DEVELOPMENT OF DYNAMIC FULLY INTEGRATED WELL-RESERVOIR MODELS FOR SIMULATION OF OIL RECOVERY THROUGH ADVANCED WELLS

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KEYWORDS

advanced wells, well-reservoir coupling, FCD, AICD

ABSTRACT

Oil recovery can be enhanced by maximizing the well-reservoir contact using advanced wells. The successful design of such wells requires an appropriate integrated dynamic model of the oil field, well, and production network. In this study, the model of advanced wells developed in the dynamic multiphase flow simulator OLGA® is linked to a reservoir model to develop transient fully-coupled well-reservoir models for the simulation of oil recovery through advanced wells. The obtained results from the developed models in OLGA are compared with the results from the widely used MultiSegment Well (MSW) model. Flow Control Devices (FCDs) are the key component of advanced wells and the functionality of the main types of FCDs is investigated. According to the obtained results, by employing advanced wells with an appropriate completion design, the production of unwanted fluids (water and/or gas) can be highly reduced while the oil recovery is slightly increased compared to using conventional wells. Besides, by comparing the performance of the OLGA and MSW models, it can be concluded that OLGA is a robust tool for conducting an accurate simulation of oil recovery through advanced wells. However, running such simulations with OLGA is relatively slow and may face convergence problems.

INTRODUCTION

The application of advanced wells to increase the profitability of oil recovery is getting popularity today. The term *advanced* in this context refers to horizontal wells equipped with various technologies such as downhole Flow Control Devices (FCDs), Sand Control Screens (SCSs), and Annular Flow Isolation (AFI) as schmatically is illustrated in Figure 1. Advanced wells improve oil recovery both by delaying water and/or gas coning and by reactively (or actively) choking the unwanted fluids back. This is a transient process and the simulation model must be able to capture the transient interaction between the reservoir and well during this process. As a result, for accurate simulation of oil recovery through advanced wells, a dynamic fully-coupled well-reservoir model is required.

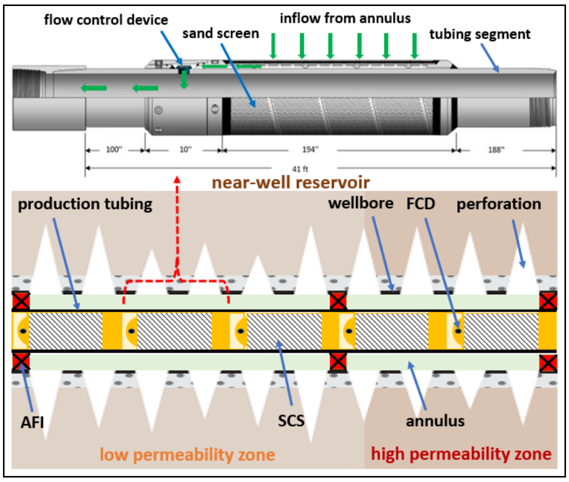

Figure 1: Schematic of Advanced Well Completion (Tendeka 2017; Moradi et al. 2023)

There are two approaches for developing a model for advanced wells using commercial simulators. The first approach which has been used in several papers is using the MultiSegment Well (MSW) model. This model is based on homogeneous models and it is used in the majority of simulators like ECLIPSE®, NETOOL®, etc. In the homogeneous models, it is assumed that the fluid properties can be represented by mixture properties, and single-phase flow techniques can be applied to the mixture. These models can also allow slip between the phases and are called drift-flux models (Shi et al. 2005).
The other approach is using a dynamic multiphase flow simulator like OLGA® or LEDAFLOW® to develop a model for advanced wells based on mechanistic models. This approach has been proposed by Aakre in (Aakre 2017) and improved by Moradi and Moldestad in (Moradi and Moldestad 2021). Mechanistic models are more accurate than homogenous models because they introduce models based on the detailed physics of each of the different flow patterns (Shi et al. 2005).
So far a few studies have been performed for the simulation of oil recovery through advanced wells using dynamic multiphase flow simulators and comparing the results with the MSW model. This study aims to develop appropriate dynamic well-reservoir models for predicting the long-term performance of advanced wells in oil recovery by using both OLGA and the MSW model and comparing the functionality of these models

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in terms of speed, stability, and accuracy. The developed well models by OLGA and MSW are coupled to the PUNQ-S3 reservoir model. The simulations are conducted for horizontal wells with no completion (OPENHOLE) as well as advanced wells with passive Inflow Control Device (ICD), and Autonomous Inflow Control Device (AICD) completions as well as AFI.

PUNQ-S3 RESERVOIR MODEL

PUNQ-S3 (Production forecasting with UNcertainty Quantification, variant 3) is a synthetic reservoir model that has been built based on a reservoir engineering study on a real field performed by Elf Exploration Production. The model contains 19×28×5 grid blocks (2660 grid blocks), of which 1761 blocks are active. The grid blocks in the *x* and *y* directions have an equal size of 180 m (Petroleum Reservoir Engineering Simulation Models 2023). The reservoir has a dome shape with a maximum thickness of 30 m where initially there is a saturated oil rim with a gas cap at the center of the model, and an active aquifer on the north and west as shown in Figure 2. The reservoir is quite heterogeneous and consists of five layers with a top depth of 2430 m and a 1.5° dip angle, and it is bounded by a fault to the east and south. The reservoir is modeled using corner point geometry and the Carter-Tracey aquifer (Hutahaean 2017). The rock and fluid properties of the reservoir are given in Table 1 and the distribution of porosity and permeability is illustrated in Figure 3.

In this study, the oil recovery from the PUNQ-S3 reservoir is simulated for 10 years through a long advanced horizontal well with a length of 3240 m, a Bottom Hole pressure (BHP) of 220 bar, and a maximum liquid production rate of 2500 m^3/day. The reservoir pressure is maintained with an open-hole horizontal water injection well with a length of 1500 m, an injection rate of 1500 m^3/day, and a maximum pressure injection of 285 bars. The locations of the production and injection wells for delaying the water and gas breakthrough, and increasing oil recovery have chosen based on a trial and error process. Figure 4 depicts the location of the production and injection wells in the reservoir.

Table 1: Rock and Fluid Properties of PUNQ-S3 Model

Parameter	Value
Porosity	0.01 to 0.3, Mean = 0.14
Rock Compericibility	4.5e-4 1/bars
Horizontal Permeability	0.5 to 999, Mean = 269 mD
Vertical Permeability	0.2 to 498, Mean = 122 mD
Reference Depth	2355 m
Reference Pressure	234.5 bar
Reservoir Temperature	105 °C
Oil Viscosity @ res. con.	1.46 cP
Oil, Gas, Water Densities	912, 0.8266, 1000 kg/m^3
Water-Oil Contact	2395 m
Gas-Oil Contact	2355 m
Dissolved Gas-Oil Ratio	74 sm^3/sm^3

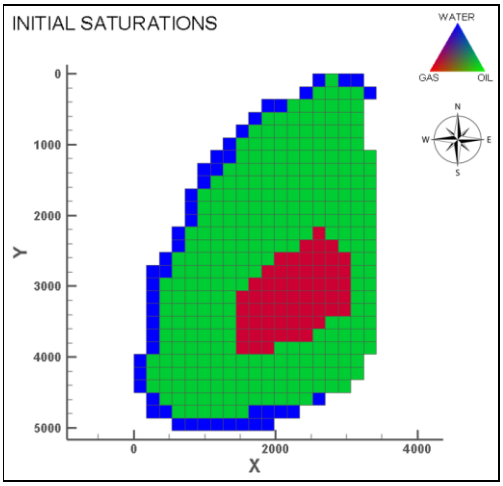

Figure 2: PUNQ-S3 Reservoir Model in the XY Plane

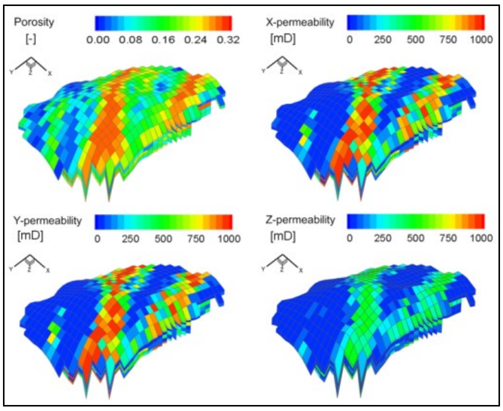

Figure 3: Porosity and Permeability Distributions

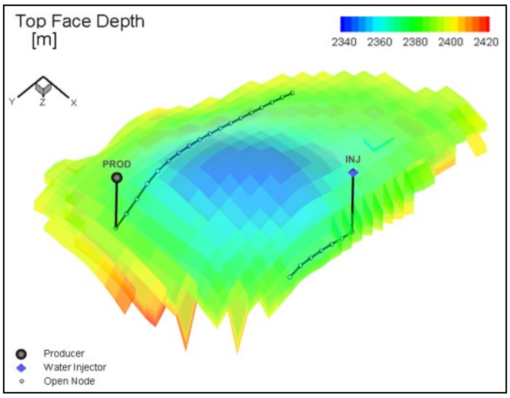

Figure 4: Topology of Production and Injection Wells

WELL MODEL DEVELOPMENT IN OLGA

In order to develop a model for the advanced production well in OLGA, the well is divided into 18 production zones, each 180 m long, and the annulus in each zone is isolated by two packers. As shown in Figure 1, each real production tubing segment is 41 ft or 12 m, and it is assumed that one FCD is mounted on each segment. As a result, the production tubing in each zone contains 15 real FCDs. However, it is assumed that in each zone, the production tubing has one equivalent segment with one equivalent FCD for 15 real segments. The simplified model for oil production from each zone in the OLGA simulator is illustrated in Figure 5. As shown in the figure, both wellbore and production tubing in each production zone is divided into two sections. The wellbore in the first section is connected to the dynamic reservoir model via the near-well source. The reservoir fluids enter the second section of the wellbore after passing through FCDs. Then the reservoir fluids enter the production tubing via a leak connected to the second section of the production tubing and in this way oil is produced from each zone.

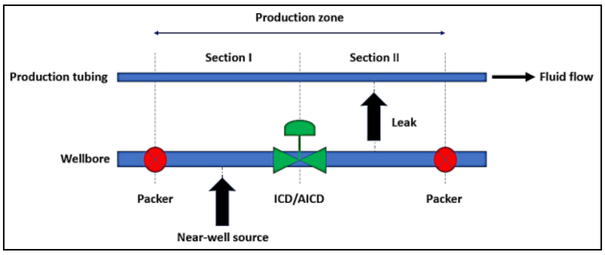

Figure 5: Simplified Model of an Advanced Well Segment in OLGA (Moradi and Moldestad 2022)

ICDs are mounted on the production tubing as a passive (fixed) flow to counteract the nonuniform inflow along the horizontal well. To model ICDs, an orifice valve is used. Therefore, the pressure drop across an ICD, ΔP_{ICD}, can be described by Equation (1), where A is the valve cross-sectional area, and C_D is the discharge coefficient. ρ_{mix} and $\dot{Q}_{ICD}$ are the density and flow rate of fluid mixture passing through ICD respectively.

$$\Delta P_{ICD} = \frac{\rho_{mix} \dot{Q}_{ICD}^2}{2A^2 C_D^2} \tag{1}$$

AICDs are classified as reactive FCDs and are able to choke low-viscosity fluids (compared to oil) back reactively and autonomously after breakthrough. These valves can partially be closed by increasing the water cut. In order to model AICDs, an orifice valve with an adjustable opening controlled by a control function describing the opening of the valve based on water cut is used. A mathematical model for describing pressure drop across an AICD can be derived based on available experimental data in (Halvorsen et al. 2016), presenting the performance of AICDs for fluids with similar properties as the reservoir fluids in the PUNQ-S3 model. Doing non-linear multi-variable linear regression on the experimental data, the mathematical model describing the pressure drop across an AICD, ΔP_{AICD}, can be described by Equations (2) and (3). In these equations, ρ_{mix}, μ_{mix}, and $\dot{Q}_{AICD}$ are the density, viscosity, and flow rate of fluid mixture passing through AICD respectively. α_{oil}, α_{water}, and α_{gas} are the volume fractions of oil, water, and gas in the mixture. The comparison of the derived mathematical model for AICD vs. the experimental data is shown in Figure 6.

$$\Delta P_{AICD} = 1.03 \times 10^{-5} \cdot \left(\frac{\rho_{mix}^2}{1000}\right) \cdot \left(\frac{1}{\mu_{mix}}\right)^{0.33} \cdot \dot{Q}_{AICD}^{3.05} \tag{2}$$

$$\begin{aligned} \rho_{mix} &= \alpha_{oil}\rho_{oil} + \alpha_{water}\rho_{water} + \alpha_{gas}\rho_{gas} \\ \mu_{mix} &= \alpha_{oil}\mu_{oil} + \alpha_{water}\mu_{water} + \alpha_{gas}\mu_{gas} \end{aligned} \tag{3}$$

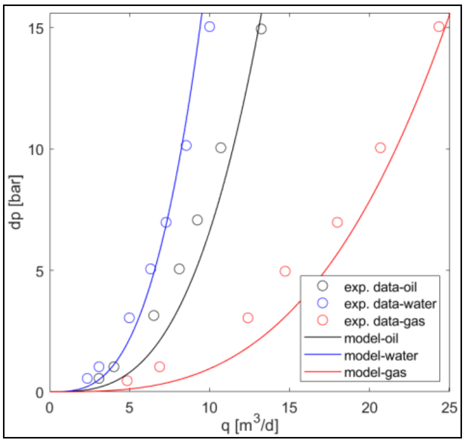

Figure 6: Derived Mathematical Model of AICD Against the Laboratory Test Data

By combing Equations (1), (2), and (3) the control function for controlling the opening of the orifice valve, a, based on the performance of AICD can be presented by Equation (4) as:

$$a = \frac{\left[\dfrac{\Delta P_{AICD}}{1.03 \times 10^{-5} \cdot (\rho_{mix}^2 / 1000) \cdot (1/\mu_{mix})^{0.33}}\right]^{\frac{1}{3.05}}}{3600 \times 24 \times A \times C_D \cdot \sqrt{\dfrac{2 \times \Delta P_{ICD}}{\rho_{mix}}}} \tag{4}$$

where A = 3.462e-6 m^2 and it is the equivalent cross-sectional area for 15 orifice valves with a diameter of 2.1 mm and C_D = 0.85 (as it is used for ICDs). Using Equations (3) and (4) the control function describing the performance of AICDs based on the fluid properties in the PUNQ-S3 model is illustrated in Figure 7.

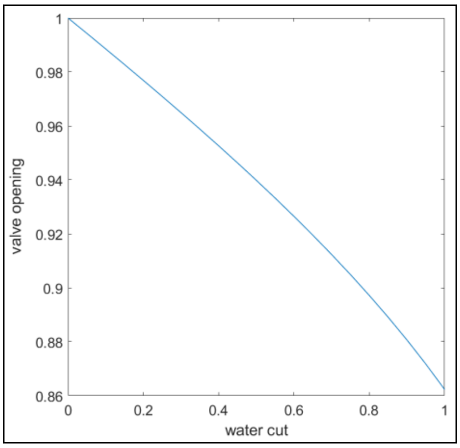

Figure 7: Valve Opening vs. Water Cut for AICDs

WELL MODEL DEVELOPMENT BY MSW

To model advanced wells completed with FCDs and AFI with the MSW model, as it is depicted in Figure 8, one branch is considered for modeling the production tubing, and a separate branch is used for modeling each isolated zone of the annulus. Each branch consists of a series of one-dimensional segments with a node and a flow path. The annulus segments are connected to the reservoir model for accepting the inflow from the reservoir. An extra segment based on Equations (1), (2), and (3), can be added between the annulus and tubing segments for modeling pressure drop across ICDs and AICDs. With this setup, at first, the reservoir fluids enter the annulus via the annulus segments and then pass into the production tubing through FCDs (Moradi et al. 2022; GeoQuest 2014).

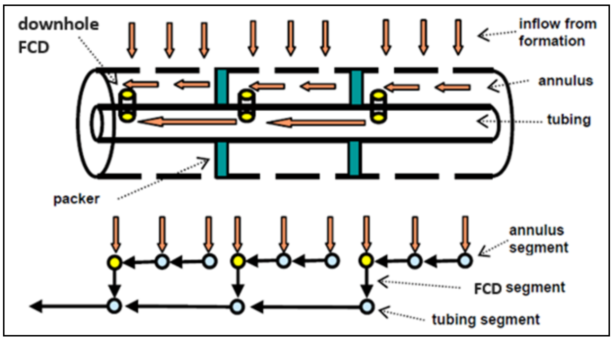

Figure 8: Schematic of an Advanced Well Model Uisng MSW (Neylon et al. 2009)

RESULTS AND DISCUSSIONS

The simulation results for production rates of oil, water, liquid, and gas as well as the total oil and water production obtained by both the OLGA and MSW models are presented and discussed.

Oil and Water Production Rates

The oil and water production rates simulated by the OLGA and MSW models are shown in Figure 9. As can be seen in the figure, both the OLGA and MSW models predict almost similar trends for the oil and water production rates for all cases. However, the OLGA model calculates a lower rate for oil production and a higher rate for water production compared to the MSW model. This can be due to the fact that the OLGA model is based on mechanistic models while the MSW model is based on the drift-flux model. In the OLGA model, by using the mechanistic models, at each time step, five mass conservation equations are solved for the gas phase, the water droplets, the oil droplets, the water film, and the oil film for the transient three-phase gas-oil-water flow simulation in pipes. However in the MSW model based on the drift-flux model, for such simulations, only three mass conservation equations for the gas phase, as well as oil and water films, are solved. Besides, the correlations used in the mechanistic models, and the drift-flux model are different. Therefore, some differences between the results obtained by these two models are expected. According to the results shown in Figure 9, the mismatch between the results from the OLGA and MSW models is higher for the AICD and ICD cases compared to the OPENHOLE case. This is justifiable because the well model and the reservoir model interact with each other through the near wellbore region, and with using AICDs and ICDs, the pressure variations near the wellbore are much higher compared to the OPENHOLE well.

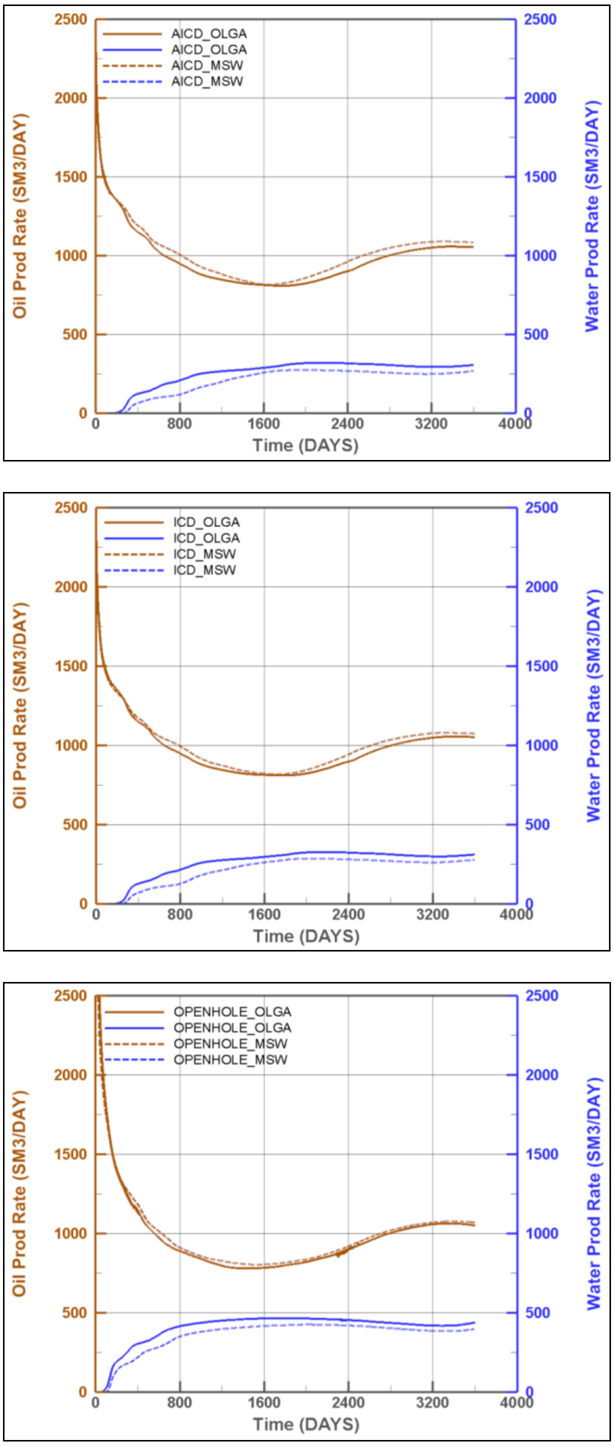

Figure 9: Comparison of Oil and Water Production Rates from the OLGA and MSW Models

Liquid and Gas Production Rates

Figure 10 illustrates the prediction of total liquid and gas production rates by the OLGA and MSW models. As can be seen in the figure, in all cases there is a good match between the prediction by the two models. The largest deviations from the model predictions start after the water breakthrough. Water breakthrough is a transient process and as the graphs show, the OLGA and MSW models capture the transient interaction between the reservoir and well after water breakthrough with some differences. When water enters the well, the multiphase flow regime in the well changes, and the OLGA and MSW models due to different formulations, calculated the well pressure differently.

Performance of Advanced Wells in Oil Recovery

The performance of advanced wells with AICD and ICD completions compared to the OPENHOLE well modeled by the OLGA and MSW models is shown in Figure 11 and Figure 12 respectively. Both models predict the impact of the well completion on oil and water production almost with the same trend. According to the obtained results from the OLGA model, after 10 years, the total production of water significantly decreased by 38% and 36% respectively using advanced wells with AICD and ICD completions compared to the OPENHOLE well. The MSW model shows a relatively higher water production reduction of 43% and 40% respectively by using AICDs and ICDs compared to the OPENHOLE completion. ICDs act as flow restrictors to balance inflow along the horizontal well and in this way, delay water breakthrough and restrict water production passively. AICDs are self-adjusting fluid-dependent devices and can partially choke the water back after the breakthrough, and reduce the water production further compared to ICDs. Both the OLGA and MSW model results show that with ICD and OPENHOLE completions the same amount of oil is produced after 10 years. However, the AICD technology can slightly improve oil recovery. According to the results from the OLGA model, total oil production is increased by 0.5 % using AICDs while the MSW model predicts a slightly higher oil production of 1.2 % for the AICD case compared to the ICD and OPENHOLE cases. In general, the AICD completion has a better performance in improving oil recovery and reducing water production where there is a large difference between the viscosity of oil and water. In our case study, the impact of AICD completions is limited due to a relatively small difference between the viscosities of oil and water in the PUNQ-S3 model.

Simulation Speed, Stability and Accuracy

Mechanistic models are more accurate than the drift-flux model. Therefore, more accurate results are expected to be obtained by the OLGA models. However, Since the mechanistic models display discontinuities in pressure drop and holdup at some flow-pattern transitions, several convergence problems occur during the simulation with the OLGA model. In contrast, the drift-flux model is relatively continuous, and differentiable which leads to fewer convergence problems. Besides, in simulation with the OLGA model, an adaptive time step selector with much shorter time steps compared to the MSW model is used to control nonlinear iterations as well as to balance accuracy and robustness for challenging nonlinear simulations. As a result, running a simulation with the OLGA model takes much longer time than using the MSW model.

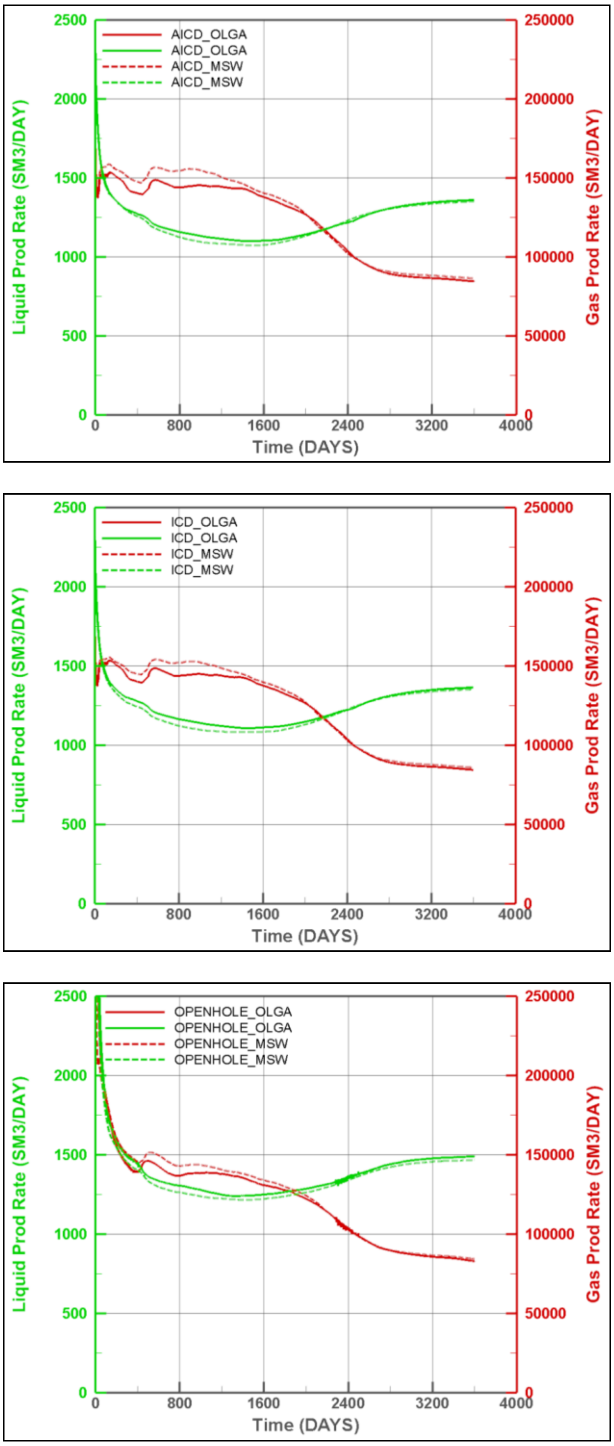

Figure 10: Comparison of Liquid and Gas Production Rates from the OLGA and MSW Models

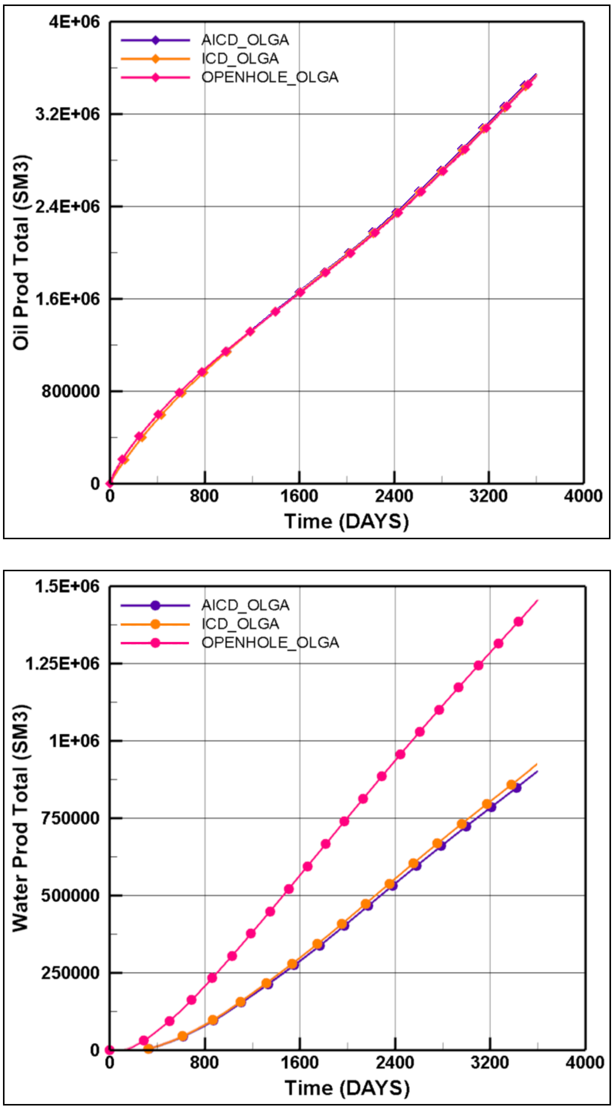

Figure 11: Cumulative Oil and Water Production from Open-hole and Advanced Wells Simulated by OLGA

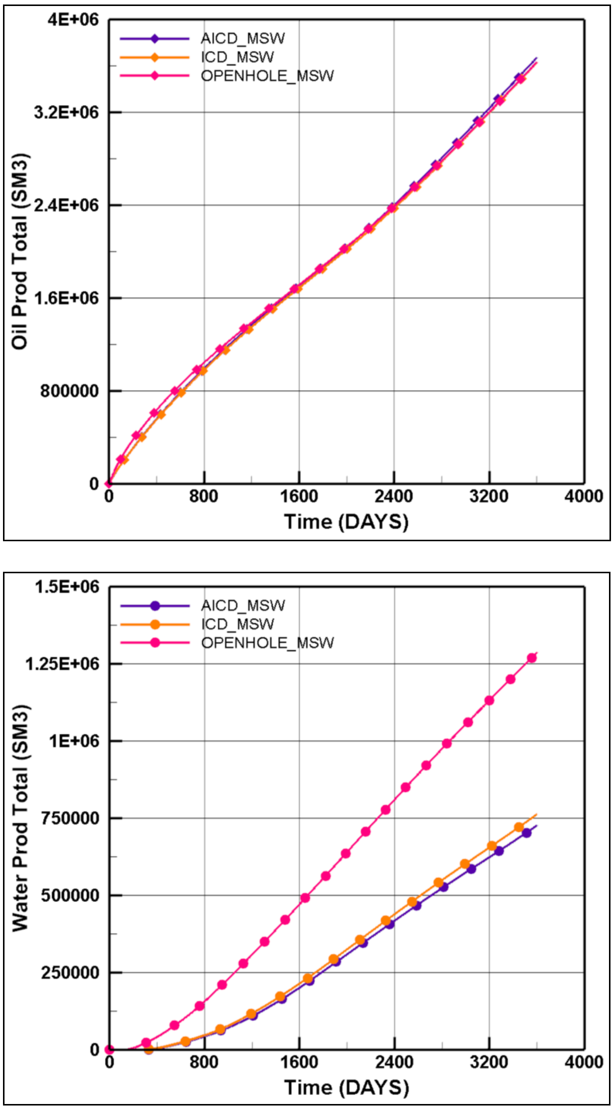

Figure 12: Cumulative Oil and Water Production from Open-hole and Advanced Wells Simulated by MSW

CONCLUSION

According to the obtained results, by using advanced wells the production of water significantly decreases while the oil production is improved. Besides, the results prove that reactive FCDs have better functionality than passive FCDs in improving oil recovery. Production and then separation of water is costly with high carbon emissions. Therefore, by applying advanced wells more cost-effective and environmentally-friendly oil recovery is achieved.

By comparing OLGA and MSW models in simulation of advanced wells it can be concluded that although more accurate results can be obtained by the OLGA model, it is much slower than the MSW model. Besides, several convergence problems occur during simulation with OLGA. Therefore, although OLGA is a robust and accurate tool for performing well-reservoir transient simulations, it is not a suitable choice e.g. for optimization or uncertainty quantification studies where several simulation runs are required.

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