow performance of hydrocarbon fluids. Nodal analysis can be done at any location of the integrated model, but generally, there are three preferred locations for coupling point [3]: a) bottom hole, b) wellhead, and c) riser based (for offshore systems). Figure 1 shows a general schematic of the main idea that exists behind the nodal analysis of PPS.

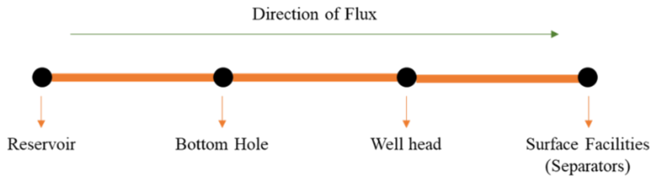

Figure 1. Example of analysis flow in the network for PPS

According to the logic presented above, the fluid flow begins from the node which has the highest potential. For PPS, the driving force is pressure. Thus, the direction of fluid flow is from the reservoir through the bottom of producing wells, and it reaches the surface by the wellhead. Once the fluids get out of the wellhead, they are transferred into the separation facilities. Figure 2 shows five nodal points, which are described as follow: 1) reservoir pressure, 2) bottom hole pressure, 3) wellhead pressure, 4) downstream pressure, and 5) separator pressure.

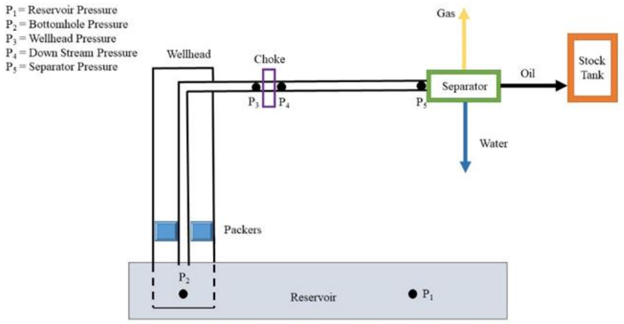

Figure 2. A PPS that works with a choke, flowline, and a separator

The choke valve is a mechanical device that can control the rate of production fluids on the surface. However, one can also neglect the choke device if the separator is capable of receiving all of the production fluid. In this way, the wellhead is connected to the separator directly, and therefore wellhead and separator pressures are interacting correspondingly. Bigdeli *et al.* (2019) [1] reported an example of such an integrated model without considering the choke valve. For the same integrated model, different types of fluids (3 and 6 components) showed different behaviors for the pressures of the wellhead and separator.

The last and simplest type of surface facility consideration is without the surface pipeline and choke valves. In this case, all of the produced fluids enter the separator units immediately from the wellhead. Figure 3 shows a system that does not consider the flow line and choke valves.

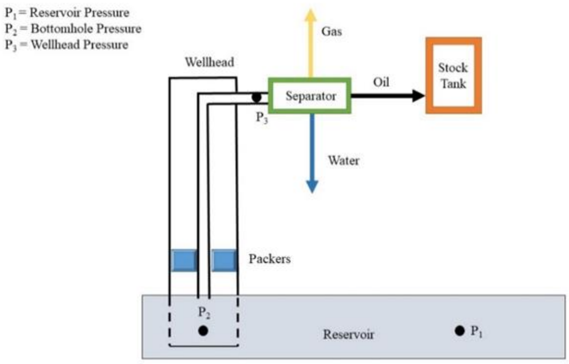

Figure 3. Example of PPS that is connected to separator directly

As it can be seen from Fig. 3, point 3, which is the wellhead pressure, is equal to the inlet pressure of the separator. Regarding this notation, Brill and Mukherjee [4] noted two important assumptions:

1) In the absence of the flow line, the pressure of the separator can be equal to the wellhead pressure.
2) The separator or wellhead pressures are normally known and can be used as input values for determining the unknown pressures.

The above two assumptions are very important. We will use these two assumptions throughout the course of this paper. Herein, although it was tried to cover the concept of nodal analysis, this topic is very immense, and there are many technical difficulties associated with it. A reliable nodal analysis description is an essential step for accurate modeling of the integrated models.

3 Different wellbore boundary conditions

Wellbore and the method of its treatment, whether to consider the wellbore as a part of the surface or as an element of sub-surface facilities, is a practical issue that has been discussed vastly in the literature. The main reason for that is because the location of the bottom hole pressure and wellhead pressure is fixed. Thus, from one perspective, they can be considered as a boundary condition of each system. Reported by Barroux *et al.* [5], the integration procedure, the coupling location, the nature of the algorithm (explicit or implicit), and the type of fixed boundary conditions for exchanging information between the programs are some issues that are related to the type of coupling. Figure 4 shows a coupling configuration where the coupling is at the wellhead (left) and bottom hole (right) levels.

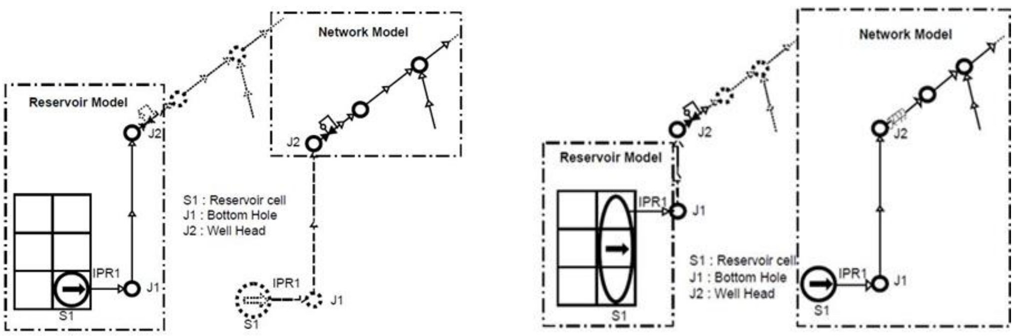

Figure 4. Coupling configuration where the coupling point is at the wellhead (left) and bottom hole (right) level. From [5].

As it can be seen, for coupling at the wellhead level, the first section of the network is starting from the node where the wellhead is located (J2). For such a system, the convergence of the integrated model is checked in terms of wellhead pressure. The second type of coupling configuration is at the bottom hole level (J1). As it can be seen from Fig. 4, the reservoir model is only considered up to the bottom hole pressure node and the network model considers the reservoir as single boundary cell. These details are very important for the mathematical formulation of the integrated model. More coupling configurations can be found in Barroux *et al*. [5].

Based on what has been described in the above, the wellbore boundary condition should be defined precisely. Figure 5. shows two boundary conditions for tubing [6].

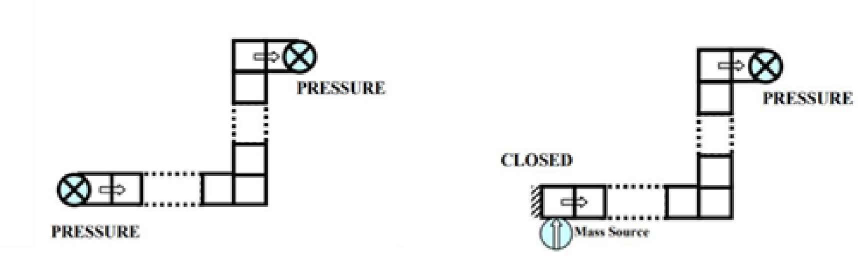

Figure 5. Different wellbore boundary conditions. From [6].

In both situations, at the top of the tubing, the wellhead is considered as a node of pressure. But the difference is at the bottom hole condition. In the first case, the boundary condition of the bottom hole is treated as a node of pressure. In the second, the bottom hole is considered as a node of mass source. This means that the mass that comes from the reservoir has to enter into the bottom hole, due to the continuity equation. For the horizontal well, the same methodology can be used with some extension of external nodes. However, this type of well is not considered in this work.

4 Algorithm for 3D reservoir models

Previously we have described the algorithm of the flow tables for 2D reservoirs. Figure 6 shows 2D and 3D reservoirs that are assigned with the flow table option.

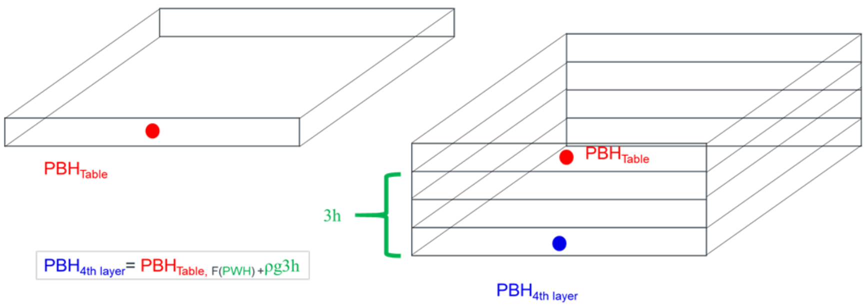

Figure 6. Example of 2D and 3D reservoirs and how the 2D calculation can be extended for 3D models.

For the 2D reservoir, the bottom hole pressure (BHP) is obtained from the flow table directly. But, for 3D reservoirs, an additional consideration is required. For a given reservoir, with four layers for example, the first layer is assigned with the value that comes from the flow table, but for the other layers, the hydrostatic pressure should be added to the BHP of the first layer as we presented in Fig. 6 using red and blue notations.

5 Case studies

We used two cases with different gas injection rates in order to investigate the behavior of the flow table option for 3D reservoirs. The gas injection rates selected as the comparison parameter were 1,000 and 5,000 SCF/day. The objective here is to evaluate the BHP calculated with the flow table in these two different scenarios and compare them to results obtained from a commercial compositional simulator.

Table 1. Reservoir and fluid properties

Properties	Value
Number of grid blocks in x,y,z direction	16x16x5
Size of grid blocks in x,y,z direction	30.48x30.48x24.38 m (100x100x100 ft)
Porosity	0.35
Permeability in x, y, z directions	10x10x10 md
Initial reservoir pressure	10342.13 KPa (1500 psi)
Components	"C1","C3","C6","C10","NC15","C20
Initial concentration	0.5, 0.03, 0.07, 0.2, 0.15, 0.05
Injection fluid concentration	0.77, 0.2, 0.01, 0.01, 0.005, 0.005
Type of producing well	CFT
Injection rate	Constant Rate, gas injection
AWCO for injector and limited pressure	activated, 11721.09 KPa (1700 psi)
Operating wellhead pressure	4136.85 and 8273.70 KPa (600 and 1200 psi)
Coupling point	bottom hole
LFG	0.0 (no lift gas condition)
Simulation run time	2000 days

Figure 7. shows the shape of the reservoir in this study.

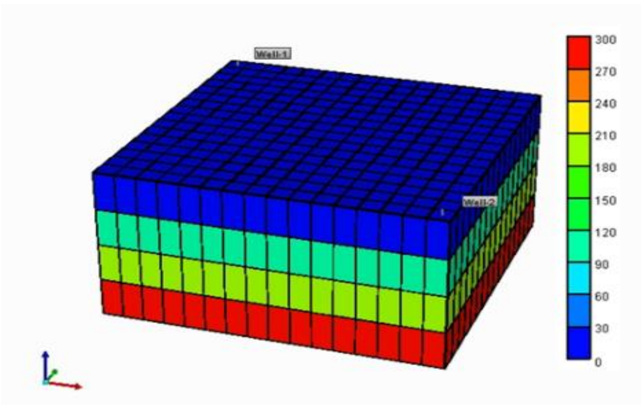

Figure 7. 3D reservoir model.

Figures 8 and 9 show the oil and gas production rates for high (5,000 SCF/day) and low (1,000 SCF/day) gas injection rates. As it can be seen, during the low injection rate scenario, in both oil and gas production profiles, there appears an oscillation at 763 days in the UTCOMPRS' results. This oscillation is due to the change of the location of the interpolated BHP in the flow table.

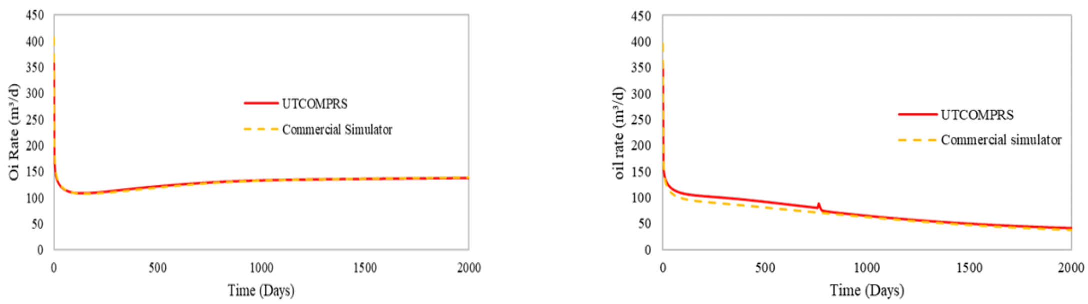

Figure 8. Oil production for high (left) and low (right) gas injection rate.

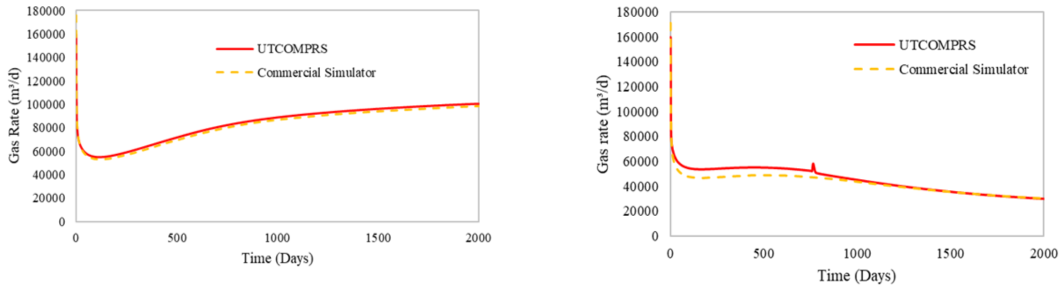

Figure 9. Gas production for high (left) and low (right) gas injection rate

Figure 10. shows the BHP for high and low gas injection rates.

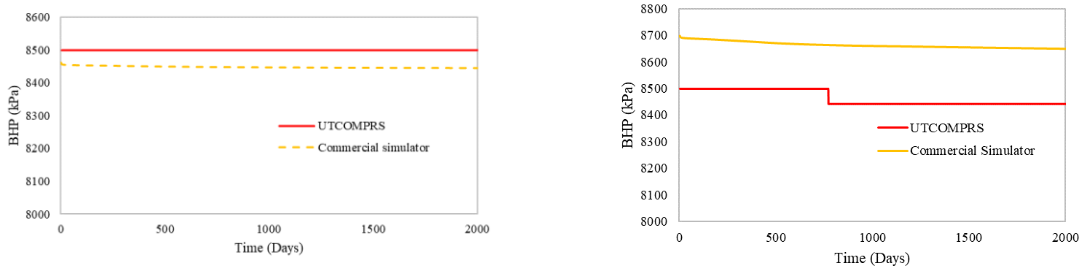

Figure 10. Interpolated PBHs for high (left) and low (right) gas injection rates

From Fig. 10, the obtained BHP values of the UTCOMPRS simulator for the higher injection rate scenario are very similar to the commercial simulator, and the largest difference between the results of the two simulations is 42.74 KPa (6 psi). For the low gas injection rate, a higher difference between the simulations is verified, 206.84 KPa (30 psi). This is due to the different injector pressures, 337.84 KPa (49 psi). The notable outcome of this study is the activation of the injector limit, which is shown in Fig. 11. As it can be seen, in the lower injection rate, the injector constraint is not activated. For the low gas injection rate, the BHP changes at 763 days, and this is the reason for the oscillation in the oil and gas production curve. Also, for the pressure of the injector, in the lower injection rate, once the value of BHP is shifted to the lower section of the table, the injector responded to this change. This information shows that for the implementation of the flow tables in UTCOMPRS, the injector plays a significant role.

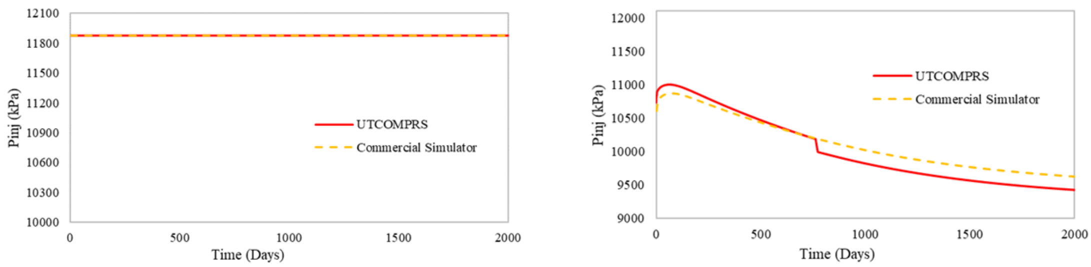

Figure 11. Pressure of the injector for high (left) and low (right) injection gas rates.

Figure 12 shows the gas-oil ratio (GOR) for these case studies.

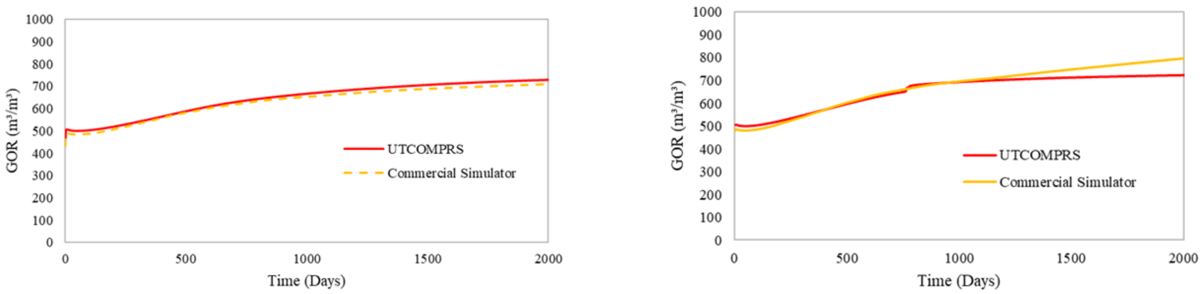

Figure 12. GOR profiles for high (left) and low (right) gas injection scenarios.

Similar to the other curves, GOR has differences between the commercial and UTCOMPRS simulators. Also, the change in the bottom hole pressure in the table is affecting the GOR at 763 days.

6 Conclusions

This paper presents a successful extension of flow tables for 3D reservoirs, which are coupled with well and surface facilities in a sequential explicit manner. Here, the importance of nodal analysis and different wellbore boundary conditions are highlighted for the accurate coupling. The two case studies, for low and high injection gas rates, were presented and the results showed that the degree of accuracy of the developed framework for 3D reservoirs is highly dependent on the activation of the maximum pressure constraint for the injector. The operational parameters, such as bottom hole pressure, pressure of injection, oil, gas, and water rates, among others, are in good agreement between UTCOMPRS and the commercial simulator. The change in the bottom hole pressure had also a great impact on the production profiles.

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