Simulation of Light Oil Production from Heterogeneous Reservoirs

Well Completion with Inflow Control Devices

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Abstract

Water breakthrough is a big challenge in light oil production, and different types of inflow control devices are developed to delay or reduce breakthrough. Light oil production from a heterogeneous reservoir is simulated to study the effect of three types of inflow control devices, one passive control and two autonomous controls. NETool is used as the near-well simulation tool. The functionality of passive inflow control device (ICD) and the autonomous rate control production device (RCP) is included in NETool, whereas the autonomous inflow control valve (AICV) is simulated based on expected behaviour. The total production rates and the water cut versus drawdown and the performance curves for ICD, RCP and AICV are studied. The results confirm that RCP and AICV reduce the water production and water cut significantly. The water cut is about 27% for RCP and 44% for ICD at 15 bar. AICV is designed to close 99% for water, and produces negligible amounts of water. The RCP completed well produces about 310 m^3 oil and 110 m^3 water per day at drawdown 15 bar. ICD produces about 230 m^3 water per day, whereas AICV produces insignificant amount of water. The results confirm that the water production decreases with RCP and AICV compared to ICD. Delayed and reduced water production will result in increased oil recovery.

Keywords: light oil, heterogeneous reservoir, ICD, RCP, AICV, water cut, water breakthrough

1 Introduction

A major challenge in oil production is to increase the ability to recover the residual oil. Estimates show that although the oil is localized and mobile, more than half of the oil is remaining in the reservoir after shut down. There are different challenges regarding increasing the oil recovery, and the biggest challenge is water and gas breakthrough to the well. In this study, only water breakthrough in a heterogeneous light oil reservoir will be considered. Oils are categorized based on the density or °API (American Petroleum Institute) of the oil. API gravity is calculated by using the specific gravity of oil, which is defined as the ratio of oil density to the density of water. Light oil is specified by low viscosity, low specific gravity and high °API gravity.

New technology can increase the recovery in new and mature fields significantly. Production data from Statoil's horizontal pilot wells on the Norwegian Continental Shelf show that the cumulative oil production increased with about 20% when new inflow control technology was implemented (Halvorsen *et al.*, 2012) Reservoir and near-well models to show the potential of implementing the new technology are important in order to speed up the implementation of new completion technology. The near-well simulation tool NETool, is used in this study.

1.1 Well completion

Different types of passive Inflow Control Devices (ICDs) have been installed in a number of oil fields all over the world and the implementation has contributed to increase the oil production and recovery significantly compared to open-hole wells (Al-Khelaiwi 2007; Krinis *et al.*, 2009). Newer technology called Autonomous Inflow Control devices (AICDs) has the potential to increase the oil production and recovery even more. Halliburton, Statoil and InflowControl AS have developed AICDs based on different principles (Least *et al.*, 2012; Mathiesen *et al.*, 2011; Aakre *et al.*, 2013). Near well simulations with AICV completion, show high potential regarding increased oil recovery (Aakre *et al.*, 2013). Statoil has currently several wells completed with RCP at the Troll field where the purpose of the RCP is to restrict the gas and maintain the oil production. Results show that the cumulative oil production with RCP completion is 20% higher than a corresponding branch completed with ICDs. Reservoir simulations carried out prior to the installation of RCP, indicated an increased oil production up to 15% (Halvorsen *et al.*, 2012).

1.2 Water breakthrough

Early water breakthrough and high water production result in early shut down of oil wells and low oil recovery. Long horizontal wells are used to obtain maximum reservoir contact. Due to frictional pressure drop along the long well, the driving forces are different from one location to another. This is called the heel to toe effect. In a homogeneous reservoir, the oil production rate can be significantly higher in the heel than in the toe, and this may lead to early water or gas breakthrough in the heel. The heel toe effect is demonstrated in Figure 1. In heterogeneous or fractured reservoirs, early breakthrough will occur in the high permeable zones due to low flow resistance in the reservoir. Figure 2 presents a fractured reservoir, where the water has high mobility and flows easily to the production well. This is also the challenge in high permeable zones in heterogeneous reservoirs.

New and improved inflow control technology that can spontaneously choke or close for unwanted fluids can solve the problem with early gas or water breakthrough.

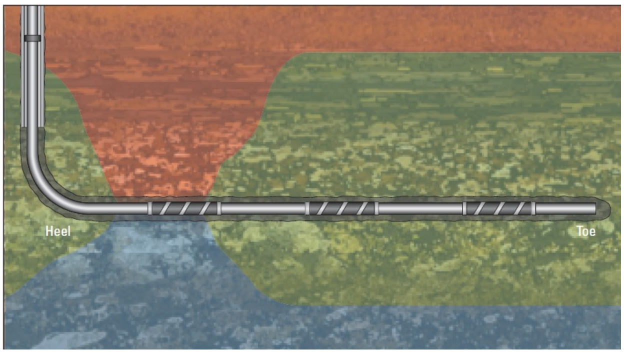

Figure 1. Heel toe effect. Water (blue) and gas (red) breakthrough in the heel (Ellis *et al.*, 2010)

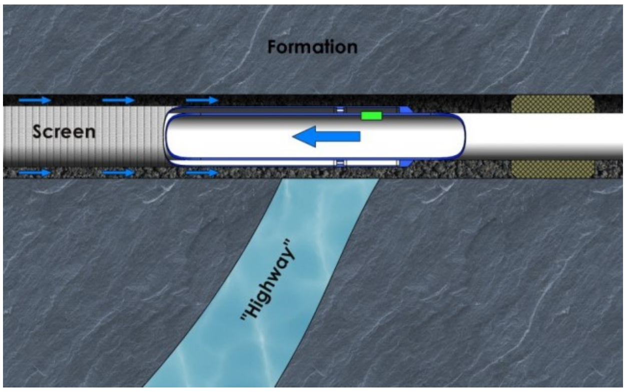

Figure 2. Fractured reservoir with water breakthrough (Aakre *et al.*, 2014)

2 Inflow control devices

Different types of inflow control devices are developed. One passive and two autonomous inflow control devices are described in this chapter.

2.1 Passive inflow control devices

Different types of passive Inflow Control Devices (ICDs) are developed to delay the early breakthrough by restricting the flow. In this study oil production, using nozzle ICD is studied. Well completion with ICDs includes a large number of ICDs evenly distributed along the well. ICDs are designed to give a more uniform oil production along the well. The diameter of each nozzle is chosen to obtain the desired pressure drop over the ICD at a specific flow rate. The pressure drop highly depends on the nozzle diameter and the density of the fluid and less on the viscosity. Passive ICDs are capable of delaying the water breakthrough significantly (Al-Khelaiwi, 2007), and the technology has opened up for production from reservoirs with thin oil columns. The total oil recovery increases significantly with use of ICDs. However, ICDs neither choke nor close for the undesired fluids like water, and after breakthrough, the whole well has to be choked to avoid the downstream separation facilities to be overloaded. Reservoir simulations have been performed for different types of ICD completions and the results have been useful to improve the ICD design (Krinis *et al.*, 2009). Krinis *et al.* used the reservoir model NETool to determine the optimal number and location of ICDs along the well, and they stated that the simulations were the key factor to succeed in optimization of the horizontal well performance. The principle behind the nozzle ICD is based on the following equations (Al-Khelaiwi, 2007):

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

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

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

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

2.2 Autonomous inflow control devices

In addition to the heel-toe effect that is initializing the coning, coning also occurs due to heterogeneities in the reservoir. Robust inflow control that can choke back and/or close locally the water producing zones has the potential to increase the oil recovery significantly compared to standard ICDs. Statoil has installed one type of Autonomous Inflow Control Devices (AICDs) called Rate Controlled Production (RCP) in wells in the Troll field (Halvorsen *et al.*, 2012). The RCPs delay gas and water coning and in addition, the RCPs have the capability to choke for low viscous fluids after breakthrough. Halliburton has developed an AICD that behave like a traditionally ICD before breakthrough, and choke for the low viscous fluids after breakthrough (Least *et al.*, 2012). The autonomous function of the AICDs, enables the wells to produce for a longer period of time, and the total oil production and oil recovery from a given field will increase (Least *et al.*, 2012). The AICDs are installed in the wells in the same way as the ICDs, and are suitable for production in long horizontal wells. In this study, simulations have been performed with Statoil's RCP.

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 (Halvorsen *et al.*, 2012; Mathiesen *et al.*, 2011):

$$\delta P = f(\rho, \mu) \,.\, a_{AICD} \,.\, q^x \tag{4}$$

$$f(\rho, \mu) = \left(\frac{\rho_{mix}^2}{\rho_{cal}}\right) \cdot \left(\frac{\mu_{cal}}{\mu_{mix}}\right)^y \tag{5}$$

$$\rho_{mix} = \alpha_{oil}\, \rho_{oil} + \alpha_{water}\rho_{water} + \alpha_{gas}\rho_{gas} \tag{6}$$

$$\mu_{mix} = \alpha_{oil}\mu_{oil} + \alpha_{water}\mu_{water} + \alpha_{oil}\mu_{oil} \tag{7}$$

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 the calibration density and viscosity.

InflowControl AS has developed an autonomous inflow control valve (AICV) which is completely self-regulating and does not require any electronics or connection to the surface. AICV gives low flow restriction for oil production and has the ability to close almost completely for water and gas. The valves will locally close in the zones with gas and/or water breakthrough, and simultaneously produce oil from the other zones along the well. The AICV technology utilize the fact that flow behavior through laminar and turbulent flow elements are different. The AICV technology consists of two different flow restrictors placed in series. The first one is a laminar flow restrictor and the second is a turbulent flow restrictor. Figure 3 presents a sketch of the combination of flow restrictors, where 1 is the laminar flow element and 2 is the turbulent flow element. The pressure in chamber B activates the piston in the valve to close or open. If oil is flowing through the AICV, the pressure drop through the laminar flow element is high, resulting in low pressure in chamber B and the valve is open. Water gives lower pressure drop through the laminar restrictor, resulting in high pressure in B, and the valve closes.

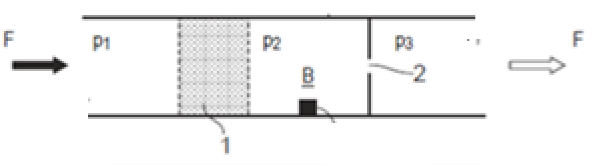

Figure 3. Combination of laminar and turbulent flow restrictors in series

The pressure drops through laminar and turbulent flow elements are expressed by Eq. (9) and (10) respectively. (Aakre *et al.*, 2013; Aakre *et al.*, 2014) The laminar flow element is considered as a pipe segment, and the pressure drop through the element is expressed as:

$$\Delta P = f \,.\, \frac{L.\rho.v^2}{2D} = \frac{64}{Re} \,.\, \frac{L.\rho.v^2}{2D} = \frac{32.\mu.\rho.v.L}{D^2} \tag{8}$$

where ΔP is the pressure drop, f is the laminar friction coefficient, ρ is the fluid density, μ is the fluid viscosity, L is the length of the laminar flow element, D is the diameter of the laminar flow element, Re is Reynolds number.

The pressure drop through the turbulent flow element is proportional to the density and the velocity squared, and is given as:

$$\Delta P = k.\frac{1}{2} \,.\, \rho \,.\, v^2 \tag{9}$$

where k is a geometrical constant, ρ and v is the fluid velocity.

AICV is a new technology and is still not included as an option in NETool. However, AICV has the same function as ICD in open position, and when closed, the flow rate through the valve is reduced to less than 1%. This relationship between open and closed valve is used to simulate the AICV functionality.

Near-well simulations are important to be able to anticipate or predict the economic potential of well completion with different types of inflow controllers. The near-well simulation tool NETool is used in this project.

3 NETool

NETool is a one dimensional steady state near-well simulation tool. The NETool models include fluid properties, reservoir properties and well completion. The required information is imported or defined by the user via a graphical user interface. NETool evaluates the logic and algorithms.

Regarding completion, different options are included in NETool. In this study, different types of inflow controllers are installed in a long horizontal well. The design parameters are specified by the user to fit the specific reservoir and fluid conditions. The well is divided into zones, and the user specifies reservoir and fluid properties for each zone. In addition, the user specify the implementation of inflow controllers, packers, etc. for each zone. The most important user defined inputs to NETool are described below.

3.1 Relative permeability

In numerical reservoir simulation, the relative permeability is significant to predict the oil, water and gas production during the reservoir operation. It is a big challenge to estimate the relative permeability curves for a given field. Relative permeability curves are determined based on experimental core plug tests, and models for relative permeability are developed based on the experimental data.

The relative permeability, K_i, is defined as the effective permeability divided by the absolute reservoir permeability. Darcy's law describes the absolute reservoir permeability as:

$$q = -\frac{k \cdot A}{\mu} \cdot \frac{dp}{dL} \tag{10}$$

where q is the volume flow rate, k is the absolute permeability, dp/dL is the pressure gradient, A is the reservoir cross section area and μ is the fluid viscosity.

The relative permeability is the ratio between the effective permeability and the absolute permeability, and is a function of the saturation of the different phases in the reservoir. (Selley, 1998; Ahmed, 2006)

$$k_{r,i} = \frac{K_i}{k} \tag{11}$$

where $k_{r,i}$ is the relative permeability for phase i.

In this study, the Corey model and the Stone II model are used to define the relative permeability curves for water and oil respectively. The Corey model [10] for predicting the relative permeability of water is given by:

$$k_{rw} = k_{rowc}\left(\frac{S_w - S_{wc}}{1 - S_{or} - S_{wc}}\right)^{n_w} \tag{12}$$

where k_{rw} is the relative permeability of water, k_{rowc} is the relative permeability of water at the maximum water saturation, S_w is the water saturation, S_{wc} is the irreducible water saturation, S_{or} is the residual oil saturation and n_w is the Corey fitting parameter for water.

The Stone II model estimates the relative permeability of oil in an oil-water system based on the following equation [11]:

$$k_{row} = k_{rowc}\left(\frac{S_w + S_{or} - 1}{S_{wc} + S_{or} - 1}\right)^{n_{ow}} \tag{13}$$

where k_{row} is the relative oil permeability for the water-oil system, k_{rowc} is the endpoint relative permeability for oil in water at irreducible water saturation and n_{ow} is a fitting parameter for oil. (Li &Horne, 2006)

3.2 Input to NETool

Different types of passive and autonomous inflow control devices are available in NETool. In this study the nozzle ICD and Statoil's RCP are utilized. The functionality and equations for these devices are presented in Chapter II. The diameter of nozzle ICD is set as 4 mm. The design parameters for the RCP, x, y and a_{AICD} are set as 4, 1.1 and 10^{-7} respectively.

AICV is a new technology and is still not given as an option in NETool. However, AICV has the same function as ICD in open position, and when closed, the flow rate through the valve is reduced to about 1% of the flow rate in open position. This relationship between open and closed is used to simulate the AICV functionality in NETool.

A sketch of the base-pipe including annulus, inflow control devices and packers are presented in Figure 4. The packers are installed to isolate the different zones, and thereby avoid annulus flow from one zone to another. The well has a total length of 500 m, and is divided 32 zones, with two inflow-controllers in each zones. Each section isolated with packers, includes three or two inflow zones. Three different cases are simulated, one with nozzle ICD, one with RCP and one with AICV.

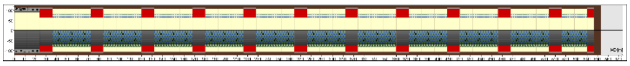

Figure 4. Well completion including packers (red squares) and inflow control devices (black dots).

Figure 5 represents the reservoir permeability along the production well. The reservoir is heterogeneous and has two high permeability zones with permeability 1D, and the permeability in the other is 100 mD. Figure 6 shows the oil saturation in the reservoir. The oil saturation is assumed as 100% in the low permeability zones, whereas the water saturation is assumed 100% in the high permeability zones. Since NETool is a steady state simulation tool, it is not possible to study the changes in oil and water saturation with time nor is it possible to determine the breakthrough time. These simulations are therefore based on the assumption that the water breakthrough has already occurred in the high permeable zones, whereas the low permeable zones are still saturated with oil. This simplification of the oil and water saturation in the reservoir is made to be able to study the effect of the different inflow control devices after water breakthrough.

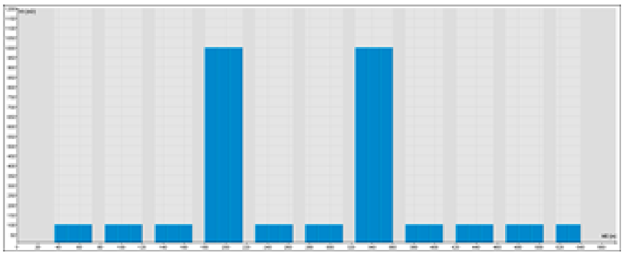

Figure 5. Permeability. The permeability is 1D and 100 mD in the high and low permeability zones, respectively.

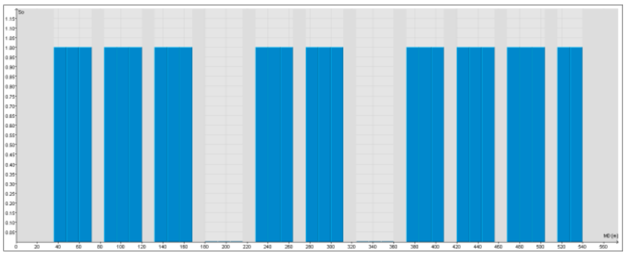

Figure 6. Oil saturation. The low permeability zones are saturated with oil (100%) and the low permeability zones are saturated with water (0% oil).

Tab. 1 represents a summary of the input parameters used in this study, and the estimated relative permeability curves are presented in Figure 7.

Table 1. Input to NETool

Reservoir Parameters and well specifications	
Well length	550 m
Reservoir thickness	200 m
Reservoir width	4000 m
Reservoir Pressure	302 bar
Porosity	0.20
Permeability	100 mD and 1D
Oil viscosity	2cP
°API gravity	33
Reservoir Temperature	68°C
Dissolved gas/oil ratio	**130^3/Sm^3**

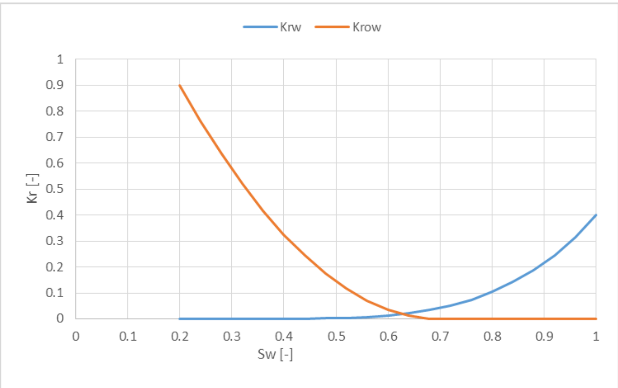

Figure 7. Relative permeability curves for oil-wetted reservoir.

4 Results and discussion

The aim of this study is to find the effect of different types of inflow control devices on oil and water production. Three different cases are performed, one with ICD completion, one with RCP completion and one with AICV completion. The input parameters for the simulations are the same for the three cases. The simulations are run with drawdown of 2, 5, 10 and 15 bar, and the total production rates versus drawdown, the water cut versus drawdown and the performance curves for ICD, RCP and AICV are studied.

These shortcuts Figure 8 shows the oil performance curves for ICD, RCP and AICV. The curves are calculated based on the total production rate from the well and presented as the volume flow of oil through one inflow control as a function of pressure drop over the completion. Due to low permeability in the oil zones, the pressure drop in the reservoir is high which gives a low differential pressure, ΔP, over the inflow controls and low production rates. At the actual ΔP over the inflow control devices, RCP gives the lowest pressure drop per volume flow. The oil flow rate through RCP is about 500 l/h at differential pressure 0.7 bar. ICD and AICV produces less than 500 l/h at ΔP 1.15 bar and 1.25 bar respectively. Figure 9 shows the typical functionality of ICD and RCP. The curves are plotted based on the equations presented in Section 2, and shows that RCP has higher production rates versus ΔP at low ΔP, whereas above a certain pressure it changes. The reason is that ΔP is proportional to the volume flow in the power of 4 for RCP and proportional to the volume flow squared for ICD. Figure 10 gives the comparison between the water performance curves for ICD, RCP and AICV. The water is produced from the high permeability zones where the flow restriction through the reservoir is low. This results in high production rates of water and high pressure drop across the completion. The figure shows that the RCP is choking for water and that the ICD is producing significantly higher amounts of water compared to RCP at ΔP above 1 bar. The functionality of AICV is to close almost completely for water, and at closed position, the flow rate will be about 1% of the flow rate through open valve. Since AICV is not included in NETool, the AICV was simulated by using 4 mm ICDs in the oil zones and 0.4 mm ICDs in the water zones. This will indicate the potential of AICVs. The water curve for AICV shows that the amount of water flowing through the AICV is insignificant.

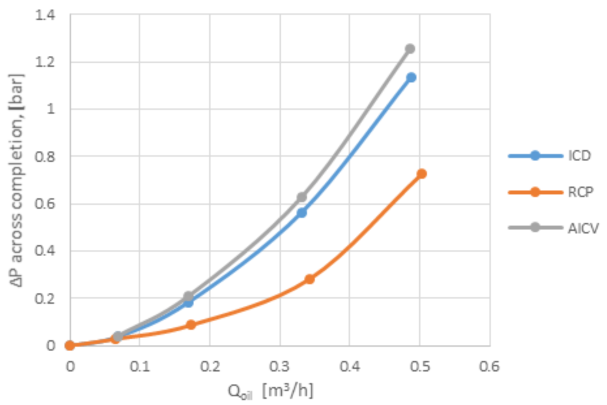

Figure 8. Oil production as a function of differensial pressure through the inflow controllers.

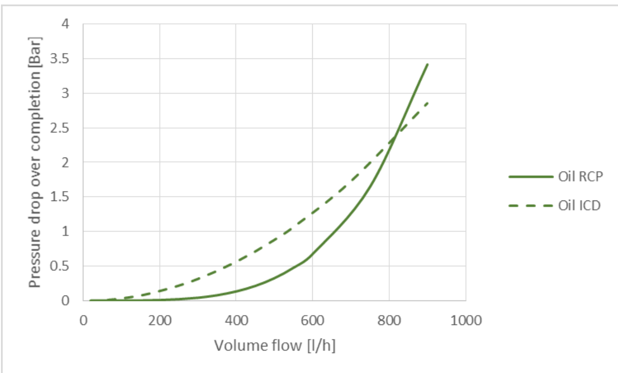

Figure 9. Calculated performance curves for RCP and ICD.

Figure 11 presents the water cut versus drawdown when using ICD, RCP and AICV. The water cut decreases with increasing drawdown, and at drawdown 15 bar the water cut is about 27% for RCP and 44% for ICD. The water cut differs less at low drawdowns, and at 2 bar, the water cuts are 59% and 64% for RCP and ICD respectively. When the AICV technology is used, the water cut is negligible for the range of simulated drawdowns.

The total production rates for the horizontal well are presented in Figure 12. The figure shows that ICD is producing more water than oil when the drawdown is lower than 10 bar. At higher pressure drops, the oil production is higher than the water production. However, the well is producing water from only 6 zones and oil from 26. RCP is designed to choke for water, and the oil production exceeds the water production at drawdown higher than 3 bars. The ratio between the oil and water production depends on the relative permeability, the fluid properties and the fuctionallity of the inflowcontrol devices. Since ICD is a passive inflow control, the water flow will not be restricted, and water through each ICD will be produced at higher flow rates than oil. RCP is autonomous and chokes for water, which results in low water production and unrestricted oil production at the range of drawdowns used in this study. The simulations are able to predict the benefits of using autonomous inflow control devices.

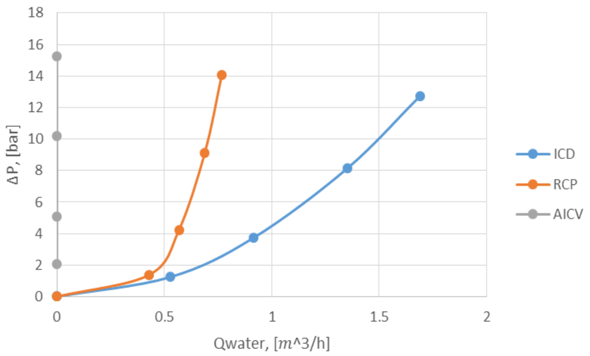

Figure 10. Water production through ICD, RCP and AICV

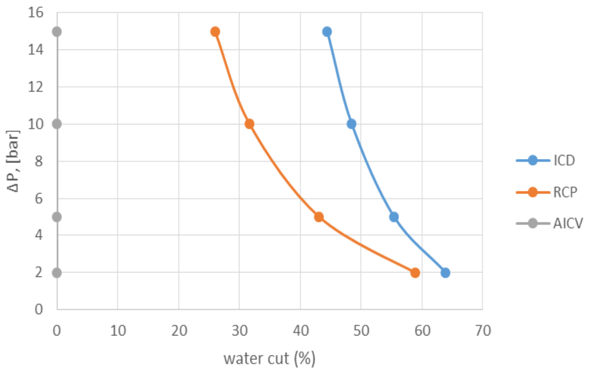

Figure 11. Watercut as a function of drawdown.

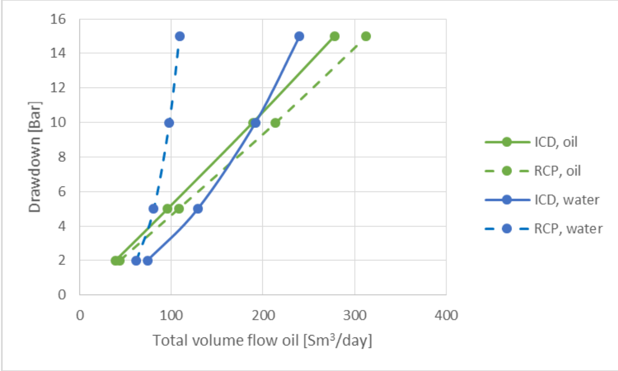

Figure 12. Total production rate of oil and water as a function of drawdown.

5 Conclusions

Water breakthrough is a big challenge in light oil production, and different types of inflow control devices are developed to delay, reduce or avoid breakthrough. Light oil production from a heterogeneous reservoir is simulated to study the effect of the three types of inflow control devices, nozzle ICD, autonomous RCP and AICV. NETool is used as the near-well simulation tool. The functionality of ICD and RCP is included in NETool, whereas AICV is simulated based on expected behaviour. The simulated horizontal well is 550 m long and packers and inflow control devices were evenly distributed along the well. The wells with ICD, RCP and AICV completion were simulated using different drawdowns ranging from 2 to 15 bar. The total production rates versus drawdown, the water cut versus drawdown and the performance curves for ICD, RCP and AICV were studied. The results confirm that autonomous inflow controls, RCP and AICV, reduce the water production and water cut significantly compared to passive ICD. The water cut decreases with drawdown, and is about 27% for RCP and 44% for ICD at 15 bar. When the AICV technology is used, the water cut is negligible for the range of simulated drawdowns. RCP gives the highest oil production rate at drawdown ranging from 2 to15 bar, but this is expected to change when the drawdown is further increased. The RCP completed well produces about 310 m^3 oil and 110 m^3 water per day at drawdown 15 bar. ICD produces about 230 m^3 water per day, whereas AICV produces a negligible amount of water. The results confirm that the water production decreases with RCP and AICV compared to ICD. Delayed and reduced water production will result in increased oil recovery.

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