Simulation of heavy oil production using smart wells

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Abstract

The application of long horizontal wells, especially in heavy oil reservoirs with a water drive, is associated with some challenges including the early breakthrough of water into the well. To solve this challenge, smart horizontal wells completed with downhole flow control devices (FCDs) and zonal isolation are widely used today. Therefore, evaluating the functionality of different types of FCDs in reducing water cut is necessary to achieve a successful design of smart wells for heavy oil production. In this paper, heavy oil production from smart wells completed with the main types of FCDs is modeled and simulated through a case study. According to the obtained results, compared to conventional wells, by using smart wells more oil and at the same time, less water can be produced from heavy oil reservoirs. Besides, in comparison with ICDs, AICDs and AICVs have better functionality in improving oil recovery and reducing water cut. It can also be concluded that among the main types of FCDs, AICVs have the best performance in achieving cost-effective heavy oil production.

Keywords: smart wells, ICD, AICD, AICV, heavy oil

1 Introduction

Despite the rapid growth of renewable energies, the world is still dependent on oil in years to come. Therefore, the focus must be on improving oil recovery with less carbon footprint to meet future energy demands. One of the main principles to achieve this purpose is maximizing the well-reservoir contact by using long horizontal wells. One of the main challenges of using such wells, especially in heavy oil reservoirs, is early water breakthrough. This problem happens due to the heel-toe effect and heterogeneity along the horizontal wells. To tackle this problem, smart wells are widely applied today. Smart (advanced or intelligent) wells are horizontal wells equipped with downhole Flow Control Devices (DFCs), zonal isolation as well as monitoring and control systems, etc. DFCs are the key elements of smart wells. The main types of such devices are passive Inflow Control Devices (ICDs), Autonomous Inflow Control Devices (AICDs), and Autonomous Inflow Control Valves (AICVs). In order to achieve a successful design of smart wells, a suitable type of these devices must be chosen for completion of the well based on the characteristics of the reservoir. So far, few studies have been performed for investigating the performance of FCDs in reducing water cut in heavy oil reservoirs with a large water aquifer. This paper aims to provide more insight into the functionality of the main types of FCDs in heavy oil reservoirs needed for the suitable design of smart wells. The study is performed through near-well simulation of heavy oil production from a smart horizontal well with zonal isolation and FCD completion in a synthetic heavy oil reservoir with a strong water drive. The OLGA® simulator coupled with the ROCX® simulator is used for developing the simulation models.

2 Inflow control technologies

2.1 Passive inflow control devices

ICDs have been developed since the 1990s for mitigating the risk of early water and/or gas breakthrough in horizontal wells. ICDs are mounted on the production tubing as a passive flow restrictor device with no moving part. ICDs are used for counteracting the non-uniform inflow throughout the length of the horizontal by adding extra pressure drop. Figure 1 shows the functionality of such devices to delay the early water breakthrough by balancing the inflow along the well (Aakre, 2017).

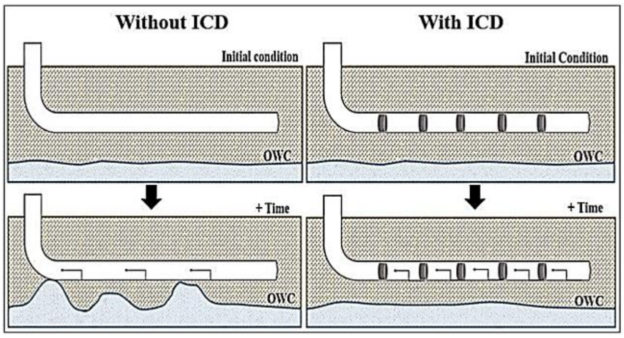

Figure 1. Application of ICDs in mitigation of the early water breakthrough (Chammout et al., 2017).

One of the main disadvantages of ICDs is not having the capability for choking unwanted fluids (water or gas) back after the breakthrough. As a result, the well must be shut in to avoid producing unwanted fluids more than the capacity of the separation facilities (Aakre, 2017).

One of the common types of ICDs is the orifice ICD and the mathematical equation governing the behavior of this type of ICDs is:

$$\dot{Q} = C_D A \sqrt{\frac{1}{1-\beta^4}} \cdot \sqrt{\frac{2\Delta P}{\rho}} \quad (1)$$

where $\dot{Q}$ is the volume flow rate of the fluid passing through the ICD, ΔP is the pressure drop over the ICD and ρ is the fluid density. In this equation, C_D is called *discharge coefficient* and it can be calculated as $C_D = A / A_{vc}$ in which A is the cross-sectional area of the orifice hole and A_{vc} is the minimum jet area just downstream of the orifice. Moreover, $\beta = d / D$ in which d and D are the diameters of the orifice and production tubing respectively (The Engineering ToolBox, 2004).

2.2 Autonomous inflow control devices

Since passive ICDs can not choke the unwanted fluids back after breakthrough, AICDs have been developed as a robust alternative in recent years. Owing to the special design of AICDs, they can be partially closed for low-viscosity fluids compared to oil like water and gas. Consequently, in addition to delaying the water or gas breakthrough, AICDs are able to reduce the production of unwanted fluids after breakthrough autonomously and thereby increase oil production (Aakre, 2017).

Rate-Controlled Production valves (RCPs) that are also known as the Equinor AICD is one of the most widely used types of AICDs today. Figure 2 shows the schematic of an RCP valve that is consists of a body, nozzle, and a moving plate. These types of valves are designed based on the fluid properties in such a way that the moving plate rests at the sit and consequently the valve is fully open when oil passes through the valve. However, when low-viscosity fluids compared to oil enter the valve, according to Bernoulli's equation, the pressure at the inlet becomes lower. Therefore, the total force acting on the moving plate pulls it towards the inlet and the valve gets partially closed. Owing to this mechanism, these types of valves can reduce the flow rate of unwanted fluids like water or gas autonomously (Mathiesen et al., 2011; Askvik and Sørheim, 2017).

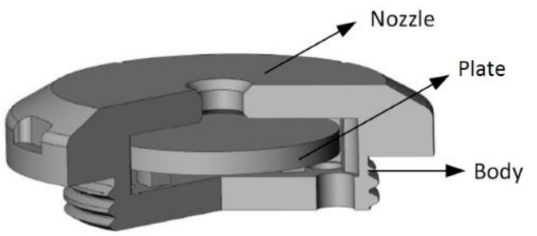

Figure 2. Schematic sketch of RCP-type AICDs (Mathiesen et al., 2011).

The empirical function describing the behavior of the RCP valves developed and validated by Equinor is represented by Equations 2 and 3 as:

$$\Delta P = f(\rho, \mu) \cdot a_{AICD} \cdot \dot{Q}^x \tag{2}$$

$$f(\rho, \mu) = \left(\frac{\rho_{mix}^2}{\rho_{cal}}\right) \cdot \left(\frac{\mu_{cal}}{\mu_{mix}}\right)^y \tag{3}$$

where $\dot{Q}$ is the volumetric flow rate of fluid passing through the RCP, and ΔP is the pressure drop over the RCP. In this equation a_{AICD}, x and y are user-input parameters that depend upon the RCP design and fluid properties. $f(\rho,\mu)$ is an analytical function of fluid density and viscosity in which ρ_{cal} and μ_{cal} are specified as calibration density and viscosity respectively. Moreover, ρ_{mix} and μ_{mix} are the density and viscosity of the mixture of fluids passing through the RCP valve and are calculated by Equation 4 as:

$$\begin{aligned} \rho_{mix} &= \alpha_{oil}\rho_{oil} + \alpha_{water}\rho_{water} + \alpha_{gas}\rho_{gas} \\ \mu_{mix} &= \alpha_{oil}\mu_{oil} + \alpha_{water}\mu_{water} + \alpha_{gas}\mu_{gas} \end{aligned} \tag{4}$$

where α_{oil}, α_{water} and α_{gas} are the volume fraction of oil, water, and gas in the mixture respectively (Halvorsen et al., 2016).

2.3 Autonomous inflow control valves

AICVs are the newest generation of inflow control devices developed by InflowControl AS. Unlike the AICDs that are capable to be partially closed against unwanted fluids, AICVs can be almost completely closed when low viscous fluids like water or gas pass through them. AICVs are self-regulating and reversible and are able to reopen when oil is the surrounding fluid. AICVs act rests on the difference in pressure drop in laminar and turbulent flow restrictors. The pressure drop across a laminar and turbulent flow restrictor is expressed by Equation 5 and 6 respectively as:

$$\Delta P = \frac{32\mu\rho v L}{D^2} \tag{5}$$

$$\Delta P = k\frac{1}{2}\rho v^2 \tag{6}$$

Figure 3 shows the principle of AICV technology which is based on a combination of laminar and turbulent flow restrictors in series. According to Equations 5, the pressure drop across a laminar flow restrictor depends on density and viscosity. Therefore, when a viscose fluid like oil passes through a laminar flow restrictor, it experiences a higher pressure drop compared to low-viscosity fluids like water and gas. Because of less pressure drop after the laminar flow restrictor, low-viscosity fluids have higher pressure in the chamber between the laminar and turbulent flow restrictors. Therefore, low-viscosity fluids move with higher velocity before passing through the turbulent flow restrictor. Based on Equation 6, the pressure drop across a turbulent flow restrictor is proportional to density and velocity squared. As a result, low-viscosity fluids experience higher pressure drop across the turbulent flow restrictor compared to oil. Based on these principles AICVs are designed to remain open for oil and get almost completely closed for unwanted fluids (Mathiesen et al., 2014).

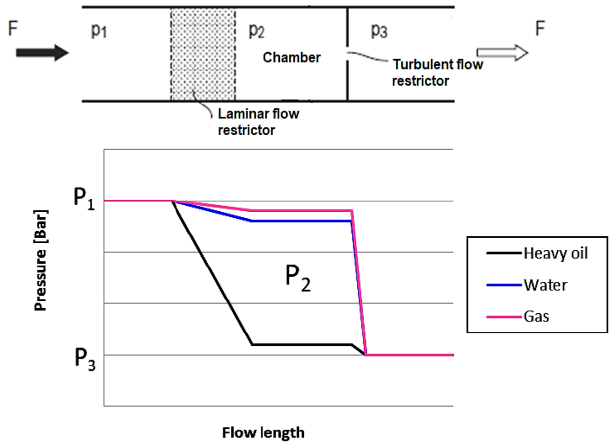

Figure 3. Combination of laminar and turbulent flow restrictor in series (Mathiesen et al., 2014).

2.4 Characteristics of the synthetic reservoir

For simulation of heavy oil production from smart wells, a synthetic (with hypothetical properties) reservoir is considered for developing the simulation models. However, to achieve realistic results, the rock and fluid properties of the synthetic reservoir are specified to be similar to those of a real reservoir. The characteristics of the synthetic reservoir are given in Table 1.

Table 1. Characteristics of the reservoir used for developing the simulation models.

Parameter	Value
Oil Density	950 kg/m^3
Oil Viscosity	10 cP
Water Density	1050 kg/m^3
Water Viscosity	0.45 cP
Gas-Oil Ratio (GOR)	50 Sm^3/Sm^3
Absolute Permeability	Kx=Ky=2000, Kz=600 mD
Porocity	0.25
Capilary Pressure	3 bar @ Sw=0.12, 0 bar @ Sw=1
Initial Water saturation	0.12
Reservoir Temperature	80 °C
Reservoir Pressure	200 bar

It is assumed that the reservoir has a mixed-wet wettability state. The Corey model is used for determining the oil and water relative permeability curves. Figure 4 shows the relative permeability curves for oil and water obtained based on the recommended Corey model parameters for a mixed-wet reservoir.

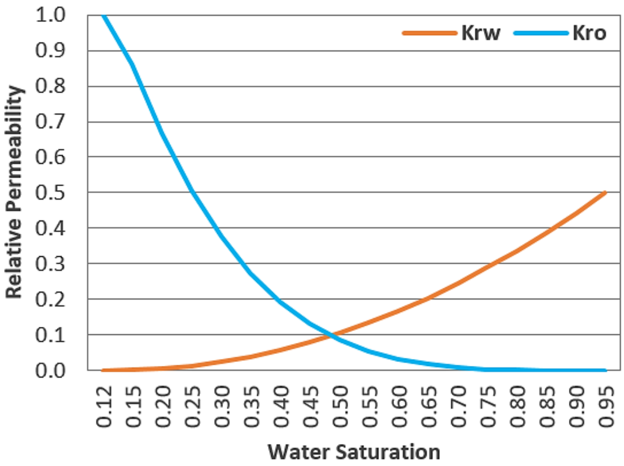

Figure 4. Relative permeability curves used for developing the simulation models.

3 Development of the OLGA/ROCX model

OLGA is a dynamic multiphase flow simulator and ROCX is a near-wellbore reservoir simulator that can be coupled to the OLGA simulator. The OLGA-ROCX coupling is commonly used for dynamic modeling and simulation of multiphase flow behavior from the reservoir pore to the production pipe and process facilities. When the OLGA simulator is combined with the ROCX simulator, an implicit scheme couples the OLGA and ROCX simulators based on the same PVT file. The OLGA simulator calculates the wellbore pressure and sends the information to the ROCX simulator. Then the ROCX simulator calculates the flow rate for each phase of the reservoir fluids and sends the information back to the OLGA simulator for calculating the new wellbore pressure. Likewise, the simulation is moved forward and completed (Schlumberger, 2020).

3.1 Development of the near-well reservoir model in the ROCX module

One of the main steps in developing a near-wellbore reservoir model in the ROCX simulator is determining the geometry and dimensions of the drainage area near the well. In reality, the drainage area of a horizontal well has an ellipsoidal shape. However, due to the ROCX limitations, a rectangular drainage area as it is illustrated in Figure 5 is considered for developing the near-wellbore reservoir model. In this study, the length of the reservoir is assumed to be the same as that of the horizontal well and equal to 992 m. The thickness and width of the reservoir are considered to be 30 m and 70 m respectively. It is also assumed that the well is located 5.5 m below the top of the drainage area.

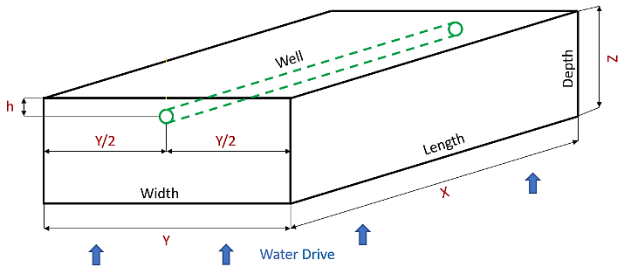

Figure 5. Schematic geometry of the reservoir near the well (Moradi and Moldestad, 2020).

The cross-section of the reservoir is located in the *Y*-*Z* plane and the well is in the *X*-direction. Therefore, the fluid pressure experiences higher variations in the *Y* and *Z* directions compared to the *X* direction. To achieve a suitable grid setup, in the *Y* and *Z* directions finer meshes have been used near the wellbore and uniform meshes are considered in the *X*-direction (Moradi, 2020). In order to develop the near-well reservoir model, for simplifying the model it is assumed that the horizontal well has 8 equivalent joints, each 124 m long. As a result, 8 uniform cells are considered for the reservoir in the *X* direction. The grid resolution in *Y* and Z directions is illustrated in Figure 6.

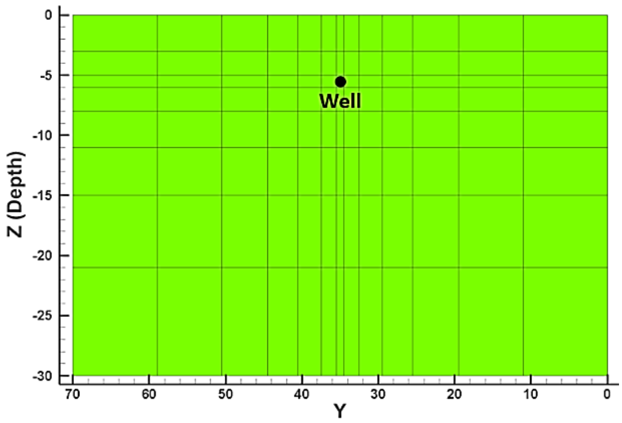

Figure 6. Grid resolution in the *Y*-*Z* plane.

3.2 Development of the well model in the OLGA simulator

For developing the well model in the OLGA simulator, one pipe with a length of 992 m, a diameter of 5.5 inch, and roughness of 15 µm is considered for representing the production tubing. Another pipe with the same length but a diameter of 8.5 inch is considered for representing the wellbore. It is assumed that the well consists of 8 equivalent joints with only one equivalent inflow control device for each joint. Besides, for each joint, the wellbore is isolated by two packers to stop flowing the reservoir fluids between different zones in the annulus. As a result, oil is produced from 8 separated zones. The simplified model for oil production from each zone in the OLGA simulator is illustrated in Figure 7. As can be seen in the figure, each production zone is divided into two sections. The wellbore in section one is connected to the ROCX simulator via the near-well source. The reservoir fluids enter the second section of the wellbore after passing FCDs. Then the reservoir fluids enter the production tubing through a leak connected to the second section of the production tubing and in this way oil is produced from each zone. This setup has been proposed and used in (Aakre, 2017).

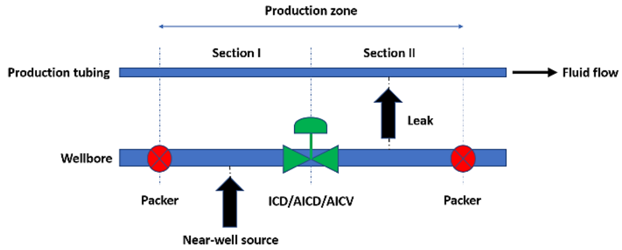

Figure 7. Simplified model of a single production zone in the OLGA simulator (Moradi and Moldestad, 2021).

The pressure drawdown used for developing the simulation models is considered to be 10 bar. For modeling ICDs in the OLGA simulator, a simple orifice valve with a diameter of 0.01 m is used. In order to model AICDs and AICVs, a controller is added to the ICD model for choking the orifice valve based on the characteristics of AICDs and AICVs. Moreover, to add a regulating flow valve to the model for keeping the total liquid production rate under a specific value, a valve with a PID controller is used.

4 Results and discussion

In this chapter, the obtained simulation results from the OLGA-ROCX model are presented and discussed. The functionality of ICDs, AICDs and AICVs in reducing water cut and improving heavy oil recovery is evaluated and compared with an open-hole well. The simulations have been conducted under two production strategies. In Case a, it is assumed that oil is produced from the smart wells by a constant pressure drawdown of 10 bar without any limitations for total liquid production. In Case b, the production strategy is the same as Case a, but it is assumed that oil production is constrained by the maximum liquid production of 800 m^3/day. Case a is a hypothetical case assuming no limit for the transportation and separation of the total liquid produced from the well. Case a has been chosen to investigate the unrestricted functionality of different FCDs where there are no limitations for fluid production from the well. However, since in reality there is a limitation in the transportation system and the separation unit, Case b has been chosen to evaluate the performance of different FCDs in a realistic case.

4.1 Cumulative oil and water production

To investigate the functionality of the different types of inflow valves, accumulated oil and water are the two most important parameters that must be taken into account. Figure 8 illustrates the accumulated oil and water produced by the smart well compared to the open-hole well in Case a. In Case a, there is no restriction for the total liquid production rate. So, as can be seen in the figure, both the total oil production and the total water production from an open-hole well in Case a is more than those of smart wells. However, the increase in water production from the open-hole well is significantly higher than the increase in oil production from the open-hole well compared to smart wells. Therefore, although in this case more oil can be produced, much more water is also produced. Besides, in Case a, the smart well with AICDs and AICVs has produced relatively less oil but considerably less water compared to the smart well with ICDs.

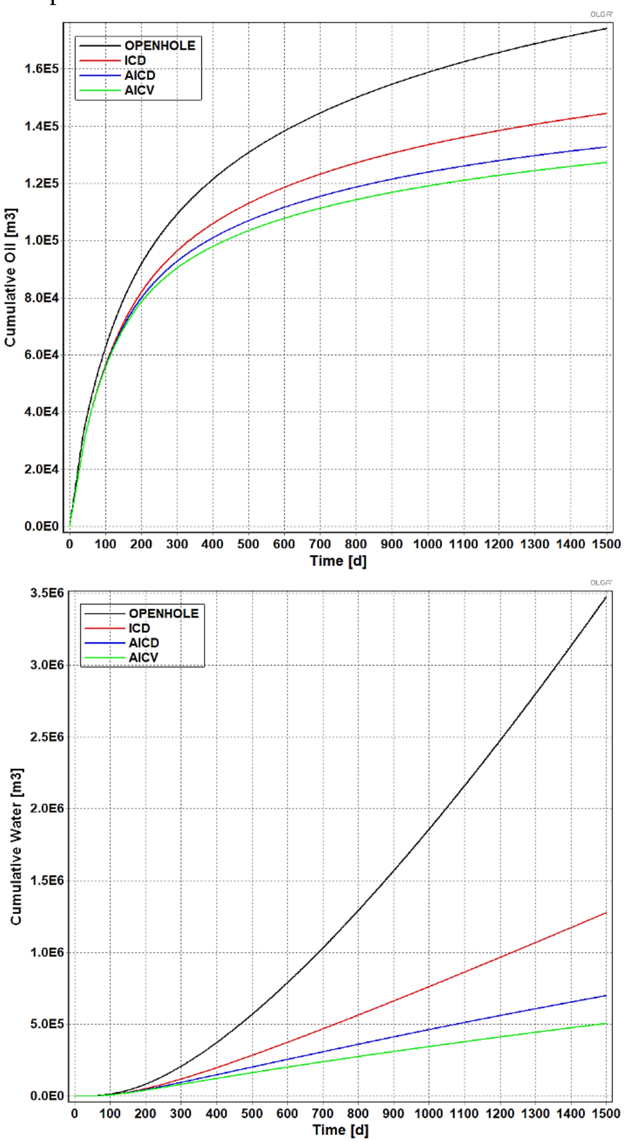

Figure 8. Cumulative oil and water production in Case a.

The cumulative oil and water production from the smart well compared to the open-hole well in Case b are shown in Figure 9. In Case b, there is a flow regulating valve for limiting the total liquid produced from the well. Therefore, in Case b, the smart well can produce more oil with less water compared to the open-hole well. Moreover, according to the figure, a relatively higher amount of oil with considerably less amount of water can be produced by using AICDs and AICVs compared to ICDs. The smart well completed with AICVs produces the lowest amount of water and has the best performance in reducing water cut compared to ICDs and AICDs.

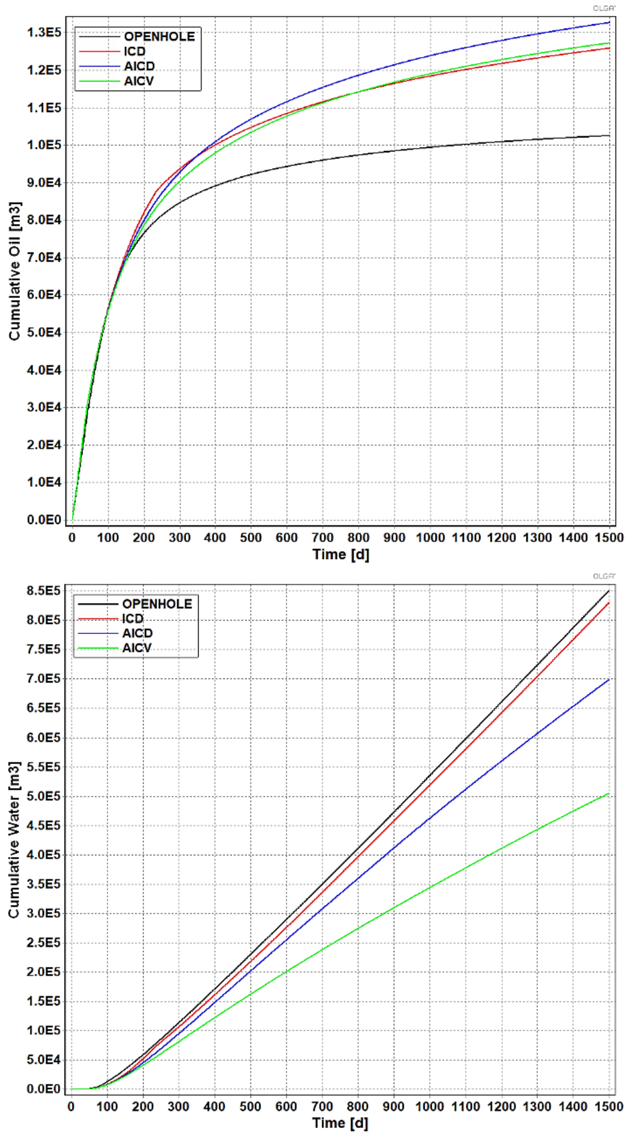

Figure 9. Cumulative oil and water production in Case b.

The values of cumulative oil and water production for the smart well with ICD, AICD, and AICV completions compared to the open-hole well after 1500 days of production are presented in Table 2. According to the obtained results, in Case a, the total oil production from the smart well completed with ICDs, AICDs, and AICVs compared to the open-hole well is decreased by 17.1%, 23.8%, 26.9% respectively. In the same way, the total water production is reduced by 63.3%, 79.9%, 85.5%.

According to Table 2, unlike Case a, the total oil produced from the smart well with ICD, AICD and AICV completions in Case b is increased by 22.7%, 29.4%, 24.1% respectively compared to the open-hole well. At the same time, the total water production is decreased respectively by 2.4%, 17.9%, 40.7%. for ICD, AICD and AICV completions in Case b.

Table 2. The values of cumulative oil and water production in Case a and b after 1500 days.

Parameter [m^3]	Open-Hole	ICD	AICD	AICV
Cum. Oil (Case a)	174143	144423	132706	127262
Cum. Water (Case b)	3475290	1277150	699178	505078
Cum. Oil (Case a)	102530	125841	132695	127251
Cum. Water (Case b)	851399	830752	699178	505078

4.2 Oil and water flow rate

Figure 10 illustrates the volumetric flow rate of oil and water in Case a during 1500 days.

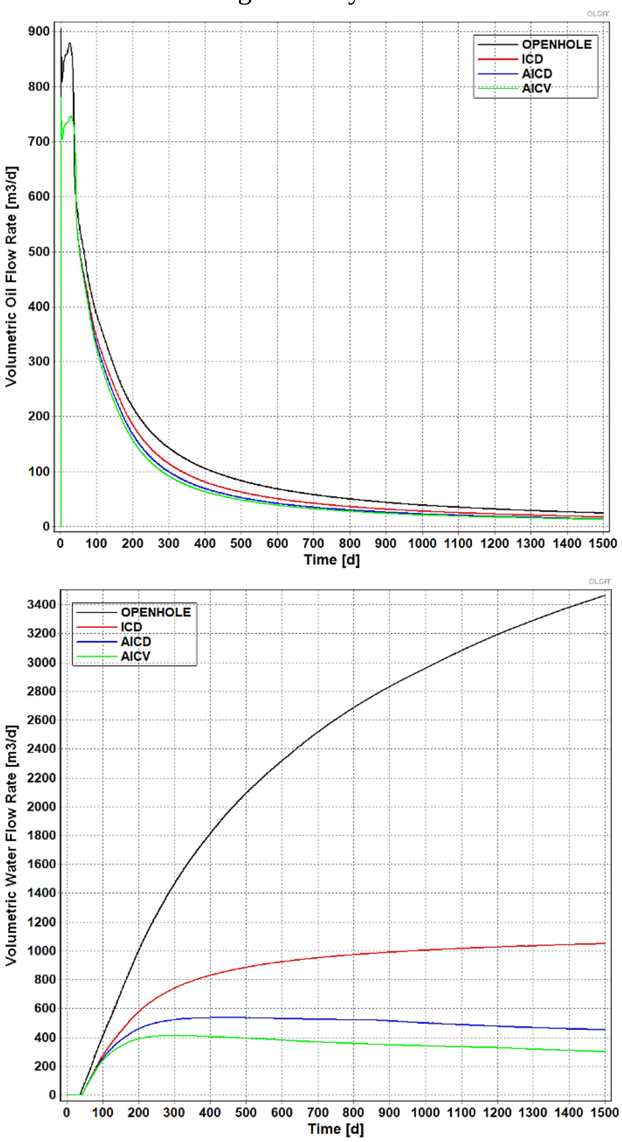

Figure 10. Volumetric oil and water flow rate in Case a.

As can be seen in Figure 10, in Case a, the rate of oil production for the open-hole well and the smart well with ICD completion is slightly higher than the smart well with AICD and AICV completions. This is due to the fact that for the open hole-well and the ICD completion (after the water breakthrough), the cross-sectional area for entering reservoir fluid to the well is bigger compared to AICD and AICV completions. However, unlike the open hole well and the smart well with ICD completion, after a while, the rate of water production from the smart wells completed with AICDs and AICVs experience a decreasing trend. This is based on the autonomous behavior of AICDs and AICVs for choking the unwanted fluids after the breakthrough.

The volumetric flow rate of oil and water in Case b are shown in Figure 11. In Case b, there is a regulating flow valve to limit the rate of total fluid production by using a valve with a PID controller. As a result, the diagrams of oil and water flow rate for the open-hole well and the smart well with ICD are noisy.

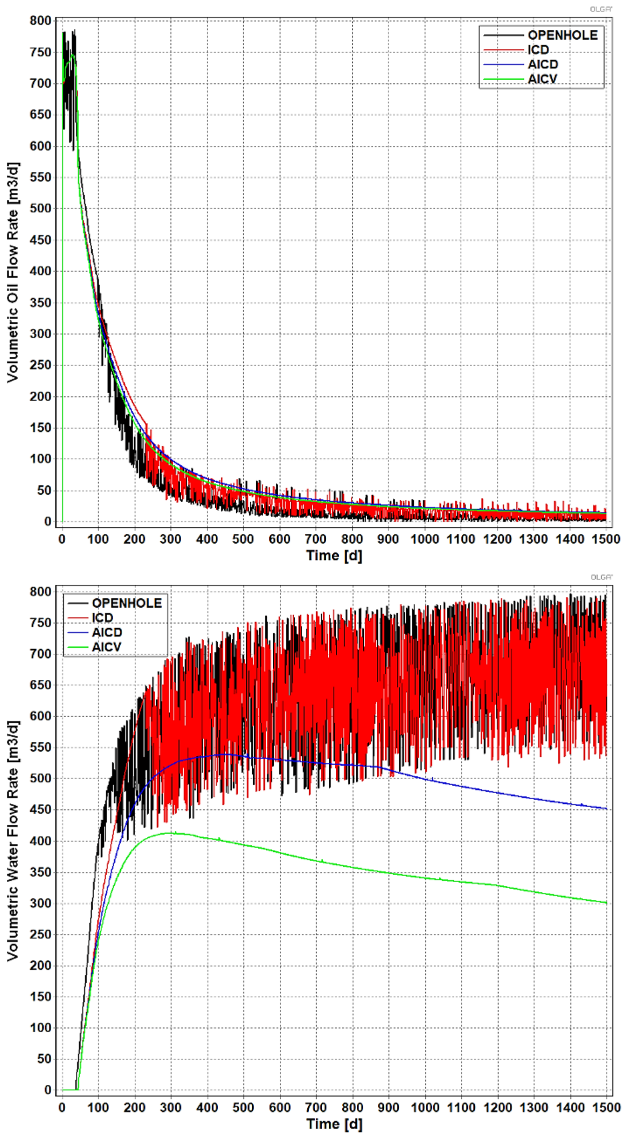

Figure 11. Volumetric oil and water flow rate in Case b.

As can be seen in Figure 11, due to the existence of a regulating flow valve, the flow rate of water for the open-hole well and the well with ICD completion remains below 800 m^3/day during the whole period of production. However, owing to the capability of AICDs for getting partially closed against water, the flow rate of produced water is autonomously decreased after almost 500 days for the smart well with AICD completion. AICVs are able to be close almost completely when water passing through them. Consequently, as can be seen in the figure, after almost 300 days the rate of water production is reduced for the smart well with AICV completion.

The values of volumetric oil and water flow rate in Case a and b after 1500 days have been given in Table 3. According to the given data in this table, the flow rate of oil after 1500 days in Case a is respectively decreased by 28.6%, 43.3%, 46.9% for ICD, AICD and AICV completions compared to the open-hole well. In the same way, comparing the open-hole well, the flow rate of water is reduced by 69.7%, 87.0%, 91.3% with ICD, AICD, and AICV completions sequentially.

In Case b, the flow rate of oil after 1500 days is increased by 77.7%, 165.7%, 150.3%, and the flow rate of water is decreased by 5.0%, 37.7%, 58.5% for the smart well with ICD, AICD and AICV completions compared to the open-hole well respectively.

Table 3. The values of oil and water production rate for Case a and b after 1500 days.

Parameter [m^3/day]	Open-Hole	ICD	AICD	AICV
Oil Rate (Case a)	24.5	17.5	13.9	13
Water Rate (Case b)	3464.3	1049.9	451.8	300.9
Oil Rate (Case a)	5.2	9.2	13.8	13.0
Water Rate (Case b)	725.6	689.3	451.8	300.9

4.3 Water cut

Since extracting, transporting, and then separating the produced water from an oil well is costly, reducing water cut is of key importance to achieve cost-effective oil production. Figure 12 shows the diagram of outlet water cut for the smart well completed with ICD, AICD, and AICV compared to the open-hole well in Case a (up), and Case b (down). As can be seen in the figure for both cases, oil is produced with considerably lower water cut buy using AICDs and AICVs compared to the open-hole well and the smart well with ICD completion. Besides, according to the obtained results, AICVs have better functionality in reducing the water cut compared to AICDs. This is due to the fact that AICVs have more capability for choking water back after breakthrough compared to AICDs.

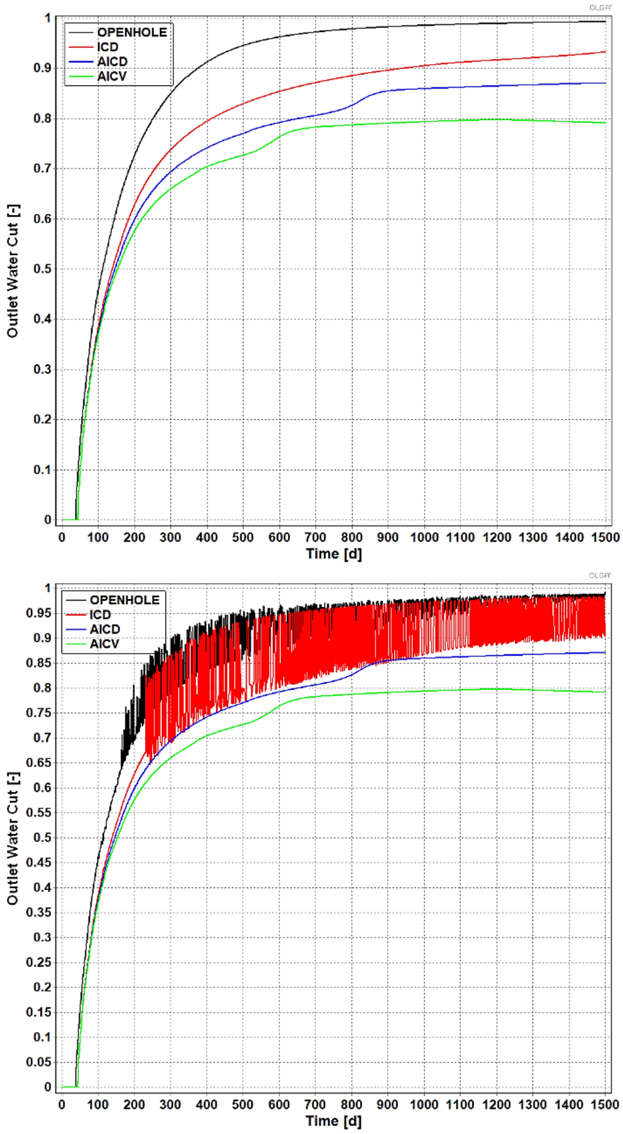

Figure 12. Outlet water cut in Case a (up), and Case b (down).

The values of outlet water cut in Case a and b after 1500 days of production are presented in Table 4. According to the given values, comparing the open-hole well, the water cut is decreased by 6.0%, 12.3%, 20.3% by completing the smart well with ICDs, AICDs, and AICVs sequentially compared to the open-hole well. Also, with a negligible difference with Case a, in Case b the water cut can be decreased by 6.5%, 11.4%, 19.5% when ICDs, AICDs, and AICVs are used for completing the smart well respectively.

Table 4. The values of outlet water cut for Case a and b after 1500 days.

Parameter [%]	Open-Hole	ICD	AICD	AICV
Water cut (Case a)	99.3	93.3	87.1	79.1
Water cut (Case b)	98.2	91.8	87.1	79.1

5 Conclusion

According to the presented simulation results, the breakthrough of water from the aquifer into the horizontal wells leads to a significant drop in oil production from heavy oil reservoirs. Considering the realistic case (Case b) it can be concluded that by using smart wells more oil and at the same time, less water can be produced from heavy oil reservoirs compared to using open-hole horizontal wells. The obtained results show that compared to the open-hole well, smart wells with ICD, AICD, and AICV, are able to increase heavy oil production by 22.7%, 29.4%, 24.1% respectively. At the same time, the amount of water produced from the smart wells using ICD, AICD, and AICV completions is reduced by 2.4%, 17.9%, 40.7% sequentially, compared to the open-hole well. Also, the outlet water cut after 1500 days of production is decreased by 6.5%, 11.4%, 19.5% when ICDs, AICDs, and AICVs are used for completing the smart well respectively, compared to using the open-hole well. Therefore, applying smart wells can noticeably improve the heavy oil recovery by reducing the water cut. Moreover, based on the simulation results, it can be said that autonomous inflow control devices (AICDs and AICVs) have better functionality for increasing oil production and reducing water production in comparison with passive inflow control devices (ICDs). Besides, it can be argued that among the main types of inflow control devices, AICVs have the best performance in reducing water cut during heavy oil production. As a result, more cost-effective oil production can be achieved from heavy oil reservoirs by using AICV completion for smart wells compared to AICD and ICD completions.

Acknowledgments

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