Simulation of Heavy Oil Production using Inflow Control Devices

A Comparison between the Nozzle Inflow Control Device and Autonomous Inflow Control Device

Emmanuel Okoye , Britt M. E. Moldestad
Department of Process, Energy and Environmental Technology, University of Southeast Norway, Porsgrunn, Norway.
Britt.Moldestad@usn.no, Chuksokoye2@gmail.com

Abstract

Production of heavy oil requires the application of new technologies in order to handle the challenges associated with the production. The main challenges are early water breakthrough, resulting in high water cut and low oil recovery. Especially in heterogeneous reservoirs, early water breakthrough and high water cut lead to low productivity and high separation costs. Different types of inflow control devices (ICDs) have proven to be effective in delaying water breakthrough and the newer technology has also the ability to choke for water after breakthrough. The near well simulation tool, NETool, was used to simulate oil production from homogeneous and heterogeneous heavy oil reservoirs after water breakthrough has occurred. The oil and water production, using nozzle ICD and autonomous ICD (RCP) completion, has been simulated and compared. ICD is producing more oil than RCP, but it is also producing significantly more water. The well with ICD completion gave about 4 to 5 times higher water cut than the well with RCP completion. Estimates indicate that by utilizing the newest technology, autonomous inflow control valve (AICV), the water cut can be reduced significantly without reducing the oil production.

Keywords: ICD, RCP, AICV, water cut, water breakthrough, heavy oil

1 Introduction

Heavy oil is a type of unconventional oil with a viscosity above 100cP and API gravity less than 22.3°. Heavy oil has in the past years been used as a source of refinery feedstock due to its lower quality compared to conventional oil (Meyer *et al*, 2007). Due to a high population growth and a massive decline in conventional oil reserves in recent times, there has been a need of developing advanced technologies to improve heavy oil recovery. Inflow control devices as an advanced technology have the ability to reduce the water-cut and improve oil recovery. Early water breakthrough poses a real challenge in the recovery of heavy oil in reservoirs with water drive. An estimate gives that about 70% of heavy oil is left behind in the reservoir after the production is shut down since it is no longer economical to produce oil (Aakre *et al*, 2014). For both homogenous and heterogeneous reservoirs, high differential pressures are needed to aid production of heavy oil. This leads to an early water breakthrough to the well. The inflow control devices, on the other hand, have the potential of delaying water breakthrough, and as a consequence the production can run with a higher drawdown to increase the production rate (Aakre *et al*, 2014).

In this study, a comparison between two different types of inflow control devices namely the Nozzle inflow control device (ICD) and the Autonomous inflow control device (RCP) is considered using the NETool reservoir simulator. Simulation of oil flow rates, water flow rates and water-cut (WC) at various drawdown pressures are carried out. Result analysis, discussion and conclusions are given.

2 Inflow control devices

2.1 Nozzle inflow control device

The nozzle ICDs are often used in long horizontal wells and to balance the production rates between different zones of the well. ICD has the ability of delaying early water breakthrough, thus reducing the average water cut in the well. Moreover, the ICD is passive – meaning it neither chokes nor closes after water breakthrough has occurred (Aakre *et al*, 2014). The principle behind the nozzle ICD is based on the following equations (Halliburton, 2014):

$$\Delta P = \frac{\rho v^3}{2C^2} = \frac{\rho Q^2}{2A_{valve}^2 C^2} = \frac{8\rho Q^2}{\pi^2 D_{valve}^4 C^2} \quad (1)$$

$$C = \frac{C_D}{\sqrt{(1-\beta^4)}} = \frac{1}{\sqrt{K}} \quad (2)$$

$$\beta = \frac{D_2}{D_1} \quad (3)$$

where ΔP is pressure drop across orifice, ρ is average fluid density, v is fluid velocity through orifice, Q is fluid flow rate through orifice, A is area of orifice, D is diameter of orifice, C is flow coefficient, C_D is discharge coefficient, and K is pressure drop coefficient.

2.2 Autonomous inflow control device

The Autonomous Inflow Control Device (AICD) used in this study, is known as Rate Controlled Production (RCP) and is developed by Statoil. The view of the RCP is to delay water breakthrough and autonomous chocking of water after water breakthrough. Autonomous, means that the inflow control device is self-regulating and it is not controlled from the surface. This autonomous behavior enables the RCP to produce more heavy oil from the long horizontal wells (Mathiesen *et al*, 2011) by chocking the zones that are producing water, and at the same time produce oil from the other zones. This implies that high drawdown can be used, and the oil recovery can be increased significantly. The performance of the RCP is based on Bernoulli's equation:

$$P_1 + \frac{1}{2}\rho V_1^2 = P_2 + \frac{1}{2}\rho V_2^2 + \Delta P_{Friction\ loss} \tag{4}$$

Where P_1 and P_2 are static pressures, the velocity terms represent the dynamic pressures, $\Delta P_{Friction\ loss}$ is pressure loss due to friction and ρ is density of the fluid.

The RCP is characterized by being very little sensitive to changes in differential pressure, and gives a more uniform flow rate over a range of drawdowns compared to the ICD. The following equations describe the functionality of the RCP:

$$\delta P = f(\rho, \mu) \,.\, a_{AICD} \,.\, q^x \tag{5}$$

$$f(\rho, \mu) = \left(\frac{\rho_{mix}^2}{\rho_{cal}}\right) \cdot \left(\frac{\mu_{cal}}{\mu_{mix}}\right)^y \tag{6}$$

$$\rho_{mix} = \alpha_{oil}\,\rho_{oil} + \alpha_{water}\rho_{water} + \alpha_{gas}\rho_{gas} \tag{7}$$

$$\mu_{mix} = \alpha_{oil}\mu_{oil} + \alpha_{water}\mu_{water} + \alpha_{oil}\mu_{oil} \tag{8}$$

Where δP is pressure drop through RCP, q is the flow rate, x and y are user input constants, a_{AICD} is the valve strength parameter, α is the volume fraction of the actual phase, ρ_{cal} and μ_{cal} are calibration density and viscosity.

2.3 Autonomous inflow control valve

Autonomous Inflow Control Valve (AICV) is developed by Inflow Control AS. Unlike other inflow control devices that delay and/or choke the water production, the AICV closes completely when water breakthrough occurs and re-opens again when the oil is well saturated around the valve. The AICV technology can be used in long horizontal wells for various type of oil production, ranging from light oil to bitumen production using SAGD. The device is said to be self-regulating and gives very low restriction for oil flow (Aakre *et al*, 2014). The working principle of the AICV is based on the difference in pressure drop through a laminar and a turbulent flow restrictor. The pressure drop through the laminar flow restrictor is proportional to the viscosity and the velocity and is expressed by the equation for pressure drop through a pipe segment (Aakre *et al*, 2014). The pressure drop through the turbulent flow restrictor is proportional to the density and the velocity squared. The pressure drops through the laminar and turbulent flow restrictors are expressed by eq. (9) and (10) respectively (Aakre *et al*, 2014):

$$\Delta P = f \cdot \frac{L \cdot \rho \cdot v^2}{2D} = \frac{64}{Re} \cdot \frac{L \cdot \rho \cdot v^2}{2D} = \frac{32 \cdot \mu \cdot \rho \cdot v \cdot L}{D^2} \tag{9}$$

$$\Delta P = k \cdot \frac{1}{2} \cdot \rho \cdot v^2 \tag{10}$$

Where ΔP is pressure drop, f is friction coefficient, ρ is the fluid density, μ is fluid viscosity, L is length of laminar flow element, D is diameter of laminar flow element, Re is Reynolds number, k is geometrical constant and v is fluid velocity.

Since AICV can close for water and gas, it has a very high potential for increased oil recovery. However, the AICV is a new development and is still not included as an option in NETool. The simulations are therefore focused on the nozzle ICD and the RCP, and the potential of the AICV will be discussed based on the results from these two types of inflow controls.

3 NETool

NETool is a steady state near well simulation tool, and can be used for analysis of the effect of different completion components, near-wellbore effect on productivity of the well, modeling of completion components in the production and injection interval, design of inflow control devices to delay water and gas breakthrough, etc. NETool can also be linked with other software like design software and reservoir simulators such as Eclipse and Nexus. The black oil model is included in NETool, and is used in all the simulations.

3.1 Input parameters

In the simulations, two different cases were considered; one case for homogenous reservoir and one case for heterogeneous reservoir. The same reservoir properties were utilized for both reservoir types except for the reservoir permeability as shown in Table 1.

Table 1. Reservoir input parameters

Reservoir Parameters and well specifications	Case 1 Homogeneous Reservoir	Case 2 Heterogeneous Reservoir
Well length	800m	800m
Reservoir thickness	100m	100m
Reservoir Width	2500m	2500m
Reservoir Pressure	300bar	300bar
Porosity	0.2	0.2
Permeability	2000 md	2000md & 10000md
Oil viscosity	43.7cP	43.7cP
API gravity	18	18
Reservoir Temperature	24.87	24.87
Water gravity	1000 kg/Sm^3	1000 kg/Sm^3
Dissolved gas/oil ratio	80 Sm^3/Sm^3	80 Sm^3/Sm^3

A simple well completion was used, as more emphasis was placed on contrasting between the two inflow control devices, ICD and RCP. The well completion data is shown in Table 2.

Table 2. Well completion

Well completion parameters	Case 1 Homogeneous Reservoir	Case 2 Heterogeneous Reservoir
No of well segments	32	32
Length of well segment	25m	25m
No. of Packers	1	4
Total no. of ICDs/RCPs	62	56
No. of ICDs/RCPs producing water	8	8

3.2 Relative permeability

The relative permeability of a given fluid is the ratio of the effective permeability at a particular saturation to the absolute permeability. The relative permeability is used to predict the movement of oil, water and gas in the reservoir. The velocity of fluids flowing in the reservoir are dependent on the relative permeability (Dake, 1978). The reservoir used in the simulations was assumed to be water-wetted. Furthermore, Corey's model and the Stone II model were used in the determination of the relative permeability curves for water and oil. The relative permeability curves for the particular reservoir has to be specified in NETool. The estimated relative permeability curves are presented in Figure 1.

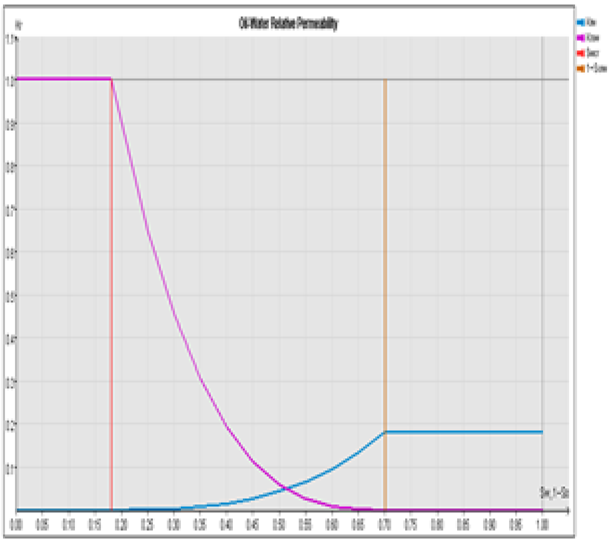

Figure 1. Relative permeability curve for water-wetted reservoir

3.3 Tuning of performance curves

To obtain updated performance curves for ICD and RCP, the constants in the equations were adjusted to fit the production rates as a function of pressure to experimental data. The functionality of the nozzle ICD is well-known, and the default values in NETool gave good fit to experimental data. The discharge coefficient for ICD was set to 0.79. Experimental data (Halvorsen *et al*, 2012; Mathiesen *et al*, 2011) were used to tune the RCP user input parameters x and y. The values of x and y were found to be 3.8 and 1.1 respectively.

3.4 Homogeneous Reservoir

When simulating the homogeneous reservoir, the reservoir parameters in Table 1 were utilized. The permeability of the reservoir was taken to be 2000mD as shown in Figure 2. Some zones in the near-well reservoir were assumed to have 100% oil saturation while other zones had 100% water saturation. At the heel area of the well, the water saturation in the first two zones was set to 100%. A drawing of the well with completion and packer is presented in Figure 3. Packers are used for zonal isolation, in order to prevent water flowing to other zones through the annulus. ICD and RCP completion was used when simulating oil production at different drawdown pressures. The drawdown was set as 5bar, 10bar, 15bar, 20bar, 25bar, 30bar. The diameter of the nozzle ICD was given as 5.0mm while the input strength parameter for the RCP was 1.0e^{-5}. The rest of the completion parameters used in the simulations can be found in Table 2.

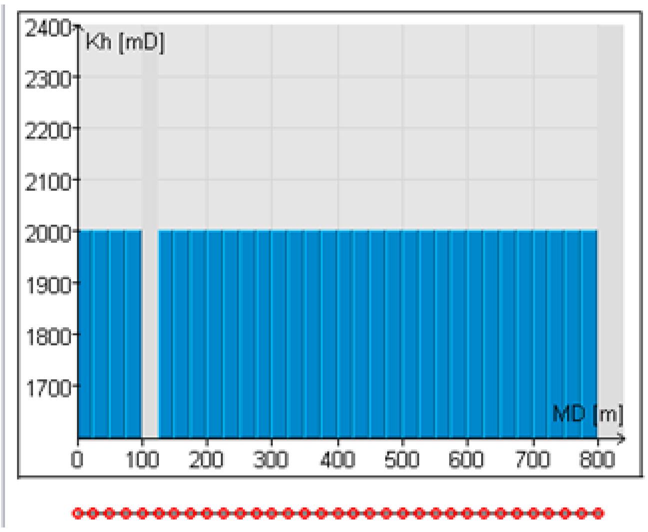

Figure 2. Permeability of homogeneous reservoir

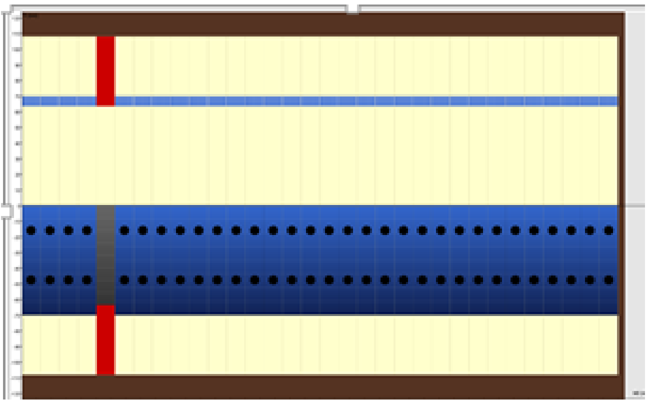

Figure 3. A sketch of the well with inflow controllers (black dots) and packers (red rectangels).

3.5 Heterogeneous Reservoir

In the case of the heterogeneous reservoir simulation, the permeability was set to 10000mD in two near-well zones and 2000mD in the rest of the zones as shown in Figure 4. The zones with high permeability were assumed to have water saturation of 100% while the zones with 2000mD had oil saturation of 100%. Zonal isolation using packers on both sides of the high permeability zones were applied. Figure 5 shows the well with completion and packers. Several drawdown pressures ranging from 5 to 30 bar were used to show the comparative strengths of the ICD and RCP. In addition, the percentage water-cut was also compared for the two types of inflow control devices.

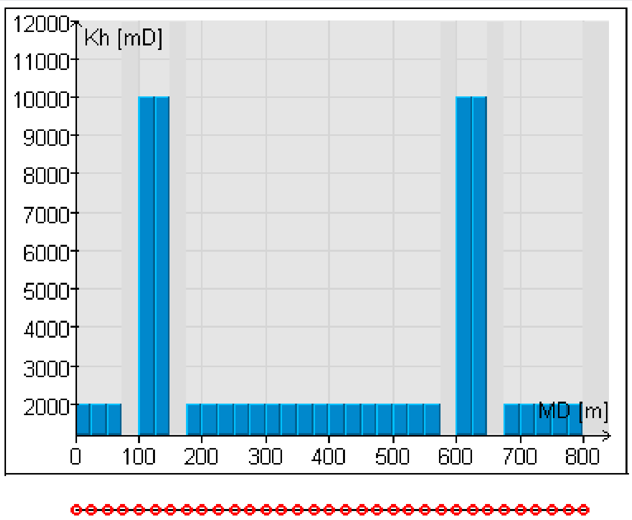

Figure 4. Permeability of heterogeneous reservoir

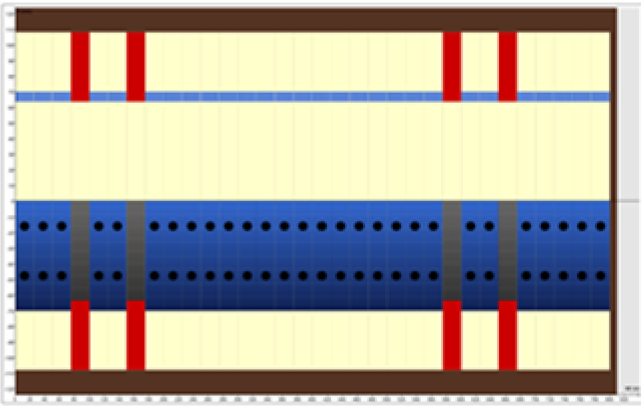

Figure 5. A sketch of the well with inflow controllers (black dots) and packers (red rectangels)

4 Simulation results and discussion

In this section, the results of the two simulation cases with varying drawdown pressures will be analyzed and discussed

4.1 Homogeneous Reservoir

Figures 6 and 7 show the pressures drop through the completion plotted against the oil and water flowrate per RCP and ICD. In Figure 6 the comparison between oil production through ICD and RCP is presented. As can be seen, RCP has a much steeper performance curve than ICD. The ICD has a strength of 2.2 bar. The ICD strength is defined as the pressure drop over the ICD when producing 1 m^3 of oil. By extrapolating the RCP curve, the strength is found to be about 17.5 bar. The strength of the inflow control, influence on the time of water breakthrough. It is also possible to produce with a higher drawdown when the inflow control has a high strength. Since NETool is a steady state simulator, the time of water breakthrough cannot be estimated. The simulations were therefore run assuming that the water breakthrough had already occurred. Figure 7 shows that the water production through ICD is significantly higher than through RCP. This can also clearly be seen in Figure 8 where the water-cut is plotted as a function of drawdown for RCP and ICD. The water-cut using RCP completion decreases from 14% to 6% when the drawdown is increased from 5 to 30 bar, whereas the water-cut using ICD completion decreases from 58% to 38% when the drawdown is increased from 5 to 30 bar. In Figure 9, the total production rates for oil and water are presented. At drawdown above 10 bar, the ICD are producing more oil, but also significantly more water than the RCP. ICD and RCP are both producing 450 m^3/h of oil at drawdown 10 bar, but at this pressure ICD is producing 10 times more water than RCP. These results indicates that a well with RCP completion can improve the oil production and increase the oil recovery.

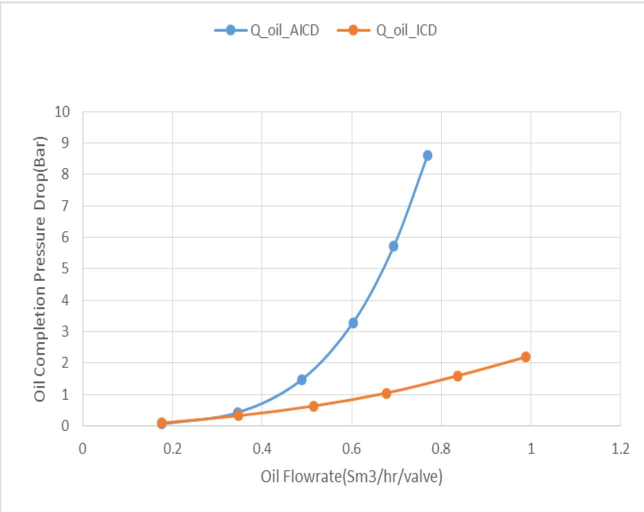

Figure 6. The plot shows the oil completion pressure relative to the oil flowrate per valve for AICD and nozzle ICD

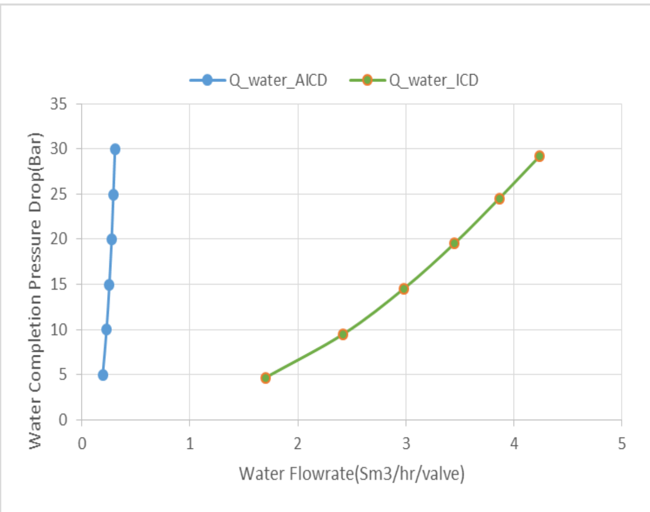

Figure 7. Comparison between the AICD and nozzle ICD showing the plot of water completion pressure versus water flowrate

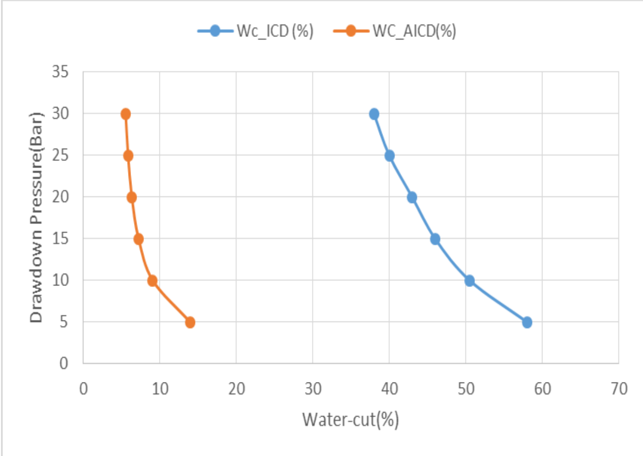

Figure 8. Comparison of water-cut between the AICD and nozzle ICD

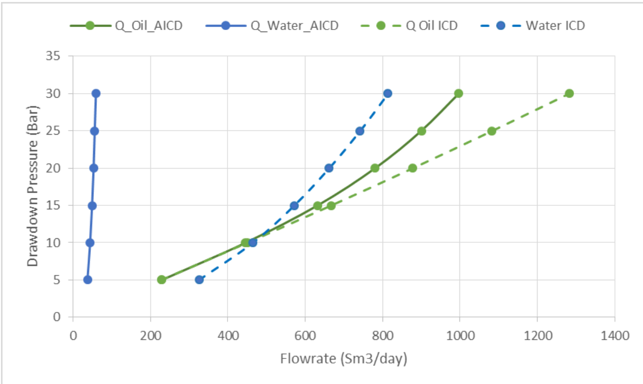

Figure 9. Total production rates as a function of drawdown; homogeneous reservoir.

4.2 Heterogeneous Reservoir

The two figures, Figures 10 and 11, represent the production rate of oil and water for the different inflow control devices with respect to the completion pressure drops. The pressure drop over RCP is proportional to the volume flow rate of oil in the power of about 4 (q^4), whereas the pressure drop over ICD is proportional to the volume flow rate squared (q^2). The strength of the RCP is approximately 10 times the ICD strength. The valve strength of the inflow control devices are calculated by taking the completion pressure corresponding to 1 m^3/h oil production. Figure 11 shows that the production rate of water per ICD is considerably higher than the water flow rate through RCP. At 15 bar differential pressure, the ICD is producing 12 times more water than the RCP.

The water-cut presented in Figure 12 clearly shows that the RCP has a significantly lower water-cut compared to the ICD. Both devices show a decreasing water-cut with increasing drawdown. The water-cut is defined as the ratio of water to total liquid in the well. It is important to have in mind that the water cut shown here is based on water production through 8 of 56

ICDs/RCPs. With time, more and more of the ICDs/RCPs will start to produce water, and the water cut will increase dramatically, especially for the ICD wells. Since the RCP is able to choke for water, RCP completed wells will be able to produce oil for a much longer period before they have to shut down due to high water-cut.

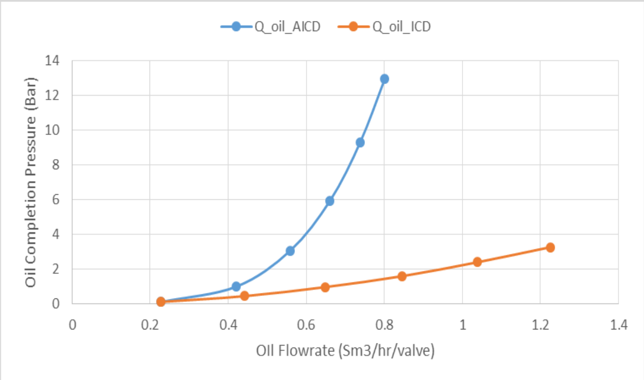

Figure 10. Plot shows the oil completion pressure relative to the oil flow rate per valve for AICD and nozzle ICD.

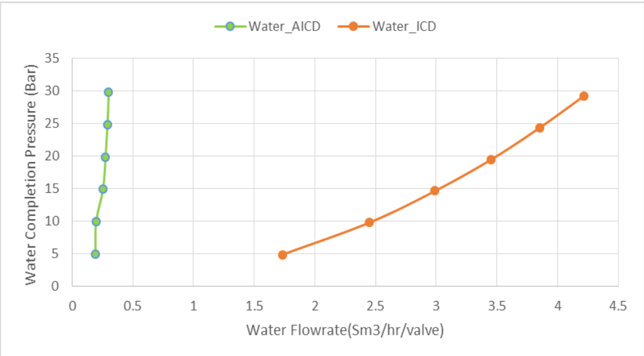

Figure 11. Comparison between the AICD and nozzle ICD showing the plot of water completion pressure versus water flowrate

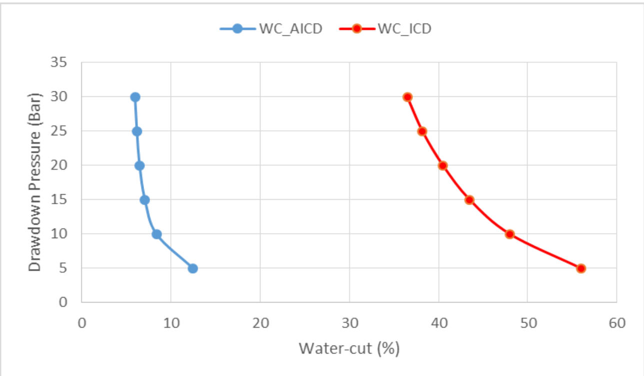

Figure 12. Comparison of water-cut between AICD and nozzle ICD.

Figure 13 show the total production of oil and water from RCP and ICD completed wells at drawdowns ranging from 5 to 30 bar. The flow rate is given in Sm^3/day. At 10 bar drawdown, the production rate of oil is about 500 Sm^3/day for both types of completion. The water production at the same drawdown is about 40 and 470 Sm^3/day for the RCP and ICD completed wells respectively. These results show that wells with RCP completion have a high potential to improve the oil recovery also from heterogeneous reservoirs with high permeable zones where water breakthrough can occur after very short time of production.

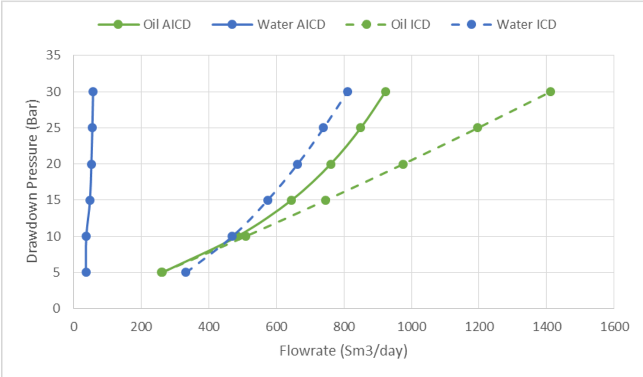

Figure 13. Total production rates as a function of drawdown; heterogeneous reservoir.

4.3 Comments to simulations and results

The simulations have shown that NETool is able to predict oil and water production for different types of well completion. Oil and water production is dependent on the permeability and the relative permeability in the reservoir. It is therefore crucial to have knowledge about the reservoir properties in order to estimate the most appropriate permeability curves for the different types of reservoirs. Production data are needed to tune the relative permeability curves for the particular reservoir. Experimental data are also needed to get a good prediction of the functionality of the RCP and ICD.

AICV completion has not been simulated in this study. However, the functionality of AICV, is that it acts as an ICD when it is surrounded by oil, and closes down to less than 1% of the flow area when it is surrounded by water. This means that AICV is able to produce high amounts of oil and negligible amounts of water after water breakthrough. Since the AICV closes off zones with water, a higher drawdown can be used, and oil can be produced with higher production rates. A rough estimate gives that at 25 bar drawdown, a well with AICV completion in the heterogeneous reservoir has the potential to produce 1200 m^3 oil and about 10 m^3 water per day. Simulations and experimental research confirming the potential of AICV for increased oil recovery are presented by Aakre et al. (Aakre *et al*, 2013; Aakre *et al*, 2013).

5 Conclusions

The near well simulation tool NETool have been used to simulate oil production from homogeneous and heterogeneous heavy oil reservoirs after water breakthrough has occurred. Inflow controls, RCP and ICD, and packers are used to reduce the water production. RCP has the ability of choking the water rate after breakthrough, whereas ICD only delay the water-breakthrough. NETool is a steady state 1-dimensional simulator, and it cannot predict the time of water breakthrough. However, the strength of the ICD and RCP indicates how much these two devices will restrict the production and thereby delay the time of breakthrough. The oil and water production using ICD and RCP completion have been simulated and compared. ICD is producing more oil than RCP, but it is also producing significantly more water. The well with ICD completion gave about 4 to 5 times higher water cut than the well with RCP completion. Simulations of homogeneous and heterogeneous reservoirs gave about the same results. Estimates indicates that by utilizing AICV completion the water cut can be reduced significantly without reducing the oil production.

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